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PAPER 10

THERMAL COUPLING OF LEAKAGE FLOWS AND HEATING LOAD OF BUILDINGS

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SYNOPSIS

The actual heating load of a building differs often from the designed load. One reason for this is the uncontrolled ventilation through a building envelope. The heating load of air infiltration has, in practical calculations, been calculated according to the predicted leakage flow rate and to the indoor and outdoor air temperature difference.

We suggest, however, that the value of transmission heat losses should be corrected by a factor, Nusselt number, because of the thermal interaction of leakage flows and conduction heat transfer in wall structures. According to computer simulations and experiments, the warming up of leakage flow may be as high as 90 % of the indoor and outdoor air temperature difference. Correspondingly, the Nusselt numbers describing the mean relative reduction of transmission heat losses can be 0,65. The seasonal heating energy savings are of the order of 10 - 15 %.

The thermal interaction of leakage flows and wall structures was analyzed by computer simulation and experiments with some elementary flow cases in typical wall structures. The results are, however, so obvious that some theoretical and practical conclusions could be made.

NOMENCLATURE

A	= area, m^2
C	= capasity flow rate, W/K
C'''	= volymetric heat capasity, J/m^3 K
c_p	= specific heat capasity, J/kgK
d	= thickness, m
d_h	= hydraulic diameter, m
g	= gravity force, = 9,81 m^2 /s
h	= specific entalpy, J/kgK height, m
K_v	= permeability, m^2
k	= thermal transmittance, W/m^2 K
L	= length, m
Nu	= Nusselt number, defined in text
n	= unit normal vector
p	= static pressure, Pa
q	= heat flux, W/m^2
q_m	= mass flow rate, kg/s
q_v	= volume flow rate, m^3/s
Ra^*	= modified Rayleigh number, defined in text
Re	= Reynolds number, = vd_h /n
T	= temperature, K or °C
t	= time, s
v	= velocity, m/s
Y	= response factor, W/m^2 K
α	= convective heat transfer coefficient, W/m_2 K
β	= thermal expansion coefficient, 1/K
ε	= response factor
η	= viscosity, kg/ms
λ	= thermal conductivity, W/mK
ρ	= density, kg/m^3

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. 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 assuming that the leakage air flows in at the outside temperature. The thermal coupling of leakage flows and transmission heat flow should be considered in simulation of dynamics of room spaces as well.

In heat balance considerations we should be aware of the control surface of the system, for which the heat balance is formed, is located. In steady-state considerations, it is reasonable to consider the outer surface of a structure as the control surface. Thus, the transmission heat flow is less in the case of infiltration flow compared with pure conduction and the inlet temperature (inflow temperature at the control surface) of infiltration air is equal to the outdoor air temperature. In the case of exfiltration the transmission heat flow is higher than in the case of pure conduction and the outlet temperature is less than indoor air temperature. The heat recovery effect of leakage air is approximatelly the same for both infiltration and exfiltration. The difference arises only from the nonlinearities of the system. In nonsteady-state heat balance considerations, it is, however, preferable to set the control surface at the inner surface of wall structures, i.e., the heat balance is formed for the indoor air. This approach enables us to use the ordinary simulation programs for energy analysis of buildings with minor changes. Exterior walls should be divided into sections where pure conductive or combined convective and conductive heat transfer occurs. In the case, there are two- or three-dimensional flow cases, two- or three-dimensional response factors, transfer functions, finite difference approaches, etc, should be used correspondingly.

In this paper the thermal influences of leakage flows are considered at two levels:

1. At the building component level, the thermal effect (heat recovery) of typical leakage flows will be considered. The types of leakage flows are crack flow, pure infiltration and combined infiltration and crack flow. The interaction of airflows and heat transfer in structures is analyzed both in steady-state and dynamic conditions by computer simulation using the finite difference approach. Some results of experiments will also be shown.

2. At the building (envelope) level, the correlation between airtihgtness, air change rates, and thermal performance will be considered. A multi-cell approach will be applied

in the calculation of leakage rates, while the thermal coupling of leakage flow and conductive heat transfer is based on two-dimensional transfer function and finite difference approaches. Some results of experiments will also be shown.

2. HEAT BALANCE OF A BUILDING

2.1 Heating load of leakage flows and transmission losses

Our preliminary calculations (Kohonen et al.) showed that warming up of leakage air is rather efficient on leakage routes. With allowable leakage flow rates in relation to thermal comfort (0,5 - 0,7 dm^3 /sm), the heating is 25 - 60 % of the outside and inside temperature difference, corresponding to Nusselt's numbers 0,9 - 0,7. Based on this fact, we suggested the heating load of infiltration, exfiltration and transmission be calculated according to Eq. 1 (see Fig. 1)

$$\phi = (-\sum_i q_{m,i} T_o + \sum_e q_{m,e} T_e + (\sum_i q_{m,i} - \sum_e q_{m,e}) T) c_p + \sum_k Nu_k \cdot \bar{k}_k \cdot A_k \cdot (T - T_o) \quad (1)$$

where subscripts i, e, and o denote infiltration, exfiltration, and outdoor temperature, respectively. T is the indoor temperature and k the overall average thermal transmittance (k-value) of a structure. The Nusselt numbers Nu_k take into account the thermal effect of leakage flows (infiltration/exfiltration) as well as internal convection flows of structures. In a case of pure conduction the Nu-number is equal to 1. The Nusselt number is defined by Eq. 2 (see Fig. 2)

$$Nu = \frac{\int_\Gamma q \, d\Gamma}{\int_\Gamma q_o \, d\Gamma} \quad (2)$$

where q and q_o denote the heat fluxes on the control surface (a wall section) with and without convection or leakage flows, respectively.

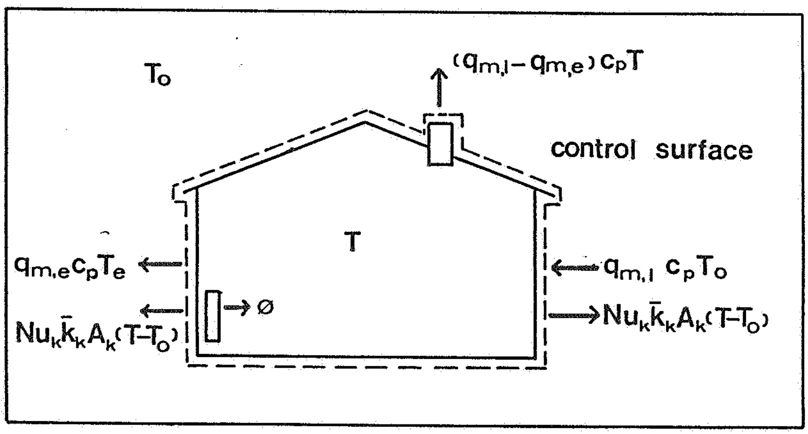

Figure 1. Heat balance of a building

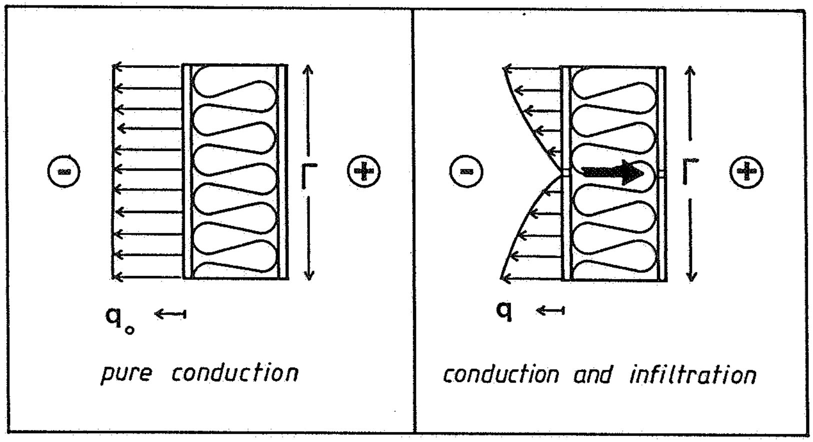

Figure 2. Nusselt-number definition.

