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Air Flow and Thermal Analysis of a Forced Air Heating and Ventilation System

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1. Synopsis

The prediction of energy use, air flows and temperatures in different rooms of a building and at different climatic conditions is very important, especially when evaluating new concepts for heating and ventilation systems in combination with different building envelope constructions. A thorough system analysis considering coupled air flow and thermal calculations becomes very complex if e.g. thermal bridges and dynamic conditions are considered. The substance of this paper is to describe a relatively simple methodology for system analysis that has been applied to a house and to compare obtained results from measurements and calculations.

The methodology consists of initial calculation of air flows using the multi-zone model IDA-MAE for different configurations and climatic conditions. The air flows are then included in a TSBI3 computer model for temperature and energy use calculations.

User-friendly computer tools that combine multi-zone air flow and thermal calculations are desired to simplify a sensitivity analysis, and this will also increase the precision in the predictions. This development is in progress internationally. Further development of field methods to measure the air leakage characteristics of building components and individual air leakage paths would be useful to increase the knowledge of especially interior air leakage paths in buildings.

The evaluated building concept, called TEEG, uses a heated crawlspace to distribute ventilation and heating air through gaps in the floors along the external walls. As the system relies on distribution of warm air through gaps in the floors, it becomes very sensitive to uncontrolled air leakage paths. Measurements of air leakage become an important quality control tool for buildings using this concept.

2. Introduction

The thermal performance of a heating and ventilation system in a building is influenced by a number of factors, as outdoor climate, heat gains and losses through the building envelope, building thermal mass, internal loads, occupant behaviour etc. In today's dwellings, the heating supplied by the heating system is far less dominant than before as a result of our concerns to save energy for space heating. In new low energy houses, about one third of the supplied energy is used by the heating system, one third for domestic hot water production and one third for domestic electricity use, which also produces more or less useful heat. This proportion could, however, vary to a great extent depending on the occupant behaviour. When designing a robust system concept, it becomes increasingly important to consider the building envelope and the heating and ventilation systems as a total system in order to obtain energy efficient buildings with thermally comfortable indoor climate.

It is then essential to predict system performance at different outdoor climates and loads. A multi-zone approach is required to find air flow patterns and temperature variations between rooms as a result of e.g. air leakage and internal loads. A system analysis could be performed using a multi-zone computer model to find the range of air flow sizes between zones and then use these results as input in a thermal model. The computer calculations should preferably be supported by measured data, because values on air leakage, especially between zones, are difficult to estimate and could vary substantially from house to house even when the same constructions are used. Computer calculations could be useful to extrapolate system performance at other loads than measured. The procedure gives a better basis for e.g. down-sizing heating equipment or lowering system temperatures etc. Estimating the yearly energy performance of the total building is then a fairly straightforward procedure.

The operating costs and long-term performance of a building concept is very important. One main concern is that air flows in ducts are maintained and not significantly reduced by contamination or that air leakage is not increased both within the living space and to the exterior or adjacent volumes as crawlspaces and attics.

The substance of this paper is to describe the application of a methodology for system analysis on a house where a heated crawlspace was used to distribute the heating and ventilation air, and to show obtained results from measurements and calculations.

3. The house concept

The studied test house was built about 50 km North of Stockholm in 1994-1995, using the so-called TEEG principle (Engwall 1994) which consist of a warm crawlspace foundation where all building services are placed. The heating and ventilation air is distributed to the living space via the crawlspace through filtered air gaps along the external walls. Separate ducts with fans from the crawlspace to the intermediate floor structure moves heated air to the second floor. Because of the uninsulated floors, the heating system works as a combination of floor and forced air heating systems. The TEEG principle is illustrated in Figure 1.

The studied house is about 220 m^2 and built in 1 1/2 - storey. It contained an office in the bottom floor and an apartment in the upper floor, which only cover about half of the bottom floor. There is no internal staircase between the floors. The house is boomerang-shaped and contains a glazed patio, wood burning stove, central vacuuming system etc. which all causes potential air leakage paths.

