

Description of a Modelica-based thermal building model integrating multi-zone airflows calculation

Frédéric Ransy*¹, Samuel Gendebien*² and Vincent Lemort*³

* *Thermodynamics Laboratory, University of Liege,*

Quartier Polytech 1

Allée de la Découverte, 17

4000 Liège, Belgium

¹frederic.ransy@ulg.ac.be

²sgendebien@ulg.ac.be

³vincent.lemort@ulg.ac.be

Abstract

Nowadays, in newly built housings, energy losses due to the ventilation can represent up to 50 % of the total building energy consumption. As a result, heat recovery ventilation units are widely used in order to save primary energy and different control strategies for ventilation systems are investigated. For instance, demand control ventilation sounds like a promising solution to decrease the energy impact of the ventilation system in the residential sector. An accurate building model integrating the influence of ventilation (so called thermo-aeraulic building model) is necessary in order to investigate the control and the impact of the ventilation system on a yearly basis.

The aim of the present paper consists in a description of a combined multi-zone airflow network model and thermal building model implemented in the Modelica language. The thermal model is a simplified dynamic model using equivalent thermal resistance and capacity. The airflow network is based on the traditional electrical circuit analogy. The model can be used for ventilation systems design, infiltration rate calculation, inside air quality calculation, energy consumption calculation, etc.

The first part of the paper details the multi-zone thermal building model. The results obtained from the model are compared to experimental in situ results collected in the typical single family house test facilities. Those experimental results have been obtained in the frame of the IEA-EBC Annex 58.

The second part of the paper introduces the multi-zone airflow network building model. Obtained model results are compared with the results provided by a typical multizone airflow analysis software, for a simple three zones test case.

The third part of the paper describes the coupling between both thermal and airflow models. The different numerical problems encountered are described and solutions are discussed.

Keywords – Building; thermal modeling; airflow modeling; Modelica.

1. Introduction

According to the European directive 2012/27/EU of October 2012 on energy efficiency, buildings represented 40 % of the EU's final energy consumption in 2011. The major part of this energy consumption is due to the

residential sector for space heating and domestic hot water production. Moreover, buildings are crucial to achieve the EU objective of reducing greenhouse gas emissions by 80-95 % by 2050 compared to 1990.

In order to reduce these greenhouse gas emissions, retrofit measures regarding insulation and air-tightness have to be taken. However, such improvements of the building envelope lead to a relative increase in consumption related to ventilation. Indeed, according to Orme (2001), Roulet et al. (2001) and Fouih et al. (2012), the heating demand due to ventilation can reach more than 50 % of the total building heating demand for new and retrofitted buildings. As a result, heat recovery ventilation units are widely used in order to save primary energy.

In order to minimize the energy consumption due to the ventilation system, the following solutions may be considered:

- The use of a heat recovery unit with a high heat recovery effectiveness and a low pressure drop.
- The use of high efficiency fans to avoid high electrical consumption.
- The use of an insulated and airtight ducting system with low pressure drops.
- The use of a smart ventilation regulation based on the real occupancy (so called demand control ventilation).

Thus, it is important to develop building models that can be used for the design of high-efficient ventilation systems. The model should predict the annual primary energy consumption of the building (for the space heating, the DHW production and the auxiliary equipments), the airflow rates and the pressure drops in the ducting system and the indoor air quality for each room of the building.

In order to predict these three variables, a building model that combines the building thermal behavior and the building airflow distribution is necessary. In the literature, a large amount of simulation softwares combining heat flows and airflows calculation in buildings already exist. The different existing simulation programs are listed in the following.

