Development of a compact single room ventilation unit with heat recovery dedicated to tertiary building

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ABSTRACT

In the frame of the European project called Bricker, a new prototype of single room ventilation with heat recovery has been developed. This new unit is supposed to be installed in class rooms of an educational institution. This paper deals with the development of the first prototype of this unit. An empirical model of such device is also proposed in order to be coupled with a building model. This aims at determining the seasonal performance of the device and thus the potential energy saving (compared to other technologies) resulting from its use.

The first part of the paper presents the specifications and the final characteristics of the developed device. In this context, a by-pass for free cooling in summer conditions as well as the strategies under frosting conditions are described.

Secondly, the coefficient of performance (COP) of such device is recalled. In the early stage of the development process, the COP is determined based on the manufacturer data of the heat recovery exchanger and the fans. The coupling between fan curve and the predicted hydraulic performance of the unit allows for determining a first approximation of the fans electrical consumption for several delivered flow rates.

The third part of the paper focuses on the experimental investigations carried out in order to determine the flow rate really delivered by the unit. Electrical consumptions of several flow rates are also measured in order to characterize the COP of the unit in those conditions.

Finally, a comparison between the measured and the predicted performance based on manufacturer data has been realized in terms of COP. A performance map based on experimental results is proposed in order to be coupled with a building model.

KEYWORDS

Innovative ventilation, heat recovery, laboratory measurement, air-to-air heat exchanger, fan energy use

1 INTRODUCTION

The Bricker project (2013) aims at developing a retrofitting solution package for existing public-owned non-residential buildings in order to achieve a drastic reduction of the energy consumption (beyond 50%) and GHG emissions in this sector. The retrofitting package is based on envelope retrofitting solutions, zero emissions energy production technologies and the integration and operation strategies. The so-called solutions will be implemented in three real demonstration multi-buildings complexes, located in three different climate conditions and with different end-users. One of the investigated solutions focuses on the development of decentralized ventilation with heat recovery also called single room ventilation with heat recovery (SRVHR). This kind of unit has recently been investigated for residential application by Gendebien (2014) but in the frame of the Bricker project, the units are supposed to be installed in tertiary buildings and more particularly in classrooms of an educational institution, in Liège (Belgium). It involves a higher delivered flow rate by the unit compared to a decentralized system dedicated to a residential application.

The development of such units faces many challenges. The major ones are listed herebelow:

- The device has to be constructed in such a way that it can be installed in the windows frame, or in the false ceiling of a room. The device can also be wall mounted in a horizontal or a vertical position. For each case, the condensate evacuation has to be well designed;
- As for every heat recovery ventilation system, the developed device faces a trade-off between a high thermal effectiveness and a related rise of pressure drops inducing a degradation of the global performance of the unit due to a higher energy use for the fan. Greater attention has to be paid to hydraulic performance than in centralized systems since they are directly related to the noise generated by the fans;
- Strategies under frosting conditions have also to be carefully investigated;
- The device has to be equipped with an electronic control to manage the overheating, during summertime, by opening a by-pass valve. The electronic control has also to allow for an auto-regulation of both air flow rates by using a CO_2 sensor or a time clock;
- The device has to be properly designed in order to allow for a high easiness of placement and maintenance by also taking care of the compactness.

2 FEATURES OF THE DEVELOPED DEVICE

2.1 Main components description

The developed single room ventilation unit with heat recovery mostly consists of a parallelepiped box containing:

- two **AC fans** (one dedicated to the indoor air and one dedicated to the outdoor air);
- **filters** (for both indoor and outdoor air flow rates)
- a **by-pass valve** for ventilative cooling during summer time;
- a **mixing chamber** dedicated to frosting strategies;
- an **electronic fan control** for manual or automatic regulation;
- a **heat recovery exchanger**, often considered as the key component of the unit.

