COMMUNAUTÉ FRANÇAISE DE BELGIQUE
UNIVERSITÉ DE LIÈGE – GEMBLOUX AGRO-BIO TECH

A FEASIBILITY STUDY OF DIRECT INJECTION SPRAYING TECHNOLOGY FOR SMALL SCALE FARMING: MODELING AND DESIGN OF A PROCESS CONTROL SYSTEM

Abdellah EL AISSAOUI
Dissertation originale présentée en vue de l'obtention du grade de docteur en sciences agronomiques et ingénierie biologique

Promoteurs :

Pr Frederic Lebeau	ULg (Gx ABT), Belgium
Pr Karim Houmy	IAV Hassan II, Morocco

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Abstract

El Aissaoui Abdellah (2015). *A feasibility study of direct injection spraying technology for Small Scale Farming: Modeling and design of a process control system.*
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Abstract: The study aims to develop a process controller of direct injection spraying system (DIS) that can fit to carry out precise chemical application using variable rate application based on speed sensing in the context of small scale farming. It has the specific objectives of studying the feasibility of DIS by optimizing the hydraulic system and the process control designs as the main requirements for the best system reactivity and performance. The final design of DIS assessed to implement hydraulic system (hardware) and process controller (software) of a sprayer framework mounted on a rolling chariot propelled by walker operator. A logical approach is used of reviewing the state of art and formulating a specification book to develop a cost effective prototype to eventually adapt DIS expertise to the context of small scale farming. The demarche consists on giving low cost solution of variable rate technology to solve the technical problems related to usage and inefficiency of pesticide application mainly done by portable sprayers.

The state of art gives a light on the development process of direct injection spraying technology (DIS) within the scope of precision agriculture progress. It also deals with technical options, advantages and problems related to DIS and control engineering solutions developed for improving spraying application efficiency and safety measures for human and environment.

After that we have specified requirements of the researched DIS prototype by referring to existing art of DIS technologies and by diagnosing problems of chemical application in the context of small scale farming. It concerns specifically the technical requirements, setting values and performance of DIS process controller according to the working conditions of intensive cropping in small farming.

The materials and methods consist on presenting the approach used for modeling the DIS prototype (splitting the problematic to the two main design aspects of hydraulic system and process control system) and evaluating it in laboratory conditions using simulated velocity data input. The data acquisition system is implemented for assessing the performance of DIS hydraulic and process controller performances. After that, the process controller is

implemented in a cost effective electronic kit (box) to be mounted on a small sprayer framework propelled by worker.

The hydraulic modeling of DIS served for optimizing the lag transport task as main problem of system reactivity performance and concentration process change. An algorithm is implemented in VB program to assess effect of hydraulic serial boom design (diameter and number of mounted nozzles in serial scheme) on flow dynamic to find compromise between lag transport, mixing ability (turbulence) and friction loss tasks that yield lateral and longitudinal uniformities application of standard boom layout. The modeling results showed lag transport and uniformity of respectively 2 s and 96 % for optimal conventional boom of 6 mm inner diameter having ten tip nozzles (ISO11003, 1.2 L/min~3bars). To solve systematic problem of lateral miss uniformity of serial boom layout (standard scheme), improved parallel boom layout (equidistant tubing lines of 4 mm diameter) is adopted for obtaining an even lag transport between nozzles. The test of parallel boom layout showed even lag transport approximating 1.5 s for ten mounted nozzles. The total response time of DIS is optimally improved to be within 2.5 s by installing electrical pumps close to boom and injecting chemical in suction side to the carrier pump assumed to perform online mixing without use of static mixer.

The PID feedback controller is modeled in MATLAB^{TM} software. The process is considered as a first order process having a time constant of 0.2 s and a delay transport less than 2 s. Two control strategies of constant carrier flow control (CCFC) and total flow control (TFC) are modeled and implemented for test in laboratory conditions. Both strategies were tested and evaluated on the basis of different solicitations of variable speed input within the range of 0 - 2 m/s as a field working condition of walker operating a rolling sprayer chariot.

Finally, on the basis of the results of modeling and experimental assessment, an affordable kit of PLC process controller and PWM modules for actuating carrier pump and metering pump is performed in compact electronic box for potential usage on small sprayer framework to be propelled by walker operator in agricultural field. The controller is based on a PLC microcontroller implemented for carrying out a constant carrier flow rate and a variable chemical injection rate proportionally to the operating speed. The prototype is tested for applying variable rate application using simulated step solicitations within the range of the operator working conditions of 0 - 2 m/s. The study showed the feasibility of implementing a cost effective process controller design for applying variable rate chemical in small farming context. The controller is adaptable for sprayer mounted on wheeled chariot to be propelled by worker assumed to walk at variable velocity.

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Dedication

For the memory of Mother, Grandfathers and Grandmothers,

To my Father,

For giving me power and protection during my childhood,

For educating me and assisting me to endure and to overcome life constraints and barriers,

To my cheerful family,

Naima, Mohamed Adnane, and rose Rim,

For supporting me and giving me the sense of happy living and worship,

To all family members,

To all friends and colleagues.

Little wisdom…

Wisdom, Experience, Knowledge, Theory and Practice

In nature, everyone always has a reason. If you understand the reason, you do not need experience…Wisdom is the daughter of experience.

[Leonard De Vinci]

The knowledge is acquired through experience; everything else is just information.

[Albert Einstein]

Theory is when we know everything and nothing works. Practice is when everything works and nobody knows why. When we met theory and practice: Nothing works ... and nobody knows why!

[Albert Einstein]

Happiness and Progress

Happiness is when your actions are in accordance with your words.

[Ghandi]

Happiness is always a by-product. It is probably a matter of temperament, and for anything I know it may be glandular. But it is not something that can be demanded from life, and if you are not happy you had better stop worrying about it and see what treasures you can pluck from your own brand of unhappiness.

*[**Robertson Davies**]*

The word progress is meaningless as long as there are unhappy children.

[Albert Einstein]

Knowledge and Imagination

Imagination is more important than knowledge. Knowledge is limited; whereas imagination embraces the entire world, stimulates progress, provokes evolution.

[Albert Einstein]

Many times in my life, reality disappointed me because when I perceived it, my imagination which was my only way to enjoy the beauty, could not be applied to it regardless to the inevitable law implying that we cannot imagine else that what is absent.

[Marcel Proust]

Life is a mystery to be lived, not a problem to solve.

[Ghandi]

God's Light, Creature and Guidance

Allah is the Light of the heavens and the earth. The example of His light is like a niche within which is a lamp, the lamp is within glass, the glass as if it were a pearly [white] star lit from [the oil of] a blessed olive tree, neither of the east nor of the west, whose oil would almost glow even if untouched by fire. Light upon light. Allah guides to His light whom He wills. And Allah presents examples for the people, and Allah is Knower of all things. (Ch24, V35)

In the creation of the heavens and the earth, and the alternation of night and day, and the ships that run in the sea with that which profits men, and the water that Allah sends down from the sky, then gives life therewith to the earth after its death and spreads in it all (kinds of) animals, and the changing of the winds and the clouds made subservient between heaven and earth, there are surely signs for a people who understand. (Ch2, V164).

[Quran]

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Terminology (ASABE Standard)

Active ingredient (a.i.) rate: *The amount of active ingredient applied per unit treated, expressed in terms of mass per relevant unit treated (kg or L/ha; mg a.i./m^3).*
Application rate (or technical application rate): *The amount of any material applied per unit treated. May be expressed as active ingredient or formulated product in L/ha.*
Application variation (spray pattern uniformity): *Expressed as the coefficient of variation (CV) of deposits collected by flat samplers or cups in the 2-dimensional plane of the field.*
Boom sprayer: *A sprayer apparatus consisting of a pressure source and controls, and employing a boom with atomizers (hydraulic, rotary or other).*
Carrier (diluent): *A gas, liquid, or solid used to dilute the active ingredient and give it volume and mass to aid in metering and delivery.*
Concentration: *Amount of active ingredient contained in the chemical formulation expressed as a percent or mass per relevant unit basis (mg a.i. /L).*
Deposit density: *Number of droplets deposited per unit area (impact/cm^2). It can be measured visually from deposits on cards, natural materials, or slices.*
Deposit rate: *The amount of any material deposited per unit area.*
Deposit variation: *Expressed as the coefficient of variation of any number of statistical indicators of droplet-stain deposition on targets at different points in a canopy.*
Diluent: *A gas, liquid, or solid used to reduce the concentration of the active ingredient in the formulation or application (the terms signify water in this document).*
Direct injection lag time: *The interval of time required to deliver the mix of product and diluent to the discharge point (nozzle).*
Process lag times depend of three properties of the process influencing flow dynamic according to capacitance, resistance and transportation time.
Direct injection lag transport: *The interval of time required for transport of concentration mixture of product and diluent to the discharge point (nozzle).*
Direct injection sprayer: *Sprayer that on-board meters and mixes one or more products with diluent. No tank mixing required.*
Drift: *The movement of liquid or particulate material outside the intended target area by air mass transport or diffusion.*
Effective spray deposit rate: *The mean deposit from center to center of adjoining swaths.*
Efficacy: *Percentage of control of targeted pest after application and appropriate time intervals.*
Formulation rate: *The amount of formulated product applied per unit treated, expressed in terms of mass or volume per relevant unit treated (L or kg/ha; mg/m^3; mg/plant).*
Formulation: *The form of a chemical that is supplied to the user, and which includes both the active and inert ingredients.*
Manually carried or operated sprayers: *A sprayer apparatus that is carried or operated by an individual.*
Mean deposit rate: *The average amount of deposit over the entire spray swath.*
Spray mix uniformity: *Uniformity of product and diluent determined by sampling at the nozzle.*
Variable rate applicators: *Application device that has the capacity to intentionally vary the spray or dry product rate based on a predetermined map or by a sensor.*
Volume deposit rate: *The amount of spray liquid deposited per unit area. (L/ha, gal/ac, µg/cm^2).*
Volume rate (or volume application rate): *The total amount of spray liquid applied per unit treated (L/ha; mL/m^3; L/plant, or L/tree).*

List of Abbreviations

a (m/s^2)	Acceleration
AC	Alternative current
AI	Air induction (nozzle)
ASABE	American Society of Agricultural and Bio resource Engineering
BDIS	Boom direct injection system
C	Chemical concentration
CCFC	Constant carrier flow control
CDIS	Central direct injection system
Ci	Chemical concentration input or at injection point
Cm	Chemical mixture concentration
Cn	Chemical concentration at nozzle
CTS	Closed transfer system
CV	Coefficient of variation or control volume
D	Diameter
DC	Direct current
DIS	Direct injection system
DPAE	Electronic spray control using proportional flow rate to forward speed
e, e(t)	Error (average or instantaneous error),
ECPA	European Crop Protection Association
Eq(s).	Equation (s)
FAO	Food and Agriculture Organization
g	Gramme
G	Transfer function
gpm	Gallons per minute
in	Inch
IPM	Integrated pest management
ISO	International Standard Organization
k	Constant of conversion unit used in TAR equation
K, K_d	Static gain, derivative gain
kg	Kilogram
Km/hr	Kilometer per hour
k_n	Orifice nozzle coefficient
k_v	Voltage correction factor
L/ha	Litre per hectare
PAU	Precision Agriculture Unit
m, mm	Meter , millimeter
m/s	Meter per second
mce	Water column meter for measuring pressure
min	Minutes
mV	Millivolt
NDIS, DNI	Nozzle direct injection system
Ni	Nozzle of index i
pi	Constant (22/7)
PID	Proportional integral derivative
PLC/PIC	Programmer logic/integer controller
PWM	Pulse Width Modulation
Q	Carrier flow rate
q_{inj}	Injection flow rate

q, qi , qn	*Flow rate of nozzles (without or with indices i and n)*
rpm	*Revolution per minute*
RPU	*Rational pesticide use*
s	*Second*
SD	*Standard deviation*
TAR	*Technical application rate of chemical formulation (L/ha)*
TFC	*Total flow control*
t_c	*Lapsed time*
T_l	*Lag time*
T_{tr}	*Lag transport*
USDA	*United States Department of Agricultures*
V (m/s)	*Velocity (m/s)*
V	*Volt*
VRA	*Variable rate application (technology)*
VAR	*Volume application rate of chemical mixture (L/ha)*
VB	*Visual basic*
VRT	*Variable rate Technology*
VVMC	*Variable volume metering/crushing*
W	*Watt*
W_b	*Boom width*
WSP	*Water sensitive papers*
XR	*Extended range (nozzle)*
τ	*Time constant or time reaction of a concentration process change*

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Chapter 1: General Introduction

The biggest challenge for agriculture today consists on feeding sustainably a growing population and protecting precious natural resources against pollution. Agricultural technologies can allow farmers to grow more crops on less land while reducing chemical use. However, more efforts should be integrally focused on shifting actual farming behavior toward sustainable farming and protecting environment from degradation and irrational diffusion of chemical.

Small scale farmers in developing countries are facing serious problems of accurately and safely applying pesticides by hand-operated sprayers. Pesticide overdosing and hazardous diffusion are very common in small farms due to poor application efficiency. Accurate and timely applications of pesticides are of increasing importance in an integrated pest management (IPM) program to minimize pollution (Van Emden and Peakall, 1996).

The agricultural engineering branch of FAO (1998) evaluated pesticide application techniques in 17 countries of West Africa. The report showed that the portable spraying equipments are mostly used and concluded that farmers lack knowledge and means to efficiently protect their crops against pests and this problem overruled problem of health and environmental hazards. Manual application methods potentially increase risks during spraying process and risks during mixing chemical ingredients, filling and cleaning sprayers which have been shown to have a significant impact on human health and environmental pollution. In another study, most third world smallholder pesticide users are still using those equipments that grossly contaminate themselves and the environment (Matthews and Friedrich, 2004).

A layout of a policy was prepared on pesticides and their application in developing countries. The importance was given to the inevitability of pesticide use by farmers and the role that policy makers could play for promoting research and extension programs on rational pesticide use (RPU) as a sub-set of IPM. This later combines accurate diagnosis of pest problems, selection of less hazardous pesticides and improved application to optimize dose transfer to the biological target, reducing costs, residues, operators and environment exposure (IPARC, 2004).

The United State Department of Agriculture (USDA, 2006) funded a three-year extension project to assess the use of back-pack sprayers by small organic farmers. The study evoked technical problems due to varying designs and standards used by manufactures, and the lack of back-pack sprayers' turnkey information supporting accurate and efficient applications. The study showed that 62.5% of back-pack sprayers of eight labels have an average rating less than 50% due to differences in pumping efficiency.

According to OECD (2000), the Norwegian referential of pesticide risk indicators classifies manually operated sprayers as application method that induces high exposure risk for user. Typical situations in which the user can be exposed to pesticide are during mixing and loading the product in the tank and when applying the diluted product.

New technology for chemical application has means of improving pesticide sprays efficiency and therefore minimizes human and environmental risks during application, particularly, with advances in computer and control technologies. However, this potential should be concretized by policy-makers, regulators and agrochemical companies for benefiting society in general as pesticide usage "best practice" improvements. The role of application technology in reducing risk of pesticides residues in food is not yet recognized. Residue depends on active ingredient used on the target and the time of its application.

Further advances for reducing operator and environment contamination could limit human intervention by carrying pesticides in closed transfer systems. In this regard, direct injection sprayers are of great importance to develop this process (Matthews, 2007). Direct injection is an electronically controlled system in which a pesticide is injected into a carrier. Application rate management is a real time operation done by devices to maintain spatially an even distribution of chemicals independently of a variation in working speed. The advantage of using sprayers equipped with an integrated direct injection system results in keeping separately chemical and carrier, and only the required pesticide amount is diluted online. Therefore, problems of washing water, left-over, tank mixtures and exposure of applicators during mixing and loading, are systemically avoided.

1.1 Problems of chemical application in developing countries

In North Africa countries, as in others developing countries, chemical application in small scale farms, is problematic due to lack of equipment performance for carrying out efficient applications. In fact, small farmers practicing cereals, leguminous and horticulture crops are facing problems to apply plant protection product safely and accurately due to lack of possibility to acquire or rent efficient spraying equipment. They mainly use hand operated knapsack sprayers (90%) that potentially induce hazardous diffusion and chemical overdosing.

The application by knapsack sprayer is a plodding and time consuming activity. The working capacity of one half day per hectare is an average for a walking worker operating hand lever sprayer to apply chemical with one nozzle's lance. The deficiency of such sprayer is due to its inability to apply chemical at reduced volume rate as pump pressure potential is low. Demand for using reduced volume rate (100 L/ha) in arid area is important to minimize water use in chemical application and to reduce logistic for pumping and carrying water, filling and mixing hand operated sprayer. The risk of pollution and operator contamination by chemical is potentially high during this filling and mixing process. Furthermore, operator cannot maintain constantly an even distribution and application rate because of the occurring variation of the pump flow rate and the operating speed that create intolerable application errors.

The idea of proposing a new sprayer design takes advantages from the possibility of solving such constraints due to use of hand operated sprayers and their lack of performance. It is likely to develop a prototype of small trailed sprayer based on bi-wheels or tri-wheels chassis and carrying a multi nozzles boom. The prototype can be designed to be propelled by a walker worker as alternative to improve conditions of spraying pesticides compared to portable sprayers. Furthermore, the use of direct injection and precision metering of chemical can be of great importance to solve the problem of application rate errors due to variation of working speed in agricultural field and to reduce risk contamination for the human and the environment.

However, the challenge in developing technology for variable chemical application potentially adapted for small scale farms in developing countries cannot be fully approached without apprehension of technical, economical and sociological aspects related to the sprayer design. The adapted design could satisfy the criteria of simplicity and affordability to promote such a new spraying technology to be adopted in small farming system.

According to Fowler (2000), chemical sprayers suitable for small-scale farmers in developing countries should require as little water as possible, be small but light and robust, be ground metered, be simple but profitable to use, be acceptable to both the farmer and the laborer, affordable and produce minimal drift. Abdul-Fattah et al (2001) designed and evaluated a peristaltic pump of iroko wooden wheel and rubber tubing for precise application of herbicide with variable metering proportional to working speed. They stated that design of cost effective pump contribute to promote sustainable agricultural development in arid and semi arid regions of developing countries and lead to economic gain and protection of the environment.

1.2 Objectives

The present study focuses on a study of the feasibility to develop a variable rate spraying technology based on chemical direct injection that can be potentially adapted in the context of small farmers in developing countries. The justification of the project comes from the actual statements of pesticide use deficiency and inaccuracy of methods used to apply chemical in small scale farms.

The choice of sprayer prototype development based on direct injection metering system comes from the technical advantages that presents in terms of precision application, safety and energy use efficiency. The direct injection spraying method makes possible development of an electrical variable rate applicator based on direct current (DC) battery and process control system to actuate carrier flow pump and injection metering pump through the variation of speed rotation of motors with a pulse width modulation technique (PWM).

Designing an automatic metering system is of great importance to limit operator influence for carrying out accurate application rate. In fact, small farmers do not have accessibility to variable rate sprayers as they mainly use back-pack sprayers and do not have the possibility to use sophisticated spraying equipments through sharing or local service.

This study aims to develop a simple, accurate and affordable direct injection spraying system to be used for small scale farming. The following objectives are particularly accomplished on the logical basis of reviewing the state of art and studying technical feasibility of DIS in terms of the framework, the hydraulic and the process control designs:

- The first part gives a review on the development process of direct injection spraying technology within the scope of precision agriculture progress. It also deals with technical options, advantage, problems related to DIS systems and the control engineering solutions developed to improve safety measures of spraying application.
- The second part focuses on establishing requirements and specifications of the suggested prototype of direct injection system. It provides technical requirements and set values of DIS process controller and of the working conditions for its use in small scale farming,
- The third part consists on presenting materials and methods used for modeling hydraulic layout and process controller of DIS, studying performance of DIS in laboratory conditions and finally presenting the DIS process controller in electronic box for an eventual usage on the sprayer framework. The hydraulic modeling of DIS serves to optimize lag transport task for the best dynamic performance of the concentration process change. Installation of the test bench of DIS on the basis of the

modeling results serves for evaluating the performance of the process controller using simulated solicitations of the field working conditions.

- The fifth part consists on presenting and discussing modeling and experimental results. The modeling results concern hydraulic circuit and process control of DIS. Two control strategies are modeled and implemented for test in laboratory conditions. The strategies of constant carrier flow and total carrier flow were tested and evaluated for different solicitations of variable speed potentially adapted to field working conditions of walker operators.

  Results concerns also a test of the process controller mounted in an electronic box for ulterior usage on the sprayer framework in the field crop. The controller is based on a PLC microcontroller implemented to perform constant carrier flow and variable chemical injection. The prototype is tested for applying variable rate application using simulated speed solicitations within the range of field working conditions.

1.3 Dissertation outline

The present thesis was prepared on the basis of actual logical progress followed to study the feasibility of developing direct injection spraying system adapted for small scale farming. In fact, there is a potential need to adequately apply variable chemical rate for intensive cropping systems based on excessive use of chemical to improve production in small scale farms.

1.3.1 Chapter I

The first chapter has introduced the problematic as perceived in developing countries and defined the objectives of the thesis. An outline is attached to show the planning used to organize the dissertation.

1.3.2 Chapter II

The second chapter treats the state of art on the direct injection spraying technologies, the progress of process control and electronic technologies to evaluate feasibility of using variable rate spraying technology in the context of small scale farming. In fact, the feasibility of designing direct injection spraying technology for the targeted context comes from the hypothesis that affordability of electronic actuators and sensors makes possible the implementation of cost effective design of variable rate sprayer. The advantages of doing accurate and safe chemical application and of high water and energy use efficiencies also make possible the design of a sprayer based on electrical batteries for its power supply.

The review treats also the performance of direct injection system mainly referring to the problem of transport lag and response time of the online concentration process change and to the problem of mixture uniformity depending on the quality of online mixing process.

1.3.3 Chapter III

The third chapter outlines the specification book for designing small direct injection spraying systems. The prototype is based on electrical energy of rechargeable battery and on a rolling chassis to be pulled by a walking worker with possible traction assistance done by an electrical bike wheel.

1.3.4 Chapter IV

The fourth chapter concerns the materials and methods used to simulate and evaluate the dynamic of concentration process change as a main parameter of direct injection spraying system (DIS) to improve performances of reactivity and mixing quality. It gives the necessary information on experimental design and data acquisition system implemented to simulate application rate using online fluorescein sensing method, to measure the sprayer operating speed and the pressure/flow rate of the hydraulic nozzles of the DIS.

The hydraulic design and the process control designs were modeled on the basis of the working speed conditions and of the sprayer design specifications presented in the precedent chapter. Both hydraulic and process control designs influence dynamic behavior of the spraying system for applying variable rate according to actual speed change in agricultural field. The process control system requires implementation of robust control strategy that can effectively fit to variable speed solicitations of walker operator propelling a small rolling sprayer.

1.3.5 Chapter V

The fifth chapter treats the results of modeling and experimental tests done to evaluate the performance of proposed DIS prototype. The results analysis refers to the indicators performance in terms of concentration process change dynamic and of mixing quality to evaluate the metering system and spraying application errors.

1.3.6 Chapter VI

This chapter presents implementation of DIS process controller using a PLC electronic box and results of its preliminary test in laboratory by simulating working speed input of the sprayer framework. The hardware and software implementations of the strategy of control are presented on the basis of the results of process control modeling and of the hydraulic requirements approached in the modeling study. The DIS controller box test and evaluation is done on the basis of the input speed solicitations simulating working conditions in agricultural field.

1.3.7 Chapter VII

The last chapter gives the conclusions and recommendations. It presents also what need to be studied further to continue the research work on the aspects concerning adaptation and adoption of DIS technologies in the small scale farming context.

Chapter 2: State of the Art

2.1 Introduction

Development of direct injection spraying is a result of the emergence of variable rate technology within the context of precision farming. Development of electronic and process control technologies played a primordial role in implementing cost-effectively sprayers with controllers and actuators to improve their performance and precision application.

The present study gives an overview of the configurations of direct injection systems according to injection point location in hydraulic sprayer circuit; upstream or downstream of the main pump, at the boom section level or at the nozzle tip level. Performance and safety requirements of direct injection systems are discussed on the basis of the literature review. Problems of chemical risk exposure for human and environment are stated by referring to control engineering solutions developed for sprayers to limit risk of pesticide handling and improve safety measures for operators.

2.2 Control of variable application rate

Calibration of conventional sprayer is done on the basis of the nozzle flow rate q_n (L/min), number of nozzles n, chemical concentration of the mixture solution in the tank Cm, boom working width W_b (m) and forward speed V (km/hr) in order to apply chemical at a given technical application rate per area TAR (L/ha). The relation between these variables is expressed by the following equation:

$$TAR = \frac{600 * n * q_n * Cm}{V * W_b} \qquad \textbf{(1)}$$

There are different methods for achieving a constant application rate, independently of operating speed. These methods are classified into three categories based on application rate control (Stafford and Miller, 1993):

- Flow control of the tank mixture (conventional method). The active ingredient is pre-mixed with the carrier in the tank; hence, the chemical concentration in the spray mixture during application is constant and the flow kept constant or varied proportionally to working speed.

- Chemical flow based on a constant carrier flow
- Combination of chemical and carrier flow control (total flow control).

Although the first method is based on applying chemical mixture at a constant or variable operating hydraulic pressure in accordance with constant or variable ground speed, the second and third methods are based on metering and injecting chemical active ingredient proportionally to a variable working speed.

Direct injection spraying technique is based on applying variable rate by injecting active ingredient in a predetermined constant carrier flow rate or in a variable carrier flow rate. Change in active ingredient is done in real time, for instance proportionally to the ground speed variation.

As said before, the active ingredient can be injected at downstream or upstream position of the sprayer pump and prior to branching of the distribution hose to the boom section. The injection point can also be situated close to the nozzle tip. The injection point location is known to have direct effect on dynamic behaviour of the injection system as response time and delay as well as on mixing of chemical with carrier.

The major advantage of developing direct injection systems (DIS) comes from improving the controllability of the spray application process for instance by adding a chemical on a site specific basis (site specific spraying), or quickly changing applied chemical according to phytotechnical requirements. This method also satisfies safety and environmental requirements as the water tank keeps clean of pesticides. As a result, tank residues are avoided.

Main drawbacks of the method are risks associated to concentrate handling and injectability of some formulations. This may result in use of premixing tank for preparing intermediate concentration of incompatible formulations. Figure 1 illustrates three schemes comparing the DIS control methods based on constant carrier flow control (CCFC) and total flow control (TFC) with a conventional control method.

2.2.1 Constant carrier flow control (CCFC)

The principle of constant carrier flow control is based on varying chemical concentration in carrier flow proportionally to the working speed and maintenance of a constant total flow rate (Fig. 1b). This concept is known as the "Injection Metering" or the "Direct Injection" systems

(Koo and Sumner 1998). The chemical active ingredient is metered, injected, and mixed online into diluent flow which kept constant.

The CCFC method offers the possibility to keep nozzle flow rate steadily unchanged without influence on spray pattern. However, the speed increase gives a reduced coverage of the target. Therefore, the biological efficacy of chemical may be affected as a consequence of a decreasing number of droplets impacts per unit area (Hughes and Frost, 1985).

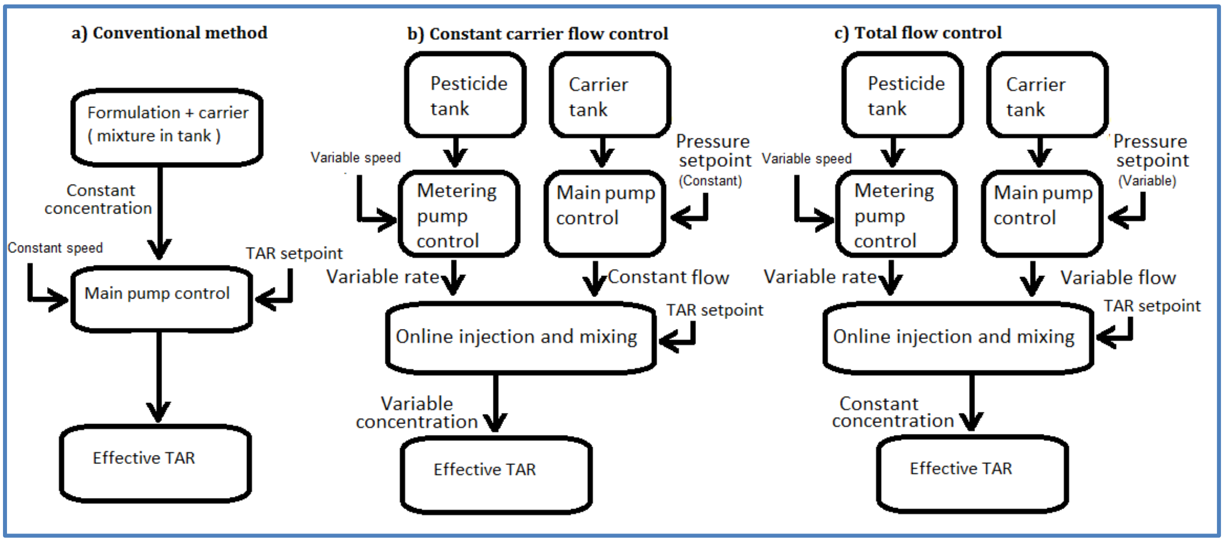


Figure 1 : Chemical application methods: a) conventional, b) Constant carrier flow control, and c) Total flow control

2.2.2 Total flow control (TFC)

TFC method is mainly based on varying simultaneously the chemical injection flow rate and the carrier flow rate proportionally to a working speed (Fig. 1c). The application rate is kept constant by varying nozzles' flow rate through adjustment of its operating pressure.

Koo and Sumner (1998) developed a direct-injection sprayer based on TFC. The response time of this flow control system averaged 8.5 s at an absolute steady state error of 0.8 % of flow rate. The average response time for the injection rate was 0.53 s and the coefficient of variation (CV) of concentration was 3.2 %.

Steward and Humburg (2000) evaluated the performance of Raven SCS-700 chemical injection system with carrier flow control by modelling chemical and carrier control sub-systems. They found as results that chemical injection with carrier control resulted in less application error compared to chemical injection without carrier control. The carrier control minimizes the concentration variations caused by dynamic response differences between the two sub-systems and reduces the effect of transport delays. However, TFC cannot provide consistent spray characteristics over a wide flow range without use of variable flow nozzles (Koo and Kuhlman, 1992).

2.3 Configurations of DIS

Landers (1999) characterised the injection system as a system in which carrier (water) and plant protection product are kept in separate containers and the metering and injection of active ingredient can be done into the carrier at any point between the tank and the nozzles. In this regards, direct injection systems is classified into central direct injection systems (CDIS), boom section direct injection systems (BDIS) and nozzle direct injection systems (NDIS) (Lammers et al, 2010).

2.3.1 Central Direct Injection System (CDIS)

In the CDIS, pesticides can be injected into the system at upstream or downstream point of the main sprayer pump and prior to the distributor carrying the solution to the boom sections (Fig. 2). The CDIS can potentially provide a slow dynamic response as a consistent lag time can occur to change the chemical concentration at the nozzle level relatively to corresponding change at the delivery points (Walker and Bansal 1999). Although, a multitude of CDIS have been developed, the adoption of this technology is limited by the performance of such system DIS that is not satisfactory because of the lag transport between the injection point and the tip nozzle causing problem of a delay in response time. This time delay can potentially be more than 20 s, causing application error of more than 100 m in the field (Koo et al., 1987; Tompkins et al, 1990; Sudduth et al., 1995; Qui et al, 1998; Zhu et al, 1998; Anglund and Ayers, 2003).

2.3.2 Boom Direct injection system (BDIS)

The injection of chemical into the carrier can be done in downstream position to distributor serving solution to different boom sections and at the centre of each boom section carrying solution to different nozzles (Fig. 3). In comparison with CDIS, there is a reduced distance between injection point and nozzle and consequently the response time is also reduced.

Hloben (2007) studied a BDIS and found a system response times less than 4 s, resulting in an application error of less than 20 m in the field. BDIS can have slow or fast responses for real-time controlled application depending on the sprayer operating speed that varies from 1 to 4 m/s.

2.3.3 Nozzle Direct Injection System (NDIS)

The injection point can be localised closer to the tip nozzle (Fig. 4). This direct nozzle injection reduces lag transport and provides less response time in comparison to that of the boom section injection. However, problems of mixture homogeneity can arise when using direct nozzle injection (Zhu et al., 1998). In the case of boom injection systems, the mixing quality is usually not affected as a pesticide has sufficient time to be mixed with the carrier before being sprayed throughout sprayer’s nozzles. For direct nozzle injection the time for mixing is reduced (Rockwell and Ayers, 1996). NDIS has a disadvantage of high cost needed for implementation chemical delivering equipment for each nozzle.

Giles and Brock (2008) studied feasibility of using commercial air induction (AI) nozzle with an embedded venturi for NDIS. The venturi air inlets were closed to air and redirected to liquid injection lines where the vacuum was used to induce liquid flow. They stated that volumetric concentration of injected fluid in the nozzle discharged could be controlled over 3% to 20% through use of metering orifice plates in the inlet lines. The results established the feasibility of AI nozzle for passive injection.

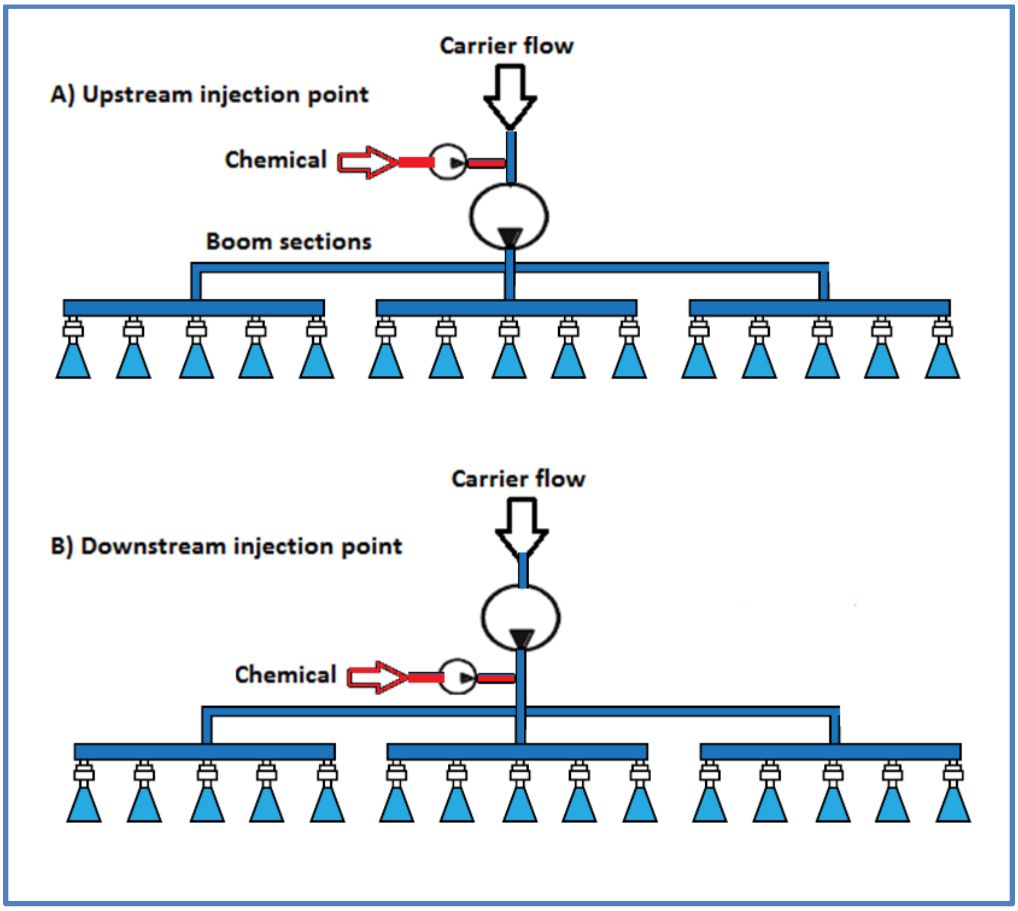


Figure 2 : Schemes of Central Direct Injection System: Upstream (A) and downstream injection points

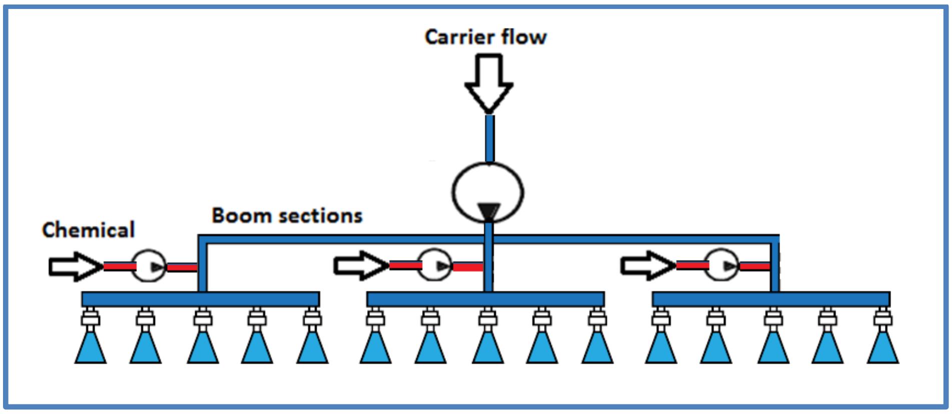


Figure 3 : Scheme of boom direct injection system

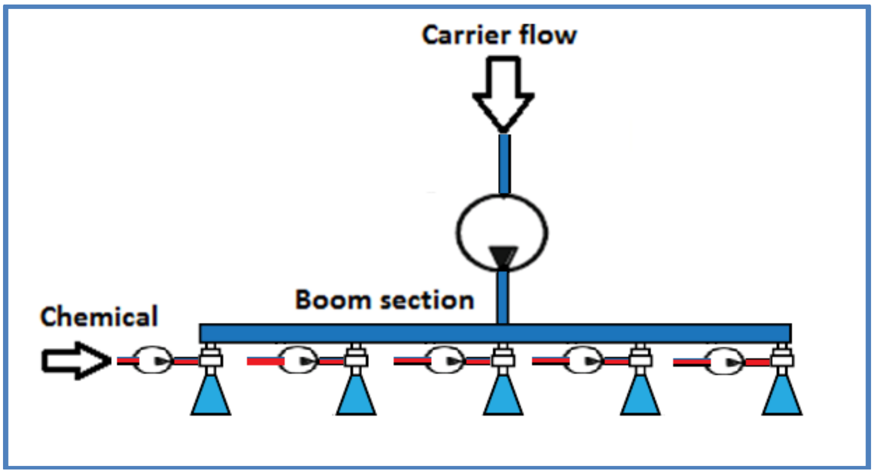


Figure 4 : Scheme of Nozzle Direct Injection System

2.4 Comparison of DIS configurations

Lammers and Vondrika (2010) compared DIS systems on the basis of their characteristics such as application flexibility, response time, mixing quality and system cost. The improvement of application accuracy by reducing the response time of a direct injection system is not achieved without affecting the time needed for the mixing preparation. Table 1 shows this controversy by considering response time and mixing quality performances criteria. The comparison between CDIS, BDIS and NDIS shows that their cleaning from residual pesticides can be of advantage in the first system and tend to be negative for the other systems according to dead volume and length of chemical metering circuit served for transferring concentrated formulations to injection points (case of DNIS). Furthermore, the system cost is of great importance for the technology spreading. The technical complexity of DIS leads directly to higher costs and limits its adoption.

Table 1 : Comparison of direct injection and conventional sprayers (adapted from Lammers et al., 2010).

	conventional sprayers	Central direct injection	Boom direct injection	Nozzle direct injection
Application flexibility	--*	0	+	++
Response time	++	--	0	++
Mixing quality	++	++	+	0
Cleanability	--	++	-	--
System cost	++	0	-	--

*Impact factor: ++ very positive; + positive; 0 neutral; - negative; -- very negative

2.5 Historical overview on development of DIS

2.5.1 Context of variable rate application technology development

According to Stone et al. (2008), the potential of applying microprocessor-based technology in agricultural equipment was greatly increased with the first introduction of microcontroller in 1976. The first sprayer control system in USA was commercialized by Raven Industries Company in 1978. Midwest-technologies Company presented its first model of chemical injection sprayer control in 1980. Giles et al. (2008) stated that early introduction of electronics into spray application technology began in the 1980s with simple rate controllers. These devices monitored the ground speed initially by tachometer-type sensors and later by radar sensors to adjust the liquid pressure and maintain the desired application rate.

Since the 1980s, development of control solutions for precise chemical application became of importance to satisfy requirements of emerging modern agriculture. There was a clear effect of technologies progress in automation and process control to induce and promote research and development of precise farming technologies. According to Bode and Bretthauer (2008), the progress of variable rate application technology has been perceived through two development stages put into global context of precision agriculture (Fig. 5):

The first stage was noted by the appearance of microprocessors for use in the field of agriculture and development of application rate controllers for adaptation to conventional sprayers. However, extension of such equipment was dependent on development of most reliable and affordable control systems. Although, the trend in developing spraying equipments was towards integration of greater degree of automation; possibilities of designing more efficient control system were not yet used up (Hughes and Frost, 1985).

The second stage starts from 1990s when a remarkable development of electronics, computer sciences and process control technologies had been made. This progress in those technologies has a great impact on the emergence of farming precision technologies. The promotion of variable rate application was technically assisted by development of process control systems and tendency of designing cost effective technologies. Otherwise, recommendation for keeping chemical application error within 5% (USDA, 1989) speeded up development of electronic control systems for reliable and efficient sprayers having the ability to reduce errors and undesired variation in chemical application rate (Steward et al, 2000).

Bode and Bretthauer (2008) stated the importance of development of electronic and process control technologies in improving performance of spraying technologies by reducing chemical application errors and avoiding human exposure and environment contamination. In this context, the development of new chemical application technologies such as direct injection, on-board application systems and control systems contributed in increased application efficiency while protecting the environment (Bode and Bretthauer, 2008).

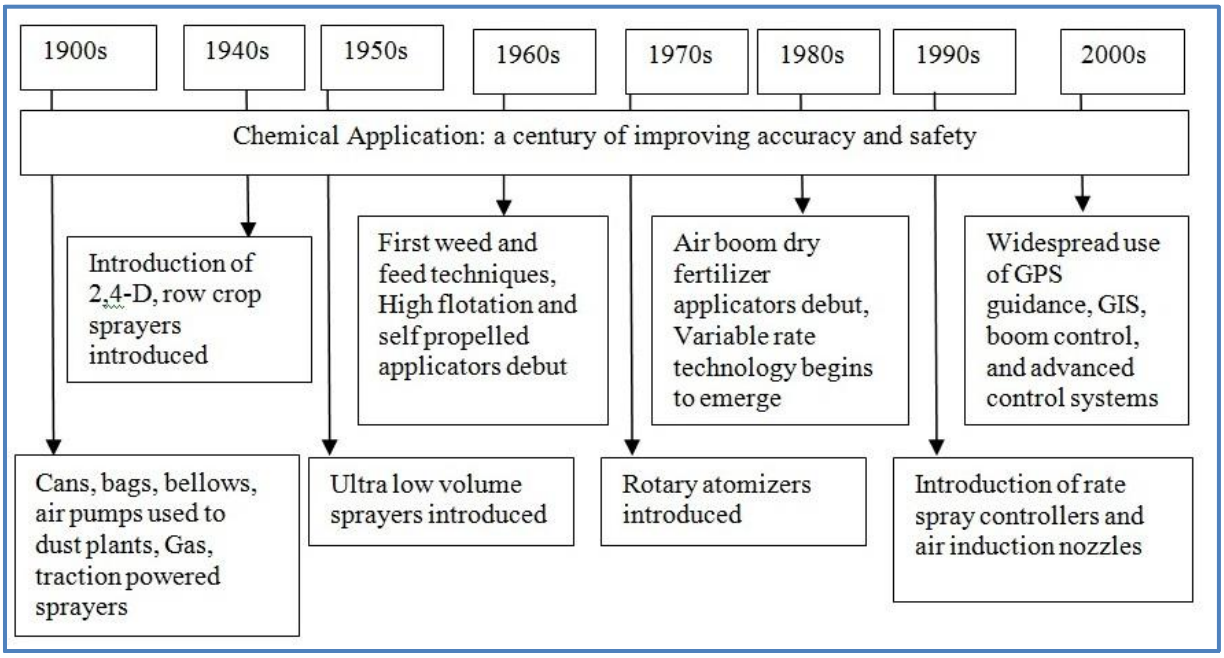


Figure 5: Timeline of major development in application technologies (Bode et al, 2008)

2.5.2 Research and Development process of DIS technologies

The first attempt to design a DIS system has been done in early 1970s. Amsden (1970) firstly attempted to describe and test various methods of direct injection of pesticides into carrier. Gohlich (1970) studied the possibility of metering and injecting chemical into the carrier and presented different options to maintain the chemical flow rate proportional to the forward speed while keeping the carrier flow constant (Hloben, 2007). Later on, Vidrine et al. (1975)

developed a direct injection system and evaluated the performance of a metering system to provide a constant chemical application rate. This prototype was based on a positive displacement metering pump that injected chemical into the spraying boom. The carrier flow rate was constantly maintained by a hydro-pneumatic pressure of a compressed tank. The metering pump speed was actuated proportionally to ground speed for centrally injecting chemical at the boom level.

Schmidt (1983) developed a direct injection system using a venturi nozzle for chemical metering. The prototype was designed to split the carrier flow into two lines for acting the venturi through the injection line of the chemical flow reconnected to the carrier flow line before mixture application at the boom level. Gebhardt et al. (1984) evaluated two injection metering strategies by actuating a positive-driven pump via an open-loop control system and by monitoring a pump with a flow meter serving as consign for a close-loop control system. The concentrated chemical was pumped from the container through a control valve regulated by a controller.

Chi et al. (1988) designed and tested a flow control system using electro mechanical feedback for a positive displacement pump as a metering pump system. The feedback system kept the pressure drop across the metering pump at zero and controlled the metering pump speed according to the desired flow rate. The test results showed that the system worked well for fluids with varying viscosities from 90 to 300 mPa.s and flow rates from 3 to 20 mL/s. A linear relationship was drawn between the flow rate and pump speed. The response time performance test showed that the system reached the steady state with a maximum of 5 s after start or during the travel speed change.

Frost (1990) proposed a hydrostatic metering system in which the carrier is pumped to the nozzles with a constant pressure. Some water is extracted from the lines feeding nozzles and sent by the metering pump into the cylinder containing the chemical. Water and chemical are separated in the cylinder by a free piston or a flexible membrane. A metered flow of a carrier displaces the chemical, which is injected into a mixing chamber where it is mixed with the carrier and delivered to nozzles.

During the two decades years of 1970s and 1980s, the research and development process is interested only for test and evaluation of DIS options related to usage hydrostatic and pneumatic solutions with use of simple process control methods according to progress and affordability of the electronic and computer technologies in this period. After that, researcher interested to improve dynamic performance of DIS with accordance to development shown in digital electronic and to requirements needed to develop sophisticated sprayers for VRA use.

Since 1990s, scientists investigated direct nozzle injection (DNI) for improving reaction time of spraying systems to satisfy requirements of site specific spraying as a main option of VRA and map-based precision farming. As shown before in Table 1, DNI can be advantageous to improve reactivity of direct injection system but cannot be done without affecting online mixing process of chemical. Tompkins et al. (1990) investigated a direct nozzle injection (DNI) system that used a metering pump for active ingredient flow control. Compared to others DIS using central or boom injections, this system has the advantage of significantly reducing lag transport.

Other authors developed and evaluated direct injection prototypes by injecting chemical at each tip nozzle through a small metering orifice (Miller and Smith, 1992; Rockwell and Ayers, 1996). In those systems, variation of discharge concentration through nozzles was achieved by the variable differential pressure across the metering orifices. Bennet and Brown (1997) developed a direct nozzle injection system based on a bank of actuated pumps which were individually coupled with nozzles.

Walker and Bansal (1999) developed a direct injection system to accomplish VRA by spraying the carrier at a predetermined constant flow rate while varying the concentration of the active ingredient proportionally to ground speed. The usage of the CCFC is of importance to develop simple DIS technology based on implementing a control process for actuating only the metering pump stage. Development of such simple DIS can be easily operated to switch from DIS control mode to conventional control method in the case of a potential malfunction or fault of control system. Such switching mode can be of importance to overcome problem of technicality lacking of operator to repair DIS faults in appropriate time. Furthermore, the design of a simple VRA technology can be affordably adopted in small scale farming.

2.6 Trademarks of direct injection systems

The development of precision agriculture is based on the development of VRA and especially on commercial progress of direct injection spraying and online metering technologies. According to Koo and Sumner (1998), many direct injection systems have been tested and evaluated but the control systems trademarks are mainly commercialised by the Midwest-Technologies, Inc., Raven Industries, Micro-Track Systems, Inc., and BEE Ag-Electronic.

The main trademarks of direct injection spraying technologies have been marketed for the first time in North America. In fact, there is a favorable context of big scale farming that needs improvement of safety conditions of handling chemical, efficiency and precision application of spraying equipment. The North American market is dominated mainly by the trademarks of Mid-technologies and Raven industries:

The Midwest-technologies has proposed two direct injection control systems, the TASC 6600® and the Legacy 6000® that can be equipped with a MT500 peristaltic injection pump or a MT600 piston injection pump (Fig. 6). Both systems can be set to monitor different chemical specialties in a parallel scheme of one to three tanks. The system designated for injecting chemical in downstream point to the carrier pump, is equipped with a positive displacement piston pump unit giving a common flow rate ranging from 0.015 to 7 L/min. The pumps are driven by 12 V variable-speed electric motors through the electronic controller.

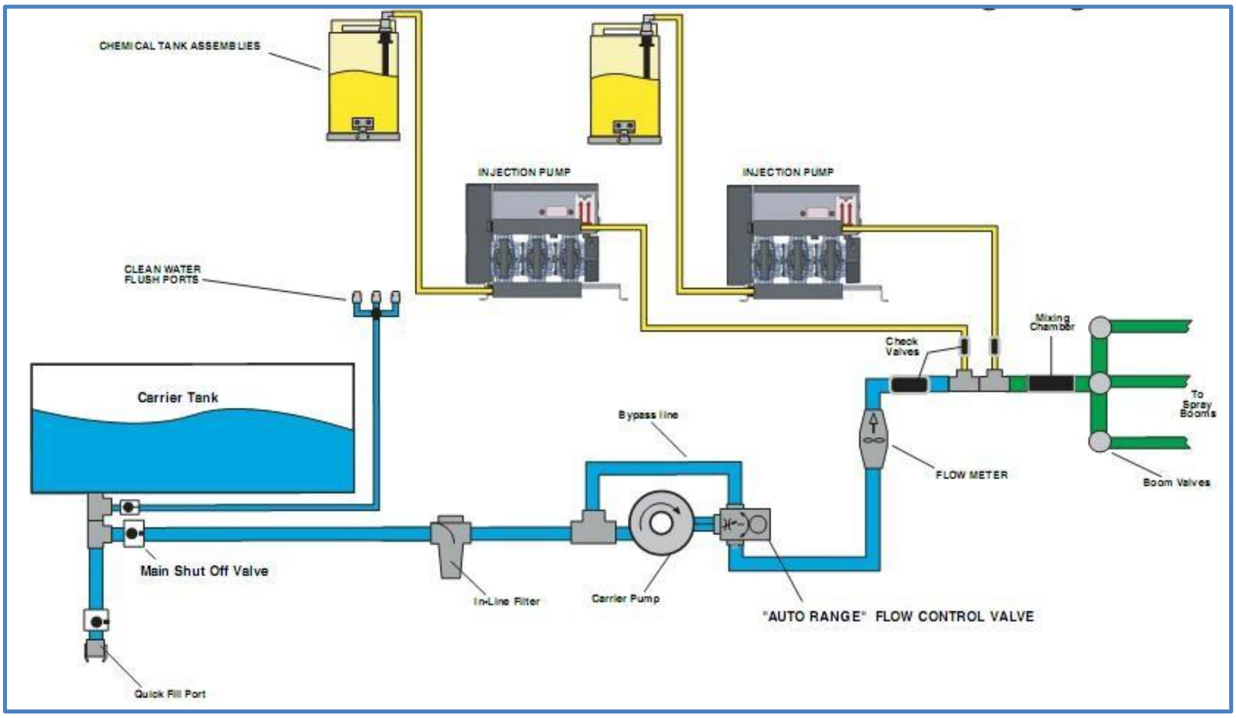


Figure 6 : Layout of DIS MT600 of Midwest technology

The Raven® Industries is commercializing a Sidekick Pro™ and Sidekick™ direct injection systems that can be monitored by the SCS or DCS control consoles (Fig. 7). The Raven designs are adaptable to existing conventional sprayers. Both systems are based on a variable-stroke piston pump which meters chemical into the pressured side of the carrier flow line. The maximum operating pressure can reach 10 bars by controlling pump speed for increasing chemical flow rate. The control is done with respect to feedback of flow meter integrated into the pump body. The Sidekick Pro™ direct injection system is designed to deliver a maximal capacity of carrying four chemicals in parallel scheme at once.

