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CONVECTION AND MOISTURE DRIVEN HEAT TRANSFER

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1. INTRODUCTION

The hygrothermal performance of a wall structure with air convection may considerably differ from that of a non-convective case. Convection may take place as a flow in macro-porous material layers or locally as a crack flow in material joints. Convection can be caused by temperature differences (natural convection), or pressure gradients in structures (wind, pressure differences over building envelope etc.), which may be present both separately or at the same time.

Phase changes between all the phases of water may occur, which may locally have a strong effect on the temperature field and also on the heat losses through the structure. The location and effect of phase changes may vary in time depending on, for example, the initial moisture distribution and the boundary conditions.

This paper presents numerically analyzed cases of air convection and phase changes in wall structures. Also the numerical study of dynamic insulation structures, which includes analysis of the potential effects of the heat recovery and risks for moisture accumulation are presented. The simulation model TCCC2D, which was used in the analysis, has been verified with several laboratory and field experiments (Kohonen et al. 1985, 1986 /1,2/).

2. NUMERICAL SIMULATION MODEL TCCC2D

TCCC2D (Transient Coupled Convection and Conduction in 2-Dimensions) solves the two-dimensional heat and moisture flow in multilayer building structures. Pressure, temperature, and partial vapor pressure are used as driving potentials. Darcy flow equation with Boussinesq approximation for incompressible fluid is used. Local thermodynamic equilibrium is assumed between stagnant and flowing phases. Phase changes may, however, occur.

The continuity, momentum, energy, and mass balance equations can be given in component form with Equations 1 through 4:

Mass balance:

$$\frac{\partial \rho_f}{\partial t} + \frac{\partial (\rho v_x)}{\partial x} + \frac{\partial (\rho v_y)}{\partial y} = 0 \qquad (1)$$

Momentum:

$$v_{x,f} = -K_{v,x}/\eta_f \frac{\partial \rho_f}{\partial x} \qquad (2\ a)$$

$$v_{y,f} = -K_{v,y}/\eta_f \left(\frac{\partial \rho_f}{\partial y} - \rho_f g\right) \qquad (2\ b)$$

Energy balance:

$$C'' \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(\lambda_x \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda_y \frac{\partial T}{\partial y}\right) - \frac{\partial}{\partial x}(\rho\, c_p\, v_x\, T)_f - \frac{\partial}{\partial y}(\rho\, c_p\, v_y\, T)_f + \sum_{\alpha} h_\alpha \sum_{\beta} q_{\alpha\beta} \qquad (3)$$

Moisture balance:

$$\frac{\partial (u \rho_0)}{\partial t} = \frac{\partial}{\partial x}\left(\lambda_{D,x} \frac{\partial p_v}{\partial x}\right) + \left(\lambda_{D,y} \frac{\partial p_v}{\partial y}\right) - \frac{\partial}{\partial x}(\rho_v v_x) - \frac{\partial}{\partial y}(\rho_v v_y) \qquad (4).$$

An ordinary finite-difference method is used in the numerical solution. Variables are calculated at the grid points and air velocities at the mid-point of grids. The upwind discretizing method is used in the solution of the convection terms. Moisture content of each material is coupled with vapor pressure and temperature by sorption isotherms.

3. THERMAL EFFECTS OF PHASE CHANGES OF WATER

Moisture transfer and phase changes in glass fibre thermal insulation may considerably increase the heat losses of a structure. The measurements by Kumaran /4/ with wet glass fibre thermal insulation under temperature gradient were analyzed numerically. Figure 1 shows the measured and calculated histories of heat flux through a glass fibre test specimen.

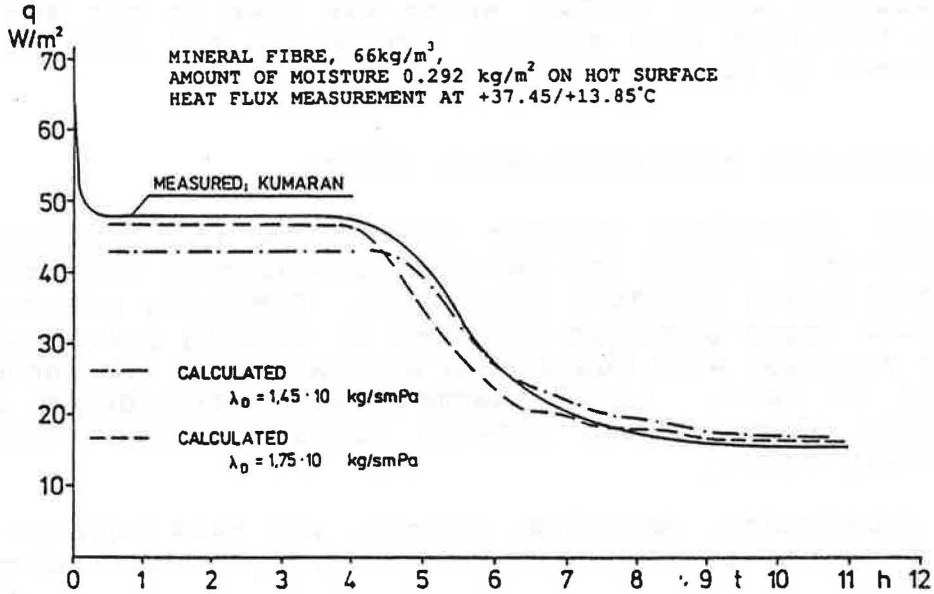


Fig. 1. Measured /4/ and calculated histories of heat flux through a wet glass-fibre insulation.