For practical calculations, Nusselt numbers for different leakage (ex-/infiltration) cases should be determined. In the following experiments in VTT's test houses, in an existing building and in laboratory as well computer simulation will be described in order to introduce some practical value, for Nu_k:s.

2.2 Experiments

Measurements concerning the thermal effects of leakage flows have been done in test houses, in laboratory and in the field. In a test house controlled conditions were created, so that it was exactly known where and how much air flows in through building envelope. The test house was provided with an exhaust ventilating system and the wall sections were separated from each other with convection cuts. Thus, the internal convection flows from one wall to another were eliminated.

In Fig. 3 are shown the measured, and also calculated steady-state results for one wall section. The outside temperature is 4.5 °C and inside temperature is 21.0 °C, respectively. The measured pressure difference over the wall was 27 Pa. The inside surface is absolutely airtight, except one crack through which the air flows in. The measured air flow rate was q'_v = 0.87 l/sm. The air flow field, shown in Fig. 3, is calculated. Also the temperature isotherms are calculated. We can see that there is a good agreement with measured and calculated temperatures.

The according to Eq. 2 calculated mean Nusselt number, for the whole wall section, is in this case Nu = 0.13. The temperature of incoming air is 13.7 °C. As it can be seen from Fig. 3, the temperature gradient is relatively strong near the inflow point. If the temperature of incoming air is 10 °C, the mean Nu -number would be 0,70.

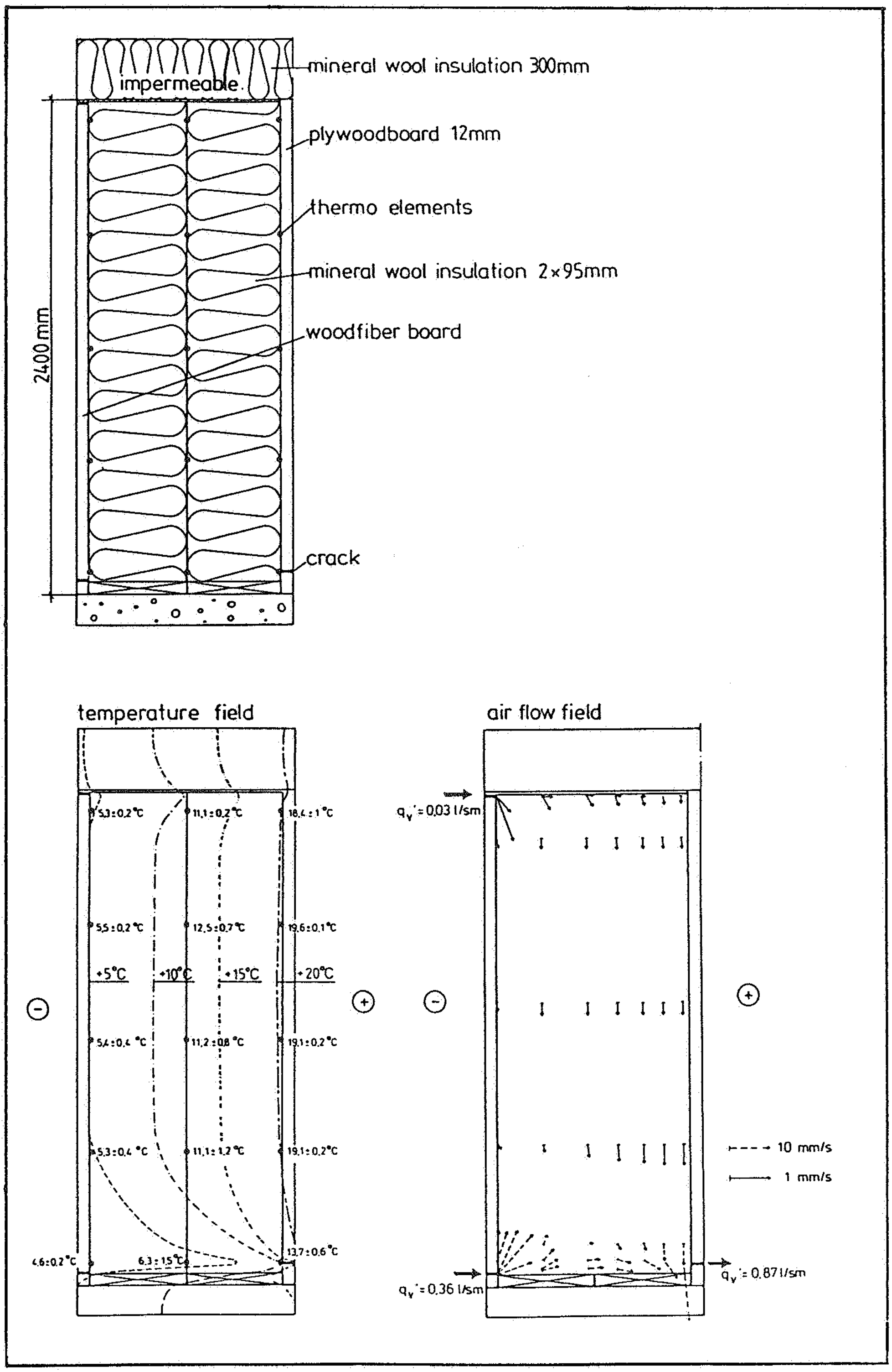

Figure 3. Measured and calculated temperature and air flow field

The mean Nusselt number was determined also for the whole building (test house). The supply air came in through several leakage routes in a building envelope. The total air change rate was n = 2.4 1/h and the corresponding mean Nusselt number was Nu = $0.67^{+.17}_{-.10}$.

In Fig. 4 is shown the measured and calculated heating of leakage air in a crack as well as the heat flux profiles of inside surface. The measurements have been done in laboratory conditions. The outside temperature was -12.8 °C and inside temperature was 22.7 °C, respectively. The measured airflow rate was $q^{\cdot}_{v}$ = 2.7 l/sm and the mean Nusselt number was for the wall Nu = 0,45.

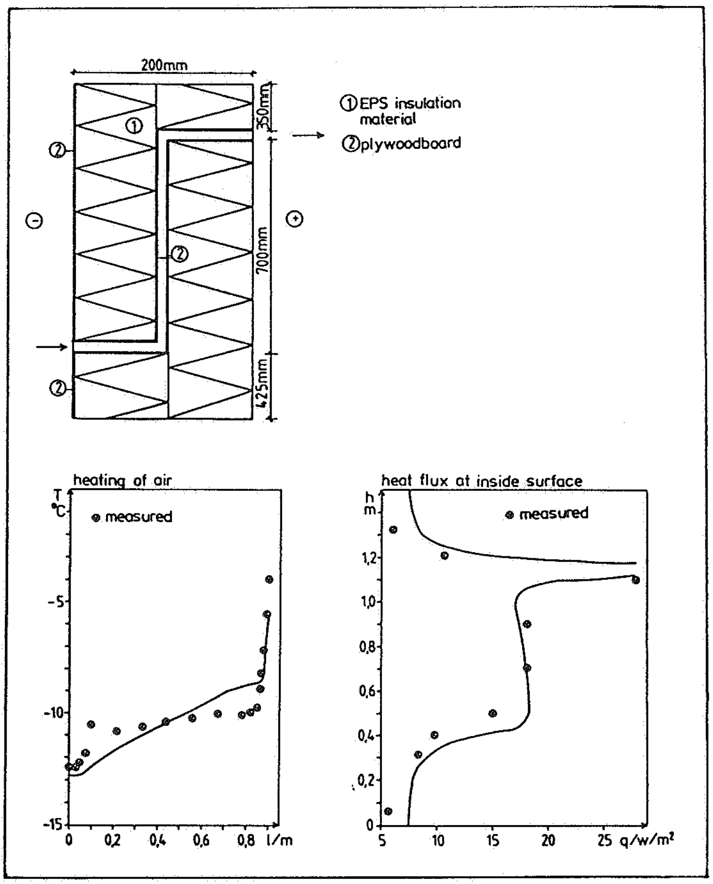

Figure 4. Measured and calculated heating of leakage air in a crack (h = 10 mm), and the heat flux profiles of inside surface.

