Combined Heat, Air, and Moisture Transport in Loose-Filled Insulation – Experiment and Simulation

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ABSTRACT

The paper presents the experimental and simulation results of a study on simultaneous heat, air, and moisture transport in a loose-fill insulation. The study was aimed at investigating the thermal and moisture effects of natural air convection with no liquid transport present and to validate a numerical model. The vertical rectangular cavity of the structure was filled with preconditioned expanded polystyrene material. The structure was positioned between two climate chambers at different temperatures. The quasi-steady-state temperature distribution in the cavity and the transient moisture condition were measured. The material properties were also measured for use in numerical simulations. Both measurement and simulation results indicate that natural convection in a porous cavity not only increases heat flow through the structure but also significantly influences moisture redistribution within the structure. The model can predict the moisture distribution fairly well in a qualitative sense, and the heat flows quantitatively, in a good way.

INTRODUCTION

Heat, air, and moisture transport processes are often present simultaneously, and interact with one another in building interiors and envelopes. Requirements concerning energy saving have led toward thicker insulation in building envelopes. The thicker insulation may lead to an increase in the importance of natural convection on energy consumption and vapor transport. The natural convection of humid air within a porous building material depends on its temperature distribution. The flow of humid air, in either forced or natural convection, contributes to convective heat flow and convective moisture flow. The vapor transport, either by diffusion or by convection as a part of humid air convection, may induce a latent heat effect.

Effects of coupled heat, air, and moisture transport due to natural convection in building components have been investigated in laboratory tests and in simulations by Janssens (1998) and Økland (1998) and in laboratory tests only by Hens et al. (1993). Investigations about the heat transfer in external walls influenced by natural convection were carried out by Dyrbøl (1998) and Lecompte (1990). Nevertheless, there is a need for validated tests with just a few parameters that influence the results. The convective moisture transport is very sensitive to changes in parameter values. It is difficult to obtain evaluated test results. This experimental investigation contributes to knowledge of the thermal and moisture behavior for cases with large temperature differences and a clear dependence on natural convection. That is why the study can contribute to the understanding of thermal and moisture effects of natural air convection in a building structure and can validate a numerical model for combined heat, air, and moisture transport.

Natural (humid) air convection within a vertical cavity filled with loose-fill insulation was investigated. Preconditioned polystyrene spheres were used as the insulation material. The investigated insulation structure is shown in Figure 1. Experiments were conducted to measure temperature and moisture profiles under steady-state boundary conditions, and the measured results were used to compare with those from simulations of the numerical model validated.

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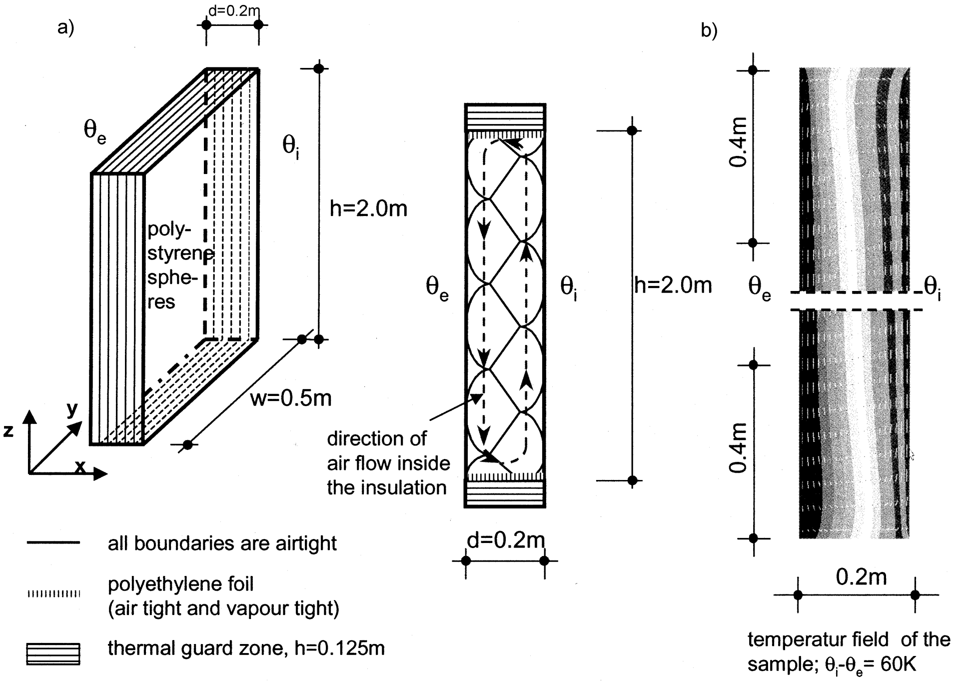

Figure 1 *(a) Model of the test in the climate chamber and boundary conditions and (b) model of temperature field near the top and the bottom influenced due to natural convection.*

The paper begins with the theory on which the numerical model is based and a brief introduction of the WINHAM2D program implementing the numerical model. It then presents the experiments conducted, the results of the experiments, and comparisons with simulation results. The final section is conclusions.