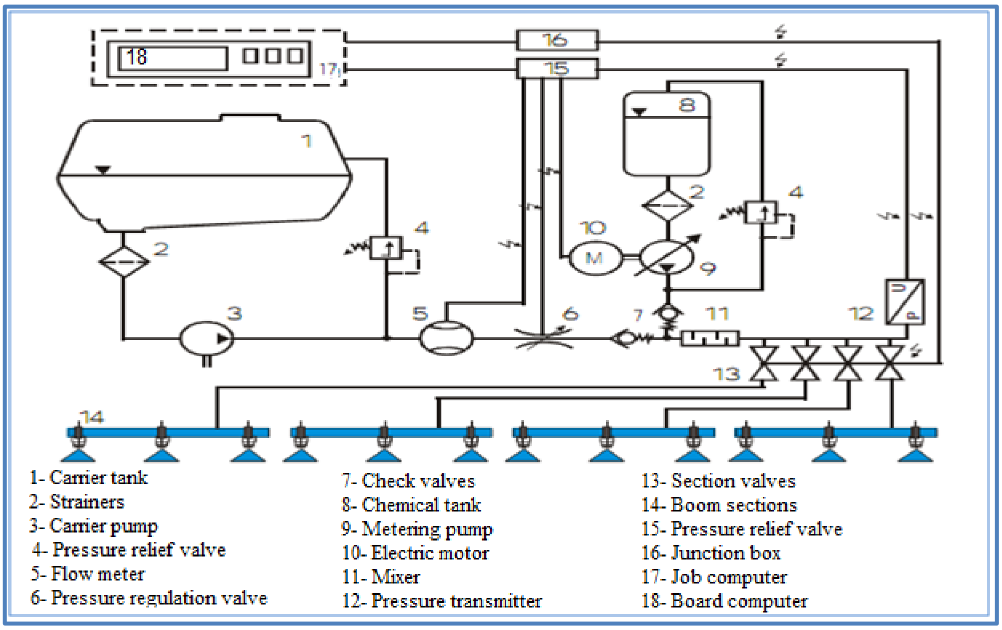


Figure 7 : Direct injection system of Raven Technology (Hloben, 2007)

The company John Deere (2011) developed a "Direct Injection Ready" system mounted in self propelled sprayer JD 4990 (Fig. 8). The system is designed to inject in centrally point up to four high volumes and one low volume of different formulations. The metering system is based on two piston pumps adapted for high and low flow rate ranges to inject in online mixer situated in pressure side between the main pump and distributor serving the boom sections.

The company Berthoud (2012) developed a DIS based on metering pumps and hydro cyclone to inject simultaneously up to three products upstream to a sprayer main pump. The injection system is adaptable for sprayers equipped with electronic system used to control flow rate proportionally to forward speed (DPAE). This DIS improves online mixing quality with its hydro cyclone concept but reactivity of the system and application uniformity in the traveling direction is affected by consistence of lag transport due the hydro cyclone dead volume and the upstream position of injection point.

The company Spray Concept developed the direct injection SP-ID that can dose separately up to four formulations in upstream side of a sprayer main pump. ARVALIS-Institute (2012) tested performance of SP-ID and SIDEKICK PRO systems mounted on conventional sprayers for applying modulated dose rate on the field. The test results showed that response time of both systems varied between 60 and 80 s depending on dead volume of the sprayer hydraulic circuits. This lag time potentially caused spraying misapplication up to 220 m for typical working speed of 10 km/h but it can be taken into account for application based on the prescription map.

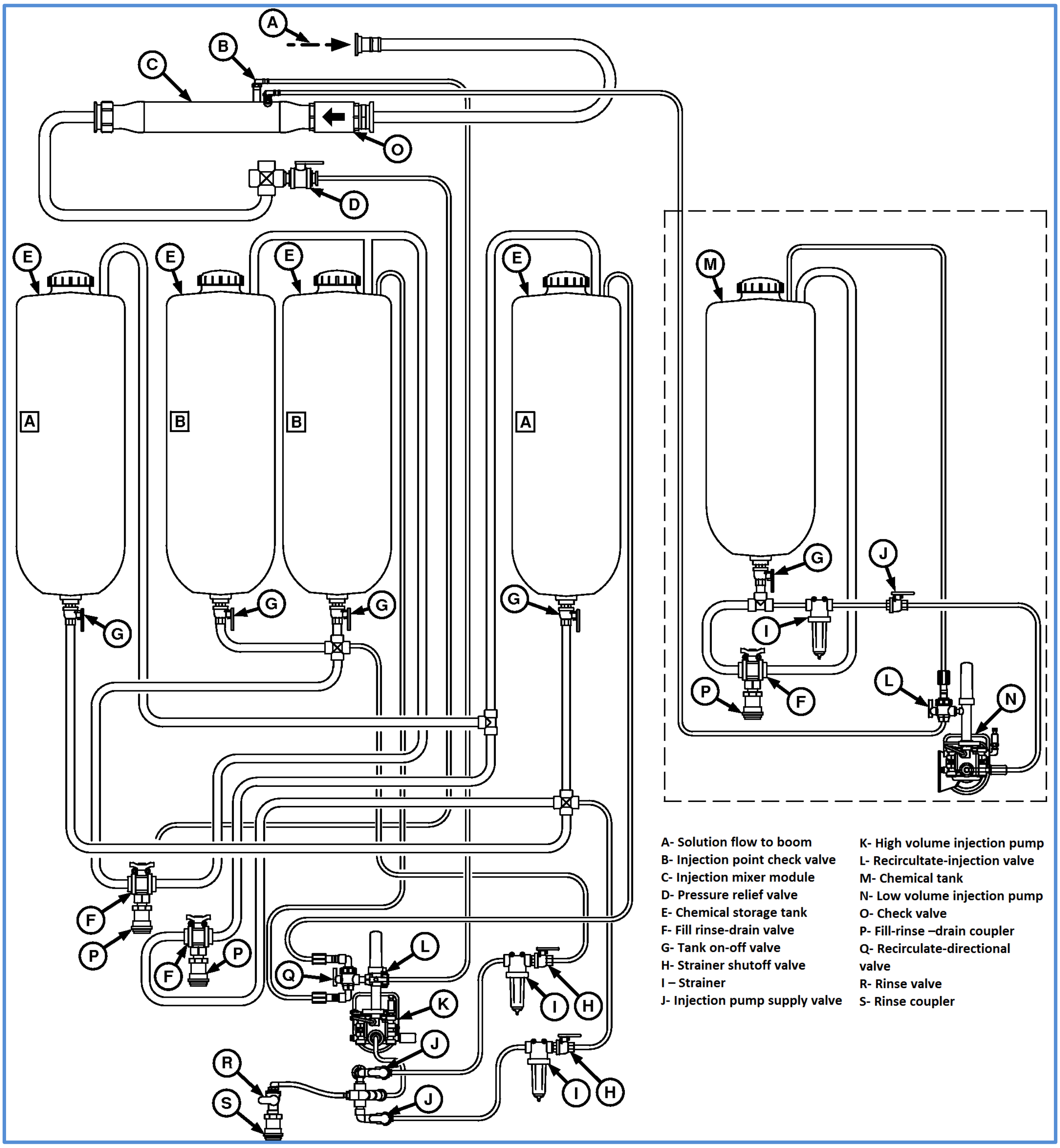


Figure 8 : Scheme of direct injection “Ready” system (John Deere)

The company Hardi (1997) developed a direct injection spraying system for “need dosage” based on CDIS with downstream injection point for applying chemical at a maximal permissible concentration related to a maximal operating speed in the field (Fig. 9). However, this method needs pre-dilution of concentrated formulation which potentially presents risk of contamination during handling of chemical. This later cannot be recuperated for further use after the pre-dilution. The need dosage method is proposed to limit effect of potential concentration application error arising from slightly incorrect dosage of highly concentrated formulations need to be mixed with water. The design is presented as a solution to avoid risk of amplifying metering error of using concentrated chemical from one tank.

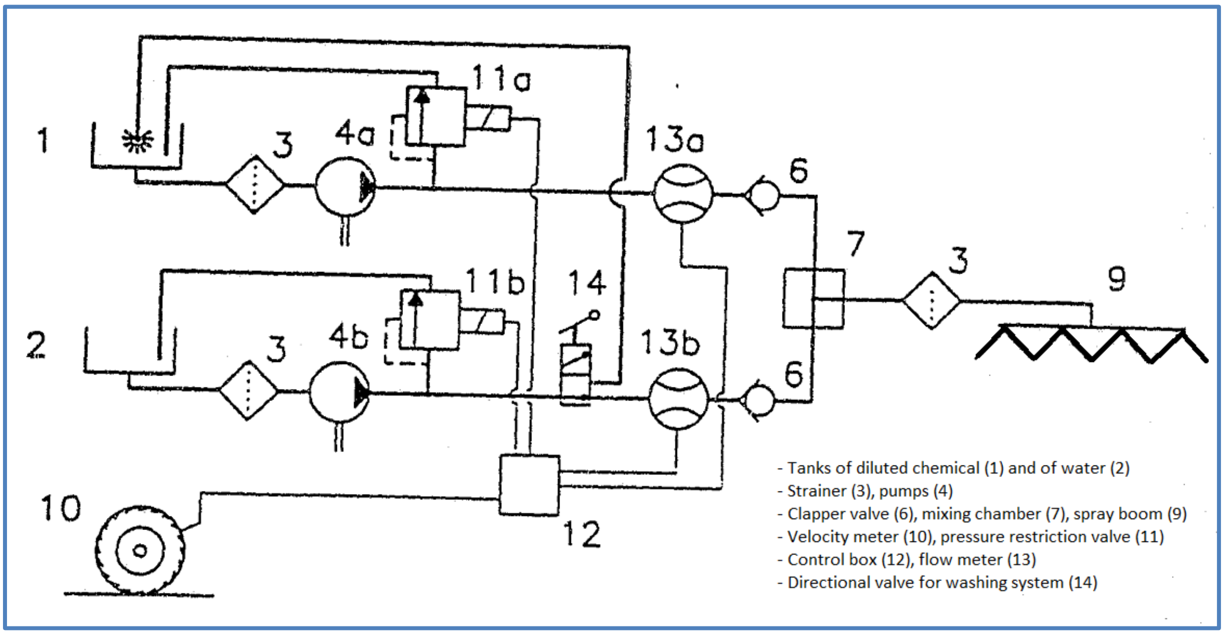


Figure 9 : Spray system for need dosage (Hardi$^{\text{TM}}$ DIS).

The company Amazone developed also a direct injection system based on premixing the pesticides with water in a proportion of 10% volume of the dilution tank. The premixing solution limits the dimension of the injection device to operate with a constant pesticide volume independently of the initial volume of active ingredient. The chemical premixed solution is injected into the carrier downstream of the carrier pump in front of the boom section valves (Hloben, 2007).

The hydraulic injection system Agroinject is a trade mark developed by MSR-Ciba-Geigy. Its principle consists on actuating the metering pump by the carrier water flow to proportionally inject chemical through spray booms. The dosing pump can suck chemical from their original containers in a closed transfer way of chemical to avoid the contact and potential contamination of the operator. The powdery formulations must be pre-diluted in water before a direct injection application. The company Tecnoma implemented their conventional sprayers with Dosatron DIS. This system is based on the same principle of Agroinject using main pressure energy of carrier flow for actuating the metering pump (Hloben, 2007).

The Micron Sprayers Company (U.K) developed an injection system based on a syringe cylinder container which can be used for extracting and metering chemicals into the carrier

(Fig. 10). The evaluation of this metering device showed a limited performance with viscous pesticides due to a lack of linearity in pressurizing the plunger in the cylinder container (Frost, 1990).

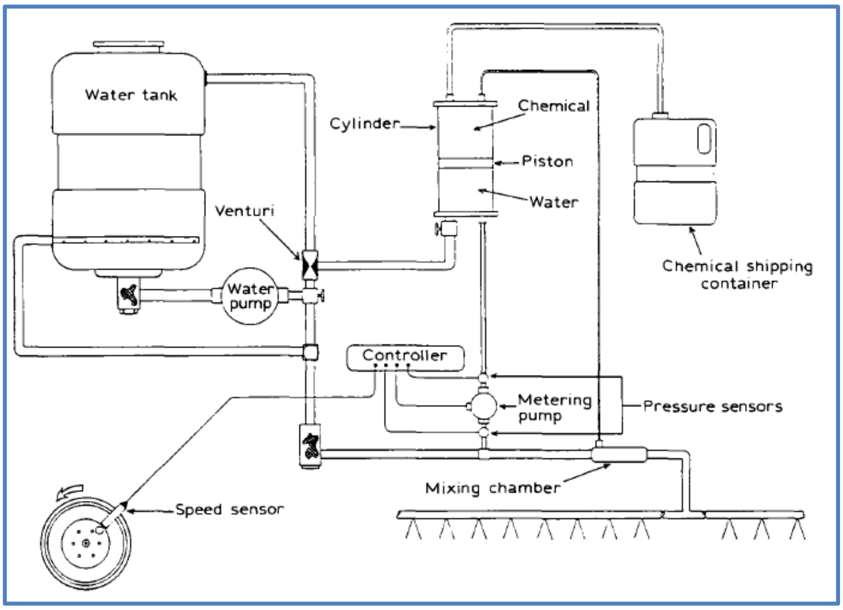


Figure 10 : Direct injection system based on a syringe cylinder container (Frost, 1990).

The company LECHLER developed a direct injection system based on a hydraulically driven piston pump to deliver pesticides from two different containers in a range of 0.2 to 5 L/ha. This system is equipped to return unused chemicals to their containers and to rinse the hydraulic circuit.

The Dos-Intro DIS trade mark uses a needle valve for metering the pesticide into the carrier flow in front of the boom section valves. The needle valve is actuated by electric motor on the basis of the wheel flow meter feedback for adjusting the pesticide flow rate into the mixing chamber. The pesticide is delivered from air pressured tank supplied by pneumatic compressor (Lammers et al., 2010).

2.7 Control techniques of VRA spraying systems

There are different techniques that can be used to vary application rate on the basis of variation of the system pressure and/or the flow rate as follow:

- Control of operating pressure by using two ways or three ways valve for controlling flow rate,
- Variation of the speed of electrically driven pumps using PWM technique.
- Control of the nozzles flow rate with PWM actuated valves.

2.7.1 Pressure control technique

Variation of spraying system pressure is based on the principle of the square root model governing hydraulic nozzle flow (eq. 2). According to the operating pressure range of hydraulic nozzle, the flow rate is varied in a narrow range control, as doubling nozzle output (flow rate) needs four time pressure increases according to the following equation:

$$Qn = k_n \sqrt{P} \qquad (2)$$

The range of operating pressure for conventional nozzles is narrow according to the potential of drift that can occur by increasing significantly the pressure (Frost, 1990; Qiu et al., 1998). This technique needs nozzles that operate in an extended pressure range such as the Teejet^{TM} XR. These nozzles provide a consistent spray pattern within a pressure range of 1 to 4 bars. However, conserving spraying quality and volume distribution pattern generally is a limiting factor for the conventional hydraulic nozzles. In fact, when the pressure drops below or goes above the specified level, the spray pattern becomes distorted or able to drift as a consequence of coarse or small generated droplets.

The range of applied rate to spread out with a given size of conventional nozzle size by changing the liquid pressure in a recommended range is limited to ±25 % of the nominal output of 1.25 times. The control of the sprayer output for a wide range of application rates can be improved by using a twin-fluid nozzle that can carry out a flow rate in a range of 3 times (Paice et al., 2001).

Otherwise, the development of variable rate nozzle can adequately solve the problem of working in wide range of pressure-flow rate. The use of variable rate nozzle improves coverage and avoids drift (Bui, 2005). In fact, the variable orifice allows a variable flow rate within a range of 10 times without affecting droplet size (Fig. 11). The performance test of Varitarget nozzles showed a better coverage at higher pressure in comparison to conventional nozzles (Daggupati, 2007). However, its adoption is limited by its affordability due to its price ten times higher.

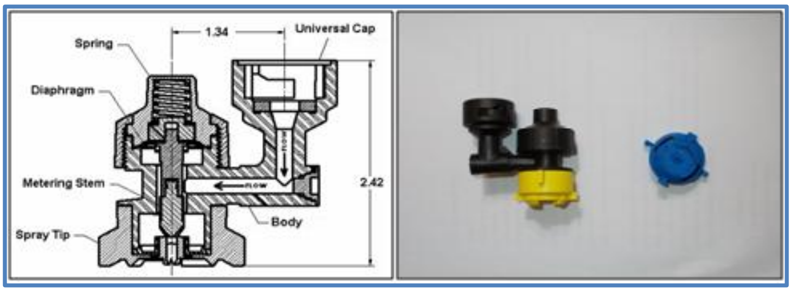


Figure 11 : Scheme and body of Varitarget nozzle (Bui, 2005)

2.7.2 Pulse width modulation control

The Pulse-Width Modulation (PWM) is a technique for controlling power of an electrical device, made practically by electronic power switches. The average value of voltage fed to the load is controlled by turning the switch between supply and load on and off at a fast speed. The term duty cycle describes the proportion of on time to the regular interval or period of time; a low duty cycle corresponds to low power, because the power is off for most of the time. Duty cycle is expressed in percent, 100% being fully on. The main advantage of the PWM is that power loss in the switching devices is very low. When a switch is off there is no current, and when it is on, there is almost no voltage drop across the switch. Power loss, being the product of voltage and current, is thus in both cases close to zero. PWM works also well with digital controls that can easily set the needed duty cycle.

There are two ways to control flow rate with a PWM technique:

- Use of PWM actuated solenoid valves to control flow rate of individual nozzles.
- Use of PWM to control the pump rotational speed for changing the operating pressure and flow rate conditions.

Pierce and Ayers (2001) tested the accuracy of PWM for field sprayer equipped with the nozzles pulsing at duty cycle settings of 25 to 100%. They found that nozzle pulsation had no effect on the spray pattern along the boom but the longitudinal uniformity varied with sprayer working speed and suggested faster actuation frequencies for short duty cycles to obtain a finer pulse resolution for a more uniform spray pattern along the working travel line (Pierce et al., 2001).

Han et al. (2001) modified a commercial sprayer with 25 tip nozzles for variable rate application. This sprayer was equipped with pulse-width modulation solenoids, a pressure controller and a nozzle control system interfaced to computer. They found that the flow rate change due to inaccuracy of the pressure controller ranged from 0.5 to 2.5%. They also found that the flow rate control errors for valves ranged from -15 to 12% when a single flow rate calibration curve was used (Han et al., 2001)

2.8 Application rate error of DIS

2.8.1 Approach for evaluation of application rate error

Application error of spraying system is generally presented as an average value or as the percentage of application exceeding the tolerable application rate within the range of 5%

(USDA, 1989). Evaluation of current application technology leads to quantifying error in chemical application and globally approaching static and dynamic performances of systems for different working speed solicitations in agricultural field.

Miller and Smith (1992) studied an example of direct boom injection system inaccuracy due to time delays caused by speed change. Assuming application of a chemical at a technical application rate of reference (TAR) and actual application rate at any time t (TAR (t)), the error associated with the application is described as:

$$e = \frac{TAR(t) - TAR}{TAR} \qquad (3)$$

The TAR can be expressed as:

$$TAR = \frac{k * q_n * C}{Ns * V} \qquad (4)$$

Where k is a constant, q_n is the nozzle flow rate, C is the concentration at the nozzle, N_s is the nozzle spacing, and V is the ground speed.

The TAR has to be maintained constant for any ground speed; the concentration must be a function of time, assuming that ground speed is a function of time. Thus, solving for C in equation 4 and specifying concentration as a function of time:

$$C(t_c) = \frac{Ns * V(t_c) * TAR}{k * q_n} \qquad (5)$$

Where t_c is the lapsed time used to calculate a specific concentration as there is a delay between concentrations in injection and application points. A different variable is used for this time to separate it from the time of concern, t, since the two are not the same if a time delay exists between the point of injection and the point of application at the nozzle. This concept is developed by Miller and Smith (1992) for evaluating application error if ground speed varies and the application system is not instantaneous in adjusting the concentration of a chemical. The TAR as a function of time is as follow:

$$TAR(t) = \frac{k * q_n * C(t_c)}{Ns * V(t)} \qquad (6)$$

Substitutions can now be made in the error term above (eq. 3) to develop an error as a function of time, as shown in equation 7:

$$e = \frac{\frac{k * q_n * C(t_c)}{Ns * V(t)} - TAR}{TAR} \qquad (7)$$

Assuming that a controller attempt to maintain a constant TAR with speed, and that speed is a function of time, the expression for concentration as a function of time can be substituted into the error term to yield:

$$e(t) = \frac{\dfrac{k * q_n * TAR * Ns * V(t_c)}{k * q_n * Ns * V(t)} - TAR}{TAR} \qquad (8)$$

The equation 8 is reduced to:

$$e(t) = \frac{V(t_c)}{V(t)} - 1 \qquad (9)$$

Equation 9 describes the fractional error of an application at any time t. The consideration of a perfect chemical application by carrying out instantaneous change in chemical concentration at the nozzle level for any change in ground speed require that the speed upon which the concentration is based is identically equal to the current ground speed then the error at any time t is zero.

2.8.2 Time delay and application error

In the case of applying a chemical mixture by conventional sprayer, concentration is constant over time. The premixed concentration in the tank is based on an intended ground speed. In this case, $V(t_c)$ mentioned in eq. 9 is assumed to be constant for any preparation of the chemical mixture in the sprayer tank and error is solely based upon deviation from the intended ground speed. But in the case of direct boom injection system, there is a complication as the concentration process change depends on time delay due to transport of chemical between the point of injection and the point of application. Furthermore, the time delay associated with each nozzle increases with boom width. The farther a nozzle is from the point of application, the longer is the time delay. Thus, when considering the concentration of a chemical at a given nozzle, the ground speed upon which the concentration is based is not the current time, it is the current time less the time delay for the nozzle (Tomkins et al., 1988; Budwig et al., 1988).

2.8.3 Lateral application error in boom of DIS

To study the effect of time delay on application error, Miller and Smith (1992) evaluated the response of 10 meters’ boom (20 nozzles spaced of 0.5 m) of 1 inch diameter and having a central chemical injection situated at 0.3 m in upstream point to feed two half boom in parallel layout. They found that for a flow rate of 1.5 L/min per nozzle the time delay varied from 0.8 s for nozzle 1 to 29.7 s for nozzle 10 (Table 2).

Table 2 : Injection lag times of typical sprayer's boom (Miller and Smith, 1992).

Nozzle	Time delay (s)	Nozzle	Time delay (s)
1	0.8	6	8.2
2	1.9	7	10.9
3	3.2	8	14.4
4	4.7	9	19.5
5	6.3	10	29.7

According to the equation 7, the determination of error at each nozzle can be done by substituting V (t_c) by V (t-tn), with tn equals time delay associated with a given nozzle. Approaching error on the basis of this method supposes that the history of speed changes is known.

2.8.4 Error propagation in DIS boom

Miller and Smith (1992) studied the error behaviour on the basis of a sinusoidal variable of ground speed to examine the effects of time delay and speed change on application accuracy. They assumed that a direct boom injection system working under a constant speed solicitation for 30 s and after that the speed changes to sinusoidal form (eq. 10):

$$V(t) = V_0 \sin(2\pi At / T) \qquad (10)$$

Where V_0, A, t, and T are the reference speed of 8 km/h, the fractional speed variation of 0.05, time and periodic oscillation of 10 s, respectively.

The authors used sinusoidal function form for representing the minor speed variation that can potentially occur around a target speed value due to tire slippage or irregular field working conditions. Such sinusoidal form function gives appropriate description of speed at any time other than the time of interest, t, as a t_c takes speed values affected to the delayed response of a given nozzle.

As a result, Miller and Smith (1992) noted that for a typical direct boom injection system, a small error in ground speed can be amplified into a larger application error. In fact, the application errors for nozzles 3, 4, 5 and 8 exceeded the acceptable range limited at 5% (Table 2). The amplification of such errors is due to the variation of ground speed in cyclic discordance added to the variation of concentration along the boom due to a consistent delay response.

Miller and Smith (1992) found also that the minimum error occurred in nozzles 9 and 10 having time delays of 19.5 and 29.7 s, respectively. These time delays present a cyclic accordance in phase with the 10 s period in the speed oscillation. However, the performance was practically poor for nozzles having time delays occurrence in mid-cycle.

Koo et al. (1987) similarly quantified application error due to a direct boom injection transient response and found that for a 12 nozzles' boom injection system solicited by a change in speed of ±1.6 km/h in a period of 10 s with a nominal speed of 9 km/h, 24% of the total area was mistreated in excess of 10%.

Studying application error of a typical sprayer boom used for chemical direct injection leads not only to expose its nature but also to make its magnitude under consideration for different situations of speed change that occurs in an agricultural field. The study of the case of direct boom injection system without improving performance to overcome existing time delays showed that the application accuracy cannot be better than of the conventional application system based on tank chemical pre-mixing. However, the direct injection boom can be of superior performance to the conventional spraying when the system requirements of hydraulic design and process control have been deeply implemented to improve the dynamic of spraying system in different speed solicitations.

2.9 Performance requirements of DIS

Deficiency of direct injection systems mainly originates from transient errors in active ingredient application and spray coverage variation related to changes in operating speed. There is also a potential variability of active ingredient deposition due to inadequate mixing process.

According to Luck et al. (2012), the two most common performance factors related to direct injection systems are lag time (delay time between injection and discharge) and mixing uniformity of the chemical with the carrier prior to discharge. In fact, when chemicals are injected prior to or into a spray boom, a lag time is required for a change in concentration to become fully established by reaching spray nozzles (Fig.12). The lag time results in a transient error of application rate (Koo et al., 1987; Budwig et al., 1988; Tompkins et al., 1990).

Use of direct injection technology has advantages of reducing worker exposure to chemicals and leftover of spray mixture. There are also possibilities of recuperating chemical for reuse and of injecting different chemicals from separate containers in a parallel scheme (Tompkins et al, 1990; Zhu et al., 1998). However, the advantages of variable chemical application cannot be fully taken without use of injection systems with accurate dose controller, high response to speed variation and ability to operate over a wide range of delivered dose with variable concentration of mixtures (Miller et al., 1997).

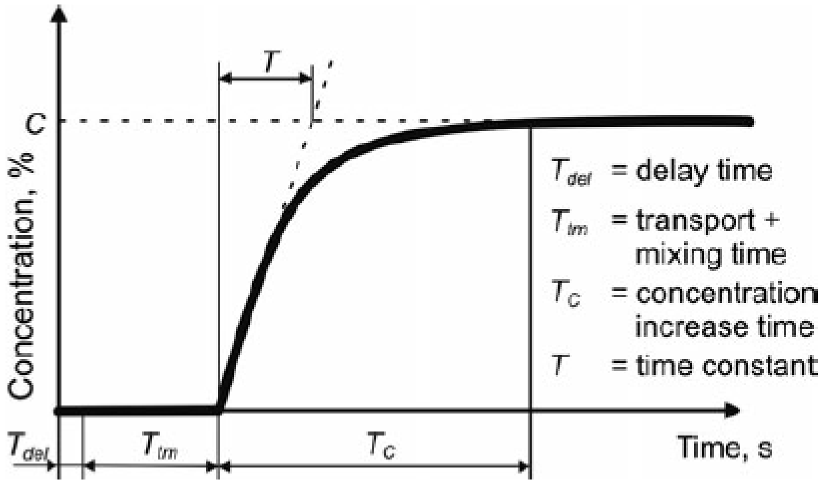


Figure 12 : Concentration process change of DIS (Lammers et al., 2010)g

2.9.1 Concentration process change and lag transport

Lag transport is the most important indicator in evaluating the dynamic ability of a direct injection system to change concentration equilibrium of applied mixture as a response to change in working spraying conditions when speed or rate application are varied. The reactivity performance of DIS system depends not only on hydraulic hardware design but also on process control system dynamic to change applied chemical and volume rates (through formulation injection flow rate and carrier flow rate) in less time possible to fasten establishment of chemical concentration before its spraying at the nozzles level.

Zhu and al. (1998) evaluated lag times at boom section of an inline injection sprayer system. They measured time period between a change in chemical injection rate and the new chemical rate reaching nozzles at the boom. Lag time factors investigated were: number of active nozzles, boom size, travel speed changes, and pesticide viscosity. An equation was developed to predict the lag time at the nozzles at the end of the spray boom. Lag time was greatly reduced by reducing the boom diameter, but was not reduced substantially by decreasing the number of active nozzles on the boom. Lag times were not affected by viscosity of the simulated pesticide.

Table 3 summarizes the works done by several authors that evaluated performances of direct injection systems. The table shows a lag time ranging from 1 s for the case of DNIS to 80 s for the case of CDIS according to systems configurations of injection point and type based spraying.

Table 3 : Recapitulative of dynamic test performance of different DIS (several authors).

Year	Authors/ Institute	DIS type	Trademarks and Specifications	Reaction time (s) and Misapplication (linear m or %)	Type based spraying
2012	Arvalis Institute	CDIS	SP-ID of Spray Concept (upstream injection); Sidekick-Pro of Raven (downstream injection)	60 to 80 s vs dead volume of hydraulic circuit; Up to 220 m (@10 km/h)	Map-based
2011	El Aissaoui et al.	CDIS	Research prototype (upstream injection)	< 3 s; Up to 2 m, (< 5%) (@3,6 km/s)	Speed based
2009	Hoogterp	CDIS	Hardi sprayer (Raven DIS)	20 s; 33 m (@6km/h) (downstream injection)	Map based
2007	Hloben	BDIS DNIS	Research prototype	- 2.8 s to 4 s (BDIS, 6 nozzles, XR80015/XR8005 at 3 bars). - 0.5 s to 1 s (DNIS, nozzles XR80015 and XR8005 at 3 bars).	Spot based
2003	Gillis et al.	CDIS	Roadside spraying with Raven-SCS750 (upstream injection)	25.5 to 128.1s (vs active nozzles number); Large error of 20%.	Site specific spraying
2005	BBA	CDIS	Teejet-LH	10 to 40 s; Up to 120 m	Speed based
2003	Anglund et al.	CDIS	Raven-SCS750	15 to 55 s; include 2.35 s of GPS response; Up to 160 m; 2,25% (controller error)	Map-based
2003	Ruixiu et al.	CDIS	Mid-Tech TASC 6300	Lag time (38,3 s), rise time (65,9 s)	Map-based
2002	Baio et al.	CDIS	Mid-Tech TASC 6600	28 s; Up to 55 m	Map-based
1998	Koo et al.	CDIS	Prototype	8,5 s; 3,2 % (of concentration error)	Speed based
1998	Zhu et al.	CDIS	Raven-SCS700	20.3 to 42.8 s	Speed based
1998	Qui et al.	CDIS	-	15 to 52.6 s; Up to 7,46 %	-
1997	Benneth et al.	DNIS	Prototype	< 1 s	Site specific spraying
1996	Rockwell et al.	DNIS	prototype based on Raven injection module	< 4 s; 5,3%	Speed based
1995	Sudduth et al.	CDIS	Raven-SCS750 (upstream injection)	14 to 21 s include 4 s response of metering pump; Up to 50 m.	Speed based
1992	Landers	CDIS	Commercial sprayers	Up to 30 s	Map based
1992	Miller et al.	CDIS	Research prototype	29,7 s	Speed based
1990	Frost	CDIS	Research prototype	4,3 s	Speed based
1990	Tompkins et al.	CDIS	Research prototype	23 to 26 s (upstream injection); 12 s (downstream injection).	Speed based
1988	Budwig et al.	CDIS	Research prototype	22 s (@8km/hr); Up to 49 m	Speed based
1987	Koo et al.	CDIS	Raven-SCS700	20 s; Up to 50 m	Speed based
1987	Chi et al.	CDIS	Research prototype	5 s	Speed based
1987	PAMI*	CDIS	Test report of SSCIMS**	10 to 30 s(@10km/hr); 30 to 80 m; Max error of 25%	Speed based

*Prairie and Agricultural Machinery Institute

**Computorspray Spot Spraying Chemical Injection Metering System of Australian Canadian Agricultural Machinery Corp.

2.9.2 Mixing quality requirement

Mixing quality is a determinant requirement for chemical application by direct injection method. The uniformity of mixture concentration and spray deposit distribution in lateral and longitudinal directions are the most important performance criteria for testing crop sprayer equipment. The concentration uniformity of applied mixture depends on hydraulic system designed to satisfy turbulence flow for intensifying online mixing and on physical and chemical characteristics of active ingredient. The mixture homogeneity is an indicator of uniform spray deposition and distribution.

Hloben (2007) reported the limit of maximal admissible variation (CV) for mixture concentration in a solution tank to 15 % as fixed by the German Federal Biological Research Centre. According to Vondricka et al. (2009), the maximum deviation from homogeneity for direct injection system should be within 5% coefficient of variation at the nozzle output. They evaluated the system’s mixing characteristics using decolourization method and developed sensor for mixture quality measurement. The result showed necessity of installing mixing device for direct injection system with short lag times such as DNIS and CDIS for chemical injection in upstream point to main sprayer pump.

Problem of mixture uniformity depends on system ability to provide sufficient mixing of chemical during hydraulic transport process. Degree of mixing pesticide online into carrier depends on time available, flow turbulence and on design of mixing chamber, if it exists. For the cases of boom and nozzle injection systems, there is not enough time for complete mixing of chemical and carrier before a discharge through nozzles (Tompkins et al., 1990; Rockwell and Ayers, 1996; Zhu et al., 1998; Sumner et al. 2000). Installation of mixing apparatus for injection system can improve turbulence in the case of direct nozzle injection due to a momentary mixing period. The mixing process can also be influenced by chemical proprieties such as formulation type, polarity, and viscosity. Highly viscous herbicides tend to exhibit a large drag effect and may be difficult to mix with the carrier.

Tompkins (1990) investigated mixture uniformity in three injection systems with different injection positions: upstream and downstream of the carrier pump and in the individual nozzles. In a comparison of direct injection immediately upstream and downstream of the carrier pump, the chemical concentration variations at the nozzle were usually greater with downstream injection. The systems with a central injection point had maximum deviations from the average concentration of about 2.3 % to 11 % respectively. Direct injection of the chemical into the individual nozzles failed to achieve a uniform chemical concentration from nozzle to nozzle. The concentrations deviated by 19.5 to 39 % from the average concentration. Rockwell et al., (1996) similarly found a maximum coefficient of variation of 16.3% by studying a direct nozzle injection system.

Zhu et al, (1998) studied mixture uniformity in diameters 3/8 and 1/2 inch of spraying boom sections of 5 meters length and across spray patterns. They used three water-soluble liquids (water, Prime Oil I and Prime Oil II) and one non-water-soluble liquid (Silicon Oil) of viscosities ranging from 0.9 to 97.7 mPa·s for simulating pesticides spray delivery in both diameters booms. The viscosities of tested liquids slightly influenced mean flow rate from the metering pump and the two highest simulated viscosities were difficult to mix with water that it was necessary to use a spiral mixer to maintain a uniform mixture. The variation from 770 to 15,000 of the flow Reynolds number in the nozzle supply line did not have a statistically significant effect on the mean concentration collected at the boom section nozzles. The average coefficient of variation among concentrations was 4,22% which tended to be greater for boom sections with 2 and 4 active nozzles than for sections with more than 6 active nozzles. The mixture across the spray pattern of all nozzles was uniform, even if the mixture in the boom was not. The average coefficient of variation was 1.31 %.

The uniformity variability of applied chemical along the spray path can be due also to pulsation of the metering pump or valve. Sumner et al. (2000) evaluated the effect of four spray nozzle arrangements and injector pump frequency on uniformity along the spray path using collector strings sprayed with fluorescent dye. They found that injector pump frequency and nozzle type were the significant factors affecting spray deposit uniformity differences along simulated path of crop rows. The low pump frequencies affected less the uniformity along the path for cone nozzles with large wetted areas than for fan type nozzles. The injector pump frequencies of 300 rpm resulted in string fluorescence CV less than 10% with no significant difference between CVs for pump frequencies of 1725 rpm.

2.9.3 Cleaning requirement of DIS

DIS is a promising technology for applying chemical but it cannot fulfill all benefits without having improved cleaning process and closed transfer plumbing circuit for safe management of residual concentrated chemical that can be hold in metering system after spraying operation. According to Landers (1992), the cleaning of CDIS is easy as only a small part of the piping system gets contaminated with concentrates pesticides. Rockwell and Ayers (1996) stated that DNIS disposes of long plumbing to hold concentrated pesticide chemical. However CDIS and BDIS have only short part of hydraulic circuit that can be contaminated regarding the cleanability of the three DIS.

The company Hardi (1997) proposed a DIS for “need dosage” (see figure 8 shown before) that disposes of a cleaning system based on a directional valve for passing water from the carrier tank to the chemical tank through one or more washing nozzles. The nozzles are used in a simple manner in the field for cleaning internally the chemical tank and plumbing of the metering system. This DIS is also designed to be equipped with chemical filler device having a graded scale for simple and safe filling and subsequent flushing of both liquid and powder-formulated preparations.

Dorpmund (2012) identified strategies for efficient cleaning of DIS including reclamation of residual concentrated pesticide from the injection pipe and rinsing of the contaminated parts of the hydraulic system. He studied the cleaning ability of DNIS in laboratory condition using a safe-to-use mixture solution of polyvinylpyrolidone (PVP) and water as a test pesticide before cleaning. The cleaning process was divided into two steps of (1) reclamation of the simulated pesticide by pushing it back into the pesticide tank using pressurized air (pre-cleaning) and of (2) rinsing the contaminated part of the hydraulic system with water.

Evaluation of the process included variation of pre-cleaning time and air pressure as well as water inlet positions. The measurements for a 3 m test section showed that the initial concentration (30%) of the simulated pesticide in the rinsing water can be reduced by one third when extending the pre-cleaning time. Change of the water inlet position reduced also the initial concentration of the simulated pesticide in the rinsing water to be 5%. The author found that these concentrations were much higher than concentration of common sprayed solutions and need further dilution in the rinsing water to be sprayed on a crop. The author found that the tested cleaning process can be improved by including the homogenization of the contaminated rinsing water for uniformly dosing and applying it in the field after spraying operation.

2.10 Direct injection of flowable pesticide

Performance of direct injection system depends on its ability to deliver and inject a wide range of chemicals having varying physical proprieties with satisfying metering precision. Injection of flowable pesticides cannot be done by DIS without technical device for maintaining constant injected concentration. This later can be affected by non Newtonian behavior of injected particulates in suspension. The non Newtonian fluids cannot be perfectly processed without using continuous mixing device to maintain homogeneous injected fluid. The metering pump requires calibration for each flowable formulation depending on its physical and chemical characteristics.

Injection of dry flowable pesticides was studied to contribute in solving the problem of liquid injection of flowable pesticides. Hart and Gaultney (1989) developed and tested a prototype of laboratory direct injection system for dry flowable agricultural pesticides. They designed a variable volume metering/crushing (VVMC) screw to reduce packaged formulation particle sizes, meter formulations, and introducing it into a hydraulic conduit. The unit reliably metered and successfully mixed pesticides into a liquid conduit. However, the tested DIS was not compatible with all dry flowable pesticide formulations. As a next step, Hart and Gaultney

(1991) tested an improved design based on a near-constant volume screw to broad the range of commercially available dry flowable pesticide formulations in the previously developed direct injection system in order to reduce screw operating temperatures, improve the output characteristics and particle size distribution over a broader range of dry flowable pesticides. They tested this screw apparatus with a laboratory scale agricultural sprayer equipped with 8004 flat fan nozzles and 50 mesh screens. Four dry chemicals (Lorex at 0.98 kg/ha, Gemini at 0.98 kg, Lexone at 0.56 kg and Preview at 0.56 kg) were injected into the liquid carrier for evaluating liquid dispersion, including dispersion times and formulation metering. Results indicated that dispersal times for packaged formulations were lengthy but reduced with increasing agitation. Reduction of the formulation particle size was also found to decrease dispersal time. Tests indicated that metering and crushing were consistent, repeatable and successfully reduced the formulation to a quickly dispersible particle size.

Falini and Gaultney (1995) patented an apparatus for direct in-line injection of particulate compositions in spraying systems. The invention was an improvement of the precedent screw design developed by Hart and Gaultney for providing a simple and practical method for direct injection of particulate compositions. According to the inventors, it would be advantageous to directly inject solid and particulate compositions because they have many desirable characteristics relative to liquids, including easier handling, storage, package disposal and less potential for worker exposure.

2.11 Exposure to pesticide and engineering solutions for sprayers

Handling of agricultural chemicals potentially poses health risks to farmers and custom applicators. Transporting, pouring, and mixing liquid chemicals are especially risky due to splashing, dripping, and spillage onto skin or clothes. Leftover chemicals in sprayer bulk tanks must be disposed of, resulting in the introduction of excess chemicals into the environment (Tompkins et al., 1988). Awareness of the operators’ exposure to pesticides during measuring, pouring and mixing, concentrated formulations, leaded to evaluation of risk and development of different engineering solutions for sprayers. Recently, a great concern arises to overcome problems of operator's contamination and environmental pollution due to pesticide handling during spraying operations. The protection of worker from pesticide effect had led to development of sprayers equipped with technical package to limit or eliminate exposure to hazardous substances.

2.11.1 Point and diffuse sources of pollution

The project EOS (Environmentally Optimised Sprayer) has been done by ECPA (European Crop Protection Association) to evaluate how spray equipment can contribute to the mitigation of chemical losses to water through the two main entry routes of point and diffuse sources. The point sources concern the handling of chemical on farm during cleaning, filling, remnant management, transport and storage. However, diffuse sources are due to run-off from fields after application and to off target deposition of drifted spray. This EOS approach offered the opportunity to analyse the significance of risk areas related to equipments and evaluate different technologies on their capabilities to reduce these risks. The biggest risks for point sources pollution are cleaning and filling sprayers and management of diluted remnant liquids resulting from sprayer filling, cleaning or maintenance work (Roettele et al., 2012). The amendment of the machinery directive (EC/127, 2009) came in force in 2011 to mention the aspect of environmental protection related to sprayers' design and performance.

2.11.2 Closed transfer of plant protection product

A closed transfer of pesticide is a method used to extract concentrated pesticide from original container and to transfer it to water or to mixing tank of sprayer to avoid direct contact and handling of pesticide by operator. Engineering solutions such as closed transferring and/or direct injection of chemical were developed for improving safety of pesticide application. Development of new sprayer system relies on the usage of closed transfer system (CTS) to avoid leakage of chemical into nature as most high peaks of pesticide concentration are detected in water from point sources than from spray drift. CTS and direct injection techniques are of importance to be integrated in sprayers' designs for reducing environmental pollution with elimination of tank mixing and washing of pipeline prior to injection point (Matthews, 2007).

According to Matthews (2007), use of (CTS) needs support from governments to attenuate actual problem of environment pollution and operator contamination when chemicals are transferred to sprayer, and empty containers are disposed of.

The possibility of connecting directly the pesticide container to the injection pump constitutes a closed system that potentially reduces operator contamination. The British Standard (BS 6356 Pt 9) stated the maximum amount of operator contamination when using CTS for liquid pesticide formulations. The standard stipulates that during a transfer operation no more than 0.25 mL of pesticide could leak and maximum residue left should be less than 1 mL during the disconnection from the spraying equipment. The FastTrans-850 is a trademark of CTS commercialised in UK that fulfil these requirement.

The use of CTS has been seen as relevant technique for adoption of returnable container system by chemical industry. In USA, there was an increasing adoption of refillable containers from 1991 due to existence of large farms where over 200 million litres have been shipped, in Europe the chemical producers showed hesitation to adopt refillable containers as the number of trips from suppliers to farms is low and diversity of used pesticide by farmers is high (Matthews, 2007). Otherwise, different handling techniques for pesticides were implemented with its standard procedures to fulfil spraying equipment requirements and to promote the best practice methods.

2.11.3 Safety solutions for small sprayers' designs

Machado-Neto et al. (1998) evaluated the safety of applicators during loading/mixing and application of paraquat on maize crop by knapsack sprayers and determined the efficacy of safety measures applied to the sprayers. They evaluated potential dermal exposure (PDE) in 22 worker body parts using Cu^{2+} cation of a copper-based fungicide as tracer in the spray solution. The sanitary pads and cotton gloves were used to collect the pesticide solution on the sampled body parts. They found that paraquat application in front of the applicator's body (0.5 and 1.0 m lance) is unsafe and control of PDE can be improved by the use of protective garment on the legs and feet only, which received 92–93% of the PDE. They found also that switching the spray nozzle to the back of the operator reinforced working conditions safety and reduced the PDE by 98%.

Godeaux et al. (2008) studied the risks for the operators handling small portable sprayers to apply herbicides in public areas of communes and districts of Wallonia department in Belgium. They found that risks are generally much higher because of the important recourse to use of small sprayers (93% of communes and 73% of districts use knapsack sprayer). Furthermore, they found that users were mostly protected during spraying using personal protective equipments but the riskiest moments concerned the mixing and loading as concentrated products are handled.

Craig et al. (1993) developed a closed transfer system (CTS) based on a venturi injector for hand operated sprayer. The design limits the contact of operator with pesticide concentrate contained in a bag inside a leak proof bottle screwing into the lance of the sprayer. The concentrate is injected into the lance where it is mixed with water pumped from the tank. The test of the CTS for different formulation viscosities showed a consistent dilution rates between 0.5 and 10% for an overall flow rates between 0.5 and 2 L/min.

Awadhwal et al (1993) designed and tested CTS suitable for use with knapsack sprayers. They found that use of the CTS resulted in significantly lower ($P<0.05$) operator exposure (15.95 µL) compared with the exposure resulting from the mixing and pouring method (42.65 µL) as well as the splash from pouring chemical directly into the sprayer tank (72.55 µL). They also noted that integration of CTS to knapsack sprayer reduces the frequency of handling concentrated chemicals from the usual 8 to 12 times per day to only once or twice a day, which considerably reduced operator contamination.

2.11.4 Safety solution for mounted sprayers' designs

Helms and Landers (2001) identified five areas of potential pesticide exposure in mounted sprayer and listed the possible engineering solutions that limit the risk for operator and environment (Table 4). Such solutions concern the mechanical devices of induction bowls, container rinse systems, diaphragm check valves, hydraulic folding booms, multiple nozzle bodies, low drift nozzles, air induction nozzles, and tank rinse systems. The induction bowl is a filling tank situated at low level of the sprayer for facilitating chemical pouring and premixing for easy transfer to the main tank without expositing operator to risk of direct loading of chemical. The container rinse system is a mechanical rinsing device used to rinse containers and closures with a volume of rinse water equivalent to 10% to 20 of the container volume (DEFRA, 2006). The diaphragm check valves are used in sprayer to block back flow and to avoid dripping of chemical when hydraulic circuit of the sprayer is opened for check or repair.

Table 4 : Potential risk areas in spraying systems and its engineering controls solutions (adapted from Helms and Landers, 2001).

Areas and methods of reducing exposure				
Spray drift contaminated clothing in cab	Loading sprayer	Spray drift	Changing blocked nozzles or moving the boom	Cleaning spray equipment
Pressurized cab with carbon air filter Protective clothing locker	Closed transfer system Direct pesticide injection Container rinse system Chemical induction bowl	Air assisted boom Low drift nozzle Twin fluid nozzle Varitarget nozzle	Multiple nozzle body Hydraulic boom fold/extend system Diaphragm check valves Hand wash water supply	Tank rinse system

The solutions mentioned above, have been tested and showed their efficacy to reduce pesticide exposure. However, spray equipment manufacturers offer most of control engineering solutions (Fig. 13) as options, not as for a standard design of spraying equipments (Helms et al., 2000).

In developing countries, adoption of basic control engineering solutions in marketed tractor-mounted sprayers keeps far with lack of standards arsenal that can help to control performance of marketed agricultural sprayers mainly imported without sufficient exigencies on quality and safety measures. Tractor mounted sprayers should be equipped with control engineering solutions as necessary requirements not as facultative options. However, portable sprayers are of high exposure risk and cannot technically fulfil conditions to adopt control engineering solutions and safety measures as it can be done for tractor-mounted sprayers (Fig. 13).

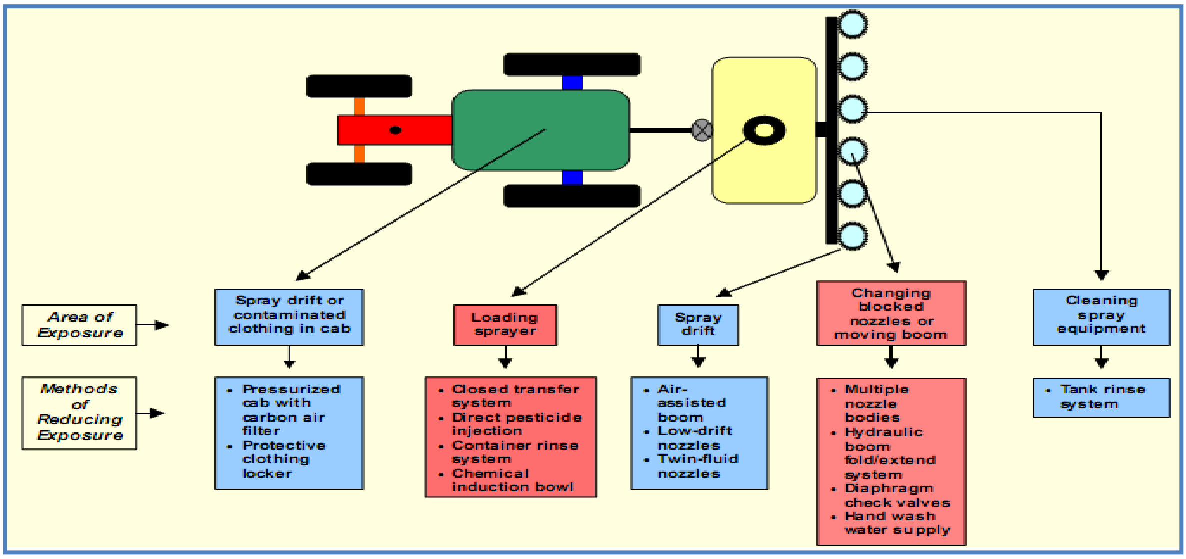


Figure 13 : Area of exposure and technological solutions for tractor mounted sprayers

2.12 Conclusion

As stated before, injecting pesticide online is a relatively clean method to reduce operator exposure and left over chemical mixtures, but DIS technologies are not yet widely disseminated and adopted by users. There are technical and economical reasons for lack of the technology diffusion and adoption.

The technical problem depends on the system performance regarding the slow response dynamic for concentration process change, the inadequate mixing of chemicals in the spray line resulting in application miss-uniformity and the cleanability of contaminated circuit of DIS with concentrated chemical.

The reduction of the lag time has been studied by many researchers using direct injection at the nozzle body but this improvement cannot be done without affecting the performance of mixing and cleaning process (see indicators performance of CDIS, BDIS and NDIS shown in tables 2 and 3).

There is a continuous progress in research for improving design of DIS and variable rate controller's performances in term of lag transport and system dynamic reactivity but the complexity of DIS keeps in solving the controversy between the parameter's performances. In fact, uniform mixing of chemicals into the carrier and easy cleaning of contaminated parts with concentrated pesticides cannot be perfectly done while looking for better dynamic performance in adopting local points injection and shortcut mixture transport (case of BDIS and NDIS). Otherwise, the complexity also keeps in designing cost effective and energy efficient DIS.

According to the usage context of DIS, the technology progress keeps focused on searching solutions for precise and easy chemical application in big scale farming of developed countries. There isn't yet any interesting offer for small scale farming despite of different attempts to adopt technology in some developing countries (case of India). The technology adoption is economically constrained by its high cost and lack of offers of DIS technically adapted for the context of small scale farming.

