THE EFFICIENCY OF A DYNAMICALLY INSULATED WALL IN THE PRESENCE OF AIR LEAKAGES

by

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The movement of air in and through the building envelope often plays a leading role in the transport of heat and moisture into the building. It is caused by pressure and temperature variations around the building envelope, inbuilt ventilation system, occupancy, etc. In order to improve the energy consumption, alternative designs for the ventilation systems are considered. One of them is a dynamically insulated wall as an inlet unit for the supplying air.

In order to predict the performance of a dynamically insulated wall, it is necessary to make an analysis of the building as a system. This paper presents such system analysis which takes into account the interaction between the building components and indoor and outdoor climate, both in terms of the air leakage and heat and mass transfer to and from the building components. It is shown that, in the presence of air leakages (unintentional openings) in the enclosure of the building, the efficiency of the dynamic insulation is significantly decreased.

Key words: *dynamic insulation, air leakages, building simulations, energy efficiency*

Introduction

A dynamically insulated wall is a part of the building structure that is actively included in the ventilation system. The wall is open to the air flow, allowing that a certain or total amount of supplying air can be drawn into the building through its insulation. The aim of this concept is to preheat and filter the air. When sized correctly, the dynamically insulated wall may contribute to the energy savings of up to 30%. However, in the presence of air-leakages in the building enclosure, the actual flow rate through the dynamic wall can significantly differ from the calculated one.

The Optima house is an experimental house with the dynamic insulation in the ceiling, built during 1992-1993 in Sweden. The supplying air to the house is sucked in through the insulation by a negative pressure in the living area, accomplished by the use of an exhaust fan. Measurements of the air flow rates performed on the house in operating conditions 1 , showed that only about 50% of the total supplying air flow passed through the attic insulation. The rest of the air entered the house through leakage paths, mainly discovered and measured along the wall/floor connections.

Since that particular design obtains some important information for the air transport, namely: a coupling of the inbuilt ventilation system with the breathing wall and leakages, and the measured data of the flow characteristics are provided for each of the considered air flow path, it has been used for the present analysis. The investigation focused mainly on the air flow distribution through indicated openings in the presence of the wind, and thus, on the functionality of the dynamic insulation.

Computational model

The house computational model has been composed using a special calculation tool, "HAM-Tools" [2]. The tool is developed for the building physics applications, using MATLAB / Simulink environment [3].

"HAM-Tools" is a software library specially constructed for hygro-thermal analyses in building physics. "HAM" stands for *H*eat, *A*ir and *M*oisture transport processes in a building and a building envelope that can be simulated by this program, and "Tools" describes its modular structure. Namely, the program consists of separate calculation procedures (tools), each representing a certain building part of interest, with an advantage that all elements may be changed and adjusted according to specific user demands.

Tools are designed as graphical block diagrams, fig. 4. Five categories of blocks have been defined: constructions (*e. g.* walls and windows), zones (*e. g.* room models), systems (*e. g.* *H*eating, *V*entilating and *A*ir-*C*onditioning equipment – HVAC systems), helpers (*e. g.* handling of weather data), and gains (*e. g.* internal heat gains). Each tool provides one-dimensional calculations of the heat, air and moisture transport processes. However, by combining different tools such as a single-layer wall in a multi-layer wall, a couple of different walls in a zone, several zones in a building, and finally together with climate load and HVAC equipment, this one-dimensional simulation program provides a sound representation of the three-dimensional reality.

Blocks are easily assembled in more complex structures by signals with well-defined data flow [4]. A unique signal structure and a material database definition are a "backbone" for the separated and leveled development of the components. A graphical interface provides a clear perspective of the complex interaction between different parts of the model.

Model of the house

The design of the "Optima house" follows the reality up to a certain level: building envelope type and air flow characteristics for the dynamic insulation, ventilation system and cracks are similar to the original version. However, the model is simplified to one floor and one zone, whereas the real building has the crawl space and the attic, as well as other common partitions inside the dwelling. By this the investigation is focused on the functionality of the dynamic insulation as a whole. Some design details are presented in fig. 1.