THEORY

A mathematical model for combined heat, air, and moisture transport in building envelope components in two-dimensional situations has been developed at Chalmers University of Technology (Wang and Hagentoft 1999). Natural convection and the latent heat effect are included in the model. The governing equations for air, moisture, and heat transport processes in two-dimensional Cartesian coordinates are the following:

Mass conservation:

$$\frac{\partial q_{a,x}}{\partial x} + \frac{\partial q_{a,y}}{\partial y} = 0 \tag{1}$$

The air mass flow (Darcy's law):

$$q_{a,x} = -\rho_a \frac{k_{a,x}}{\mu_a}\left(\frac{\partial P_a}{\partial x} + \beta\rho_{a,0} g \cos\theta \cdot (T - T_0)\right)$$

$$q_{a,y} = -\rho_a \frac{k_{a,y}}{\mu_a}\left(\frac{\partial P_a}{\partial y} + \beta\rho_{a,0} g \sin\theta \cdot (T - T_0)\right)$$

Mass balance for moisture flow:

$$\frac{\partial w}{\partial t} = -\frac{\partial q_{v,x}}{\partial x} - \frac{\partial q_{v,y}}{\partial y} \tag{2}$$

Moisture flow (Fick's law):

$$q_{v,x} = -\delta_{p,x}\frac{\partial p}{\partial x} + q_{a,x}\xi_a p, \qquad q_{v,y} = -\delta_{p,y}\frac{\partial p}{\partial y} + q_{a,y}\xi_a p$$

$$w \le w_{max}(T, RH, P^a), \qquad p \le p_{max}(T, P^a)$$

The symbol ξ_a is the specific vapor capacity of air—a defined coefficient assuming that vapor ratio of air is approximately proportional to vapor pressure in the situations of interest (Wang and Hagentoft 1999).

Energy conservation is

$$\frac{\partial(\rho c T)}{\partial t} = -\frac{\partial q_x}{\partial x} - \frac{\partial q_y}{\partial y} + h_v \frac{\partial w}{\partial t}. \tag{3}$$

The heat flow is given by (Fourier's law),

$$q_x = -\lambda_x \frac{\partial T}{\partial x} + q_{a,x} c_a (T - T_{ref}),$$

$$q_y = -\lambda_y \frac{\partial T}{\partial y} + q_{a,y} c_a (T - T_{ref}).$$

The model is based on the following assumptions:

1. Thermodynamic equilibrium is established instantly between the stagnant solid phase and the flowing fluid phase in porous materials.

2. General gas law holds for dry air, water vapor, and their mixture.
3. Fick's law holds for vapor diffusion and Fourier's law holds for heat conduction.
4. Darcy's law is applicable to the air transport in porous building materials.
5. Boussinesq approximation is valid in the situations of interest.
6. Moisture transport occurs only in a gaseous phase by water vapor.
7. Thermal effect of the phase change between water vapor and liquid water is accounted for.

Assumptions one through four are commonly made in building physics and give no important restrictions to the applicability of the mathematical model. Assumptions five through seven imply that the proper application of the mathematical model will be restricted to the building envelopes consisting of noncapillary active materials and operated in moderate climates. The detailed derivation of the model is presented in Wang and Hagentoft (1999).

BRIEF DESCRIPTION OF WINHAM2D PROGRAM

Based on the governing equations, a simulation program named WINHAM2D has been developed. The numerical model incorporated in the program employs a conditionally stable algorithm (Wang 1999) for obtaining a stable numerical solution of combined heat, air, and moisture transport. The algorithm combines the explicit and relaxation schemes. The former is used for heat and moisture transport and the latter is used for air transport. Along with the algorithm, a criterion for a determination of the time step is developed to ensure numerical stability. The calculation time step is determined in terms of the stability criteria for heat and moisture transport and a criterion for controlling latent heat release or absorption. Detailed numerical formulations of the model have been reported separately (Wang 1999).

Although WINHAM2D was aimed at simulating combined heat, air, and moisture transport processes, it has been developed in such a way that different types of problems can be handled. It can be applied for heat conduction problems, for instance, to study various thermal bridge problems. It can be used for combined heat and air transport problems, for instance, to study the thermal effect of air convection, such as air infiltration or exfiltration through a structure and natural convection within a structure insulated with air-permeable insulation material. It can be used for combined heat and moisture problems, for example, to evaluate the thermal and moisture effect of vapor diffusion. Most generally, it can be applied to problems involving heat, air, and moisture processes simultaneously. Program users can also choose whether or not to account for some effects, such as latent heat effect, moisture contribution to heat capacity, etc. Such design makes it easier for the user to perform sensitivity analyses and study the effects of certain processes or parameters.

The program is also capable of handling orthotropic materials. The defined orthotropic properties (Wang 1999) can be chosen for transport properties, such as air permeability, thermal conductivity, and vapor permeability. Also, the numerical model is able to handle nonlinear problems where the material properties are dependent on, for instance, the moisture conditions. Both thermal conductivity and air permeability can be linearly dependent on moisture content. Vapor permeability can be a function of relative humidity. Detailed formulations are described in Wang (1999).