DTFAM, developed in 1989, was the first simulation program able to predict the heat flows and airflows transfers in buildings. The program is the result of the collaboration between Axley J. (Massachusetts Institute of Technology, Cambridge), Grot R. and Walton G. (National Institute of Standards and Technology, Gaithersburg, MO). The building is divided in several well-mixed zones, linked together with thermal and airflow elements. The thermal part of the building is modelled with the RC network analysis approach and the airflow problem considers the multi-zone airflow network approach and the power-law pressure-flow model. The computational solution strategy is the following. The nonlinear flow problem is formed and solved, given the current estimate of system temperatures. Then, the thermal problem

is formed and solved, given the current estimate of system pressures. In other words, the thermal and the airflow problems are not solved simultaneously.

Many simulation tools have been developed using exactly the same simulation method and computational solution strategy.

For example, K. Klobut from the Helsinki University of Technology developed in 1991 a new simulation tool called **TFCD (Temperatures, Air Flows, Concentrations of contaminant and air quality in terms of Predicted Percentage of Dissatisfied)**. This program was the first one capable of simultaneously calculating contaminant concentrations, airflows and temperatures distribution.

We can also cite the ESP-r modelling tool developed in 1977 by Joe Clarke. Initially, the simulation program was used for the thermal modeling of buildings. Afterwards, in 1986, the modelling of building air flows was included. The simulation tool is still currently available and is open-access.

Other well-known and documented programs have also integrated airflow calculations. For example, Lixing Gu described in 2007 the integration of an airflow network model into the EnergyPlus energy simulation software (open-access building energy simulation program from the US Department of Energy) The model is able to simulate multizone wind-driven airflows.

Similarly, Weber et al. described in 2003 the combination of the COMIS airflow model with the transient system simulation tool TRNSYS, called TRNFLOW. Contrary to EnergyPlus, TRNSYS is non open-access. For both EnergyPlus and TRNFLOW, the thermal problem and the air flow distribution problem are solved sequentially (for the resolution method, see Hensen, 1999)

Many other programs have also been developed in the two last decades. In the commercial and research programs, we can cite the software CODYRUN (Boyer et al., 1993) developed by the university of the Reunion Island, the simulation tool COMFIE (Salomon et al., 2005) developed by Mines ParisTech, the CLIM2000 software environment (Bornneau et al., 1993) developed by the French utility company EDF, the BSIM program (Jensen et al., 2007) developed by the Aalborg University, the IDA ICE simulation tool developed by the EQUA company and the toolbox for the Matlab/Simulink environment SIMBAD (El Zaki et al., 2005) developed by the CSTB (Scientific and Technical Center for Building) in France.

A few open-access simulation tools are also currently available. For example, the solver SPARK (Musy et al., 2001) can be used for calculating indoor air temperature and air flow distributions in buildings. Similarly, the software HAMLAB (Van Schijndel, 2005) developed by the university of Eindhoven can be used for heat, air and moisture modeling in Matlab.

Recently, the object-oriented and open-access programming language Modelica has been widely used by the scientific community to model complex physical systems. The language is increasingly used in the particular case of building modeling. Several open-access libraries used to model the thermal behavior of buildings are currently available, for example AixLib, IDEAS or

the Buildings library. This one includes also the possibility to model multizone airflow in buildings. However, the combination between the thermal model and the airflow model is not considered.

The present paper describes a multizone building model combining heat flows and airflows calculation implemented in the Modelica language. The model predicts the annual primary energy consumption, the airflow transferred between zones, the fan consumption and the CO₂ concentration for all the rooms in the building.

1 Thermal building model description

1.1 Modeling approach

The thermal behavior of the building is modeled using an electrical analogy. The entire building is modeled with an equivalent electrical circuit, with several nodes, resistances and capacities. The modeling method is shown in Figure 1.

The building is divided into different zones connected together by partition walls, and connected to the external environment by external walls. Each node in the electrical circuit corresponds to the temperature of each building zone and the electrical currents correspond to the heat flows between the zones. A zone is a constant volume of air characterized by a homogeneous temperature. Typically, in residential building modeling, one zone in the model corresponds to one room of the building. The internal thermal gains (solar, occupancy, lighting) are directly injected into the appropriated node.