The trademarks of DIS are mainly commercialised by precision farming companies and typically used in the context of big scale farming to solve problem of mixing high quantities of herbicide applied in no-till agricultural system typical of North America. The commercialised DISs are nowadays mainly reserved for modern and big farms in developed countries of North America and Europe.

The difficulty in adopting extensively the existing DIS technologies is due mainly to its high price and maintenance requirements. Those commercialised technologies are not adapted for extensive usage in the context of medium and small scale farming. There isn't practically any trademark of DIS adapted to the context of intensive chemical usage in developed and developing countries.

From the technical point of view, the commercialised designs of DISs are typically based on using hydrostatic pressure to control the return flows of the carrier and/or of the chemical to respectively the carrier tank and the chemical tank in order to adjust injected chemical and carrier flows for processing variable applied rate. The injection of chemical is typically done into the central point and downstream to the carrier pump with necessary use of online mixers. The injection in pressurized side of the sprayer pump cannot be done without use of online mixers for satisfactory mixing quality.

The injection in the pressurized side requires usage of robust and powerful metering piston pump for injecting at a pressure higher than operating pressure of carrier flow, consequently this technical choice cannot be considered as low cost solution due to demand for high pressure injection pump, important energy use and potential difficulty of cleaning contaminated circuit.

As low cost solution, the injection of chemical at low pressure in suction side requires usage of simple and affordable peristaltic metering pump (two to five times lower price) with low energy requirement (five to ten times lower consumption) comparatively to exigency of injection in pressurized side. Furthermore, the technical choice of hydrostatic pressure control based on regulator pressure or flow valve is energy consuming and expensive comparatively to using hydrodynamic control of metering and pressuring pumps actuated by direct PWM without return flows of carrier and/or chemical to tanks.

To take advantage from the art of DIS technology referenced before, it is possible to develop a small DIS based rechargeable electrical source according to the advantage of reducing energy use by eliminating the carrier flow return needed in conventional sprayer for permanent chemical mixing in the tank. Furthermore, the choice of efficient energy of DIS options (injection in low side pressure and usage of hydrodynamic mode control) is of importance for potential usage of the technology in intensive cropping systems of small scale farming in developing countries. The pretended DIS design should satisfy criteria of affordability, energy and application efficiencies.

As mentioned above, the choice of options such as hydrodynamic control and injection in suction side with possibility of displacement of electrical carrier pump close to centre of boom line are important for designing energetically efficient DIS with improved dynamic performance.

The hydrodynamic control of injection and carrier flows can be performed using electrical PWM actuators to dynamically control metering and carrier pumps. It helps to reduce electrical energy consumption and cost of DIS as return flows can be avoided and cost of hydraulic circuit and process control hardware can be reduced. In fact, the hydrodynamic control option make possible to actuate pumps without use of back flow control that need use of regulator valves. This option is energetically efficient and economically affordable for promoting use of DIS by small scale farmers. Furthermore, the possibility of developing low cost process control system using a PLC and limited numbers of sensors to manage feedback control information of operating pressure and working speed. The pumps can be actuated with reference to their variation of rotational speed.

The technique of injecting in upstream injection point is an interesting option of online mixing of chemical through the main pump without use of online mixer that can economically reduce energy use due to friction loss and cost of the mixer device. This choice can improve cost and energy efficiency of the pretended DIS design. However, the dynamic performance of upstream injection can be maintained as there is a flexibility of placing electrical pumps closes to boom line in order to reduce distance and dead volume between injection and tip nozzles points. Modelling hydraulic design optimizes the lag transport and reactivity of DIS.

The use of electrical motors makes possible to flexibly positioning pumps closely to the spraying boom and overcoming problem of lag transport. This choice improves the dynamic performance of DIS and has a fast reaction time for optimal processing of concentration change.

The working condition of tractor-mounted sprayers at high variable speed (3 to 4 m/s) amplifies the problem of lag time with use of large spraying boom. This causes a long distance (and area) of chemical misapplication. However, small DIS sprayers equipped with 5 meters’ boom and operated at low variable speed (1 to 2 m/s) do not expose the problem of lag transport as important as in tractor-mounted sprayers.

Chapter 3 Specifications for Design of DIS Controller

3.1 Introduction

The precedent chapter stated the art of direct injection spraying technologies. We have concluded that the existing DIS technologies fit only to big farming context of developed countries. There are technical and economical reasons limiting its adoption and spreading in the context of small scale farming. The present study takes as hypothesis that there are many advantages to take from the existing expertise of spraying technologies for studying the feasibility of developing a prototype of DIS that can fit to the context of small scale farming based on intensive cropping system. Otherwise, focusing on developing a DIS technology is taken as a reference study for evaluating the feasibility of implementing cost effective sprayer for variable chemical application rate proportionally to variable working speed using chemical premixing (proportional mixture volume rate) or direct injection (proportional carrier and/or chemical flow rates) methods.

As mentioned before, this project aims to develop a kit of variable rate applicator and its process controller to be mounted on a chariot (of bi-wheels or tri-wheels) sprayer propelled by operator for usage in small intensive farming systems practicing vegetable crops, cereals and food legumes. The intensive cropping systems are based on using high chemical amount and repetitive spraying applications in short cropping cycle (e.g. potatoes production can demand from ten to fifteen fungus treatments during three months crop cycle. Small farmers in developing countries typically use portable sprayers that are technically inefficient for carrying out precise chemical metering and minimizing risks related to operator safety and environmental pollution.

The idea of designing a small DIS firstly comes from diagnostic of occurring problems of inefficient chemical application typically of the portable spraying equipment widely used in small scale farming. The approach used consisted of characterizing the technical constraints limiting spraying performance and safety of applying pesticides in small scale farms and after that proposing simple and low cost engineering solutions to be technically and economically accepted by the targeted end users. This approach aid to specify requirements of a variable rate spraying system based on direct injection metering device to be fitted to existing propelled sprayer chassis which is performed in the past for use as improved design of conventional sprayer (El Aissaoui et al., 2005).

3.2 Chemical application inefficiency of portable sprayer

Small farmers apply chemical by portable sprayers due to their simplicity and affordability. However, such sprayer has a low efficiency and low metering accuracy due to its simple design of lance and pump and its low field capacity and inability to apply reduced volume rate. Otherwise, usage of the spinning disc portable sprayer cannot be a good solution by referring to problems due to applying ultra low volume of concentrated formulations and to handling of small rotary atomizer.

Small scale farming systems are facing to a high potential of human contamination and pollution of environment. This situation can be technically correlated with poor efficiency of pesticide application and lack of engineering solutions for improving chemical spraying in the context of small farming.

3.2.1 Spraying performance of lance

Portable sprayers are equipped with lance of simple of multi nozzle(s) that cannot be efficient as operator cannot constantly maintain the lance level in the same position. Spatial deposition of chemical mixture applied by the lance cannot be uniform as there is considerable influence of variable working speed of operator and difficulty to maintain nozzle(s) jet at constant height. Furthermore, the operator’s behavior to laterally displace lance in zigzag for covering large width contributes to amplify considerably lateral and longitudinal application errors.

As solution to poor spraying field capacity, small farmers practically tried to use lance of multi tip nozzles (four nozzles) for improving field capacity of portable sprayer. However pumping performance of portable sprayer cannot yield performance of satisfying operating pressure of multi nozzles boom.

As solution to the mentioned problems, it is possible to adapt multi nozzles pliable boom on a rolling sprayer framework. The boom mounted on tri-wheels sprayer chassis makes possible to set the spraying height and the rate application with reference to speed sensing. The use of 5 meters boom width can fulfill the requirements of even mixture distribution and precise chemical application similarly to the case of tractor mounted sprayer. Furthermore, it will be possible to adequately apply chemical at a reduced volume rate and to increase the working capacity.

3.2.2 Stability of operating pressure and flow rate

Hand sprayer operator cannot maintain uniform pressuring rhythm due to the potential of occurring pumping fluctuations. In fact, the operating pressure of the sprayer depends on energy capacitance and behavior of worker to continuously maintain constant pumping cadence during the spraying exercise.

All spraying parameters should be constantly maintained to apply uniform chemical rate by hand operated sprayer. The parameters of working speed, level position of lance, and boom working width are influenced by operator behavior. But nozzle operating pressure, uniformity and spraying width of nozzle are influenced by the pumping performance of the portable sprayer and its varying cadence.

The control of variable or constant operating pressure can be performed cost effectively on the basis of implementing robust strategy control for PWM actuation of adaptable DC diaphragm pump.

3.2.3 Volume rate application and water use efficiency

Hand operated sprayer are recommended for applying high volume rate around 200 L/ha and cannot adequately perform reduced volume rate lower than 100 L/ha due to its low pump pressuring potential. It cannot be powerful to enough break up liquid for efficiently applying reduced volume rate around 100 L/ha, key of water use efficiency for spraying chemical in water scarce areas of dry land context. Use of electrical energy efficient pumping system can be of importance to adequately apply chemical at the reduced volume and satisfying the requirement of water use efficiency in dryland farming system.

3.2.4 Field working capacity

Working capacity of portable sprayers is low due to the time required for preparing chemical mixture, refilling tanks, and spraying operation. The spraying experience in arid land context of Morocco showed that working capacity of portable sprayer cannot be more than one hectare per day (1 ha/day). The experience showed that usage of multi nozzle boom of 6 to 10 nozzles mounted on a rolling sprayer (El Aissaoui et al., 2005) considerably improves the working capacity to around 1 hr/ha. Furthermore, usage of reduced volume rate (around 100 L/ha) contributes to improve the working capacity by reducing the frequency of tank refilling.

3.2.5 Operator safety and pollution

Usage of portable sprayers is a potentially source of risk for operator contamination and environmental pollution. The experiences in small farming systems context of developing countries showed the critical situations of pesticide applications by portable sprayers due to lack of measures safety, material performance and operator awareness (Matthews et al., 2004). Design requirements of adapted sprayer for usage in small farms should require as little water as possible, be small but light and robust, be ground metered, be simple but profitable to be acceptable to both the farmer and the labor, affordable and produce minimal drift (Fowler, 2000).

3.3 Requirements for design of direct injection sprayer

According to Stone (2000), design of agricultural chemical applicator should be at least take into account the key components that present the main design considerations with reference to its cost effectiveness and its performance in the field. The key components concern the functions of container, transport circuit, metering system, distribution and placement of chemical mixture. Such functions should satisfy the major consideration related to system capacity to process chemical by adequately handling, cleaning, loading, carrying capacity, and operating speed, and by satisfying requirements of accuracy, safety, robustness, uniformity and effectiveness.

The technical characteristics required to design DIS depend on its ability to process applied chemical, the tanks capacities and the time needed for their reloads, the targeted crops and its adaptation for boom design, the framework and its handling ability by operator, the total volume rate and field efficiency, the chemical injection rate and capacity, the field working speed, the boom width and nozzles selection, the pressure and metering pumps selection, the control system components selection, and the hose size dimensions of carrier flow, and chemical injection circuits.

3.3.1 Layout of DIS spraying system chassis

Development, test and evaluation of a human propelled sprayer adapted for use in the context of small farming systems was done in the past as a R&D project in Morocco (El Aissaoui et al, 2005). The first sprayer configuration (chariot based on bi-wheels chassis) was developed for proposing solutions to existing problems of inefficiency, metering, safety and ergonomic related to use of portable sprayers. The second sprayer configuration was performed to be based on tri-wheels chassis (see layout in Fig 14)

The idea of developing DIS process controller comes in the way of scaling up the existing spraying technology with the possibility of integrating the technical expertise of variable rate application based on the sensing of the sprayer speed in agricultural field. In fact, homogeneous spraying of chemical independently of speed variation is of importance to overcome difficulty of maintaining constant working speed by walking operator, key condition for precise chemical spraying in a constant pressure/flow rate.

The DIS prototype (Fig. 15) is expected to be based on rechargeable electrical batteries as shown before that is possible to design hydraulic spraying system of high energy efficiency. The DIS is energetically efficient due to energy saving from annulment of bypass flow assuring mixing as chemical and carrier are kept in separate tanks. Furthermore, technical options of injecting chemical in suction side of carrier pump and spraying at low pressure come in the sense of improving energy economy and autonomy of the assumed DIS.

The sprayer framework is designed to be operated by walker applicator with possible usage of traction assistance when the sprayer tank capacity is chosen to be big for improving autonomy and work field capacity.

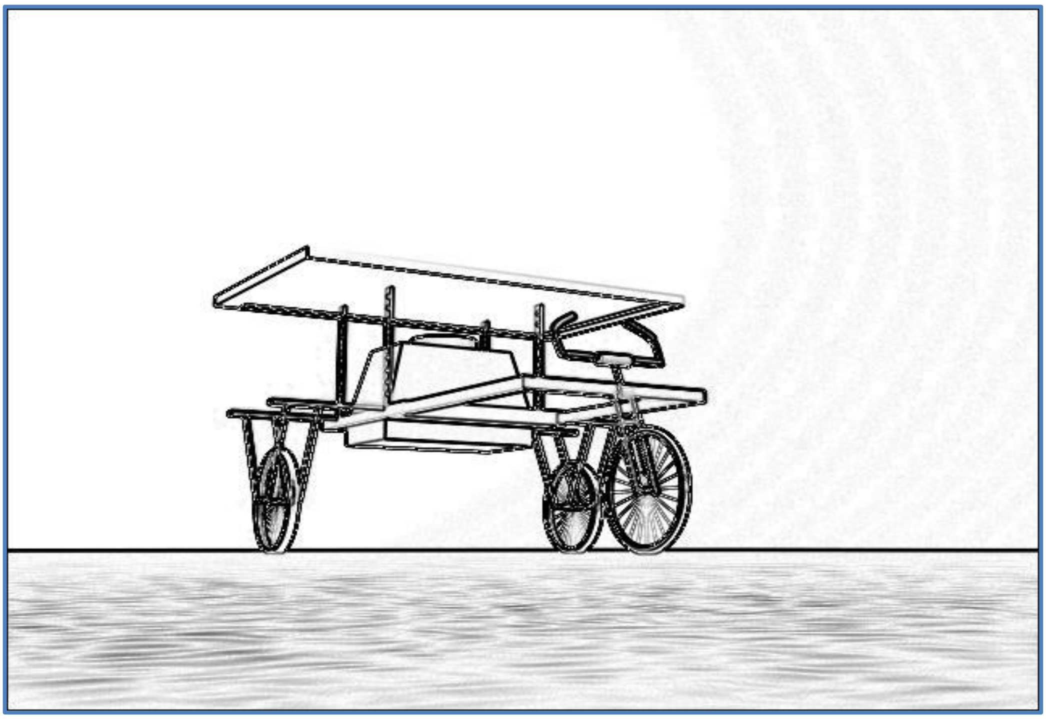


Figure 14 Layout of tri-wheels mounted sprayer design fitted for use in small scale farming

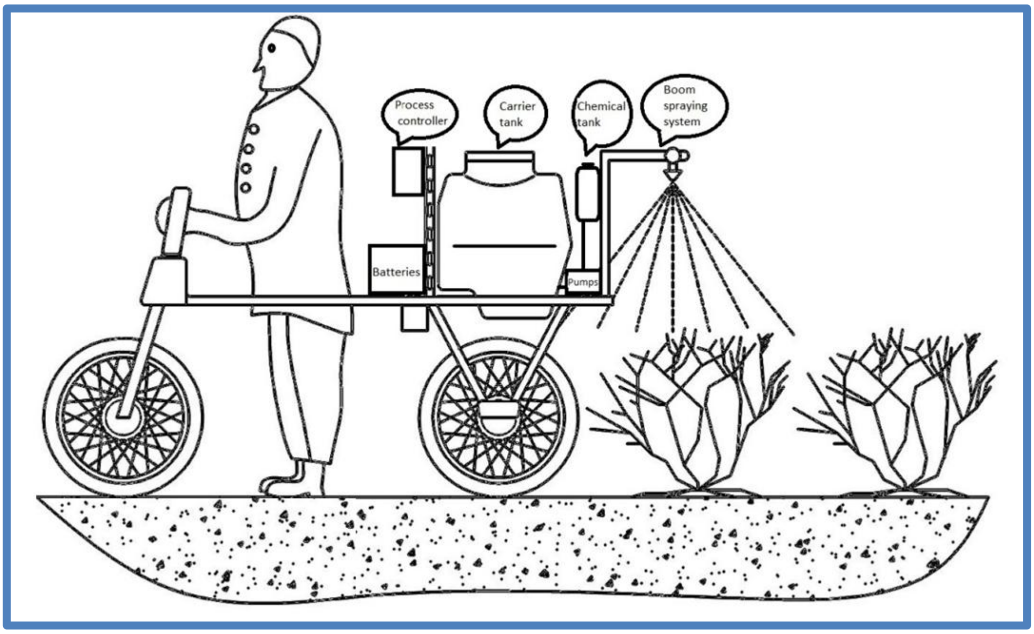


Figure 15 Layout of DIS tri-wheels sprayer operated by walking operator

3.3.2 Layout of DIS and process controller

Our study specifically aims to develop a process control kit presenting performance requirement of precisely applying chemical in accordance with the variable working speed cadence of the walking operator manipulating ground metered sprayer (Fig. 16). Hand operated sprayers don't have any control on application error and require maintain of a constant pressure/flow rate for a constant working speed. The variation of operator working speed in agricultural field induces application error as there isn't any feedback control to adjust the application rate.

The process controller kit could fit to a small DIS mounted on the sprayer chassis (Fig. 15). The added value of such DIS and process control design consists on solving the technical's problems of applying chemicals in small farming system while adapting the existing expertise of variable rate application technologies that is until now focused only on the context of big farming systems.

Development of spraying system based on rechargeable module of electrical batteries is of importance according to system autonomy that can be improved using technical options of energy and water use efficiency to apply variable chemical rate. In fact, DIS is deprived of hydraulic bypass flow needed for the tank mixing. Furthermore, the electronic actuation of the pressuring and metering pumps is energetically efficient. The advantage that can be taken from conceiving efficient DIS can be appreciable to present small electrical sprayer prototype of sufficient autonomy and of ability to precisely metering chemical and applying variable chemical rate.

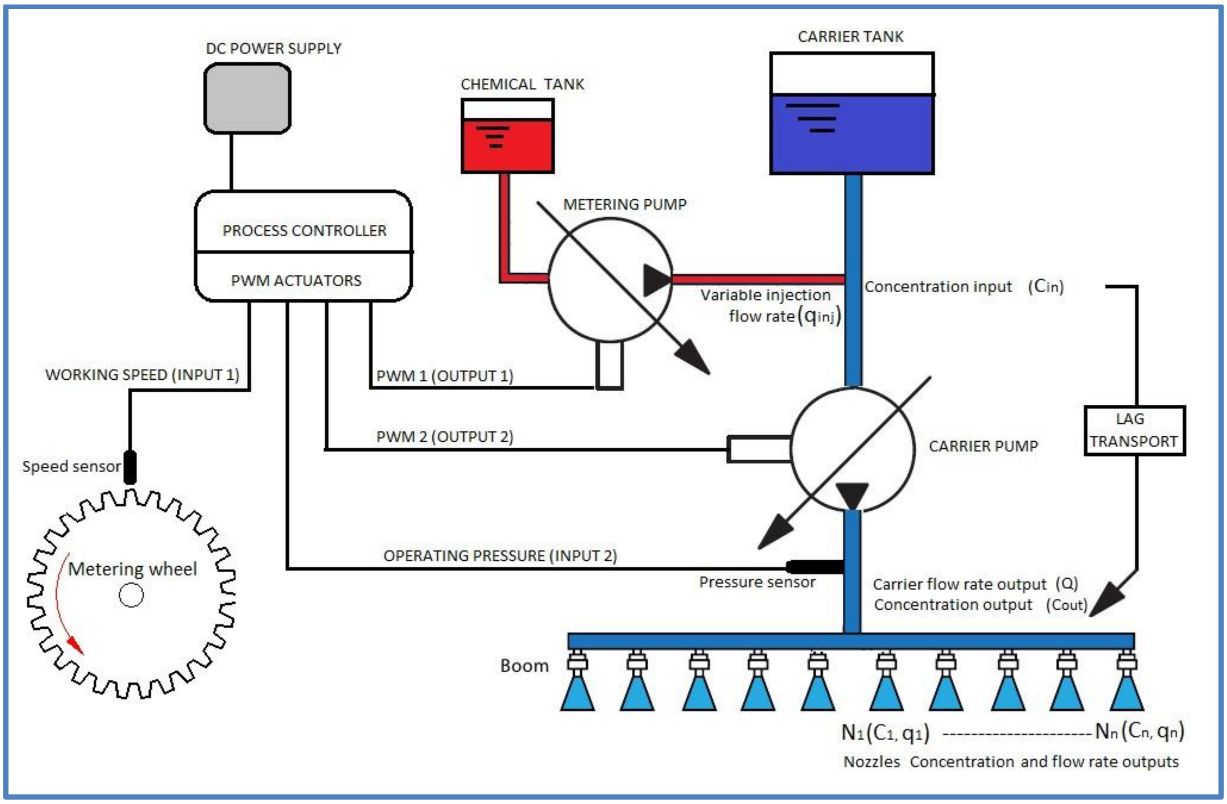


Figure 16 : Layout of a DIS controller adaptable to based wheels sprayer

3.4 Specific requirements for design of DIS prototype

After presenting the sprayer framework and the layout of the proposed DIS, the specific requirements of applying chemical using direct injection metering are summarized as follow:

3.4.1 *Sprayer framework specification*

3.4.1.1 Chassis ergonomic

The practicability of the sprayer framework (Fig. 15) was positively tested in the context of small farming systems of Morocco. There was satisfactory reaction from the farmers to adopt it as alternative to the use of portable sprayer for efficiently applying chemical at reduced volume rate of 100 L/ha, for increasing the working capacity to be around 1 ha/hr and to overcome safety problems of portable sprayer.

Sprayer ergonomic depends on its load for easy pulling by operator. The sprayer load is evaluated to be 70 kg without water tank charge. The total charge of more than 100 kg needs installation of traction assistance for easy manipulation of the sprayer by walker operator. When the tank capacity is more than 30 liters, the chassis should be equipped with traction assistance for alleging operator work.

The net pull force of the sprayer load of 150 kg with full tank of 50 kg is approached to be around 100 N with minima of 50 N and maxima of 200 N. The power requirement for the working condition within the speed of 2 m/s is approached to be around 200 W with minima and maxima of 100 and 400 W, respectively.

3.4.1.2 Boom layout design

A boom of ten nozzles is adapted to the sprayer chassis for an effective width spraying of 5 meters. DIS technique requires hydraulic boom structure that satisfies performance of reduced lag transport and its even distribution in all nozzles. The hydraulic boom performance is treated in details for yielding criterion of an optimal boom design.

3.4.1.3 Working speed

The sprayer framework is operated by worker walking in the speed range of 0 to 2 m/s. The typical working speed of walker operator turns around 1m/s. The working speed profiles are generated in crop field condition for use as references value for the process control modeling study (see details in materials and methods)

3.4.1.4 Chemical and carrier application rates

3.4.1.4.1 Chemical application rate (TAR)

TAR of 1 L/ha is typically taken as a reference value to design the metering injection system that should satisfy maximal flow rate of 60 mL/min (V_{max} = 2 m/s, W_b = 5 m). The TAR can be technically doubled up using two injection lines (in the case of using peristaltic metering pump) or by implementing the possible technical options of increasing the dosing gain (K = 2) in hardware or software stages (in the case of using both peristaltic or piston metering pumps).

3.4.1.4.2 Volume application rate (VAR)

Typical applied volume rate can vary from less than 100 to 300 L/ha depending on operating pressure, nozzles caliber and working speed. Typical applied VAR is around 200 L/ha. The carrier pump should satisfy the maximal flow rate requirement for serving boom of ten nozzles (reference ISO11003) at the maximal operating pressure (12 L/min ~ 3 bars). This maximal flow rate requirement offers possibility of applying 200 L/ha by working at the speed of 2 m/s (see table 5). Usage of small nozzles caliber (ISO11002 or less) makes possible to reduce VAR according to the assumed speed working within the range of 0- 2 m/s. Table 5 showed possible VAR to be applied by the pretended spraying system within the defined condition of working speed in [0-2 m/s] and operating pressure of 2 bar and according to the chosen nozzle caliber between 11001 and 11003. At the typical operating pressure of 2 bar and working at speed around 4 Km/hr (1.1 m/s), the VAR can be around 100, 200 or 300

L/ha with reference to use of the nozzle calibers of ISO 11001, ISO 11002 or ISO 11003, respectively (Table 5). The maximal flow rate requirement of the carrier pump is around 10 L/min according to exigency of applying a maximal pretended VAR of 300 L/ha at reasonable working speed around 4 km/hr and pressure less than 3 bar.

Table 5: Potential applied VAR (L/ha) within the operating speed range of [3 – 7 km/hr]

Nozzle reference	Flow rate (L/min) at 2 bar	Sprayer operating speed*				
		3 km/hr	4 km/hr	5 km/hr	6 km/hr	7 km/hr
ISO11001	0.32	128	96	76	64	54
ISO11002	0.65	260	196	156	130	112
ISO11003	0.96	384	288	230	192	164

*the potential working speed range of the sprayer [0-2 m/s] corresponds to [0-7.2 km/hr]

3.4.1.5 DIS performance requirements

3.4.1.5.1 System reactivity and lag transport

Reactivity of DIS is a primordial requirement to perform variable concentration process change according to variable working speed conditions. According to state of art, the lag transport requirement should be studied adequately (see details in material and methods) for limiting the response time of DIS within the levels of 2 s to 3 s. This response time is of importance to steadily maintain the mean application error within 5 % (error standards). The DIS dynamic is studied in details in the next chapter according to the importance of optimizing hydraulic and process control designs for satisfying this requirement.

3.4.1.5.2 Mixing quality

The choice of injecting chemical in suction side of carrier pump improves online mixing process without use of static mixer. This option is economically chosen to avoid installation of static mixer as done in the case of injecting chemical in pressured side of the carrier pump.

3.4.1.6 Electrical energy use efficiency

Injection in low pressure side is energy use efficient but need installation of carrier pump close to spraying boom for reducing lag transport time. The electronic command of pumps can be efficiently designed as energy required for actuation of a variable pump speed is low. PWM actuation of carrier and metering pumps is also an energetically efficient method according to hydrodynamic adaptation of pumps regimes to the solicitations needed for satisfying flow-pressure requirements without use of bypassing or back flow regulation as done in hydrostatic control mode. The use of PWM for operating injection and pressuring pumps at variable speed is of importance to reduce the DIS energy requirements to be within 150 W.

The sprayer can be advantageously supplied using rechargeable batteries mounted in 12 or 24 V DC. The choice of 24 V DC supply is of importance to reduce current transport losses as the amperage required is half of that needed in the case of using 12 V DC supply voltage. Furthermore, the current transport can be more efficient in the case of planning to assist electrically the traction of the sprayer using 24 DC electrical-bike motor. Otherwise, it judged also possible to optionally implement the sprayer with integrated solar panel-charger kit for continuously charging the batteries to improve its autonomy in the field.

3.4.1.7 Water use efficiency

As shown before, spraying chemical in arid context requires use of reduced amount of water to limit logistic needed for pumping and transporting water. Usage of small caliber of AI nozzles reduced volume rate while improving anti drift performance. Furthermore, usage of adapted strategy control based on constant carrier flow is of importance to maintain constantly applied flow rate for optimal operating pressure (2 bars) while varying chemical application rate proportionally to variations of the working speed.

3.4.2 Process controller specification

3.4.2.1 Metering pump control

The control of chemical flow is achieved by actuating the DC volumetric pumps using the technique of PWM. Implementation of a PID controller serves for managing the pump actuator on the basis of optimal metering strategy that satisfies requirements of dynamic performance. The DC metering pump should be robust and of dynamic (constant time within 0.2 s) for responding to exigency of accuracy in repetitive chemical dosages. The metering control strategy is studied in details of modeling and implementation in the next chapter of the thesis.

3.4.2.2 Carrier pump control

The control of carrier flow rate is done too by actuating the DC pump using PWM. The choice of DC pump should take into account the electric motor constant time to be within 0.2 s for satisfactory control dynamic and exigency for fastening response to increase hydraulic pressure demand in acceptable lag time. The PID controller can be fitted to actuate both pumps (metering and carrier flows) using constant carrier flow control or total flow control (see definition in state of art). Both control strategies are studied in details in the next chapter.

3.4.3 *Safety and cleaning requirements*

3.4.3.1 Operator safety

Sprayer framework design is of importance to reduce operator exposition to pesticide. The sprayer design supposes that operator keeps far forward from the spraying boom and potentially from drift jet. Furthermore, adaptation of DIS to this spraying framework makes possible to benefit from its advantages of keeping carrier tank clean and avoiding potential contamination due to its rinsing. Otherwise, it is possible to fit the existing control engineering solutions (see details in state of art) to the pretended DIS for more improvement of operator safety.

3.4.3.2 Rinsing of chemical metering circuit

DIS is deprived of premixing chemical in the sprayer tank and consequently of rinsing operation of totally contaminated hydraulic circuit as required for conventional sprayer. Only the metering circuit of DIS that carry concentrate chemical which needs adapted hydraulic design for rinsing of the metering circuit at the end of every spraying operation. It assumed possible to design hydraulic line to transfer water from the carrier tank to the chemical tank for cleaning of the metering circuit and spraying the rinsing solution on crops. The process controller can be implemented with rinsing mode logic for filling chemical tank and actuating metering pumps in a reasonable short time to spray the rinsing solution on crops after finishing spraying operation.

3.5 Conclusion

This chapter presented the specifications required for implementing the pretended DIS design. Table 6 summarized the technical choices taken to satisfy the requirements in terms of system dynamic performance, water and energy uses efficiencies according to working conditions of the DIS sprayer framework within the speed range of [0-2 m/s]. After the presentation of the specifications, the next chapter will focuses on methodology and experimental design used to study and evaluate hydraulic and process control performances of the DIS.

Table 6: Requirements of DIS for use in small scale farming context

Designations	Reference values	Justifications/ Observations
Applied technical rate (TAR) Chemical tank	The TAR typically is 1 L/ha (possible to apply in parallel of 2 formulations or doses of 2 L/ha using two channels peristaltic pump or increasing flow rate gain of injection pump)	Most of liquid formulations are applied at the rate of less than 2 L/ha. Dry formulations require premixing preparation of mother solution and installation of mixer device for permanent homogenization of liquid in the chemical tank as a key of precise metering of flowable (particulates in suspension) pesticides
Applied volume rate (VAR)	Typical rates used in crop protection are from 100 to 300 L/ha.	Chemical spraying requires use of reduced volume rate around 100 L/ha as water keeps limiting factor in arid context.
Carrier tank	Tank capacity should be between 30 to 50 liters depending on the total sprayer load around 100 kg for easy manipulation of sprayer.	The tank capacity cannot be more than 50 % of the sprayer weight Possible usage of traction assistance kit for easy handling of sprayer chassis by operator.
Water use efficiency	Use of typical VAR of 100 L/ha Use of adapted AI nozzles for reduced volume rate and drift.	Reduced volume rate (100 L/ha) improves the work capacity and reduce the number and cadence of the tank refilling.
Energy use efficiency	DIS energy requirements for injection and carrier pumps are within 150 W	PWM and variable speed acting of pumps reduce significantly the DIS energy requirements
Working speed	The speed of operator pulling a rolling sprayer typically varies between 0 and 2 m/s	Walker operator typically works at the mean speed rating of 1 m/s in agricultural field.
Process controller	Use of PLC and PWM actuators, Implementation of PID variable chemical rate controller	Possible use of cost effective electronic devices (PLC, PWM actuators, pressure and speed sensors).
Carrier pump	DC diaphragm pump satisfying requirements of the minimal flow rate 10 L/min for operating ten nozzles at the maximal pressure of 3 bars.	Possible use of cost effective pump
Metering pump	The maximal flow rate should be around 100 mL/ha to cover application of 1 L/ha at the maximal working speed of 2 m/s (possibility of applying up to 2 L/ha using pump of two channel or increasing the gain by two.	Use of DC metering pump, PWM actuator and PLC. Use of peristaltic pump is adapted for upstream injection as low cost option. The piston pump is relatively expensive for more metering performance and robustness.
Boom width Work capacity	Typically boom of 5 m (10 nozzles). Field work capacity of 0.5 to 1 ha/hr.	Boom design should be optimal for low dead volume that reduces lag transport. Parallel boom scheme gives equal lag transport for even lateral application error.
Injection point	Upstream injection in the suction side demands low energy use and mixes chemical trough carrier pump without using static mixer.	Usage of electrical pump makes easy to install it very close to the center of the boom to overcome lag transport task due to upstream injection.
Reactivity of DIS	The total response time of system should be around 2 s	The response time depends on lag transport that can be yielded by optimizing hydraulic design and installing carrier pump close to the boom.
Boom application uniformity	Usage of optimal boom configuration for low and even lag transport between the nozzles along the boom. Low and even lag transport is the key for having limited application error.	Longitudinal uniformity depends on the response time of system to limit transitory application error. Lateral uniformity depends on the transport along boom.
cleaning of chemical supply line	Design of hydraulic line to transfer water from carrier tank to chemical tank for cleaning and end spraying the rinsing solution on crops.	Concentrate chemical persists in injection supply line and requires dilution in closed transfer way. Controller should be implemented with rinsing logic for filling water in chemical tank and actuating metering pumps in reasonable short time to spray the rinsing solution on crops field at the end of spraying operation.

Chapter 4: Materials and Methods

4.1 Introduction

As mentioned in the precedent chapter, our project aims to design a DIS feeding a spraying boom of ten tip nozzles. The present chapter describes the material and methods used to test and evaluate the pretended optimal design of DIS process controller (Fig. 17).

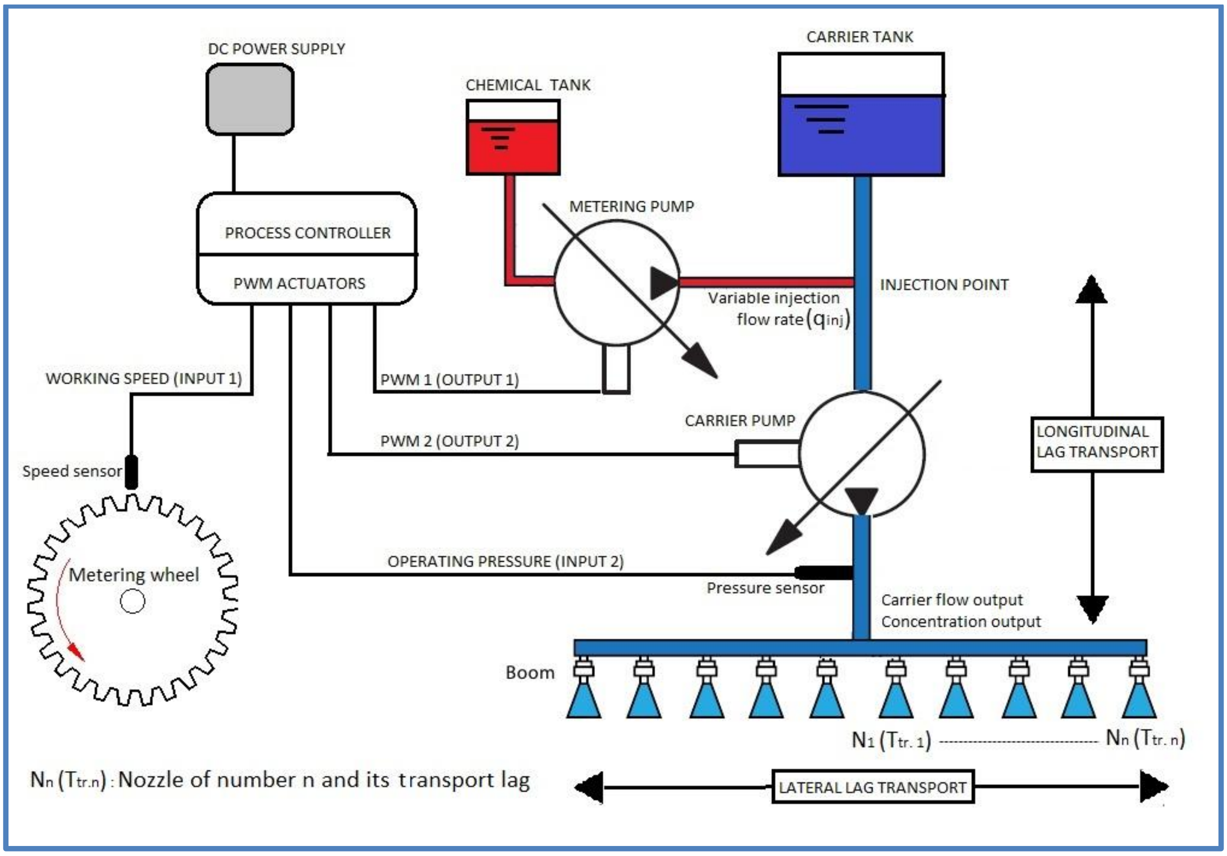


Figure 17: Layout of the assumed DIS process controller design

According to the specification book, the reactivity requirement of DIS is the key to optimally process concentration change of variable rate application based on varying working speed in field crop. The performance of the pretended DIS design cannot be yielded without optimizing its hydraulic scheme (hardware) and its process controller (software) for improving the system response dynamic in terms of lag transport and control strategy reactivity.

As shown in the state of art, the influence of hydraulic scheme on DIS performance mainly depends on the boom layout arrangement and housing diameter to improve lag transport and its transversal behavior between nozzles. Spraying application error is mainly due to lag transport effect. Such effect can be limited mainly to hydraulic boom scheme as we have the possibility of installing the injection and carrier electrical pumps close to the boom center.

For improving hydraulic boom architecture, it is possible to perform optimal boom arrangement having an even and reduced lag transport behavior by studying and comparing possible schemes of serial and parallel nozzles as mentioned below (Fig. 18).

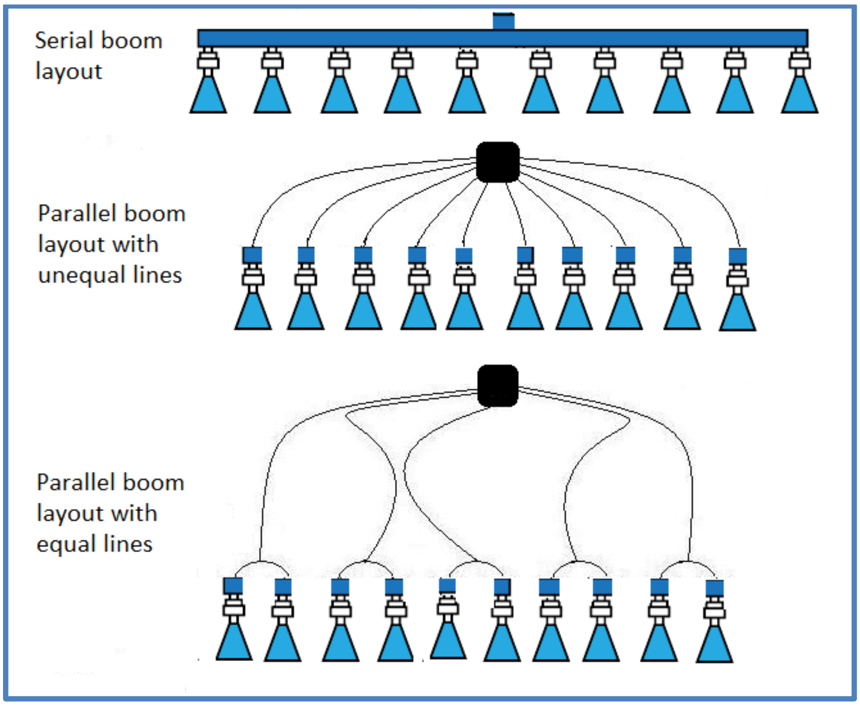


Figure 18 : Possible boom layout arrangements for improving concentration lag transport

By referring to the assumed scheme of DIS presented above and to its optimal hydraulic configuration, the following steps are carried out to validate the prototype design:

- Modeling and evaluating hydraulic boom layout as a main key to improve lag transport task and lateral application error of the pretended design of DIS spraying.
- Implementation of laboratory DIS process controller on the basis of hydraulic modeling results for studying performance of the pretended DIS controller design within the requirements specified in the precedent chapter.
- Modeling and implementation of two process control strategies for evaluation of the controller algorithm design in laboratory conditions using simulated speed solicitations of the real working conditions.
- Implementation of validated process control strategy into electronic kit (PLC and PWM pumps actuators) to present a cost effective controller design to be preliminary

tested in laboratory using simulated speed inputs for eventual assemblage to DIS sprayer framework and test in field.

4.2 Study of hydraulic boom performance

The boom design affects DIS performance when its hydraulic structure cannot yield conditions for satisfying dynamic and mixing performance in terms of lag transport and turbulence. The conventional boom scheme concerns existing configuration of tip nozzles mounted in serial scheme of standard boom section. The parallel boom scheme concerns the tip nozzles mounted in boom section and independently fed in parallel scheme (Fig. 18).

We look for optimizing boom design of DIS by characterizing standard design to evaluate its response to lag transport task and comparing it to response of parallel design. The latter can be performed to carry out equal nozzles responses avoiding lateral application error of DIS boom independently of its dynamic and mixing performance.

The assessment of standard boom layout was done using computational model developed (VB codes in annex A) to predict behavior of flow dynamic according to variable hydraulic solicitations in term of flow, pressure, turbulence and friction loss. Among simulated boom diameters, the optimal serial boom layout was validated to fulfill condition of optimal diameter housing for optimal delay transport without reference to variability response of concentration process change of interconnected tip nozzles of standard boom scheme.

After that, an optimal diameter can be chosen for feeding nozzles in parallel scheme to solve both problems of lag transport and of lateral variability response between nozzles due to usage of standard serial scheme for DIS prototype. In fact, as stated before in bibliography, typical boom (serial layout) cannot perform an even response time for the mounted nozzles in serial scheme (different lag transport response) independently of the total occurring lag transport.

4.2.1 Study of standard boom layout

The standard boom layout concerns boom scheme of existing conventional sprayer based on mounting tip nozzles in serial order. The feeding of such scheme is done through the boom side creating a dependent behavior of concentration process change in tip nozzles according to their hydraulic interconnection and their order in boom flow line.

4.2.1.1 Computational approach

There is a compromising point to search between the processes of concentration transport and friction loss. In fact, maximizing flow transport fastens DIS response time and improves mixing process due to induced flow turbulence but friction loss should be lower to avoid considerable pressure drop along serial boom layout for satisfying acceptable spraying uniformity. Moreover, chemical formulation can have a reduced effect on hydraulic performance when the applied mixture tends to be viscous. The change in flow dynamic due to viscosity can affect the system response and applied mixture tends to be missuniform.

According to Zhu et al., (1998) the viscosity of the most applied formulations is lower than 100 mPa.s. The viscosity of applied mixture of water and formulation tends to be of lower than the viscosity of the formulation only. Consequently, it cannot have an important effect on hydraulic dynamic of the flowing mixture. The mixture viscosity of ten times higher than water viscosity (10^{-6} $m^2.s^{-1}$) is taken as reference to compute the optimal boom design on the basis of simulated viscosity covering potentially the effect of the applied mixture found in practice.

Computation of optimal diameter of a boom section having five tip nozzles is done to take a fast response time (minimal lag transport) of the DIS system. The computational approach is based on using physical and chemical parameters of boom and sprayed mixture such as width, diameter, pipe material roughness, number of nozzles, nozzle flow rate coefficient, upstream boom pressure, downstream boom pressure, linear and local friction losses, density, and viscosity. The model gives a numerical gradient scheme of pressure, flow speed, Reynolds number, friction loss and lag time for each tip nozzle supposed elementary control volume (CV) and then for a lateral boom section of five tip nozzles. It consists of implementing numerical method for doing iterative incremental search (James et al., 1993) to solve non linear algebraic equations of pressure and flow rate. Computation of friction losses is done using the Darcy-Weisbach friction losses model (Sullivan, 1989; Gleen, 2003) and the Newton-Raphson numerical method for yielding friction factor in Colebrook equation.

4.2.1.2 Governing equations and control volume

The computation is done for each control volume of indices (i) among a spraying boom section of n tip nozzles mounted in serial scheme for transporting mixture of water and online injected chemical. The parameters H, V, Re, and f indicate respectively pressure, flow speed, Reynolds number and friction factor of the sprayed mixture in upstream (i) and downstream (i+1) points of defined control volume (Fig. 19).

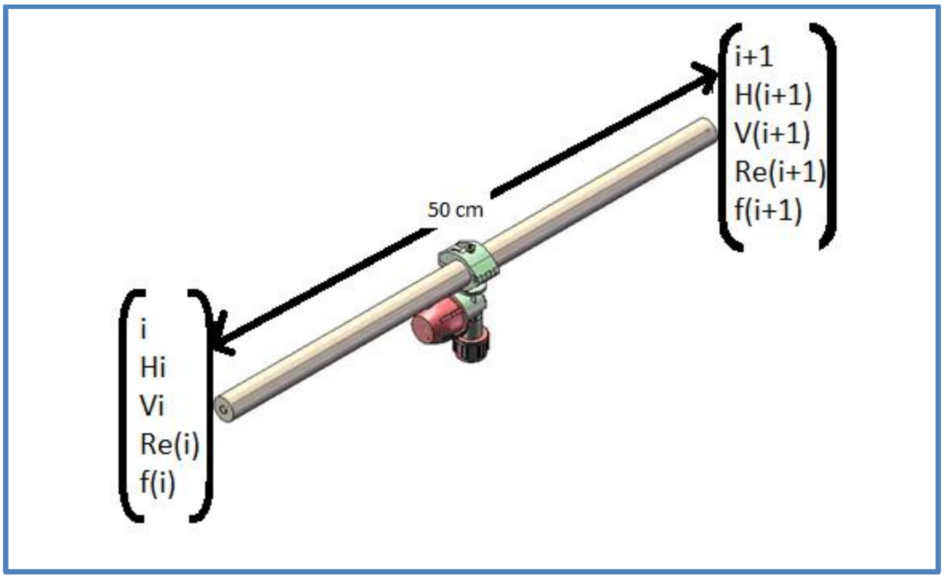


Figure 19 : Control volume indicating tip nozzle mounted in serial boom section

The average flow rate $\bar{q}_i$ depends on upstream pressure H_i, downstream pressure H_{i+1}, nozzle flow rate coefficient (k_n) and pressure exponent (x):

$$\bar{q}_i = k_n \bar{H}^x \quad \Rightarrow \bar{q}_i = k_n \left[\frac{H_i + H_{i+1}}{2} \right]^x \qquad (11)$$

The mass balance computation at any control volume of indices (i) depends on upstream and downstream flow rate (or on pipe section area A and upstream V (i) and downstream V (i+1) flow speeds) and on nozzle flow rate:

$$A.V_i = A.V_{i+1} + \bar{q}_i \qquad (12a)$$

$$\text{With} \quad A = \pi D^2 / 4 \qquad (12b)$$

$$V_{i+1} = V_i - \left(4\bar{q}_i / \pi D^2\right) \qquad V_{i+1} = V_i - \left(4 / \pi D^2\right).\left(\frac{H_i + H_{i+1}}{2}\right)^x \qquad (13)$$

The energy balance computation at control volume i is based on Bernoulli theorem. It depends mainly on hydrostatic pressure, kinetic energy and induced friction loss between input and output points of CV (potential energy keeps zero for horizontal boom position):

$$H_i + \frac{V_i^2}{2g} = H_{i+1} + \frac{V_{i+1}^2}{2g} + \Delta Hf_{i,i+1} \qquad (14a)$$

$$\Rightarrow H_{i+1} = H_i + \frac{V_i^2}{2g} - \frac{V_{i+1}^2}{2g} - \Delta Hf_{i,i+1} \qquad (14b)$$

The friction loss computation for CV of ΔL length is based on Darcy-Weisbach equation and depends on upstream and downstream linear friction factors (f(i) and f(i+1)) and minor loss factor ξ at nozzle body level:

$$\Delta Hf_{i,i+1} = \frac{1}{2g}\left[\left(\frac{f(i)+f(i+1)}{2}\right)\frac{\Delta L}{d}+\xi\right]\left(\frac{V_i+V_{i+1}}{2}\right)^2 \qquad (15)$$

The friction factor f(i) computation depends on flow regime:

- For laminar and transitory flow (Re≤3000), f(i) depends only of Reynolds number:

$$\mathrm{Re}(i) = \frac{dV_i}{\nu} \qquad f(i) = \frac{64}{\mathrm{Re}(i)} \qquad (16)$$

- For turbulent flow (Re>3000), f(i) can be computed by Colebrook equation and depends on Reynolds number and pipe absolute roughness (ε):

$$\frac{1}{\sqrt{f(i)}} = -2\log\left(\frac{\varepsilon}{3.7d}+\frac{2.51}{\mathrm{Re}(i)\sqrt{f(i)}}\right) \qquad (17)$$

For solving numerically the Colebrook equation, the model was implemented by Newton-Raphson iterative method subroutine. This method quickly yields f (i) values for minimal iteration number (James & al., 1993).

The lag transport computation depends on input and output flow speeds and CV length:

$$T_{tr}(i) = \frac{\Delta L}{2}\left(\frac{1}{V_i}+\frac{1}{V_{i+1}}\right) \qquad (18)$$

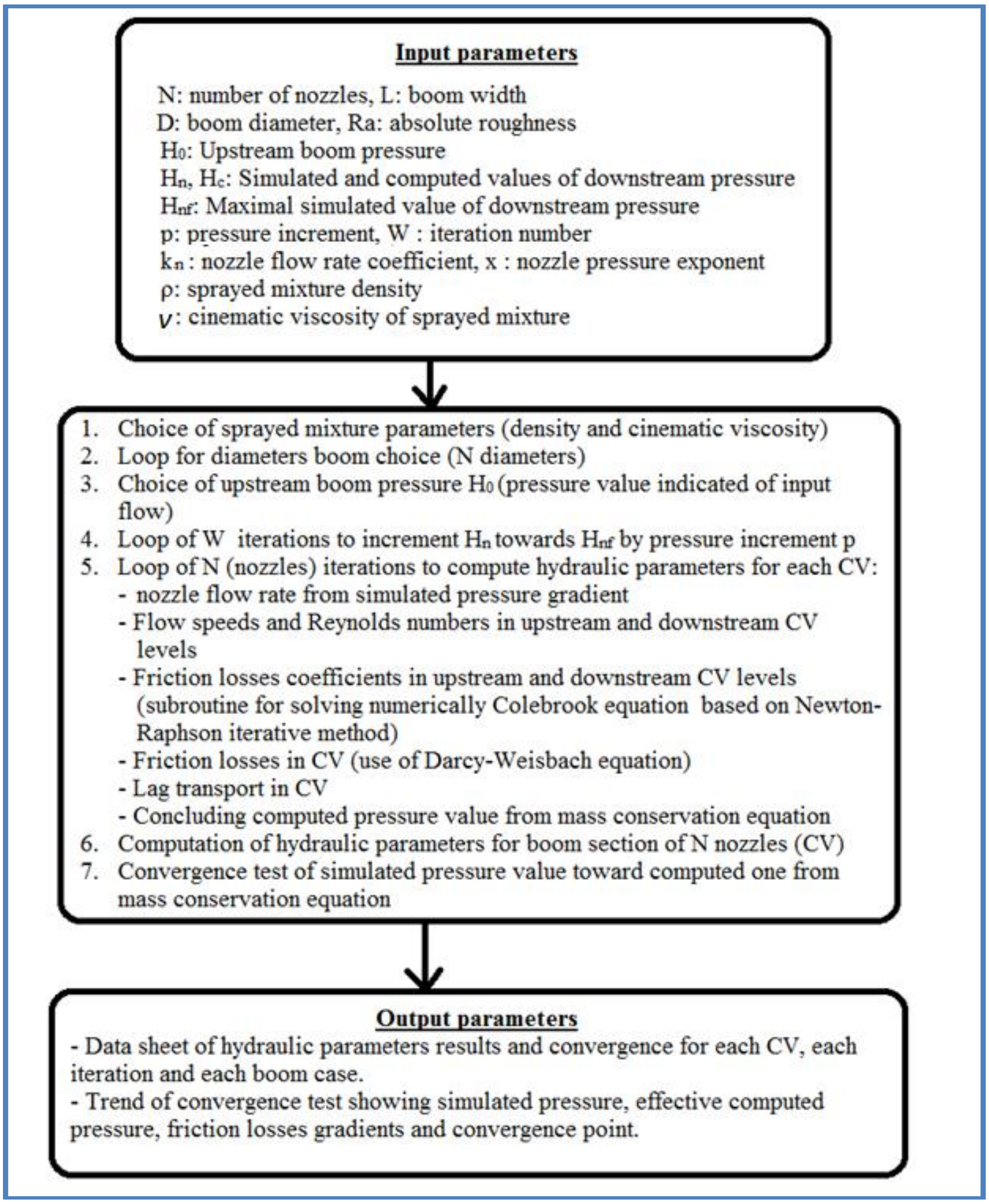
The convergence test was based on simulating H_n value and incrementing it by step “p” toward H_{nf}. The optimal H_n for each boom diameter moved toward computed pressure H_c to satisfy the chosen convergence ratio (practically less than 10^{-3}). This ratio is the absolute value obtained by subtracting simulated pressure gradient ΔH_s (H_0-H_n) from computed pressure gradient ΔH_c (H_0- H_c).