Let us consider the significance of the warming of the leakage air with example from an existing building. Our example building is a day nursery whose building volume is 2700 m³. The building is provided with an exhaust ventilating system. The measured airtightness of the building envelope was n_{50} = 3.2 1/h. The main leakage routes were packing leakages of windows and doors. The leakages were analyzed by smoke tests and IR-camera tests. The heating load of the building was determined by calculation and measurements. The thermal transmittance representing the transmission heat losses was according to calculations 820 W/K. The capasity flow rate of the exhaust air was (according to measurements) 1370 W/K. The mean underpressure of the inside air was 12 Pa. Thus the measured air flow rate represents the total ventilation. The mean inside temperature was 20 °C. Fig. 5 shows the measured and calculated heating loads of the building as a function of the outdoor temperature. We find that Nu = 0.8 gives the measured heating load.

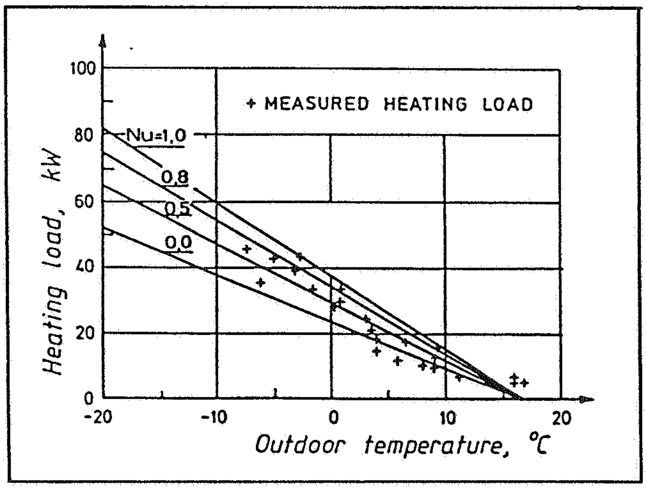

Figure 5. The measured and calculated heating load of building.

2.3 Computer simulations

When evaluating the effect of leakage flows on the heating load of a building in a dynamic condition, the heat balance and the airflow balance have to be solved simultaneously.

We are now considering a building that is supplied with an exhaust ventilating system (Kohonen & Virtanen). The total air change rate is assumed to be constant, n = 0.5 1/h. The inside temperature is also constant, T_i = +20 °C (ideal control system). The airtightness of the building envelope is n_{50} = 3.0 1/h.

The supply air flows in through a crack that is equal over the building perimeter (Fig. 6). Two simplified cases will be considered: a short crack and a long crack . In both cases the dependency of leakage flow rate and the pressure difference between the outside and inside air is the same.

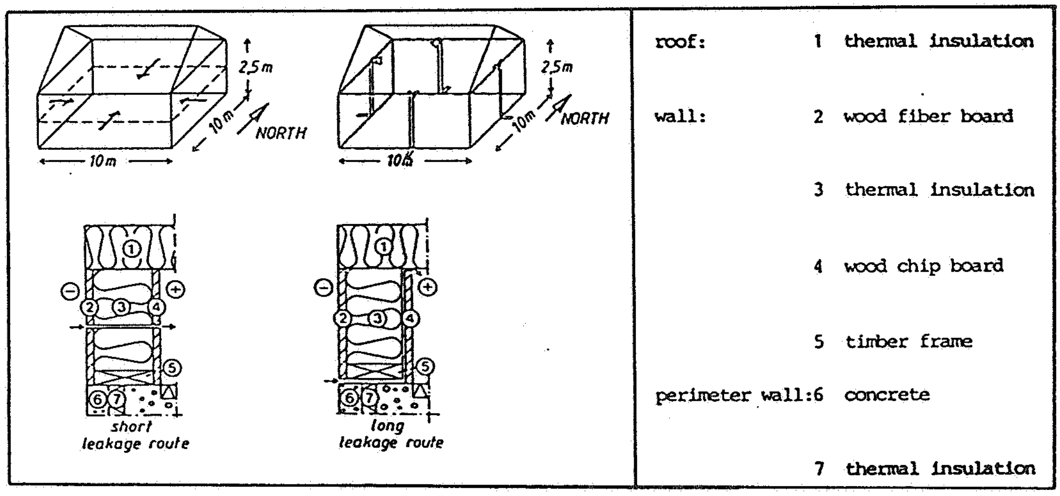

Figure 6. The leakage routes of the example building

The heat balance of the building is calculated with both the two-dimensional finite-difference method and the transfer function approach with one hour time steps. The heating load calculation was done for a two-week period. The weather data of the period is shown in Fig. 7. The wind direction 0° refers to north.

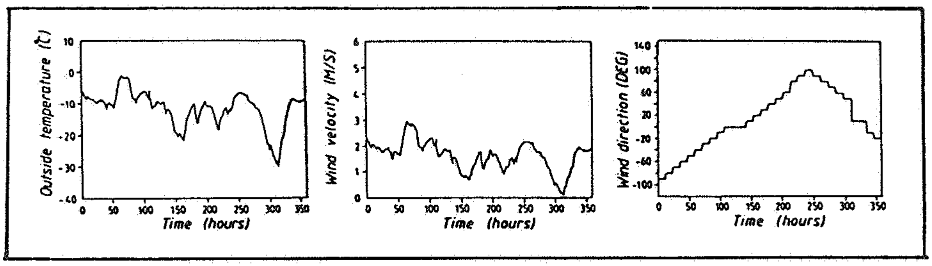

Figure 7. The weather data of the calculation period.

The heating load of conduction and ventilation and the total heating load in a case of a short crack over the building perimeter are shown in Fig. 8. The mean Nusselt number for the period (representing the whole building envelope) is 0.73 and the reduction of total energy for the period when the heat recovery is taken into account is 12.3%. There is a good agreement with the results calculated with the finite-difference and with response factors.

The heating load components for the long leakage route are shown in Fig. 9. It seems that the heating load of conduction calculated with response factors is too optimistic. The according to finite-difference method calculated mean Nu-number for the period is 0.65 and the reduction of total energy is 15.2%.

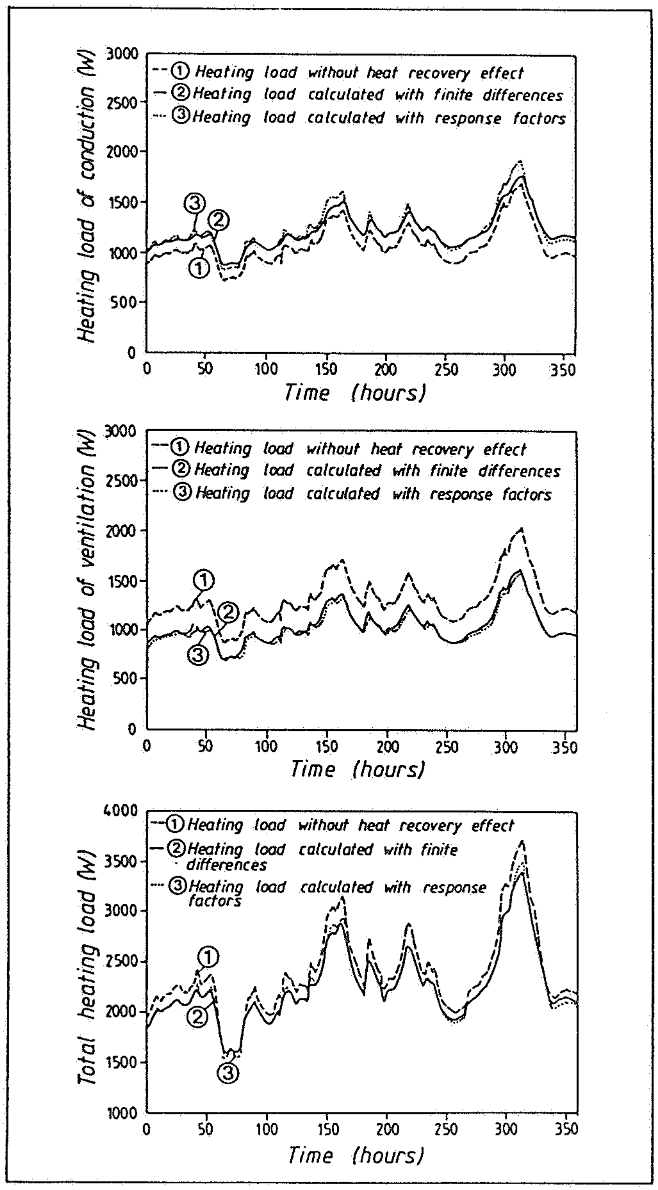

Figure 8. The heating load of conduction and ventilation as well as the total heating load of building in the case of a short crack.