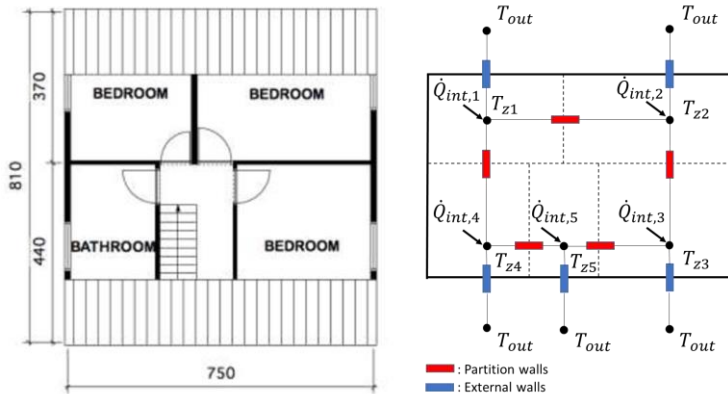


Figure 1: Typical rooms arrangement for a Belgian freestanding house (left) and the corresponding electrical analogy (right)

1.2 Zone model

The zone model consists in a constant volume of air characterized by three variables: the temperature, the pressure and the humidity. The CO₂ concentration is also considered. For the moment, the humidity is not taken into account in the model.

The mass and energy balance equations are applied to each control volume. In building modeling, the mass accumulation inside the volumes is negligible. In other words, the mass that enters and leaves each control volume is the same. However, depending on heat losses and heat gains, the internal energy changes over time.

The indoor air quality is estimated using the CO₂ concentration in the mixing volume. This concentration is determined using the mass balance equation for the CO₂. In this case, the mass of CO₂ contained into the volume can vary over time. It should be noted that CO₂ mass flow rate from occupants is supposed to be constant and equal to 40g/h.

1.3 Modeling of multi-layer walls

It is important to model accurately the multi-layer walls in order to predict conduction heat losses and take into account the thermal mass of buildings.

The multi-layer walls are modeled with the classical RC network analogy method. The light walls, for example doors or windows, are modeled with one thermal resistance given by $R = 1/U_{wall}$. The massive walls are modeled with a combination of resistances and capacities. The number of resistances and capacities used in the model depends on the wall type. Figure 2 shows the RC network model approach for three types of walls. This method has been described in detail by Masy (2008) and Fraisse et al. (2002).

The external walls, surrounding the zone and being in contact with the external environment, are modeled with 2R1C network models. The four parameters are the wall thermal resistance R and capacity C , the accessibility θ and the factor φ . This factor represents the proportion of the wall capacity accessed by a 24 h time period, and the factor θ gives the position of the capacity C on the wall resistance R .

The model of an internal wall, which is entirely included into a zone, consists in one resistance in series with one capacity. As before, the four parameters are the resistance R and capacity C , the accessibility θ and the factor φ .

The partition walls, surrounding the zone and being in contact with another heated zone, are modeled with 3R2C network models. In that case, the model includes 7 parameters: $R, C, \theta_1, \theta_2, \varphi_1, \varphi_2$ and ψ .

The parameters R, C, θ, φ and ψ depend on the wall composition, i.e the characteristics of the materials constituting the wall. The parameter values for different typical walls are provided in Annex 1.