4.2.1.3 Computational algorithm and software

The computational algorithm is performed in VB language (Annex A) to introduce hydraulic parameters of serial boom case and of simulated mixture. Theses parameters are related to:

- The studied boom section such as length (L), diameter (D), number of nozzles (Ns), operating pressure (H) and tubing roughness (Ra).
- The specification of the nozzle flow rate model (q, k_n and x).
- The density and viscosity of the simulated mixture (**ρ** , ***ν***)

The software program is conceived to perform iterative calculus for presenting optimization results in Excel worksheet with reference to the convergence test chosen to fit simulated and computed reference conditions. The data outputs of the iterative computation are presented with the convergence ratio of simulated ΔH_s and computed ΔH_C.



Input parameters

N: number of nozzles, L: boom width
D: boom diameter, Ra: absolute roughness
H_0: Upstream boom pressure
H_n, H_c: Simulated and computed values of downstream pressure
H_{nf}: Maximal simulated value of downstream pressure
p: pressure increment, W : iteration number
k_n : nozzle flow rate coefficient, x : nozzle pressure exponent
ρ: sprayed mixture density
ν: cinematic viscosity of sprayed mixture

1. Choice of sprayed mixture parameters (density and cinematic viscosity)
2. Loop for diameters boom choice (N diameters)
3. Choice of upstream boom pressure H_0 (pressure value indicated of input flow)
4. Loop of W iterations to increment H_n towards H_{nf} by pressure increment p
5. Loop of N (nozzles) iterations to compute hydraulic parameters for each CV:
   - nozzle flow rate from simulated pressure gradient
   - Flow speeds and Reynolds numbers in upstream and downstream CV levels
   - Friction losses coefficients in upstream and downstream CV levels (subroutine for solving numerically Colebrook equation based on Newton-Raphson iterative method)
   - Friction losses in CV (use of Darcy-Weisbach equation)
   - Lag transport in CV
   - Concluding computed pressure value from mass conservation equation
6. Computation of hydraulic parameters for boom section of N nozzles (CV)
7. Convergence test of simulated pressure value toward computed one from mass conservation equation

Output parameters

- Data sheet of hydraulic parameters results and convergence for each CV, each iteration and each boom case.
- Trend of convergence test showing simulated pressure, effective computed pressure, friction losses gradients and convergence point.

Figure 20: Synoptic of computational algorithm

4.2.1.4 Cases of simulated boom diameters

For testing the model, boom diameters of 5, 6 and 8 mm are simulated to study flow behaviour of DIS boom section of 5 serial nozzles. Furthermore, two viscosities of 10^{-6} m²/s (water) and 10^{-5} m²/s (10 times more than water) are used to simulate viscosity effect on flow dynamic, turbulence and friction loss. The simulated cases resulted in numerical schemes of pressure gradient, nozzles flow uniformity, flow regime and lag transport that helped to approach boom quality application. The input parameters are presented in table 7.

Table 7 : Input parameters of simulated serial boom cases

Designation	Input parameters
Section boom of N tip nozzles	**N** = 5, **L** = 2,5 m, $\mathbf{D}_1$ = 8 mm, $\mathbf{D}_2$ = 6 mm, $\mathbf{D}_3$ = 5 mm, $\mathbf{R}_a$ = 2 µm, $\mathbf{H}_o$ = 30 m (3 bars), ξ = 0.03
Nozzle flow rate (ISO 11003)	$\mathbf{K}_n$ = 10^{-5}, x = 0.5, **q** = 2.10^{-5} m^3/s (1.2 L/min ~ 3 bars)
Sprayed mixture	$\boldsymbol{\rho}$ = 1000 kg/ m^3, $\boldsymbol{\nu}1$ = 10^{-6} m^2/s (water), $\boldsymbol{\nu}2$ = 10^{-5} m^2/s

4.2.2 Choice of optimal parallel boom configuration

The study of standard boom case (serial layout) is performed to yield design for optimal lag transport but it cannot satisfy equal response time for all nozzles mounted in serial scheme (different lag transport response independently of the total occurring lag transport).

To perform optimal hydraulic design of DIS, it is of importance to use parallel boom configuration with equal housing tubes to satisfy optimal and equal lag transport for all mounted nozzles of spraying boom. According to the study results of serial boom scheme in terms of optimal diameters compromising reduced lag transport and friction losses, an equal tubing houses of parallel line (diameter and length) can be chosen by computation to satisfy equal lag response.

The computation of lag transport is done to compare two configuration of feeding in parallel scheme one or two tip nozzles using quick connect tubing line of 4 mm internal diameter (Fig. 18). Practically, the quick connect tubing are commercialized in 2, 4, and 6 mm internal diameters that could be used for computation to choose the optimal one with reference to compromise between lag transport and friction loss requirements.

4.3 Implementation of laboratory DIS process controller

4.3.1 Chemical application rate

The Technical Application Rate [TAR (mL/m^2)] depends actually on the total carrier flow rate Q (L/s) due to product of the number (n) of operating nozzles by the flow rate of the nozzle (q_n), the chemical concentration at the nozzles *C (mL/L)*, boom width W_b (m) and ground speed V (m/s). The TAR can be simplified as shown in the eq. (19) by referring to the precedent TAR form (equation 1) given by Miller and Smith (1992):

$$TAR(t) = \frac{Q*C(t)}{W_b*V(t)} \qquad (19)$$

The chemical concentration is the ratio between injection pump flow rate q_{inj} (mL/s) and carrier flow rate Q (L/s). The occurring application error (e) depends on the real time application rate TAR (t) and the technical application rate of reference TARr as shown in equation (20):

$$e(t) = \frac{TAR(t)-TARr}{TARr} \qquad (20)$$

4.3.2 Field working speed considerations

For studying the controller in laboratory condition, the field working speed conditions of the pretended DIS sprayer are simulated using input frequency data of step, ramp, and sweep solicitations. The test of the PID feedback control to assess the response dynamic of the process to lag transport is done using simulated input value of speed with reference to the actual values that can be taken through generation of working speed profiles from field.

The ground speed profiles are generated by operating the rolling sprayer platform in no-till agricultural field (experimental field in Arid Land Research Center, Settat, Morocco). The front wheel (of 1.2 m circumference) of the sprayer is equipped with a gear (38 square teeth) and a Hall Effect proximity sensor (Fig. 21).

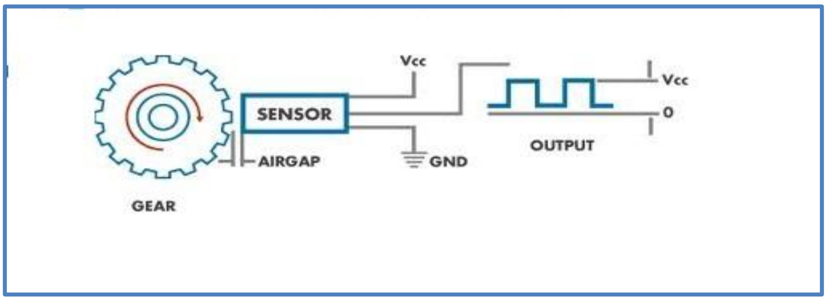


Figure 21: Scheme of sensor and gear mounted on front wheel for measuring the sprayer speed

Six profiles (serial time of frequency data) of working speed are acquired using Fluke 289 True-RMS logging Multimeter while walking worker pulled the sprayer platform (70 kg) prepared to be equipped with the DIS process controller (Fig. 22).

Figure 22: Speed acquisition profiles using Fluke 289 True-RMS

The frequency data files are used to compute the speed with reference to the relation relying it to switching frequency of the Hall Effect sensor as follow:

$$Speed\ (m/s)\ =\ Frequency\ (Hz)\ x\ Circumference\ (m)/Gear\ teeth\ number\ (n)$$

Figure 23 showed the generated speed profiles of actual walker behavior operating the DIS framework in field. The speed profiles turned around averages of 1.2 m/s (CV = 0.2 m/s) with minima and maxima values situated within the range of 0.2-2 m/s. The profiles showed that speed change in two (low and high) frequencies according to the variation of the pulling force of the walker operator and of the field practicability.

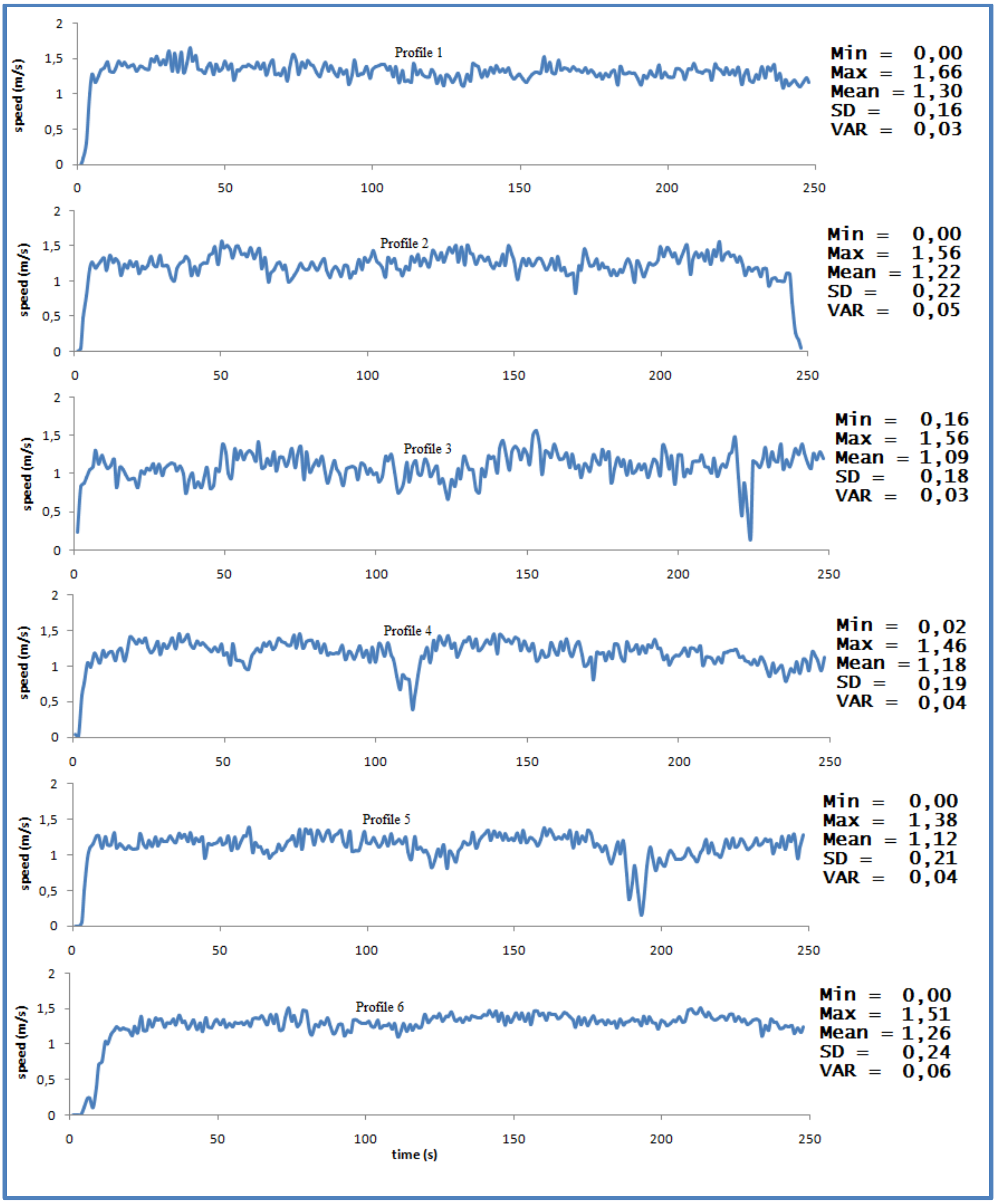


Figure 23: Speed profiles generated in agricultural field by walking operator pulling the sprayer framework

Figure 24 shows the acceleration profiles computed to express the rate of speed change and influence of its high frequency component in term of acceleration range. The maximal accelerations (or decelerations) were within 0.7 m/s² that occurred in transitory situations during the starting, turning or stopping the sprayer chariot implemented for measuring the speed profiles. The acceleration profiles showed a variation between - 0.3 and + 0.3 m/s^2 in steady state conditions (Fig. 24).

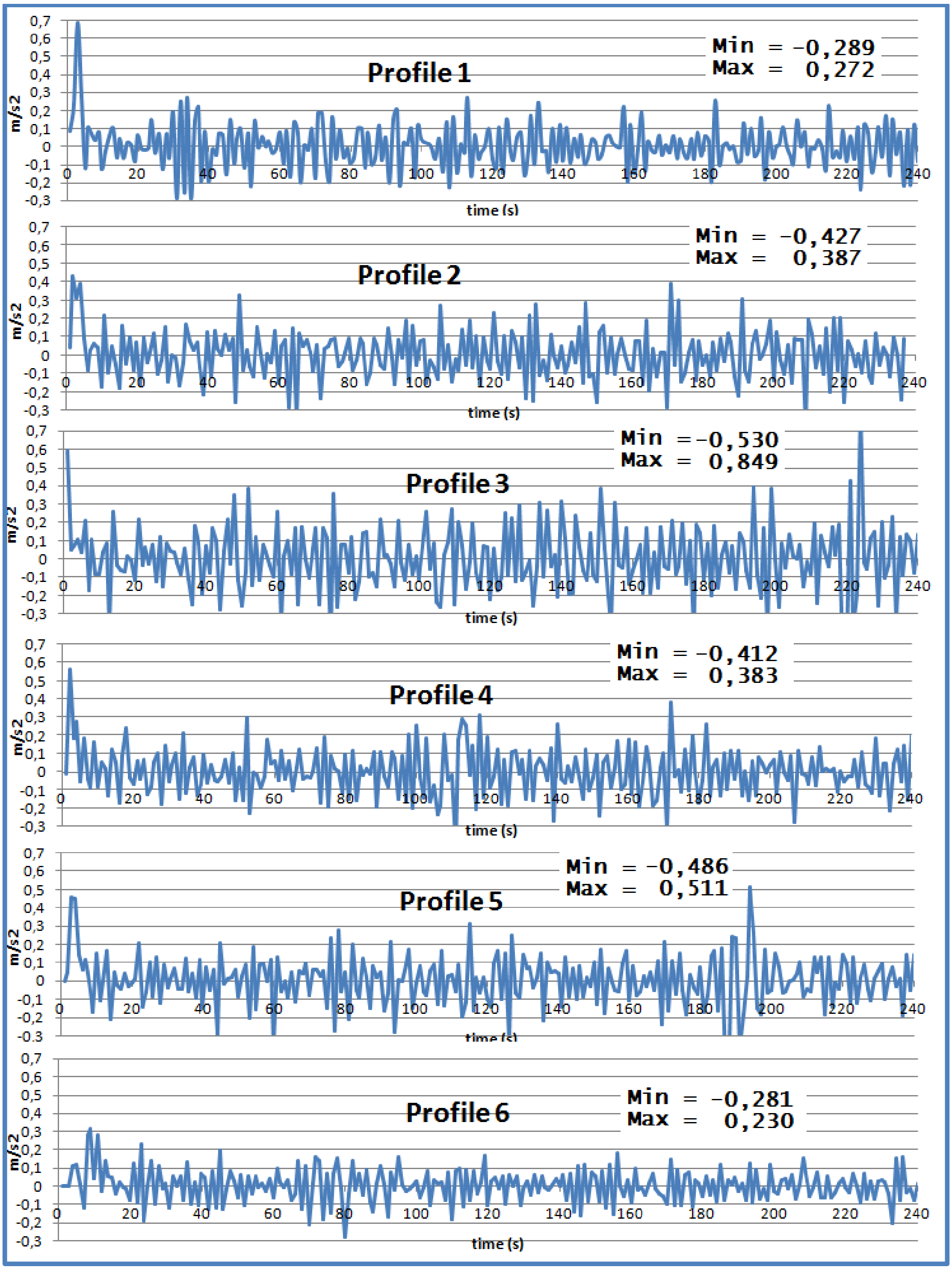


Figure 24: Acceleration profiles of walking operator pulling the sprayer framework

According to the speed profiles taken from field, the speed range of 0.5 to 1.5 m/s was taken as reference to proportionally vary the injection metering flow from q_{min} = 15 mL/min to q_{max} = 45 mL/min in order to apply a typical chemical amount of 1 L/ha (0.1 mL/m²). The carrier flow was performed to turn around 6 L/min according to the operating pressure in the range of 1-3 bars for a typical nozzle of reference (ISO 11002) and to the requirement of the tested flow control strategy.

4.3.3 Measurement of the concentration process change

The measurement of concentration process change is of importance to evaluate dynamic performance of DIS and injected fluorescein concentration that can be simulated as processed liquid chemical formulation for studying DIS performance.

4.3.3.1 Principle of the fluorescence sensor

A sensor is designed to sense the fluorescence of fluorescein injected solution and to evaluate dynamic performance of DIS process controller. The sensor principle consists of using an emitter of a blue light to excite the flowing mixture and a receptor of the emitted fluorescence by the excited mixture (Fig. 25). The blue light LED HLMP-CB15 of 472 nm ± 32 emission band (Agilent Technologies^{TM}) is used the mixture excitation. The fluorescence of the excited mixture is sensed by the light-to-voltage converter TSLG257 (TAOS^{TM}) equipped with integral optical green filter.

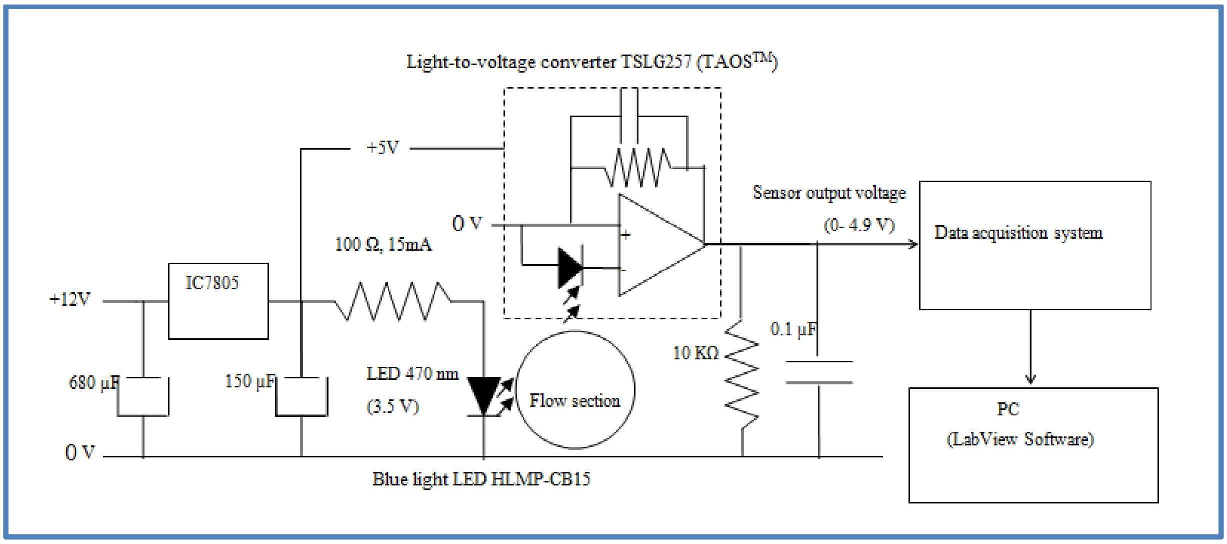


Figure 25: Scheme of the fluorescence sensor design

The fluorescence lifetime of excited state is less than 3 ns. This short time provides fluorescein sensor of high dynamic response time to sense instantaneously varying fluorescence correlated to variable concentration in flow line.

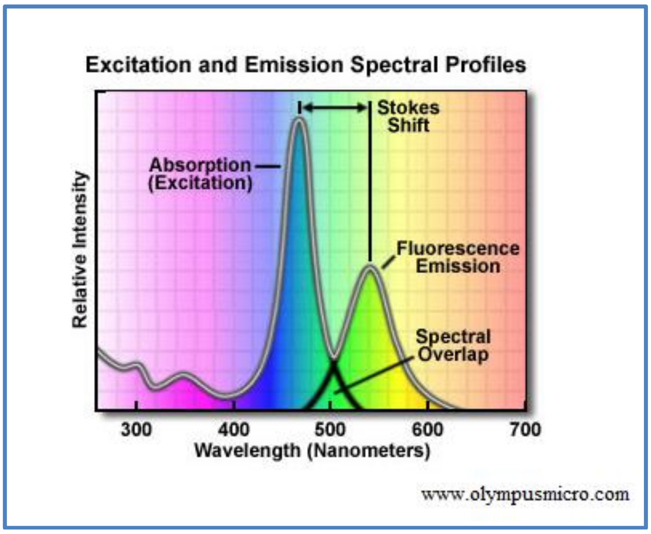


Figure 26 : Fluorescein wavelength chart

4.3.3.2 Fluorescein sensor design

Five sensors were designed and calibrated for sensing the transmittance voltage of variable injected fluorescein solution upstream to tip nozzles of DIS system. The emitter LED and the light-to-voltage receptor of each sensor are placed in perpendicular position to the flow line of 6 mm diameter thrown inside an aluminium matrix. The matrix is equipped in both sides with quick connects for easy integration to hydraulic line at any point of sprayer's circuit situated between the carrier pump manifold and the tip nozzles (Fig. 27).

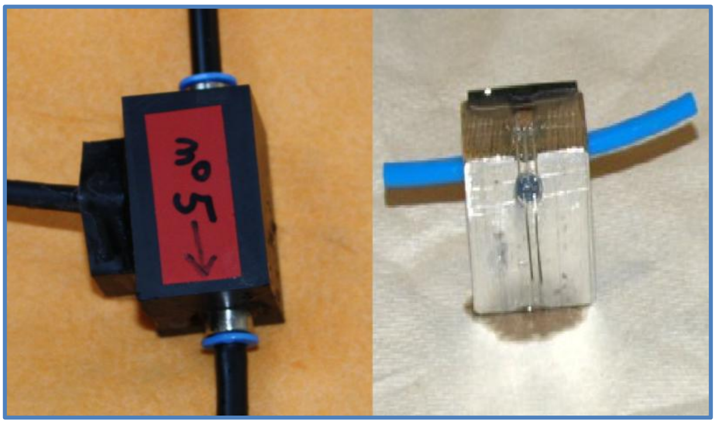


Figure 27: Matrix of the fluorescence sensor equipped with emitter LED and light to voltage transmitter

The reading of fluorescein transmittance voltage in the manifold and tip nozzles levels helps to evaluate separately lag transports contributions with reference to their origins from carrier pump and manifold dead volume and/or from tube lines feeding tip nozzles. The quick connects (Festo®, tube housing of internal diameter of 4 mm) are used for easy mounting and test of the possible configurations of parallel boom layouts with and without equal feeding lines.

The sensors are used for evaluating concentration process change at the level of each mounted tip nozzle in serial and/or parallel boom design in order to compare lag transport responses of both hydraulic configurations and to study performance of DIS controller (Fig. 31).

4.3.3.3 Fluorescence sensor calibration

To calibrate the sensors, a mixture of fluorescein and water is used for simulating injected chemical at the suction side of the carrier pump. In first step, mother solutions of varying concentrations from 0 to 2500 µg/L are prepared to calibrate each of the five fluorescence sensors performed to measure the voltage of fluorescein transmittance in each tube of tip nozzle feeding line (Fig. 28).

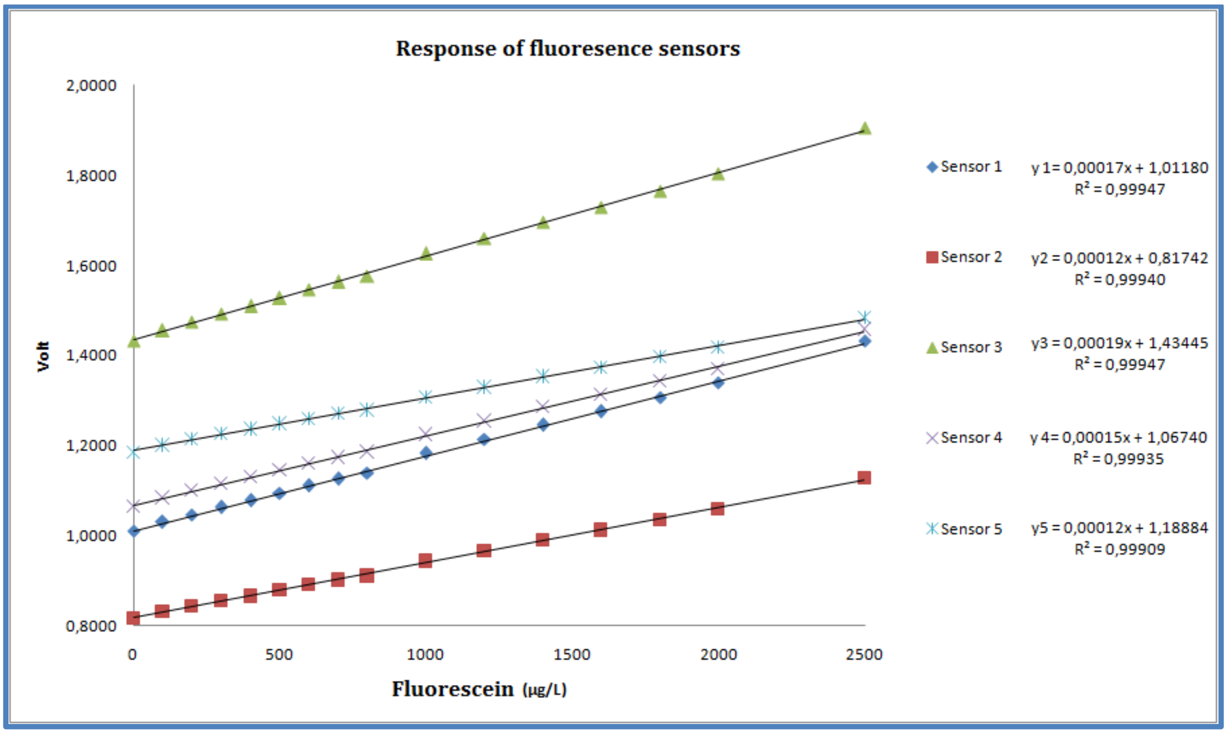
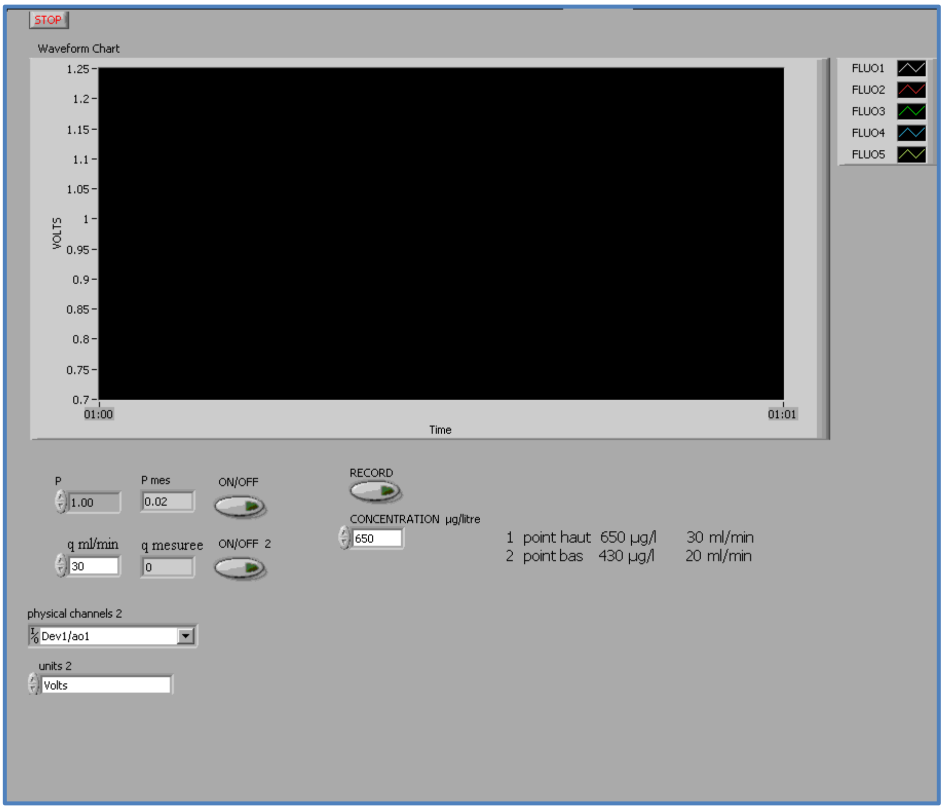


Figure 28 : Transmittance voltage response of sensors for fluorescein concentration in the range of [0-2500 µg/L]

According to calibration results (Fig. 28), the sensors responses are linearly behaved with different slopes (from 12E-5 to 19E-5) due to design variability of sensors matrixes. The variability is potentially due to specific confection of each sensor according to heterogeneity design that can be occurred to precisely throwing the matrix holes, positioning emitters and receptors on it, and/or molding the epoxy resin to firmly glue the LEDs in direct contact with the flow line of the sensed fluorescein concentration. This variability of sensor responses is taken into account in acquiring data as each sensor voltage is evaluated with reference to its calibration curve independently of the heterogeneous voltage outputs (Fig. 28).

Furthermore, an auto-calibration process of the fluorescence sensors is implemented in a virtual instrument (VI) to calibrate their voltage responses by referring to the effective fluorescence of the used concentration solution at the beginning of the experimentation (Fig. 29). In fact, the fluorescein transmittance is subject to degradation potentially due to daylight intensity. Consequently, it cannot be possible to carry out constant light transmittance response in long time period using repetitively the same mother solution. The temperature variation of ambiance and of tap water used as carrier, constitute also a source of inconstant light transmittance response of the fluorescein (El Aissaoui et al., 2007).



P: 1.00
P mes: 0.02
q ml/min: 30
q mesuree: 0
CONCENTRATION µg/litre: 650
1 point haut 650 µg/l 30 ml/min
2 point bas 430 µg/l 20 ml/min
physical channels 2: Dev1/ao1
units 2: Volts

Figure 29: VI for generation of the calibration curves parameters (intercept and slope) of the fluorescein sensors.

The auto calibration process is performed, not only to attenuate the fluorescein response variation, but also to adopt the current values of voltage transmittance with reference to the effective concentration response of the injected fluorescein solution in order to evaluate both dynamic and real rate of the processed concentration.

By referring to the best response of the sensors in low fluorescein concentration range, the 1000 µg/L solution is used as reference of injected liquid to study the concentration process change and process control dynamic in the all laboratory testing and evaluation of DIS. The mother solution of fluorescein (870 µg/L) is effectively used to calibrate the five sensors according to their optimal sensitivity responses within the range of [0 to 1000 µg/L]. To take similar response with reference to the used mother solution, the five sensors are mounted in serial scheme to be simultaneously supplied and their voltage responses of zero (constant carrier flow only) and maximal fluorescein concentration (constant carrier flow + maximal flow of injected fluorescein) are recorded in file for eventual use in computation of the linear regression parameters (intercept and slope) for each sensor and of conversion factor to switch from the voltage reading to the real concentration processing.

The main VI is performed to import saved data of the actualized calibration parameters from the file recorded by the auto-calibration VI. Such data served for converting the transmittance data output of each sensor from voltage to concentration (µg/L). The calibration parameters are assumed to be generated at the beginning of each experimental test according to the effective voltage response of the sensors to the actual fluorescein state of the prepared mother solution and to the occurring temperature and daylight.

The calibration results of the five sensors (Fig. 30) showed a repetitive (6 repetitions) and linear behavior of voltage responses with slopes varying from 17E-5 to 27E-5. The sensors calibration within 1000 µg/L relatively showed increased sensitivity (V/ (µgL^{-1})) of sensors due to their higher slope responses (ΔV/Δ(µgL^{-1})). The data acquisition system is implemented to acquire sensors voltages with reference to their calibration curves.

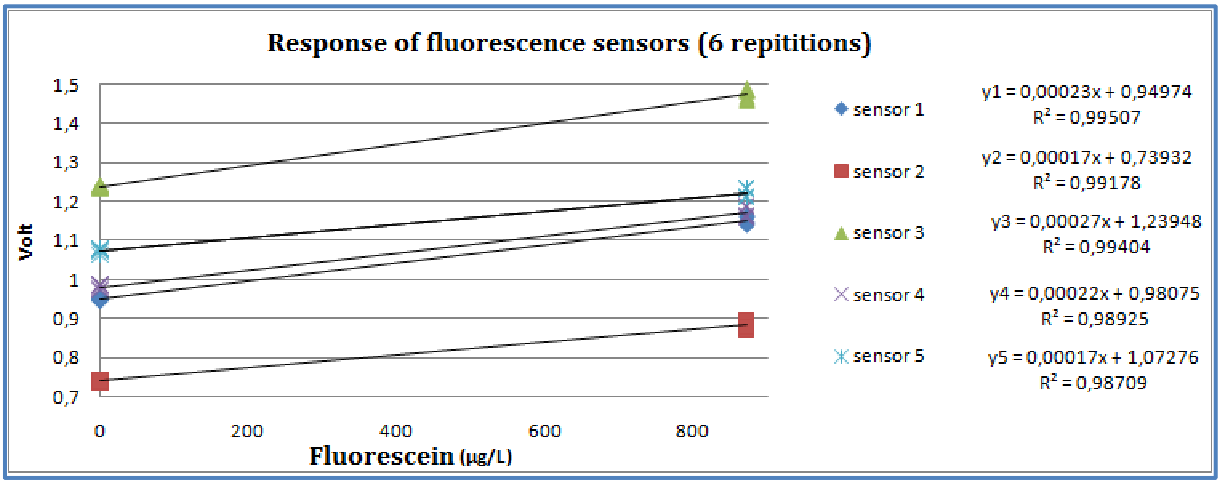


Figure 30: Transmittance voltage response of sensors for fluorescein concentration in the range of [0-1000 µg/L]

4.3.4 DIS process controller and data acquisition

A LabView software is used for implementing a process control virtual instrument (VI) based on two PID closed loop controllers for piloting the metering and carrier pumps using the PWM driven actuators. According to hydraulic requirements specified in the precedent chapter, the preliminary laboratory test of DIS is equipped of carrier diaphragm pump (Flojet^{TM}, 24V DC, 10 L/min~2,8 bars), and peristaltic pump (Marlow Watson^{TM} 400D/E, 24V DC) having two channels of 38 mL/min (Fig. 31). Two PWM (2020S of CJ Controls LTD) actuators are used for piloting the pumps to adjust concentration injection ratio, operating pressure and/or to induce step change according to the assessment of different process control algorithms.

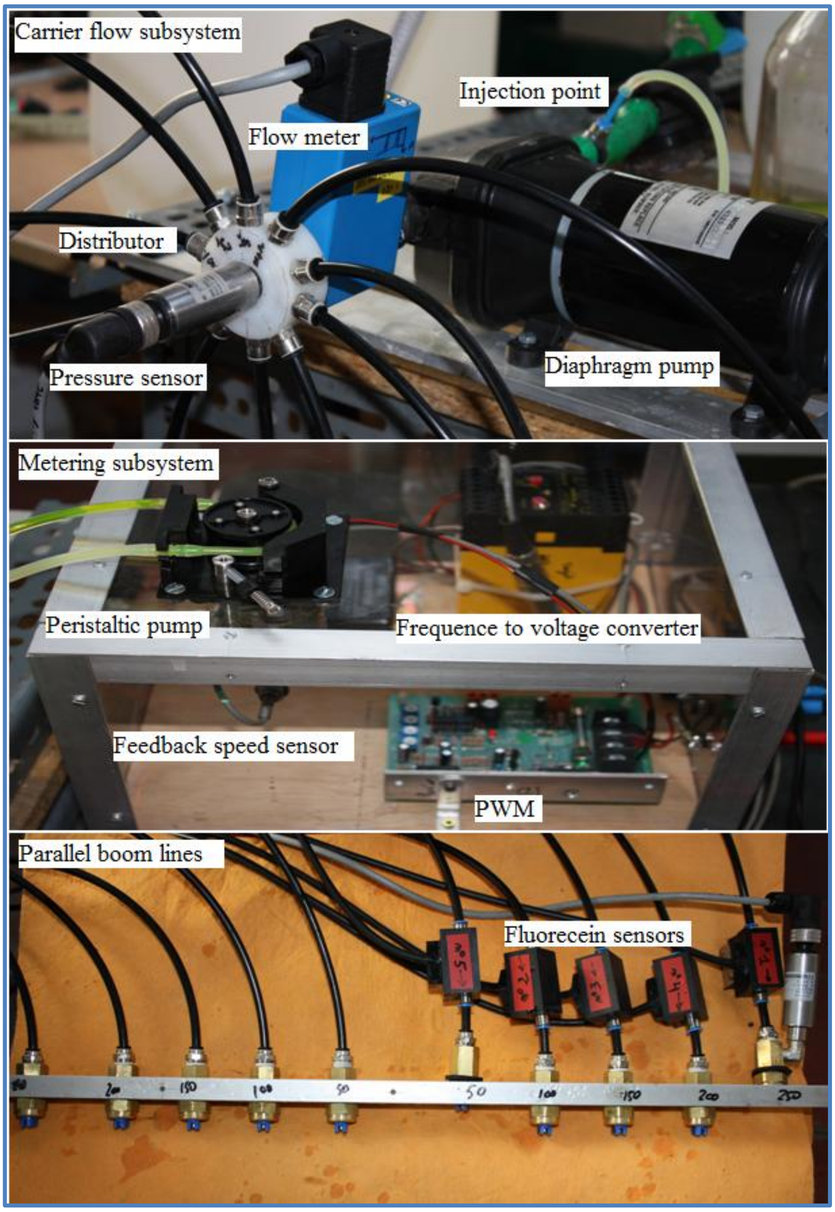


Figure 31 : Laboratory DIS and its parallel boom lines with fluorescein sensors mounted by quick connect to five tip nozzles.

4.3.4.1 PID controller principle

A PID controller is based on three separate components:

- ***Proportional action:*** provides a contribution which depends proportionally on the instantaneous value of the control error.
- ***Integral action:*** gives a controller output that is proportional to the accumulated error.
- ***Derivative action:*** acts on the rate change of the control error.

The sum of the proportional, integral and derivative terms constitutes the command signal acting on the process actuators, in our case the carrier and metering pumps.

The so called parallel structure of the PID controller is given by equation 21:

$$Vm\,(t) = Kp\,e(t) + K_i \int_0^t e(t)dt + K_d \frac{d}{dt} e(t) \qquad (21)$$

This can be written as:

$$Vm\,(t) = P_{out} + I_{out} + D_{out} \qquad (22)$$

Where, P_{out}, I_{out}, and D_{out} are the contributions of the three PID actions.

The proportional gain serves to create a change in the control system for powerful process design. The gain is thought as an amplifier to the controller to multiply the current error value. A large gain value yields a large change in the process output for a given error that amplifies the speed of controller reaction. However, when the gain is too large, process can become unstable very quickly and inversely the controller has a small response to an error value if the gain value is too small. The latter condition results in a less-sensitive controller, which may not respond correctly to errors or disturbances.

The value contributed from the integral loop is proportional to both the magnitude and duration of the error. Summing the error values over time (integrating the error) gives the offset value that should have been previously corrected. This accumulated-error value is then multiplied by the integral gain (which defines the magnitude of the contribution of the integral loop) and added to the controller output. When added to the proportional term, the integral loop accelerates the response of the process towards the set-point value and eliminates the residual steady-state error of a proportional-only controller. The integral loop is only responding to the summation of errors, however, which causes the response to overshoot the set-point value and thus creates an error in the opposite direction.

The derivative rate loop plays a role to increase response time and minimize errors. It is needed to calculate the rate at which the error term is changing which is the first derivative of the error function. This value is multiplied by the derivative gain K_d to obtain the derivative contribution to the process. As with the proportional and integral loops, the derivative gain can have a great impact on the system's response. The derivative loop controls the rate at which the controller's response overshoots the input value of the proportional and integral loops. However, derivative loops amplify noise and are thus very sensitive to noise in the error term. The increasing of derivative gain is of importance to increase system stability, but in real hydraulic applications may contrarily behave when transport delay is present and hydraulic oscillations can be induced. This can lead to exclude the derivative term entirely from the control system for powerful process design.

4.3.4.2 Tuning of PID controller

The process of tuning a PID controller involves adjusting its control parameters—proportional band, integral gain and derivative gain—in response to a given input until the desired response is attained. It concerns the characteristics of its three loops P, I, and D and involves the control of four variables:

- ***Rise time***: the amount of time necessary for the system's initial output to rise past 90% of its desired value
- ***Overshoot***: the amount by which the initial response exceeds the set-point value
- ***Resolving time***: the amount of time required by the system to converge to the set-point value.
- ***Steady-state error***: the measured difference between the system output and the set-point value.

There are practically three main methods of tuning a PID controller consisting of manual tuning, empirical tuning and theoretical tuning:

4.3.4.2.1 Manual tuning

The manual tuning which is the best used for a system that must remains online during the tuning process. There are four steps for process setting consisting of setting Ki and Kd to zero and increase Kp until the loop output begins to oscillate. After that, the Kp could be reduced to one-half of the value to obtain a quarter-wave decay. The Ki could be increased to adjust the behavior of the offset so that the system reacts in acceptable amount of time. The fast PID loop usually requires a slight overshoot to resolve to the set-point more quickly. As the hydraulic system cannot accept the overshoot, the over-damped system is required. For the case, the Kp value could be less than half of the value causing oscillation.

4.3.4.2.2 Empirical tuning

One of the traditional ways to design a PID controller was to use empirical tuning rules based on measurements made on the real plant. The rules are often packaged as simple recipe procedures. The Zeigler-Nichols tuning method is among the best known of the classical tuning techniques. It is based on dealing with mathematical calculations to find an initial estimation of the PID values. This method is used when the system behavior is unknown and the creating of the state matrices for the system keeps impractical. As in manual tuning, the integral and derivative gain values are first set to zero in Ziegler-Nichols tuning (Aström and Murray, 2008). The proportional gain is then increased from zero until the system reaches an oscillatory state. This proportional gain value is named the *Ku* ultimate gain. The system's oscillatory period at this gain value is named the *Tu* ultimate period. These two ultimate values are then used to set the proportional, integral and derivative gain values using the table 8.

Table 8 : Ziegler-Nichols tuning values using ultimate gain method

Controller type	K_p	K_i	K_d
P	0.5 Ku	-	-
PI	0.45 Ku	1.2 Kp/Tu	-
PID	0.6 Ku	2 Kp/Tu	Kp*Tu/8

The limitations of Ziegler-Nichols tuning are due to the fluctuation of the controller response as the successive oscillation peaks decrease sequentially by only one-fourth the amplitude of the peak. The tuning of hydraulic application requires more improvement for less fluctuation and faster resolving time. There is a second Ziegler-Nichols tuning method named "reaction curve method" which is adapted for process models having step responses resembling to S-shaped curve with no overshoot. This method is suitable for hydraulic processes that cannot tolerate overshoot or oscillations and resembling to typical reaction curve (Fig. 32).

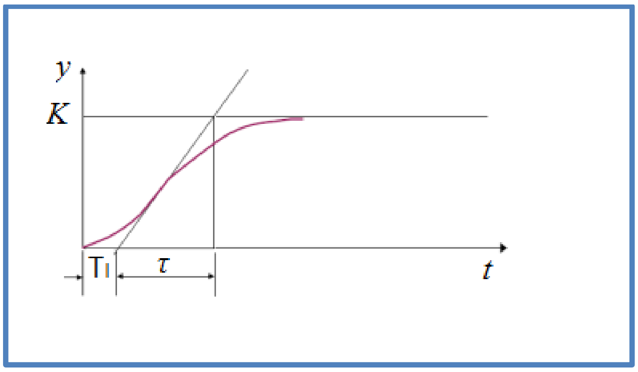


Figure 32 : Typical reaction curve

The lag time T_l and constant time τ are found by drawing a tangent line to the reaction curve through its inflection point and finding the intersection points with the time axis and the set point line. Once these intercepts are determined, the setting values are calculated by referring to table 9. The calculated parameters give a system response with an overshoot of approximately 25%, and the system will resolve to the set-point value within a polynomial.

Table 9 : Ziegler-Nichols tuning values using reaction curve method

Controller type	K_p	K_i	K_d
P	T/L	-	-
PI	0.9 T/L	$0.27\ T/L^2$	-
PID	1.2 T/L	$0.6\ T/L^2$	0.6 T

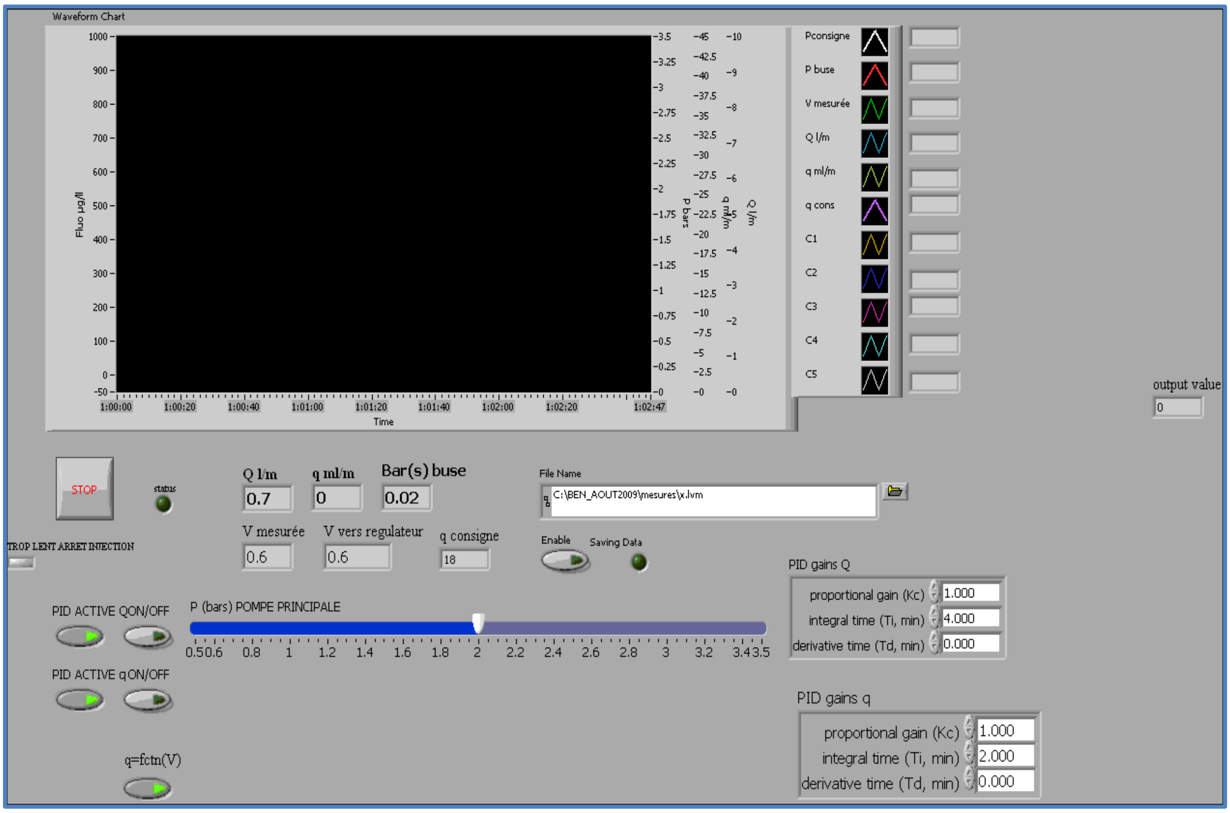
4.3.4.2.3 Theoretical tuning

The theoretical methods are based on an identified mathematical model of the control process, namely a transfer function. Usage of control software as *MATLAB/SimuLink* helps to easily perform tuning control. It makes possible designing model of real process by referring to the parameters of its physical system and their integration in modeling for adequately presenting the real experimental dynamic behavior of the process. The tuning and optimization software is used for taking optimum results from fitted model i.e. to a first order process that can closely present the hydraulic system dynamic.

4.3.4.3 Data acquisition

A virtual instrument (VI) is implemented in LabVIEW software to acquire data from sensors measuring operating pressure, metering pump speed, fluorescein concentration and simulated working speed (Fig. 33).The DAQ NI-USB6251 is used to acquire information from the sensors at the sampling frequency of 10 Hz. The VI is performed for manual control of metering and carrier pumps and also for automatic control via a PID control algorithm. The

VI is interfaced to monitor pressure and fluorescein concentration data and to save it in file for ulterior treatment and interpretation.



output value: 0

Q l/m: 0.7

q ml/m: 0

Bar(s) buse: 0.02

File Name: C:\BEN_AOUT2009\mesures\x.lvm

V mesurée: 0.6

V vers regulateur: 0.6

q consigne: 18

PID gains Q

proportional gain (Kc): 1.000
integral time (Ti, min): 4.000
derivative time (Td, min): 0.000

PID gains q

proportional gain (Kc): 1.000
integral time (Ti, min): 2.000
derivative time (Td, min): 0.000

Figure 33: LabView interface VI performed for control of DIS pumps and concentration processing

4.3.5 Sensing pressure of carrier flow

Pressure in spraying boom was measured via two sensors (Sensortechnics^{TM} CTE 8005GY7, P_{max} = 5 bars, non-linearity = 0.1, hysteresis = 0.015) mounted upstream at the level of carrier pump output and downstream at the level of each tip nozzle in the case of testing parallel boom scheme (Fig. 28) or at the level of the last tip nozzle in the case of testing serial boom scheme. The upstream sensor pressure is used to evaluate volume rate application as information for the closed loop PID controller regulating the carrier flow pump rotational speed (Fig. 28). According to the principle of hydraulic spraying nozzles (see the paragraph 2.7.1, eq. 2), the pressure is correlated to the square of the flow rate.

4.3.6 Sensing of flow rate injection

Chemical injection flow rate is evaluated using speed sensor to give the frequency input that is processed as analogical output using frequency to voltage converter (TURCK MS 25-10).

The voltage data is used as feedback to the closed loop PID controller regulating the metering pump rotating speed (Fig. 31).

As low cost option for PLC controller development, the flow rate is evaluated with reference to PWM consign and operating batteries voltage by correlating the pump metering rate to the variation of operating voltage depending on batteries charge level.

4.3.7 Confection of boom layout

Two boom schemes of serial and parallel boom layouts are mounted for testing and comparing dynamic behaviors responses of spraying nozzles in both boom configurations. The standard boom layout is studied as a reference for designing and evaluating an optimal boom layout to be adapted for the pretended DIS design.

A standard boom layout of ten tip nozzles (ISO 11002) is mounted using commercial copper piping (D = 6 mm, roughness~2 µm) and tee junctions to attach the Teejet copper tip nozzles.

The parallel boom layout was performed using quick connect flexible (Festo^{TM}, D = 4 mm, roughness ~ 2 µm) to attach each nozzle body to the distributor mounted downstream to the carrier pump (Fig. 31).

4.4 Study of DIS process controller

4.4.1 *Modeling the concentration process change*

According to Stone (2000), injection of chemical into carrier water can be simulated to mixing chemical process in tank level system for studying dynamic of concentration process change (Fig. 33). The simulation is used to study online dilution of chemical in DIS. In fact, the water level H (m) in the tank area A (m^2) analogically presents the pressure potential to control dynamic of concentration and flow rate dynamic in the spraying boom according to the variable inputs of concentration Ci (g/L) and/or flow Q_i (Fig. 34). The feeding of boom layout (of serial or parallel scheme) assumed to be controlled at constant carrier flow (Q_i) and variable concentration (Ci) of injected chemical.