TESTS

Test Procedures

To validate the numerical model, the hygrothermal behavior due to natural convection within a vertical rectangular cavity filled with loose-fill insulation was tested at the following boundary conditions:

- the boundaries of the cavity are impermeable to air and almost impermeable to moisture and
- constant air temperatures at the two vertical boundaries.

The test material is expanded polystyrene spheres of 1 to 4 mm in diameter. This material is suitable for the following reasons: the spheres have closed cells, their moisture content is very low, the air permeability of the insulation is relatively high, and no liquid water transport occurs inside the material.

The test material was preconditioned in a well-defined climate of 20°C and 50% RH, and the sample box was filled in the same climate to make sure that the initial moisture condition of the material remained unchanged prior to the tests. Combined diffusive and convective moisture transport existed in the sample box during the experimental tests. The sample box had dimensions of 2.0 by 0.5 by 0.2 m. The sides perpendicular to the isothermal surfaces are made of chipboard. A polyethylene membrane is placed between polystyrene spheres and chipboard walls to prevent moisture exchange between them. The side facing the cold chamber is made of acrylic plastic. The warm side is a plate of PUR foam. The model of the cavity is shown in Figure 1. The properties of the sample box materials are given in Table 1.

The hygrothermal behavior of the porous insulation was investigated in a climate chamber in the following experimental tests:

- **Test 1 (seven days duration).** Heating to +45.3°C at the warm side with RH = 50% and R_{si} = 0.14m^{2}W/K and cooling to –15.3°C at the cold side with RH = 95% and R_{se} = 0.13 m^{2}W/K; non-steady-state temperatures at the

TABLE 1
Material Properties of the Sample Box and the Guard Zone

Material	Thickness d [mm]	Thermal conductivity λ [W/(m·K)]		Vapor resistance factor μ	
PUR plate	21.55		$0.024746+0.000084*\theta$	0-100%RH	255
Acrylic plastic plate	3		0.18	0-100%RH	302300
Chipboard	18	$\parallel$	0.30	0%RH	42
		$\perp$	0.13	100%RH	121
Thermal guard zone (PUR)	200		0.028	0-100%RH	255

TABLE 2
Initial Material Properties of Polystyrene Spheres—Measurement Method and Measurement Results

Material property	Symbol	Dimension	Measurement method	Standards	Measurement results
Thermal conductivity	λ	W/(m·K)	Guarded hot plate apparatus	DIN EN 12667	$\lambda_{30\%\ RH} =$ 0.033369+ 0.000175·θ $\lambda_{50\%\ RH} =$ 0.033478+0.000172·θ
Density	ρ	kg/m^3	Estimation of volume and weight of the sample		21.50
Air permeability	k_a	m^2	Method after Darcy's law in a pressure box	DIN ISO 4638, DIN EN 29053	$1.25 \cdot 10^{-8}$
Vapor resistance factor	μ		Dry and wet cup diffusion test	DIN EN 12086	2.9
Sorption values		kg/kg	Climatization above saturated salt solution	EN ISO 12571	Shown in Figure 3
Relative humidity	RH	%	Capacitive humid air sensor: if the relative humidity of air changes, then there is a changing of the dielectric constant of water		First test: 48.0 (20.0°C)
Initial moisture content of material	w	kg/m^3	Drying and weighting until mass continue	DIN 52620	First test: 0.0484, Second test: 0.25

cold side for about 1 hour every 24 hours due to defrosting of the climate aggregate (see Figure 2); the material properties of the polystyrene are shown in Table 2.

- **Test 2 (48 days duration).** Initial moisture content: 0.25kg/m^3, non-steady-state temperatures at the cold side for about 0.5 to 1 hour every 24 hours due to defrosting of the climate aggregate.

1. First step (22 days): air temperatures: +23.3°C /+2.9°C
2. Second step (9 days): air temperatures: +26.1°C /-14.3°C
3. Third step (17 days): air temperatures: +46.3°C /-13.7°C

During these tests, the surfaces of the cavity were inspected by thermography. There were not thermal bridges and settlings inside the expanded polystyrene spheres shown in these checks.

The material properties (i.e., thermal conductivity, air permeability, vapor permeability, sorption isotherm, and density) were also measured for use in numerical simulations. The designation of the test methods and the test results of the material properties are shown in Figure 3 and Table 2.

The tests and the measurements of the material properties were made at the University of Rostock, Germany.