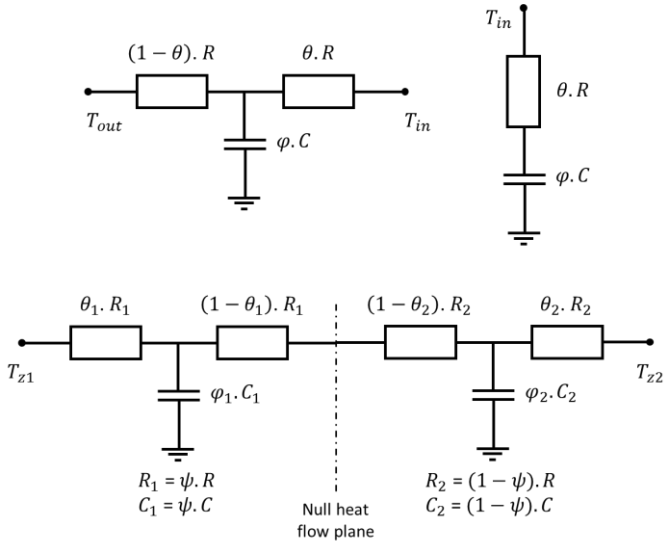


Figure 2: RC network model of an external wall (upside left), an internal wall (upside right) and a partition wall (below)

1.4 Modeling of internal gains

The internal gains can have a large influence on the heating and cooling loads calculation. The four main sources of internal heat gains are the solar radiation, the occupancy, the lighting and the household appliances.

The solar heat gains comprise the heat flow transmitted through windows, the solar radiation absorbed by opaque walls and infrared radiation losses transmitted to the sky. For the moment, only the first term is taken into account in the model.

The heat flow transmitted through windows is directly injected into the indoor temperature node. The heat flow is proportional to the window surface area, the window solar heat gain coefficient and the total solar radiation incident to the window. In the model, the frame to window ratio is also taken into account (equal to 0.3 for typical windows). A constant window shading factor can also be considered. It should also be noted that the solar heat gain coefficient is constant and independent of the angle of incidence.

The total radiation is the sum of the direct, reflected and diffuse solar radiations. In the model, the total solar radiation on a vertical surface for the four orientations is computed independently and stored in tables with a 1 hour time step.

The occupancy heat gains are supposed to be equal to 100 W per occupant present in the zone. The occupancy schedule for each zone is stored in a table and considered to be an input of the model.

The heat gains due to lighting and the household appliances vary from case to case. Consequently, for more flexibility, these heat gains are stored in a table with a 1 hour time step.

2 Thermal building model validation

Experimental in situ data, obtained in the frame of the IEA-EBC Annex 58, have been compared to the results given by the model. The experiment was conducted in August and September 2013 on the Twin Houses N2 and O5 at the Fraunhofer test site in Holzkirchen (Germany). All the characteristics of the buildings, the ventilation and the heating systems have been provided.

The two buildings have shown almost identical performance in terms of thermal insulation and airtightness. In order to evaluate the impact of the solar radiation, the blinds were down in the living of the twin house N2, and they were up for the twin house O5.

For both houses, the same experimental protocol, divided in four periods, was conducted. Firstly, the indoor temperature was maintained at 30°C using an electrical heater. Secondly, heat was injected into the living in order to measure the dynamic response of the building. For this purpose, the heat injection followed a Randomly Ordered Logarithmic Binary Sequence (ROLBS). Thirdly, the indoor temperature was maintained at 25°C. Finally, the heat injection was stopped to measure the temperature in free-floating conditions.

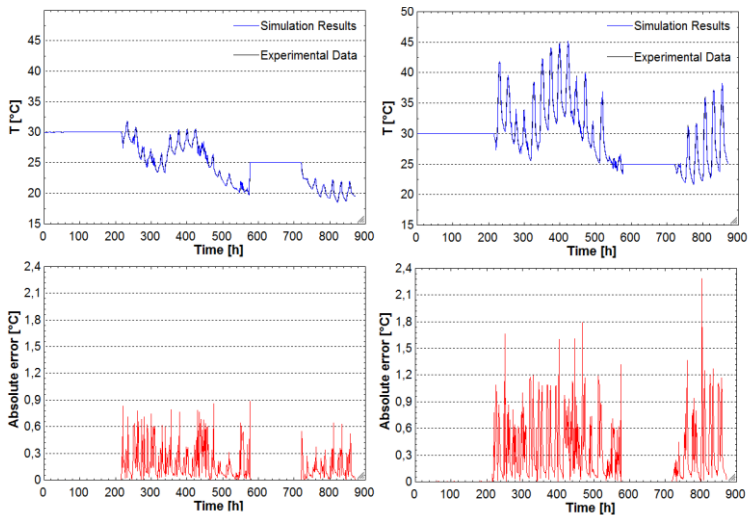


Figure 3: Experimental data comparing to the simulation results (top) and absolute error between simulation and experimental data (bottom) for the twin houses N2 (left) and O5 (right)