The heated air is intended to pass from the crawlspace (or middle floor structure) to the living area through the filtered air gaps before it is exhausted from the kitchen and bathrooms. An air-to-air heat exchanger in the crawlspace recovers heat from the exhaust air to the supply air. In order to achieve the desired direction of the air flows, the crawlspace should be slightly depressurised relative to the outside, in the order of about -2 Pa. When Radon gas is present, the pressure may have to be increased to the ambient to avoid the risk of soil gas entering the crawlspace, which is sealed from the ground by a polyethylene film with overlap joints. There is, however, a drain in the lowest part of the crawlspace. The pressure in the bottom floor has to be lower than in the crawlspace. Internal overpressures relative to the ambient should be avoided as they present a risk of moist air convection into the attic. If density-related pressure differences shall be compensated for a two storey house, the negative pressure relative to the outside at floor level for the bottom floor should be about -7 Pa (estimated using -5 °C outside and 22 °C inside).

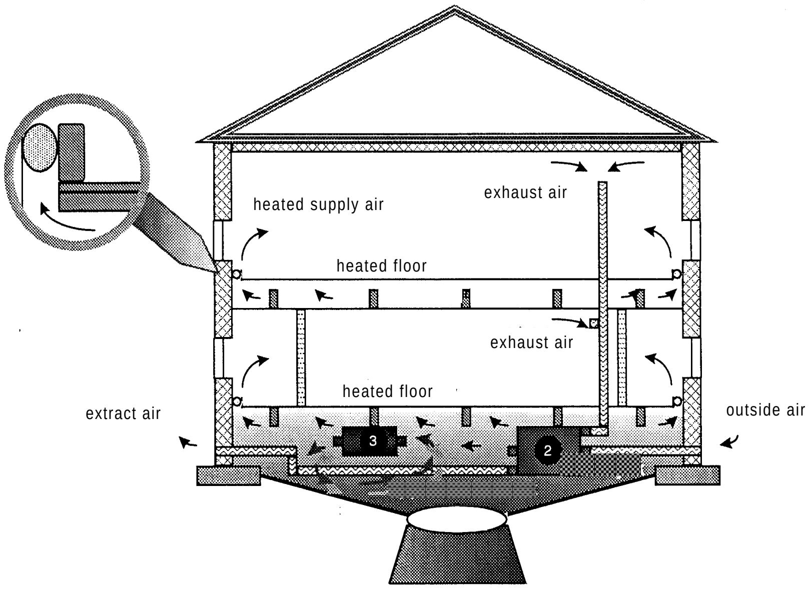

Figure 1. The patented TEEG-principle. The warm crawlspace foundation distributes heat and ventilation air in the filtered air gaps along the external walls. All building services equipment is placed in the crawlspace for easy access (Source TEEG AB).

4. Methodology and models

A thorough system analysis considering coupled air flow and thermal calculations becomes very complex if e.g. thermal bridges and dynamic conditions are considered. In this paper, a simplified analysis model is given and applied to the TEEG housing concept.

First, air flows were calculated using the multi-zone model IDA-MAE (Sahlin and Bring, 1995) for different configurations and climatic conditions. The air flows were then included in the TSBI3 program for temperature and energy use calculations (Johnsen, Grau and Christensen, 1993). Field measurements of temperatures, air leakage, air change rates, pressure differences and energy use was performed in the winter of 1995-96 to provide more reliable input data and to verify the calculation results.

4.1 Air Leakage Calculations and inputs

An air flow sensitivity study was performed in order to find out system sensitivity to wind speed at different distributions of air leakage. The following calculations were performed:

- Influence of wind speed
- Influence of uneven distribution of air leakage paths

- Influence of removed filter in air gap
and various combinations of those.

Air flows through significant air leakage paths (unintentional and intentional) and mechanical ventilation air flows needs to be established by measurements or other means as e.g. calculations, building code values or manufacturers data. Field measurements on air leakage characteristics of building components or individual air leakage paths, especially within buildings, are difficult to perform and relevant data is hard to find. Attempts to catalogue data have been made through the AIVC (Orme et al 1994). Even though literature data could be found for a specific type of air leakage path, the deviation in an individual case could be big depending on the workmanship.

Fan-controlled air flows are in most cases regarded as constant while air leakage is expressed by a relationship between flow and pressure difference. Most common is the empirical power law, also used by the IDA-MAE program. Results from Fan Pressurisation tests could easily be expressed in power law form which makes it very practical to use. Also, individual air leakage paths are normally not tested, thus an average of air flow characteristics for a measured enclosure is obtained from Fan Pressurisation tests. A drawback using results from these tests is that they are performed at elevated pressure differences, typically 50 Pa, and the conversion to normal operating pressure differences in a building, normally less than 10 Pa, is not always reliable.

