The influence of air transport in and around the building envelope on energy efficiency of the building

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ABSTRACT: Air movement in and through the building envelope often plays a leading role in the transport of moisture and heat into the building. It is caused by pressure and temperature variations around the building envelope. Pressure changes are caused not only by the weather conditions, but also by the ventilation system, the distribution of air leakages, building geometry, occupant activities, etc.

In order to predict the influence of the air movement on the building performance, it is necessary to make an analysis of the building as a system. This paper presents such system analysis, taking into account the interaction between the building components and indoor and outdoor climate, both in terms of air leakage and heat and mass transfer to and from the building components.

1 INTRODUCTION

This paper presents state of the art in developing an integrated building design toolbox for an overall system analysis in building physics. It shows how different building components, each developed separately and with the sound physics in the background, are assembled in a system with a very complex nature – a house. The goal is to improve analyses in energy consumption and durability of the construction, by taking into account the effects that various subcomponents have on the building as a whole.

The toolbox is developed as a modular simulation tool, with an advantage that components and systems can be changed and adjusted to specific user demands. For that reason, it is designed in Simulink, a graphical programming language built on the top of Matlab (MathWorks), which provides necessary environment.

All components in the toolbox are made as block diagrams. A 'block' is a common term for the basic element in modeling process. Five categories of blocks have been defined: constructions (e.g. walls and windows), zones (e.g. room models), systems (e.g. HVAC systems), helpers (e.g. handling of weather data) and gains (e.g. internal heat gains). One example is given hereafter (Fig. 4).

Blocks are easily assembled in more complex structures by signals with well-defined data flow, (Rode et al. 2002). Unique signal structure and material database definition are the "backbone" for a separated and leveled development of the components. A graphical approach enables a clear overview of the complex interaction between different parts of the model.

To illustrate this, we investigated a house with normal external and internal heat, air and moisture loads. Structural details, materials, meteorological data and applied equipment are designed in such details to represent the reality in a credible way. From the number of data that resulted from this simulation, the ones that illustrate the sensitivity of airflow paths regarding the wind caused pressure fluctuations in surrounding air are presented.

2 MODEL OF THE HOUSE

Instead of designing the model house from scratch, we tried to collect necessary input data from the existing one with measured performances. This appeared as a problem, although such complete measurements, which cover heat, moisture and air at the same time, are rarely available. So far, we used data provided in the report for the "Optima house", (Elmroth & Fredlund 1996). The data are used to certain extent. Building envelope type and air flow characteristics for the dynamic insulation, ventilation system and cracks are similar to the original version; still, the model is simplified to one floor and one zone, while the real building has crawl space and attic, as well as other common partitions inside the dwelling. By this we focused our investigation on the functionality of the dynamic insulation as a whole.

A single-family house in one floor, with a living area of 96 m^2, is shown in Figure 1. The external timber frame construction walls are with 145 mm cellulose insulation. The internal lining consists of 13 mm plaster board underlined by vapor barrier, and the outside consists of 9 mm plasterboard and facing brick.

The ceiling (attic floor) consists of 250 mm cellulose, 45 mm air space and 13 mm plaster board.

Windows are doubled glazed sealed units with U-value of 1.5 W/m^2K. The total window area is 15 m^2, of which 5 m^2 are placed in the north wall and 10 m^2 in the south wall.

The house is placed in an open area and exposed to the climate described by the Danish Reference Year. Internal heat and moisture loads are the result of an interaction between construction components, HVAC systems and prescribed climate conditions. In addition, a constant internal moisture supply 4g/m^3 is applied throughout the simulating period.

The Simulink model for the house from Figure 1 is presented in Figure 4.