Figure 3 shows the simulation results comparing to the experimental data (top) and the absolute error between experiment and simulation results (bottom), for the twin houses N2 (left) and O5 (right).

When the blinds are down (twin house N2), the maximum and the mean absolute errors between simulation and experimental results are respectively equals to 0.9°C and 0.16°C .

However, when the blinds are up (twin house O5), the error is higher, i.e. 2.3°C and 0.33°C for the maximum and the mean absolute errors. This difference can be explained by different factors. Firstly, the solar radiation which is an input of the model could be wrong. Secondly, the parameters such as the window areas or the window solar heat gain coefficients could be inaccurate. Lastly, over-simplified assumptions of the model (constant solar heat gain coefficient, equivalent and unique indoor temperature node) could explain the difference.

Despite this observation, the thermal model can be considered reliable because the error relatively small.

3 Description of the airflow building network model

3.1 Modeling approach

The modeling approaches for the thermal and the airflow network building models are quite similar. In fact, the airflow network model consists in a set of generators and resistances. By analogy with electricity, the pressure corresponds to the electrical potential and the air flow rate corresponds to the electrical current. As an example, Figure 4 shows the multizone airflow network model of a typical Belgian freestanding house.

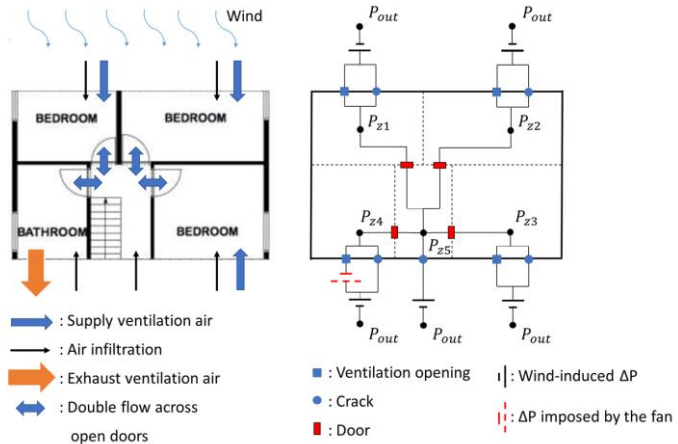


Figure 4: Multizone airflow network model of a typical Belgian freestanding house

The pressure differences (the generators, by analogy with electricity) can be induced by the wind, the buoyancy effect or by mechanical elements, such as fans.

The resistances in the electrical circuit correspond to the pressure drops in the aerualic circuit. For example, the resistances are the internal doors, the ventilation openings, the transfer orifices and the ducting system. For these elements, the relation between the airflow and the pressure drop is non-linear.

3.2 Wind, buoyancy and fans

The wind exerts a force on the building's facades, which can cause uncontrolled air infiltration inside the building. The wind aerodynamic pressure on a vertical obstacle is proportional to the pressure coefficient C_p , the external density and the local building wind speed.

The wind pressure coefficient depends on the surface orientation and the wind direction. The local building wind speed depends on the local shelter, the building location (city center, suburban area or open terrain) and the reference wind speed measured at the nearest meteorological station. In the model, the determination of the local building wind speed and the pressure coefficient is based on the ASHRAE Handbook—Fundamentals, especially about ventilation and airflow around buildings.