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

The ceiling (attic floor) consists of 250 mm cellulose, 45 mm air space and 13 mm plaster board. Windows are double-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 a result of an interaction between construction components, HVAC systems and prescribed climate conditions. The Simulink model for the house from fig. 1 is presented in fig. 4.

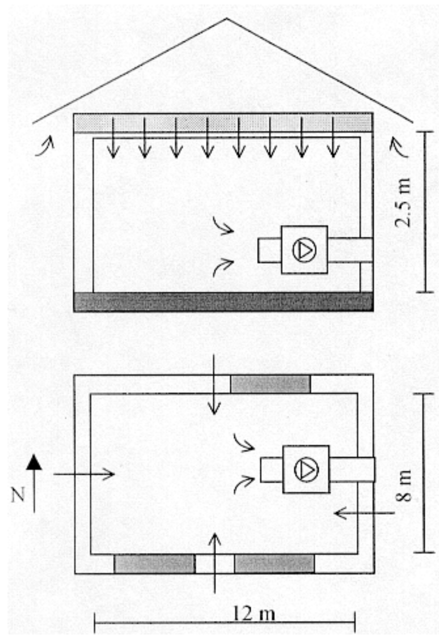


Figure 1. Section and plan of the house; airflow paths are indicated with arrows

Heating system

The house is heated by an integrated floor heating system, 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 from the heat flow through the floor construction.

Ventilation system

The design of the house ventilation system originates partly from the "Optima house" concept. In brief, the supplying air is drawn into the house through the attic floor by the fan, which in turn, provides the constant inner below-atmospheric pressure during the operation. On its way through the attic insulation, the air is filtrated and preheated before entering 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 an 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 calculations presented, the reported flow characteristics for the attic floor and unintentional openings are used, as well as the airflow through the fan and the pressure difference. Details are presented in fig. 3. The attic floor characteristic includes the characteristics of the insulation and supply terminals, *i. e*. openings that are placed in the gypsum board underneath the insulation. Certain sub-pressure in the dwelling is necessary to secure the desired performance.

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

By mistake, the number of supply terminals turned out to be very low (only 5), which resulted in a higher resistance of the ceiling. Although the designed airflow through the ceiling was 68 l/s, it is seen from fig. 3 that a pressure depression of approximately 30 Pa was necessary to fulfill this and in the case that there are no other openings. The investigation starts from that point.

Air pressure at the outdoor surface

The pressure drop model of the house is shown in fig. 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, taking into account the surface relative orientation to the wind direction and the tilt of the wall:

$$P_{\mathrm{air},j} \quad P_{\mathrm{air}} \quad C_j \rho_a \frac{\kappa S^2}{2} \tag{1}$$

where P_{air} is the air pressure of the still outdoor air, $P_{\mathrm{air},j}$ – actual static pressure at the specified surface, j – surface index, C – pressure coefficient, ρ_a – air density, and S – wind speed.

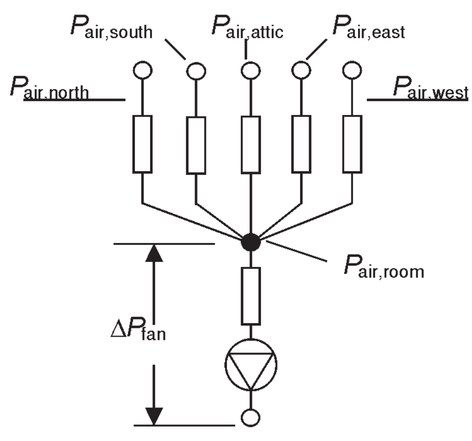


Figure 2. Air pressure drop model of the house

The wind speed and direction are deduced from meteorological data. The original value is reduced by the κ factor, which takes into account the terrain profile and the height of the building. For this case, κ is set to 0.68, according to the British standard 5 for an open flat country position and a 1 m height. Surface pressure coefficients are given in Table 1.