Test Methods

The following parameters were measured to investigate the thermal and moisture effects of natural convection:

- The temperature of six locations in the cold and warm chambers and the temperature field inside the insulation at 52 locations, using a T-type thermocouple.
- The local heat flux distribution along the warm surface

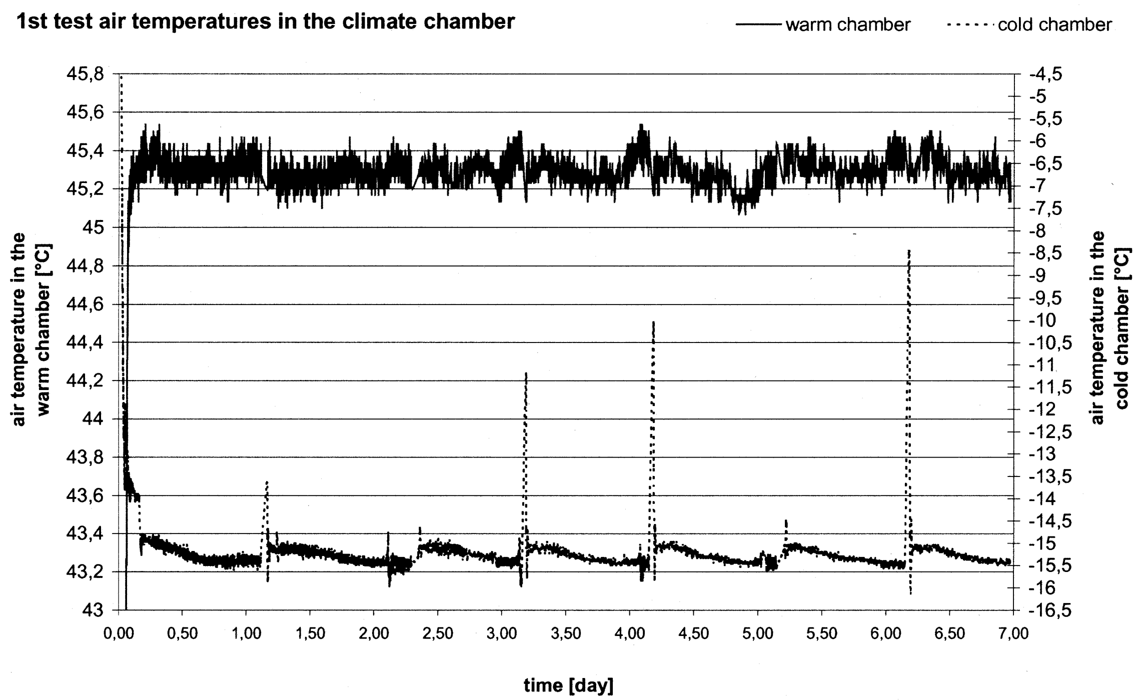

Figure 2 *First test: Air temperatures in the climate chambers.*

using a specially designed heat flux meter made of PUR-plate, shown in Figure 4 (Riesner and Mainka 2000).

- The relative humidity (%) of air at several locations inside the insulation using sensors by the capacitive method (which can be transformed to the moisture content w [kg/m^3] by the sorption isotherms).
- The initial moisture content and moisture content at the end of the tests at seven locations by drying and weighting.
- The border of the condensation area, which was indicated by sucking away dry nonstick polystyrene spheres from wet, sticking ones at the end of the test, shown in Figure 5**.**

Other parameters, especially air velocity, could not be verified by measurement because of very small values.

Results of Measurements and Observations

A small selection of measurement results are described here.

Heat Transfer. The quasi-steady-state heat transfer is influenced by natural convection. A significant redistribution of the temperature field in comparison with the one-dimensional distribution is found in the upper and lower 0.40 m area (Figures 1 and 6). The lowest temperatures are measured in the cold corner near the bottom of the sample box. The highest temperatures are given in the warm corner near the top of the sample box. The measured Nusselt numbers over the height

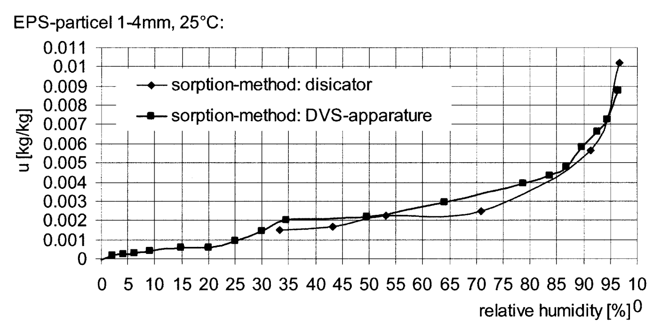

Figure 3 *Sorption curves of polystyrene spheres (diameter: 1 to 4 mm).*

confirm this (Figure 7). The measurement shows that the convective moisture transport influences the heat transport, and should not be neglected.