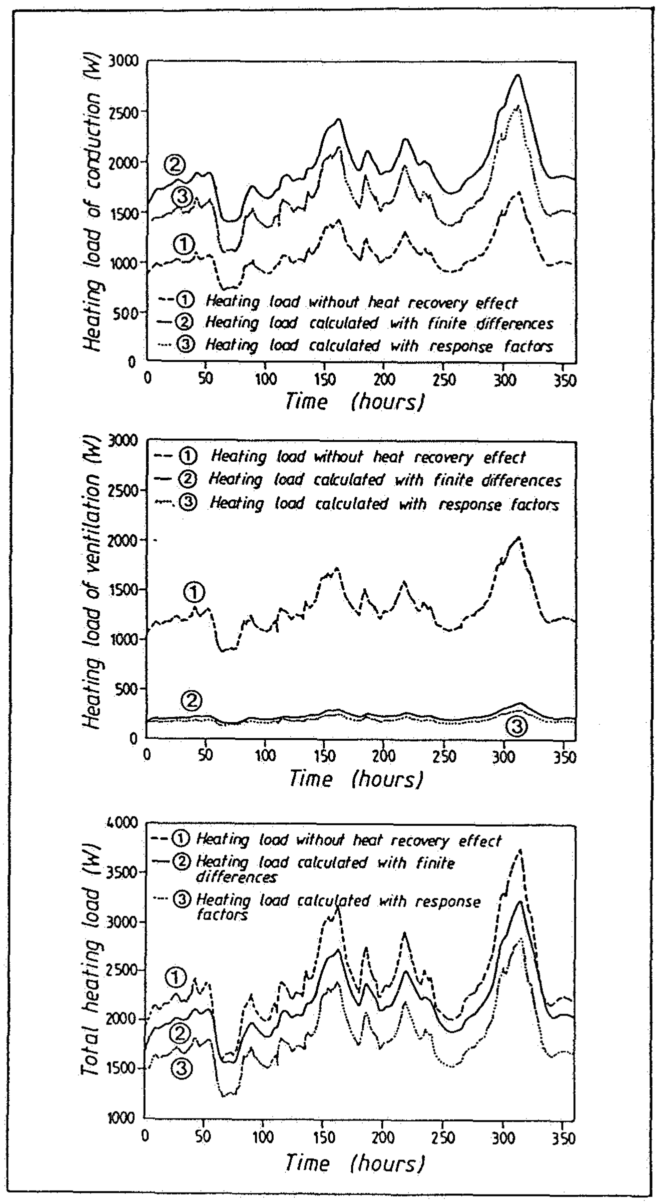

Figure 9. The heating load of conduction and ventilation as well as the total heating load of building in the case of long crack.

3. INFLUENCES OF LEAKAGE FLOW ON THERMAL PERFORMANCE OF A STRUCTURE

3.1 Elementary flow cases

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

In the case of pure filtration, the continuity, momentum and energy equations are (Kohonen, R et al.):

$$\frac{\partial}{\partial t} \langle \rho_f \rangle = -\nabla \cdot \langle \vec{q}_{m,f} \rangle \tag{3}$$

$$\frac{\partial}{\partial t} \langle \rho_f \vec{v}_f \rangle = \frac{K_{v,f}}{\eta_f} \cdot (\nabla^2 \langle p_f \rangle^{(f)} + \beta \langle \rho_{f,ref} \rangle^{(f)} \vec{g} \cdot \nabla \langle T \rangle) \tag{4}$$

$$\frac{\partial}{\partial t} \sum_{\alpha=s,f} \langle \rho_\alpha h_\alpha \rangle = -\nabla \sum_{\alpha=s,f} \langle \vec{q}_\alpha \rangle - \nabla \cdot \langle h_f \cdot \vec{q}_{m,f} \rangle \tag{5}$$

When deriving the momentum equation, we have assumed that the airflow is a Darcy-type flow; the density of air is a function of temperature and the air behaves as ideal gas; the air and the solid matrix (wall structure) have equal temperatures locally; and the body force (f) may be replaced by gravity force (g). In building physics applications, the capasity terms in Eqs 3 and 4 can be assumed zero.

In a building structure, there may occur internal convection allthough there are no cracks through it.

Fig. 10 shows the Nusselt number as a function of the modified Rayleigh number, Ra, for closed and at the cold surface open cavities (Kohonen and Ojanen).

As we can see in Fig. 10 convection has only a slight influence on the mean heat flux. In experiments (Nu may be as high as 1.2 with Ra* = 5 and h/d = 7) we found, however, that the excess of transmission heat transfer is significantly greater owing to non-ideal filling of the test cavities.

A more detailed analysis of the influences of natural convection on transmission heat losses is given by Kohonen et al.

In the case of crack flow, the energy equation of the flowing component can be written in the form

$$\frac{\partial}{\partial t} \langle \rho_f h_f \rangle = -\nabla \cdot \langle \vec{q}_f \rangle - \nabla \cdot \langle h_f \vec{q}_{m,f} \rangle - \frac{1}{V} \int_{\partial V_{fs}} \vec{q}_f \cdot \vec{n}_{fs} \, dA \tag{6}$$

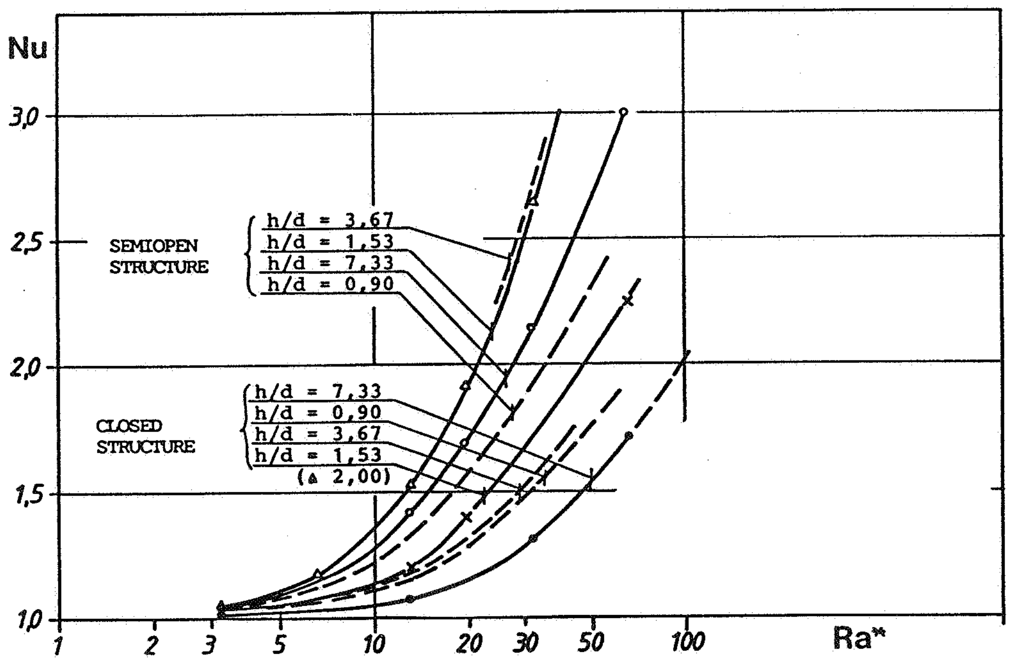

Figure 10. Nusselt number for closed and at the cold surface open cavities (Kohonen & Ojanen).