Table 1. Surface pressure coefficients on an exposed low-rise building 5

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

Air pressure balance

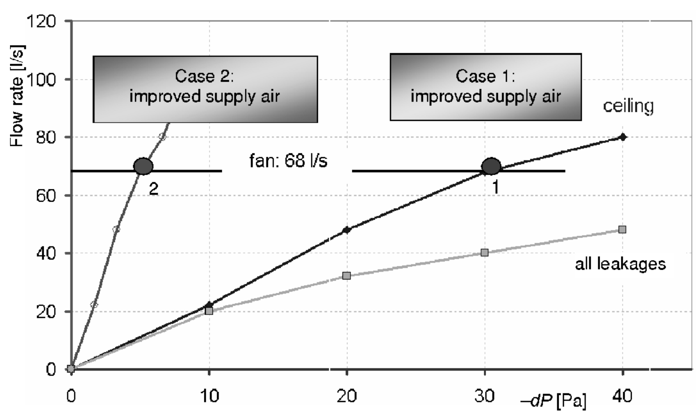
The characteristics of the fan is set to be the same as the characteristics of the ceiling. In the ideal case (no other openings), the flow through the fan equals the flow through the ceiling (supply flow). That point is indicated by number 1 in fig. 3, providing the air flow rate of 68 l/s and the pressure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

Example 1: Four leakage paths uniformly distributed in vertical walls and the 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 manner to illustrate the influence of the wind-induced outdoor air pressure fluctuations on the whole system.

From the measurements on the "Optima house", the joint flow characteristics for all indicated unintentional openings, is provided. It is given in fig. 3 as the "all leakages" line. The flow characteristics for a single leakage in this example is obtained from the joint

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



one, by dividing the flow by four. In the parallel scheme, the sum of all four flows equals the one specified by the joint characteristics.

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

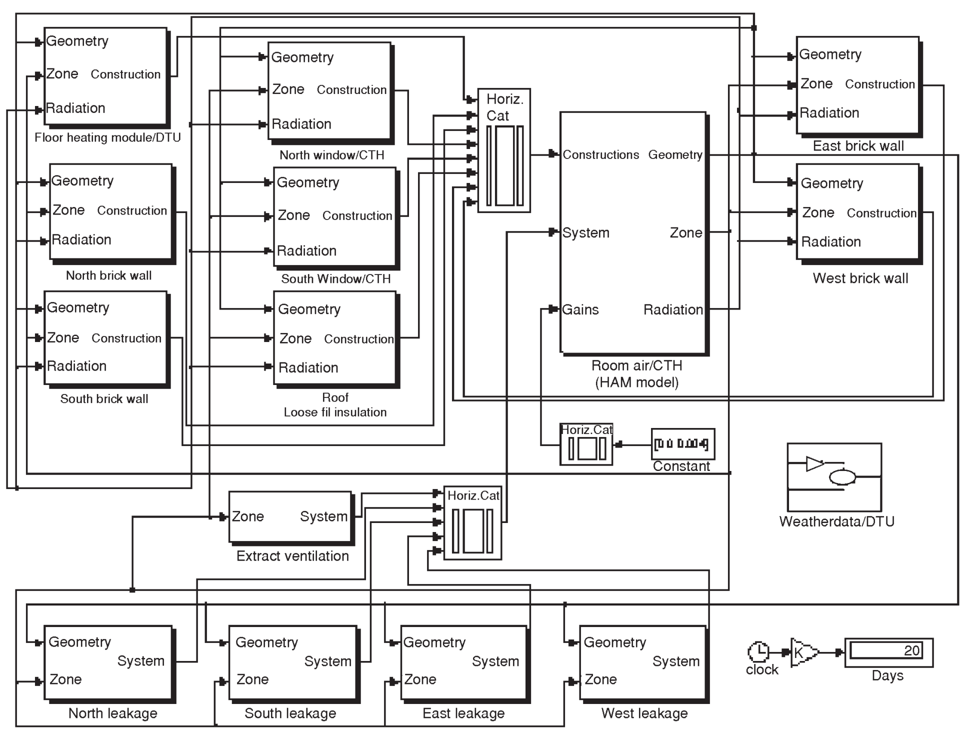
$$\sum_j k_{a,j}(P_{\mathrm{air},j} - P_{\mathrm{air,room}}) + q_{\mathrm{fan}} = 0 \qquad (2)$$

where $k_{a,j}$ is the air conductance and q_{fan} – air flow through the fan.