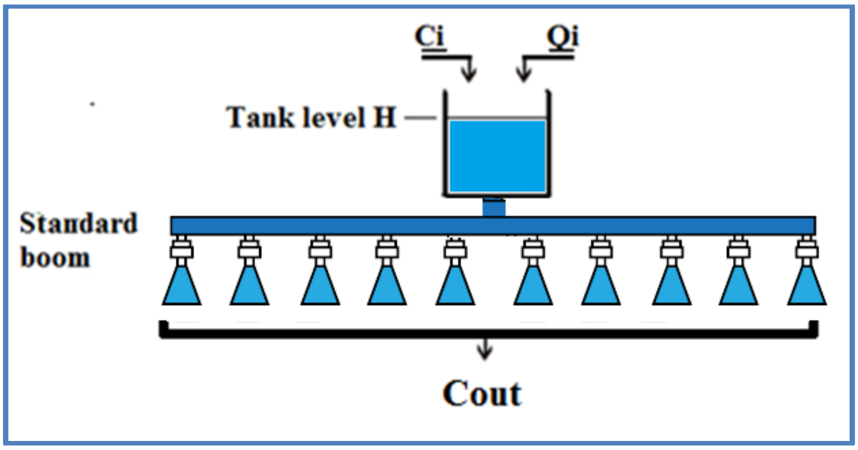


Figure 34 : Simulation of chemical concentration process change by tank level problem

According to Stone M. (2000), the modeling approaches of simple tank can be used to approach concentration process change of DIS according to pressure potential of pump that can be simulated to level of water in a tank feeding a spraying boom.

The dynamic of DIS process control depends on dead time due to transport of concentration from the injection point to the nozzle and on charge time required to establish concentration equilibrium in new steady state point. This process is approached by the transfer functions of dilution problem in tank level plus dead time to characterize its dynamic behavior for each case of nozzle feeding in serial or parallel boom scheme.

4.4.1.1 *Dilution problem*

The output concentration C_{out} (g/L) can be taken by applying the mass balance equation on the tank volume V (m^3) based on the area A (m^2) and the level H (m) (eq. 23):

$$Q * \mathrm{C_i} - Q * C_{out} = \frac{d(V * C_{out})}{dt} \qquad (23)$$

The system running at the steady state point means that:

$$(\mathrm{C_i})_{ss} - (C_{out})_{ss} = 0 \qquad (24)$$

And the equation 23 takes the forms 25a et 25b as the $(C_{out})_{ss}$ is a constant

$$\mathrm{C_i} - (\mathrm{C_i})_{ss} - C_{out} - (C_{out})_{ss} = \frac{d(V * C_{out})}{Q * dt} \qquad (25a)$$

$$[\mathrm{C_i} - (\mathrm{C_i})_{ss}] - [C_{out} - (C_{out})_{ss}] = \frac{Vd(C_{out} - (C_{out})_{ss})}{Q * dt} \qquad (25b)$$

After that, the equation can take the form 26 of variable deviation around of equilibrium point:

$$[\mathrm{C_i}] - [C_{out}] = \frac{Vd(C_{out})}{Q * dt} \qquad (26a)$$

And finally the concentration change can be presented in time domain or Laplace domain by the transfer function of a first order differential equation (eqs. 26b and 26c):

$$\mathrm{C_i} = \frac{Vd(C_{out})}{Q * dt} + C_{out} \qquad (26b)$$

$$\frac{C_{out}}{\mathrm{C_i}} = \frac{1}{\frac{V}{Q}s + 1} = \frac{1}{\tau s + 1} \qquad (26c)$$

Where τ is a time constant of the concentration process change.

4.4.1.2 Transport lag

The concentration change in boom line is characterized mainly by the lag transport that can be approached by theorem of the real translation on an homogeneous boom control volume of length L (m) and diameter D (m) (Fig. 35).

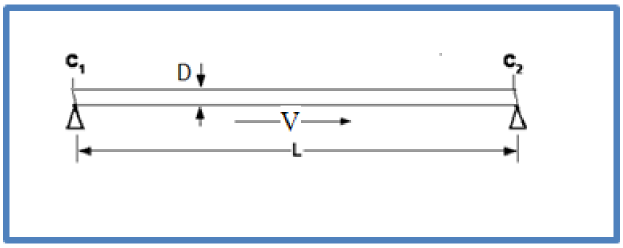


Figure 35 : Concentration transport delay in serial boom line

The expression of transported concentration by constant carrier flow between two points C_1 and C_2 in a considered control volume of boom layout is given in t domain as follows:

$$C_2(t) = C_1(t - t_0) \qquad (27)$$

The Laplace transformation is given using real translation theorem and the transfer function of lag transport is deduced (eq. 28a and 28b):

$$C_2(s) = C_1(s)e^{-st_0} \qquad (28a)$$

$$\frac{C_2(s)}{C_1(s)} = e^{-st_0} \qquad (28b)$$

The time t_0 determined from the pipe characteristics L, d and the flow rate q:

$$V = q / A = 4q / \pi D^2 \text{ And } V = L / t_0$$

$$t_0 = \pi D^2 L / 4q \qquad (29)$$

And finally, the transport transfer function become:

$$\frac{C_2(s)}{C_1(s)} = e^{-s(\pi D^2 L/4q)} \qquad (30)$$

The combination of the dilution and lag transport transfer equations (eqs.26 and 30) gives the transfer function of the total concentration process change plus dead time that can fitted to each tip nozzle by considering the transport distance between injection and spraying tip nozzle points.

$$\frac{C_{out}}{C_{in}} = \frac{e^{-s(\pi D^2 L/4q)}}{\frac{V}{q}s + 1} \qquad (31)$$

4.4.2 Modeling the process control subsystems

The control loops of metering and carrier pumps are studied using SimuLink^{TM} tool to obtain optimal parameters setting of their PID algorithms.

4.4.2.1 Modeling the injection flow subsystem

According to test of the peristaltic pump in open loop, its response to flow injection was approached as a first order system $G_{inj}(s) = K_1 / (\tau_1 s + 1)$ using the open loop reaction curve method, where K_1 is the static gain (the quotient in amplitudes between converted frequency to voltage output and command voltage input) and τ_1 is time constant evaluated to be 0.2 s (Fig. 36). The peristaltic metering pump is experimentally set to vary the flow rate from 0 to 45 mL/min with the gain K (q_{inj}/V) of 30 to satisfy the requirement of TAR response for the ground speed change from 0 to 1.5 m/s. The controller was set to reversibly operate the command voltage (Uc) of the pump within the magnitude of (1.5 V to 4.7 V). The flow rate of the metering pump is sensed with reference to its rotating speed frequency using Hall Effect sensor. A frequency/voltage converter was used for acquiring voltage-speed data as feedback information for the metering PID loop. The frequency-to-voltage feedback (Uf) was set within (2.2 V to 9.6 V) corresponding respectively to the shaft rotating speed (w) and flow rate (q_{inj}) magnitudes of (60 rpm to 280 rpm) and (10.73 mL/min to 48.77 mL/min).

Calibration curves of linear regression were established to experimentally express relationship between the voltage command and the delivered flow rate [$Uc = f(q_{inj})$], the frequency to voltage and the pump rotational speed [$w = f(Uf)$], and between the delivred flow rate of the pump and its rotating speed [$q_{inj} = f(w)$].

The metering subsystem was modeled in SimuLink^{TM} (MathWorks, Inc.) to simulate step responses and to set optimal PID parameters values (P = 1, I = 16, D = 0.2).

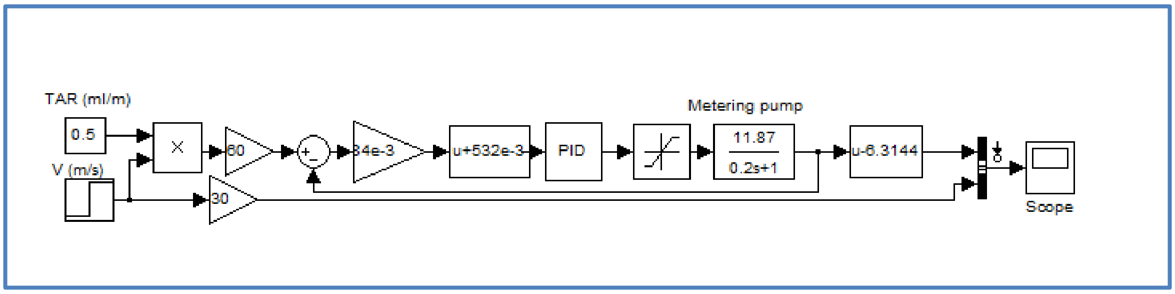


Figure 36 : Modeling peristaltic metering pump subsystem in SimuLink^{TM}

4.4.2.2 Modeling the carrier flow subsystem

The carrier flow rate process was similarly approached as a first order system with dead time $G_p(s) = K_2e^{-sto}/(\tau_2 s+1)$. The delay was mainly due to transport lag in boom tubing. The controller commands the diaphragm pump on the basis of the pressure feedback sensed at the tip nozzle level. The command voltage ($U_{cmax} = 5V$) was tested experimentally to operate the pump at different pressures (*P_{max} = 3bar; Q = 7.9 L/min for ten nozzles Teejet XR11002*). The relationship between the command voltage (Uc) and the pressure (P) was empirically approached by linear regression:

$$U_c = 1.075P+1.63;\ R^2 = 0.99 \qquad (32)$$

The total carrier flow rate (Q) depends on the number of the used nozzles (ten tip nozzles) and their flow rate model:

$$Q = 0.46P^{0.49}; R^2 = 0.99 \qquad (33)$$

According to the adopted control strategy of constant carrier flow control or total flow control, the controller aims to set a constant pressure for a constant carrier flow control or to vary pressure (P) from 1 to 3 bars proportionally to ground speed (V) from 0.6 to 1.2 m/s with a constant gain to carry out the total flow control with reference to the pressure sensor feedback. The usage of the pressure feedback is cost effective to control the pump flow rate with reference to the working speed independently of the number of the operating nozzles. The carrier pump is calibrated on the basis of the following equation to increase the carrier flow rate proportionally to the speed:

$$P = 3.33\ V - 1; R^2 = 1 \qquad (34)$$

The control loop of the carrier subsystem is modeled in Matlab/SimuLink to carry out constant or variable carrier pressure. A sinusoid disturbance module was used to test the PID response according to different setting of P, I and D parameters to obtain the optimal values of P = 1, I = 20 and D = 0.2.

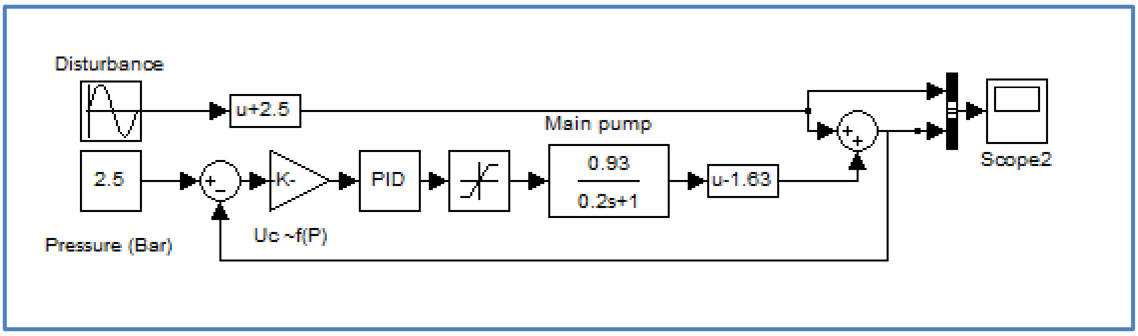


Figure 37 : Modeling carrier pump subsystem in SimuLink™

4.4.2.3 *Modeling of the lag transport process*

The lag transport dynamic process depends on the existing dead volume between the injection point and the spraying nozzles that need to be overcome dynamically by an over carrier flow rate according to the used strategy of constant carrier flow or total flow control.

Figure 38 shows the computational diagram model performed in SimuLink to process lag transport dynamic by referring to the dead volume of the transport line and the occurring carrier flow rate. The computation is done on the basis of the assumption of feeding nozzles through parallel boom layout of DIS using equal lines of 2.5 m length and 4 mm diameter. Two feeding configurations of simple and double nozzles by line are simulated. In the case of double nozzles feeding, the line is split to two parts having length of 2.3 and 0.3 m respectively to transport double flow rate in the first part and simple flow rate in the second part connected to each of both nozzles. The model of lag transport computation is performed to monitor in the same scale time the concentrations at the injection (Ci) and at the tip nozzle (Cn) levels in order to evaluate delay effects on TARs according to different inputs of speed solicitations.

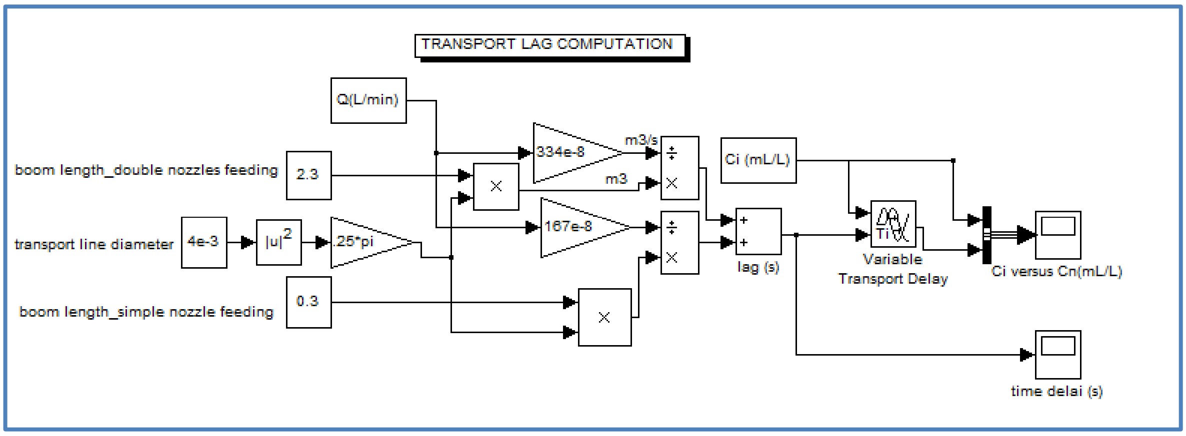


Figure 38 : Modeling of concentration lag transport in parallel boom scheme with a simple or double nozzles feeding by line (SimuLink^{TM}).

4.4.3 Modeling the control strategies

4.4.3.1 Constant carrier flow control strategy

In the case of using the control strategy of constant carrier flow control, the carrier flow control loop is set a constant operating pressure of 2 bars for maintaining a constant carrier flow rate (Fig. 39). However, the injection metering loop is set to vary the injected flow rate proportionally (gain of 30) to the simulated working speed for applying the TAR of 0.1 mL/m^2.

4.4.3.2 Total flow control strategy

In the case of using the control strategy of total carrier flow control, both the carrier flow control loop and the injection metering loop are set to vary the operating pressure from 1 to 3 bars ($P = 3.33V-1$; $R^2 = 1$) and the injected flow proportionally (gain of 30) to the simulated working speed for applying the TAR of 0.1 mL/m^2 (Fig. 40).

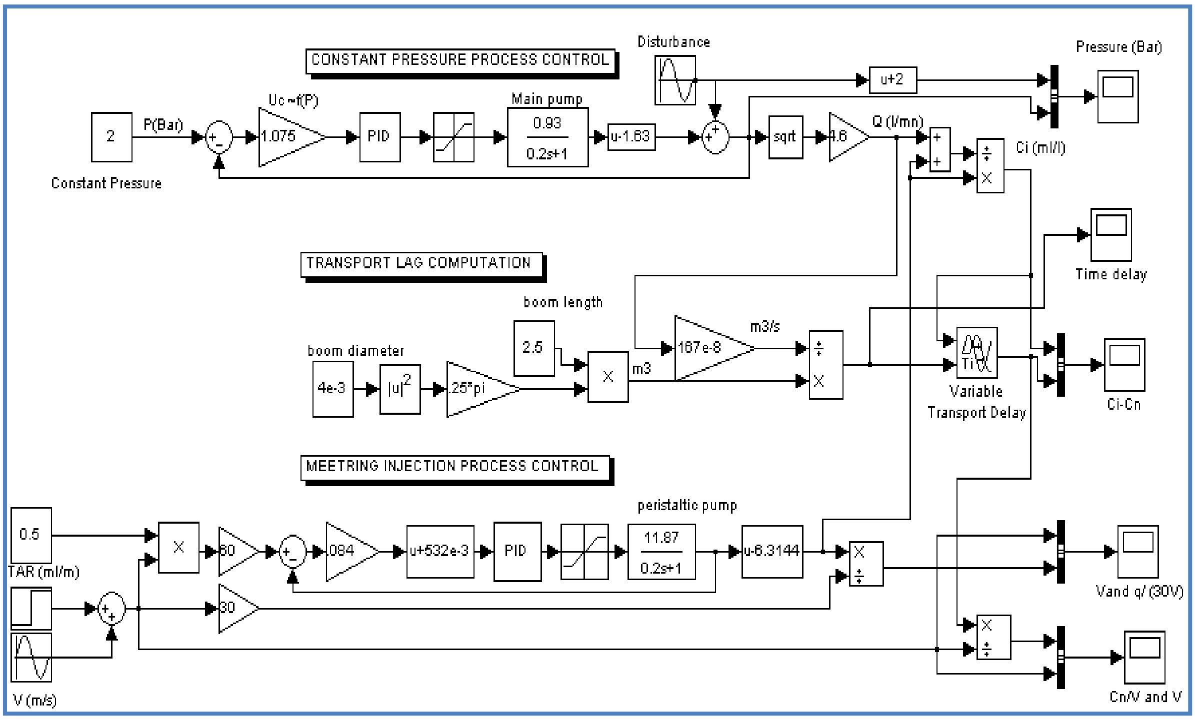


Figure 39 : Constant carrier flow control modeling by SimuLink^{TM}

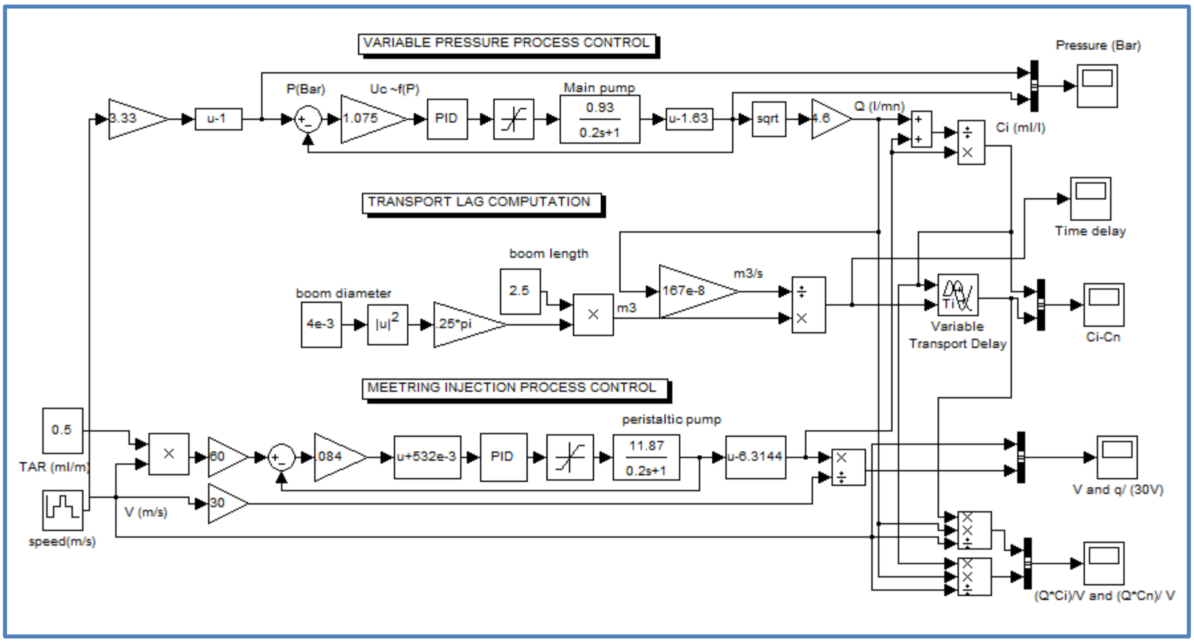


Figure 40 : Total flow control modeling by SimuLink^{TM}

4.5 Implementation of the process control strategy in PLC kit

The precedent paragraph 4.4 treated implementation of the process control in laboratory conditions using LabView software to assess the controller software on the basis of simulated velocity input. After that, the present paragraph concerns the implementation of a cost effective controller in an electronic box that can be fit to the framework of the DIS sprayer.

The technical choice of electronic components could satisfy the performance requirements of the process control studied in laboratory conditions. Otherwise, it should be affordable and simple for usage in the context of small scale farming. The process controller kit is proposed in an electronic box to be fit to the pretended usage.

4.5.1 Process controller hardware design

The process controller kit is based on the PLC controller (PIC 18F4520) mounted on the electronic card (PIC Ready 1 of MikroElectronika) and on two modules of PWM actuators (Pololu High-Power Drivers 36v9 and 18v25) for controlling the carrier flow and the metering pumps. The DIS design is based on DC electrical energy supplied by standard 12 V batteries (Figs. 41 and 42).

By referring to the hydraulic test bench mounted in the preliminary laboratory test, the second laboratory bench is mounted to test the DIS based on the PLC controller and parallel boom layout of eight nozzles (Teejet, ISO11002, 0.8 L/mn~3 bars) supplied by equal lines (Quick-connect tubes, D = 4 mm, Festo^{TM}).

The DIS is performed using the carrier diaphragm pump (Flojet^{TM}, 12 V DC, 10 L/min~2.8 bars, Sherflo), and the metering piston pump (Fluid Metering, 100 mL/min, 12 V DC).

Although, the cost of the piston metering pump is twice higher compared to peristaltic pump, the pump performance is of importance to build accurate injection metering system and to simply process its flow rate with reference only to the operating battery voltage without use the proximity sensor for feedback control. In fact, the choice of the piston pump is of importance to assess the PLC kit without implementing a proximity sensor for measuring the pump rotating speed as a feedback input for its process control.

The metering accuracy of piston pump is of importance to perform the sensing of its flow rate output according to its calibration curve correlated with its PWM actuation rate and to the operating battery voltage. The correlation of the injected flow rate with the PWM actuation of the metering pump and the batteries voltage is done for use as a possible low cost alternative to the feedback control of the pump with reference to its rotating speed.

The option of avoiding usage of the Hall Effect proximity sensor for the feedback control of the metering rate is of importance to simplify the DIS design and to balance the supplement cost due to the use of the piston metering pump.

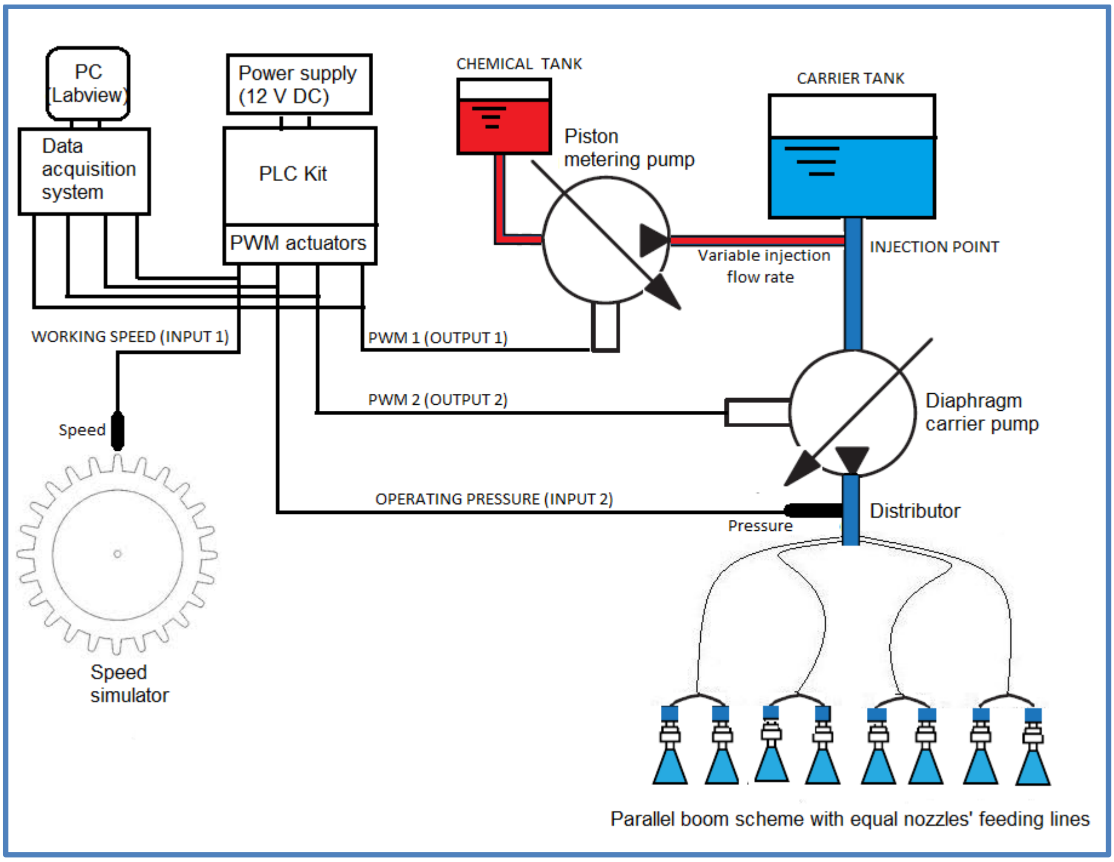


Figure 41: Scheme of the laboratory DIS mounted for testing of the PLC kit

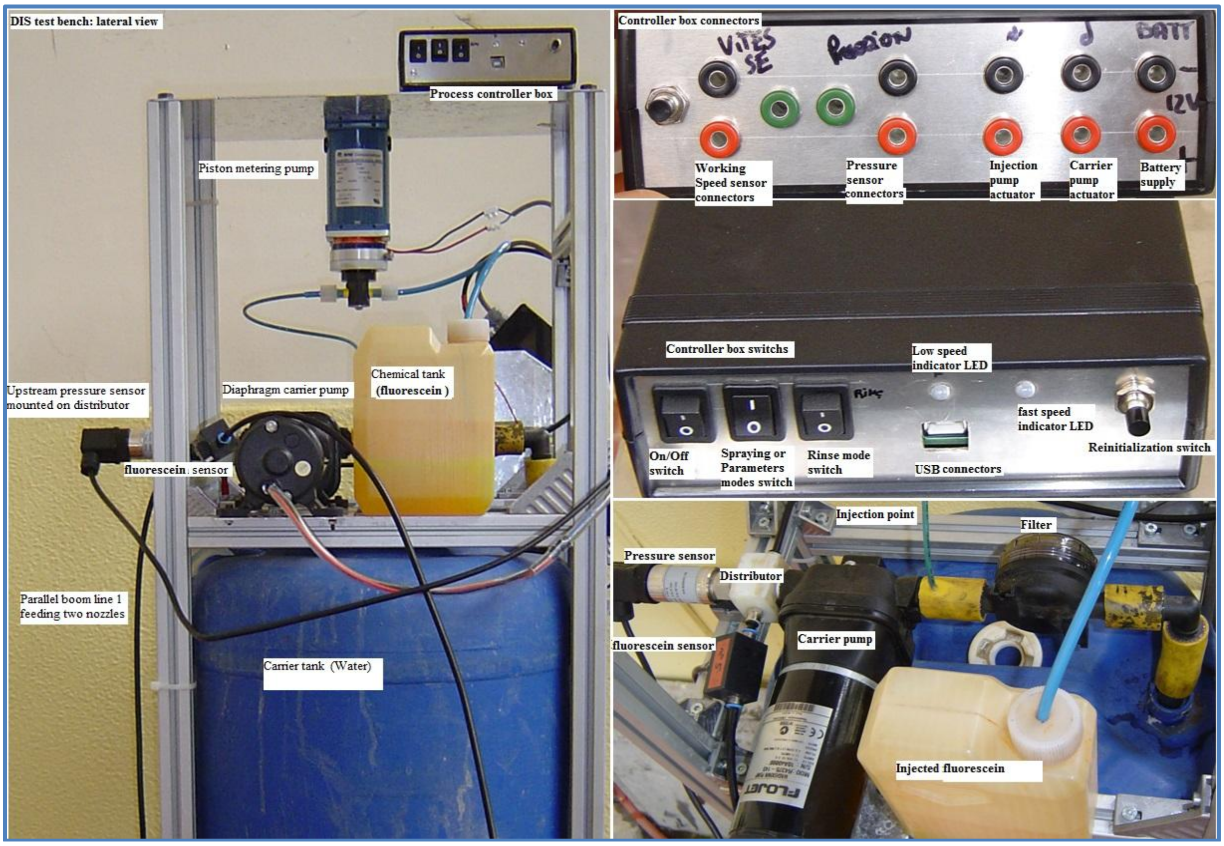


Figure 42: Laboratory DIS mounted for testing the PLC electronic box

4.5.2 Process controller software design

The algorithm of the PLC controller is based on two PID closed loops to control the metering and the carrier pumps using the PWM actuators that could respond to the requirements of operating pumps according to the working speed of the DIS sprayer chariot (Fig. 43).

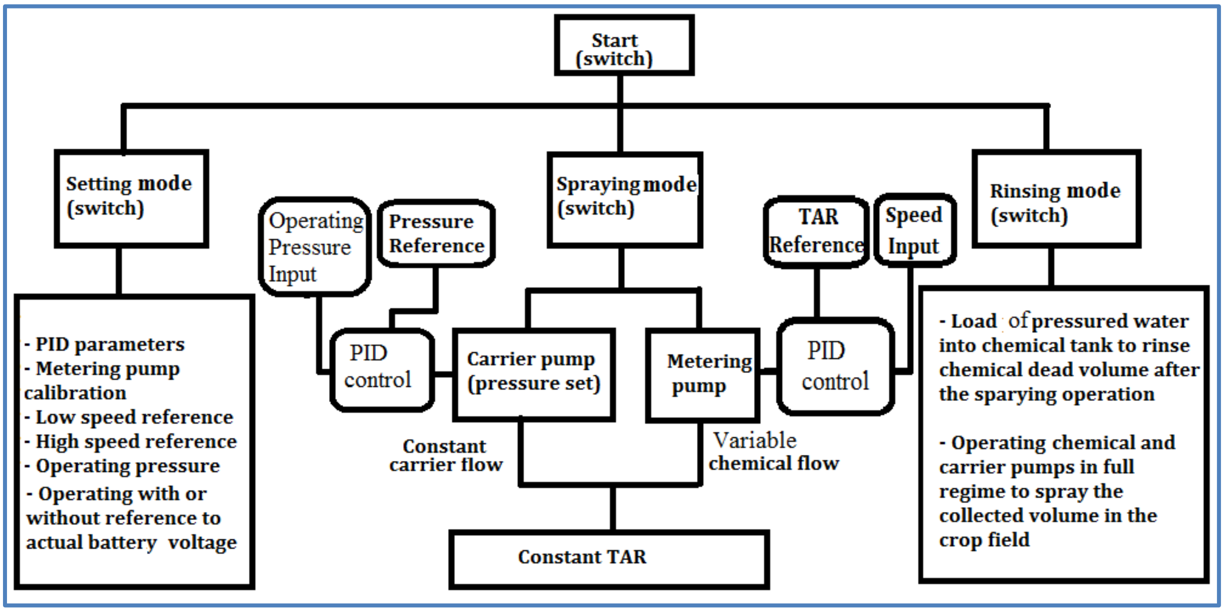


Figure 43: PLC algorithm design based on parameters setting, spraying and rinsing modes

The software is compiled in C program (Annex B) to implement the process control strategy of constant carrier flow (CCFC). The PLC is programmed to manage the PWM1 and PWM2 actuators performed for piloting the metering pump to adjust the concentration injection rate and the carrier pump to maintain the set operating pressure, respectively. The PWM1 is set within the range 30-255 (8 bit) to control the carrier pump output for obtaining operating pressure within the range of 0.36-3.95 bars. The PWM1~P relationship is established on the basis of manual calibration as follow:

$$PWM1\ (\%) = 37.84\ P\ (bar) + 21.68,\ R^2 = 0.997 \qquad (35)$$

The PWM2 is set within the range 40-255 (8 bit) to control the metering pump output for obtaining variable chemical injection flow rate within the range of 6.2-55.1 mL/min. The PWM2~q_{inj} relationship is established on the basis of the average battery voltage of 12.4 V (Umin = 12.27 V, Umax = 12.52 V) by calibration as follow:

$$PWM2\ (\%) = 4.454\ q\ (mL/min) + 12.09,\ R^2 = 0.999 \qquad (36)$$

The measurement of the working speed is done by the Hall Effect proximity sensor (Airpax^{TM}) performed to generate the frequency of the square data input in laboratory condition. The input is similarly generated as done previously in the measurement protocol of the working speed profiles using the square tooth gear mounted on the chariot wheel to assess the operating speed (V). The gear is set to generate the frequency of 38 Hz for one turn wheel of circumference of 1.2 m (31.66 Hz~1 m/s) according to the design of a gear of 38 square teeth mounted on a wheel circumference of 1.2 m (Fig. 44) to sense the operating speed on the sprayer chariot:

Figure 44: Design of a gear of 38 square teeth mounted on a wheel circumference of 1.2 m for sensing speed of the DIS sprayer chariot

The voltage command U_{c2} of PWM2 is set to work within the range of 0-6 V and calibrated to manage the metering pump in automatic mode on the basis of the operating speed varying within the range of 0-2 m/s as follow:

$$U_{c2} = 3.191\ V\ (m/s) + 0.029,\ R^2 = 1 \qquad (37)$$

The injection flow rate (q_{inj}) is computed with reference to the working speed to fulfill the condition of applying technical rate (TAR) of 1 L/ha. It practically depends on the number of operating nozzles (eight nozzles) mounted in parallel scheme and feed by equal lines (Fig. 18).Test and evaluation of the PLC performance is based on controlling chemical injection relative to DIS boom of eight nozzles (eq. 38):

$$q_{inj}\,(mL/mn) = 24*V\,(m/s) \qquad (38)$$

As the operating voltage change according to the battery charge level, the metering piston pump is calibrated with reference to the operating batteries voltage. The injected flow rate is correlated to the PWM2 actuation with reference to the batteries voltage U_{batt}. In fact, as the batteries load decreases the voltage decreases and correction is needed to adjust the equation relying the PWM actuation and the injection flow rate (q_{inj}) with a voltage correction factor (k_v). The factor k_v is computed according to the calibration done by varying the operating voltage from 11 to 13 V with reference to the average voltage of 12.4 V used in normal testing condition:

$$k_v = -\,0.5757\,U_{batt}\,(V) + 12,\ R^2 = 0.969 \qquad (39)$$

$$PWM2 = k_v * q_{inj}\,(mL/min) + 16,\ R^2 = 0.99 \quad (40)$$

The graph 45 shows results that compare the injected concentrations due to implementing the piston metering pump with and without correcting voltage variation in the range [11-13 V] using a step of 0.5 V. Results showed the importance of the battery charge level on changing the pump delivery consigns that need to be corrected to the voltage battery reference for constant metering performance.

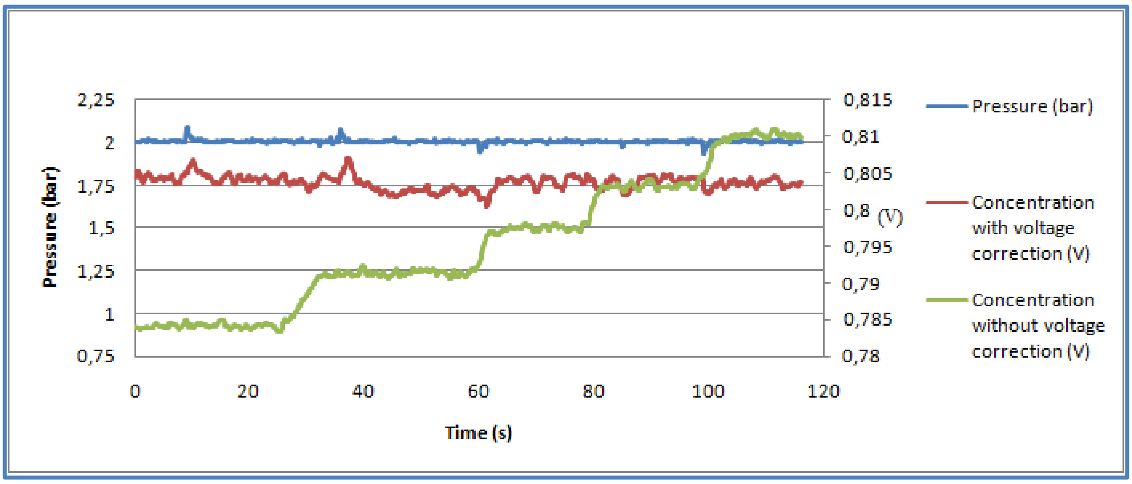


Figure 45: Injection response of the metering piston pump with and without voltage correction using 0.5 V steps from 11 to 13 V

The PWM2 actuation of the injection pump is deduced from equations 39 and 40 as the injection flow rate is automatically depending on the operating speed when the process controller is working in spraying mode:

$$PWM2 = 24*k_v*V\,(m/s) + 16 \qquad (41)$$

The choice and calibration of the injection flow rate and the operating constant carrier flow pressure are done in the parameters setting mode. The process controller is performed to communicate with PC through USB connection to monitor the processing data and to set different parameters via hyper terminal interface.

The parameters setting mode serves to actuate the injection pump in manual mode for choosing or calibrating the injected flow rate. The processing of the actual metering flow rate serves for comparison with the output flow rate established in the reference calibration of the dosing pump for periodical evaluation of the metering performance and/or recalibration. In fact, the manual checking of the effective injected flow rate after a certain period of use serves to evaluate the pump output and to calibrate it with reference to the theoretical injection flow rate and to the PWM2 curve calibration.

4.6 Conclusion

This chapter presented the methods and materials used to validate the optimal hydraulic design and to model and implement the laboratory process controller and the PLC kit of the pretended DIS. The next chapter treats the results related to 1)the modeling and evaluation of the hydraulic boom layout, 2) the modeling of the process control strategies and their evaluation using experimental DIS process controller mounted in laboratory and 3) the evaluation test of the PLC controller kit implemented for eventual assemblage to DIS sprayer framework and test in field.

Chapter 5: Results and Discussions

The present chapter presents the results concerning the modeling and experimental assessments done to study the hydraulic and process control aspects related to the final design of the pretended electrical DIS and its process controller. The results concern the following points:

- the study of the hydraulic configurations of serial and parallel boom schemes to assess lag transport and dynamic performance of DIS design,
- The modeling of the process control system using *MATLAB/SimuLink* tools,
- The experimental evaluation of the process control system in laboratory condition,
- The test results of the process controller performed using a PLC kit.

5.1 Study of hydraulic boom scheme

5.1.1 Simulation of serial boom scheme

The simulation of serial boom section of five nozzles on the basis of three diameters of 5, 6, and 8 mm using the computational model presented in the previous chapter (materials and methods) showed that the 6 mm boom diameter could be satisfactory for keeping application uniformity up to 97% and short lag transport (dead time within 1.5 s for the boom section length of 2.5 m) as shown in table 10.

The simulation of viscosity showed that its effect kept insignificant by varying it from 10^{-6} to 10^{-5} m^2/s as the boom flow uniformity is slightly affected to decrease by less than 1% for the three diameters simulations.

The simulation of the small diameter of 5 mm showed a missuniformity of 7% between the up and down nozzles mounted in serial scheme. However, usage of small diameters of 4 and 5 mm can be of importance to supply separately nozzles mounted in parallel scheme from a common collector mounted downstream on the carrier pump.

The computation of friction loss ($\Delta Hf = 3.6\ \% \sim D = 8$ mm; $\Delta Hf = 9\ \% \sim D = 6$ mm; $\Delta Hf = 22\ \% \sim D = 5$ mm) showed its importance when the small diameter is chosen. The 6 mm boom diameter showed a compromising case between the friction loss variable that affect lateral uniformity along the serial boom section and the flowing velocity variable that decrease the lag transport when liquid is speed up. The optimization of hydraulic design focuses on improving DIS dynamic performance. It consists on solving the dilemma of reducing lag transport impact by speeding up liquid flow while reducing friction loss to maintain uniform application for all the nozzles mounted in serial scheme along the spraying boom.

Table 10: Computational results of simulated serial boom schemes of five nozzles (ISO11003~3 bars)

Nozzles number	D (mm)	viscosity (m²/s)	Convergence $\lvert\Delta H_s-\Delta H_c\rvert$	ΔH_c (m) (H_0-H_n)	$\Delta H_c/H_0$ (%)	ΔHf (mce)	Lag transport (s)	Uniformity q_5/q_1 (%)
5	8	10^{-6}	0.00035	0.614	2.05	0.935	2.41	99.33
		10^{-5}	0.00049	0.991	3.30	1.312	2.40	98.91
5	6	10^{-6}	0.00027	1.958	6.53	2.664	1.50	97.40
		10^{-5}	0.00016	2.675	8.92	3.381	1.48	97.28
5	5	10^{-6}	0.00024	4.999	16.66	6.461	1.00	93.13
		10^{-5}	0.00003	5.696	18.99	7.157	0.99	92.11

Computation of lag transport in serial scheme showed that lag transport considerably increased from 9 % in the upstream side of the boom section (nozzle 1) to 43% in the downstream side (nozzle 5) (Fig. 46). The fourth and fifth nozzles took a total lag transport of 65 % due to lower flow speed (lower gain) of liquid at the end of boom section that causes a long dead time to erase the relative dead volume.

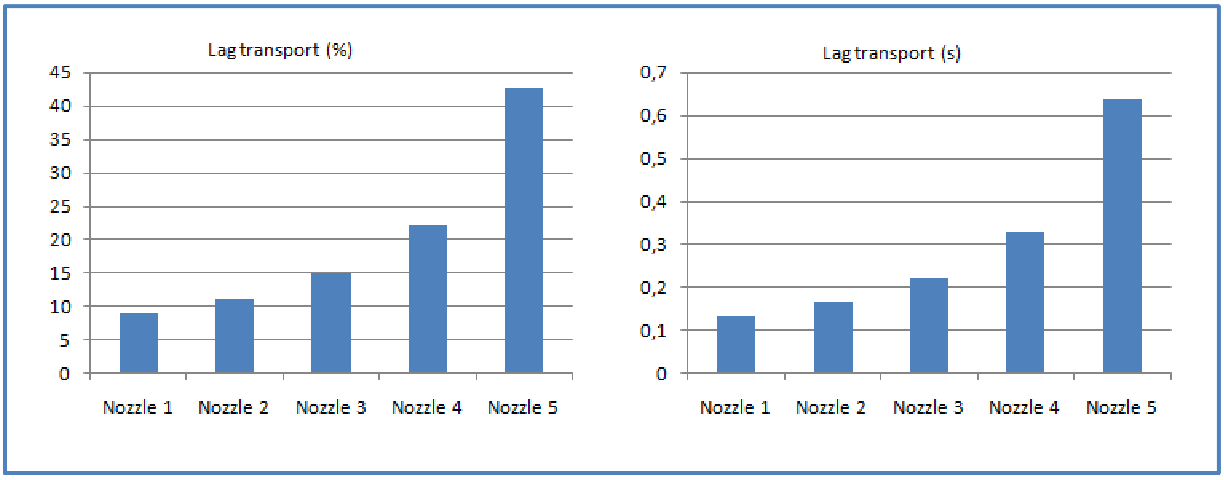


Figure 46: Discrete lag transport in serial boom section of five nozzles at 3 bars (d = 6 mm)

The computation of discrete profiles of Reynolds number in the boom section of diameter of 6 mm showed that the flow is kept turbulent (Re > 3000) for all the five nozzles (ISO 11003) mounted in serial scheme (Fig. 47). The turbulent flow regime is advantageous for satisfying the condition of a good quality online mixing. However, the simulation of two viscosities of water only (10^{-6} m^2/s) and mixture of water and glycerin (10^{-5} m^2/s) showed that the Reynolds number decreased considerably as a laminar flow regime can be induced. Practically, such case cannot occur as the viscosity range of the most used chemical formulations keeps far from the simulated case (Zhu et al., 1998).

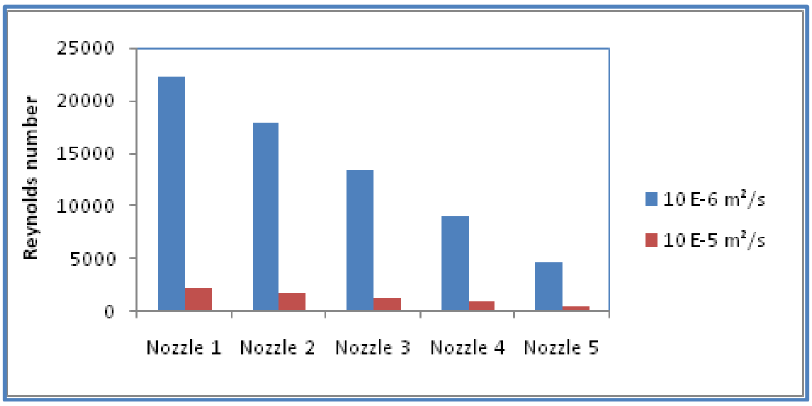


Figure 47: Reynolds numbers in serial boom scheme (6 mm diameter, 3 bars, and two viscosity levels)

5.1.2 Simulation of parallel boom scheme

It is important to use parallel boom configuration with equal housing tubes to satisfy optimal and equal lag transport for all mounted nozzles on the spraying boom. In fact, according to the results of serial boom scheme simulation, the optimal diameter (D = 6 mm) compromising reduced lag transport and friction losses cannot satisfy the condition of equal lag response between the mounted nozzles in the serial scheme of the spraying boom. Consequently, equal tubing houses of parallel lines (diameter and length) with simple and double nozzles feeding (Fig. 48) can be chosen with reference to existing choice of the commercialized quick-connect tubing (of 2, 4, and 6 mm internal diameters). Practically, the quick-connect tubing of 4 mm internal diameter is chosen to satisfy the condition of improving and giving an equal dynamic response for an even concentration process change along the researched DIS spraying boom.

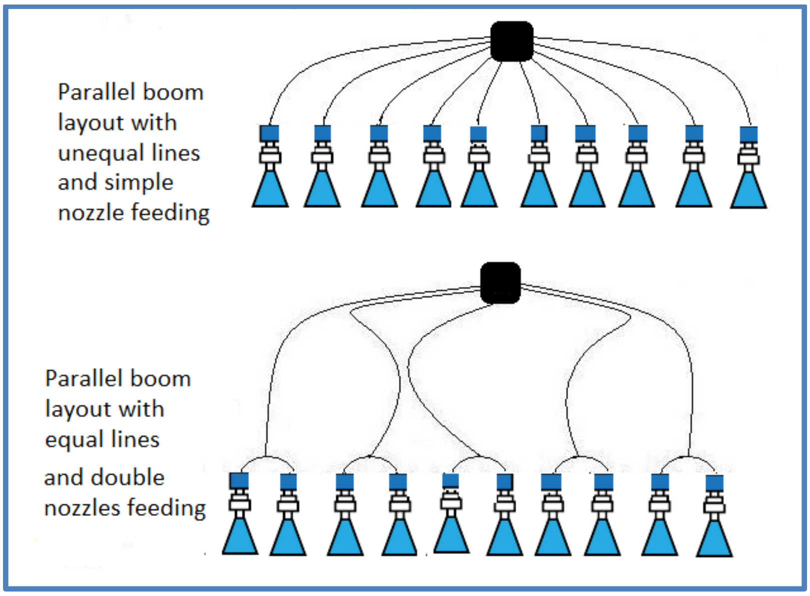


Figure 48: Two parallel boom designs with unequal and equal lines, simple and double nozzles feeding

The computation is done to show the behavior of pressure drop, turbulence and lag transport that can occur in parallel boom scheme with reference to pressure setting and flow rate output due to use of standard nozzles ISO11003 (1.2 L/min ~ 3 bar) and ISO11002 (0.8 L/min ~ 3 bar) (table 11).

Table 11: Computation of hydraulic parameters in parallel boom schemes of five nozzle lines (D = 4 mm, q = 0.8 and 1.2 L/min~3 bars)

Cases of parallel boom scheme		Pressure drop (bar)	Turbulence (Re)	Lag transport (s) (1.2 L/min~3 bars)	Lag transport (s) (0.8 L/min~3 bars)
Unequal lines:	$L_1 = 0.5$ m	≤ 0.05	>4000	0.314	0.471
	$L_2 = 1$ m	≤ 0.1		0.628	0.942
	$L_3 = 1.5$ m	≤ 0.15		0.942	1.413
	$L_4 = 2$ m	≤ 0.2		1.256	1.884
	$L_5 = 2.5$ m	≤ 0.25		1.57	2.355
Equal lines, simple nozzle feeding: $L_1 = L_2 = L_3 = L_4 = L_5 = 2.5$ m		≤ 0.25	>4000	1.57	2.355
Equal lines, double nozzle feeding: $L_1 = L_2 = L_3 = L_4 = L_5 = 2.2 + 0.3 = 2.5$ m		≤ 0.3	> 8000	0.69 + 0.19 = 0.88	1.036 + 0.2826 = 1.319

The comparison of the simple and double nozzles feeding using equal lines of the parallel boom scheme showed that the computed lag transport can be reduced from 1.57 s (case of the simple nozzle feeding) to 0.88 s using double feeding with the blue nozzles ISO11003 at 3 bars. However, the reduced flow rate using the yellow nozzles ISO11002 showed a lag transport of 1.32 s when the same configuration of double nozzles feeding is tested at 3 bars. This comparison showed the importance of using double nozzles feeding while choosing operating the DIS boom configuration at reduced pressure-flow rate regime (table 11).

Although, the pressure drop increased slightly in the case of using double nozzle feeding according to double flow rate transported by line (table 11). It can be technically taken into account by mounting the pressure sensor at the tip nozzle level instead of the downstream level of the carrier pump. Otherwise, the pressure drop can be adjusted by integrating a correction factor in the process control design. Practically, the maximal pressure drop found within 10% (table 11) induced only a flow rate decrease of 3 %. The right assessment of the processed pressure/flow rate is of importance to precisely manage the feedback control of the carrier flow with reference to the operating pressure.

The computation of the Reynolds number showed that in the three cases studied of parallel boom schemes the flow regime kept turbulent in the studied cases ($Re \geq 4000$) to improve the online mixing quality of mixture as a researched criteria of optimal DIS design. The pressure drop showed an increase of about 10 % in the case of double nozzles feeding but it can be compensated using pressure sensor at the tip nozzle level. Otherwise, this pressure drop kept tolerable in term of energy use. In fact, the relative improvement in term of lag transport (around 1 s) and of flow turbulence ($Re \geq 8000$) are of great importance to satisfy concentration process change dynamic and online mixing process for the best researched performance of DIS hydraulic design.

5.1.3 Conclusion

The computation results (Tables 10 and 11) showed the importance of adopting the parallel boom scheme with equal lines and double nozzles feeding. The quick-connect tubing (internal diameter of 4 mm) can be adopted as an optimal and cost effective solution for designing a DIS boom of ten tip nozzles mounted in parallel scheme.

5.2 Experimental results and discussion

The serial and parallel boom layout were studied experimentally to evaluate their effective pressure drop and lag transport according to flow and pressure reference conditions used before (ISO11003, 1.2 L/min ~ 3 bar).

5.2.1 Pressure drop

The test of boom section of 5 serial nozzles (Fig. 49) showed that the pressure drop kept around the simulated values (7 % ± 1). There was a divergence between the simulated and experimental results around operating pressure of 1 bar. Such difference can be explained by the miss adaptation of the nozzle law at this low pressure as the specified pressure of hydraulic spraying nozzles is within the range of 1.5 – 5 bars. There was practically a difficulty to predict accurately the pressure gradient. In fact, the use of two standard pressure sensors cannot precisely evaluate the gradient pressure comparatively to using adapted differential pressure sensor. As a consequence, the minor losses occurring in different junctions is roughly approached with the linear losses for having a global indicative information of the pressure decrease and its influence on flow rate uniformity between the mounted nozzles on the boom. The results showed also in the case of the study of the serial boom scheme (simulation and experimentation) that the number of the mounted serial nozzles affect significantly the pressure gradient by comparing the cases of using 4, 5, and 6 mounted nozzles (Fig. 49).