Moisture Transfer. A moisture content field comparable to the one shown in Figure 5 is established in all of the tests. That means that the convective moisture transfer has an influence length of about 40 cm from the top of the sample, if there is given the aspect ratio height/thickness = 2.0 m/0.2 m. That is equivalent to the convective flow field, described by the temperature field (Figures 1 and 6). The measurement results on the moisture content w (kg/m^3) after the end of the tests and the visual observations indicate

$$w_{warm\ side} < w_{cold\ side};$$
$$w_{cold\ side\ on\ the\ top} > w_{cold\ side\ at\ half\ height}.$$

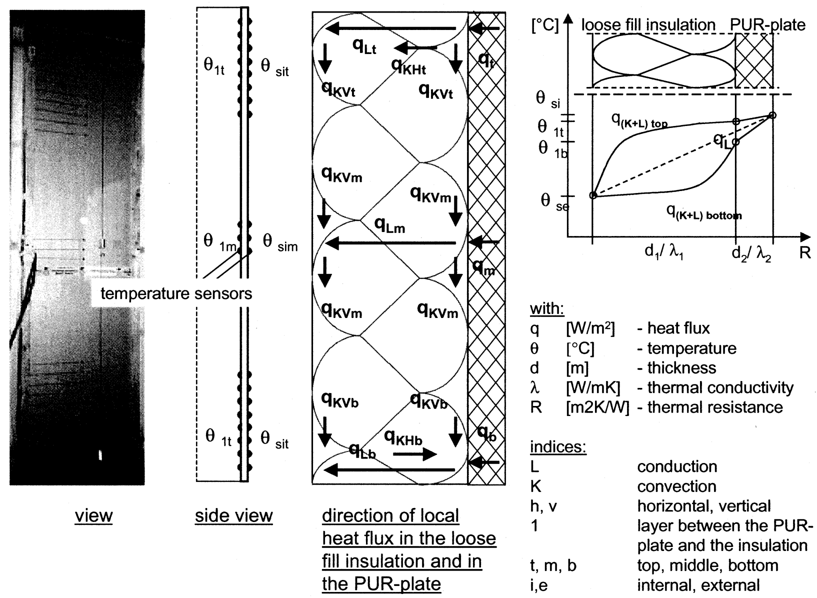

Figure 4 *Measurement method to estimate the local heat flux* q *(W/m²) influenced by natural convection (Riesner and Mainka 2000).*

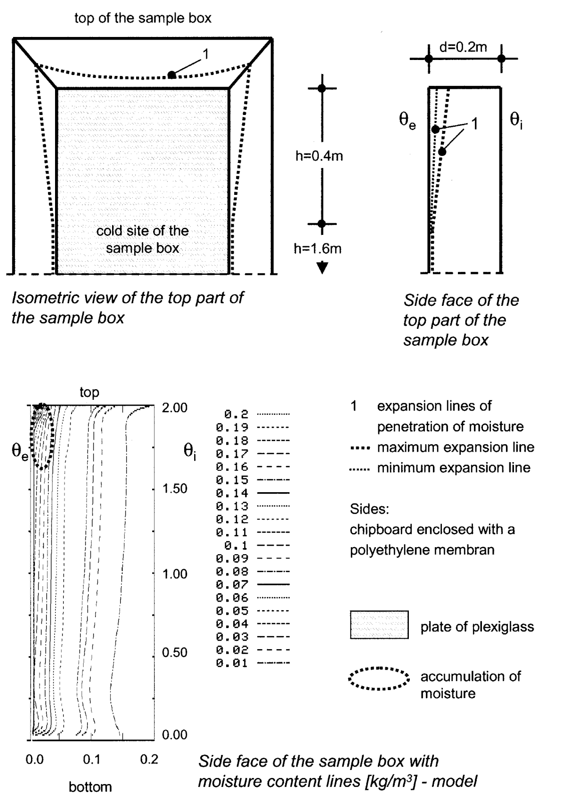

Figure 5 *Observations about penetrations of moisture in the sides of the sample box—material chipboard and the polystyrene spheres.*

This is caused by the horizontal flow from the warm side to the cold side near the surface on the top of the sample box and the ratio of $Z_{p,warm\ boundary} / Z_{p,cold\ boundary}$. The amount of the moisture content of polystyrene spheres depends on the time of the test, the temperature difference, the mean temperature, and the initial moisture content. It seems that moisture within the cavity was pumped to the cold upper corner where it froze and even could have caused a fungal attack.

COMPARISON OF RESULTS AND DISCUSSION

Measurements of the quasi-steady-state temperature field inside the polystyrene insulated layer show a coincidence with calculated results (Figures 6 and 8). A good agreement of the measurement and the simulation exists in the area between the half thickness of the sample and the warm side, shown in the diagrams in Figure 6. Differences near the boundaries on the top and the bottom are caused by defects of installation, small gaps of 0.5 mm between the chipboard and the guard zone, found after the first test. The agreement of measured temperatures and calculated temperatures near the boundary of the cold side is not as good as in the other locations. Reasons could be the input of a uniform thermal conductivity in WINHAM2D across the whole sample, the latent heat effect, presence of water and drainage, water drops, or ice on the temperature sensors.

The measured Nu-curves over the height agree well with the calculated results (Figure 7). These results demonstrate the good suitability of the measurement method used to estimate the heat flux (W/m²) over the height influenced by natural convection (Figure 4).