By changing the moisture transport properties given for the solution model, the measured heat flux distributions could be simulated relatively accurately. These results show that the latent heat is significant for the hygrothermal behaviour of wall structures and similar results are given in /3/.

4. HYGROTHERMAL EFFECTS OF AIR CONVECTION

4.1 Thermal Effects of Natural Convection

In numerical simulation, the structures are usually assumed to be ideal, so that different material layers are joined together without any extra surface resistances or local air leakage flows. Real structures are, however, non-ideal, which can be seen especially by increased local convection effects.

In an ideal, vertical wall structure with light weighted glass fibre thermal insulation covered with air impermeble material, natural convection can increase the heat losses with no more than 1 % according to calculations. Without any wind barrier, the calculated heat losses through a corresponding semi-open structure can be increased with about 8 % by natural convection. The experimentally measured increase of mean heat flow through a closed structure could be even from 10 to 15 % varying case by case /1,2,5/. This difference is due to the non-idealities of real multilayer structures, while the effects of convection are incresed with more material layers.

The difference between ideal and measured cases are most probably caused by locally increased air convection. These small air crack flows can be approximated by increasing the local permeability values in structural joints. Location and effect of these non-idealities varies case by case, so that they can not be accurately predicted. Calculations on ideal structures give the minimum limit for the influence of convection, which can be considered as a reference for the hygrothermal behavior of a structure. According to the numerical analysis and measurements, the structural air tightness is one of the main parameters which affect the hygrothermal behaviour of building structures.

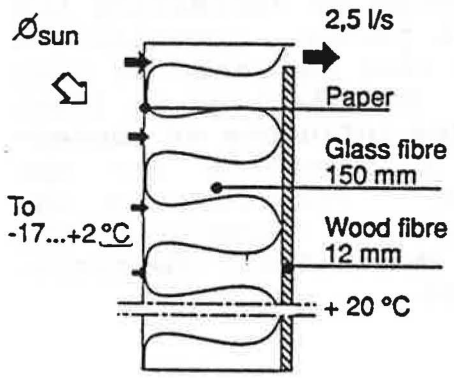
4.2 Air Infiltration / Exfiltration

When the air infiltrates through the building envelope, the heat recovery from transmission heat losses warms up the incoming air. Though the conductive heat losses are increased, the total heat losses reduce from those without any heat recovery. The total heat recovery effect of the structure (Nu^*) with a certain airflow rate from outside to inside air space can be given as the ratio between the total heat losses of the infiltration case (with heat recovery) and those of the reference case (without heat recovery) (Eq.5).

$$Nu^* = \frac{\Sigma\ q\ (\text{heat recovery})}{\Sigma\ q\ (\text{no heat recovery})} \quad (5).$$

The efficient use of a dynamic wall structure requires the airflow to be uniformly distributed over the structure. Nu^* has a minimum value, (about < 0.8), with a certain air flow rate typical for the U-value of the structure. This minimum value corresponds to the maximum relative heat recovery, and the airflow rate of this value can be considered as an optimum value for the structure. If the thickness of the thermal insulation layer increases, the optimum value decreases because the smaller transmission heat losses can be covered with smaller airflow rate.

Figure 2 shows a 2,5 m high dynamic wall structure with an air crack on the top of the inside covering board. Simulations using fixed infiltrating air flow rate (2,5 l/s) and weather data in Middle-Finland during one week in March were done. The outside temperature varied from about -17 to +2°C and the total radiation coming to the south facing facade was relatively high, about 3,2 kWh/m^{2}d. Table in Fig. 2 shows the numerically solved heat losses. In the cases, when the air is taken directly to inside air space at outside temperature, and there is no radiation to the surface, the total heat losses are about 44.2 W per structural area. With air infiltration, the convective heat losses are reduced with about 43 %, but the total losses only with about 10 %. When also the radiation on the surface is taken into account, the total heat losses are reduced with about 26 % (Nu^*=0.74) during the one week simulation period.



CASE	SUN RAD.	HEAT RECOV. & INFILTR.	HEAT LOSSES q_{COND} W/Km^2	q_{CONV} W/Km^2	q_{TOT} W/Km^2
REFER.	NO	NO	6.63	37.6	44.2
DYNAM.	NO	YES	18.5	21.4	39.9
DYNAM.	YES	YES	15.0	17.7	32.7

Fig. 2. Numerically analyzed dynamic wall structure and heat losses during one week period with and without air infiltration and radiation (3.2 kWh/m^{2}day).