The overall dimensions of the developed box and its integration in the building façade are given in Figure 1:

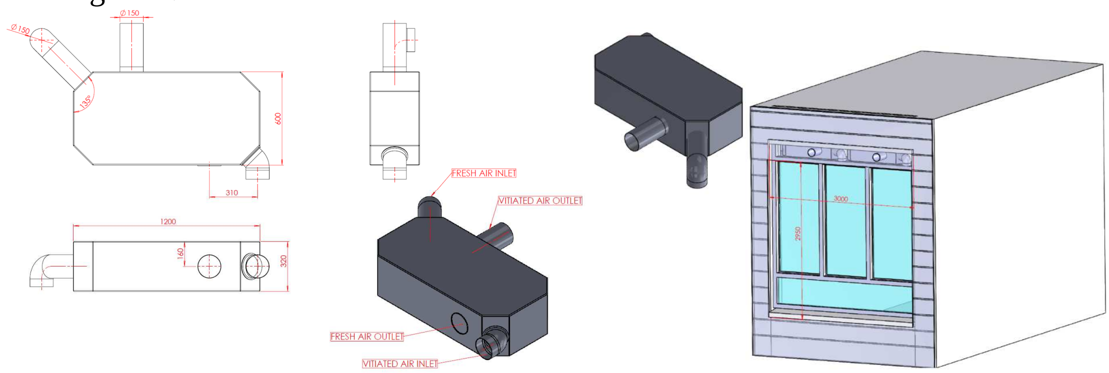

Figure 1: Overall dimensions of the investigated unit

2.2 By-pass

During summertime, when the indoor temperature is higher than a comfortable temperature (25°C for instance) and the outdoor temperature is lower than the indoor temperature, the passage of the outdoor air through the heat exchanger should be avoided in order to take benefit of this “free cooling”.

The principle of the by-pass is explained in Figure 2. The fresh air is going through a secondary channel, in parallel of the heat exchanger, while the indoor air is still going through it. When the by-pass valve is open, no heat transfer occurs between the two flows while the room is still ventilated.

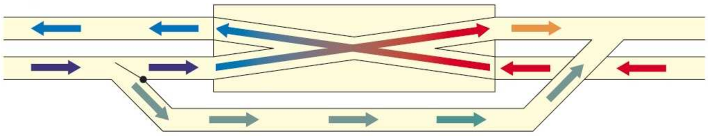

Figure 2: Principle of the by-pass

The by-pass mode is based on two temperature sensors, one measuring the outdoor air and one measuring the indoor air. 3 conditions must be fulfilled for the by-pass to be automatically activated:

- The indoor air is higher than 25°C,
- The outdoor air is lower than the indoor one (with a difference of minimum 1°C),
- The outdoor air is higher than 10°C.

When one of these conditions is not fulfilled anymore, the by-pass is automatically deactivated.

2.3 Strategies under frosting conditions

Every ventilation system equipped by a heat exchanger needs to adopt a defrost strategy. Indeed, when the outdoor temperature is lower than 0°C, a risk of frost appearance may occur in the heat exchanger on the indoor air side. The increasing frost layer leads to a diminution of the indoor airflow rate. This promotes the frost formation resulting in the complete freezing of the whole heat exchanger.

One method under frosting conditions consists in a preheating of the fresh air going to the heat exchanger by means of a mixing with indoor air. The principle is to derive a part of the indoor air flow rate to the fresh air side heat exchanger supply. It can be realized by adding a duct/section/chamber in direct contact with outdoor air. When the threshold temperature is reached, a valve can be proportionally opened and the mixture can take place. In other operating conditions, the valve remains closed. The situation under frosting conditions is schematically represented in Figure 3:

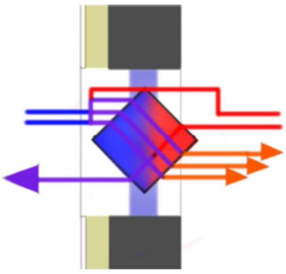

Figure 3: Schematic representation of the “preheating by mixing” strategy

The newly developed ventilation unit is equipped with a mixing chamber. A trap is closed when the outdoor air is above 0°C and can take three different positions when the outside temperature is negative. The three positions are respectively activated at 0°C, -5°C and -10°C. The openings of the trap are studied in order to ensure a positive temperature of the mixing air entering the heat exchanger. By this strategy, no frost can appears inside the heat exchanger but a drawback of this process is the partial recirculation of the different contaminants of the room.