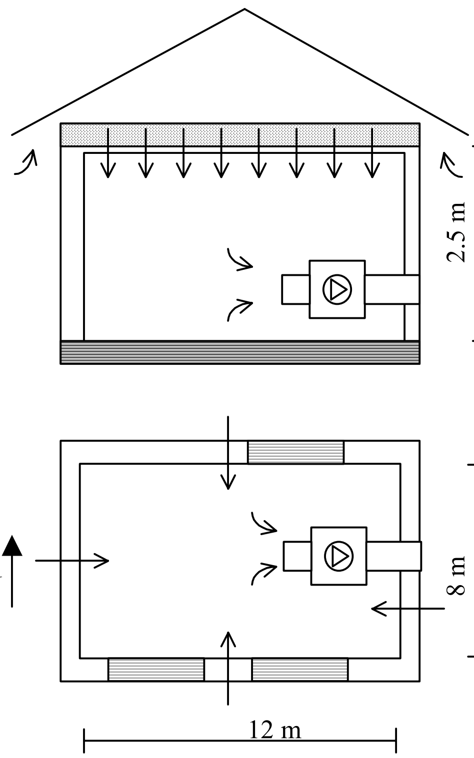


Figure 1. Section and plan of the house. Airflow paths are indicated with arrows.

2.1 *Heating system*

The house is heated by an integrated floor heating system which is set to the 21°C indoor air temperature, and controlled by the simple on-off system. The water temperature, with the mean value of 35°C and flow of 0.2 l/s is calculated regarding the heat flow through the floor construction.

2.2 *Ventilating system*

The house ventilation system design originates partly from the optima house concept, (Elmroth & Fredlund 1996). In brief, the supply air is drawn into the house through the attic floor by the fan, which provides constant inner below-atmospheric pressure during the operation. On its way through the attic insulation, the air is filtrated and preheated before it enters the dwelling. The whole system is found to be an alternative to the classical mechanically balanced ventilation, where the air is drawn in through intentional openings by additional supply fan and therefore without preheating.

The optima house is of the modern "air-tight" design; still, some unintentional air leakages were registered and measured during the investigation.

For the presented calculations, the reported flow characteristics for the attic floor and unintentional openings are used, as well as the airflow through the fan and pressure difference. Details are presented in Figure 3. The attic floor characteristic includes the characteristics of insulation and supply terminals, i.e. openings that are placed in the gypsum board underneath the insulation. A certain under pressure in the dwelling is necessary to secure the intentional performance.

From the standpoint of both filtration and preheating, it is desirable that as much as possible of the total supply airflow should really pass through the dynamic insulation. This means that the negative pressure difference between the dwelling and the surroundings shall be small enough to prevent the air from entering through leakage paths in the walls. A reasonable value is somewhere around –10 Pa or preferable –5 Pa.

By mistake, the number of supply terminals was very low (only 5), which resulted in a higher resistance of the ceiling. Although the designed airflow through the ceiling was 68 l/s, from the characteristic in Figure 3, an air pressure depression of –30 Pa was necessary to fulfill this, in the case that there are no other openings. We started our investigation from that point.

2.3 *Air pressure at the outdoor surface*

The pressure drop model of the house is shown in Figure 2. Pressure of the still outdoor air is 1atm . When the wind blows, the model calculates the actual static pressure acting on each of the outdoor surfaces, regarding the surface relative orientation to the wind direction and tilt:

$$P_{air,j} = P_{air} + C_j \cdot \rho_a \frac{\kappa \cdot S^2}{2} \tag{1}$$

where P_{air} = air pressure of the still outdoor air; $P_{air,j}$ = actual static pressure at specified surface; j = surface index; C = pressure coefficient; ρ_a = air density; S = wind speed.

The wind speed and direction are taken from meteorological data. The original value is reduced by the factor κ, which takes into account terrain profile and the building height. For this case, κ is set to 0.68, as the British standard (Sanders, 1996) for an open flat country position and 1m heights propose it. Surface pressure coefficients are given in Table 1.

