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THERMAL COUPLING OF LEAKAGE AIRFLOWS AND HEATING LOAD IN BUILDING COMPONENTS AND BUILDINGS

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SYNOPSIS

Simulation models basing on 2-dimensional finite-difference approach were developed for the steady-state and dynamic analyses of the thermal coupling of leakage airflows and building components. The considered types of leakage flows were crack flow and filtration through porous materials. At building level analyses a static flow network approach was applied in order to calculate airflow balance of a building, while for the thermal coupling of convective heat flows of air leakages and transmission heat flows of leaky structures a 2-dimensional modified transfer-function approach was applied.

It is suggested in the paper that the value of transmission heat losses should be corrected by a factor, modified Nusselt number, in order to take into account the heat recovery effect of leakage airflows. Depending on leakage airflow rate, thermal properties and dimensions of the structure as well as the leakage route, the correction factor of transmission heat losses can be as low as 0.60. The correction factor of total heat losses can be 0.86, respectively. According to measurements the correction factor of transmission heat losses was 0.35-0.85, while it for total heat losses was 0.86-0.96. The heat recovery effect is approximately the same for both infiltration and exfiltration.

At the building level, the correlation between airtightness, leakage distribution, air change rates and thermal performance of a single family house was analyzed. The house was supplied with mechanical exhaust ventilation system and the supply air was taken in as leakages through building envelope. The calculated annual heating energy consumption of the building was 6-9 % less compared with the calculation results where the heat recovery effect was not taken into account. If the heat recovery effect was taken into account in calculation of transmission heat losses, the average correction factor was 0.85-0.90. Actual values depend on airtightness and leakage distribution of building envelope.

1. INTRODUCTION

The actual heating load of a building often differs from the designed load. One reason for this is the uncontrolled ventilation through a building envelope. Differences in calculated and measured heating loads have usually been explained with the uncontrolled ventilation using the leakage ventilation rate as a correction parameter of heating load analyses. Hydraulic properties of different leakage routes have been studied widely and leakage flow rates can nowadays be predicted rather well. The thermal coupling of leakage flows and heating load has not, however, been studied and therefore the heating load of leakage ventilation has been calculated according to the leakage flow rate and the temperature difference of inside and outside air.

The thermal coupling of leakage airflows and conduction heat flows of structures has been omitted. Nevertheless, if we consider for example through a structure infiltrating air, the cold outside air is heated by conduction heat flows inside a structure before it enters the room space. Due to infiltrating airflow also the conduction heat flow at the interior surface is increased. If we consider the interior surface as control surface of the system, the total heating load due to convection heat losses of infiltrating air and conduction heat losses of a structure is less compared with the case where pure conduction of a structure occurs and infiltrating air is assumed to flow in at outside temperature. The difference in the total heating load is due to the heat recovery effect of infiltrating air.

In this paper the effect of both infiltrating and exfiltrating airflows on thermal behavior of structures are considered. The considered flow cases are crack flow and filtrating airflow through porous materials. The interaction of airflows and heat transfer in structures is analyzed by computer simulation using the finite difference approach. Some results of experiments will also be shown.

In building simulation the correlation between airtightness, leakage distribution, air change rates and thermal performance will be considered. In analyses a static flow network approach was applied in order to calculate the airflow balance of a building, while for heating load calculation of leaky wall structures a 2-dimensional modified transfer-function approximation was applied.

2. INFLUENCES OF LEAKAGE AIRFLOWS ON THERMAL BEHAVIOR OF A STRUCTURE

2.1 Basic model equations

In general, the types of leakage flows are crack flow, crack flow and infiltration, and pure infiltration.

In case of pure infiltration the continuity, momentum and energy equations are /1/

$$\frac{\partial}{\partial t} <\rho_f> = -\nabla \cdot <q_{m,f}> \tag{1}$$

$$\frac{\partial}{\partial t} <\rho_f \vec{v}_f> = \frac{K_{v,f}}{\eta_f} (\nabla^2 <p_f>^{(f)} + \beta <\rho_{f,ref}>^{(f)} \vec{g} \cdot \nabla <T>) \tag{2}$$

$$\frac{\partial}{\partial t} \sum_{\alpha = sf} <\rho_\alpha h_\alpha> = -\nabla \sum_{\alpha = sf} <\vec{q}_\alpha> - \nabla \cdot <h_f \vec{q}_{m,f}> \tag{3}$$

When deriving the momentum equation it is assumed that the airflow is a Darcy-type flow. In energy equation it is assumed that the air and the solid matrix (structure) have equal temperatures locally. In building physics applications, the capasity terms of Eqs 1 and 2 can be assumed zero.

In a building structure there may occur internal convection allthough there are no cracks through it. Analysis of the influences of natural convection on transmission heat losses is given by /2/. In examples which will be considered in this paper the effect of gravity forces is not taken into account, ie. the second term of the righthand side in Eq. 2 is omitted.