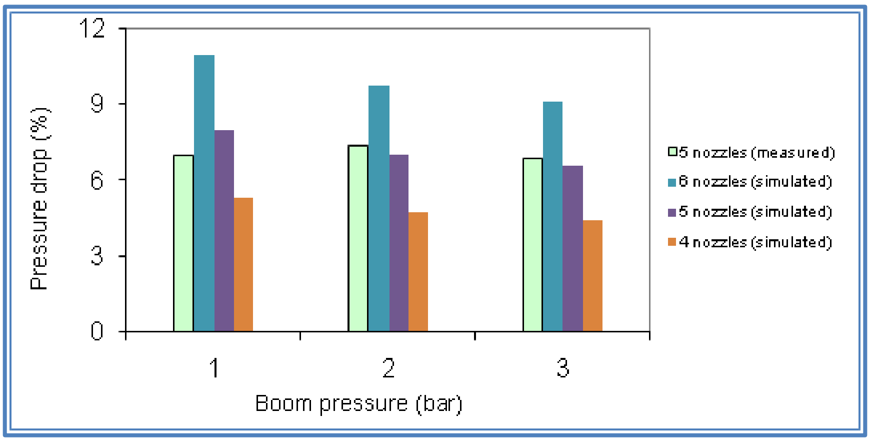


Figure 49: Pressure drop in serial boom layout (D = 6 mm)

The test of the parallel boom layout using unequal feeding lines was carried out by sensing pressure gradient between each tip nozzle (the nearest nozzle (0.5 m) and the farthest nozzle (2.5 m)) and the collector mounted on the carrier pump. The pressure gradient between the upstream and downstream nozzles kept around 7% ± 1 (Fig. 50).

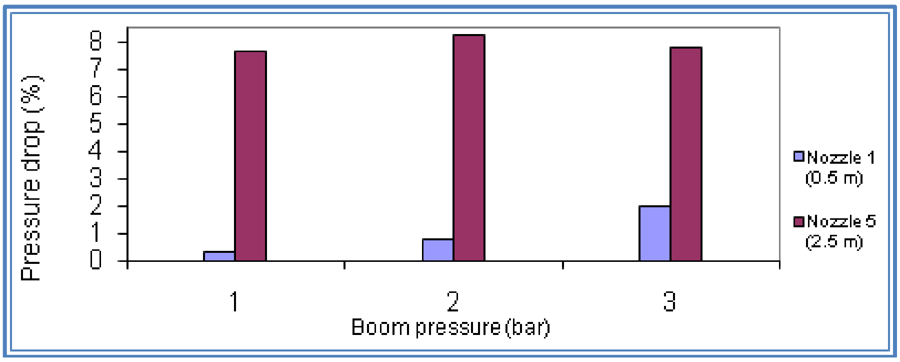


Figure 50: Pressure drop measured in parallel boom layout (D = 4 mm)

5.2.2 Lag transport

Lag transport in serial and parallel boom layouts is characterized using the parameters of dead time, time constant, and rise time. As defined before (see materials and methods), the first time is the lag time from the start input point to the start of response which depends on dead volume and flow speed in each control volume CV. The time constant is the time required for the concentration change to reach 63.2 %. The rise time is the time needed for concentration to complete the response from 10 to 90 % to a step change.

The lag transport of the five nozzles mounted in serial layout was evaluated at 4.5 s (Fig. 51). The trends showed that dead time change between nozzles to move upward from 0.3 s (Nozzle 1) to 1.8 s (Nozzle 5). The time constant changed from 1 s (Nozzle 1) to 1.3 s (Nozzle 5). The rise time increased slightly to form different S-shaped curves as a typical response of serial nozzles scheme where flow decreases according to position of each nozzle in the boom section.

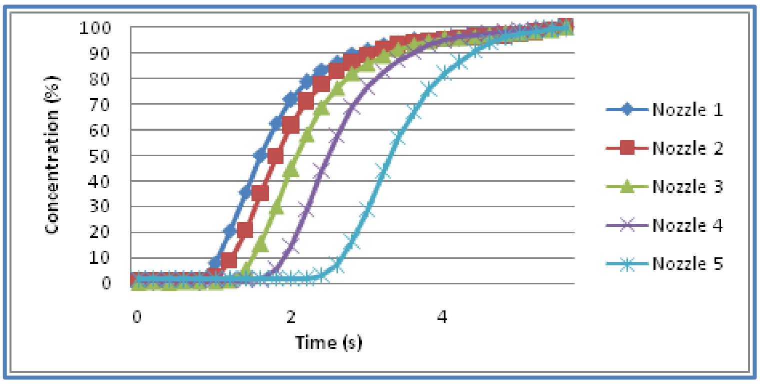


Figure 51: Experimental response of 5 serial nozzles to a concentration step change at 3 bars (D = 6 mm, nozzle ISO 11003~ 1.2 L/min)

The total lag time of the five parallel nozzles supplied by unequal lines is evaluated around 4 s. The dead time stepped constantly from 0.4 s (nozzle 1) to 2 s (Nozzle 5). The time constant kept the same for the five nozzles around 0.9 s. The rise time took the same value of 1.2 s for the five nozzles, forming similar S-shaped curves with an equal delay between them according to the equal difference in length between the parallel lines feeding the five nozzles (Fig. 52).

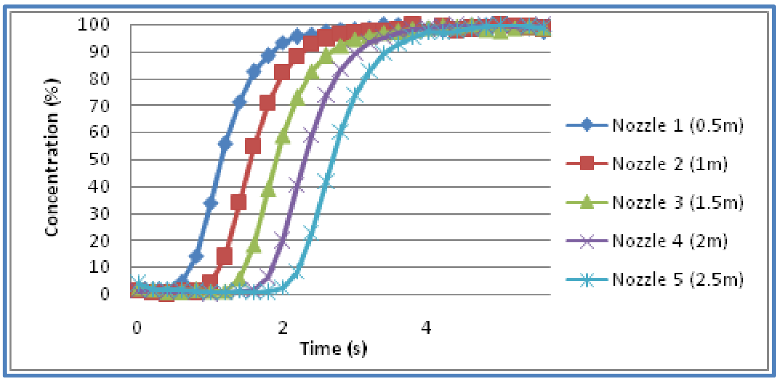


Figure 52: Response of 5 parallel nozzles to a concentration step change at 2.7 bars (D = 4 mm, nozzle ISO 11003~ 1.2 L/min)

The experimental study of parallel boom scheme with double feeding lines is done by mounting two concentration sensors in upstream point of the distributor and downstream point of one tip nozzle (Fig. 53). The difference between measurements done by both sensors, serves to evaluate the parameters of dead time, constant time, and rise time.

Figure 53: Parallel boom design with double nozzles feeding from upstream (distributor) to downstream (tip nozzle) points

The total lag time is evaluated about 2 s. The dead time is equally situated at 1 s for all the mounted nozzles. The time constant is evaluated at 0.7 s. The rise time is around 1 s forming similar S-shaped curves according to equivalent hydraulic configuration for all mounted nozzles in parallel scheme (Fig. 54).

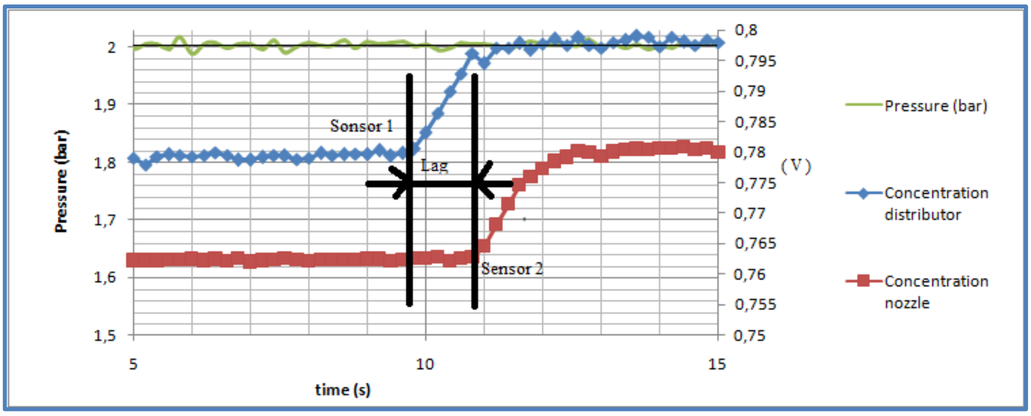


Figure 54: Concentration change response in a parallel boom with a double feeding scheme using the nozzle ISO11002 and tubing lines of internal diameter (D = 4 mm) at the pressure (P = 2 bars)

5.3 Results of the process control modeling

The results presented here concern the simulations of DIS process control done using Matlab/Simulink tools. It approaches the modeling of both constant carrier flow control (CCFC) and total flow control (TFC). The assessment of each process control algorithm is based on monitoring input and output variables processed and analyzing indicators performance to show validity of the processed variable rate application.

The main parameter input for the studied process is the operating speed which is presented in different forms and rates to test the reactivity of the control system and its ability to maintain the chemical application rate within the tolerable range error.

The output parameters concern the operating pressure, the injection flow rate, the carrier flow rate, the injection flow rate-speed ratio (q_{inj}/V) , the injected (Ci) and delivered (Cn) concentrations, the transport delay and the technical application rate (TAR ratio).

The injected flow rate ratio is performed as indication of the [q_{inj}/V]/30 for easy analyze. This indication is typically equal to the unit for a higher performance response of the PID process controller actuating the chemical injection pump.

The TAR ratio is performed as indication of the [Q*Cn/60V] ratio for showing how can the applied rate vary close to the typical rate reference of 0.1 mL/m² (chemical application rate of 1L/ha).

The processing of the injected (Ci) and delivered (Cn) concentrations constitute an indicator for approaching lag transport. In fact, the time (in s) required to transport of concentration from the injection point of chemical into carrier to the spraying point of mixture at the tip nozzle is expressed by the ratio between dead volume (L) and flow rate (L/s).

The delay is used to express application rate error in term of area (m^2) taken lower or higher concentration according to the pretended technical application rate by DIS system. In fact, the misapplied area is computed as a scalar product of both vectors relatives to the sprayed width (m) and the forward speed (m/s) during the lag transport time (s).

5.3.1 Modeling of constant carrier flow control

The modeling of the CCFC system is done using SimuLink^{TM} to study the process controller response at constant operating pressure of 2 bars. The simulation is based on the speed inputs of steps and sine waves to see the controller dynamic behavior according to the processed variables of pressure, flow rate-speed ratio, injected (Ci) and delivered (Cn) concentrations, TAR ratio, VAR ratio, and transport delay.

5.3.1.1 Response to steps input

The response of CCFC to steps input of 0.6 - 1.2 m/s showed a delay response of 3 s between upstream point (Ci) and downstream point (Cn) of the parallel boom line (Fig. 55). The delay is due to the concentration transport in the parallel boom scheme having equal lines for a simple nozzle feeding (nozzle by line). Such lag transport can be reduced to less than 2 s in the case of simulating the parallel boom layout with equal lines and double nozzle feeding (two nozzles by line) as the processed flow rate increased twice. Practically, the computed lag transport is 1.86 s for the simulated case of the nozzle ISO11002 (0.8 L/min~3 bars) operating at constant pressure of 2 bars through a feeding line having 4 mm internal diameter and 2.5 m length. The feeding line is assumed to transport double flow in 88 % of its first common part (L_{11} = 2.2 m) and simple flow in 12 % of its separate part (L_{12} = 0.3 m) connected to each of two supplied nozzles.

The simulation of CCFC using speed step input showed also that the injected flow rate ratio $[q_{inj}/V]/30$ is kept constantly equal to the unit indicating a satisfied response of the PID controlling the chemical injection pump. The ratio trend is marked by a start with an overshooting of 20 % and rapid establishment of the injected flow rate in the steady state conditions. The PID parameters are set according to the testing result of the injection pump (peristaltic pump) in open loop condition to evaluate its transfer function of first order process with a constant time $\tau = 0.2$ s (Fig. 55c). The $[q_{inj}/V]/30$ ratio should be constantly equal to the unit according to the nozzles number of ten (N = 10 for a boom width of W_b = 5 m) simulated to be supplied by the pump injection for carrying out a TAR of 1 L/min proportionally to the operating speed [q_{inj} (mL/min) = 30*V (m/s)] in the range of [0-1.2 m/s]. The results (Fig. 55d) showed also the response of the Cn/V ratio presenting a constant concentration output in the nozzle level. The lag transport effect is illustrated also according to the response of the Cn/V ratio starting after a delay of 3 s (parallel boom layout with a simple nozzle feeding). Such delay take only less than 2 s (the computed value is 1.86 s) when the parallel boom layout with double nozzles feeding by line is adopted.

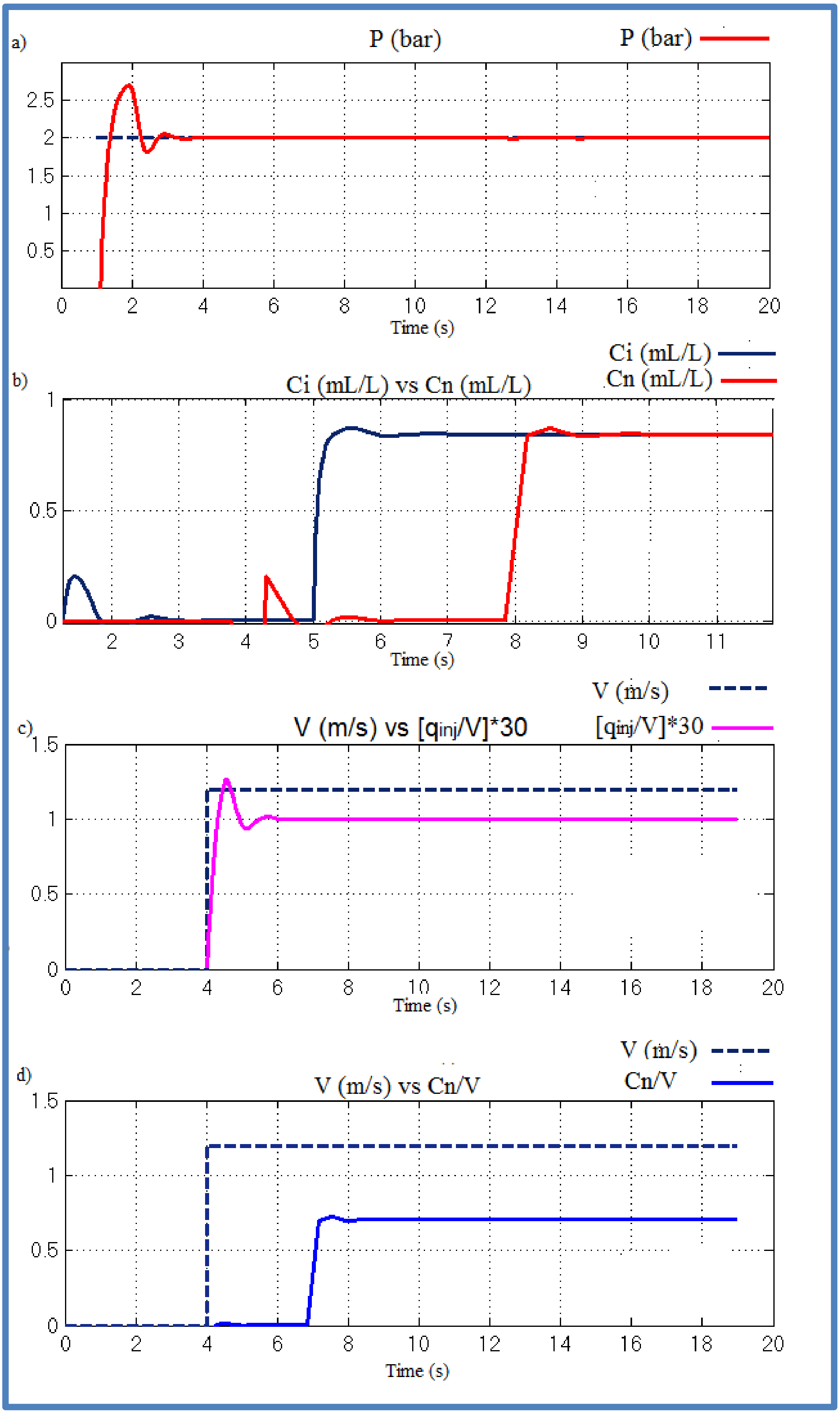


Figure 55 : Simulation of the CCFC response to speed step change for the case of parallel boom scheme with equal lines and simple nozzle feeding (Simulink^{TM}).

5.3.1.2 Response to sine wave speed input

CCFC response is simulated using sine wave speed input (Fig. 56). The sinusoidal input is based on varying the speed signal at the rate of 0.3 m/s² (0.25 Hz) between the minimum of 0.6 and the maximum of 1.2 m/s (bias = 0.9 m/s; amplitude = 0.3 m/s). The response showed similar lag transport as the same parallel boom scheme with simple nozzle feeding is used. However, the q_{inj}/V ratio showed a variable response around the unit ($[q_{inj}/V]/30 = 1 \pm 4\%$) according to the transfer function and PID setting used to simulate the real case of the peristaltic pump with saturation limits. In fact, the pump dynamic is affected as the flow rate approach the saturation point according to its capacity. Furthermore, two speed change rates of 0.45 m/s² and 0.6 m/s² are simulated to show their effect on the metering subsystem according to response of the ratio $[q_{inj}/V]/30$. The trend ratio should be constantly close to the unit (Fig. 57b and 58b) as indicator of the metering pump dynamic performance. As response to both simulated accelerations, the ratio $[q_{inj}/V]/30$ showed sinusoidal variations around the unit having amplitudes of 8% and 12%, respectively.

The $[q_{inj}/V]/30$ sinusoidal behavior showed the effect of the injection pump dynamic by referring to the ideal response that should be equal to the unit ($[q_{inj}/V]/30 = 1$). In practice the pump should have small constant time and extended saturation limits for obtaining $[q_{inj}/V]/30$ sinusoids of low amplitude and as response to sine waves speed inputs of higher acceleration.

Figure 56f showed a typical sinusoidal behavior of the $[Q^*Cn/(60V)]$ ratio as the injected flow rate varied proportionally to speed while the carrier flow rate kept constant (CCFC). The concentration at the nozzle level is affected by cumulative errors according to the effect of the injection pump dynamic due to its constant time ($\tau = 0.2$ s) and to the effect of delay transport. Figures 57f, 57f and 58f showed an increasing error according to the importance of simulated speed variation rates of 0.3, 0.45 and 0.6 m/s² in affecting injection subsystem output. The nozzle concentration output is subjected to both errors as the $[Q^*Cn/(60V)]$ ratio depends on the injected flow rate (source error) and on delay response (timing error).

The CCFC modeling showed that the simulated DIS can perform adequately the control of TAR for a variable speed rate within 0.3 m/s². The speed profiles taken in the field conditions showed also that the speed rate changes (accelerations) were also within 0.3 m/s² despite transitory conditions related to the worker behavior in starting and turning while operating sprayer chariot (Fig. 24).

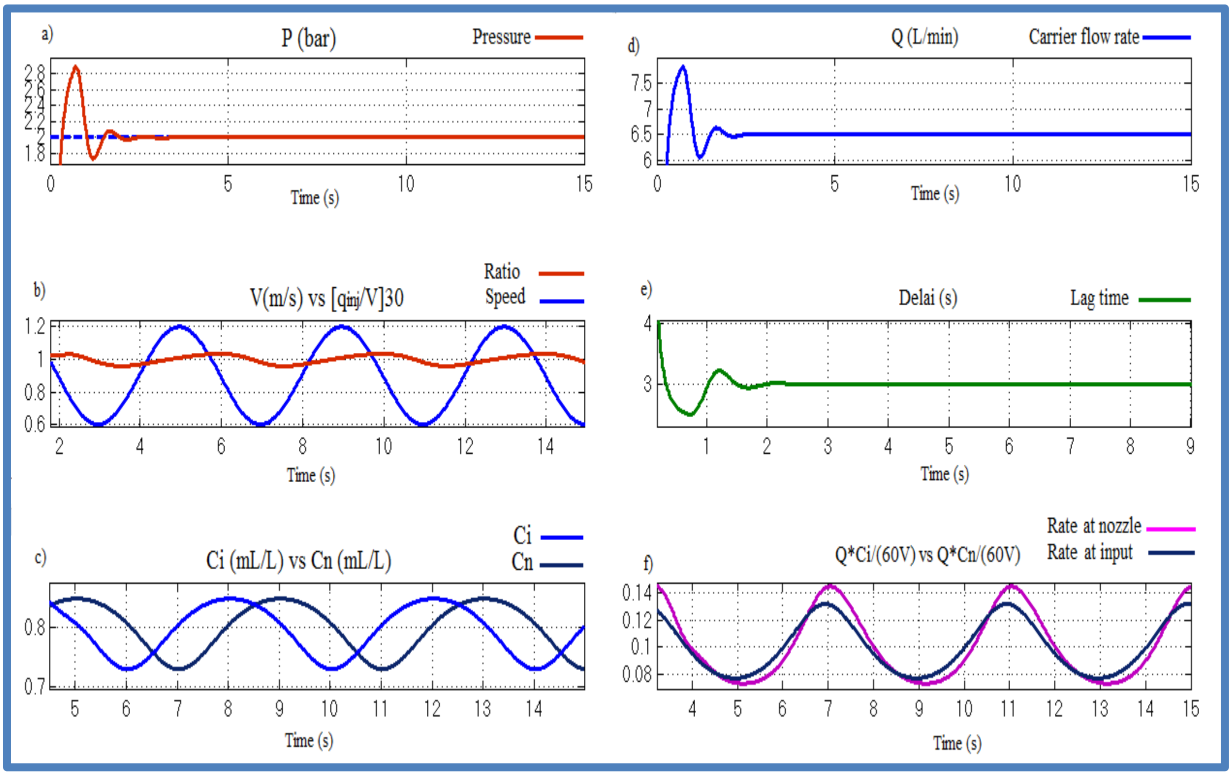


Figure 56: Simulation of the CCFC response to speed sine wave change of 0.3 m/s² using parallel boom design with equal lines and simple nozzle feeding (Simulink^{TM})

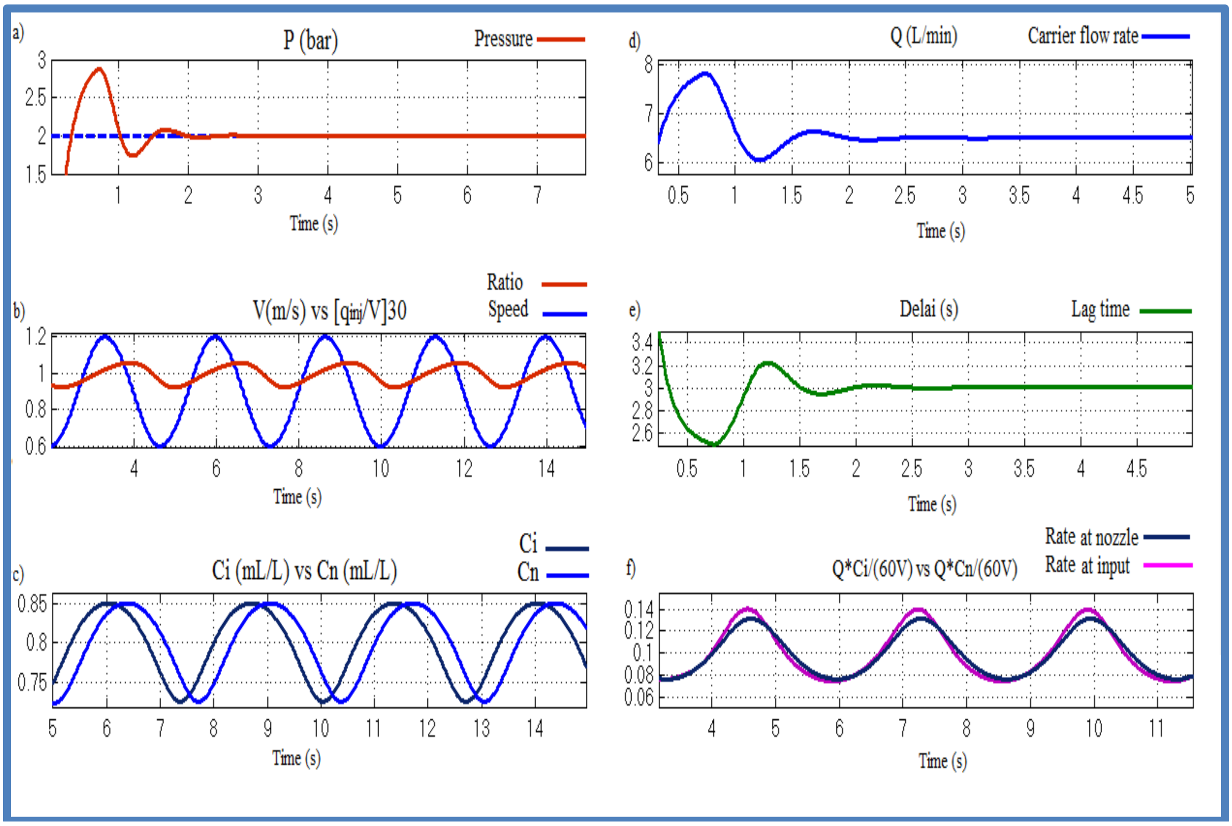


Figure 57: Simulation of the CCFC response to speed sine wave change of 0.45 m/s² using parallel boom design with equal lines and simple nozzle feeding (Simulink^{TM})

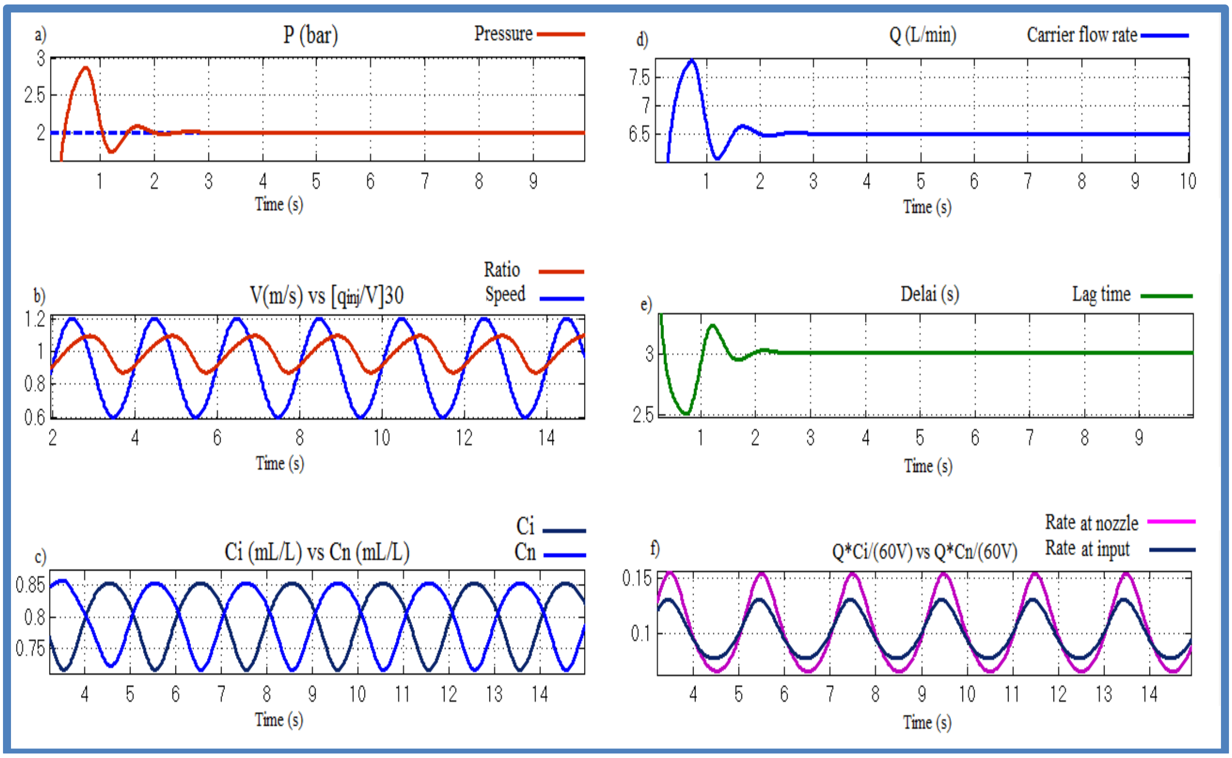


Figure 58: Simulation of the CCFC response to speed sine wave change of 0.6 m/s^2 using parallel boom design with equal lines and simple nozzle feeding (Simulink™)

5.3.1.3 Response to real speed input

Evaluation of the CCFC using real speed input (speed profile generated in the field) showed relatively a good performance in comparison to speed inputs used before (step and sine wave). In fact, the response of the metering pump is kept constant according to response of the ratio [q_{inj}/V]/30 (Fig. 59b). Figure 59c showed the delay effect on Ci and Cn fitting but without any important effect on the closeness of Q*Ci/(60V) and Q*Cn/(60V). In fact, the speed changing rate in the real profile is not consistent (maximal acceleration around 0.3 m/s^2) to affect the controller performance within the induced delay amount (Figs. 59c and 59f).

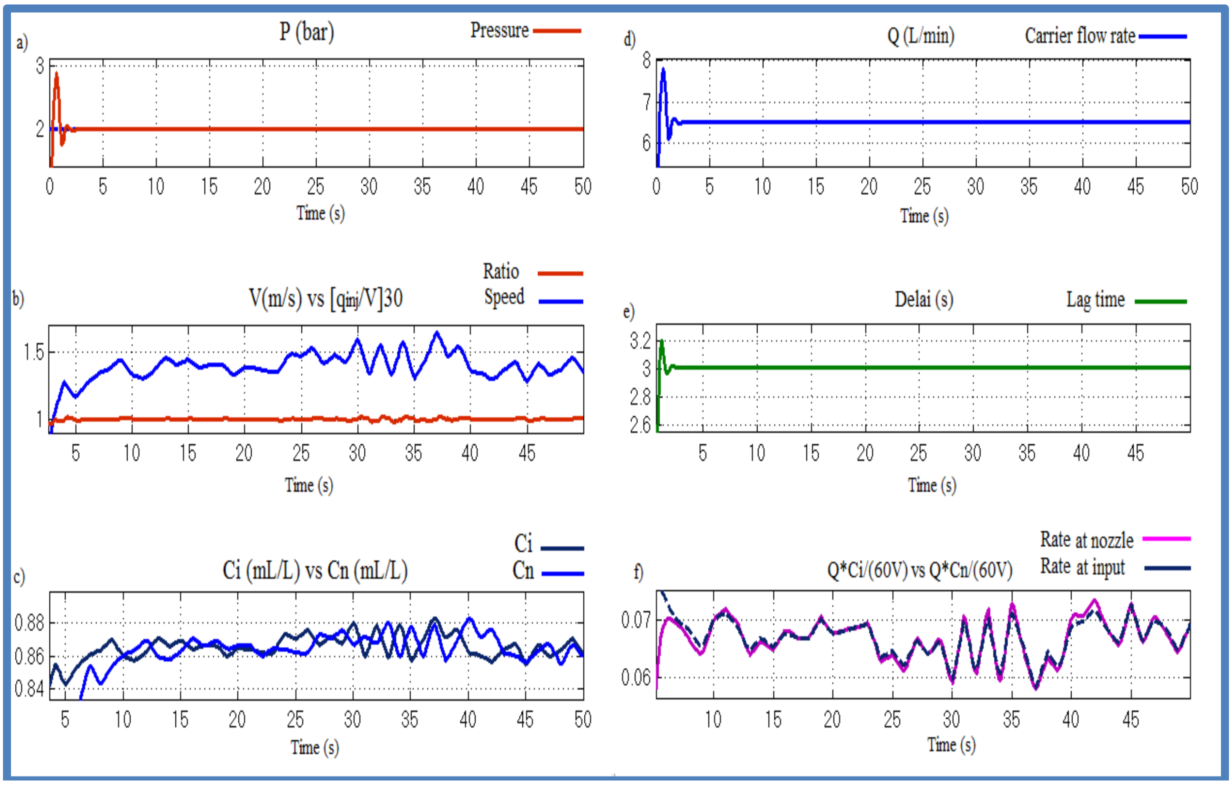


Figure 59: Simulation of the CCFC response to real speed input using parallel boom design with equal lines and simple nozzle feeding (Simulink^{TM})

5.3.2 Modeling of total flow control

The simulation of TFC system is done using variable operating pressure from 1 to 3 bars in accordance with step and sine wave speed inputs within the range of 0.6-1.2 m/s.

5.3.2.1 Response to steps input

Simulation of TFC response to speed steps of 0.6, 0.9 and 1.2 m/s, showed three different behaviors according to the three correlated pressure steps of 1, 2, and 3 bars, respectively (Fig. 60).

The PID setting of the carrier flow controller showed an important overshooting (more than 50 %) for the step of 1 bar, but only 20 % and 0 % overshoots for the steps of 2 and 3 bars, respectively (Fig. 60a). This change in dynamic behavior is due to the capacity reserve of the carrier pump according to saturation limits conditioned by the pressure-flow operating points within the ranges of 1-3 bars and 4-8 L/min.

The TFC strategy showed the advantage of decreasing lag transport from 4.2 to 2.3 s for increasing speed steps of 0.3 m/s from 0.6 to 1.2 m/s. In fact, as the speed increased, the pressure (then flow rate) increased proportionally (Q (L/min) = K*sqrt(P) and P (bar) = 3.33 V (m/s) - 1) to effectively reduce the lag transport (Fig. 60d). However, the TFC contributed to overcome lag transport only in ascendant speed steps as the flow rate increases and speed up the concentration transport, but inversely in the case of descendant speed, the controller proportionally decreases flow rate and lag transport relatively become consistent to be around 200 % (Fig. 60d).

Technically, lag transport compensation due to pressure/flow rate increase cannot be easily adapted to hydraulic spraying systems without use of nozzles operating in large pressure range. Conventional hydraulic spraying nozzles are not adapted to perform good spraying quality (avoiding driftable droplets) in accordance with the pressure/flow rate increase as a demand to the increase of operating speed. The hydraulic spraying nozzles with an extended pressure operating range and/or with anti-drift technology should be chosen to efficiently carry out variable volume rate control without affecting spray quality (details given in paragraph 2.7). Furthermore, carrier flow pump dynamic and stability of processing variable hydraulic pressure using feedback control are conditioned by the derivative (acceleration) of the operating speed input. In fact, high speed change affected pump performance and cause potential instability system due to hydraulic kinetic energy and/or water hammer effect induction. The reliability of the carrier flow pump is potentially affected when it is subjected to high pressure change. Consequently, the carrier flow control performance is affected by the pump performance durability.

The injection flow rate ratio showed a constant response equal to unit ($[q_{inj}/V]/30 = 1$) in steady state conditions (Fig. 60b). However, the establishment following transitory response to step input takes about 1 s in spite of the consistent overshoots (about 20 %). The establishment time practically depends on the constant time of the peristaltic pump ($\tau = 0.2$ s) and on the PID parameters setting, specifically the derivative component. The metering system reactivity is compromised between fastening the process response (boosting the derivative) and carrying out robust and stable control of hydraulic process. There is technically a limitation due to the peristaltic pump (modeling based on experimental pump data test) according to its saturation (operated flow rate within flow rate range capacity) and to its reaction time ($\tau = 0.2$ s).

Figures 60e and 60f showed the concentration Ci and Cn and their ratios [(Q*C)/V] presenting indication on the processed technical application rate [TAR (mL/m²)] for comparison with the TAR of reference equal to 0.1 mL/m². The Ci and Cn outputs showed similar trends as response to steps of 0.6, 0.9, and 1.2 m/s with variable concentration transport lags (T_{tr}) of 4.2, 2.9, and 2.3 s, respectively. The relative products of lags and speeds [V (m/s)*T_{tr} (s)] indicated linear distances of 2.52, 2.61 and 2.76 m that respectively received misapplication rate (under dose in ascendant speed steps and inversely over dose in descendant speed steps) (Fig. 60e). These linear distances resulted respectively in misapplication areas of 12.6, 13, and 13.8 m² according to the simulated boom width of 5 m (10 nozzle spacing of 0.5 m).

The [(Q*C)/V] ratio showed three responses presenting TARs around the value of 6 indicating the reference (TAR_{ref}) of 0.1 mL/m². The first and second responses relative to speed steps of 0.6 and 0.9 m/s were close to TAR_{ref} (TAR = 97 %) but the third response (TAR = 90%) relative to the speed step of 1.2 m/s showed a consistent deviation of 10 % (Fig. 60f). Such TAR error is due to non linear behavior of the pressure pump provoking a decrease in carrier flow rate as the operating pressure increased according to the governing model of hydraulic orifice (Q = K*sqrt (P)). This deviation was not practically relative to the injection flow rate response as the ratio [q_{inj}/V]/30 showed a close response to the unit (Fig. 60b).

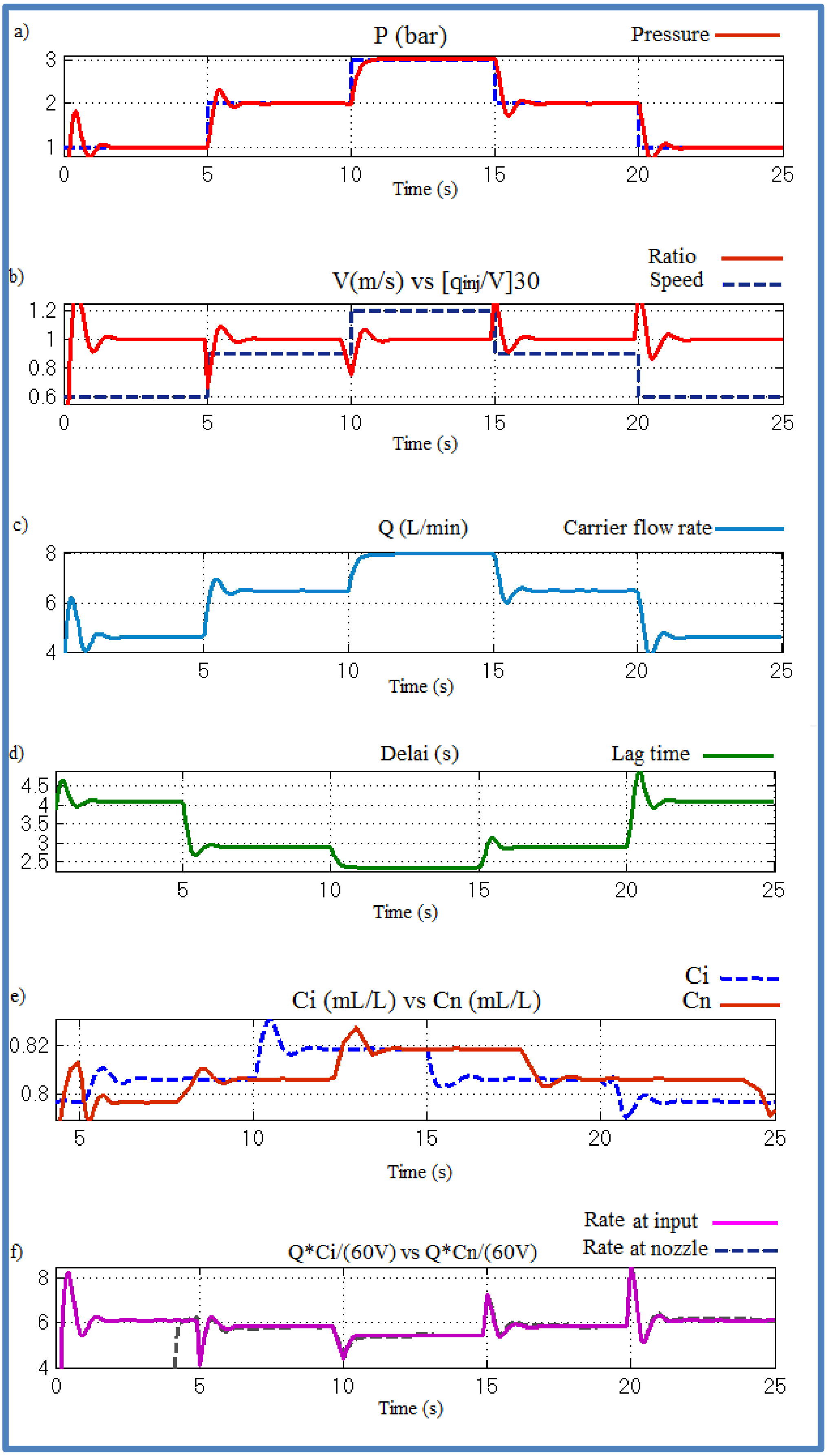


Figure 60: Total flow control response to speed step change (Simulink^{TM})

5.3.2.2 Response to sine wave speed input

TFC response to sine wave speed change is simulated using sinusoid input (frequency = 0.5 Hz, bias = 0.9 m/s; amplitude = 0.3 m/s) to induce a speed change rate of 0.3 and 0.6 m/s² between minimum and maximum of 0.6 and 1.2 m/s, respectively (Fig. 61).

The response of the PID controller to set sinusoidal varying pressure between 1 and 3 bars (Figs. 61a) showed that the processed pressure kept constantly close to the reference in the case of speed change rate of 0.3 m/s² but a slight shifting is shown in the case of increasing the rate to 0.6 m/s² (Fig. 62a). This shift is due to limitation of system dynamic that can be potentially affected by the derivative setting maintained at low level (K_p = 1, K_i = 20, K_d = 0.2). In fact, low derivative setting strategy is of importance to avoid carrier flow subsystem instability according to dynamic behavior of the pressure based hydraulic process.

Figures 61b and 62b indicated the ratio [q_{inj}/V]/30 stating the response of the metering subsystem to two sine wave (frequency = 0.5 Hz, bias = 0.9 m/s; amplitude = 0.3 m/s) speed change rates of 0.3 and 0.6 m/s², respectively. The trends presented pseudo sinusoid outputs turning around the unit with different amplitudes of 0.05 and 0.1 indicating response errors of both speed change rates, respectively.

The response of the ratio [q_{inj}/V]/30 is delayed by 0.2 s to the speed input having the rate change of 0.6 m/s² (Fig.62b). This delay is referred to dynamic limitation (constant time) of the peristaltic pump. This response is improved when the sine wave speed change is decreased to 0.3 m/s² as shown in figure 61b. Otherwise, usage of robust metering pump (low constant time, $\tau < 0.2$ s) is of importance to improve the injection system dynamic in the case of higher speed change rate ($a > 0.3$ m/s²).

Figure 61c showed the processed carrier flow rate in the case of using parallel boom design with a simple nozzle feeding and by inducing a sine wave speed rate of 0.3 m/s². The carrier flow rate sinusoid trend showed two varying behaviors of flatness in the top and inflatness in the bottom according to pressure increasing and decreasing, respectively (capacitance charging and discharging times). The relative lag transport trend (Fig. 61d) showed inversely a pseudo sinusoidal response varying between 2.5 and 5 s (simple nozzle feeding) with two varying shapes of flatness in the bottom and inflatness in the top. There is a close dependence between both triangle shaped responses as the carrier flow is the main factor defining concentration lag transport. Figure 63f illustrates the importance of using double nozzle feeding to reduce lag transport. The trend showed a varying lag between 1.4 and 2.6 s.

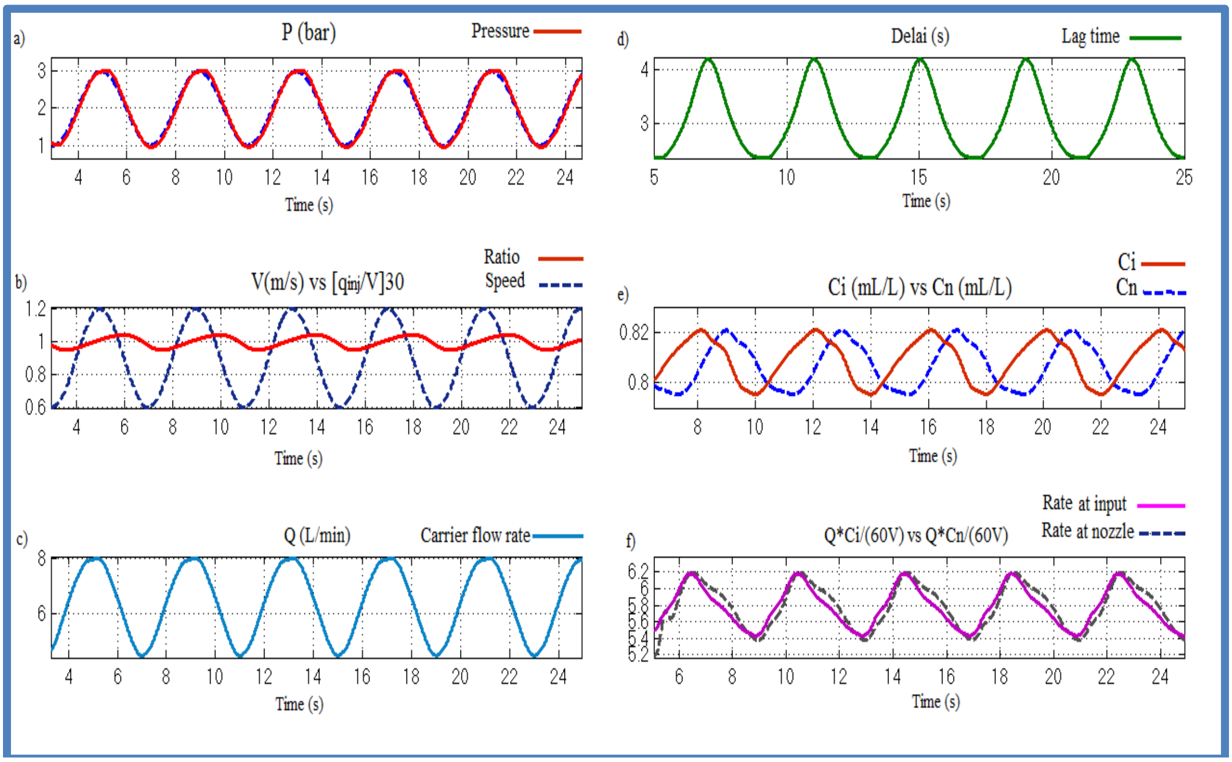


Figure 61: Total flow control response to speed sine waves change of 0.3 m/s² using parallel boom design with a simple nozzle feeding (Simulink^{TM})

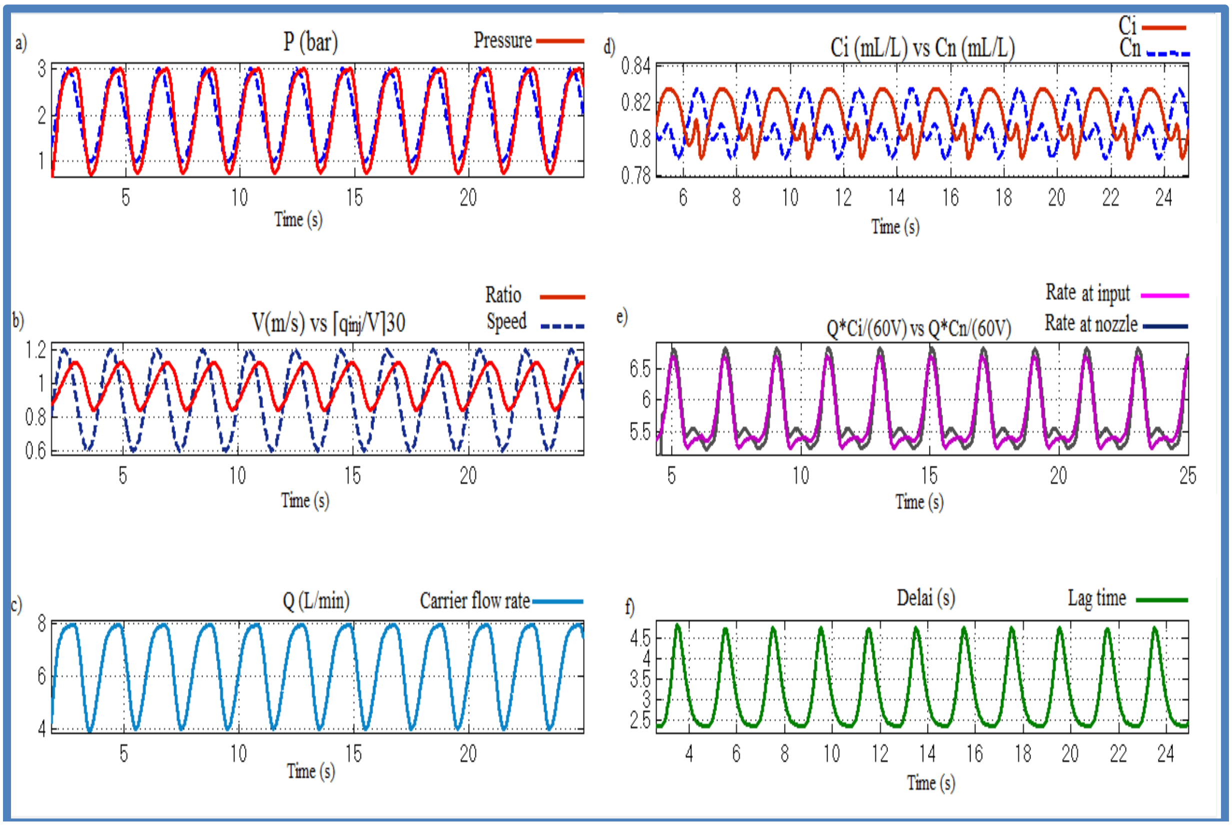


Figure 62: Total flow control response to speed sine waves change of 0.6 m/s² using parallel boom design with simple nozzle feeding (Simulink^{TM})

The simulated concentration responses (Ci and Cn) showed a slight difference by comparing simple nozzle and double nozzle feeding at the same sine wave speed change of 0.6 m/s^2 (Fig 62d versus Fig 63d).This difference is related to lag transport reduction and its contribution to reduce concentration timing error effect in the case of parallel boom design with a double nozzle feeding.

Figures 61f and 62e showed the ratios [(Q*Ci)/V] and [(Q*Cn)/V] indicating respectively TAR responses relative to sine wave speed input rates of 0.3 and 0.6 m/s^2 and to parallel boom design with a simple nozzle feeding. The first trend (case of 0.3 m/s^2) showed close responses relative to concentrations at injection and nozzle levels as the system dynamic is not affected by the speed input rate. However, the second trend (case of 0.6 m/s^2) showed a distortion between the [(Q*Ci)/V] and [(Q*Cn)/V] responses as the system dynamic is affected. Otherwise, adoption of parallel boom design with a double nozzle feeding is of importance to improve system dynamic performance as comparison shown in figures 62d, 62e, 63d and 63e in terms of responses consistence and closeness.