Table 1: pressure coefficients on an exposed low-rise building, (Sanders 1996)

Wind angle relative to the surface*							
0°	45°	90°	135°	180°	225°	270°	315°
0.7	0.35	-0.5	-0.4	-0.2	-0.4	-0.5	0.35

* horizontal surface: -0.5

2.4 *Air pressure balance*

The fan characteristic is set to be the same as the characteristics of the ceiling. In ideal case (no other openings), the flow through the fan equals the flow through the ceiling (supply flow). That point is indicated with number 1 in Figure 3, giving the air flow rate of 68 l/s and the pressure difference of - 30 Pa.

2.4.1 *Example 1: Four leakage paths uniformly distributed in vertical walls and high air flow resistance of the ceiling*

For the first example, four unintentional openings or leakage paths with the same flow characteristics are assumed, one in each vertical wall. They are positioned in this way to illustrate the influence of the wind induced outdoor air pressure fluctuations on the whole system.

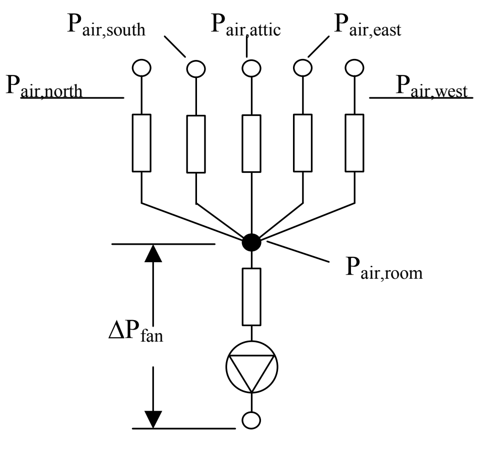


Figure 2. Air pressure drop model of the house

From the measurements on the Optima house, we have the joint flow characteristic for all indicated unintentional openings. It is given in Figure 3 as the "total leakage" line. The flow characteristic for a single leakage in this example is derived from the total one, dividing the flow by four. In the parallel scheme, the sum of all four flows is equal to the one specified with the total characteristic.

The indoor air pressure is calculated from the balance equation for all flows in and from the house:

$$\sum_j k_{a,j} \cdot (P_{air,j} - P_{air,room}) - q_{fan} = 0 \tag{2}$$

where $k_{a,j}$ = air conductance; q_{fan}= air flow through the fan.

All flows are defined as positive when they are directed into the house.

2.4.2 *Example 2: Four leakage paths uniformly distributed in vertical walls and low air flow resistance of the ceiling*

The second example is similar to the first one, but the supply air flow characteristic is improved – the same flow as in Figure 3, but 6 times lower pressure drop. The fan is again adjusted to the ceiling, having the flow rate of 68 l/s at the pressure difference of –5 Pa (point marked with number 2 in Figure 3). The leakage flows are the same as in the previous example.