In the case of crack flow the energy equation of the flowing component can be written in the form (flowing component as control volume)

$$\frac{\partial}{\partial t}(\rho_f h_f) = -\nabla \cdot \vec{q}_f - \nabla \cdot (h_f \vec{q}_{m,f}) - \frac{1}{V}\int_{\partial V_{fs}} \vec{q}_f \cdot \vec{n}_{fs}\, dA \tag{4}$$

Correspondingly, for the stagnant component (stagnant component as control volume)

$$\frac{\partial}{\partial t}(\rho_s h_s) = -\nabla \cdot \vec{q}_s - \frac{1}{V}\int_{\partial V_{fs}} \vec{q}_s \cdot \vec{n}_{sf}\, dA \tag{5}$$

The thermal coupling between the flowing and stagnant component can be given by Eq. 6.

$$\int_{\partial V_{fs}} \vec{q}_s \cdot \vec{n}_{sf}\, dA = \int_{\partial V_{fs}} \alpha_{sf}(T_s - T_f) \cdot \vec{n}_{sf}\, dA \tag{6}$$

According to previous model equations computer codes for 2-dimensional cases basing on finite difference method have been developed. Boundary condition of the first kind for solving the airflow balance of structure in pure infiltration case was used. When solving the thermal balance of a structure boundary condition of the third kind was used. In a case of crack flow, the thermal balance of flowing component was solved applying the boundary condition of the first kind. In the entrance of leakage route the leakage air temperature is either outdoor or indoor temperature, in case of infiltration it is outdoor temperature and in case of exfiltration indoor temperature, respectively /3/.

Let us define a modified Nusselt number Nu_c to characterize the heat recovery effect of leakage air. With this definition the heat recovery effect is taken into account as a correction factor for transmission heat losses. If we consider interior surface of a structure as control surface, the modified Nusselt number is defined as

infiltration:
$$Nu_c = \frac{(\int_A q\, dA + \phi_{conv}) - \phi_{conv,o}}{\int_A q_0\, dA} \tag{7.1}$$

exfiltration:
$$Nu_c = \frac{\int_A q\, dA}{\int_A q_0\, dA} \tag{7.2}$$

where

q is conduction heat flux with the effect of airflow,
q_0 conduction heat flux without the effect of airflow,
Φ_{conv} convection heat flow with the effect of thermal coupling,
$\Phi_{conv,0}$ convection heat flow without the effect of thermal coupling
A control surface area.

2.2 Computer simulations of structures

Figure 1 shows the heating of leakage air as a function of leakage route length, heat flux profiles at the outer surface, and the modified Nusselt number with different leakage flow rates on some typical leakage routes. The calculations have been carried out for steady-state conditions where the outside and inside temperatures are -10° C and +20° C, respectively.

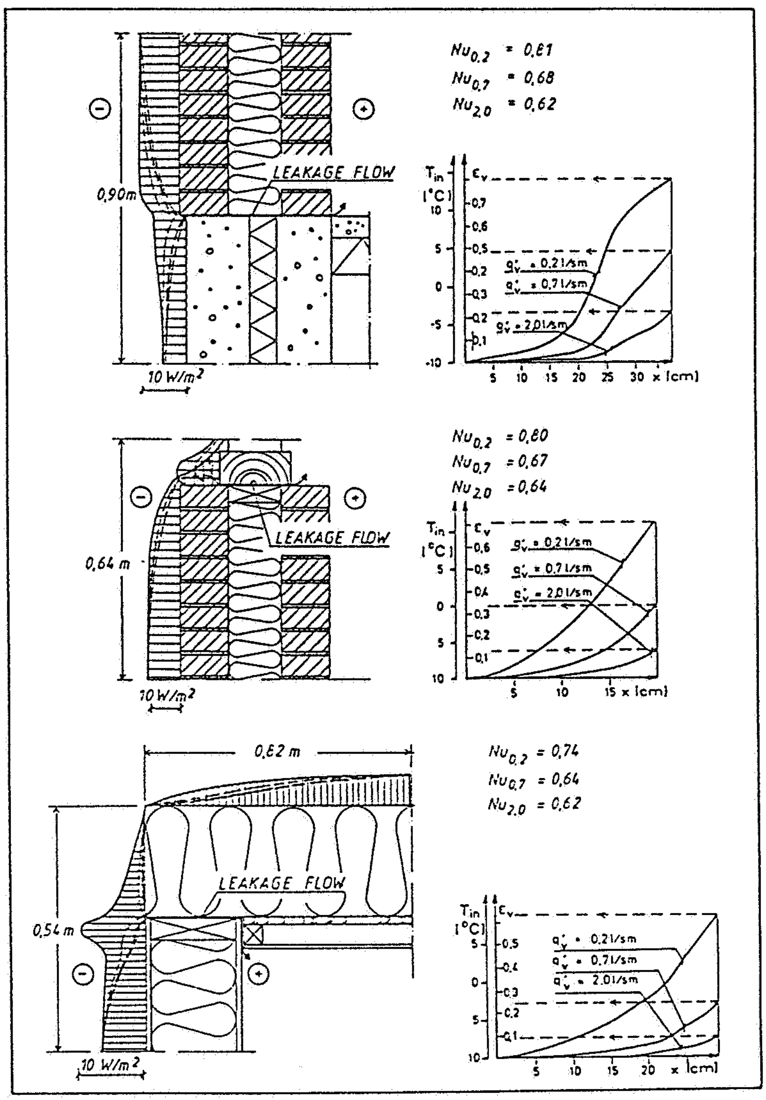


Figure 1. Warming up of leakage airflow and modified Nusselt numbers for some typical wall structures /4/.

In Fig. 1 the outer surface of the structure is cooled as the leakage air in outside air temperature flows into the crack and is heated there by conduction heat flow. As a result, heat flux at the outer surface is decreased (constant heat transfer coefficient at surface). Heat losses at the outer surface decrease more effectively the higher leakage flow rates are. Heat flux profiles drawed with a solid line represent pure conduction. The dash lines take the effect of leakage airflow into account. In this case the modified Nusselt numbers have been calculated considering exterior surface of a structure as control surface and applying Eg. 7.2.