The thermal buoyancy effect is also taken into account in the model. In order to compute the stack pressure relative to each airflow element, the height (relative to the reference level) is defined for each element.

Finally, the fans are modelled with their performance curves, i.e the static pressure and the electrical consumption in relation to the volume flow rate. In the model, that performance curves are simply fitted by a 3rd degree polynomial function.

3.3 Resistive elements

The resistive elements in the electrical analogy means pressure drops in the airflow network model. Generally, in airflow elements, the relationship between pressure drop and airflow rate is not linear and is described by the orifice equation:

$$\dot{V} = \text{sign}(dp) C_d A \sqrt{\frac{2}{\rho}} |dp|^n \text{ if } |dp| > dp_\varepsilon \quad (1)$$

$$\dot{V} = C_d A dp_\varepsilon^{n-1} \sqrt{\frac{2}{\rho}} dp \text{ if } |dp| < dp_\varepsilon \quad (2)$$

where \dot{V} is the volume flow rate through the element, dp is the static pressure difference, C_d is the discharge coefficient, A is the area of the element, ρ is the air density, n is the flow exponent and dp_ε is a small pressure difference

(typically 0.1 Pa) used for the linearization of the orifice equation around zero (Equation (2)).

The values of the three parameters C_d , A and n depend on the airflow element considered.

Table 1 shows typical parameter values for four elements: the orifice element used in natural and exhaust ventilation systems, the crack element that describes the airtightness of a building, the local pressure loss in pipes commonly used in mechanical ventilation systems and the internal open doors.

Table 1- Typical parameters for the airflow model elements

Element	C_d [-]	n [-]	A [m^2]
Orifice	0.6	0.5	$f(\dot{V}_n)^*$
Crack	0.6	0.65	$f(\dot{V}_{inf,ref})^{**}$
Local pressure loss in pipes	$\sqrt{1/k}^{***}$	0.5	$\pi \frac{D^2}{4}^{***}$
Internal open doors	0.65	0.5	$dh \cdot w_{door}^{****}$

* \dot{V}_n = volume flow rate at nominal conditions.
** $\dot{V}_{inf,ref}$ = infiltration volume flow rate at reference conditions.
*** k = loss coefficient of the pipe, D = diameter of the pipe.
**** w_{door} = door width, H_{door} = door height, $dh = \frac{H_{door}}{n}$.

The most important element in the airflow network model is the internal open door. In fact, the internal door model influences highly the robustness of the entire building airflow network model, because the airflows through the doors are extremely sensitive to the temperature differences between zones.

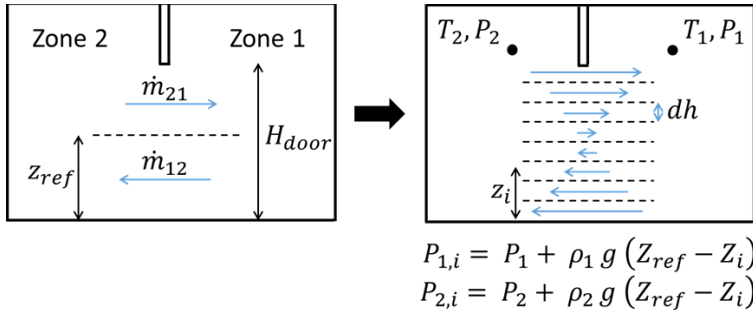


Figure 5: Modelling of an internal open door

As in the simulation tool COMIS (Feustel et al., 1997), the door is divided in n equal parts, and each part has a height $dh = H_{door}/n$, as shown in Figure

5. For each section, the stack pressure at both sides is determined ($P_{1,i}$ and $P_{2,i}$ in Figure 5), and the flow from a zone to the other is calculated using the orifice equation, given by (1) and (2). In these equations, the parameters C_d , n and A are given in

Table 1.

4 Comparison between CONTAM and Modelica

The results obtained in Modelica have been compared with those obtained in CONTAM, for a simple case study. Figure 6 shows the CONTAM model on the left and the Modelica model on the right.