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

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

The second example is similar to the first one, but with the supply air flow characteristics improved – the same flow as in fig. 3, but 6 times lower the 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 fig. 3). The leakage flows are the same as in the previous example.



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

Results

Air flow analysis

Results are provided for the one of the windiest periods in the coldest month – the second week of January. Static pressures against each of indicated surfaces are presented in fig. 5. The windy period is indicated with the pressure fluctuations around zero (the wind speed is about 5 m/s). The windward side turned out to be the west wall.

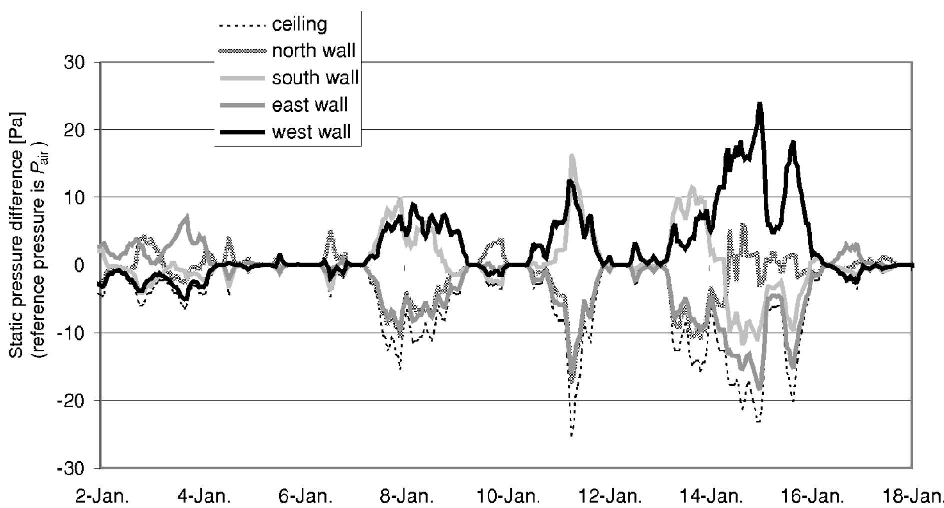


Figure 5. Static pressure difference (against the reference pressure) at each of the surfaces

Results for the first example are presented in fig. 6. Airflows through all indicated openings are presented in percents of the fan flow: the supply flow through the ceiling and four leakages in the northern, southern, eastern and the 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 characteristics of all air leakages is close to the ceiling characteristics, the leakages 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.

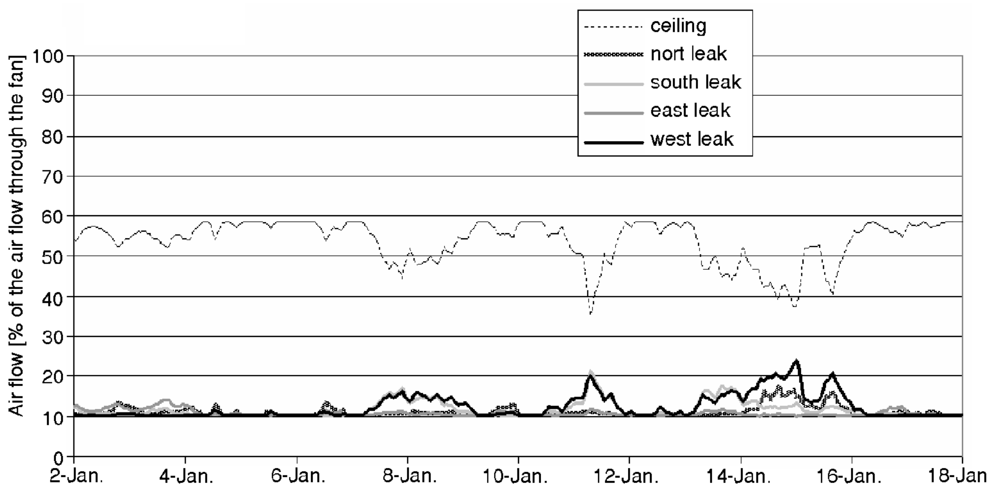


Figure 6. Results for the first example. Air flows through indicated openings

Results from the second example are presented in fig. 7. They illustrate the better performance of the supply flow system compared to the leakages, but also the similar system sensitivity to the outdoor air pressure fluctuations.