The dimensions of control surfaces are also shown in Fig. 1.

In practical cases there are difficulties to determine the actual leakage route inside a structure. Usually only the location of inflowing air is known. Let us now consider a structure shown in Fig. 2 and ,in addition, we assume four different leakage routes inside the structure. The considered leakage airflow rate is 0.34 dm^3/sm and the flow direction is from outside to inside as well as from inside to outside. In steady-state conditions $0^\circ C$ outside temperature and $+20^\circ C$ inside temperature are assumed. Table 1 summarizes the calculation results.

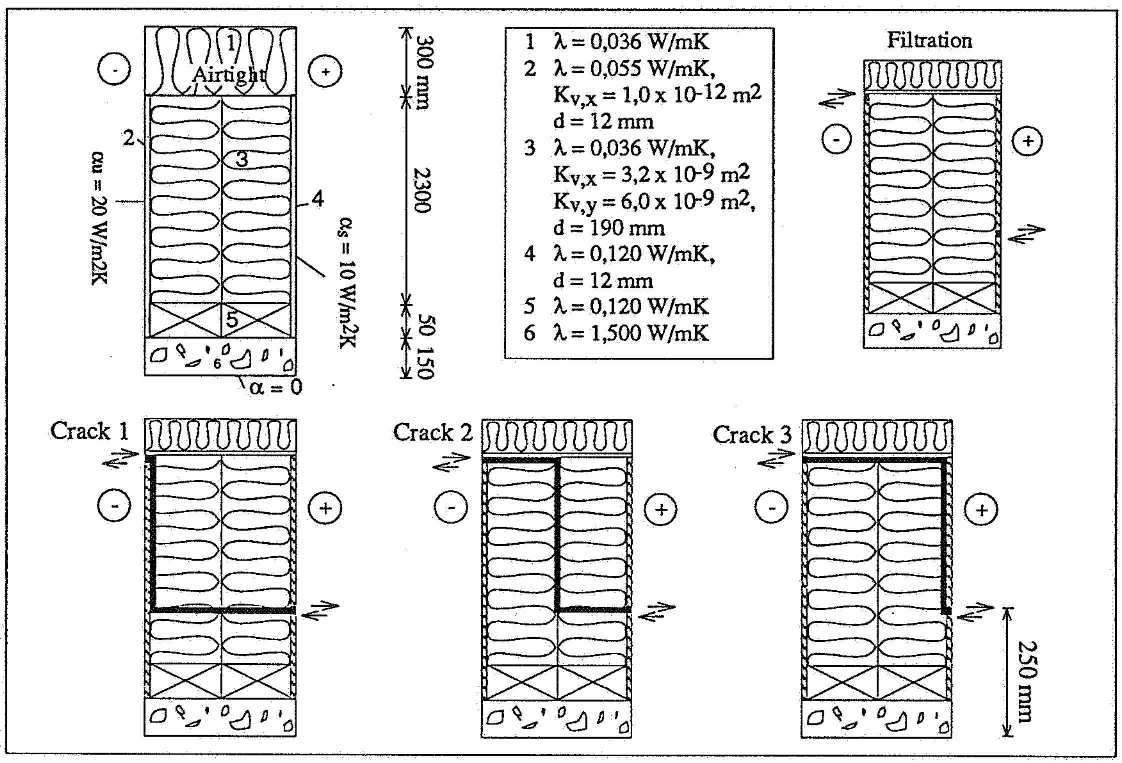


Figure 2. Example structure and four possible leakage routes.

It can first be concluded that the airflow direction does not influence the heat recovery effect. It should, nevertheless, be noticed that the thermal properties of leakage air have been determined according to the average of inside and outside air temperature. The heat recovery is the most effective in a case of pure filtration. Crack cases 1 and 3 have similar heat recovery effect, although the warming up of incoming leakage air is more effective in crack case 3 than in crack case 1.

Table 1. Transmission and convection heat flows at interior surface of a structure, and heat recovery effect in different leakage route and flow direction cases /3/.

Calculation cases	Φ_c	Φ_{conv}	Φ_{tot}	Nu_c
	W/m	W/m	W/m	-
No thermal coupling	21.6	8.2	29.8	1.00
Infiltration	25.4	1.2	26.6	0.85
Crack 1 (inflow)	24.6	4.2	28.8	0.95
Crack 2 (inflow)	25.0	2.5	27.5	0.90
Crack 3 (inflow)	28.4	0.4	28.8	0.95
Exfiltration	18.4	8.2	26.6	0.85
Crack 1 (outflow)	20.6	8.2	28.8	0.95
Crack 2 (outflow)	19.3	8.2	27.5	0.90
Crack 3 (outflow)	20.6	8.2	28.8	0.95

It also been found out that, if the leakage route (crack) is directly across the structure, the increasing of insulation thickness decreases the modified Nusselt number, ie. the heat recovery effect is improved. If the thermal conductivity of the insulation material is of the magnitude .04 W/mK, the increasing of insulation thickness has only a slight influence on the temperature of incoming leakage air /3/.

The leakage airflows influence also the thermodynamic behavior of wall structures. It has been found out that by increasing the leakage airflow rate from outside to inside, the thermodynamic delay of a wall structure will be decreased /3/. Also convective heat flows of leakage ventilation should be considered dynamic. In this paper the dynamic behavior of leaky wall structures will be taken into account by applying the modified transfer-function approximation in the calculation of conductive and convective heat flows.

