Energy Simulation of a Single Family Dwelling as a Test Bench for Climate Control System Assessment

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Abstract
In the present work a real dwelling (a semi-detached house in the Netherlands) has been modelled with an in-house modular object-oriented building simulation tool, called NEST-Buildings. This software models the whole building as a collection of elements (e.g., walls, rooms, outdoors, people, ventilation tubes and boxes, solar radiation distributor, HVAC, airflow, CO₂ transport, etc.) connected between them through boundary conditions. Special emphasis has been given to the airflow model of the house.

The main objective of the modelling of a real dwelling is to use it as a test bench for a new affordable, easy to use and apply, integral dwelling climate control system called DCCS (Dwelling Climate Control System), whose one of its objectives is reducing the energy use of buildings by optimizing the parameters of the heating and the ventilation system and ensuring the indoor quality inside the dwelling (by means of CO₂ concentration control).

In the present paper the effect of different control strategies on the energy performance of the house as well as on the quality of the air has been analysed.

Keywords - Numerical Simulation, Airflow, Energy efficiency, Indoor Air Quality, Dwelling Control System

1. Introduction

Building energy consumption has increased from 20% to 40% in developed countries, and the HVAC (Heating Ventilating and Air-Conditioning) systems account for almost half the energy consumed in buildings [1]. So, since building thermal systems are major consumers of energy as far as their construction, operation and maintenance are concerned, energy simulations of buildings are critical for optimizing the energy demands. They can give vital information of the peak loads during the heating and cooling seasons, room temperatures and velocity distributions for maintaining an adequate indoor environment, and overall energy demands during a year. This information can be used, for example, at the design of the HVAC to reduce energy costs.
Buildings can be considered as thermal systems interacting with the surroundings through heat transfer and fluid flow processes. The prediction of the thermal behaviour of buildings is challenging due to the large and complex geometry involved, transient boundary conditions, natural convection airflows, stack and wind effects, infiltration of ambient air and mechanical ventilation, and the mixture of free and forced convection flows which are often turbulent. A numerical approach to handle the heat transfer and fluid flow in such systems not only helps in saving the full scale experiment time and cost, but also helps in optimizing the governing parameters for the efficient functioning of the entire system, including HVAC.

The air quality inside buildings is one aspect that is increasingly receiving more attention and is a key aspect in HVAC design of a building. Three main sources are responsible for indoor air pollution in buildings: presence and activities of occupants, construction materials and furniture and the external environment.

The indoor air quality (IAQ) discipline includes many aspects and it is difficult to define because there are many pollutants that can affect air quality. The most important are the volatile organic components (VOCs), microorganisms, CO and NO. Given the difficulty and the cost of measuring these components (chromatographs should be used to make accurate analyses) and especially due to the low concentrations of such substances in buildings, CO₂ is used as an indirect indicator of air quality. The amount of CO₂ present in the buildings is not dangerous per se, but since CO₂ is emitted by humans when they breathe, it gives an idea of how clean is the air in a building and the degree of ventilation. To maintain pollutants at acceptable levels, the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) has established minimum quantities of fresh outdoor air that is to be supplied to buildings in order to dilute and flush out the pollutants. Therefore, it is common practice to measure CO₂ levels to determine if these recommended quantities of fresh air are being provided to the space being measured.

The present work has been developed within the “Dwelling Climate Control System (DCCS)” project [2], one of its main objectives is to develop an affordable, easy to use and apply, integral dwelling climate control system in order to reduce the energy use of buildings and improve the air quality by optimizing the parameters of the heating and ventilation systems. For the achievement of such objective, a real dwelling (a semi-detached house in the Netherlands), has been chosen and has been modelled with an in-house modular object-oriented building simulation tool. That virtual building model has been used as a test bench for the testing of the developed control system. The developed control system controls two systems in the building: the boiler, through the water setpoint temperature (which also acts as the on/off mechanism), and the ventilation system, through the whole-house extract fan speed.

One of the key aspects of the test bench has been the airflow model of the house, so it has been carefully validated and is explained in the present paper.

At the end, the thermo-fluidic simulation of the test bench under three different control situations has been analysed.
2. Modelling approach

The NEST-Buildings [3] is a parallel object-oriented code (written in C++) for building performance simulation. The overall model is based on several predefined classes that provide abstraction of the involved physical phenomena, equipment, boundary conditions and events. For illustrating this, the sketch of a house (walls, windows, outdoor, radiation element, rooms, ground, etc.) and its corresponding NEST-Buildings conceptual graph view is shown in Figure 1.