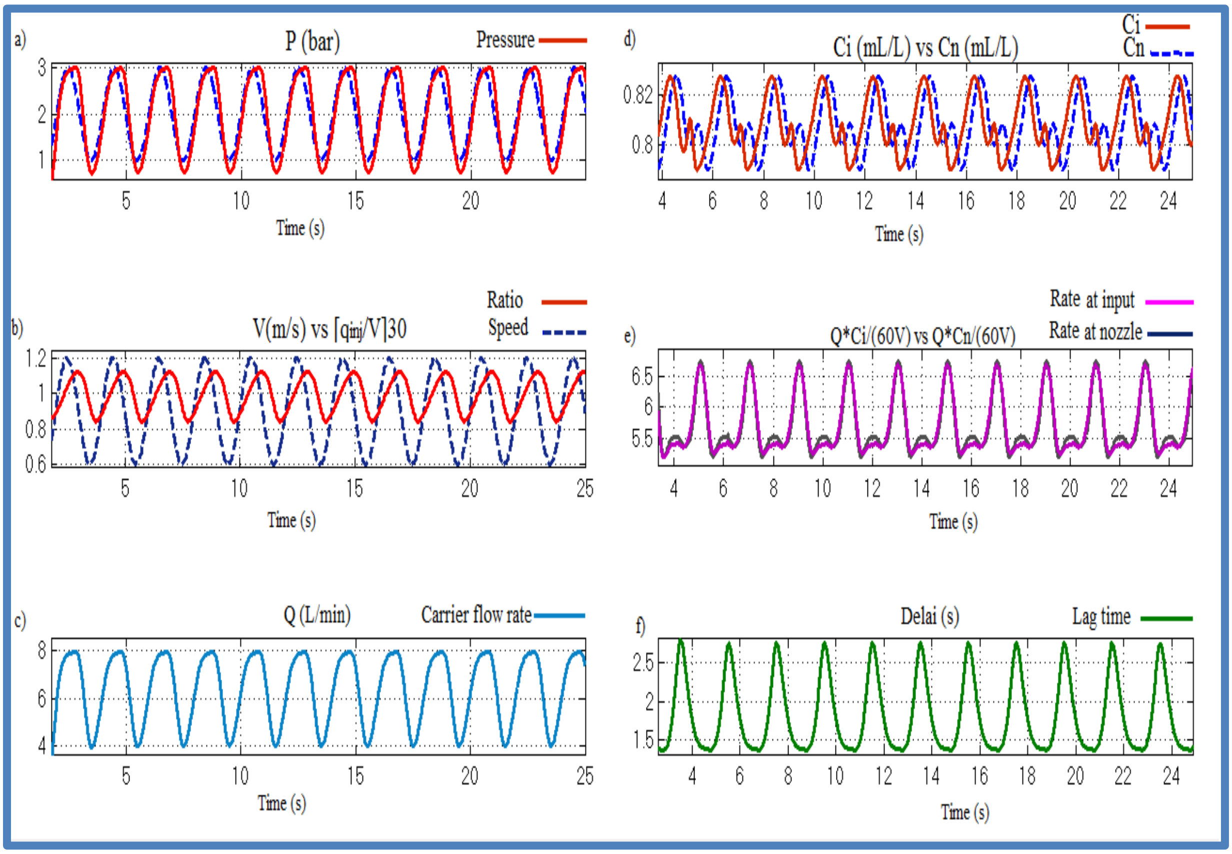


Figure 63: Total flow control response to speed sine waves change of 0.6 m/s^2 using parallel boom layout with double nozzles feeding (Simulink$^{\text{TM}}$)

5.3.2.3 Response to real speed input

Test of the TFC model using real speed input (speed profile generated in the field) showed accepted performance independently of the showed pressure saturation as the speed profile introduced is situated above 1.2 m/s. however, this value is set as reference for the maximal pump operating pressure according to limit saturation of the pump tested (Sherflo, P_{max} = 3 bar ~ 10 L/min). Response of the metering pump is kept constant according to response of the ratio [q_{inj}/V]/30 (Fig. 64b).

Figure 64c showed the delay effect on Ci and Cn. The concentration curves showed a lack of closeness due to delay effect. However, the effect is not important as the ratios Q*Ci/(60V) and Q*Cn/(60V) kept close (Figs 64f). In fact, the rate of speed change of the real profile is not high to affect the controller performance within the induced delay amount (Figs. 64c and 64f).

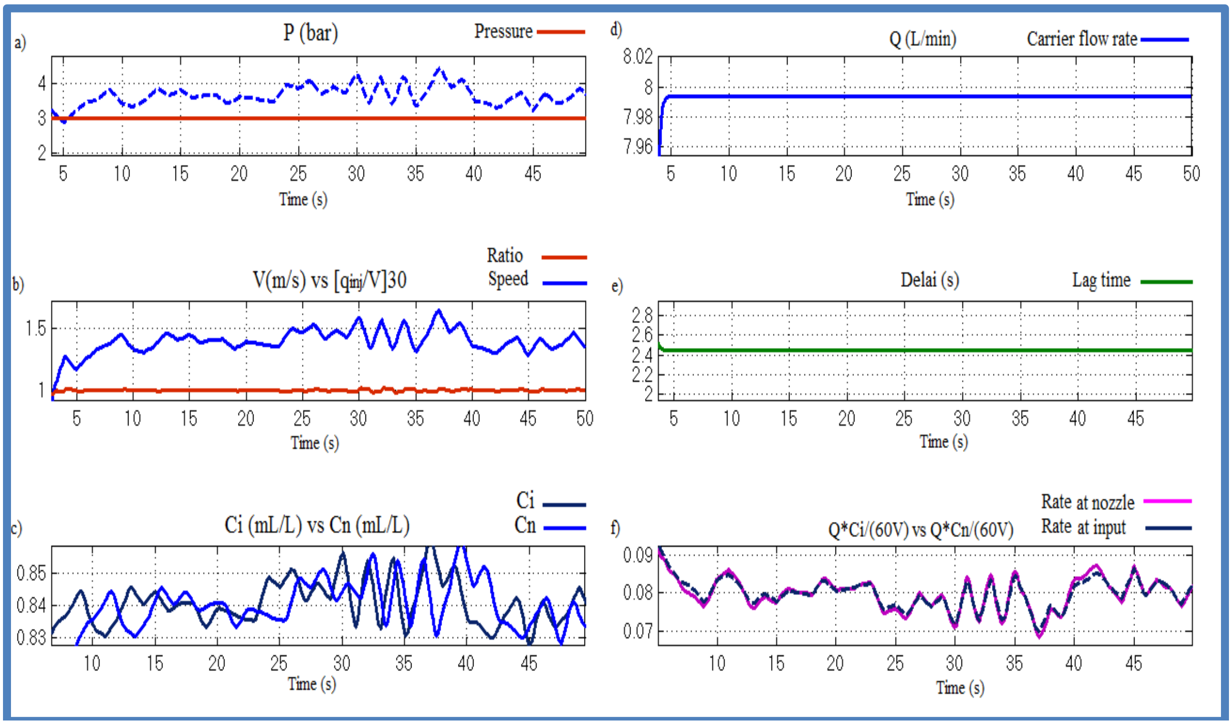


Figure 64: Total flow control response to real speed input using parallel boom layout with simple nozzles feeding (Simulink^{TM})

5.4 Process controller test in laboratory

The results presented here concern the laboratory test of the DIS process controller presented in paragraph 4.3.4. Evaluation of the process controller is based, as show before in paragraph 5.3, on monitoring input and output variables data acquired to analyze its performance according to the simulated operating speed. The indicators performance used here are similar to those presented in the introduction paragraph 5.3.

5.4.1 Evaluation of constant carrier flow control

The test of the CCFC system is mounted in laboratory to assess its response at the constant operating pressure of 2 bars. The evaluation is based on the speed inputs of step and sine wave to assess the controller dynamic performance according to processed variables such as operating pressure, injected flow rate-speed ratio, mixture concentration at the tip nozzle level and transport delay.

5.4.1.1 Response to steps input

The response of CCFC is taken using step inputs of 0.6-1.2 and 0.9–1.2 m/s. The carrier flow control kept constantly around the set pressure ($P = 2 \pm 0.02$ bars) indicating the performance of PID controller to maintain the carrier pump operating according to pressure sensor feedback (Fig. 65a).

The injected flow rate ratio $[q_{inj}/V]/30$ kept constantly equal to the unit indicating a good performance of the PID controller managing chemical injection pump (Figs. 65b and 65c).

Results showed a delay response less than 4 s by comparison step speed start and step concentration response (Fig. 65d versus Fig 65f). This delay is relative to concentration transport in parallel boom scheme with a simple nozzle feeding. It can be reduced to less than 2 s using double nozzle feeding similarly to as shown in the modeling study using Simulink^{TM}.

The resulting lag time is taken by adopting upstream chemical injection to pressure pump to improve mixing quality. It showed a comparative performance of 2.5 s found by Rockwell and Ayers (1996) using direct injection of the active ingredient into the nozzle housing (Rockwell et al., 1996). As shown in state of art, Anglund and Ayers (2003) evaluated the performance of direct injection sprayer for variable rate application and found a lag time varying from 15 to 55 s due to carrier flow rate variation (Anglund et al., 2003).

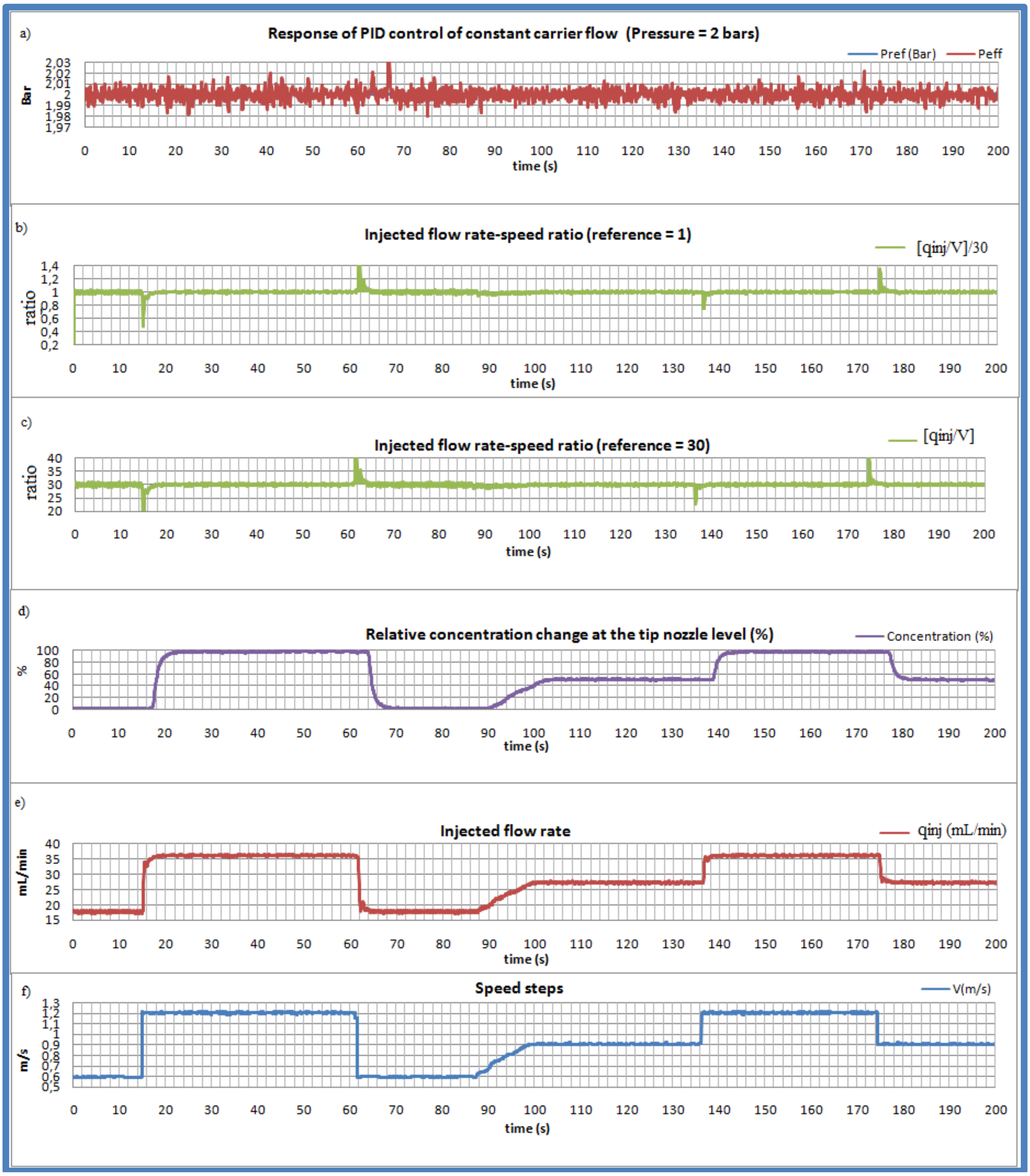


Figure 65: CCFC response to step and ramp speed inputs using parallel boom and simple nozzle feeding

5.4.1.2 Response to sine wave input

The response of CCFC to sine wave inputs inducing successive speed change rates of 0.12, 0.24, 0.36 and 0.6 m/s². The $[q_{inj}/V]/30$ trend showed a sinusoidal output around the unit with amplitude under 0.1 indicating punctual errors within 10% in the case of inducing speed change rate of 0.12 and 0.24 m/s². However, this amplitude became superior to 0.1 as the speed change rate is greater than 0.24 (Fig. 66b). Figure 67b (continuity of figure 66b) illustrated also a return of the [q_{inj}/V]/30 trend to be close to the unit as the speed rate change is lowered to 0.1 and 0.04 m/s² .There was a limit of the peristaltic pump dynamic to respond adequately for higher speed rate change cadence.

The processed relative concentration decreased from 100 to 80% (increasing application error) as the induced speed rate changes increased from 0.12 to 0.36 m/s² (Fig. 66d).

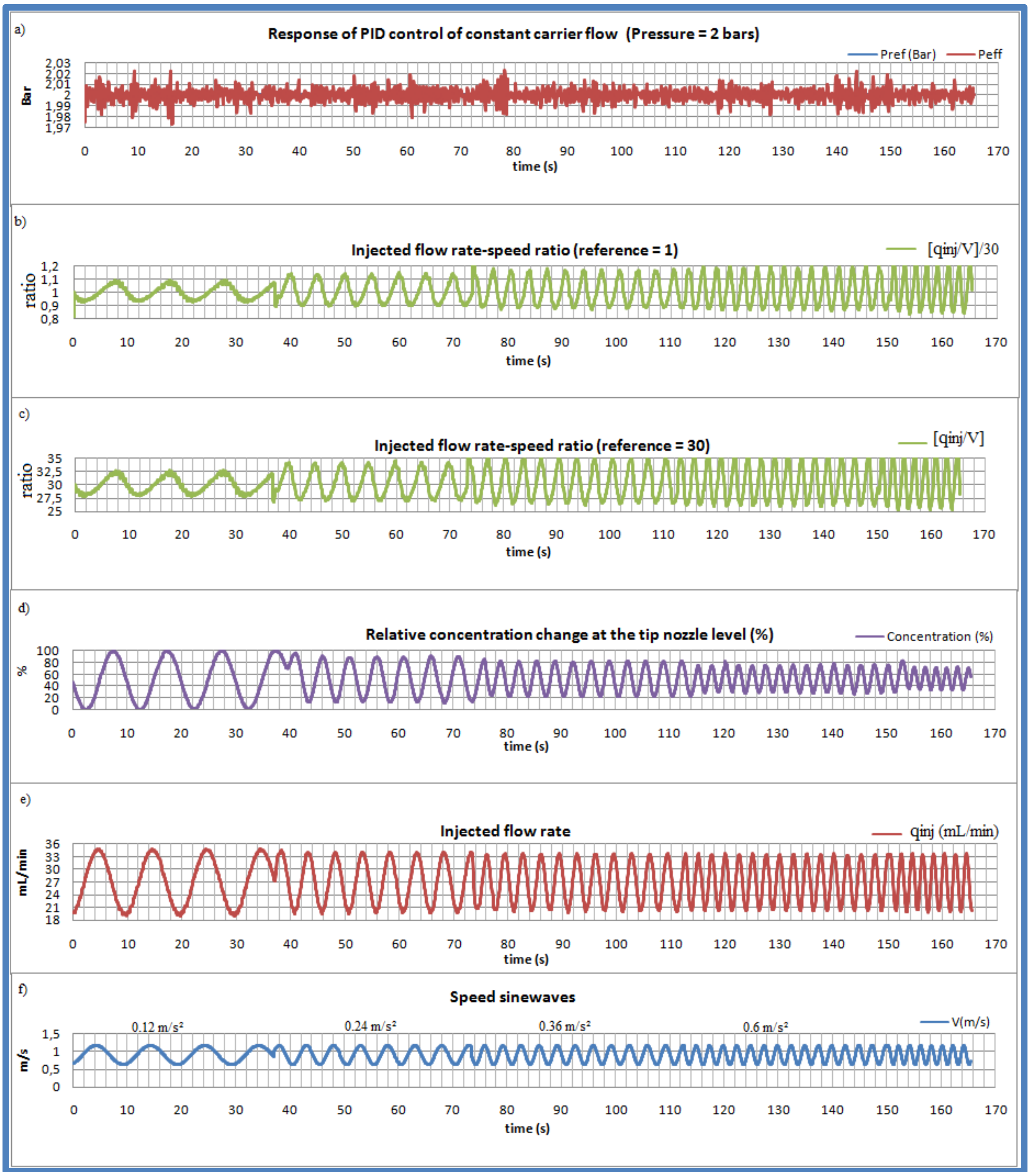


Figure 66: CCFC response to sine wave speed input using parallel boom and simple nozzle feeding

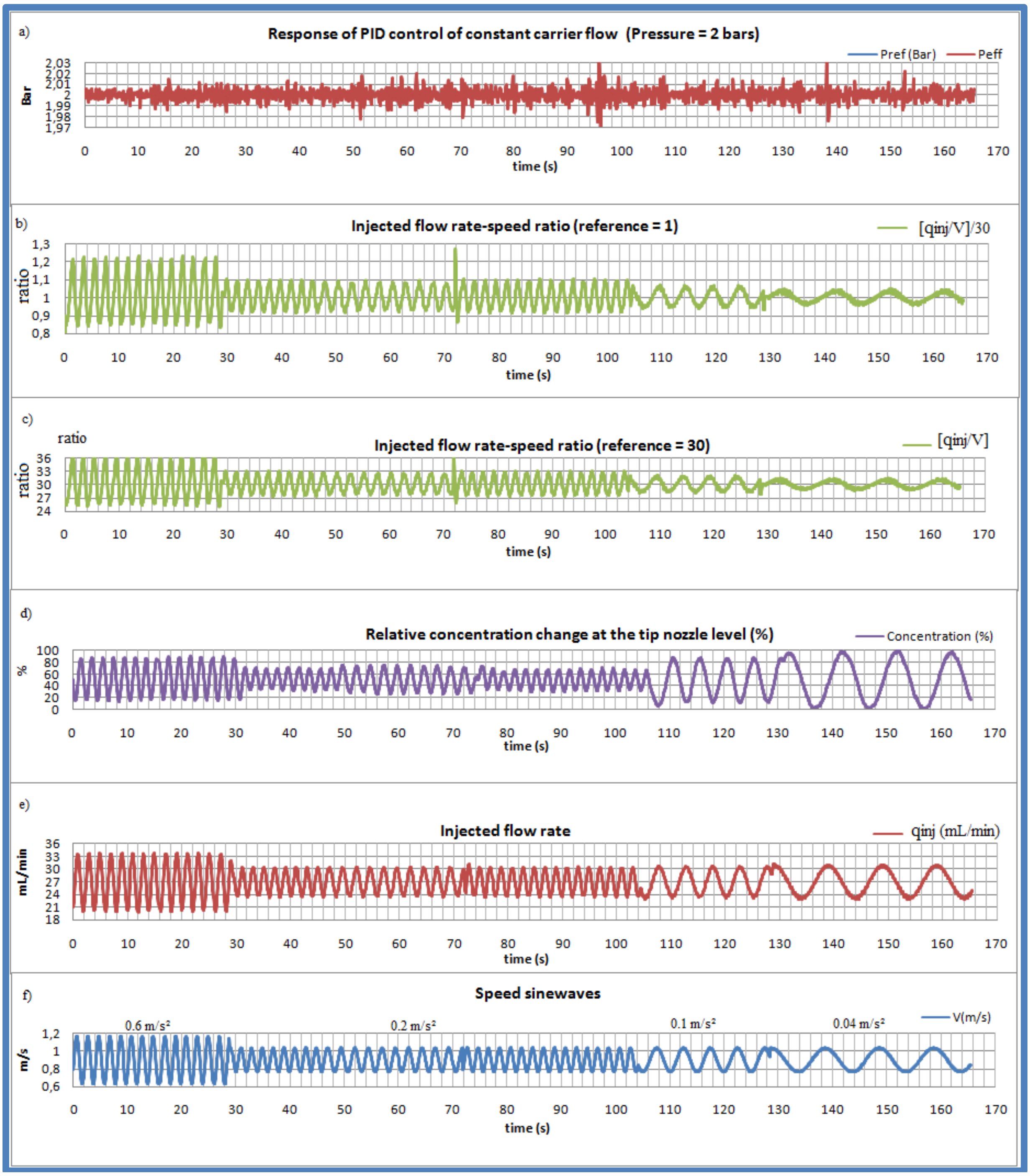


Figure 67: CCFC response to sine wave speed input using parallel boom and simple nozzle feeding (continued)

5.4.1.3 Response to sweep input

Figure 68 showed response of CCFC to sweep inputs using successive speed change rates of 0.1, 0.15 and 0.3 m/s². The [q_{inj}/V]/30 trend (Fig. 68b) indicated punctual errors less than 10% in the case of inducing speed change rate of 0.1 and 0.15 m/s². This error became superior to 10% in the case of inducing speed change rate of 0.3 m/s². The sweep trend showed also limit of the peristaltic pump dynamic to respond adequately for higher speed rate change cadence.

The concentration trend showed also similarly to the sine wave input case that application error increased as the induced speed rate changes increased from 0.1 to 0.3 m/s² (Fig. 68d).

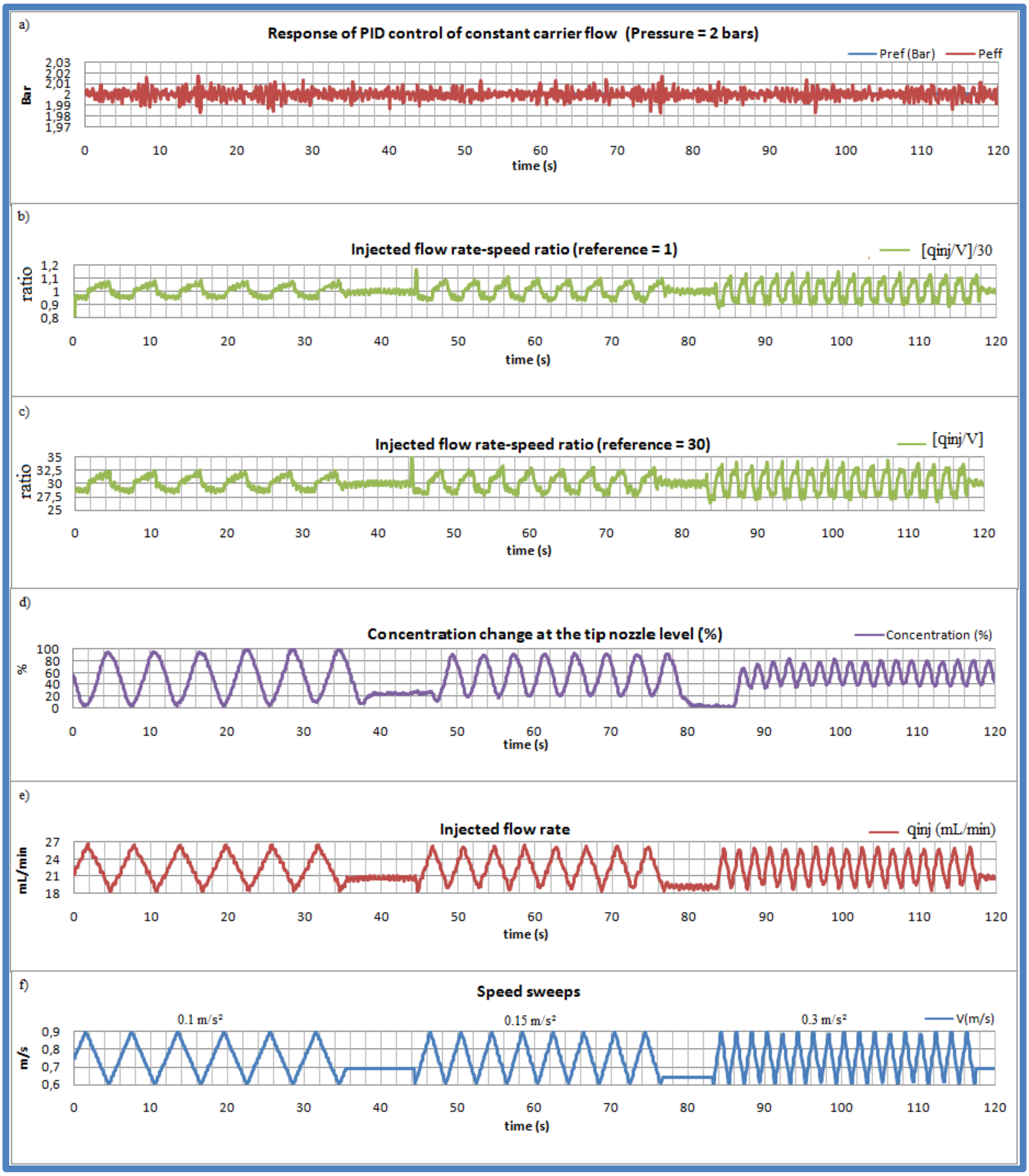


Figure 68: CCFC response to sweep speed input using parallel boom and simple nozzle feeding

5.4.2 Evaluation of total flow control

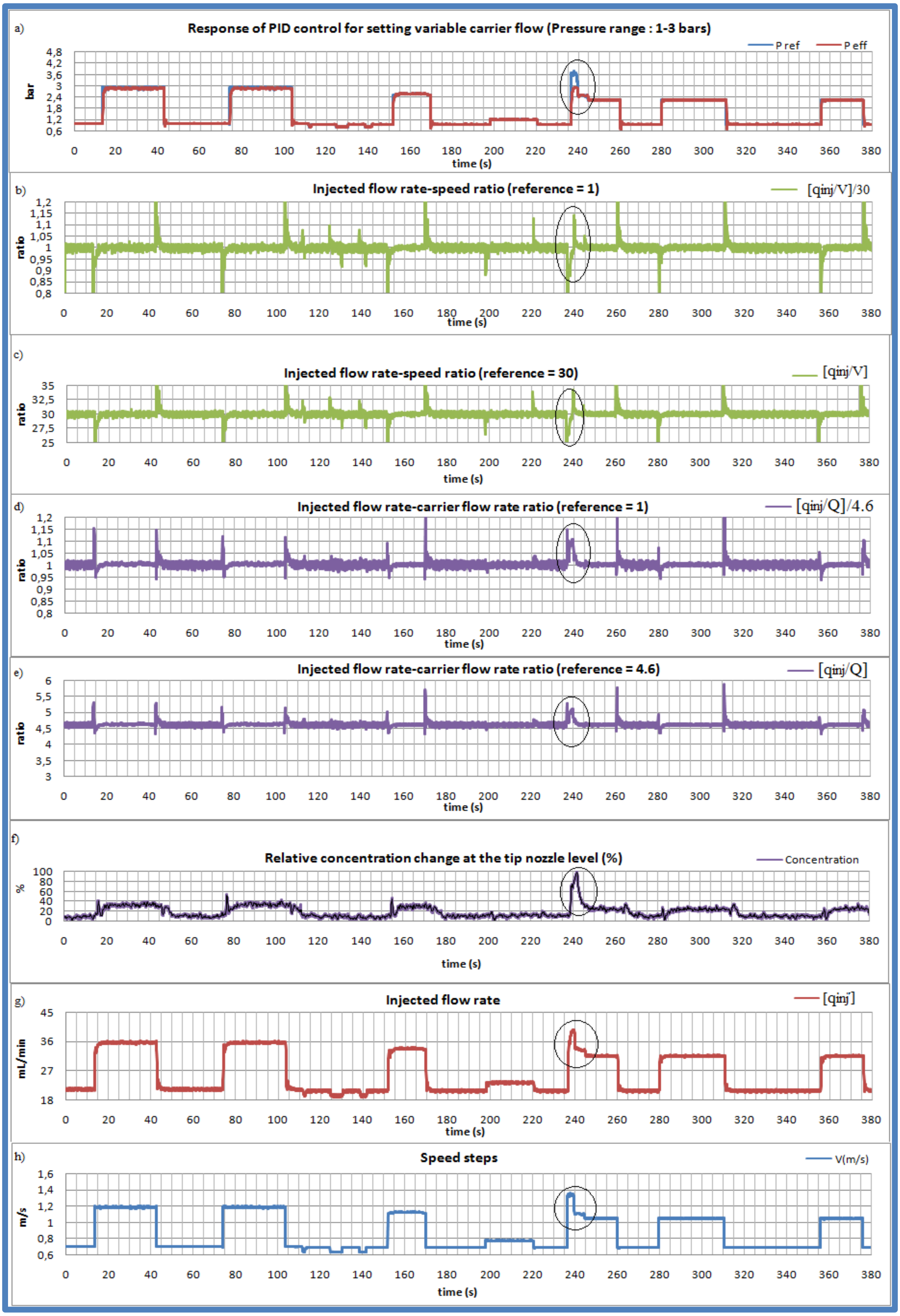
Test of the TFC system in laboratory is done on the basis of simulated speed input to assess its response within pressure range of 1-3 bars. The evaluation is based on speed inputs of step and ramp to state the controller performance dynamic according to the processed variables of pressure, injected flow rate-speed ratio, injected flow rate-carrier flow rate ratio, mixture concentration and lag transport.

5.4.2.1 Response to step speed input

The response of TFC to step inputs within 0.6-1.2 m/s showed an improved response (delay around 2.5 s) for ascendant steps (Figs. 69f and 69h). However, this response took more time in descendant steps according to pressure decreasing inducing low carrier pressure. The delay is relative to parallel boom design having simple nozzle feeding. It can be reduced to less than 2 s using double nozzle feeding. The carrier flow trend showed that its PID controller closely processed pressure to the set pressure in proportion to the induced speed change (P (bars) = 3.33 V (m/s) – 1). It indicated a satisfying PID controller setting to adequately operate carrier pump according to pressure sensor feedback (Fig. 69a).The injection ratio [q_{inj}/V]/30 kept constantly equal to the unit indicating satisfying response of PID controller managing chemical injection pump (Fig. 69b). The trend [q_{inj}/Q]/4.6 constantly kept equal to the unit indicating a constant processed concentration by the tested TFC strategy (Figs. 69d). Figure 69 showed an over speed (Fig. 69h) inducing an overshot in the processed concentration (Fig. 69f) according to saturation of the carrier pump as the pressure demand is higher than 3 bars (circled area in Fig. 69a). The PID controller can be conditioned to avoid this overshooting by controlling the maximal injection pump output with reference to the saturation limit of the carrier pump.

5.4.2.2 Response to ramp speed inputs

Ramp speed solicitations (Fig 70) are induced within the range 0.6-1.2 m/s to assess the TFC for successive speed change. This change provoked a cumulative error according to delay response and speed change rate. The injection pump maintained its dynamic performance according to its response to speed change as the trend [q_{inj}/V]/30 kept constantly close to the unit (Fig. 70b). The trend [q_{inj}/Q]/4.6 showed a close output to the unit. It indicated that the processed concentration is kept constant according to injection and carrier subsystems response without adding lag transport effect (Fig. 69d) However, the trend showing concentration at the tip nozzle level, roughly feet to speed trend according to potential application error due to continual speed rate changes (ramp solicitation) and to delay effect related to simple nozzle feeding (Fig. 70f). In fact, the control system showed limitation to correct concentration output as the ramp timely occurs in interval bigger than the lag time needed for nozzle concentration to be adjusted. The presence of ramp style change is a limitation for a simple PID to control process with transport lag (Guillermo, 2011).


a) Response of PID control for setting variable carrier flow (Pressure range : 1-3 bars)

b) Injected flow rate-speed ratio (reference = 1)

c) Injected flow rate-speed ratio (reference = 30)

d) Injected flow rate-carrier flow rate ratio (reference = 1)

e) Injected flow rate-carrier flow rate ratio (reference = 4.6)

f) Relative concentration change at the tip nozzle level (%)

g) Injected flow rate

h) Speed steps

Figure 69: TFC response to step speed input using parallel boom and simple nozzle feeding

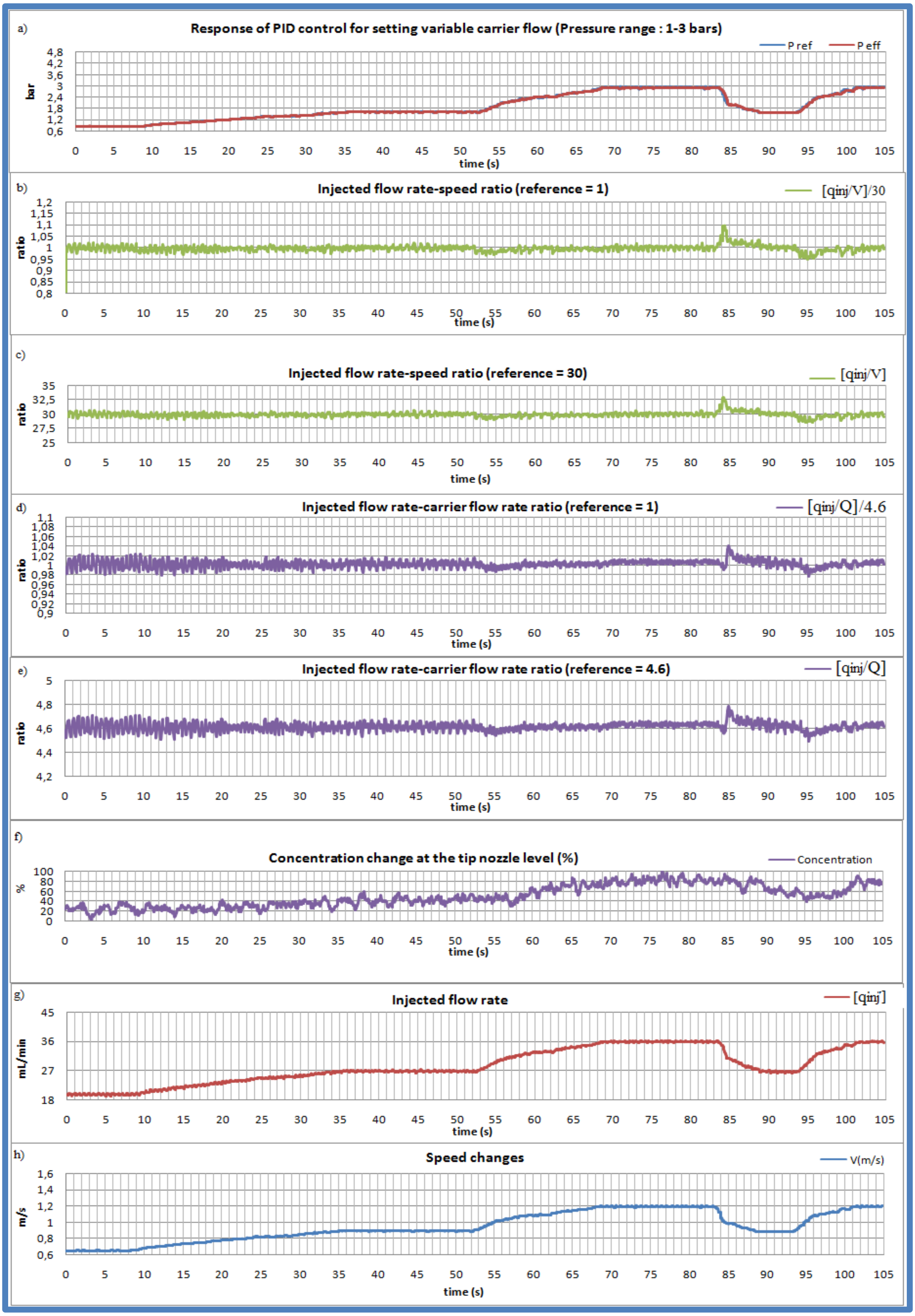


Figure 70: TFC response to ramp speed input using parallel boom and simple nozzle feeding

5.4.3 Conclusion

CCFC control is of importance for constant control performance and hydraulic system durability as constant operating pressure maintains reliability of carrier flow pump. Lag transport effect can be improved using parallel boom design and double nozzle feeding. The DIS dynamic performance using CCFC kept conditioned by the induced speed change rate according to the metering pump dynamic performance and to lag transport limitations. In this case, induction of carrier flow overshooting as an important speed change is detected can be of great concern to speed up the control of nozzle concentration and continuously maintain the recommended TAR variability within ±5% (Steward et al., 2000).

TFC response to speed inputs improved system dynamic in comparison to CCFC according to effect of increasing carrier flow rate but only for ascendant speed solicitations. Transport lag compensation due to pressure increasing can be of importance when adapted nozzles operating at the large pressure range are used to avoid potential drift due fine spray droplets. However, the performance and stability of varying pressure process kept conditioned by the rate change of operating speed and by its data processing using adapted treatment to avoid noisy and/or spiky inputs.

The experimental assessment of CCFC and TFC of DIS showed that their dynamic responses to speed inputs are mainly depending on the speed change rates. The speed profiles generated in field showed that the mean rate change of the working speed is whiting 0.2 s with punctual accelerations situated over 0.3 m/s^2 due to transitory work situations of manipulating the chassis sprayer by walker at the starting and turning points. The peristaltic pump showed a performance limitation when the speed change rate is over 0.2 m/s^2. Adoption of robust metering piston pump can be of importance to improve dynamic performance of DIS for higher accuracy in the case of high speed change rate solicitations ($a > 0.2$ m/s^2).

Chapter 6: Evaluation of the Process Controller Kit

The precedent chapter concerns the test and evaluation of the process control system in laboratory condition using PID control programmed in LabView^{TM} software. After that, the process controller is mounted in a kit electronic box (PLC controller mounted on a PIC ready card with two PWM actuators) for test in laboratory condition using step speed inputs within the range of that generated in field conditions (see material and methods). The PLC controller kit is performed as a low cost technology for an eventual use to manage TAR output of the DIS system developed for the sprayer chariot pulled by walking operator.

The assessment of the controller kit is evaluated on the basis of testing its dynamic performance according to speed input and linearity of the processed concentration output according to up and down step solicitations. According to results of the experimental testing of DIS using peristaltic metering pump (see conclusion of the precedent chapter), the test of DIS based on the PLC controller kit is done using a piston metering pump (see details in materials and methods) and a parallel boom design with double feeding using nozzle ISO 11002 (0.8 L/min ~ 3 bars). The piston pump is adopted for its better dynamic performance compared to peristaltic pump to improve DIS response in the case of high speed change rate ($a > 0.2$ m/s^2).

6.1.1 Controller response to variable speed step inputs at constant pressure

Evaluation of the PLC based process controller is carried out using CCFC strategy at the operating pressures of 2 and 3 bars. Figures 71 and 72 showed the process controller response to step speed inputs for both set pressures of 2 and 3 bars, respectively.

The pressure trends (Figs. 71 and 72) constantly kept close to the set pressure to show performance of the carrier flow control according to the PID parameters chosen by operating the PLC controller in parameters setting mode. The processing of the pressures at upstream (distributor point) and downstream (tip nozzle point) levels of parallel boom design with double nozzles feeding showed pressure drops of 9% and 11% for the pressure settings of 2 and 3 bars, respectively (Figs. 71 and 72). This pressure decrease should be taken into account by sensing the pressure at the tip nozzle level to carry out the prescript carrier flow of the mounted nozzle (0.8 L/min at 3 bars).

The processed concentration at the tip nozzle level (Fig. 71 and 72) showed a total response time of the DIS around 2 s according to the effect of processed carrier flow on decreasing it as the pressure is shifted from 2 and 3 bars. This response is relative to dead volume of the pressure pump and the boom transport lines giving to the tip nozzles. According to the experimental testing conditions of DIS with only four tip nozzles (only 50% of the processed carrier flow), the dead volume relative to the carrier pump (from injection point to distributor output) increased transport lag by about 0.5 s and can be reduced by the half to keep the total response time within 2 s as showed by the modeling study using Simulink^{TM}. In fact, the processed carrier flow rate relied on the number of operating nozzles to influence delay response in the common dead volume of DIS (relative to the carrier pump and the distributor inside volumes), but lag transport in the parallel boom line is influenced by the nozzle flow rate, house line diameter and operating pressure independently of the operating nozzles number.

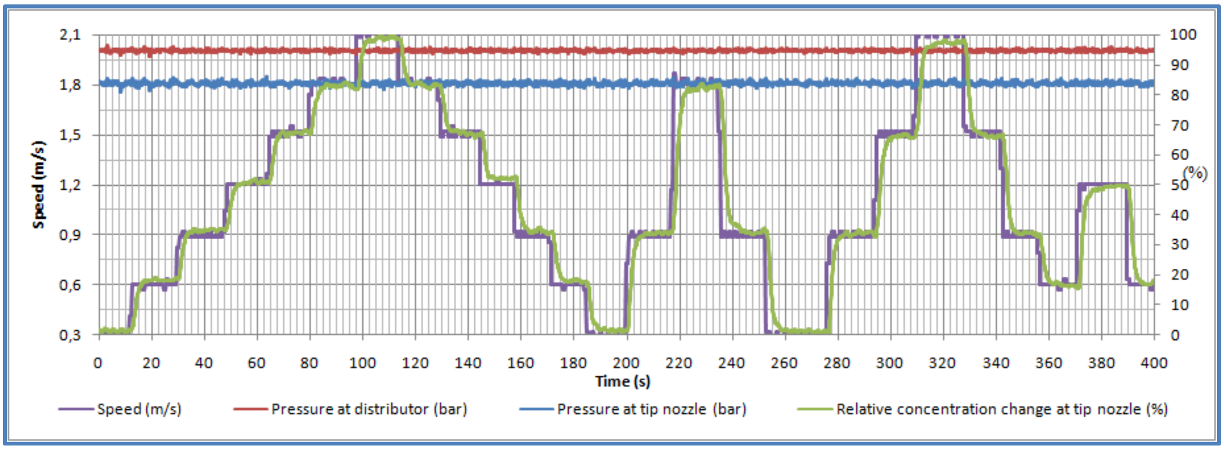


Figure 71: CCFC response of the PLC kit using speed step inputs in the range of 0.3-2.1 m/s (constant carrier flow pressure set at 2 bars)

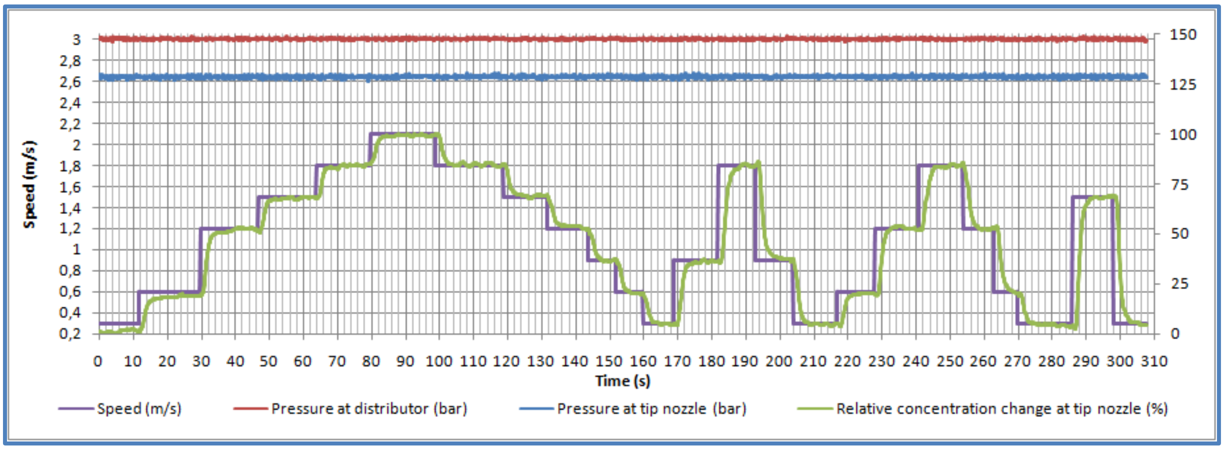


Figure 72: CCFC response of the PLC kit using speed step inputs in the range of 0.3-2.1 m/s (constant carrier flow pressure set at 3 bars)

6.1.2 Controller response to variable pressure step inputs at constant speed

Figure 73 showed the concentration process change performed by the PLC controller using up and down pressure step inputs within the range of 2-3.5 bars at constant speed of 1 m/s. The concentrations at the distributor and the tip nozzles levels are acquired to show the specific lag transport relative to parallel boom line feeding double nozzles. The delay difference between the trends of both concentrations (acquired data of concentrations at distributor and tip nozzle by two fluorescein sensors) showed that lag is around 1.5 s as shown before by the modeling study of the parallel boom design.

The variable pressure step trend (Fig. 73) created a variable concentration for a constant operating speed input of 1 m/s. It showed the PID performance of the carrier flow control to quickly establish constant operating pressure after a consistent overshoot as an indication of rightly choosing the PID parameters through the PLC setting mode.

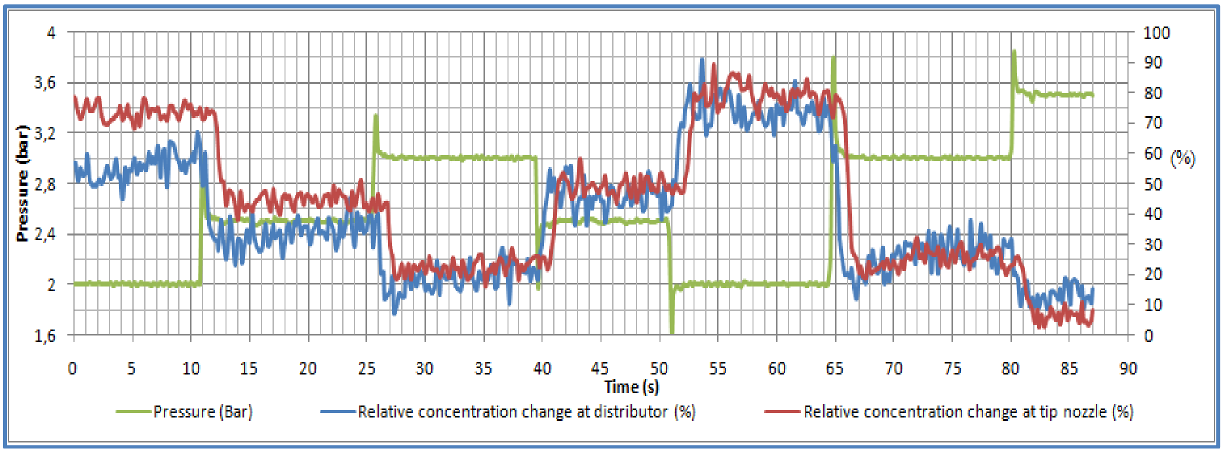


Figure 73: Concentration change processed by the PLC controller at variable pressure and constant speed of 1 m/s.

6.1.3 Linearity of the concentration process change

The linearity test is done by evaluating the closeness of concentration process change between up and down responses with reference to step inputs of speed at constant pressure and of pressure at constant speed. The input of speed at constant pressure characterized the concentration process change at constant carrier flow to indicate linearity performance of the CCFC strategy. However, the input of pressure at constant speed characterized the concentration process change at variable carrier flow to indicate linearity performance of the TFC strategy.

6.1.3.1 Concentration process linearity for speed input at constant pressure

Figure 74 showed two close concentration trends relatives to up and down speed inputs to prove the process linearity. In fact, CCFC is of importance to keeps the same hydraulic system response as the pressure is maintained constant to maintain concentration process change independent from potential hydraulic nonlinearity due to varying carrier pressure-flow rate (square model relationship).

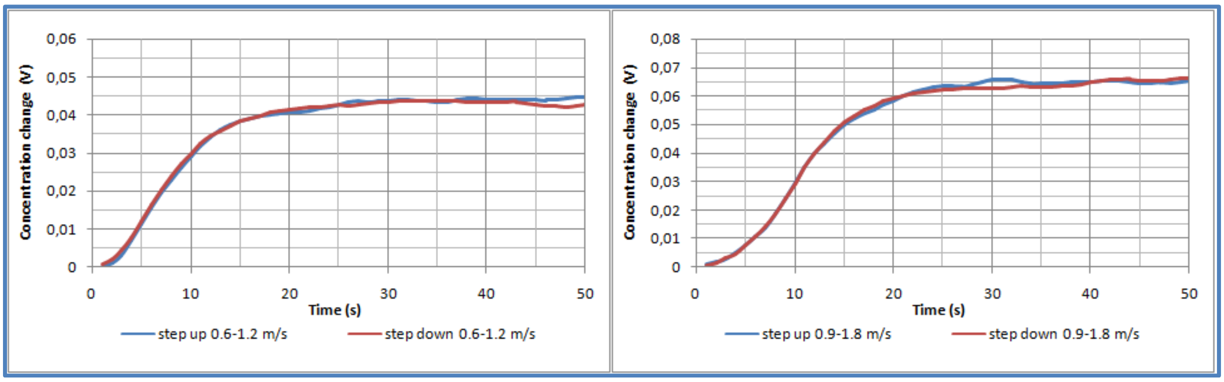


Figure 74: Linearity of the concentration change processed by the PLC kit using CCFC strategy and up-down speed steps of 0.6 and 0.9 m/s at 2 bars.

6.1.3.2 Concentration process linearity for pressure input at constant speed

The concentration change response to up and down pressure step solicitations at constant speed input is a hydraulic process based on varying the carrier flow rate (phenomena of charging and emptying hydraulic capacitance). Pressure based hydraulic process presented practically a non linear behavior as shown by the trends of up and down responses to pressure change (Fig. 75). In fact, the trends showed a lack of closeness and symmetry between the concentration responses according to up and down pressure step input of 2-3 bars. The control strategy based on varying pressure-carrier flow rate presented a potential nonlinearity that argument the choice of CCFC as strategy for the developed PLC controller design while improving lag transport task for the best system reactivity.

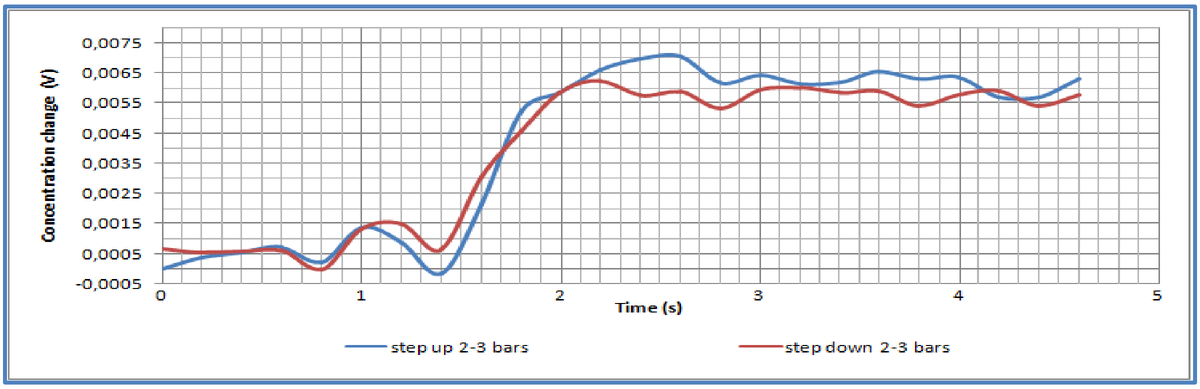


Figure 75: Linearity of the concentration change processed by the PLC controller using up-down pressure steps of 2-3 bars at 1 m/s.

6.1.3.3 Conclusion

The DIS controller implemented on the PLC Kit was evaluated on the basis of constant carrier flow and variable chemical injection. The prototype was tested for applying variable rate application using simulated step solicitations within the range of the operator working conditions in the range of 0-2 m/s. The technical results showed the feasibility of implementing a cost effective process controller design for applying variable rate chemical in small farming context. The controller can perform adequately variable chemical injection to be mounted on the sprayer chariot propelled by worker assuming that the working speed kept within the simulated range of [0 - 2 m/s.

Chapter 7: Conclusions and Recommendations

The present study aimed to develop a process controller of direct injection spraying system (DIS) that could fit to carry out precise chemical application using variable rate application based on speed sensing in the context of small scale farming. It has the specific objectives of studying the feasibility of DIS by optimizing the hydraulic system and the process control designs as the main requirements for the best system reactivity and performance.

The final design of DIS assumed to implement hydraulic system (hardware) and process controller (software) of a sprayer framework mounted on a rolling chariot propelled by walker operator. A logical approach was used to review the state of art and formulate a specification book to develop a cost effective prototype to eventually adapt DIS expertise to the context of small scale farming while giving low cost solution of variable rate technology to technical problems related to usage and inefficiency of pesticide application mainly done by portable sprayers.

The state of art gave a light on the development process of direct injection spraying technology (DIS) within the scope of precision agriculture progress. It also dealt with technical options, advantages and problems related to DIS and control engineering solutions developed for improving spraying application efficiency and safety measures for human and environment.

After that we specified requirements of the pretended DIS prototype by referring to existing art of DIS technologies and by diagnosing problems of chemical application in the context of small scale farming in developing countries. It concerned specifically the technical requirements, setting values and performance of DIS process controller according to the working conditions of intensive cropping in small farming.

The materials and methods consisted of presenting the approach aspect used for modeling the DIS prototype (splitting problematic to two main design aspects of hydraulic system and process control system) and evaluating it in laboratory conditions using simulated velocity data input. The data acquisition system was implemented for assessing the performance of DIS hydraulic and process controller performances. After that, the process controller was implemented in a cost effective electronic kit (box) to be mounted on a small sprayer framework propelled by worker.