2.3 Experiments

Measurements concerning thermal effects of leakage flows have been done in laboratory conditions. Fig. 3 shows the measured and calculated heating of leakage air in a crack, heat flux and temperature profiles at the inside surface of the structure as well as the temperature profile at the outside surface of the structure. The outside temperature was -2.8 °C and the inside temperature was 22.7 °C, respectively. The measured airflow rate was 2.7 dm^3/sm.

In Fig. 3 the temperature gradient of leakage air is very high at inside surface of the structure. Therefore, the temperature measurement of incoming air is relatively inaccurate. The measured modified Nusselt number (correction factor for transmission heat losses) was $Nu_c = 0.35$, while the calculated value was $Nu_c = 0.43$. The measured and calculated correction factors for the total heat loss (transmission and convection) were 0.94 and 0.95, respectively.

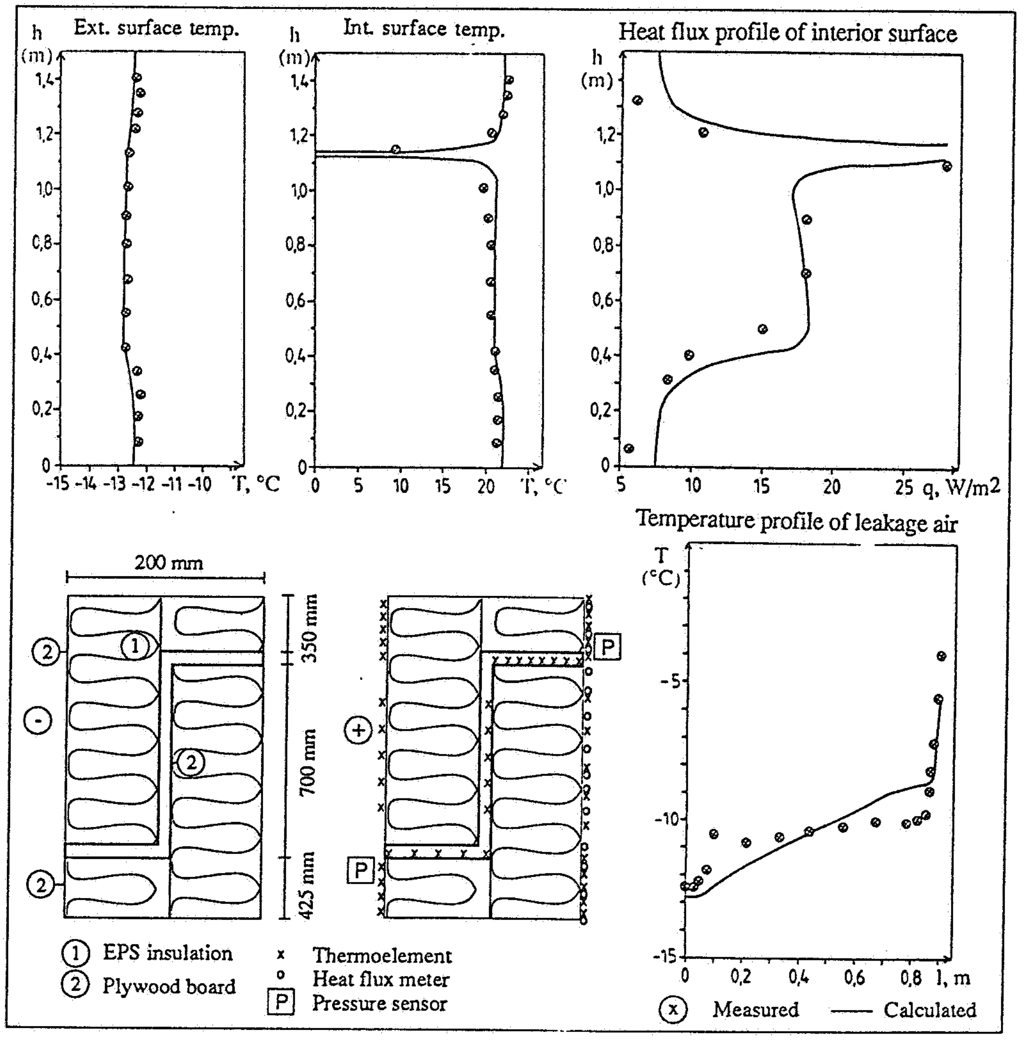


Figure 3. Measured and calculated heating of leakage air, heat flux and temperature profiles at inside surface, and temperature profile at outside surface of structure. Steady-state condition.

In Fig. 4 the measured and calculated results for one wall section are shown. The outside temperature was 4.5 °C and inside temperature was 21.0 °C, respectively. The measured pressure difference over the wall was 27 Pa and the corresponding airflow rate was 0.87 dm^3/sm. The inside surface was absolutely airtight, except one crack through which the air flows in. The airflow field, shown in Fig. 4, is calculated. Also the temperature isotherms are calculated. The calculated modified Nusselt number for this case was Nu_c=0.83, while it according to measurements was Nu_c=0.50-0.85. The calculated correction factor for the total heat loss was 0.95 and the measured value was in the limits 0.86-0.96, respectively. The measured values include the horizontal deviation of temperatures.