The air flow characteristics of the air gaps around the perimeter of the inside of the external walls were calculated using the well-known Hagen-Pouseilles laminar air flow equation for parallel plates (described in e.g. Kronvall 1980, Levin 1991). The actual width of the air gaps varied a little but an average width of 15 mm and a path length of 100 mm was assumed for gaps without filter. This case was performed to see what happened if the filter was removed on a section of the air gap. With filter, a testing protocol from a filter manufacturer was used to find the air leakage curves (filter class T7 or EU7).

The Fan Pressurisation tests were performed with supporting pressure in adjacent zones so that the external air leakage of the crawlspace, first and second floors could be separated. The results from these tests showed relatively low air leakage of the crawlspace while the upper floor was very leaky, about four times the allowed air leakage flow in the Swedish building code, BBR94. Also the air leakage of the bottom floor exceeded the BBR94 value. Houses having this amount of air leakage would not be approved, why using the BBR94 values felt more appropriate.

For the floor structures between zones and around the perimeter of the middle floor structure, air leakage values corresponding to BBR94, 0,8 l/sm^2 at 50 Pa pressure difference, were used. These values could well be less than the "real" air leakage because of the large number of penetrations for building services present. As a starting point for the air leakage of the exterior building surfaces, values corresponding to the BBR94 value were assumed. These air flows have been recalculated to air leakage curves assuming flow exponents adapted to the different types of air leakage paths, see Table 1. There is no relevant building code value for air leakage to the warm crawlspace (through the ground or through the edge). The measured average air leakage from pressurisation and depressurisation tests for the crawlspace in this house was used.

For the air flow calculations, the house was divided into five zones (denoted 0 to 4, zone 5 is outside) connected with defined air leakage paths. The bottom floor was divided into two equally sized zones so that one leeward and one exposed side could be studied. The simplified zone model of the house with air leakage paths is shown in Figure 2.

Table 1. Basic input data on the different air leakage paths through cracks and gaps, air flows in l/s.

Air flow path between zones:	Location	n	C per m^2	C_{zone}	Source
0-1:	crawlspace floor	0,7	0,0229	1,95	BBR94
	gap (with filter)	0,94	13,433	4,74	Calc.
0-2:	crawlspace floor	0,7	0,0229	1,95	BBR94
	gap (with filter)	0,94	13,433	4,74	Calc.
0-5:	crawlspace via ground	0,7	0,00687	1,09	Meas.
	crawlspace to air	0,7	0,00687	0,032	Meas.
1-2:	partition	0,7	0,0229	0,74	BBR94
1-4:	ceiling	0,7	0,0229	0,87	BBR94
1-5:	external wall/roof	0,7	0,0229	1,96	BBR94
2-4:	ceiling	0,7	0,0229	0,87	BBR94
2-5:	external wall/roof	0,7	0,0229	1,96	BBR94
3-4:	middle floor structure	0,7	0,0229	1,75	BBR94
	gap (with filter)	0,94	13,433	6,99	Calc.
3-5:	external wall/roof	0,7	0,0229	2,50	BBR94
4-5:	edge of middle floor structure	0,7	0,0229	0,32	BBR94
	gap without filter	0,5	0,1743		Calc.

Fan-controlled air flows was assumed constant, corresponding to 0,40 l/sm^2 which was the design air flow level. Design air flows was used in the calculations for exhaust air flow and 90 per cent of this was used as supply air flow, which was supplied to the crawl space and to the middle floor structure. This is a minor simplification compared to the real house where all supply air entered the crawl space and the air flow supplied to the middle floor structure was taken from the crawl space through two ducts with fans.

4.2 Indoor temperature and energy use calculations with TSBI3

For the energy use calculations with TSBI3, the same zone division and sizes were used. The constructions and areas were entered as close as possible to the real conditions (Levin 1996). As the program only handles fixed air flows, the calculated air flows from isothermal and no wind influence was entered, in principle as in Figure 2, both concerning air flows between zones and air infiltration/exfiltration to the outside.

Calculated air flows were used in the TSBI3 program to find out temperatures in the different zones and heating energy use. The TSBI3 house model results were compared to performed temperature measurements and heat loss factor measurements according to the Trätek method (Sandberg and Jahnsson, 1995).