Correspondingly, for the stagnant component, s,

$$\frac{\partial}{\partial t} \langle \rho_s h_s \rangle = -\nabla \cdot \langle \vec{q}_s \rangle - \frac{1}{V} \int_{\partial V_{sf}} \vec{q}_s \cdot \vec{n}_{sf} \, dA \, . \tag{7}$$

The thermal coupling between the components s and f can be given by Eg. 8

$$\int_{\partial V_{sf}} \vec{q}_s \cdot \vec{n}_{sf} \, dA = \int_{\partial V_{sf}} \alpha_{sf} \, (T_s - T_f) \cdot \vec{n}_{sf} \, dA \, . \tag{8}$$

Fig. 11 shows the heating of leakage air as a function of the length of leakage route, heat flux profiles at the outer surface, and the Nusselt numbers 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.

The outer surface of the structure is cooled as the leakage air in outside temperature flows into the crack and is heated there by the conduction heat flow . As a result, the 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. In Fig. 11 the heat flux profiles drawed with a solid line represent pure conduction. The dashlines take the effect of leakage flow into account. The area between solid lines and dashlines represent the heat recovery effect of the leakage flow. The Nusselt numbers have been calculated by integrating the heat flux over the wall section where there are changes due to leakage flow (determined according to the highest considered leakage flow rate), and by taking Eg. 2 into account.

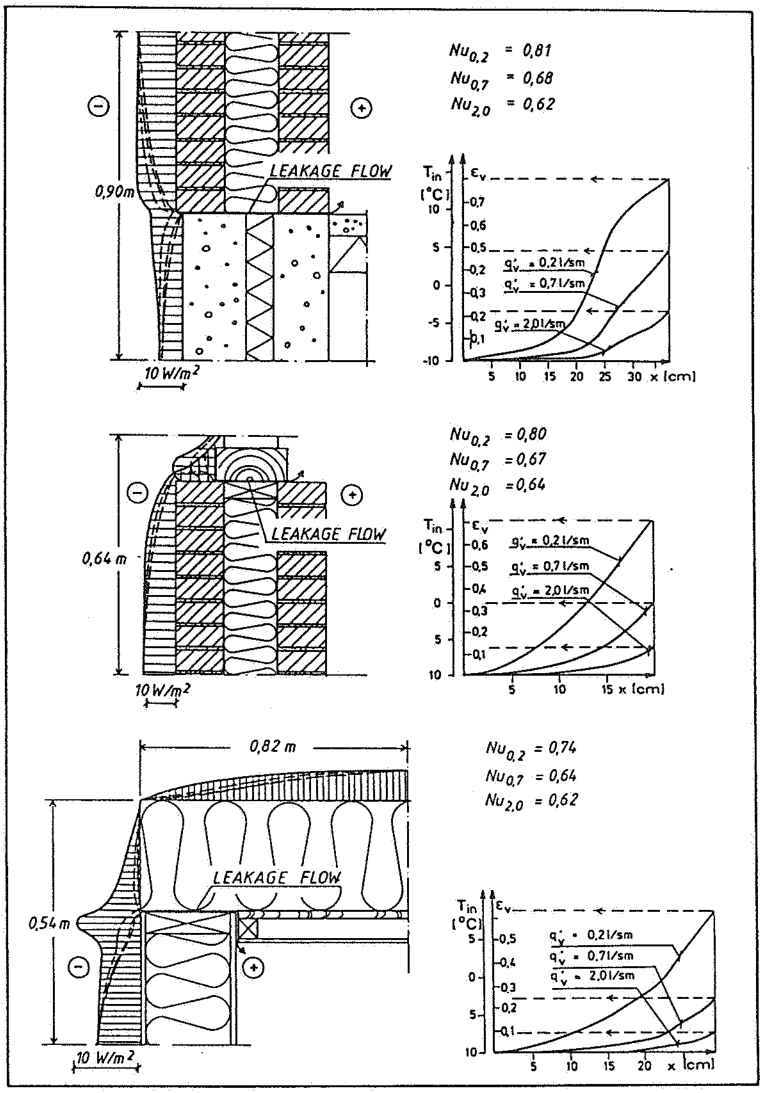

Figure 11. Warming up of leakage flow and Nusselt numbers for some typical wall structures.

Let us consider the thermal effect of airflow in the wall structure shown in Fig. 12. In our steady-state example, the air flows in first by pure infiltration. The leakage flow rate is q_v = 0.1 dm_3 /s/crack m.

The mean heat flux of the outside surface, which represents conduction heat losses, would be for pure conduction $q_{c,o}$ = 4.7 W/m² (thermal coupling not considered). If the heat recovery effect is taken into account, the corresponding heat flux is q_c = 4.33 W/m² and the air flows in at 17.7 °C temperature. The Nusselt number calculated according to Eq. 2, representing the heat recovery effect, is now Nu = 0.92.

If we assume that the same airflow rate comes in by pure crack flow through a crak whose height is h = 5 mm, the thermal effect is exactly the same as by pure infiltration. If the height of the crack is h = 2.5, 25, or even 50 mm, the mean heat flux at the outside surface would be, correspondigly, q_c = 4.14, 4.38, and 4.43 W/m²; the temperature of incoming air would be T_{in} = 17.3, 18.3 and 18.5 °C; and, finally, the Nu-number would be Nu = 0.88, 0.93 and 0.94, respectively. It can be concluded that the connection between the flowing air and the wall structure, i.e., the importance of the convective heat transfer coefficient in a crack, is rather weak. More important is the length of the leakage route.

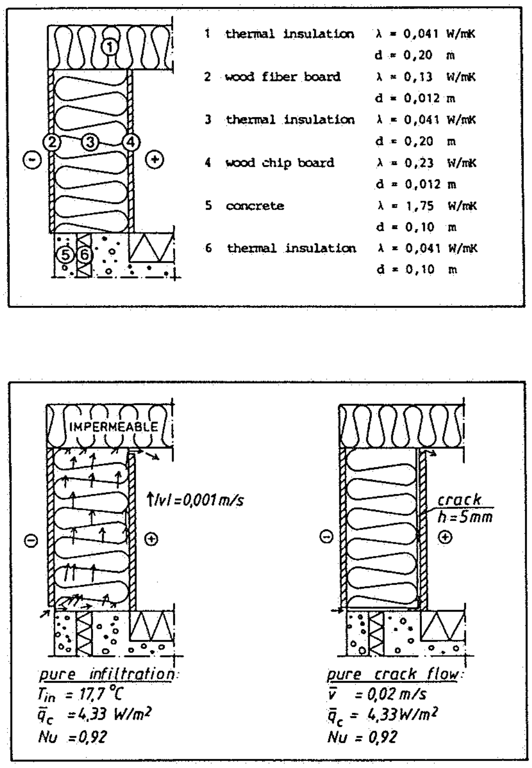

Figure 12. Thermal effect of air flow in a wall structure by pure infiltration and by pure crack flow.

We also studied the heat recovery effect on the total heat losses assuming that there was always the same airflow rate between inside and outside air spaces. Without any heat recovery, the convective heat losses are $q_m' * c_p * (T_i - T_o)$. In the case of air infiltration through the structure, the heat recovery will reduce the convective heat losses to be

$q_m * c_p * (T_i - T_{is})$ at the inside control surface, where T_{is} is the temperature of incoming air. Thus the convective heat losses are reduced but the heat conduction at the inside surface will increase.