3 OVERALL PERFORMANCE OF SINGLE ROOM VENTILATION WITH HEAT RECOVERY UNIT

Overall performance of centralized heat recovery ventilation is highly dependent on the hydraulic circuit (singularities, such as bending of the pulsing and extracting ducts) and therefore on the building and ducts configuration. In contrary, the overall performance of single room heat recovery ventilation is not influenced by the rest of the installation. As a result, performance of single room ventilation with heat recovery does not depend on the building characteristics but only on the characteristics of the device itself.

As proposed by Gendebien et al. (2013a), the overall performance of each unit can be defined as the ratio of the recovered heat transfer rate to the electrical power of the fans and is given by Equation 1:

$$COP_{SRVHR} = \frac{Recovered\ heat\ power}{Electrical\ supplied\ power} = \frac{\dot{Q}_{recovered}}{\dot{W}_{fans}} \qquad (1)$$

By only taking into account the sensible part of the heat transfer rate (the total amount of latent heat rate compared to sensible recovered heat can be neglected in moderate climate as Belgium, according to Gendebien et al. (2013b)), the recovered heat transfer rate is given by Equation 2 and depends on the heat exchanger effectiveness (varying with the mass flow rate), the delivered mass flow rate and on the indoor/outdoor difference temperature:

$$\dot{Q}_{recovered} = \dot{M}_{fresh} \, . \, cp \, . \, \varepsilon \, . \, (T_{ind} - T_{out}) \qquad (2)$$

With:
- $\boldsymbol{\dot{M}_{fresh}}$ the fresh air mass flow rate in [kg/s];
- $\boldsymbol{cp}$ the air specific heat in [J/kg-K];
- $\boldsymbol{\varepsilon}$ the heat exchanger effectiveness [-];
- $\boldsymbol{T_{ind}}$ the indoor temperature;
- $\boldsymbol{T_{out}}$ the outdoor temperature.

As represented in Figure 4, the parameters influencing the COP of the unit are:
- **Fan** performance;
- **Hydraulic performance of the unit**. This can be divided in two parts: one related to the passage of the air flow in the **heat exchanger itself** and another one related to the flows through **the rest of the unit** (filter, supply and exhaust of the unit);
- **Effectiveness** of the heat exchanger;
- **Climate**: indoor/outdoor temperature difference. From a yearly performance point of view, the interest of use of heat recovery ventilation is highly dependent on the climate (recovered heat over one year vs electrical consumption due to fans).

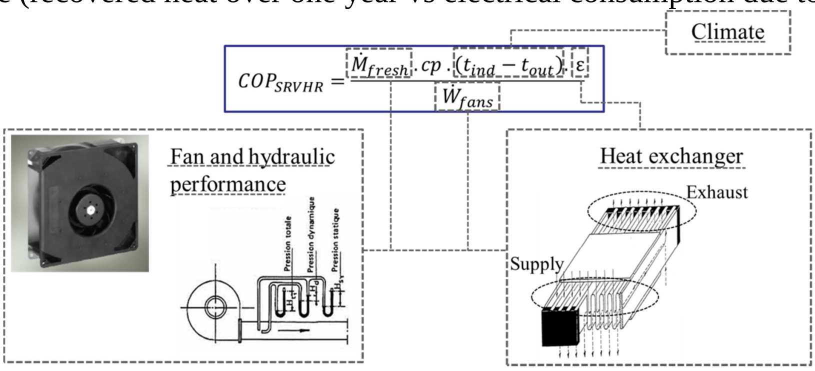

Figure 4: Parameters influencing the COP_{SRVHR}

4 DESIGN STEPS OF THE UNIT

In the frame of the Bricker project, it was decided to manufacture the overall box in order to integrate the several components in the most effective way. One important part of the design was to choose the best set of components (especially the heat exchanger and the fan). Of course, the control of the device was also a major part of the design process. The control involves a flow rate regulation based on the room occupancy, the opening of valves for free cooling during summer time and for freezing strategies during winter time.

Concerning the heat exchanger, a benchmarking between off-the-shelf products has been performed. For a same compactness and standard dimensions, the criteria of selection were the thermal performance, the hydraulic performance, the long term as well as short term mechanical robustness and of course the unitary price. The chosen heat exchanger presents a quasi counterflow configuration and overall dimensions of 360*300*360 mm.