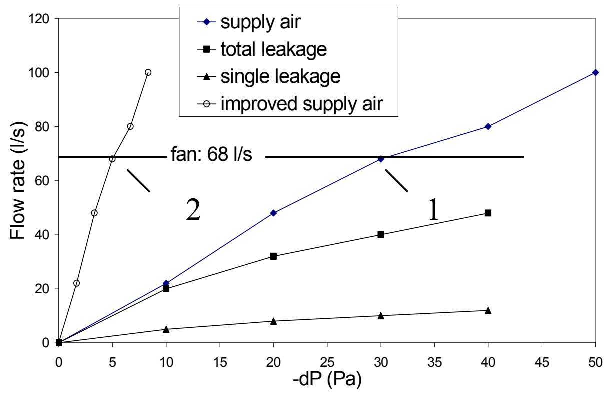
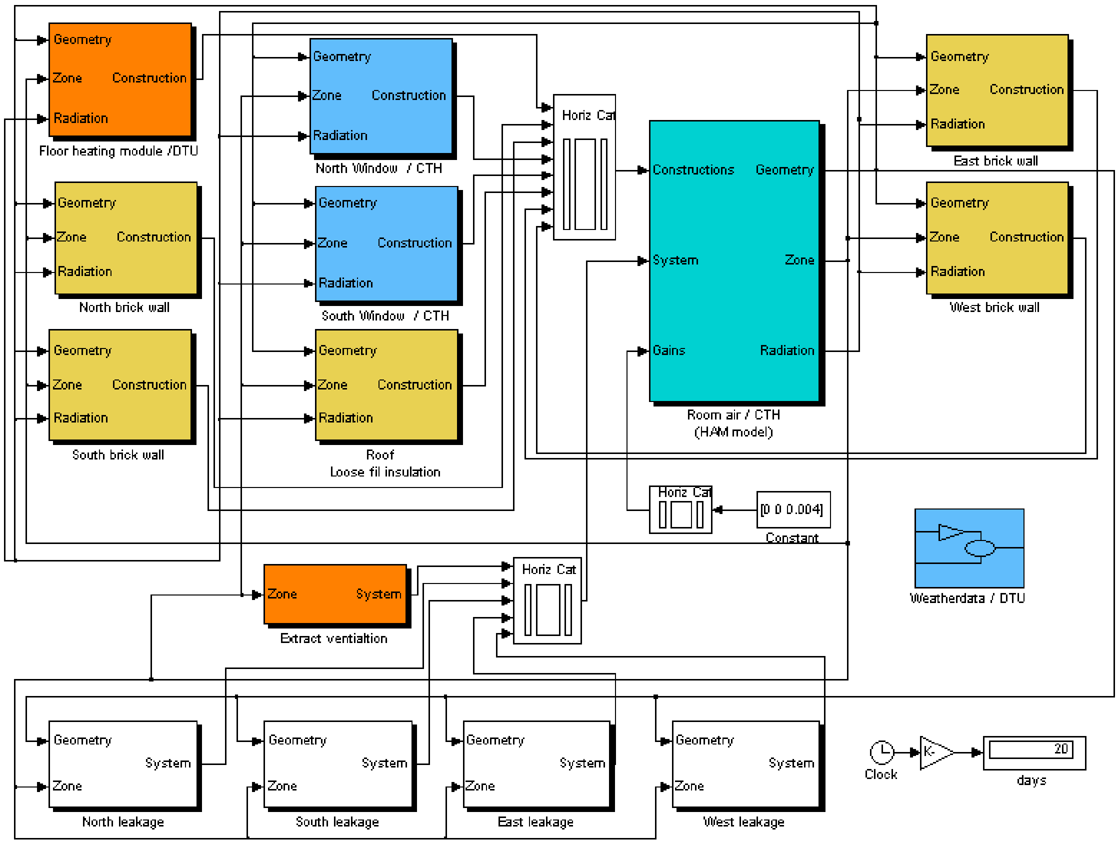


Figure 3. Flow characteristics for the supply air and air leakage paths.

3 RESULTS

3.1 *Air flow analysis*

Results are given for one of the windiest period in the coldest month – the second week of January. Static pressures against each of indicated surfaces are presented in Figure 5. The windy period is indicated with the pressure fluctuations around zero



Firuge 4. Simulink model of the house from Figure 1.

(the wind speed is about 5 m/s) . The windward side came to be the west wall.

Results for the first example are presented in Figure 6. Airflows through all indicated openings are presented in percents of the fan flow: the supply flow through the ceiling and four leakages in northern, southern, eastern and western wall.

The airflow distribution through the openings is a result of the total system performance – a superposition of all indicated flows with the fan. Although the joint characteristic of all air leakages is close to the ceiling characteristic, they significantly influence the airflow distribution, even under small pressure differences (or a weak wind). When the wind blows, due to such pressure distribution around the building, the airflow through the ceiling is almost stopped and the cold, non-preheated air is drawn into the dwelling through air leakages.

Results from the second example are given in Figure 7. They show better performance of the supply flow system compared to the leakages, but similar system sensitivity to the outdoor air pressure fluctuations.