Thus, the elements can be linked to each other to form a specific building or room configuration. This makes easy to create new configurations by adding or removing elements to/from the overall model. Each element can be represented in any form as long as it can exchange the necessary boundary information from the rest of the elements in the system. Such an approach gives flexibility of choosing a model for each element and having different levels of modelling (lumped volumes, 1D, CFD&HT...) for different elements in the system without changing the basic program structure. Furthermore, the numerical calculations can be easily done in several parallel processes as the models are uncoupled to each other at code level.

Airflow model. Verification and validation

One of the key aspects of the test bench is the ventilation in the house. In the present section the validation of the airflow model is presented. The validation of the thermal model was presented in a previous work [4]. The airflow model takes into account not only the natural ventilation but also the mechanical one.

The natural ventilation is driven by the action of two main forces: wind and temperature gradient between external and internal air. The wind hitting a building
creates a positive pressure in façades facing the wind, and negative pressure in the opposite façades. Air can thus flow in the building through their openings and infiltrations from zones of high pressure to the ones with lower pressure.

The difference of temperature between outdoor and indoor creates a difference in the air density which generates a gradient of static pressure between the indoor and the outdoor. This gradient of pressure generates air circulation inside the building. Typically the air comes in through the low level and leaves through the high level of the building.

These two forces of natural ventilation act simultaneously, they can be combined and increase the air flow rates or opposite and decrease the ventilation. They are variable in the time and depend on the location and weather conditions.

Natural ventilation is not enough sometimes to achieve the minimum ventilation required in the building, hence mechanical ventilation is used in order to extract poor air and maintain minimum ventilation rates. Single flux exhaust fan system has been used in the test bench.

The numerical model for the airflow between rooms resolution is based on the division of the house into different elements (separate rooms and ventilation channels) where the air is flowing and these in turn are divided into a given number of control volumes depending on the type of the element. For example, the air in a room is represented with only one control volume (CV) and the air through a ventilation channel is divided into an arbitrary number of CVs. For each CV a grid node is assigned at its center where pressure, temperature and velocity values are evaluated.

The general governing equations of continuity, momentum, energy and CO₂ concentration transport, over any of the element CVs described above, are written in terms of the local averaged fluid variables:

\[
\frac{\partial m_r}{\partial t} + \nabla \cdot \dot{m} = 0
\]

\[
\frac{\partial (\rho v)}{\partial t} + \nabla \cdot (\rho \dot{v}) = \nabla \cdot (\rho \varepsilon_k) + \nabla \cdot (\rho \omega)
\]

\[
\frac{\partial m_r (\bar{h} + \bar{e_c})}{\partial t} + \nabla \cdot (\dot{m} v) = \nabla \cdot (\rho \varepsilon_k) + \nabla \cdot (\rho \omega) + \dot{Q}_{\text{wall}}
\]

\[
\frac{\partial (m C)}{\partial t} = \nabla \cdot (m C) + \dot{Q}_{\text{wall}} + \dot{C}_{\text{src}}
\]

where \( m \) is the mass of air contained in the CV; \( \dot{m} \) is the mass flow rate; \( \dot{v} \), the velocity, \( F_s \) are the forces exerted on the CV (pressure, friction, buoyancy, …), \( \bar{h} \) is the enthalpy, \( e_c \) is the kinetic energy, \( p \) is the pressure and \( \dot{Q}_{\text{wall}} \) is the convective heat transfer between the air inside the element and the walls, \( C \) is the concentration of CO₂, \( C_{\text{src}} \) is the CO₂ concentration generated due to people activity.

The pressure-velocity coupling is resolved by means of the SIMPLE method. Pressure drops due to fluid flow through openings, such as windows and doors, are taken into account with semi-empirical correlations.

Fan in the mechanical ventilation system is assumed to provide a previous known pressure difference, \( \Delta p \), to overcome pressure drops within the tubes at a given pressure (electricity use for the fan has not been considered). Open/close doors and
windows schedules are imposed for considering the effect of dynamic events in the flow model.

The air flow model has been validated by the comparison with the analytical results of seven tests cases [5], the most significant ones are (see Figure 2 and Figure 3):

1. **Monowind** allows testing only the action wind in a single zone building having two orifices located in the same height.
2. **Monostack** allows testing the air circulation due to only stack effect inside a single zone building having two orifices located in different heights.
3. **Monows** combines the two above tests, it shows the effect of stack and wind forces on air flow inside a single zone building.
4. **Three zones building** having orifices in different heights, the effect of wind and temperature combined has been tested.