Concerning the fans, the choice had to be made between AC and DC power supply. Both of them presented the same volute diameter. It was decided to choose the AC one for two main reasons. First, it avoids the use of a power consuming AC/DC current converter, and thus a higher price for the fan and its control. Secondly, it presents a better acoustic performance.

Once the appropriate options for fan and heat exchanger were selected, it was possible to compute a performance map based on performance presented in manufacturer catalogues. Those predicted overall performance will be compared with measured performance in Section 6.

Delivered flow rate for a specific rotational speed of fan can be deduced from the intersection of the fan performance curve with the hydraulic performance curve of the unit. Hydraulic curve of the unit is the sum of several contributions. The total pressure drop is due to the passage of air through filter, through the heat exchanger, and through the rest of the unit (the inlet and the exhaust of the unit). During this step, one assumed the use of G4 filters for both sides of the unit (indoor and fresh air side). It has been arbitrarily assumed that the pressure drop related to passage of air through the inlet and exhaust of the unit accounts for 40% of the pressure drop related to the air passage in the filter and the HX. The hydraulic reconciliation is given here below in Figure 5.

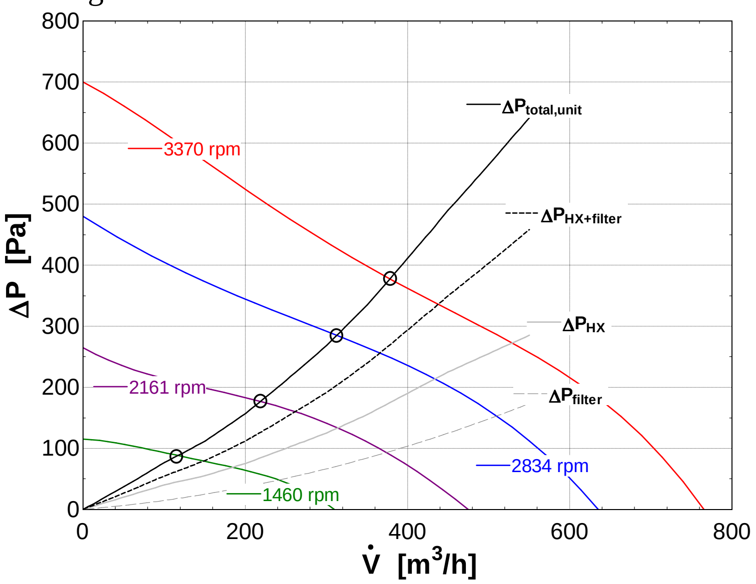

Figure 5: Intersection between the total pressure drop of the unit and fan curves

For determining a performance map, two more pieces of information are needed: the heat exchanger effectiveness and the fan electrical consumption depending on the rotational speed and on the flow rate. Those pieces of information, based on manufacturer catalogue, are given in Figure 6.

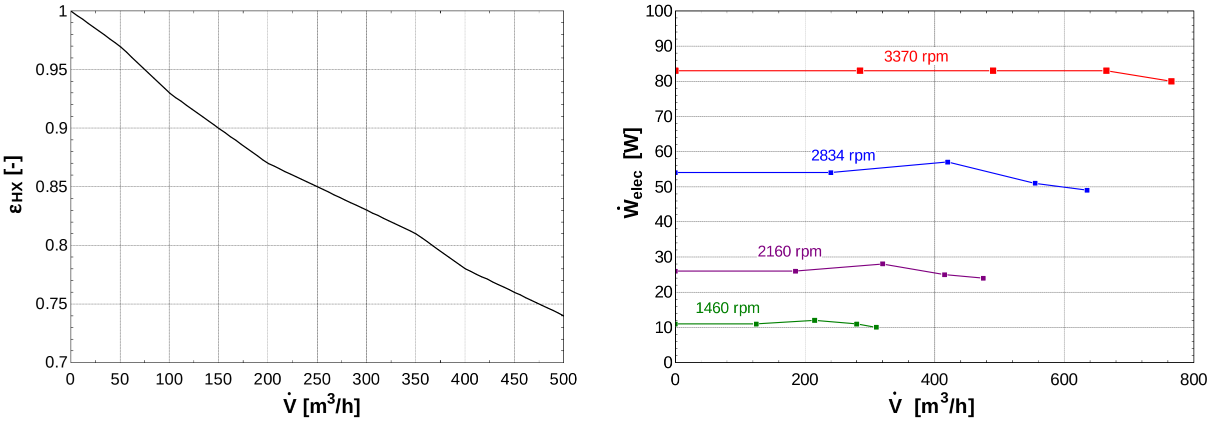

Figure 6: Heat exchanger effectiveness (left) and electrical consumption for fan depending on the volumetric flow rate and the rpm (right)