3.2 *Heat loads analysis*

Due to the system complexity, a lot of different effects are taking place at the same time, influencing each other: convective and radiative heat exchange with the surrounding, solar radiation, moisture transport inside the building materials and to the surrounding with latent heat effects, ventilation, dynamic insulation, etc. For the present study, the heat loads analysis is focused on the ventilation effects and dynamic insulation efficiency. The control surface for the heat losses calculations is placed on internal side of the walls, e.g. the indoor air temperature is the reference one.

The calculated indoor air temperature (for both cases) and the outdoor one is presented in Figure 8. For better understanding the ongoing processes, two periods are indicated: one with the lowest outdoor temperature and the weak wind, the other with the moderate outdoor temperature but the strong wind.

Due to the heating system efficiency, the ventilation heat losses do not affect the thermal comfort inside the house – the indoor air temperatures are of the same order in both cases. Still, the heating system should be redesigned regarding the desired (21°C) and achieved indoor air temperature.

Ventilation heat losses through air leakages are given in Figure 9; they are greater in the first example than in the second one. The difference is however decreased when the wind acts and the flows are of the same order.

The heat loss through the ceiling is illustrated in Figure 9; the first part represents the ventilation heat loss due to the air that is coming through the insulation, the second one is the convective heat flux

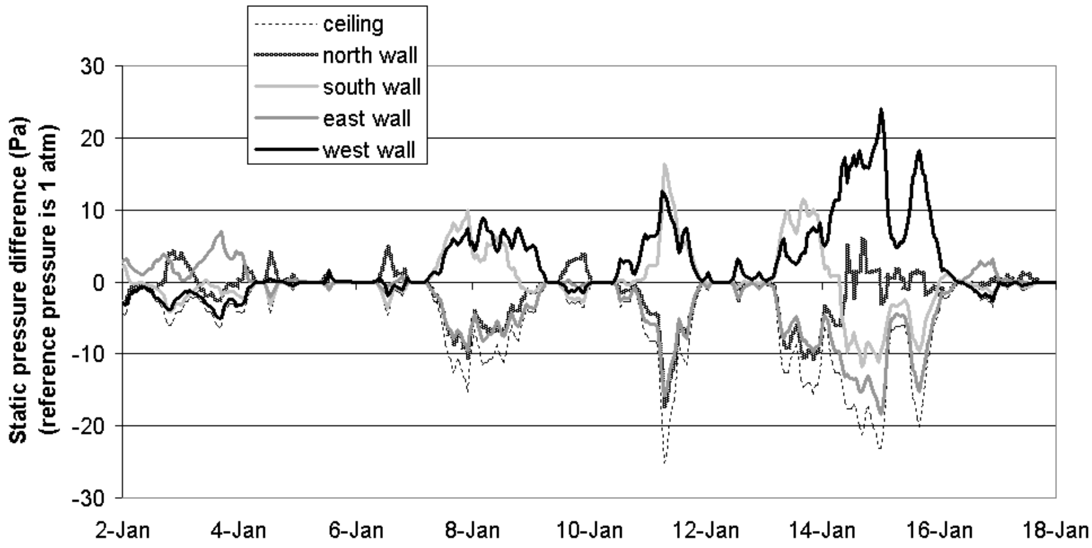


Figure 5. Static pressure difference (against the reference pressure) at each of the surfaces.