The relative change of total heat losses are presented with a modified Nusselt number, which in the case of infiltration is

$$Nu^* = \frac{\int_\Gamma q_c d\Gamma + q'_m c_p (T_i - T_{i,s})}{\int_\Gamma q_{c,o} d\Gamma + q'_m c_p (T_i - T_o)} \qquad (9)$$

where q_c and $q_{c,o}$ are conductive heat flows through the control surface in convection and pure conduction conditions, respectively. The definition of Nu-number is suitable for, for instance, optimizing calculations of so called dynamic insulation, while with Eq. 2 defined Nu-number is more practical in heat demand calculations.

Fig. 13 shows the modified Nusselt number as a function of flow rate (Ojanen) for infiltration and exfiltration.
As we can see in Fig. 13, there is an optimal flow rate, with which the total heating load is at minimum. The optimal flow rate depends, of course, on the wall structure. In the case of Fig. 13 the structure had 300 mm thick mineral wool insulation and 12 mm woodfiber board and woodchip board covers at cold and warm surfaces, respectively.

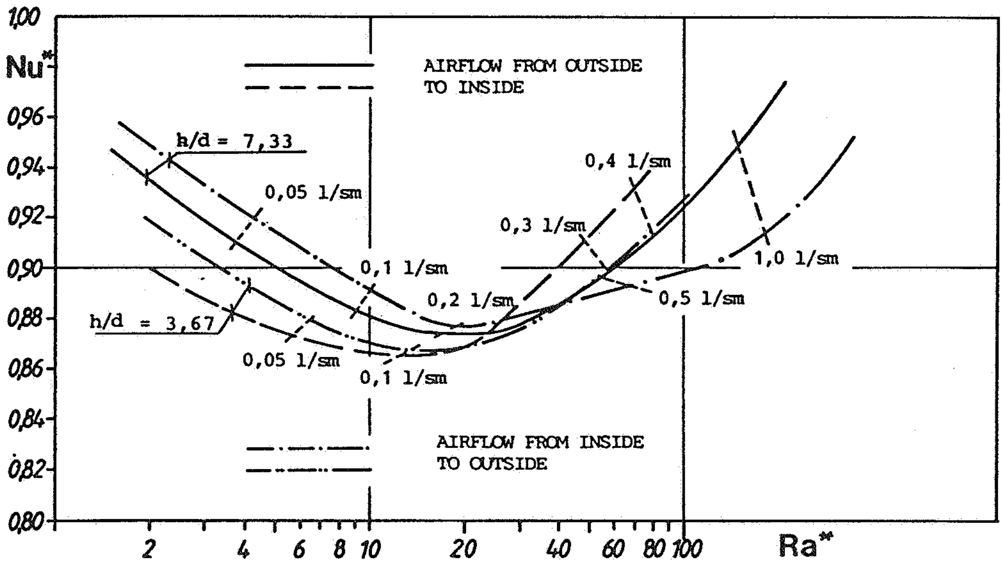

Figure 13. Modified Nusselt number vs modified Rayleigh number for ex- and infiltration flows in a wall structure (Ojanen).

We can see also that the Nusselt number is the same for in- and exfiltration. Only non-linearities of the thermal system may cause differences between ex- and infiltration. This holds, however, for steady-state conditions.

3.2 Dynamic behavior of leaky wall structures

The thermodynamic behavior of wall structure is also influenced by leakage flows. This is commonly omitted, i.e. leakage flows are considered as a passive element in relation to heat transfer due to transmission. In energy analysis programs two approaches are commonly used when calculating transmission heat transfer in wall structures with thermal capasity: transfer function and finite difference methods.

When using the transfer function approach, the mean heat flux at inside surface for each facade and roof (representing conductive heat losses) can be calculated according to Eq. 10.

$$\bar{q}_{c,n} = \sum_{j=0}^{6} Y_{j,n-j}\, \Delta T_{o,n-j} + R \cdot \bar{q}_{c,n-1}, \tag{10}$$

where

$Y_{j,n-j}$	is the response factor for heat flux at the inside surface,
R	is the common ration.

The mean convective heat load is, correspondingly

$$A\bar{q}_{v,n} = \sum_{j=0}^{6} \varepsilon_{j,n-j}\, \dot{C}_{v,n-j}\, \Delta T_{o,n-j}\ , \tag{11}$$

where

A	is the area of a wall section,
$\varepsilon_{j,n-j}$	is the response factor for the temperature of incoming air,
$\dot{C}_{v,n-j}$	is the capasity flow rate of the leakage air

The variation of leakage flow rates makes the calculation of the temperature field of the structure nonlinear. Therefore, the airflow rate has to be kept as a parameter, i.e., the response factors are time-dependent. Response factors corresponding to other leakage flow rates than the paramater values are obtained by linear interpolation. In Fiq. 14 some of the response factors used in a dynamic calculation in Chapter 2.3 are shown.

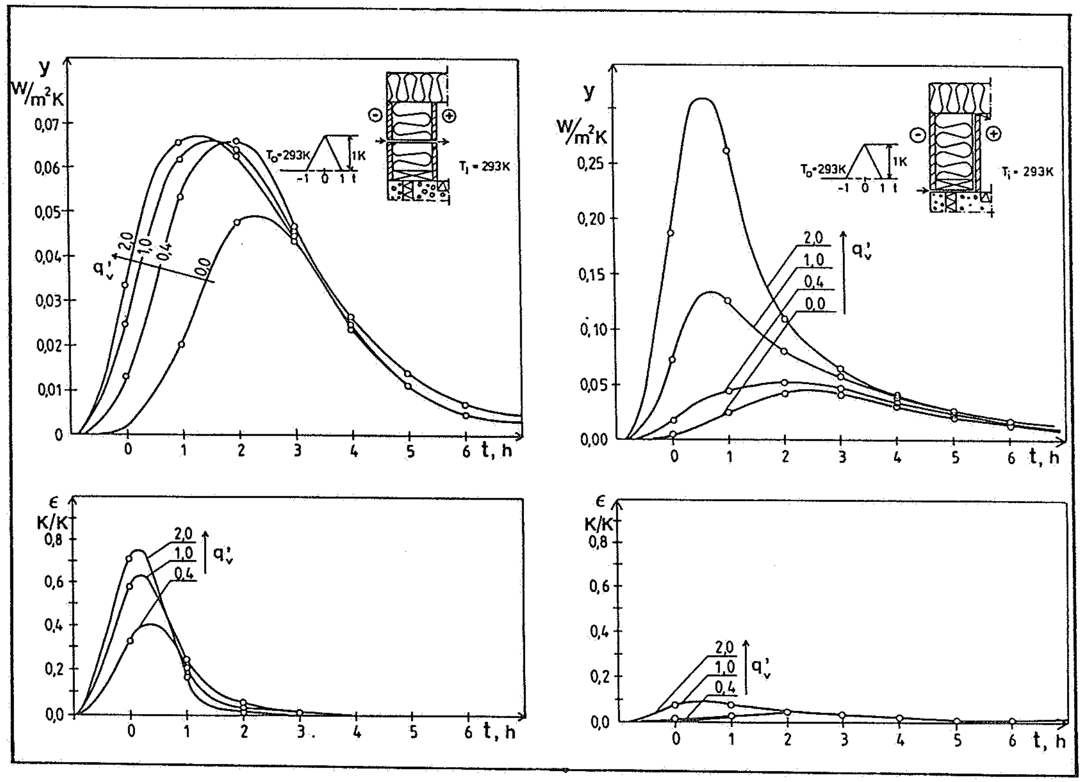

Figure 14. Response factors

It can be seen from Fiq. 14 that there is the possibility that the peak values of conduction heat loss responses are taken rather purely into account. Also the linear interpolation may cause inaccuracy. Thus, it can be concluded that response factor approach is accurate only case by case.