The hydraulic modeling of DIS served for optimizing the lag transport task as main problem of system reactivity performance and concentration process change. An algorithm is implemented in VB program to assess effect of hydraulic serial boom design (diameter and number of mounted nozzles in serial scheme) on flow dynamic for compromising between lag transport, mixing ability (turbulence) and friction loss tasks that yielded lateral and longitudinal uniformities application of standard boom layout. The modeling results showed lag transport and uniformity of respectively 2 s and 96% for optimal standard boom of 6 mm diameter having ten tip nozzles (ISO11003, 1.2 L/min~3bars). To solve systematic problem of lateral missuniformity of serial boom layout (standard scheme), improved parallel boom layout (equidistant tubing lines of 4 mm diameter) was adopted for obtaining an even lag transport between nozzles. The test of parallel boom layout showed even lag transport approximating 2 s for the ten nozzles). The total response time of DIS was optimally improved to be within 2.5 s by installing electrical pumps close to boom and injecting chemical in suction side to the carrier pump assumed to perform online mixing without use of static mixer.

The development of model to predict discrete hydraulic profile using control volume element method, helped to design optimal serial boom scheme. The model accuracy kept conditioned by the miss adaptability of the Darcy-Weisbach model to compute friction losses in transitory flow regime band and by the difficulty to approach accurately the minor losses occurring actually in boom line. The comparison between serial boom layout and parallel boom layout showed how it was interesting to consider the effect of many lags in series and in parallels, coupled and uncoupled lags, on boom dynamic response. Usage of parallel boom scheme with equal feeding lines helped to improve problem of lateral boom misapplication while maintaining acceptable lag transport within 2.5 s.

The evaluation of the two process control strategies showed the technical feasibility of the direct injection technology to be mounted on adapted rolling sprayer for small scale farms. The constant carrier flow control can be relatively the simplest and affordable solution to be used in developing countries regarding to its easy implementation, and possibility of its adaptation to existing sprayers.

The PID feedback controller was modeled in Matlab^{TM} software as first order process of time constant of 0.2 s and of delay transport approximating 2 s. Two control strategies of constant carrier flow control (CCFC) and total flow control (TFC) were modeled and implemented for test in laboratory conditions. Both strategies were tested and evaluated for different solicitations of variable speed potentially adapted to field working conditions of walker operators within the range of 0-2 m/s.

The study of constant carrier flow control strategy showed a delayed response to nozzle's concentration of 2.5 s for 0.6-1.2 m/s step change. The steps generated experimentally showed the same transport lag and control system behavior. The use of total flow control strategy by varying operating pressure from 1 to 3 bar showed a decreasing transport lag (from 4 to 2.3 s) for increasing speed (from 0.6 to 1.2 m/s). The transport lag compensation due to pressure increasing can be of great concern with the use of nozzles operating at the large pressure range.

Finally, On the basis of the results of modeling validated experimentally, an affordable kit of PLC process controller and PWM modules for actuating carrier pump and metering pump was performed in compact electronic box for potential usage on small sprayer framework to be propelled by walker operator in the field crop. The controller was based on a PLC microcontroller implemented for doing constant carrier flow and variable chemical injection. The prototype was tested for applying variable rate application using simulated step solicitations within the range of the operator working conditions in the range of 0-2 m/s.

The study showed the feasibility of implementing cost effective process controller design for applying variable rate chemical in small farming context. The controller is adaptable for sprayer mounted on wheeled chariot to be propelled by worker assumed to walk at variable velocity.

For continuing this project of developing low-cost DIS for small scale farming, it is recommended to test the controller kit in the real field conditions to validate its dynamic performance for different working conditions according to use of walker energy for pulling the sprayer chariot or of propulsion energy. Otherwise, the procedures and technical options of rinsing DIS and operator’s safety needs to be implemented and adapted according to existing spraying equipments standards and to human protection and environmental requirements for applying PPP in agricultural field.

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Annexe A: VB program for yielding lag transport in serial boom design

```
Sub EXECUTE()
***************************************************************************
***************
Sheets("f1").Range("b4").FormulaR1C1 = "V_controle(i)"
Sheets("f1").Range("d4").FormulaR1C1 = "Hs(i+1)"
Sheets("f1").Range("f4").FormulaR1C1 = "Hc(i+1)"
Sheets("f1").Range("j4").FormulaR1C1 = "Qms"
Sheets("f1").Select
Rows("5:1000").Select
Selection.Delete Shift:=xlUp
Pi = 22 / 7; g = 9.81
Dim n, l, ff, k, x, e, qe, ho, hn, fo, reo, vo, u, rega, de, w As Double
Dim t(20) As Single
Dim hs(100), h(100), V(100), df(100), qms(100), f(100), re(100) As Single
n = Range("a3").Value: l = Range("b3").Value: de = Range("c3").Value
u = Range("d3").Value: k = Range("e3").Value: x = Range("f3").Value
qe = Range("g3").Value: rega = Range("h3").Value
ho = Range("i3").Value: hn = Range("j3").Value:
d = Range("b1").Value: hnf = Range("k3").Value
pas = Range("l3").Value
' ***Loop for reading diametres
****************************************************************
kk = ""
mm = 10
nc = 1
ndiam = 0
While mm <> ""
kk = Chr(65 + nc) + Trim(Str(1))
Range(kk).Select
mm = Range(kk).Value
d = mm
t(nc) = d
nc = nc + 1
Wend
dd = 0
ddi = 4
ddf = 4
ndiam = nc - 2
w = 0
'***Incrementing h(0) towards  h(n)
*************************************************************
hnf = hnf + pas
nblig = 4
rt = 0
While hn <= hnf
kk = ""
```

```
mm = 0
nc = 1
i = 4
‘***Incrementing diameters, computing of fo and relative
roughness**************************************
While nc <= ndiam
d = t(nc)
vo = (4 * n * qe) / (Pi * d ^ 2)
reo = (vo * d / u)
If reo < 3000 Then
fo = 64 / reo
Else
fo = Macro1(rega, d, reo)
Sheets("f1").Select
End If
Sheets("f1").Select
A = (Pi * d ^ 2) / 4
shs = 0
shs1 = 0
sh = 0
sh1 = 0
sdFh = 0
sv1 = 0
sv = 0
sf = 0
sf1 = 0
sqm = 0
hs(0) = ho
V(0) = vo
re(0) = reo
f(0) = fo
h(0) = ho
' ***Main loop
n***************************************************************************************
***
While i < n
dd = 1
kk = "b" + Trim(Str(5 + i))
Range(kk).FormulaR1C1 = i + 1
kk = "c" + Trim(Str(5 + i))
Range(kk).FormulaR1C1 = hs(i)
hs(i + 1) = hs(i) - ((ho - hn) / n)
kk = "d" + Trim(Str(5 + i))
Range(kk).FormulaR1C1 = hs(i + 1)
kk = "g" + Trim(Str(5 + i))
Range(kk).FormulaR1C1 = V(i)
qms(i) = k * (((hs(i) + hs(i + 1)) * 1000) / 2) ^ x
kk = "j" + Trim(Str(5 + i))
Range(kk).FormulaR1C1 = qms(i)
V(i + 1) = V(i) - ((4 * qms(i)) / (Pi * d ^ 2))
```

```
kk = "h" + Trim(Str(5 + i))
Range(kk).FormulaR1C1 = V(i + 1)
re(i) = V(i) * d / u
kk = "m" + Trim(Str(5 + i))
Range(kk).FormulaR1C1 = re(i)
re(i + 1) = V(i + 1) * d / u
kk = "n" + Trim(Str(5 + i))
Range(kk).FormulaR1C1 = re(i + 1)
***Computing f(i) for r(i) using
macro1****************************************************
ww = 0.5 * (re(i) + re(i + 1))
If ww < 3000 Then
f(i + 1) = 64 / ww
Else
f(i + 1) = Macro1(rega, d, ww)
End If
cc = ((l / n) / V(i))
kk = "o" + Trim(Str(5 + i))
Range(kk).FormulaR1C1 = cc
Sheets("f1").Select
kk = "k" + Trim(Str(5 + i))
Range(kk).FormulaR1C1 = f(i)
kk = "l" + Trim(Str(5 + i))
Range(kk).FormulaR1C1 = f(i + 1)
df(i + 1) = ((f(i) + f(i + 1)) / 2) * ((l / n + 0.06) / (2 * g * d)) * ((V(i) + V(i + 1)) / 2) ^ 2
kk = "i" + Trim(Str(5 + i))
Range(kk).FormulaR1C1 = df(i + 1)
kk = "e" + Trim(Str(5 + i))
Range(kk).FormulaR1C1 = h(i)
h(i + 1) = h(i) + ((V(i) ^ 2) / (2 * g)) - ((V(i + 1) ^ 2) / (2 * g)) - df(i + 1)
kk = "f" + Trim(Str(5 + i))
Range(kk).FormulaR1C1 = h(i + 1)
sh = sh + h(i)
sh1 = sh1 + h(i + 1)
shs = shs + hs(i)
shs1 = shs + hs(i + 1)
sdFh = sdFh + df(i + 1)
sqm = sqm + qms(i)
sv1 = sv1 + (l / n) / V(i)
sv = sv + V(i)
i = i + 1
nblig = nblig + 1
Wend
w = w + 1
hm = sh / n: vm = sv / n
eh = Abs(hs(n) - h(n)): ev = Abs(V(n - 1) - vo)
kk = "F" + Trim(Str(5 + i))
Range(kk).Select
Selection.EntireRow.Insert
a0 = Format(hn, "## ##0.00000")
```

```
a1 = Format(d, "## ##0.00000")
a2 = Format(hm, "## ##0.00000")
a3 = Format(vm, "## ##0.00000")
a4 = Format(w, "## ##0")
cc = (ho - hs(n))
dhs = cc
kk = "c" + Trim(Str(i + 5))
Range(kk).Select
ActiveCell.FormulaR1C1 = "delta Hs"
kk = "d" + Trim(Str(i + 5))
Range(kk).Select
ActiveCell.FormulaR1C1 = cc
kk = "e" + Trim(Str(i + 5))
Range(kk).Select
ActiveCell.FormulaR1C1 = "delta Hc"
cc = (ho - h(n))
dh = cc
rapcon = Abs(dhs - dh)
kk = "f" + Trim(Str(i + 5))
Range(kk).Select
ActiveCell.FormulaR1C1 = cc
kk = "a" + Trim(Str(i + 5))
Range(kk).Select
nblig = nblig + 1
ActiveCell.FormulaR1C1 = "rapconv"
kk = "b" + Trim(Str(i + 5))
Range(kk).Select
ActiveCell.FormulaR1C1 = rapcon
cc = sv1
kk = "n" + Trim(Str(i + 5))
Range(kk).Select
ActiveCell.FormulaR1C1 = "total lag"
kk = "o" + Trim(Str(i + 5))
Range(kk).Select
ActiveCell.FormulaR1C1 = cc
kk = "h" + Trim(Str(i + 5))
Range(kk).Select
ActiveCell.FormulaR1C1 = "delta Hf"
cc = sdFh
kk = "i" + Trim(Str(i + 5))
Range(kk).Select
ActiveCell.FormulaR1C1 = cc
kk = "A" + Trim(Str(5))
Range(kk).Select
ActiveCell.FormulaR1C1 = " itération" + a4
'kk = "A" + Trim(Str(6))
'Range(kk).Select
'ActiveCell.FormulaR1C1 = "Hn" + a0
'kk = "A" + Trim(Str(7))
'Range(kk).Select
```

```
'ActiveCell.FormulaR1C1 = "d" + a1
'kk = "A" + Trim(Str(8))
'Range(kk).Select
'ActiveCell.FormulaR1C1 = "Hmyn" + a2
'kk = "A" + Trim(Str(9))
' Range(kk).Select
' ActiveCell.FormulaR1C1 = "Vmyn" + a3
hn = hn + pas
If (nc < ndiam) Or (hn < hnf) Then
For ii = 1 To i
Range("a5").Select
Selection.EntireRow.Insert
Next
End If
hn = hn - pas
nc = nc + 1
ddi = 5
ddf = 5 + n
Wend
hn = hn + pas
Wend
Range("s3").Select
ActiveCell.FormulaR1C1 = nblig
If (dd = 1) And (nc - 1 = ndiam) Then
dd = 0
kk = Trim(Str(ddi)) + ":" + Trim(Str(ddf))
Rows(kk).Select
Selection.Font.Size = 12
Selection.Font.Bold = True
Selection.HorizontalAlignment = xlCenter
If rt = 0 Then
rt = 1
Selection.Font.ColorIndex = 1
Else
Selection.Font.ColorIndex = 5
rt = 0
End If
End If
End Sub
Function Macro1(ByVal ar1 As Double, ByVal ar2 As Double, ByVal Ar3 As Double) As
Double
rega = ar1
d = ar2
fmax = 0.08
fmin = 0.01
df = 0.001
e = 0.001
mmax = 100
r1 = rega / d
ree = Ar3
```

```
f = fmax
fin = False
While Not (fin)
Logn = Log((rega / (d * 3.7)) + (2.52 / (ree * Sqr(f))))
'Log10 = Log(logn) / Log(10#)
ff = (1 / Sqr(f)) + 0.869 * Logn
fin1 = False
While Not (fin1)
f1 = f - df
Logn = Log((rega / (d * 3.7)) + (2.52 / (ree * Sqr(f1))))
ff1 = (1 / Sqr(f1)) + 0.869 * Logn
k = ff * ff1
If k = 0 Then
f = f1 - df
fin1 = True
Else
If k > 0 Then
If f1 < fmin Then
fin = True
fin1 = True
Else
f = f1
ff = ff1
End If
Else
fin2 = False
j = 1
While (j <= mmax) And Not (fin2)
fp1 = Log(10) * ((rega / (d * 3.7)) + (2.52 / (ree * Sqr(f)))) * ree
fp2 = (2 * 2.52) / fp1
fp3 = -0.5 * ((f) ^ (-1.5))
fp = fp3 * (1 + fp2)
dirf = ff / fp
f = f - dirf
If Abs(dirf) <= e Then
Macro1 = f
f = fmax
fin2 = True
fin1 = True
fin = True
Else
j = j + 1
End If
Wend
End If
End If
Wend
Wend
End Function
```

****

```
End Sub
```

Annex B: C program implementing PLC process controller

```
18F4520  quartz 10 MHz  PLL*4  40Mhz
//-------------------- -----------------------------------------------------
#include <built_in.h>
#define SWITCH_PULVE_DEBUG PORTD.B0    // 2 modes: spraying/setting parameters
//#define SWITCH_RINCAGE     PORTD.B1  // Rinsing mode not implemented
#define LED_TOO_SLOW       LATD.B6     // spraying mode: low speed_LED ROUGE
#define LED_TOO_FAST       LATD.B7     // spraying mode: high speed
#define LFEED UART1_Write_Text("\n\r") // line feed of the hyperterm console
//--------------------------------------------------------------------------
const unsigned short int longueur_rec_buffer = 11; // reception serial port UART
char rxchar, i = 0, flag = 0;                        // Variable for storing the data from UART and
array counter
char rxarray[longueur_rec_buffer];             // array to store the received characters
char txtint[7];                           // transforming type int to string  UART
char txt_float[15];                       // transforming type float to string  UART
char PULVE_MODE;                          // if = 0 setting parameters/ if =1  spraying mode
char debug;                    // DEBUG MODE monitoring values of process in PULVE
MODE
char manuel=0;                   // if true and PULVE MODE: impose injection flow rate
char corr=1;                   // take into account batterie voltage for injection flow rate
metering
unsigned int compteur_de_ms=0;       // computing speed incremented by TMR0 in ms
unsigned int nombre_ms_5_pulses=0;   // memorizing ms number for 5 pulses up flancs
unsigned char cpt_40_ms=0;          // increment of 40ms by TMR0 interrupt/F=> 25 Hz
unsigned char cpt_une_sec=0;        // measuring cpt_une_sec= 25 * 40 ms incremented by
cpt_40_ms
unsigned int watchdog=0;          // watchdog for speed if total or brutal
float consigne;                           // Pressure input in bars  ( 200 after conversion of 2,00)
float vitesse=0;                          // speed in m/s
float Pression_debug=0;                   // Mean pressure measured in  parameters/debug mode
float val_process=0;                                // P measured in process (bars)
float val_process_old=0;                  // Mean with process_old factor
float Kp,Ki,Kd;
float erreur;                              // error t
float prec_erreur;                        // error t-1
float bias_drive_pc;                               // value of PWM1 drive for satisfying P consign
in open loop
float drive_pc;                            // summing of PID terms
float P_erreur=0;
float I_erreur=0;
float D_erreur=0;
float Ei=0;                               // accumulator of Intergral error
float U_batt=12.4;                                 // batterie voltage used for injection flow rate
float U_batt_old=12.4;                    // Mean with process_old factor
float q_theo,q_man;                                // Flow injection mL/min    q_theo=24 *V
float Vit_min, Vit_max;                   // consign of forward speed limit for chariot
```

```
float m,tmp;                           // coeff for PWM2 correction of correlated injection to
U_batt
float       tmp_float;                 // variables for intermediate computation
unsigned int  tmp_Uint;
float       Taux_application;                  // TAR in integer value
char msg[50];                          // constantes monitored in hyperterminal console
const char rom_01[]  = "Pulverisation v1.0  19-10-2011";
const char rom_02[]  = "Cons P : ";
const char rom_03[]  = "Kp     : ";
const char rom_04[]  = "Ki     : ";
const char rom_05[]  = "Kd     : ";
const char rom_06[]  = "Vmin   : ";
const char rom_07[]  = "Vmax   : ";
const char rom_08[]  ="SPxxx   Set consigne P   0-500";
const char rom_09[]  ="INF1    INFOS DEBUG";
const char rom_10[]  ="INF0    PAS INFOS";
const char rom_11[]  ="MANxx   Inject mode manuel q= xx mL/min";
const char rom_12[]  ="MOFF    Inject mode AUTO   q= Ta V";
const char rom_13[]  ="CORRx   0 ou 1 compensation U batterie";
const char rom_14[]  ="consigne:  ";
const char rom_15[]  ="! 0<= P consigne <=500";
const char rom_16[]  ="! 0<= MANxx <=99";
const char rom_17[]  ="Commande invalide !";
const char rom_18[]  ="MP;MKP;MKI;MKD;Vmin;Vmax  en centiemes !";
const char rom_19[]  ="MPxxxxx     Memorise cons. Press. 0-400";
const char rom_20[]  ="MKPxxxxx    Memorise Kp          0-65535";
const char rom_21[]  ="MKIxxxxx    Memorise Ki          0-65535";
const char rom_22[]  ="MKDxxxxx    Memorise Kd          0-65535";
const char rom_46[]  ="MTAxx       Memorise Ta          0-99";
const char rom_23[]  ="MV1xxx      Memorise Vmin        0-300";
const char rom_24[]  ="MV2xxx      Memorise Vmax        0-300";
const char rom_25[]  ="PW1xxx      Set PWM1 P distrib   0-255";
const char rom_26[]  ="PW2xxx      Set PWM2 q inject    0-255";
const char rom_27[]  ="PP          Affiche parametres ";
const char rom_28[]  ="! 0<= P consigne <=400";
const char rom_29[]  ="! 0<= Vmin <=300";
const char rom_30[]  ="! 0<= Vmax <=300";
const char rom_31[]  ="Pression: ";
const char rom_32[]  ="U_batt: ";
const char rom_33[]  ="! 0<= PWM consigne <=255";
const char rom_34[]  ="! 0<= Kp <=65535";
const char rom_35[]  ="! 0<= Ki <=65535";
const char rom_36[]  ="! 0<= Kd <=65535";
const char rom_37[]  ="MODE PULVE";
const char rom_38[]  ="nombre_ms_5_pulses  : ";
const char rom_39[]  ="Vitesse  : ";
const char rom_40[]  ="q theo   : ";
const char rom_41[]  ="PWM2     : ";
const char rom_42[]  ="U_batt   : ";
const char rom_43[]  =" CORR0";
```

```
const char rom_44[]  ="Press    : ";
const char rom_45[]  ="MODE PARAMETRES";
const char rom_47[]  ="Ta     : ";
const char rom_48[]  ="! 0<= Ta <=99";
//--------------------------------------------------------------------------
char * CopyConst2Ram(char * dest, const char * src){// utile pour afficher les messages sur la
console du PC
char * d ;
d = dest;
for(;*dest++ = *src++;);
return d;
}
//--------------------------------------------------------------------------
void calc_bias_drive_from_consigne(void){           // computation of the bias drive value 0-
255 from the pressure consign in bars,
if(consigne<0.4)consigne=0.0;          //
tmp_float = 54.4 * consigne ;                      // mesures in open loop/8 nozzles
bias_drive_pc = tmp_float + 49.0;
}
//--------------------------------------------------------------------------
void calc_drive_pc(void){
drive_pc = bias_drive_pc + P_erreur + I_erreur + D_erreur ;
if ( drive_pc > 255.0 )   drive_pc=255.0;      // limitations of the PWM values in 8 bits
if ( drive_pc < 1.0 )     drive_pc=0.0;
}
//--------------------------------------------------------------------------
void mesure_P_processfloat(){                          //  Mean pressure using process_old factor
char z;
float val_process_tmp=0;
tmp_Uint=0;
for(z=0;z<8;z++){                                  // 8 mesures
tmp_Uint=tmp_Uint + ADC_Read(0);
}
val_process_tmp = (float) (tmp_Uint>>3) *0.0038867; // (4,98 volts / 1024 10 bits) * 0.8  as
pressure sensor gives 5volts output  for 4 bars input
val_process= ( 0.20 * val_process_tmp ) + ( 0.80 * val_process_old ) ;     // process_old factor
val_process_old = val_process;
}
//--------------------------------------------------------------------------
void mesure_P_debug(){                            //  Mean pressure P
char z;
float val_process_tmp=0;
tmp_Uint=0;
for(z=0;z<16;z++){                                // 8 mesures
tmp_Uint=tmp_Uint + ADC_Read(0);
}
Pression_debug = (float) (tmp_Uint>>4) *0.0038867;        // (4,98 volts / 1024 10 bits) * 0.8
as pressure sensor gives 5volts  output for 4 bars input
}
//--------------------------------------------------------------------------
```

```
void calc_erreur(){                          // PID Error computation in %
erreur =  consigne - val_process ;
}
//--------------------------------------------------------------------------
void calc_D_erreur(void){                    // D_error computation in %
D_erreur =  ( erreur -prec_erreur ) * Kd ;
prec_erreur = erreur;
}
//--------------------------------------------------------------------------
void calc_I_erreur(void){                    // I_Error computation in %
I_erreur = I_erreur +  ( erreur * Ki );
}
//--------------------------------------------------------------------------
void calc_P_erreur(void){                    // P_error computation in %
P_erreur =  erreur * Kp;
}
//--------------------------------------------------------------------------
void  ajuste_injection(void){
if( vitesse >= Vit_min && vitesse <= Vit_max && manuel==0 ){// if speed value true and
automatic mode
q_theo= Taux_application * vitesse;                  // mL/min
}
else {tmp=0;q_theo=0;}                       // else do not inject
if(manuel==1){                                        // q_man is chosen by user
q_theo=q_man;
}
m= ( -.5757* U_batt ) +12.0;
tmp=  ( q_theo * m )+ 16.0;
if ( tmp >255.0) tmp=255;
if ( tmp< 30.0) tmp=0;                       // The pump stop if speed low
PWM2_Set_Duty((unsigned char) tmp);
}
//--------------------------------------------------------------------------
void setup() {                         // common initialization for both modes
UART1_Init(19200);                     // initialisation of serial port for hyperterminal
delay_ms(100);
PWM1_Init(14970);               // frequency_PWM _Hz   using tmr2
PWM2_Init(14970);
CVRCON.B7=0;                           // CVref OFF
CVRCON.B6=0;                           // disconnect RA2 from comparator
CMCON=0b00000000;                      // desactivation of comparator
ADCON0.B0=1;                           // ADC module ON
TRISA.B0=1;                            // RA0 in mode input for pressure measure
TRISA.B1=1;                            // RA1 en mode input for battery voltage measure
ADCON1=0b1100;                         // AN0 AN1 AN2 configurated as analog RA0 RA1 and
RA2, RA2 unused
INTCON = 0xE0;                          // authorize interrupt timer0
RCIE_bit=1;                             // authorize RX interrupt for UART
T08BIT_bit =0;                         // timer0  16 bits
T0CS_bit   =0;                          // timer0 incremente with CLKO
```

```
PSA_bit    =0;                          // timer0 using prescaler
T0PS0_bit  =1;                          // prescaler 001  = division by 4  CLKO 2500000Hz
T0PS1_bit  =0;
T0PS2_bit  =0;
TMR0H= 0xF6; TMR0L= 0x3B;      //  0xF63B   65535 -63035 = 2500  to increment in 2 500
000 Hz  ➔1 ms clocking
TRISD.B0=1;TRISD.B1=1;              // PortD en mode input for reading user commutator
switching between PARAMATRES, PULVE and RINCAGE modes
TRISD.B6=0;TRISD.B7=0;              // PortD en mode output for 2 LED of speed limitations
LATD.B6=0;LATD.B7=0;                 // zero of leds
TRISC.B0=1;                             //  RC0 en input for incrementation of comptor1
LFEED;UART1_Write_Text(CopyConst2Ram(msg,rom_01));LFEED;
PULVE_MODE= SWITCH_PULVE_DEBUG ;     // read switch state
PWM1_Start();                                          // start PWM1 MODULE of controller
PWM2_Start();
} // end setup
//---------------------------------------------------------------------------
void setup_mode_PULVE(){                      // read memorized parameters in EEPROM et
transfer of globales variables
debug=0;
LFEED;
tmp_Uint = EEPROM_Read(0x00);
tmp_Uint = tmp_Uint << 8;
tmp_Uint = tmp_Uint | EEPROM_Read(0x01);
consigne = (float) tmp_Uint;
consigne = consigne / 100.0;
FloatToStr(consigne,txt_float);
UART1_Write_Text(CopyConst2Ram(msg,rom_02));UART1_Write_Text(txt_float);LFEED
;
tmp_Uint = EEPROM_Read(0x02);
tmp_Uint = tmp_Uint << 8;
tmp_Uint = tmp_Uint | EEPROM_Read(0x03);
Kp = (float) tmp_Uint;
Kp = Kp / 100.0;
FloatToStr(Kp,txt_float);
UART1_Write_Text(CopyConst2Ram(msg,rom_03));UART1_Write_Text(txt_float);LFEED
;
tmp_Uint = EEPROM_Read(0x04);
tmp_Uint = tmp_Uint << 8;
tmp_Uint = tmp_Uint | EEPROM_Read(0x05);
Ki = (float) tmp_Uint;
Ki = Ki / 100.0;
FloatToStr(Ki,txt_float);
UART1_Write_Text(CopyConst2Ram(msg,rom_04));UART1_Write_Text(txt_float);LFEED
;
tmp_Uint = EEPROM_Read(0x06);
tmp_Uint = tmp_Uint << 8;
tmp_Uint = tmp_Uint | EEPROM_Read(0x07);
Kd = (float) tmp_Uint;
Kd = Kd / 100.0;
```

```
FloatToStr(Kd,txt_float);
UART1_Write_Text(CopyConst2Ram(msg,rom_05));UART1_Write_Text(txt_float);LFEED
;
tmp_Uint = EEPROM_Read(0x08);
tmp_Uint = tmp_Uint << 8;
tmp_Uint = tmp_Uint | EEPROM_Read(0x09);
Vit_min = (float) tmp_Uint;
Vit_min = Vit_min / 100.0;
FloatToStr(Vit_min,txt_float);
UART1_Write_Text(CopyConst2Ram(msg,rom_06));UART1_Write_Text(txt_float);LFEED
;
tmp_Uint = EEPROM_Read(0x0A);
tmp_Uint = tmp_Uint << 8;
tmp_Uint = tmp_Uint | EEPROM_Read(0x0B);
Vit_max = (float) tmp_Uint;
Vit_max = Vit_max / 100.0;
FloatToStr(Vit_max,txt_float);
UART1_Write_Text(CopyConst2Ram(msg,rom_07));UART1_Write_Text(txt_float);LFEED
;
tmp_Uint = EEPROM_Read(0x0C);
tmp_Uint = tmp_Uint << 8;
tmp_Uint = tmp_Uint | EEPROM_Read(0x0D);
Taux_application = (float) tmp_Uint;
FloatToStr(Taux_application,txt_float);
UART1_Write_Text(CopyConst2Ram(msg,rom_47));UART1_Write_Text(txt_float);LFEED
;
}
//--------------------------------------------------------------------------
void EEstore_consigne_P(unsigned int P){   // adresses 0x00 et 0x01
  EEPROM_Write(0x00,Hi(P));
  EEPROM_Write(0x01,Lo(P));
}
//--------------------------------------------------------------------------
void EEstore_Kp(unsigned int Kp){         // adresses 0x02 et 0x03
  EEPROM_Write(0x02,Hi(Kp));
  EEPROM_Write(0x03,Lo(Kp));
}
//--------------------------------------------------------------------------
void EEstore_Ki(unsigned int Ki){         // adresses 0x04 et 0x05
  EEPROM_Write(0x04,Hi(Ki));
  EEPROM_Write(0x05,Lo(Ki));
}
//--------------------------------------------------------------------------
void EEstore_Kd(unsigned int Kd){         // adresses 0x06 et 0x07
  EEPROM_Write(0x06,Hi(Kd));
  EEPROM_Write(0x07,Lo(Kd));
}
//--------------------------------------------------------------------------
void EEstore_Vmin(unsigned int Vmin){      // adresses 0x08 et 0x09
  EEPROM_Write(0x08,Hi(Vmin));
```

```
  EEPROM_Write(0x09,Lo(Vmin));
}
//---------------------------------------------------------------------------
void EEstore_Vmax(unsigned int Vmax){      // adresses 0x0A et 0x0B
  EEPROM_Write(0xA,Hi(Vmax));
  EEPROM_Write(0xB,Lo(Vmax));
}
//---------------------------------------------------------------------------
void EEstore_Ta(unsigned int Ta){         // adresses 0x0C et 0x0D
  EEPROM_Write(0xC,Hi(Ta));
  EEPROM_Write(0xD,Lo(Ta));
}
//---------------------------------------------------------------------------
void interrupt() {
   if (TMR0IF_bit) {                     // overflow TIMER0  for each ms
      TMR0IF_bit = 0;                     // clear TMR0IF
      cpt_40_ms++;
      compteur_de_ms++;                  // ms chrono for speed computing
      TMR0H  = 0xF6; TMR0L  = 0x3B;  //  TIMER0  charged with 63035 =  1 ms
            //cpt_mesure_une_sec++;               //  increment 25 time => one seconde = time basis
for monitoring of debug commandes
   }// end if TMROIF_bit
   if (TMR1IF_bit) {                     // overflow TIMER1  computing speed sensor pulses
      TMR1IF_bit = 0;                     // clear TMR1IF
      TMR1H=0xFF;
      TMR1L=0xFB;                        // initial timer value 0xFFF9= 65536 - 5   => computing
5 pulses before interrupt
      nombre_ms_5_pulses=compteur_de_ms;
      compteur_de_ms=0;
              watchdog=0;                 // if wheel is turning , computer going on then reset
    }// end if TMR1IF_bit
       if (PIR1.RCIF) {                   // reception of user commands
      rxchar = UART1_Read();
      rxarray[i] = rxchar;
      i++;
      if (i >= longueur_rec_buffer) {     // overflow buffer reception
          rxchar = 0x0D;                              // force terminating character CR
      }                                  // end if check overflow buffer
      if (rxchar == 0x0D) {            // looking for a terminating character CR
         rxarray[i-1] = 0x00;          // terminate string  -1 for excluding CR
         flag = 1;                     // signal of ready chain
      } // end if (rxchar == 0x0D)
   } // end  if (PIR1.RCIF)
 }// end if interrupt
//---------------------------------------------------------------------------
void Mesure_Ubatt(void){               // mean of 8 values
  char z;
  float U_batt_tmp;
  tmp_Uint=0;
  for(z=0;z<8;z++){                    // 8 mesures
```

```
    tmp_Uint=tmp_Uint + ADC_Read(1);
   }
  U_batt_tmp = (float) (tmp_Uint>>3)  *0.015650 ;   // 4,98 volts ref  / 1024 10 bits
  U_batt_tmp = U_batt_tmp + 0.0831;                          // Attention to voltage divisor in
entry
  U_batt=  ( 0.20 * U_batt_tmp ) + ( 0.80 * U_batt_old ) ;
  U_batt_old = U_batt;
}
//----------------------------------------------------------------------------
void Vitesse_correcte(void){                    //Management of LEDs  execution, one by sec
  if( vitesse>Vit_min && vitesse<Vit_max ) {LED_TOO_SLOW=0;LED_TOO_FAST=0;}
  if (vitesse<Vit_min) {LED_TOO_SLOW=1;LED_TOO_FAST=0;}
  if (vitesse>Vit_max) {LED_TOO_FAST=1;LED_TOO_SLOW=0;}
}
//----------------------------------------------------------------------------
void traitement_commandes_PULVE() {          // analyze rxarray and execute
 unsigned short int comm_traitee=1;                      // if no IF validated , =1 ==>non treated
case
 unsigned int int_intermediaire;
   if( rxarray[0]==0x3F && rxarray[1]==0x3F ){ // ??  =>UART summarizes possible
commands
      LFEED;
      UART1_Write_Text(CopyConst2Ram(msg,rom_08));LFEED;
      UART1_Write_Text(CopyConst2Ram(msg,rom_09));LFEED;
      UART1_Write_Text(CopyConst2Ram(msg,rom_10));LFEED;
      UART1_Write_Text(CopyConst2Ram(msg,rom_11));LFEED;
      UART1_Write_Text(CopyConst2Ram(msg,rom_12));LFEED;
      UART1_Write_Text(CopyConst2Ram(msg,rom_13));LFEED;LFEED;
      comm_traitee=0;
   }// end IF ?
if(  rxarray[0]==0x53 && rxarray[1]==0x50 ){                // P  modify consign_P  without
saving of step up/down
      rxarray[0]= 0x30;
      rxarray[1]= 0x30;
      int_intermediaire=atoi(rxarray);
      if ( int_intermediaire>=0 && int_intermediaire<=500 ){         // acceptable ?
           consigne=(float) int_intermediaire ;
           consigne=consigne/100.0;
           calc_bias_drive_from_consigne();
           FloatToStr(consigne,
txt_float);UART1_Write_Text(CopyConst2Ram(msg,rom_14));UART1_Write_Text(txt_floa
t);LFEED;
      }// end if condition   0-65535
      else {                                         //erroneous value!
           UART1_Write_Text(CopyConst2Ram(msg,rom_15));LFEED;
      }// fin else
      comm_traitee=0;
   }// end IF P
   if( rxarray[0]==0x4D && rxarray[1]==0x41 && rxarray[2]==0x4E ){  // MANxx
       rxarray[0]= 0x30;rxarray[1]= 0x30;
```

```
        rxarray[2]= 0x30;
        int_intermediaire=atoi(rxarray);                    // 00123 becomes int 123
        if ( int_intermediaire>=0 && int_intermediaire<=99 ){          // acceptable ?
            q_man =(float)int_intermediaire;
            manuel=1;
        }// end if condition   0-255
        else { //valeur erronée !
          UART1_Write_Text(CopyConst2Ram(msg,rom_16));LFEED;
        }// fin else
      comm_traitee=0;
    }// end IF MANxx
 if(  rxarray[0]==0x49 && rxarray[1]==0x4E && rxarray[2]==0x46 && rxarray[3]==0x31){
//INF1
      debug=1;
      comm_traitee=0;
     }// end IF INF1
if(  rxarray[0]==0x49 && rxarray[1]==0x4E && rxarray[2]==0x46 && rxarray[3]==0x30){
//INF0
      debug=0;
      comm_traitee=0;
     }// end IF INF0
if(  rxarray[0]==0x4D && rxarray[1]==0x4F && rxarray[2]==0x46 && rxarray[3]==0x46){
//MOFF
      manuel=0;
      comm_traitee=0;
    }// end IF MOFF
if(  rxarray[0]==0x43 && rxarray[1]==0x4F && rxarray[2]==0x52 && rxarray[3]==0x52
&& rxarray[4]==0x30)      {                             // CORR0
      corr=0;
      comm_traitee=0;
    }// end IF CORR0
if(  rxarray[0]==0x43 && rxarray[1]==0x4F && rxarray[2]==0x52 && rxarray[3]==0x52
&& rxarray[4]==0x31)      {                     // CORR1
      corr=1;
      comm_traitee=0;
    }// end IF CORR1
    if (comm_traitee==1) {                  // no case listed on monitor =>ERREUR
    UART1_Write_Text(CopyConst2Ram(msg,rom_17));LFEED;
    }// end if comm_traitee
} // fin traitement_commande_PULVE()
//-----------------------------------------------------------------------------
void traitement_commandes_PARAMETRES() {       // analyze rxarray and execute
    unsigned short int comm_traitee=1;          // si aucun IF n'a été validé, =1 ==>cas non
traitable
    unsigned int int_intermediaire;
    if( rxarray[0]==0x3F && rxarray[1]==0x3F ){ // ??  =>UART summarize possible
commands
       LFEED;
       UART1_Write_Text(CopyConst2Ram(msg,rom_18));LFEED;
       UART1_Write_Text(CopyConst2Ram(msg,rom_19));LFEED;
```

```
    UART1_Write_Text(CopyConst2Ram(msg,rom_20));LFEED;
    UART1_Write_Text(CopyConst2Ram(msg,rom_21));LFEED;
    UART1_Write_Text(CopyConst2Ram(msg,rom_22));LFEED;
    UART1_Write_Text(CopyConst2Ram(msg,rom_23));LFEED;
    UART1_Write_Text(CopyConst2Ram(msg,rom_24));LFEED;
    UART1_Write_Text(CopyConst2Ram(msg,rom_46));LFEED;
          UART1_Write_Text(CopyConst2Ram(msg,rom_25));LFEED;
    UART1_Write_Text(CopyConst2Ram(msg,rom_26));LFEED;
    UART1_Write_Text(CopyConst2Ram(msg,rom_27));LFEED;
    LFEED;
    comm_traitee=0;
  }// end IF ?

  if( rxarray[0]==0x4D && rxarray[1]==0x50 ){ // MP  EEstore_consigne_P
    rxarray[0]= 0x30;                        // char 0 pour remplacer char M et P
    rxarray[1]= 0x30;                        // MP12345  devient 0012345
    int_intermediaire=atoi(rxarray);                  // 00123 devient int 123
    if ( int_intermediaire>=0 && int_intermediaire<=400 ){  // acceptable ?
        EEstore_consigne_P( int_intermediaire );
    }// end if condition   0-400
    else { //valeur erronée !
        UART1_Write_Text(CopyConst2Ram(msg,rom_28));LFEED;
    }// fin else
    comm_traitee=0;
  }// end IF MP
  if( rxarray[0]==0x4D && rxarray[1]==0x56 && rxarray[2]==0x31){ // MV1
EEstore_Vmin
    rxarray[0]= 0x30;              // char 0 pour remplacer char M et V et 1
    rxarray[1]= 0x30; rxarray[2]= 0x30;
    int_intermediaire=atoi(rxarray);     // 00123 devient int 123
    if ( int_intermediaire>=0 && int_intermediaire<=300 ){  // acceptable ?
        EEstore_Vmin( int_intermediaire );
    }// end if condition   0-300
    else { //valeur erronée !
        UART1_Write_Text(CopyConst2Ram(msg,rom_29));LFEED;
    }// fin else
    comm_traitee=0;
   }// end IF MV1
  if( rxarray[0]==0x4D && rxarray[1]==0x56 && rxarray[2]==0x32){ // MV2
EEstore_Vmax
    rxarray[0]= 0x30;                             // char 0 for remplacing char M,V and 2
    rxarray[1]= 0x30; rxarray[2]= 0x30;
    int_intermediaire=atoi(rxarray);                          // 00123 devient int 123
    if ( int_intermediaire>=0 && int_intermediaire<=300 ){  // acceptable ?
        EEstore_Vmax( int_intermediaire );
    }// end if condition   0-300
    else {                                                    //erroneous value !
        UART1_Write_Text(CopyConst2Ram(msg,rom_30));LFEED;
    }// fin else
    comm_traitee=0;
```

```
   }// end IF MV2
  if( rxarray[0]==0x50 && rxarray[1]==0x50 ){ // PP  affiche  parametres eeprom
     LFEED;
     int_intermediaire = EEPROM_Read(0x00);
     int_intermediaire=int_intermediaire<<8;
     int_intermediaire=int_intermediaire | EEPROM_Read(0x01);
     IntToStr(int_intermediaire, txtint);

UART1_Write_Text(CopyConst2Ram(msg,rom_02));UART1_Write_Text(rtrim(txtint));LFE
ED;
     int_intermediaire = EEPROM_Read(0x02);
     int_intermediaire=int_intermediaire<<8;
     int_intermediaire=int_intermediaire | EEPROM_Read(0x03);
     IntToStr(int_intermediaire, txtint);

UART1_Write_Text(CopyConst2Ram(msg,rom_03));UART1_Write_Text(rtrim(txtint));LFE
ED;
     int_intermediaire = EEPROM_Read(0x04);
     int_intermediaire=int_intermediaire<<8;
     int_intermediaire=int_intermediaire | EEPROM_Read(0x05);
     IntToStr(int_intermediaire, txtint);

UART1_Write_Text(CopyConst2Ram(msg,rom_04));UART1_Write_Text(rtrim(txtint));LFE
ED;
     int_intermediaire = EEPROM_Read(0x06);
     int_intermediaire=int_intermediaire<<8;
     int_intermediaire=int_intermediaire | EEPROM_Read(0x07);
     IntToStr(int_intermediaire, txtint);

UART1_Write_Text(CopyConst2Ram(msg,rom_05));UART1_Write_Text(rtrim(txtint));LFE
ED;
     int_intermediaire = EEPROM_Read(0x08);
     int_intermediaire=int_intermediaire<<8;
     int_intermediaire=int_intermediaire | EEPROM_Read(0x09);
     IntToStr(int_intermediaire, txtint);

UART1_Write_Text(CopyConst2Ram(msg,rom_06));UART1_Write_Text(rtrim(txtint));LFE
ED;
     int_intermediaire = EEPROM_Read(0x0A);
     int_intermediaire=int_intermediaire<<8;
     int_intermediaire=int_intermediaire | EEPROM_Read(0x0B);
     IntToStr(int_intermediaire, txtint);

UART1_Write_Text(CopyConst2Ram(msg,rom_07));UART1_Write_Text(rtrim(txtint));LFE
ED;
     mesure_P_debug();
     FloatToStr(Pression_debug,
txt_float);UART1_Write_Text(CopyConst2Ram(msg,rom_31));UART1_Write_Text(txt_floa
t);LFEED;
     int_intermediaire = EEPROM_Read(0x0C);
```

```
      int_intermediaire=int_intermediaire<<8;
      int_intermediaire=int_intermediaire | EEPROM_Read(0x0D);
      IntToStr(int_intermediaire, txtint);

UART1_Write_Text(CopyConst2Ram(msg,rom_47));UART1_Write_Text(rtrim(txtint));LFEED;
      Mesure_Ubatt();
      FloatToStr(U_batt, txt_float);UART1_Write_Text(CopyConst2Ram(msg,rom_32));UART1_Write_Text(txt_float);LFEED;
      LFEED;
      comm_traitee=0;
   }// end IF PPE
   if( rxarray[0]==0x50 && rxarray[1]==0x57 && rxarray[2]==0x31 ){ // PW1 Q
     rxarray[0]= 0x30;rxarray[1]= 0x30;
     rxarray[2]= 0x30;
     int_intermediaire=atoi(rxarray);      // 00123 devient int 123
      if ( int_intermediaire>=0 && int_intermediaire<=255 ){  // acceptable ?
          PWM1_Set_Duty(int_intermediaire);
      }// end if condition   0-255
      else { //valeur erronée !
       UART1_Write_Text(CopyConst2Ram(msg,rom_33));LFEED;
      }// fin else
     comm_traitee=0;
   }// end IF PW1
  if( rxarray[0]==0x50 && rxarray[1]==0x57 && rxarray[2]==0x32 ){ // PW2 Q
     rxarray[0]= 0x30;rxarray[1]= 0x30;
     rxarray[2]= 0x30;
     int_intermediaire=atoi(rxarray);      // 00123 devient int 123
     if ( int_intermediaire>=0 && int_intermediaire<=255 ){  // acceptable ?
          PWM2_Set_Duty(int_intermediaire);
      }// end if condition   0-255
      else { //valeur erronée !
           UART1_Write_Text(CopyConst2Ram(msg,rom_33));LFEED;
      }// fin else
     comm_traitee=0;
   }// end IF PW2
   if( rxarray[0]==0x4D && rxarray[1]==0x4B && rxarray[2]==0x50 ){ // MKP    Memorize Kp
      rxarray[0]= 0x30;                    // char 0 for remplacing char M,K and P
      rxarray[1]= 0x30;                    // MPK12345  becomes 0012345
      rxarray[2]= 0x30;
      int_intermediaire=atoi(rxarray);      // 00123 becomes int 123
      if ( int_intermediaire>=0 && int_intermediaire<=65535 ){  // acceptable ?
      EEstore_Kp( int_intermediaire );
      }// end if condition   0-65535
      else {                                              //erroneous value !
           UART1_Write_Text(CopyConst2Ram(msg,rom_34));LFEED;
      }// fin else
      comm_traitee=0;
```

```
   }// end IF MKP
  if( rxarray[0]==0x4D && rxarray[1]==0x4B && rxarray[2]==0x49 ){ // MKI     Memorize
Ki
      rxarray[0]= 0x30;                  // char 0 for remplacing char M, K and i
      rxarray[1]= 0x30;                  // MPK12345  becomes 0012345
      rxarray[2]= 0x30;
      int_intermediaire=atoi(rxarray);      // 00123 devient int 123
      if ( int_intermediaire>=0 && int_intermediaire<=65535 ){  // acceptable value?
          EEstore_Ki( int_intermediaire );
      }// end if condition   0-65535
      else {                                                        //erroneous value !
          UART1_Write_Text(CopyConst2Ram(msg,rom_35));LFEED;
      }// fin else
      comm_traitee=0;
   }// end IF MKI
  if( rxarray[0]==0x4D && rxarray[1]==0x4B && rxarray[2]==0x44 ){   // MKD Memorize
Kd
      rxarray[0]= 0x30;                  // char 0 for remplacing char M, K and D
      rxarray[1]= 0x30;                  // MPK12345  becomes 0012345
      rxarray[2]= 0x30;
      int_intermediaire=atoi(rxarray);      // 00123 devient int 123
      if ( int_intermediaire>=0 && int_intermediaire<=65535 ){  // acceptable value?
          EEstore_Kd( int_intermediaire );
      }// end if condition   0-65535
      else {                                                        //erroneous value!
          UART1_Write_Text(CopyConst2Ram(msg,rom_36));LFEED;
      }// fin else
      comm_traitee=0;
   }// end IF MKD
   if( rxarray[0]==0x4D && rxarray[1]==0x54 && rxarray[2]==0x41 ){ // MTA
     rxarray[0]= 0x30;rxarray[1]= 0x30;
     rxarray[2]= 0x30;
     int_intermediaire=atoi(rxarray);      // 00123 becomes int 123
     if ( int_intermediaire>=0 && int_intermediaire<=99 ){            // acceptable value?
         EEstore_Ta(int_intermediaire);
      }// end if condition   0-99
      else {                                                        //erroneous value !
          UART1_Write_Text(CopyConst2Ram(msg,rom_48));LFEED;
      }// fin else
     comm_traitee=0;
   }// end IF MTA
   if (comm_traitee==1) {                   // no case listed =>ERREUR
      UART1_Write_Text(CopyConst2Ram(msg,rom_17));LFEED;
   }// end if comm_traitee
} // fin traitement_commande_PULVE()
//-----------------------------------------------------------------------------------
void main() {
  setup();            //common setup for PULVE and DEBUG modes
  if(PULVE_MODE){     // if = 0 ➔mode PARAMETRES, if =1➔mode PULVE
 UART1_Write_Text(CopyConst2Ram(msg,rom_37));LFEED;
```

```
    setup_mode_PULVE();
    PWM2_Set_Duty(0);                        // pump injection OFF
    calc_bias_drive_from_consigne();
    TMR0ON_bit =1;                                  // active timer0
    cpt_une_sec=0;
    TMR1ON_bit=1;                                   // active Timer1 mode comptor
    TMR1CS_bit=1;                                   // source RC0
    T1SYNC_bit=1;                                   // no synchro
    T1OSCEN_bit=0;                                  // oscillateur timer1 off
    T1CKPS0_bit=0;                                  // pre-scaler=1/1
    T1CKPS1_bit=0;
    T1RUN_bit=0;                                    //
    RD16_T1CON_bit=0;                         // read in mode 8 bits
    TMR1IE_bit=1;                    // authorize interruptions compto1 // measure of sensor
speed pulses
    TMR1IF_bit=0;                    // no overflow TMR1 or reset interrupt state flag
    TMR1H=0xFF;
    TMR1L=0xFB;                      // initial value timer 65535-5➔ computing 5 pulses
before interrupt
    while(1){
    if (cpt_40_ms >= 40){       // computing data for PID and commands of pumps motors at
25 Hz
        cpt_40_ms=0;
        cpt_une_sec++;           // increment every 40 ms  ➔ 25 times = 1 sec
        watchdog++;              // when 25 times ➔ one sec past
if( nombre_ms_5_pulses != 0 && watchdog < 25 ) vitesse=(float)  156.04 /
nombre_ms_5_pulses ;
else vitesse=0.0;                // 1.2 m/s  === 5 pulse/ 38Hz === 131.58 ms   1 ms➔0.00912
m/s
 mesure_P_processfloat();
        calc_erreur();
        calc_P_erreur();
        calc_I_erreur();
        calc_D_erreur(),
        calc_drive_pc();
        PWM1_Set_Duty( (unsigned short) drive_pc );
        ajuste_injection();
      }//end if cpt_40_ms >= 40
 if (cpt_une_sec > 24){            // one seconde past
 cpt_une_sec=0;                 // initializing to 0 comptor of one seconde
 Vitesse_correcte();    // for management of two red leds only if(corr==1){Mesure_Ubatt();}
// if mode correctif 1 measures voltage batterie             else {U_batt=12.4;}              // else
use reference value of 12.4 V
if(debug){                  // monitoring process parameters at 1 Hz;
LFEED;
          FloatToStr(vitesse, txt_float);
UART1_Write_Text(CopyConst2Ram(msg,rom_39));UART1_Write_Text(txt_float);LFEED
;
```

```
         FloatToStr(q_theo, txt_float);
UART1_Write_Text(CopyConst2Ram(msg,rom_40));UART1_Write_Text(txt_float);LFEED
;
         FloatToStr(tmp, txt_float);
UART1_Write_Text(CopyConst2Ram(msg,rom_41));UART1_Write_Text(txt_float);LFEED
;
         FloatToStr(U_batt, txt_float);
UART1_Write_Text(CopyConst2Ram(msg,rom_42));UART1_Write_Text(txt_float);
                      if ( corr==0 )
UART1_Write_Text(CopyConst2Ram(msg,rom_43));LFEED;
         FloatToStr(val_process,
txt_float);UART1_Write_Text(CopyConst2Ram(msg,rom_44));UART1_Write_Text(txt_floa
t);LFEED;
        }// end if debug
      }// end if (cpt_mesure_une_sec > 24)
      if (flag==1){  // une chaine de caracteres est prete , elle est terminée par un NULL char
        traitement_commandes_PULVE();
        i = 0; flag = 0;         // reset variables de la réception UART ( reception du port serie du
PC )
       } // end if flag=1
       } ;// end while (1)
  }
  else{// mode debug ou parametres
        TMR0ON_bit =0;       // timer0 OFF
     UART1_Write_Text(CopyConst2Ram(msg,rom_45));LFEED;
     PWM1_Set_Duty(0);
     PWM2_Set_Duty(0);
     while(1){
       if (flag==1){  // une chaine de caracteres est prete , elle est terminée par un NULL char
         traitement_commandes_PARAMETRES();
         i = 0; flag = 0;         // reset variables de la réception UART
        } // end if flag=1
         } ;// end while (1)
  }// end else if(PULVE_MODE){
}//end main
```