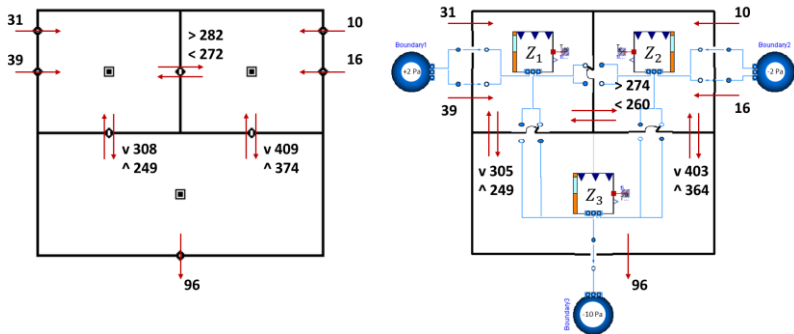


Figure 6: Comparison between a CONTAM model (left) and a Modelica model (right) of a simple three zone case study

The case study consists in three zones connected together with three open doors. The zones 1 and 2 are both connected to one orifice and one crack airflow element, and are submitted respectively to an overpressure and a depression of 2 Pa. The zone 3 is connected only to one orifice element and is submitted to a depression of 10 Pa.

The parameters of the airflow elements (C_d coefficient, exponent n , surface area A) are identical for both models. In the Modelica language, the internal doors are divided into seven compartments.

As shown in Figure 6, the airflows through orifice and crack elements are identical for the two models. However, the bidirectional airflows through open-doors are different. These airflows are systematically larger in the CONTAM model. The maximum relative difference between the two models is equal to 4 %. This error is acceptable considering that the uncertainty on the parameters (C_d , n) is of the same order of magnitude.

This error is due to the discretization of the internal door introduced in the Modelica model. If the number of compartments is much higher (for example 40), the error is close to zero, but the computation time increases. However, for a smaller number of compartments, the error increases rapidly. For

example, the error is equal to 6 and 16 % for a number of compartments respectively equals to five and three. A compromise between accuracy and computation time may be found. The value of seven compartments appears to be a good solution, with both an acceptable accuracy and computation time.

5 Coupling heat flow and airflow calculation

The numerical resolution of the coupled thermal-airflow problem is quite difficult. In fact, the two physical problems are strongly coupled. A small change in the indoor temperature results in a large variation of the airflow between zones, which in turn leads to a large indoor temperature variation. Consequently, the Jacobian matrix used in the numerical resolution is ill-conditioned and the problem is numerically difficult to solve.

To overcome this problem, the majority of the current simulation tools dissociate the two problems. As explained by Hensen (1999), the thermal problem determines the indoor temperatures with imposed flows, afterwards the airflows are determined using the calculated temperatures.

However, in the Modelica language, this methodology cannot be applied, because all the equations of the model are solved in the same block. Due to this property, the coupled thermal-airflow problem must be solved simultaneously. Thus, three simplifications are proposed in this paper to ensure the convergence.

The airflow elements, modeled with the orifice equation (Equations 1 and 2), introduce a non-linearity in the problem. In order to avoid numerical problems for pressure drops equals to zero, the orifice equation is linearized around zero, as shown by the equation 2. This approximation is limited for the low pressure drops and has therefore no influence on the accuracy of the model.

The density in equation 1 depends on the flow direction, introducing a discontinuity in the derivative dV/dp at $dp = 0$. The Modelica model translation process is therefore impossible and the model cannot be simulated. To guarantee the continuity in the orifice equation, the density is fixed at 1.2 kg/m³.