It is now possible to determine the evolution of the overall performance of the unit as a function of the volumetric flow rate for a specific indoor/outdoor temperature difference, on the basis of Equation 1 and 2. The expected evolution of the COP of the unit for an indoor/outdoor temperature difference of 11.5K is given in Figure 7. For the COP estimation, a difference temperature of 11.5K has been chosen. This corresponds to an indoor temperature of 20°C and an outdoor temperature of 8.5°C (mean indoor and outdoor Belgian temperature).

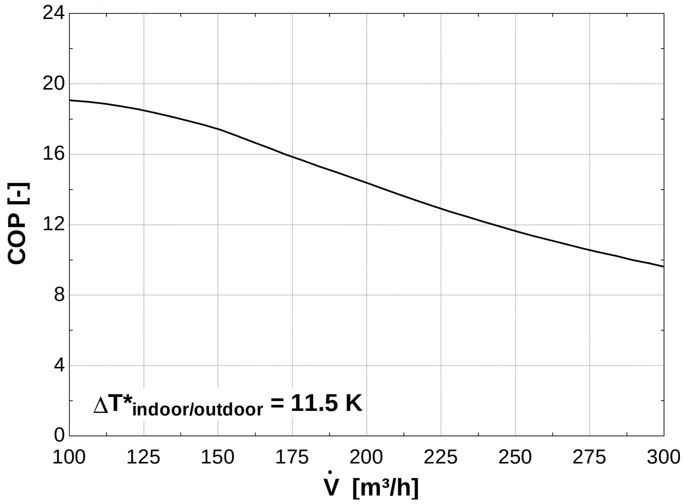

Figure 7: Expected coefficient of performance of the unit (design step)

5 EXPERIMENTAL INVESTIGATIONS

This section aims at presenting the experimental investigations carried out in order to determine the flow rates delivered by both fans, as well as their electrical consumption.

5.1 Delivered flow rate

A nozzle has been used in order to determine the flow rate delivered by both fans for various rotational speeds. The knowledge of the pressure drop between the inlet/outlet of the nozzle allows for determining the flow rate. The passage through the nozzle induces an additional pressure loss leading to a decrease of the delivered flow rate. In order to eliminate this decrease, a balancing (also called compensating) fan is used. A differential pressure drop sensor is placed between the atmosphere and the exhaust of the unit. The compensating fan rotational speed can be modified. Once the measured differential pressure between the atmosphere and the exhaust of the unit is equal to zero, the device is supposed to operate in nominal conditions and the volumetric flow rate measured by means of the nozzle is the one really delivered by the unit in normal conditions. Electrical consumption has been realized for various rotational speeds of both fans by using a calibrated AC current analyzer.

A practical achievement of the experimental set-up is given in Figure 8:

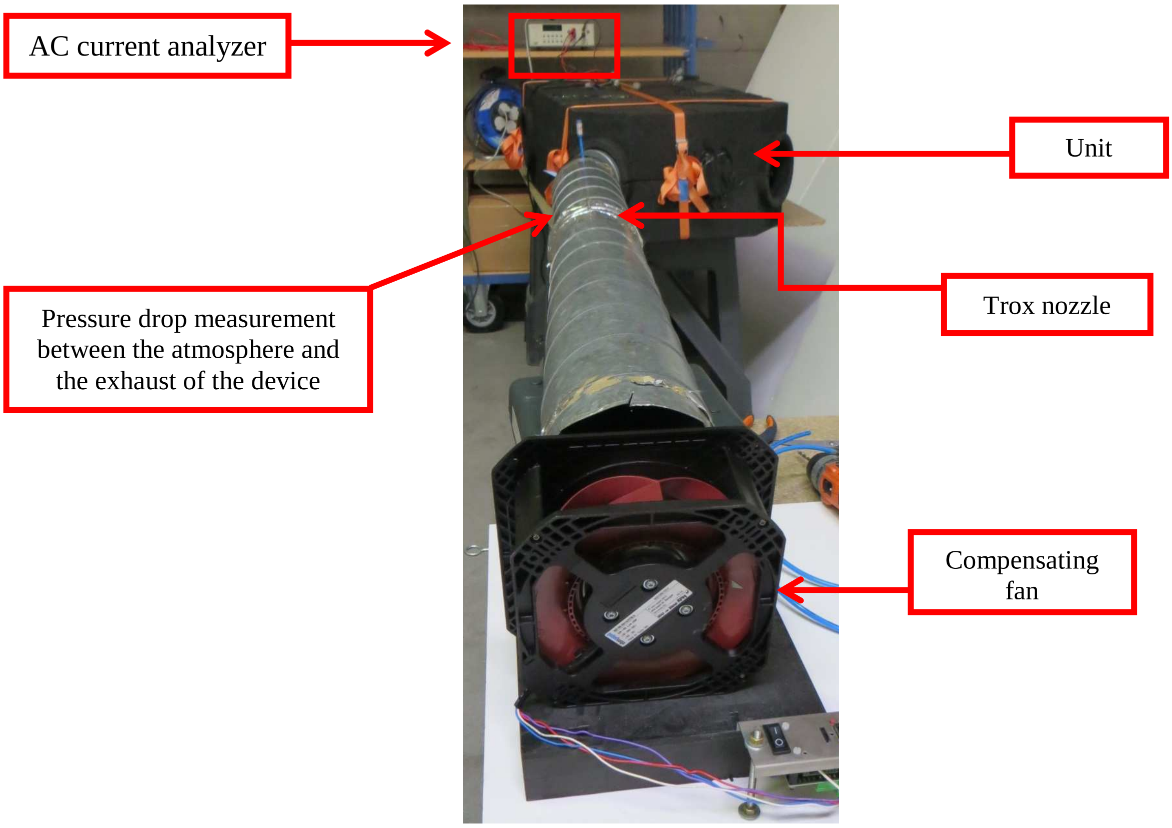

Figure 8: Practical achievement

5.2 Heat exchanger effectiveness

The heat exchanger effectiveness has been experimentally determined for three different balanced air flow rates. Thermocouples have been installed at the inlet and the exhaust of both sides of the unit. Tests have been carried out in the laboratory of the heat exchanger manufacturer on the finalized unit. Effectiveness of the recovery heat exchanger has been determined by means of stabilized tests of 10 min under dry conditions (without condensation appearance). The supply temperature of the indoor air was around 25°C and the fresh air temperature was around 5°C. Effectiveness has been determined for three different balanced mass flow rates (see Figure 9).

6 COMPARISON BETWEEN DESIGN AND EXPERIMENTAL RESULTS

The aim of this section is to compare the expected results obtained during the design steps with the measured ones obtained during the experimental campaign.

6.1 Hydraulic performance comparison

Table 1 gives a numerical comparison between the expected and the measured hydraulic performance of the unit (for both indoor and fresh air side). It can be observed that generally predictions are in good agreement with measured results. However, it can be noticed that for the lowest flow rate, measurements shows better performance compared to the predicted ones.

Table 1: Hydraulic performance comparison

Expected hydraulic performance			Measured hydraulic performance (fresh air side)			Measured hydraulic performance (indoor air side)		
$\dot{W}_{fan}$ [W]	$\dot{V}$ [m³/h]	SFP [W/m³-h]	$\dot{W}_{fan}$ [W]	$\dot{V}$ [m³/h]	SFP [W/m³-h]	$\dot{W}_{fan}$ [W]	$\dot{V}$ [m³/h]	SFP [W/m³-h]
76.29	366	0.208	86	366	0.235	84	366	0.229
55.18	315	0.175	55	315	0.175	55	314	0.175
30.5	232	0.131	27	232	0.115	27	226	0.119
15.3	153	0.1	10	153	0.065	10.5	142	0.074

6.2 Thermal performance comparison

Figure 9 shows a comparison between the expected and the measured heat exchanger effectiveness. It can be observed that the measured HX effectiveness is approximately 10 percentage points lower than the expected HX effectiveness. One reason that could explain this difference is a potential misdistribution of the air flow rate in the heat exchanger because of the proximity of the fan exhaust with the heat exchanger entrance.