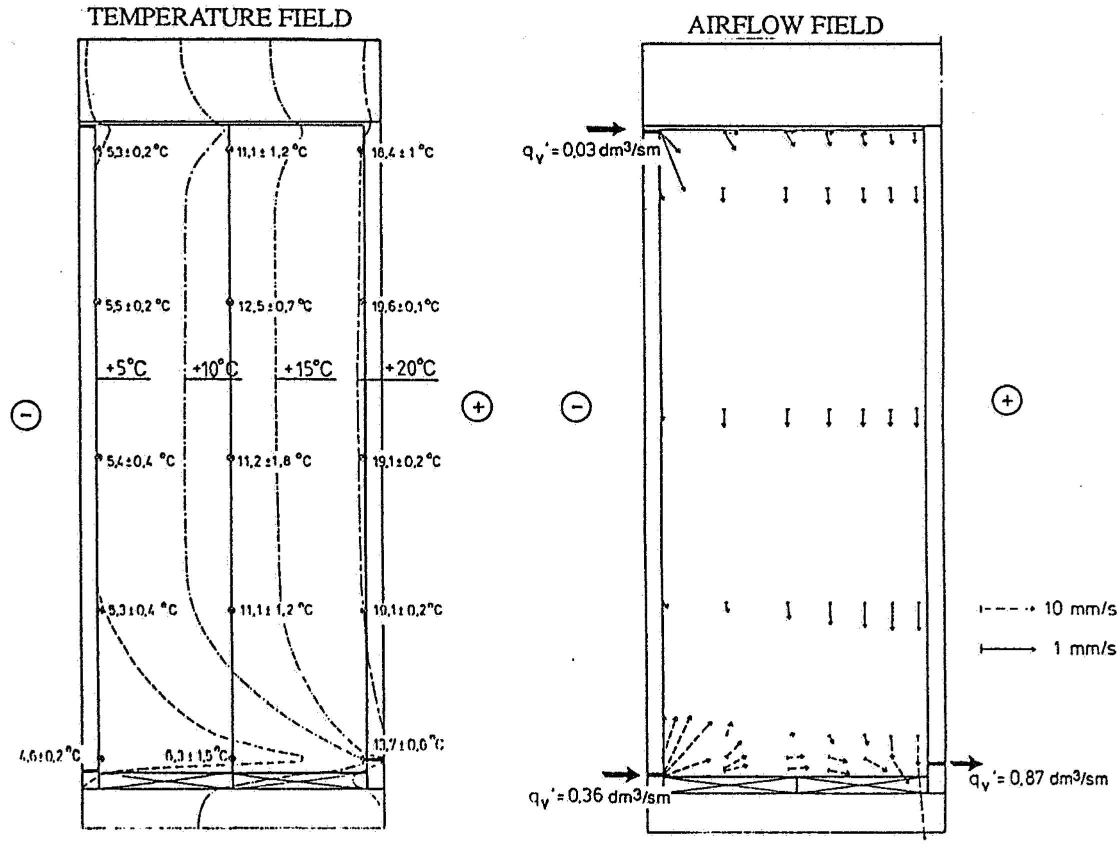


Figure 4. The calculated airflow field, and the measured and calculated temperature field of a structure.

3. HEAT BALANCE OF A BUILDING

3.1 Heating load of ventilation and transmission losses

In Fig. 5 heat balance of a building in general is shown. In our considerations certain terms of the heat balance have been omitted in order to find out the thermal coupling of leakage airflows and the heating load clearly. The solar heat gain and heat gain from people, devices etc. have been omitted. The control system of heating is assumed ideal, ie. the room air temperature stays constant at the desired value. In addition, the heat flow through floor is assumed to depend on the temperature difference of inside and outside air.

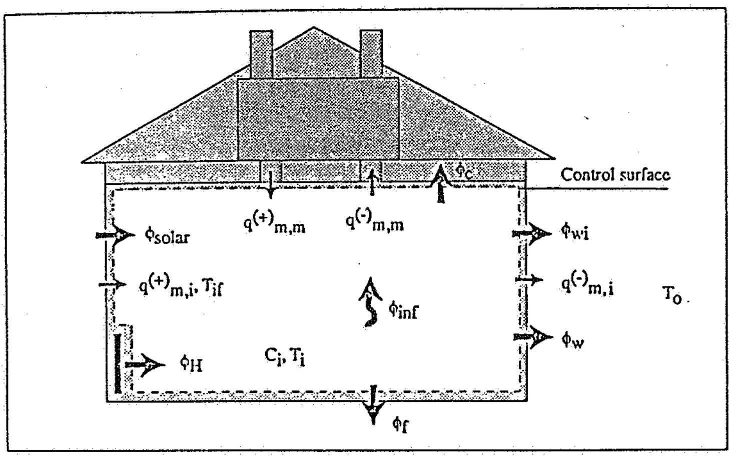


Figure 5. Heat balance of a building.

According to simplifications and assumptions made above, the heat balance of a building takes the form

$$\phi_h(t) = \phi_c(t) + (1 - \varepsilon_i(t))q^{(+)}_{m,i}(t)\, c_p (T_i - T_o(t)) \tag{8}$$

where

$$\varepsilon_i = (T_{if} - T_o)/(T_i - T_o) \tag{9}$$

It should be noticed that transmission heat loss term in Eq. 8 includes transmission heat losses of both airtight and leaky wall structures.

When evaluating the effect of leakage airflows on the heating load of a building in a dynamic condition, the heat balance and the airflow balance have to be solved simultaneosly. In our case the computer code MOVECOMP /5/ to calculate the airflow balance of a building was applied. MOVECOMP is based on a static flow network approach. For heating load calculation of leaky wall structures a 2-dimensional modified transfer-function approximation was applied and for airtight structures 1-dimensional approach was applied, respectively. The simultaneous solving procedure of airflow and heat balance of a building is described more detailed in /3/.