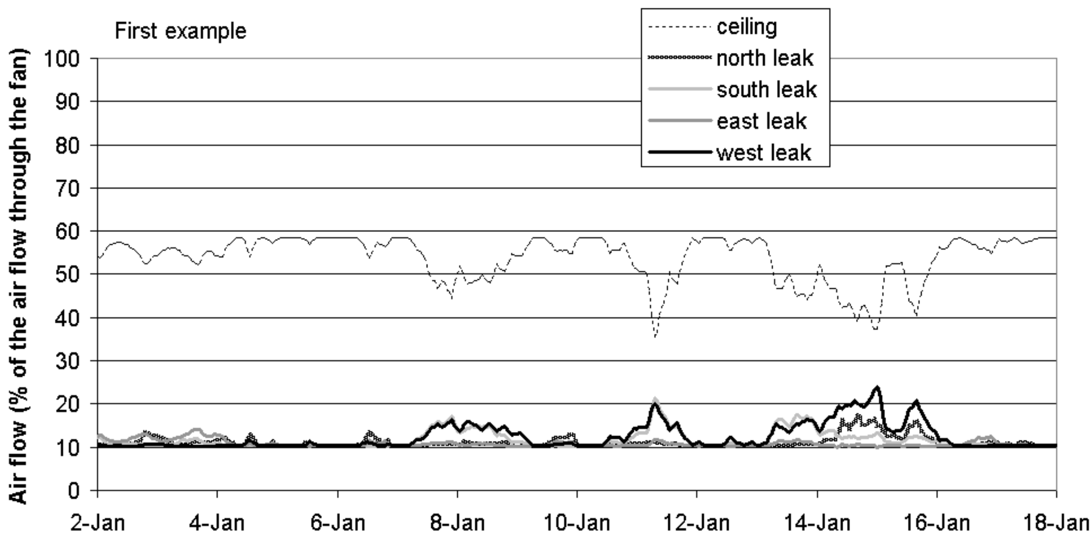


Figure 6. Results for the first example. Air flows through indicated openings.