![Figure 2. Airflow model validation cases. (Left) test1 Monowind. (Right) test2 Monostack.](image)

![Figure 3. Airflow model validation cases. (Left) test3 Monows. (Right) test4 three zones.](image)

Table 1 shows the mass flow rate through the orifices in the four analysed cases. It can be stated that in the four test cases a good agreement has been found between numerical and analytical solution.

<table>
<thead>
<tr>
<th>Test</th>
<th>Analytical</th>
<th>Numerical</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monowind</td>
<td>0.07541</td>
<td>0.07539</td>
<td>0.03</td>
</tr>
<tr>
<td>Monostack</td>
<td>0.00455</td>
<td>0.00456</td>
<td>0.21</td>
</tr>
<tr>
<td>Monows</td>
<td>0.06987</td>
<td>0.07011</td>
<td>0.34</td>
</tr>
<tr>
<td>Three zones</td>
<td>0.11038</td>
<td>0.11082</td>
<td>0.39</td>
</tr>
</tbody>
</table>
3. Test Case

A real semi-detached house located in Lemmer (Netherlands), with two floors and 12 rooms (see planes of the house in Figure 4), has been virtually modelled by linking elements like walls, composite walls, glass walls, rooms, radiation calculators, outdoors, openings, ventilation tubes, radiators, boiler, ventilation box, etc. and simulated in a transient mode. The front of the house is oriented 20º azimuth. The walls are assumed to be made of common bricks and the floors of concrete. The mechanical ventilation extracts air from the livingroom-kitchen (room3), the toilet located in the ground floor (room 5) and the bathroom (room 10).

Figure 4. Planes of the simulated semi-detached house. From left to right: ground, first and attic floors.

Figure 5. Height of the house with the airflow sketch.

The control system of the house controls two systems: the boiler and the mechanical extract ventilation system. In present work three simple control strategies have been studied (see Table 2). In all them the control of the boiler is the same: Boiler
turns on when temperature of the room where thermostat is located, i.e. the living room (room 3) drops below $T_{\text{setpoint}} - \text{threshold}$, but does not turn off until the temperature rises above $T_{\text{setpoint}} + \text{threshold}$. The boiler control is a simple timer with room setpoint temperature settings according to the occupancy schedule.

In the first case the ventilation fan does not work, rooms are closed (just infiltration are considered). In the second case, the control of the ventilation system is assumed to run at the lowest fixed speed setting, which is the default manual setting for most households. In the third case the controller controls the fan speed according to the occupancy schedule, the fan speed is the minimum (1) when the house is not occupied and to a higher speed (2) when it is occupied.

In the three situations the rooms are kept closed and just infiltrations through the doors are considered. Infiltration is set to assure minimum required ventilation rates in mechanical ventilated houses at minimum fan speed.

<table>
<thead>
<tr>
<th>case</th>
<th>Ventilation control</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>No – fan does not function</td>
</tr>
<tr>
<td>2</td>
<td>No – ventilation speed is constant</td>
</tr>
<tr>
<td>3</td>
<td>Yes – fixed schedule</td>
</tr>
</tbody>
</table>

An occupancy schedule which is the same during weekdays and different for the weekend has been used and shown in Figure 6. An adult couple living in the house. On Saturday two guests visit the house in the evening. Mainly the living room, bedroom and sporadically the bathroom are used. All doors are closed, however infiltrations through doors and windows are considered. Three days have been simulated: from Friday to Sunday. Nevertheless, simulations start 24 hours before in order to have a more reliable initial map of temperatures, velocities and pressures at the beginning of the two or week analysed days. So, the total simulated time is 96h for these 72h tests.

Simulations were performed in February, using the weather for a typical year in Eelde, Netherlands (closest meteorological station to Lemmer, where the real test bench is located [6]). A typical winter week has been chosen: temperatures around 0°C, 2 sunny days and 2 cloudy days, and not windy.

![Figure 6. Occupancy patterns and activity levels for 2 occupants, o1 and o2, plus two guests, o3 and o4, over the 72hr Friday - Sunday period.](image)
The thermal performance of the house without air flow model was previously analysed in detail in [4].

4. Results

The left side of Figure 7 shows the thermal characteristics for the three studied cases. It includes the room setpoint temperature from the controller and the resulting temperatures in the various rooms. The room 3 is the living room and kitchen, 5 is the downstairs toilet, 10 is the bathroom and 8 the master bedroom. Solar irradiation on two external vertical façades is also shown, along with the external air temperature. Thermal behaviour of the whole house in the three situations is very similar, especially in heated rooms. However, it can be observed that in case 1 at the beginning of the first day, Friday, the house is at higher temperature than in the other two cases. This is due to the fact that in this case there is not ventilation, so the house does not cool down by the infiltrated fresh air.