The temperature and energy use calculations were performed with a time step of one hour, the same interval as for the field measurements. Unfortunately, climatic data taken during the measurements could not be entered into TSBI3 within this project since it requires an additional program to create the weather files. Thus, a two-week period with similar outdoor temperature for December in Copenhagen was used for comparison of heat loss factor and temperature levels. The heat loss factor unit is defined as energy use divided by the time-integrated temperature difference, with unit W/K, and should not be sensitive to small differences in temperatures. The temperature calculations were mostly used to check whether the supplied heat to the upper floor was sufficient. As the measurements were taken in connection with the heat loss factor measurements, the ventilation system was running but short-circuited.

The yearly energy use for heating could either be estimated using the heat loss factor, or more accurately by using the house model in TSBI3 and calculate the yearly heating energy use for a reference year. For this study, the former method was used.

5. Results from field measurements

Field measurements of air leakage, outside air flows, fan-controlled air flows, pressure differences, temperatures and energy use was performed in the winter of 1995-96. The measurement results could be found in detail in (Levin 1996).

5.1 Air flow results

Very small pressure differences were measured between the crawlspace and the bottom floor, about 0,2 Pa lower in the bottom floor. For the crawlspace, -1,8 Pa was measured relative to the outside. The outdoor temperature at the time of measurement was 0,5 °C. The desired crawlspace pressure was thus achieved, but the pressure difference to the bottom floor was not, owing to poor control of the air leakage paths.

Tracer gas measurements were performed to find total external air flows. Measurements were performed both before and after sealing parts of the supply air gaps in the upper floor. Gaps in bathroom and kitchen, where filters were missing and a great risk of short-circuiting existed, were sealed with tape before the measurements. Before the second measurement, air gaps with filter in internal walls in kitchen and living room were also sealed to increase the supply air flows to bedrooms. The sealing of gaps resulted in a somewhat more even distribution of the supply air and slightly lower total air flow. The target supply air flows to bedrooms (4 l/s and bed place) were however not reached.

The exhaust air flows did not reach the design values, being 0,40 l/sm^2. Exhaust air flows corresponding to 0,28 l/sm^2 were measured. The supply air flows through the gaps were below the measuring range for air velocity. Probably, air enters through leakage in the floors to a large extent. The difference between total outside air flow and exhaust air flow for the upper floor was remarkable. The outside air flow was 40 % higher than the exhaust air flow in spite of low wind speeds at the measurements. This indicates major air leakage in the upper floor.

5.2 Temperature results

Uneven distribution of supply air was one cause for uneven temperatures between rooms as air gaps without filter existed in both the kitchen and the bathroom in the upper floor. This made that the other rooms with filtered air gaps obtained very little preheated air.

6. Calculation Results

6.1 Air Flows

Calculations of the influence of outdoor temperature on air flows could only be performed within each zone, which resulted in very marginal effect on air flows, at most 10 % for a 40 °C temperature difference variation. The rest of the calculations were performed under isothermal conditions. In Figure 2, calculated base case air flows are shown, using only fan forces and the basic air leakage paths.

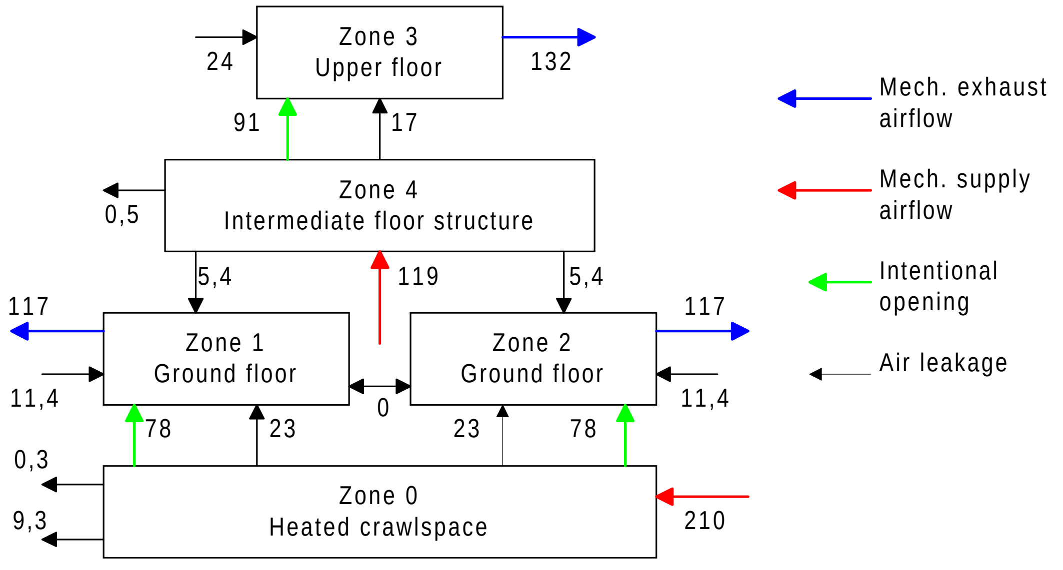

Figure 2. Air flows in kg/h for the base case with no wind and no temperature difference. Thus only air flows from fan forces through ducts and leaks are included.