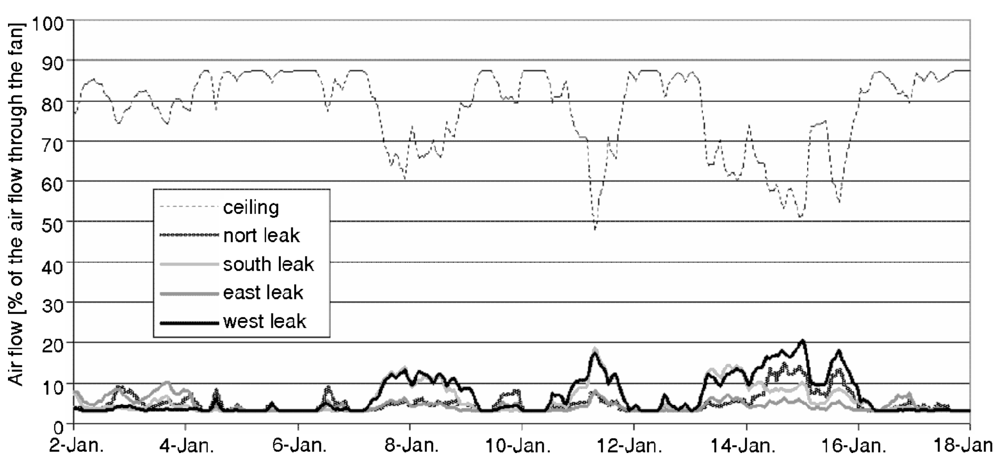


Figure 7. Results for the second example. Air flows through indicated openings

Heat input analysis

Due to the complexity of the system, a number of different effects are taking place at the same time, influencing each other: convective and radiative heat exchange with the surroundings, solar radiation, moisture transport inside the building materials and to the surrounding with latent heat effects, ventilation, dynamic insulation, *etc*. The calculated indoor air temperature (for both cases) and the outdoor one are presented in fig. 8. For the better understanding of the ongoing processes, two periods are indicated: the one with the lowest outdoor temperature and the weak wind and the other, with the moderate outdoor temperature but the strong wind.

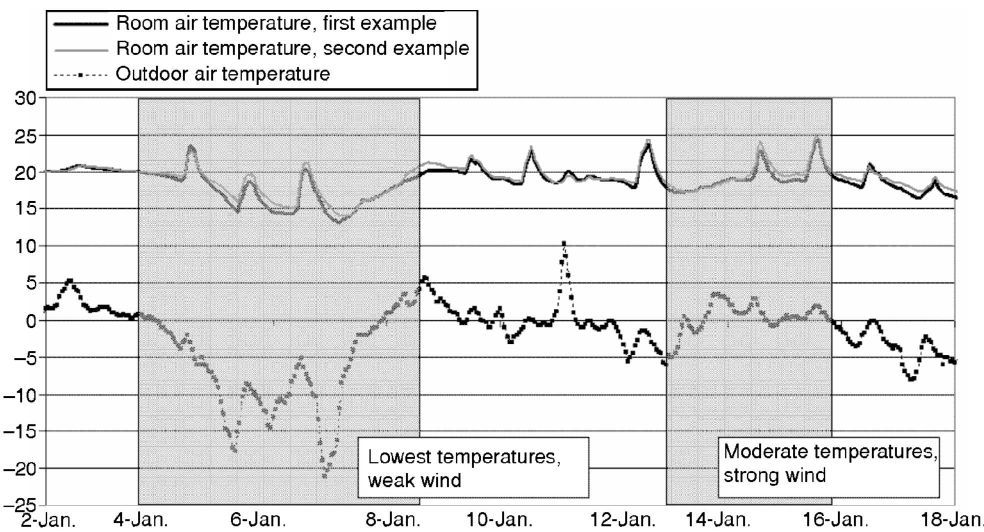


Figure 8. Room and outdoor air temperature

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 the achieved indoor air temperature.