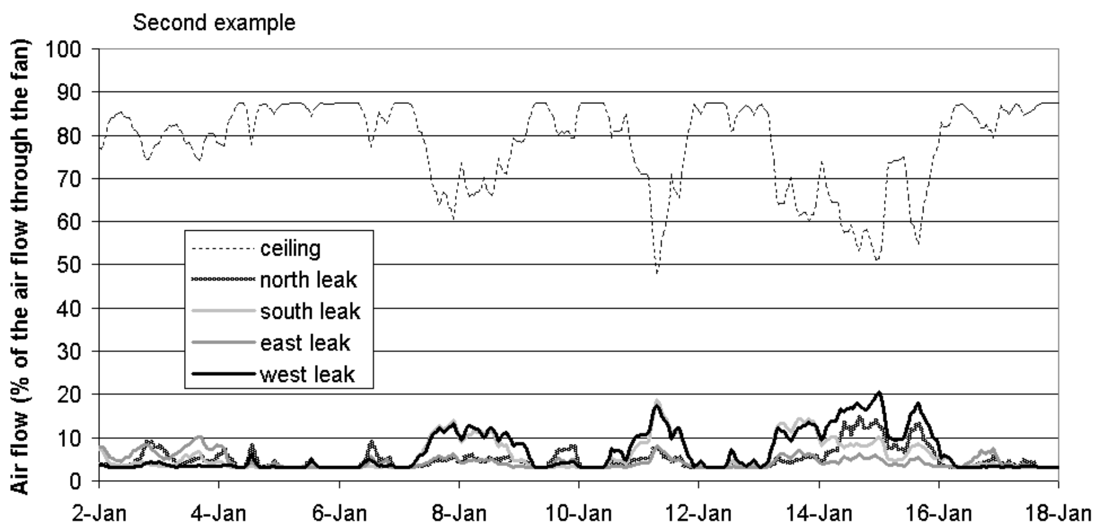


Figure 7. Results for the second example. Air flows through indicated openings

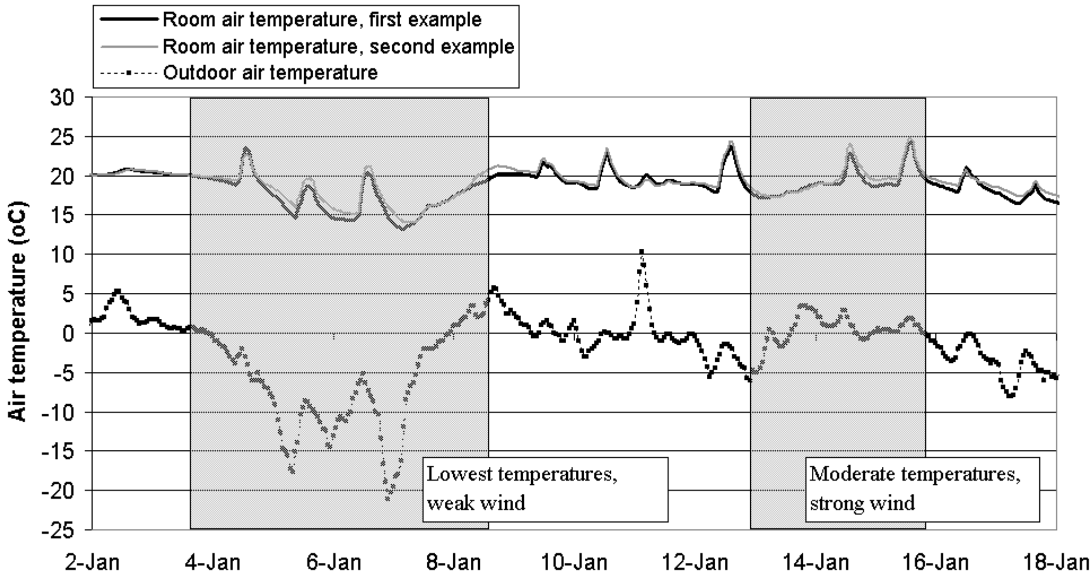


Figure 8. Room and outdoor air temperature.

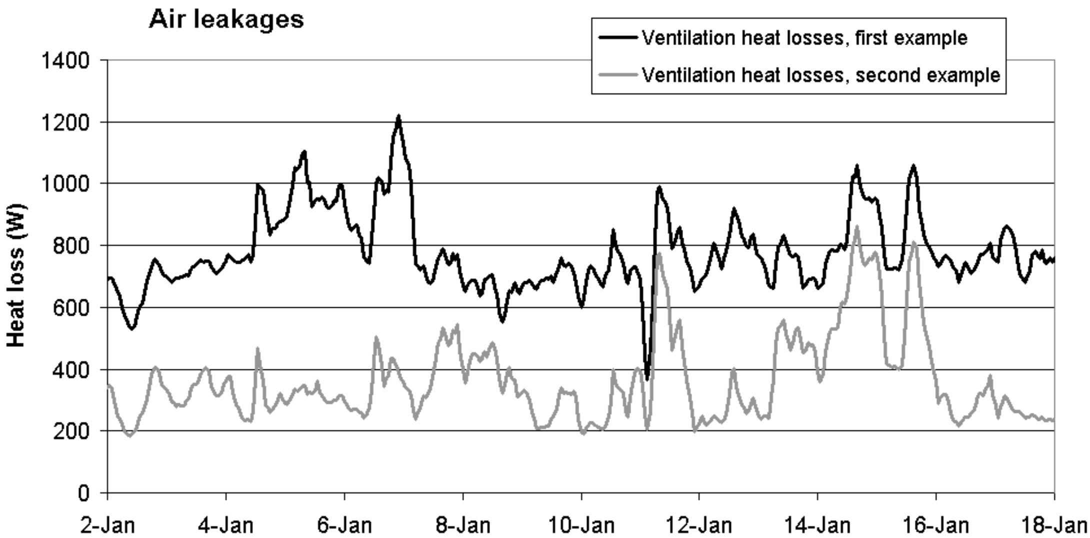


Figure 9. Ventilation heat losses through leakages. Indoor air temperature is the reference one.