3.2 Transfer-function approach for airtight and leaky wall structures

Transmission heat flows of a building are solved using 1- and 2-dimensional response factors. For airtight wall structures 1-dimensional response factors are applied /6/, and for leaky wall structures (crack flow) modified 2-dimensional response factors are applied /3/, respectively.

In a case of airtight wall structures the only time-dependent variable is the outside temperature, because inside temperature was assumed constant. If, in addition, convective heat transfer coefficients of exterior and interior surfaces of a structure are assumed constant, the heat flux at interior surface can be written as follows

$$q_t = \sum_{k=0}^{\infty} X_i (T_i - T_{o,\,t-k}) \tag{10}$$

where X_i are response factors of heat flux (1-dimensional) at interior surface against unit triangular pulse of outside temperature excitation.

Taking a more practical form for Eg. 10 (/7/), we get the total transmission heat loss for airtight wall structures

$$\phi_{c,\,t} = \sum_{n=1}^{N1} A_n \left[c_n q_{n,\,t-1} + \sum_{k=0}^{K} X'_{n,k}(T_i - T_{o,\,t-k})\right] \tag{11}$$

$$X'_o = X_o,\ k = 0$$
$$X'_k = X_k - cX_{k-1},\ k \geq 1$$

In Eg. 11 A_n is the inside surface area of airtight wall structures, N1 is the number of different airtight structures and c_n is the common ratio, respectively.

In a case of leaky wall structures the wall system is similarly linear as in a case of airtight wall structures, if constant leakage airflow rate and constant thermal properties of air are assumed. Nevertheless, airflow rate is varying with time and, therefore, an approximation for the calculation of transmission and convection heat losses is made. The transmission heat flow at interior surface of a leaky wall structure is approximated as follows (approximation is illustrated in Fig. 6)

$$\phi'_{c,\,t} = \sum_{k=0}^{\infty} Y_{k,\,t-k} (T_i - T_{o,\,t-k}) \tag{12}$$

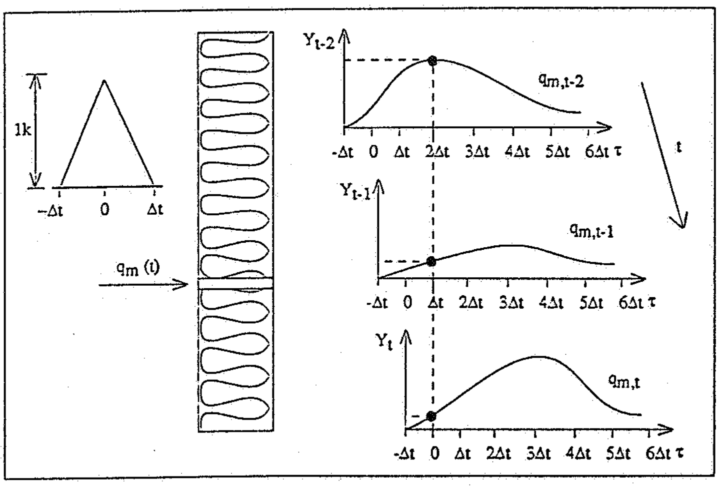


Figure 6. Response of heat flow at interior surface of structure against a unit triangular pulse of outside temperature excitation. The leakage airflow rate is variable, /3/.

The airflow rate is kept as a parameter value in the calculation of response factors. Response factors corresponding to other leakage flow rates than parameter values are obtained by linear interpolation. In addition, the common ratio reaches a nearly constant value with different airflow rates. The total transmission heat loss of leaky wall structures is thus written as

$$\phi'_{c,t} = \sum_{n=1}^{N2} L_n \left[c_n \phi'_{c,n,t-1} + \sum_{k=0}^{K} Y'_{n,k,t-k} (T_i - T_{o,t-k})\right] \tag{13}$$

$$Y'_{o,t} = Y_{o,t},\ k = 0$$
$$Y'_{k,t-k} = Y_{k,t-k} - cY_{k-1,t-k-1},\ k \geq 1$$

In Eg. 13 L_n is the inside width of a structure for horizontal cracks and inside hight of a structure for vertical cracks, respectively. Y_k are 2-dimensional response factors and N2 is the number of leaky wall structures.

In a case of convection heat losses the common ratio representation is not necessary. The total convection heat loss of a building can thus be written as

$$\phi'_{conv,t} = \sum_{k=0}^{K} Z_{k,t-k} (T_i - T_{o,t-k}),\ (q'_{m,i})_t > 0$$

$$(Z_{k,t-k})_{k=0,1\ldots,K} = 0,\ (q'_{m,i})_t \leq 0 \tag{14}$$

In Eg. 14 Z_k are 2-dimensional response factors. The total heat loss of a building can be achieved by the superposition of Egs 11, 12 and 14. The comparisions have shown that the results calculated with the present approximation agree very well with the results calculated with finite-difference method /3/.

3.3 Computer simulations of a building

The aim of building level calculations was to analyze the correlation between airtightness, leakage distribution, air change rate and thermal performance. A small house (see Fig. 7) supplied with mechanical exhaust ventilation system was considered. The mechanical exhaust airflow rate was assumed constant corresponding to ventilation rate 0.41 1/h. The supply air was assumed to be taken in as leakages (cracks) through building envelope. In addition, constant inside air temperature was assumed and real measured weather data (outside air temperature, wind velocity and direction) was used.