In building energy simulation, the external temperature varies from -30°C to 40°C. In addition, the atmospheric pressure can be considered constant in a first approach (for Brussels, the outside pressure varies from 0 to 2 % maximum compared to one standard atmosphere). Based on these numbers, the outside density varies from 1.452 to 1.127 kg/m³. Considering a constant density of 1.2 kg/m³, the relative error on the mass flow rate varies from 0 to 10 %. In the range of -10°C to 40 °C, this error is lower than 5 %, which is significantly lower than the uncertainty about the model parameter values (especially the C_d coefficients). Therefore, the simplification about the density makes sense and does not reduce the accuracy of the model.

Another important simplification concerns the open door, which is discretized along the height coordinate, instead of being described in detail by

analytical equations. This simplification is essential to ensure the convergence and the error due to this discretization is small, on the condition that the number of compartments used for the discretization is higher than seven.

In some cases, the Newton's method may fail to solve the initialization problem, due to the non-linear equations of the airflow model, and more specifically the equations of the internal open door model.

To prevent potential numerical problems, initial start values for the density and the pressure drop in the airflow elements must be fixed to nominal values. In order to propose a robust initialization of the problem, the homotopy method is used in the model. In this method, the density and the airflows, respectively given by the perfect gas law and the orifice equation, are firstly estimated through simplified and linearized equations, and secondly calculated with the complex and non-linear equations.

6 Conclusion

The combined thermal and airflow model described in this paper can be used to determine the indoor air quality in residential buildings, in order to estimate the potential of different ventilation control strategies. The impact of these control strategies on the overall building energy consumption can also be estimated. The natural ventilation and the ventilative cooling can also be simulated.

Despite its simplicity, the thermal part of the model, based on the typical RC network analogy, predicts with a sufficient accuracy the indoor temperature. In fact, the average absolute error between simulation and experimental data is equal to 0.33°K.

The Modelica airflow model is based on the electrical network analogy and the power law flow model. The equations are quite similar to those used in the software CONTAM. For a simple case study, the two softwares show similar results. In fact, the difference between the Modelica and the CONTAM models is lower than 4 %.

The airflow part of the model includes non-linear equations, making the combined thermal and airflow problem difficult to solve. As a result, three simplifications have been introduced in the model. Firstly, the orifice equation has been linearized around zero. Secondly, the density in the orifice equation has been fixed at 1.2 kg/m³. Thirdly, internal open doors have been discretized along the height coordinate. However, despite these simplifications, the model remains reliable and can be used to perform numerical studies about indoor air quality, energy performance of buildings or ventilative cooling strategies.

Acknowledgment

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Annex 1: Parameter values for typical walls

Table 1: Parameter values for typical walls

Wall Composition From indoor to outdoor	1/R [W/m ² K]	C [J/m ² K]	θ [-]	φ [-]	ψ [-]
<i>External vertical wall</i>					
Concrete block, 5 cm insulation, brick	0,51	290000	0,1	0,7	-
Massive wood, 7.5 cm insulation, brick	0,3	240000	0,1	0,5	-
Insulation, panel OSB, insulation, concrete block	0,17	230000	0,13	0,25	-
<i>Roof</i>					
Insulation between purlins (18 cm), air layer	0,28	20000	0,1	0,85	-
<i>Floor on outside</i>					
Tiled floor, mortar, insulation 6 cm, concrete, hollow concrete floor	0,47	370000	0,1	0,65	-
Tiled floor, mortar, concrete, hollow concrete floor, insulation 6 cm	0,47	370000	0,1	1	-
<i>Internal wall</i>					
Hollow concrete block	2,51	160000	0,8	1	-
Gypsum board, air, gypsum board	1,92	20000	0,5	1	-
<i>Partition vertical wall</i>					
Clay block, 2 cm insulation, clay block	0,69	300000	0,3	0,8	0,5
<i>Partition floor</i>					
Tiled floor, mortar, concrete, hollow concrete floor	2,13	360000	0,7	0,97	0,5
Tiled floor, screed, hollow concrete floor, 5 cm insulation, gypsum	0,53	330000	0,7	0,95	0,15
			0,4	0,15	