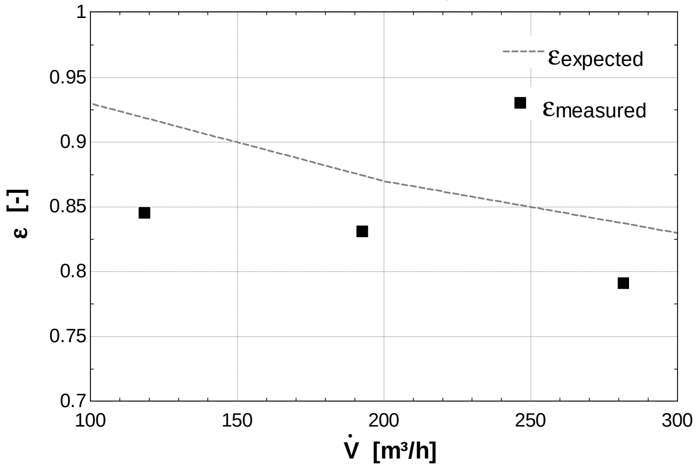

Figure 9: Comparison between expected and measured heat exchanger effectiveness

6.3 COP comparison

A comparison between the COP (as defined in section 2) obtained during the design step and the experimental procedure is given in Figure 10. Interpolation between experimental data has been realized for establishing the measured COP evolution. Once again, the indoor/outdoor temperature difference has been chosen equal to 11.5K and the flows are considered perfectly balanced.

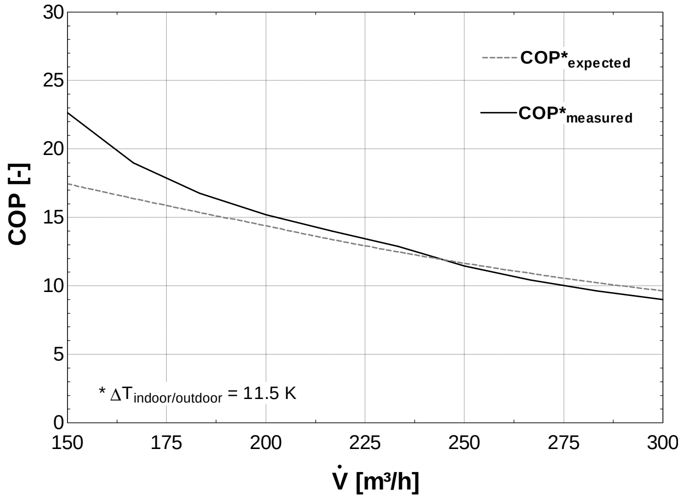

Figure 10: Comparison between expected and measured performance

As shown in Figure 10, the COP obtained during the design step shows good agreement with the measured COP, even if some differences between predicted and measured characteristics exist. The decrease of the actual heat exchanger effectiveness in comparison with expected results is counterbalanced by a better measured hydraulic/fan performance.

7 CONCLUSIONS AND FUTURE WORK

The present paper focuses on the development and the experimental characterization of a decentralized ventilation system with heat recovery to be installed in classrooms of an educational institution. The proposed system integrates solutions for avoiding freezing in the heat exchanger, for free cooling and to adapt air flow rates to occupancy. A design procedure has been performed in order to assess an expected overall performance of the unit based on HX, fan and filter manufacturer data. Then, an experimental procedure has been carried out in order to compare expected results with measured results. Expected results shows good agreement with the overall performance measured on the real unit. Future work will consist in installing the developed unit in classrooms of an educational institution in Liège (Belgium) and testing in situ the control of the unit.

ACKNOWLEDGEMENTS

This study has been carried out in the frame of the Bricker project. This project is performed with the support of the European Commission and is carried out by a large consortium of research centers and industrial partners, such as Greencom development s.c.r.l.

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