Air flows at 3, 6 and 10 m/s wind speed perpendicular to the long face of Zone 1 were calculated. The wind pressure coefficients for Zone 1 were assumed to be 0,7, for Zone 2 –0,5 and –0,3 for the rest of the zones. If no air leaks were present between Zones 1 and 2, the supply air flow from the crawlspace to Zone 1 was reduced and replaced by unconditioned air through the external wall. At 6 m/s the supply air flow from the crawlspace was reduced to half. The supply air to the leeward Zone 2 is in principle increased correspondingly. Air flow

through the ground to the outside is increased at the same time. Air exfiltration through the external wall in Zone 2 is also increased but not as much as the air infiltration to Zone 1.
If a door opens between the zones in the bottom floor, the pressure difference will equalise and the supply air flows will be close to the base case. The overall air change rate is increased owing to air leakage. Results from 6 m/s wind speed is given in Figure 3.

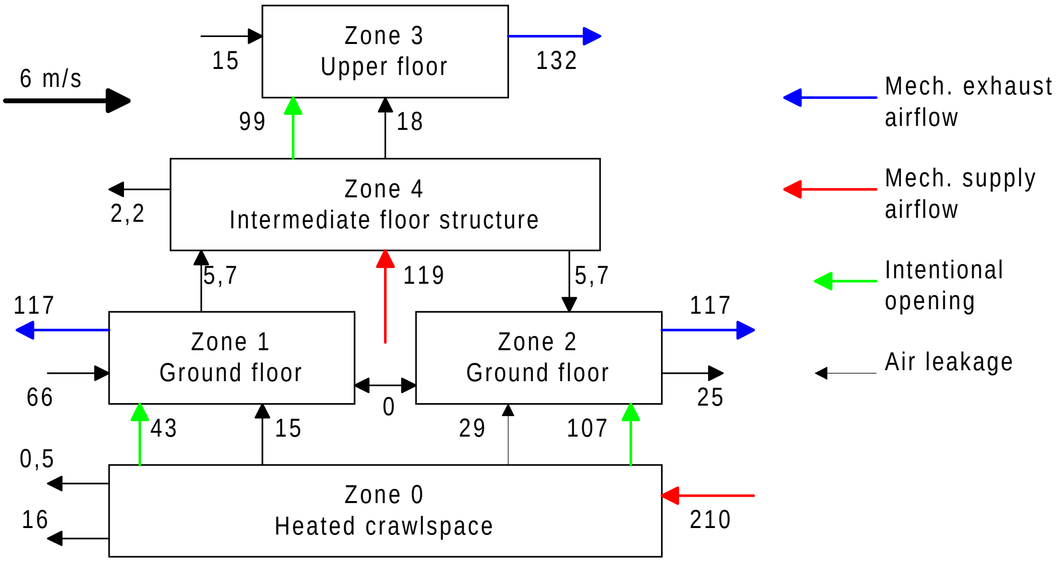

Figure 3. Example of calculation results (kg/h) for 6 m/s wind speed perpendicular to Zone 1.

For the base case calculation, air leakage values for the interior floors (excluding intentional air gaps) corresponding to the requirement in the Swedish building code for external envelopes, were assumed, an assumption that could be valid for good workmanship and a large portion of airtight flooring materials e.g. PVC. However, penetrations for building services could substantially increase the leakage area. If the leakage area is increased about 2-3 times, more supply air will enter through the leaks than through the filtered air gaps (6 m/s).

Naturally, air flows through the gaps are increased if the air gap filter is removed. As far as the calculations shows, there are no drastic changes and the air flow distribution is changed somewhat and the pressure difference across the floor is reduced. Wind influence is about the same as before. Some results are shown in Figure 4.