The observed increasing moisture at the upper cold inside the surface is caused by natural convection inside the polystyrene material. Calculations based on the heat, air, and moisture transfer simulation with WINHAM2D show this effect also (see Table 3) with a fairly good coincidence near the cold upper

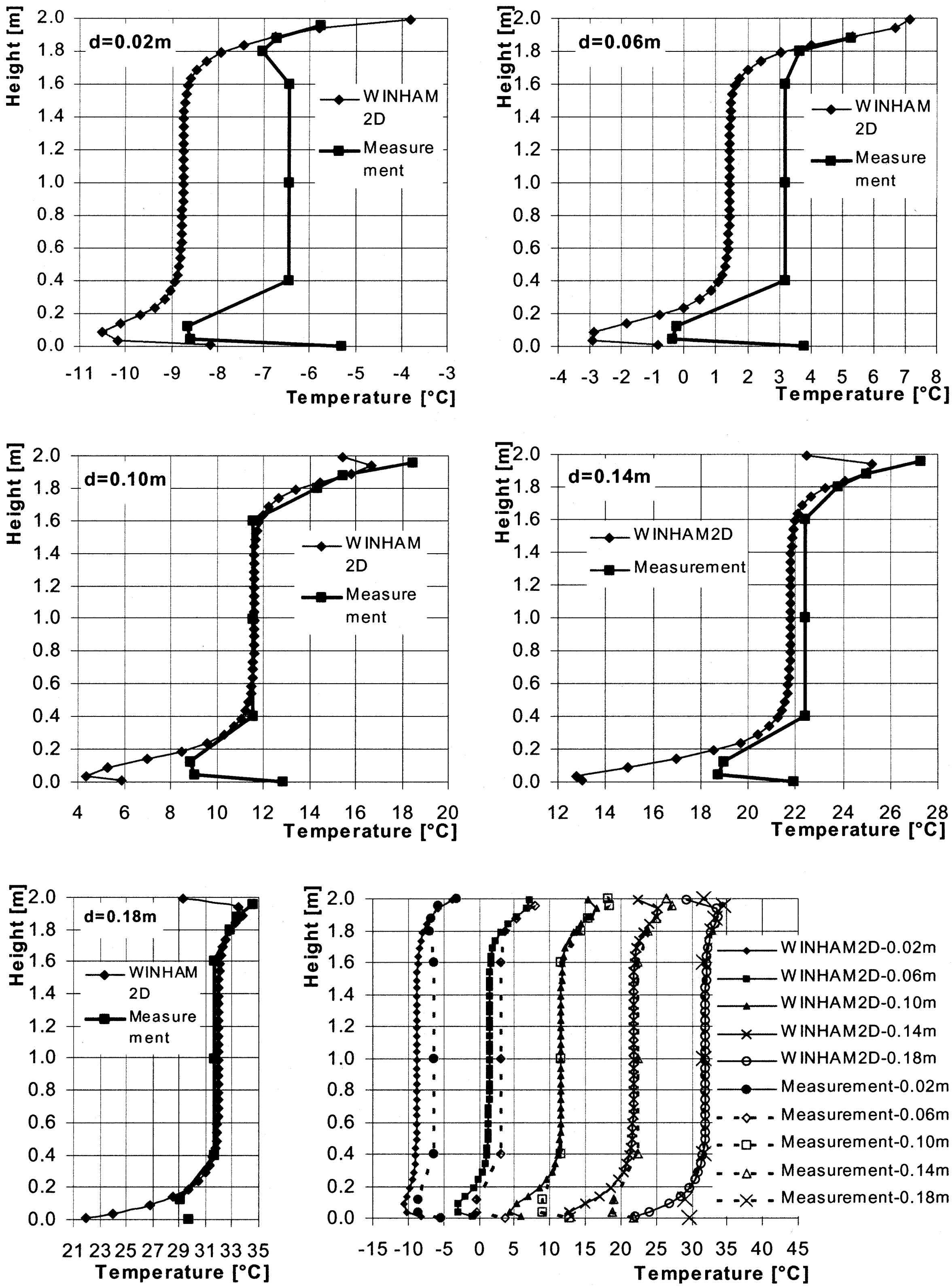

Figure 6 *Results of measurements in first test (θ_I = +45.0°C; θ_e = –15.5°C; R_{si} = 0.07 m^2K/W; R_{se} = 0.16 m^2K/W) and simulations: curves of the temperature field over the height of the cavity.*

corner. Table 3 shows that the warm side has dried out more in the simulation than was found in the measurement and, consequently, in the calculated results it is more moist at the cold side. This could be caused by an overestimation of the air flow speeds, mostly influenced by the air permeability k_a (m^2) of the material. The following facts could also have an influence on the deviations between the results of measured and calculated moisture contents near the cold side:

- The insulation material is not homogeneous after ice has been established and starts growing from the upper cold corner and the cold side.
- The very steep gradient of the moisture content curve near the cold side (see Figures 5 and 9a) explain the problem to get accurate measurement results near this region.