The ventilation characteristics are depicted in the right side of Figure 7 and show the resulting CO\textsubscript{2} levels in the rooms, along with the exhaust duct and ventilation set point. The CO\textsubscript{2} levels are a function of occupancy and changes in ventilation rates due to temperature and pressure driven ventilation effects.

CO\textsubscript{2} profiles follow the occupancy schedule: at night the CO\textsubscript{2} concentration increases in the bedroom. The air quality in this room would be regarded as poor. On Saturday, when there are two guests in the living room, CO\textsubscript{2} concentration in the living room increases noticeably. On Sunday, the occupants spend almost all day in the house, except for couple of hours at lunchtime, CO\textsubscript{2} profile shows two peaks according to these occupancy periods. When occupants leave a room, an exponential decay of CO\textsubscript{2} is observed. The higher is the fan speed, the greater is the decay.

Case 2 shows higher CO\textsubscript{2} levels than case 3, mainly in those periods where in case 3 fan speed is set to 2. CO\textsubscript{2} concentrations in bedroom are similar in these two cases since in case 3 for night period (for noise reasons) fan speed has been set to the minimum speed, which is the same as in case 2. Anyhow it can be clearly seen the beneficial effect of having mechanical ventilation since the CO\textsubscript{2} concentration is much higher in case 1.

For comparison purposes a set of performance indicators have been defined. They measure the differences of the different cases in terms of energy consumption, air quality and thermal comfort and are defined as follows:

*Energy consumption performance indicator (ECPI)*: Sum of the heat output from all the radiators of a room during a simulation period. ECPI is in kW·h.

*Air quality performance indicator (AQPI)*: The duration that a room when occupied (one or more people present) has a CO\textsubscript{2} level above the threshold of 1200ppm (which is given as air quality limit in Dutch regulations). AQPI is in ppm·min, thus gives an indication of the duration and magnitude that the threshold CO\textsubscript{2} level has been exceeded.
Figure 7. (From top to bottom) Case 1, case 2 and case 3. (Left) Temperature evolution of different rooms, setpoint and ambient and solar irradiation on south and north façades. (Right) CO$_2$ concentration evolution of different rooms and at exhaust duct, and ventilation setpoint.
Table 3 shows performance indicators for the three studied cases. ECPI indicator is higher for cases where ventilation is working, but AQPI are smaller. From a thermal and fluido-dynamic point of view it is logical: for those cases where ventilation is working means that the air sucked by the ventilation system is replaced by air coming from the outside, that it is much colder that the inner (heated) air. For that reason the heating demand is greater, which is translated directly to a higher ECPI. Case 3, since higher ventilation fan speed is used, higher is the amount of cold air that enters the house, thus, the heating demand is higher. On the other hand, since the house is more ventilated, the CO₂ concentration is lower, so the AQPI is better.

Table 3. Performance indicator of the three studied cases.

<table>
<thead>
<tr>
<th></th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECPI3</td>
<td>62.7</td>
<td>86.1</td>
<td>93.3</td>
</tr>
<tr>
<td>ECPI2</td>
<td>19.3</td>
<td>25.2</td>
<td>27.0</td>
</tr>
<tr>
<td>ECPI7</td>
<td>16.7</td>
<td>22.0</td>
<td>23.7</td>
</tr>
<tr>
<td>ECPI8</td>
<td>17.5</td>
<td>23.0</td>
<td>24.9</td>
</tr>
<tr>
<td>ECPI9</td>
<td>21.9</td>
<td>28.5</td>
<td>30.6</td>
</tr>
<tr>
<td>ECPI110</td>
<td>19.7</td>
<td>26.0</td>
<td>28.2</td>
</tr>
<tr>
<td>TOTAL</td>
<td>157.9</td>
<td>210.9</td>
<td>227.7</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>AQPI3</td>
<td>2.33·10⁶</td>
<td>1.02·10⁷</td>
<td>0.00·10⁸</td>
</tr>
<tr>
<td>AQPI8</td>
<td>4.77·10⁶</td>
<td>9.71·10⁵</td>
<td>1.03·10⁶</td>
</tr>
<tr>
<td>TOTAL</td>
<td>7.09·10⁶</td>
<td>9.82·10⁵</td>
<td>1.03·10⁶</td>
</tr>
</tbody>
</table>

5. Conclusions

A virtual building model of a dwelling has been built-up and tested at three different control situations. The effect of the ventilation on the air quality and the energy performance of the house has been analysed.

Acknowledgment

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References