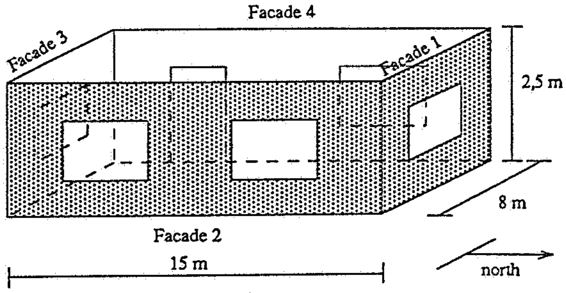
Calculations were carried out for one year period using one hour time step. In analyses two leakage route distributions (case 1 and case 2) and several airtightnesses of a building envelope (n_{50} number) were considered. In case 1 it was assumed that the relative airflow distribution through different leakage routes under 50 Pa pressure difference over the building envelope was as follows

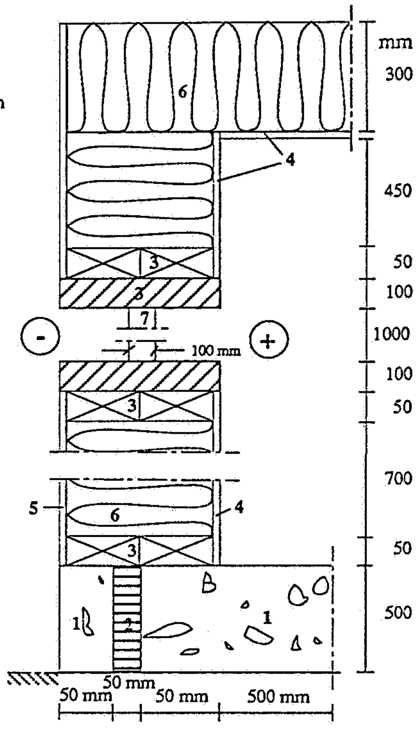
* cracks between window frame and wall structure 30 %,
* cracks between outdoor frame and wall structure 20 %,
* cracks between ceiling and wall structure 20 %,
* cracks between floor and wall structure 20 %,
* cracks between wall structures (corners) 10 %.

Correspondingly in case 2, the considered relative airflow distribution was

* cracks between window frame and wall structure 40 %,
* cracks between outdoor frame and wall structure 20 %,
* cracks between ceiling and wall structure 40 %.

The airtightness of the building envelope was varied by changing the flow resistances of leakage routes so that above conditions could be achieved.





nbr	Material	λ (W/mK)	ρ (kg/m³)	C_p (kJ/kgK)	C" (J/m³K)
1	Concrete	1,75	2300	0,88	$2{,}0 \times 10^6$
2	EPS insulation	0,041	105	1,38	$1{,}5 \times 10^5$
3	Wood	0,12	500	1,34	$6{,}7 \times 10^5$
4	Wood chip board	0,23	500	1,34	$6{,}7 \times 10^5$
5	Wood fiber board	0,13	300	1,34	$4{,}0 \times 10^5$
6	Mineral wool insulation	0,041	60	0,75	$4{,}5 \times 10^5$
7	Window	0,200	1,2	1,00	$1{,}2 \times 10^3$

Figure 7. Inside dimensions of example building and thermal properties of wall structures. Dimensions of windows and door are 1.8x1.2 m^2 and 1.0x2.0 m^2, respectively.

In Fig. 8 the effect of building envelope airtightness in calculation case 1 on the total airchange rate of the building is shown. Curves in Fig. 8 are minimum and maximum airchange rates for 24 hour periods. It can be seen that airchange rate is constant when the airtightness is n_{50} = 1.0 1/h. Already in conditions where the airtightness is 3.0 1/h, the ventilation rate is occasionally doubled in relation to the desired ventilation rate. If we consider long-term averages, for example one year, the proportion of uncontrolled ventilation of the total ventilation is only 2.5 % in our simulation case, where the building envelope airtightness is 3.0 1/h. As the airtightness is 5.0 and 10.0 1/h, the proportion of uncontrolled ventilation is 13 % and 38 %, respectively.

Simulations have shown (comparisons of cases 1 and 2) that the leakage route distribution has no significant influence on the airchange rate if buildings with similar airtightness and long-term averages are considered. Short-term differences may, however, be remarkable in a way that the less leakage routes there are, the higher occasional uncontrolled ventilation rates appear.