4.3 Moisture Accumulation due to Air Convection

Air exfiltration through the building envelope usually causes strong local moisture accumulation when continuing for a long time. Also any kind of inside air flow into the structure may cause similar moisture accumulation.

The next case represents numerically analyzed hygrothermal performance of a 2.5 m high structure with 150 mm thick mineral fiber thermal insulation (19 kg/m^3) covered from the inside with 12 mm wood chip board and from the outside with 12 mm wood fibre board (Figure 3). The inside covering board had cracks on the top and in the bottom of the structure so that air could flow between the thermal insulation layer and the inside air space through these cracks. The outside covering board was thus almost airtight when compared to the inside one. The temperature and vapor pressure conditions for the inside and outside air spaces were +20°C, 1400 Pa and -20°C, 70 Pa respectively. The temperature difference caused an air flow rate 0.033 l/sm from inside air into the structure and back again to inside air space.

These conditions were maintained constant throughout a 31 day simulation period. Figure 3 shows how the moisture has strongly been accumulated in the upper part of the structure even though the air flow rate was rather small. Thus any kind of continuous inside air flow into a structure may locally affect the hygrothermal behaviour of the structure.

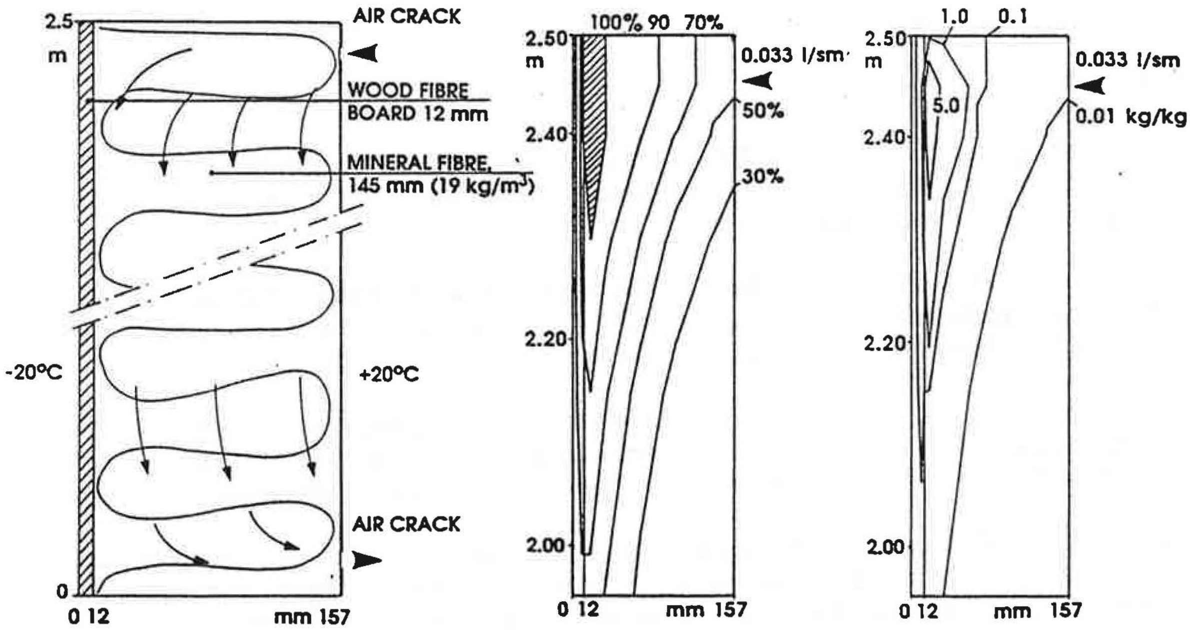


Fig. 3. Structure with air cracks at the inside covering board and numerically solved relative humidity and moisture content fields after 31 days of air convection.

CONCLUSIONS

Diffusive moisture transport can significantly increase the heat losses through a glass fibre insulation layer. The latent heat term must thus be taken into account in the hygrothermal simulation calculations when wet materials are concerned.

Convection caused effects on the thermal performance of building envelopes are highest with air infiltration or exfiltration, when the heat recovery effect decreases the total heat losses. With uniform air infiltration, the reduction of conductive and ventilation heat losses can be more than 20 %.

Long time air exfiltration or inside air flow into the structure may cause strong local moisture accumulation into the structure and thus affect its' hygrothermal performance.

NOMENCLATURE

c_p = specific heat capacity, J/kg K
g = gravitational pull, = 9.81 m^2/s
K_v = permeability, m^2
p = air pressure, Pa
p_v = partial vapor pressure, Pa
T = temperature, K or °C
v = airflow velocity, m/s

λ = thermal conductivity, W/K m
η = viscosity, kg/ms
ρ = density, kg/m^3

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