The effect of triangular shaped outside temperature change (from +20°C to +21°C and back to +20°C in 2 hours) on a macro-porous structure in constant initial temperature (+20°C) was analyzed numerically. Fig. 15 shows the calculated flow and temperature fields in the structure at different moments beginning from the first change of boundary values. Insulation thickness is 0.20 m, and inside and outside surfaces are impermeable. As the temperature raised at the other side of the structure, natural convection formed a loop in the thermal insulation. The effect of convection could be seen only in limited areas near the horisontal surfaces. In about seven hours the flow field had two convection loops due to the slightly higher temperature values in the middle of the structure.

Thus, in the case of convection the problem is not linear but dependent of temperature.

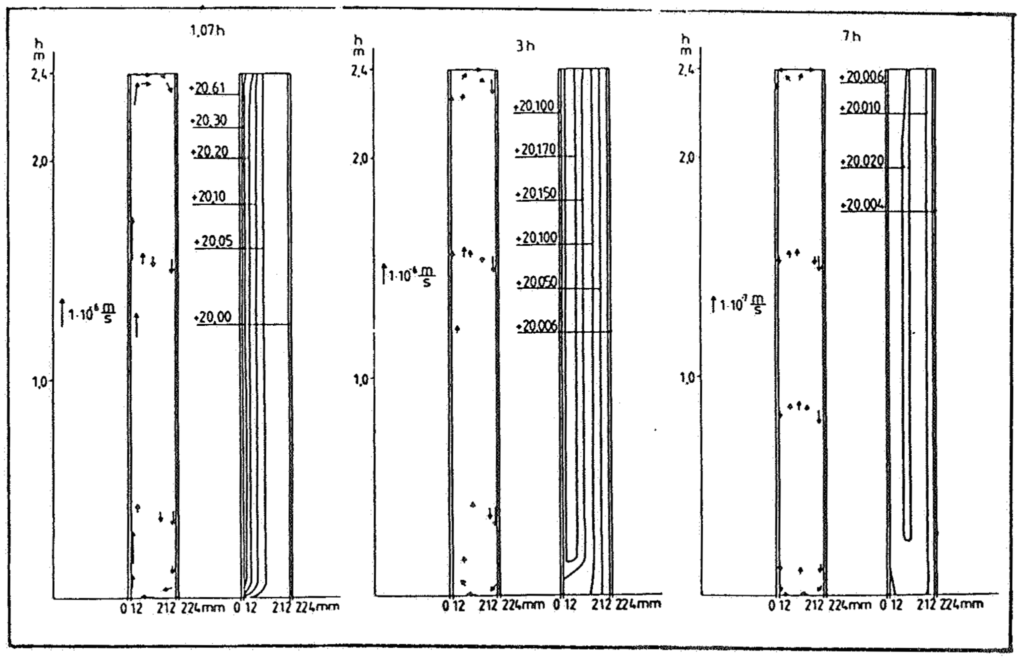

Figure 15. Temperature and air flow field as the outside temperature is changed.

3.3 Intentional exploitation of transmission losses - dynamic insulation

The profit of using intentional infiltration through wall structures (dynamic insulation) in ventilation is based on preheating the incoming air with conduction heat losses of a wall. Since the outside air is taken in through a permeable structure the rest of the building envelope should be as tight as possible. In addition, the interior underpressure should be prevailing and the effects of wind should be eliminated. The best conditions for using the counter flow wall are in a building provided with exhaust ventilation system.

In the following we shall consider with calculations the warming up of diffusively infiltrating air. The air is heated by exploiting conduction heat losses and solar energy. The calculations should be considered very prelimenary. Calculations were carried out for three different wall structures (Fig. 16). The outside temperature and the solar radiation are time dependent according to the weather data of the so called reference year (Luonetjarvi). The room air temperature is assumed to be constant, +20° C. In our particular examples the outer cover board is transparent (α is the absorption coefficient of the outer surface of the structure).

In Fig. 17 the temperature of incoming air for different structures, the outside temperature and the heat flux of solar radiation for a three day period are shown.

The minimum temperature of the incoming air was set to be +10° C (with the nominal mass flow rate). If the outside temperature is lower than -10° C then the air flow rate is a half of the nominal value. The heat transfer between the cover boards and the porous body was omitted.

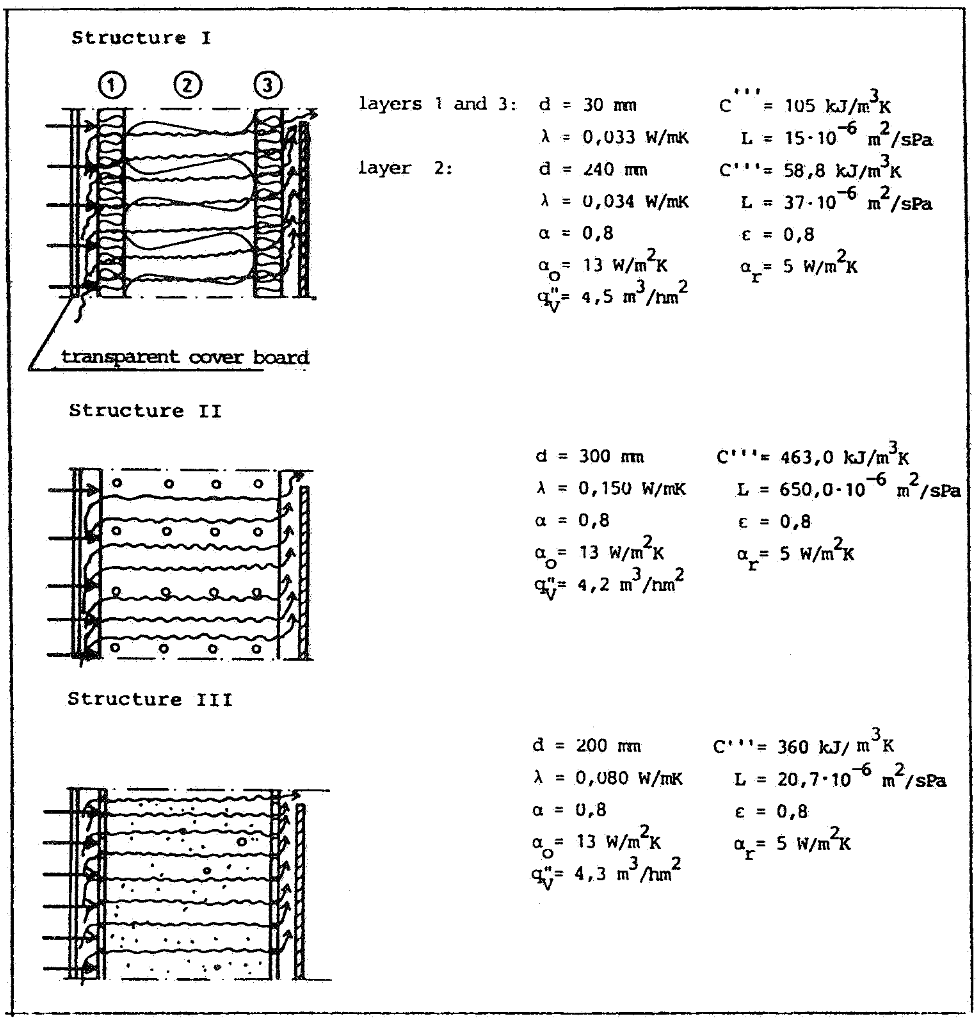

Figure 16. Wall structures in simulation and material properties.

In Fig. 18, the temperatures and the heat flux of the solar radiation are shown for a calculation period of three months.

Calculations show that the warming up of the incoming air is efficient in a porous body. The solar energy can be exploited most efficiently with a massive structure because it damps the surface temperature fluctuations effectively. The temperature of incoming air is occasionally rather high if thermally more light-weight structures are used (Fig. 18).