Different patterns of air leakage distribution in the building envelope were tested at no wind and 6 m/s. When the air leaks in the crawlspace are increased, the flow of warm air through the edge beams is increased. However, as the area is relatively small, these flows will not dominate the flow pattern even if the air leaks are increased ten times, as shown in this simplified model. Crawlspace air leaks will have a significant influence on the energy use in this case because warm air is circulated there.

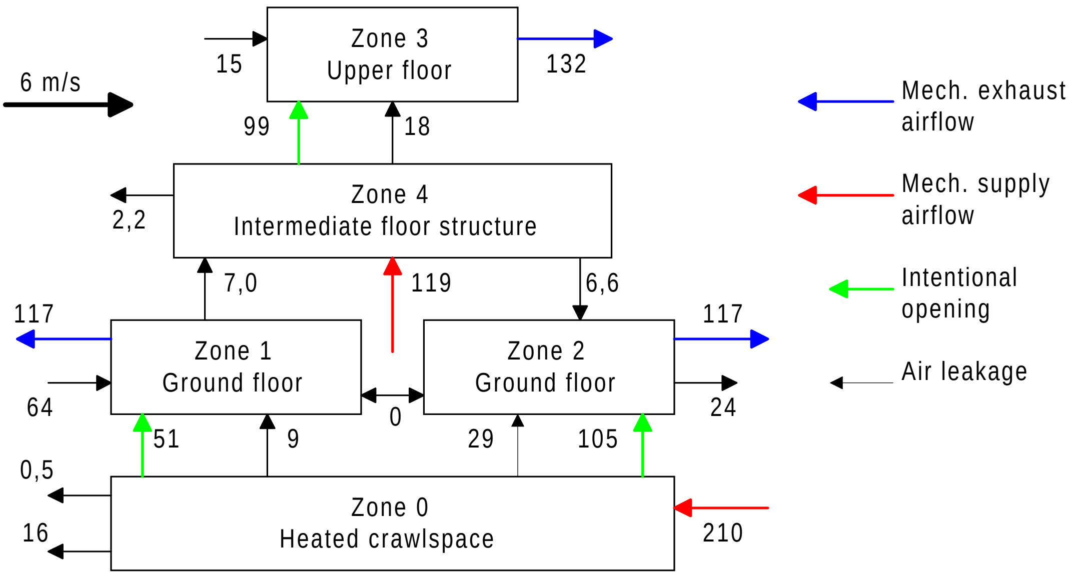

Figure 4. Calculation results when the air gap filter in Zone 1 was removed. Wind speed 6 m/s and air flows in kg/h.

6.2 Indoor temperature calculations

In the temperature calculations, the upper floor of the house had a lower temperature than the bottom floor, and there was also a problem to keep the temperature up during cold weather, using reasonable power levels in the crawlspace. This was the largest difference between the calculations and measurements were the average temperature on the upper floor, at similar outdoor and ground temperatures, was about 3 °C different. The reasons for this could be e.g. poor control of air flows owing to air leaks in the floor structures, or other simplifications used in the computer model.

6.3 Energy use

For the 2-week period calculations using Copenhagen temperatures, an energy balance according to Table 2 was obtained. Note that the ventilation system was short-circuited during the measurement and calculation periods.

Table 2. Calculated energy supply and losses for the 2-week period, with an average outdoor temperature of 0,4 °C and indoor temperature of 21,2 °C.

Calculated energy balance	kWh
Supply:	
Heating system	1233
Solar heat	108
Body heat	73
Losses:	
Conduction	-1308
Air leakage	-106
Ventilation	0

The measured heat loss factor for conduction and air leakage losses was 209 ±15,7 W/K. The corresponding value according to the calculations was 202 W/K, which is only about 3 % different. This difference falls well within the error margins for both measurements and calculations. In these calculations, temperatures according to Table 2 and values on conduction and air leakage losses were used.

7. Discussion

This system is very sensitive to pressure differences, as this is the driving force for both heating and ventilation. This calls for careful adjustment of ventilation air flows and mounting of the air gap filters. Air leakage calculations show the evident fact that care must be taken to make the floors airtight using this system, in order to direct air flow through the filtered air gaps. This involves sealing of penetrations for building services, hatches etc. in addition to the floor surfaces. Naturally, this also calls for avoidance of other air leakage paths in external walls, to the ground and through all the floor structures. The difficult parts to seal are joints between building components, especially where floor structures meet the external walls. Air leakage through the drainage layer is often neglected but could have big influence on the crawlspace temperature and heat losses.