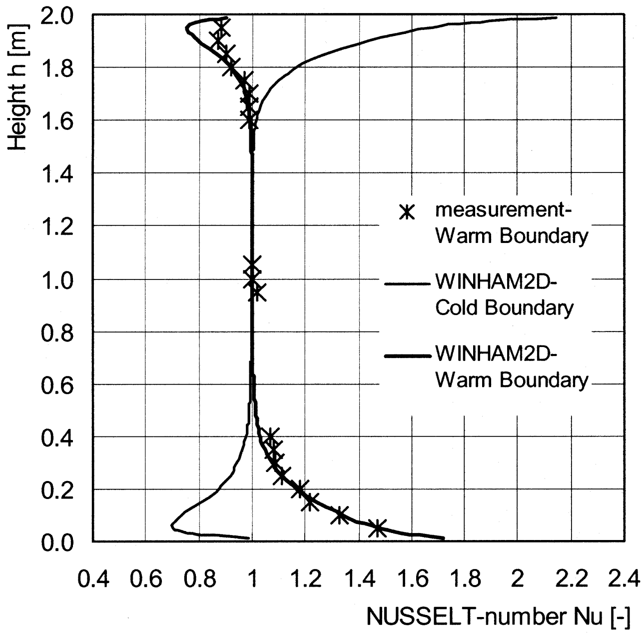

Figure 7 *Second test (θ_i = +46.2°C; θ_e = –14.6°C; R_{si} = 0.12 m^2K/W; R_{se} = 0.23 m^2K/W): results of measurements and simulations—curves of the Nusselt number Nu [-] over the height of the cavity.*

Differences between WINHAM2D and the experimental estimation of moisture content of the samples near the warm boundary are relatively small and could be caused by a small deviation between the relative humidity inside the polystyrene

TABLE 3
Comparison of Measurement and Simulation with WINHAM2D: Moisture Redistribution Due to Natural Convection—Local Moisture Content

1st test about 7 days: quasi-steady-state air temperatures +45.3°C/ –15.3°C (non-steady-state air temperatures at the cold side for about 0.5 to 1 hour due to defrosting of the climate aggregate, shown in Figure 2); initial moisture content w=0.0484 kg/m^3, initial relative humidity 48.0% RH/20.0°C				
Method	**Height h (m) volume V (m^3)**	**Moisture content w (kg/m^3)**		
		Cold side	**Middle**	**Warm side**
Measurement	1.6-2.0 m	4.111		0.077
Calculation	0.00016 m^3	3.978		0.009
Measurement	0.8-1.2 m	0.125	0.074	0.073
Calculation	0.00017 m^3	1.576	0.0263	0.0084
Measurement	0.0-0.4 m	0.102		0.069
Calculation	0.00017 m^3	0.730		0.008

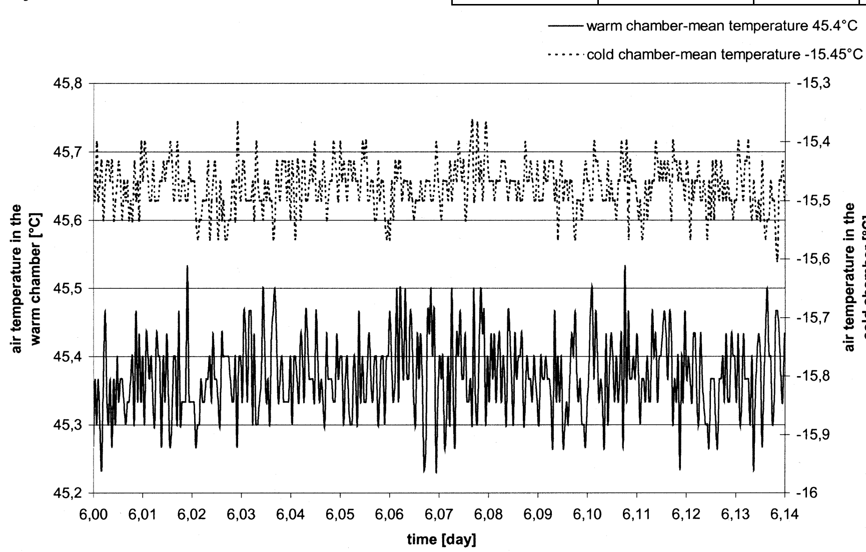

Figure 8 *First test: Air temperatures in the climate chambers during the measurement of the temperature field shown in Figure 6.*