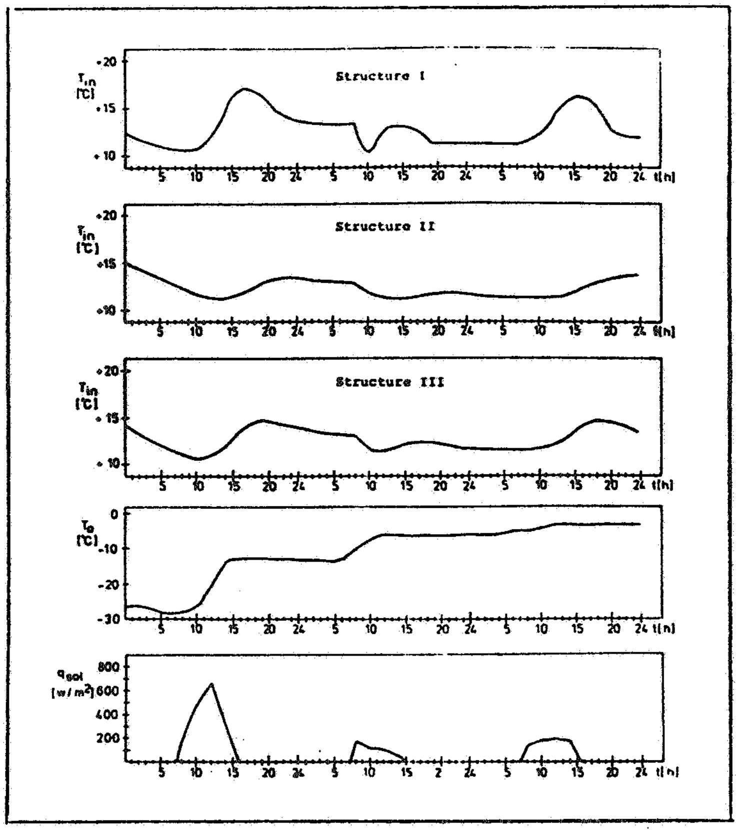

Figure 17. Temperatures of incoming air, the outside temperature and solar radition for a three day period.

The pressure differences over the structures I, II and III were 13.0, 0.5 and 11.5 Pa, respectively. The inflow and outflow resistance factors were omitted. With high inflow and outflow resistance factors it is possible to make air flow diffusively, which is assumed in our calculations.

The degree hours of the longer calculation period (3 months) are $63*10^3$ Kh, if the room air temperature is $+20^\circ$C. The total solar energy is 206 kWh/m^2. From the conduction heat losses and solar radiation exploited energy, and the energy needed to warm up the incoming air up to the room air temperature are

	Structure I	Structure II	Structure III
Exploited energy (kWh/m2)	53,5	51,1	50,7
Additional heating energy (kWh/m^2)	16,3	15,0	15,4
Volumetric flow rate (m^3/hm^2)	4,5	4,2	4,3

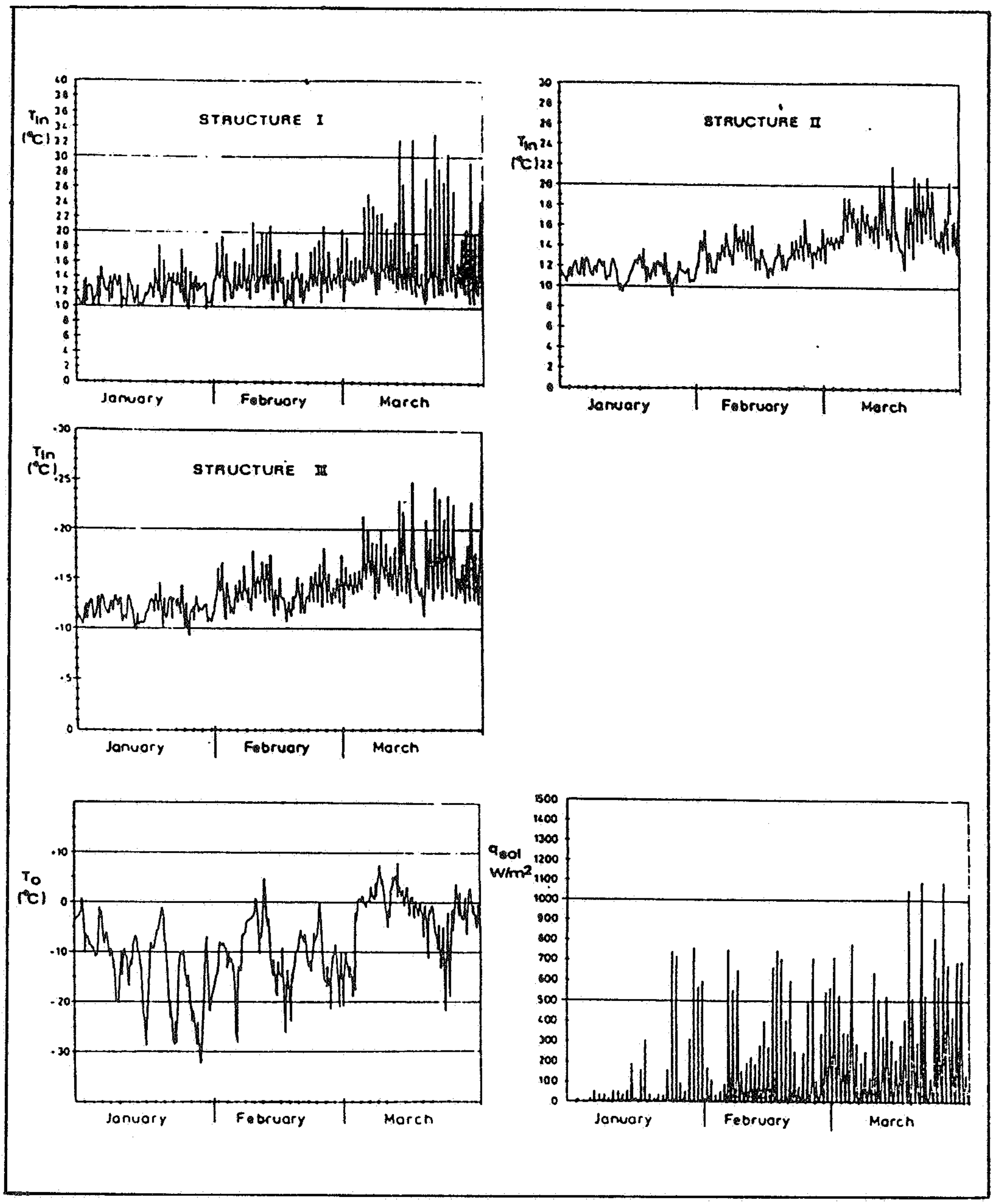

Figure 18. Temperatures of incoming air, the outside temperature and the solar radiation for a three month period.

According to our calculations the counter flow wall is a potential way to reduce the heating load of ventilation. In our further studies the thermal performance of integrated structures, including the counter flow wall, will be analyzed more thoroughly with more sophisticated calculation methods and experiments.

4. DISCUSSION AND CONCLUSIONS

The thermal coupling of leakage flows and heating load of buildings were studied by computer simulations and experiments. Based on the studies we suggest the transmission heat losses to be corrected by a Nusselt number typical for each structure and leakage flow pattern. The first approximation of the Nusselt number could be 0.8.

A clear difference should be made, whether the heat balance is formed for a room space or only for wall structure. In general, when considering a room or a building, ie., the coupling of building structures and, heating and ventilating systems, it is necessary to form the heat balance for a room space. It would also be reasonable to form the heat balance for a room space, for example, in the case the walls of a room have thermal coupling due to 3-dimensional internal air flows, which was omitted in our considerations.

Leakage flows have also influence on the dynamic behavior of wall structures. Heat flow field is two-dimensional, at least, and therefore at least two-dimensional approach should be applied. The finite difference method was found to be powerful in order to take into account the thermal coupling of leakage flows and transmission heat transfer. The time series approach,ie., the response factor approach seemed not to be useful because of strong nonlinearities.

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