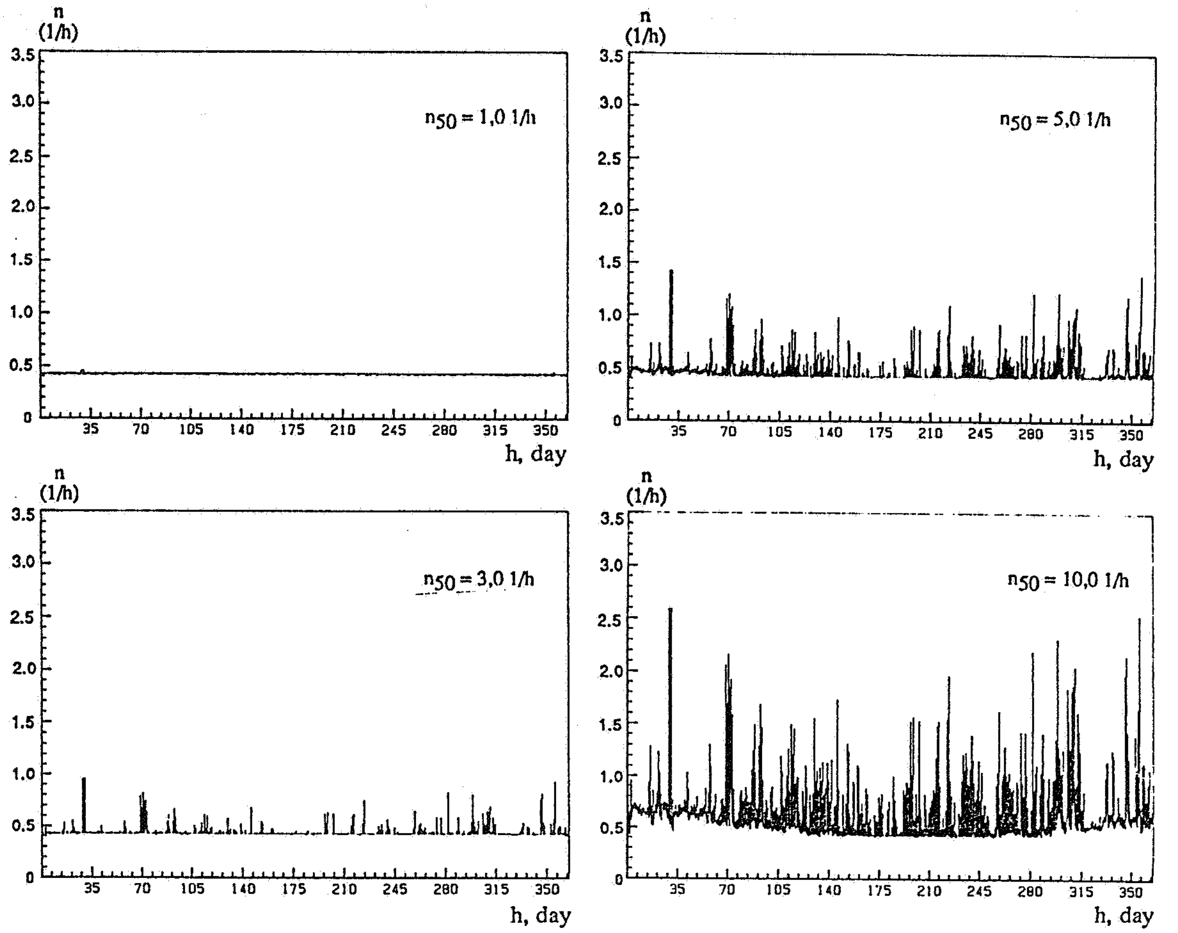


Figure 8. The correlation between the airtightness of building envelope and airchange rate. Minimum and maximum values for 24 h periods.

Table 2 summarizes the results of heat balance analyses. It can be seen that the annual heating energy consumption is in the considered cases roughly 6 - 9 % less compared with the calculation results where the thermal coupling of leakage airflows and conduction heat flows is not taken into account. To take the heat recovery effect into account, it is suggested that traditionally calculated heating energy corresponding to conduction heat losses should be multiplied with a correction factor. Heating energy due to ventilation could be calculated traditionally. In this case the mean modified Nusselt number is defined as

$$\overline{Nu_c} = \frac{\int_t (\phi_c + \phi_{conv})dt - \int_t (\phi_{conv,\,o})dt}{\int_t (\phi_{c,\,o})dt} \tag{15}$$

where Φ_c is conduction heat flow with thermal coupling,
Φ_{conv} convection heat flow with thermal coupling,
$\Phi_{c,0}$ conduction heat flow without thermal coupling,
$\Phi_{conv,0}$ convection heat flow without thermal coupling.

It should be noticed that control surface is assumed to be at interior surface of building envelope.

Table 2. The annual heating energy consumption and the mean modified Nusselt number in example cases.

$Q_{tot,0}$ is heating energy consumption as the heat recovery effect is not taken into account,
Q_{tot} heating energy consumption with the heat recovery effect,
$\overline{Nu}_c$ mean modified Nusselt number.

Leakage distribution case	n_{50} (1/h)	$Q_{tot,0}$ (kWh)	Q_{tot} (kWh)	ΔQ (%)	$\overline{Nu}_c$ (-)
1	1.0	17754.2	16557.0	- 6.7	0.90
1	3.0	17939.7	16651.1	- 7.2	0.89
1	5.0	18676.9	17296.4	- 7.4	0.88
1	10.0	21511.6	19969.9	- 7.2	0.87
2	1.0	17760.4	16736.1	- 5.8	0.91
2	5.0	18599.8	17228.7	- 7.4	0.88
2	10.0	21330.2	19522.1	- 8.5	0.84

4. CONCLUSIONS

It is suggested in the paper that the value of transmission heat losses should be corrected by a factor, modified Nusselt number, in order to take into account the heat recovery effect of leakage airflows. Depending on leakage airflow rate, thermal properties and dimensions of the structure as well as the leakage route, the correction factor of transmission heat losses can be as low as 0,60. The correction factor of total heat losses can be 0,86, respectively.

According to measurements the correction factor of transmission heat losses was 0,35-0,85, while it for the total heat losses was 0,86-0,96. The heat recovery effect is approximately the same for both infiltration and exfiltration.

At the building level, the correlation between airtightness, leakage distribution, air change rates and thermal performance of a single family house was analyzed. The house was supplied with mechanical exhaust ventilation system and the supply air was taken in as leakages through building envelope. The calculated annual heating energy consumption of the building was 6-9 % less compared with the calculation results where the heat recovery effect was not taken into account. If the heat recovery effect was taken into account in calculation of transmission heat losses, the average correction factor was 0,85-0,90. The actual values depend on airtightness and leakage distribution of building envelope.

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