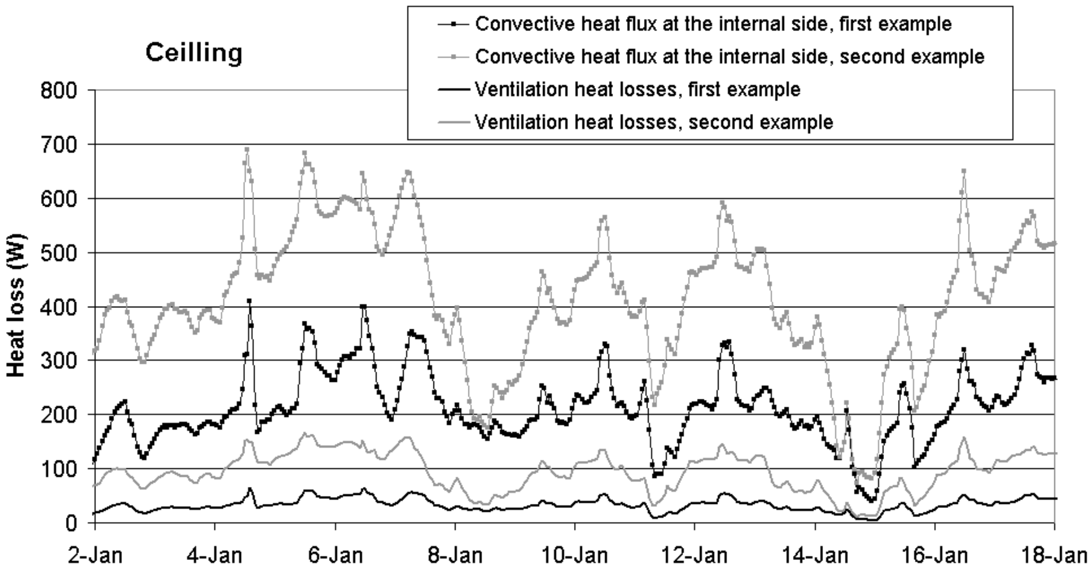


Figure 10 Heat losses through the ceiling. Indoor air temperature is the reference one.

between the indoor air and ceiling internal surface. Although the airflow through the ceiling is lower in the first example than in the second, the ceiling is generally warmer and as a result, both ventilation and convective heat losses are also smaller.

The real effect of the dynamic insulation can be seen through the heat consumption of the space. In the first example, and for the period indicated in figures, the heat input from the floor heating system was 1055.6 kWh, and in the second 1030.9 kWh. The improved air flow characteristics of the ceiling resulted in 24.7 kWh energy saving.

4 CONCLUSION

In the presence of air leakages, the actual airflow path through the house significantly deviates from the intended one.

The deviation is greater when the actual pressure differences caused by the wind are taken into account.

In order to analyze the airflow distribution in a house, the characteristics for all intentional and unintentional openings should be known. The influence of stack effects, sudden pressure disturbances due to door openings, cracks in the walls, etc., are the effects that should be considered in the future in order to improve the analysis.

By using the integrated building simulation codes, the influence of different design decisions can be investigated quickly, allowing the feedback of analysis results to various design disciplines.

5 MODEL VALIDATION

The model is still under construction and therefore not all of the used components are developed in details or fully validated.

Wall blocks are designed in accordance with the modeling procedure for 1-D transient heat, air and moisture numerical calculations, (Hagentoft, 2002a). The cited document is a reference document for the European standard proposal (CEN/TC 89). Blocks are validated through the inter-model comparison and details can be found in (Hagentoft, 2002b).

Room air is assumed to be well mixed and represented with one calculating node. Heat and moisture balance calculations, including the long wave radiation exchange between the surfaces, are based on WAVO (Witt 2000).

The model for the floor heating system comes from a PhD project that is currently going on at Technical University of Denmark. A description and validation results for the model can be found in (Weitzmann 2002). The model is originally built as a Matlab code and than transformed into Simulink block by the means of an S-function. It is chosen mainly to illustrate the possibility of integrating different design tools in more complex systems.

At the moment, all leakage paths are given only by their flow characteristic. The influence of leakage geometry and airflow rate through it on thermal and moisture state of the wall is the work still to be done through the integration with other computational codes (as it has already been done with the floor heating module).

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