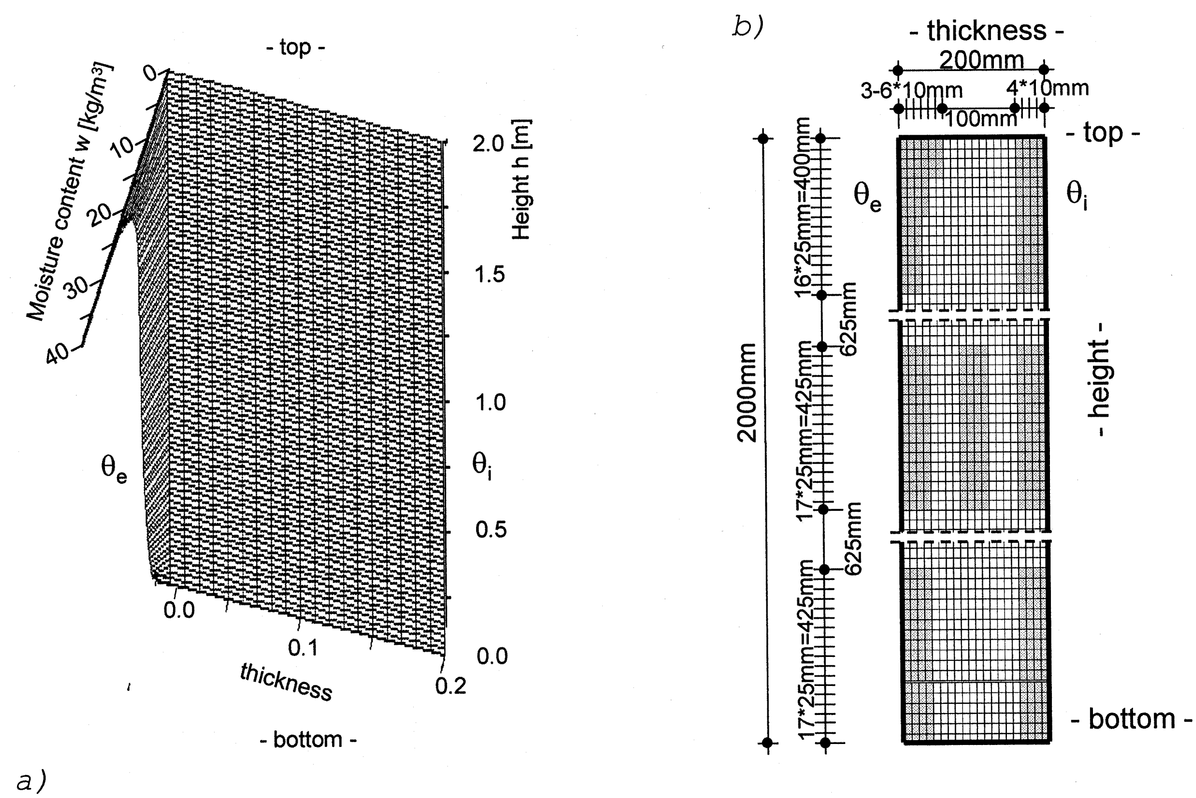

Figure 9 *(a) Results of calculation with WINHAM2D. First test: moisture content field after 164 hours; (b) location and size of samples used to define moisture content.*

spheres and the climate chamber during the process of removing the insulation out of the sample box.

CONCLUSIONS

The measurement results discussed here indicate that natural air convection induced by the temperature difference over the cavity not only increases the heat flow through the structure but also results in moisture redistribution within the structure. The behavior of local moisture accumulation during the course of moisture redistribution depends on the temperature difference across the cavity. The model can predict the moisture distribution fairly well in a qualitative sense and the heat flows quantitatively in a good way. For completeness of the experiments, the permeability for frozen insulation materials had to be investigated. Measures should also be taken in order to avoid air void within the test walls.

FURTHER INVESTIGATIONS

The following tests and analyses have been planned for the future:

- Validation of the measurement of humid air convection by using capacitive relative humidity sensors inside the insulation.
- Experimental investigations in a climate chamber with
  1. more temperature and moisture sensors and
  2. measurements with a climate cycle in the cold chamber comparable to the Central European climate.
- A sensitivity analysis of the influence of the material properties and climatic conditions on the temperature redistribution and the moisture redistribution due to natural convection in a vertical rectangular cavity filled with loose-filled insulation.

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NOMENCLATURE

c	=	specific heat capacity of material, J/(kg·K)
c_a	=	specific heat capacity of air at atmospheric pressure, J/(kg·K)
g	=	gravitational acceleration, m/s^2

h_v = latent heat of water vaporization, J/kg
k_a = air permeability, m^2
Nu = Nusselt value
Nu = $q_{conduction+convection} / q_{conduction}$
p = water vapor pressure, Pa
p_{max} = maximum water vapor pressure, Pa
P^a = atmospheric air pressure, Pa
P_a = deviation of air pressure from the hydrostatic one at reference temperature, Pa
q = heat flux, W/m^2
q_a = air flux, $kg/(m^2 \cdot s)$
q_v = moisture flux, $kg/(m^2 \cdot s)$
R = thermal resistance, $(m^2 \cdot K)/W$
RH = relative humidity of air,%
t = time, s
T = temperature, K
T_0 = reference temperature, K
T_{ref} = an arbitrary reference temperature, K
Z_P = water vapor resistance, $m^2 \cdot s \cdot Pa/kg$
w = moisture content of material, kg/m^3
ρ = material density, kg/m^3
ρ_a = air density, kg/m^3
$\rho_{a,0}$ = air density at reference temperature T_0 and height h_0 above sea level, kg/m^3
β = thermal expansion coefficient of air, 1/K
θ = the angle between x-direction and direction of gravity
λ = thermal conductivity of material, $W/(m \cdot K)$
μ = vapor resistance factor
μ_a = dynamic viscosity of air, $kg/(s \cdot m)$
δ_p = water vapor permeability, $kg/(m \cdot s \cdot Pa)$
ξ_a = specific water vapor capacity of air, $kg/(kg \cdot Pa)$

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