In the monitored test house, acceptable air tightness was achieved only for the crawlspace foundation where also the main effort was put in design and building. Many avoidable penetrations occurred for central vacuuming system, fireplace supply air duct etc. Unfortunately, air leakage of individual floor structures could not be obtained from the Fan Pressurisation tests.

Wind influence will change the distribution of air between the zones. For the windward side, warm air from the filtered air gap will be replaced by unconditioned air through the wall, which will influence the room temperature. This effect will in this case be reduced because of the warm uninsulated floors. The leeward room will get more heated air and air will also leave the room through the walls, in addition to the mechanical exhaust air flow. If e.g. a door is open between the windward and leeward side, the distribution of warm supply air will even out but infiltration/exfiltration through the walls will be the same.

The measured heat loss factor, 209 W/K, indicates a yearly energy use of about 26 500 kWh (about 120 kWh/m^2 living area) for conduction and air infiltration heat losses for a Stockholm climate (Sandberg and Jahnsson 1995). The ventilation air flow was short-circuited in the crawlspace during the measurement period, which means that the ventilation heat losses should be added to the above, about 3100 kWh/year or 15 kWh/m^2·year as estimated from measured exhaust air flows and a 65 % temperature efficiency level on the heat exchanger. Energy use for domestic hot water and electricity use is thus not included in these numbers and should be added to obtain the total energy use. These values depend on the occupant behaviour and varies greatly. Adding typical Swedish numbers, 4000 kWh/year for domestic hot water and 5000 kWh/year for domestic electricity use of which roughly 80 % turns into useful heat, gives 5000 kWh to be added. Solar gain and body heat should also be deducted, say 5000 kWh and 1000 kWh, respectively. This makes the estimate of the total energy use 28 600 kWh/year or 130 kWh/m^2·year.

The energy use for this house must be considered high compared to new Swedish detached houses. According to the calculations with TSBI3, the relatively large window area with regular triple-pane windows constitutes about 24 % of the thermal losses through the building envelope and the crawlspace ground and edge insulation about 27 %. The assumed air leakage is about 10 % of the losses. Also, the floor area to volume ratio is not ideal in this house. The heated volume of the crawlspace constitutes about 100 m^3 or a 20 % addition to the house volume.

Using a multi-zone air flow computer model together with a thermal model have the potential to be a powerful tool for temperature and energy use calculations in buildings. The results could be used together with climatic data to predict the yearly heating energy use of a building. A comparison between calculations and short-term energy use measurements, could give an indication on whether a house meets the specified quality standards or not. The results could also be used to provide checkpoints for optimal operation of the building.

The IDA-MAE multizone air flow model code allows complex combination of rooms and connections to be studied in the quasi steady state mode. Building models and running the calculations is a fairly straightforward procedure. The results are presented in a crude way without graphs and summary tables. To find air flows, each air leak has to be opened and numbers have to be noted by hand. To find relative pressures and pressure differences between zones, subtractions has to be made etc. The IDA simulation environment could manage also the thermal calculations but this requires the creation of new modules in the so called Neutral Model Format (NMF).

The TSBI3 program has fairly user-friendly input routines, although getting an overview sometimes is difficult. The results could be obtained in diagrams and tables. It does not have the capabilities to calculate air flows between zones, only fixed air flows could be used. Even fixed air flows turned out to be a problem with the studied house, that included many air flow paths. One purpose was from the beginning to study energy consequences from varying air leakage depending on varying outdoor conditions and air leakage distributions, but this turned out to be too cumbersome work for this study.

8. Conclusions

The used combination of the IDA-MAE and TSBI3 computer programs seems to be one way towards more reliable and fairly user-friendly predictions of temperatures and energy use in buildings. However, the inputs are time-consuming and a combined tool is necessary to make this type of calculations cost-effective. Efforts to create this type of combined tool are now made internationally.

The evaluated building concept that distributes warm air through gaps in the floors, is very sensitive to uncontrolled air leakage paths. A wind speed of 6 m/s could reduce the heated supply air to half in the windward room and increase correspondingly in the leeward room if the internal door is closed. The temperature in the windward room will then decrease since heated air is replaced with unconditioned air. Measurements on air leakage become an important quality control tool for buildings using this concept.

9. Acknowledgements

The field measurements were performed during the winter of 1995-96 by the Swedish National Testing and Research Institute, Dept. of Building Physics. Asima Norén, Ph.D., performed the thermal calculations with the TSBI3 program.

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