The real effect of the dynamic insulation can be understood 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 1056 kWh, and in the second 1031 kWh. The improved air flow characteristics of the ceiling resulted in 25 kWh energy saving.

These results are afterwards compared to the heat input in the case where there exists no dynamic insulation (which is a conventional case) and with the case with no air leakages present (when the dynamic insulation is 100% active). The conventional case is chosen to be the reference one, and the energy input for each case is given as a percentage of the reference one, fig. 9. The diagram confirms the expectations concerning the dynamic insulation effect. However, numbers should be taken only as approximate and informative ones. Due to numerous dynamical effects taking place at the same time, the operating conditions may vary from one case to another.

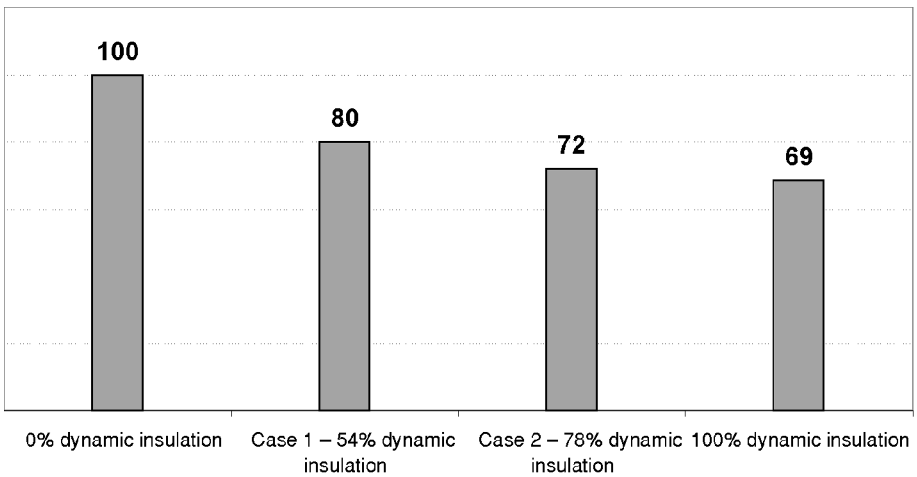


Figure 9. The energy consumption regarding the dynamic insulation efficiency

Conclusions

In the presence of air leakages, the actual airflow path through the house significantly deviates from the desired 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 readily investigated, allowing the feedback of the analysis results to various design disciplines.

Model validation

Wall blocks are designed in accordance to the modeling procedure for one-dimensional transient heat, air and moisture numerical calculations [6]. The cited document is a reference document for the European standard proposal 7 . Blocks are validated through the inter-model comparison and details can be found in 8 .

"HAM-Tools" whole model validation has been performed against measurements. As a case study, temperature and relative humidity of the cold ventilated attic space in real operating conditions, was selected. Validation results are presented as a comparison between measurements and calculations. The parametric sensitivity analyses have been performed and necessary adjustments for the lacking input parameters have been fully documented. The code has shown high degree of reliability, both in a qualitative and a quantitative way. Details can be found in 9 .

The model for the floor heating system originates from another project. Details can be found in 10 .

Nomenclature

C – surface pressure coefficient, –
j – surface (leakage) index, –
$k_{a,j}$ – air conductance, $m^3/Pa \cdot s$
P_{air} – pressure of the still outdoor air, Pa
$P_{\text{air},j}$ – static air pressure at outdoor surface number j, Pa
$P_{\text{air,room}}$ – air pressure inside the house, Pa
q_{fan} – air flow rate through the fan, m^3/s
S – wind speed, m/s

Greek letters

ΔP_{fan} – fan pressure diference, Pa
κ – terrain coefficient; defines reduction to the wind speed, regarding sheltering of the house, –
ρ_a – air density, kg/m^3

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