Condensation Risk within Loose Fill Insulation Due to Natural Convection in Vertical Cavities

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ABSTRACT

The paper presents a case study about the influence of natural convection on condensation risks and on mold growth risks within loose fill insulation of a wood-framed wall under a yearly climate cycle. The investigations were carried out using the WINHAM2D model, a two-dimensional heat, air, and moisture transport program without liquid transport suitable for noncapillary insulations. The results of WINHAM2D are compared with the German standard to show differences between both models and their results. As the focal point, the results of location, time, period, and extent of local moisture accumulation are considered. The purpose of the study is to give a first recommendation to avoid damage due to convective moisture redistribution under the coupled conditions of air permeability of the insulation and water vapor diffusion resistances of the boundary layers. The analysis indicates that material properties and boundary conditions have a significant influence on the dynamic process of the moisture migration within insulation.

INTRODUCTION

The knowledge of moisture migration within the insulation in a building envelope, due to simultaneous heat, air, and moisture transport, is very important for the characterization of its behavior and for the prevention of damage due to condensation. Requirements concerning energy saving have promulgated the tendency for thicker insulation in building envelopes. The thicker insulation may lead to an increase in the importance of the effect of natural convection on energy consumption and vapor transport.

The heat transport in the insulation is caused by conduction, radiation, latent heat, and natural convection. The driving force is the temperature gradient. The mass transport in noncapillary insulations is influenced by vapor transport, adsorbate transport, and moist airflow. Here the driving forces are the pressure gradient, the concentration, and the temperature gradient.

The driving force of natural convection within open porous materials is the pressure difference due to thermal buoyancy caused by high temperature differences between the interior and external boundaries of the building structure. Natural convection leads to air circulation within the insulation, shown in Figure 1 in a qualitative presentation. This circulation causes a change of the temperature field and the moisture field. In the presented case of insulation in an external wall, the coupled heat, air, and moisture transport within open porous insulation may lead to a local moisture accumulation in the cold upper corner.

Investigations of the heat transfer in external walls influenced by natural convection have been carried out by Lorentzen and Brendeng (1960), Bankvall (1972), Lecompte (1989), Silberstein et al. (1990), Hens (1992), and Dyrbøl (1998). Effects of coupled heat, air, and moisture transport due to natural convection in building components were investigated in laboratory tests and in simulations by Geving et al. (1997), Janssens (1998), Økland (1998) in laboratory tests only by Hens et al. (1993). The International Energy Agency (IEA) concentrated research projects about coupled heat, air, and moisture transport (HAM) in building components in Annex 24, HAMTIE, between 1990 and 1995.

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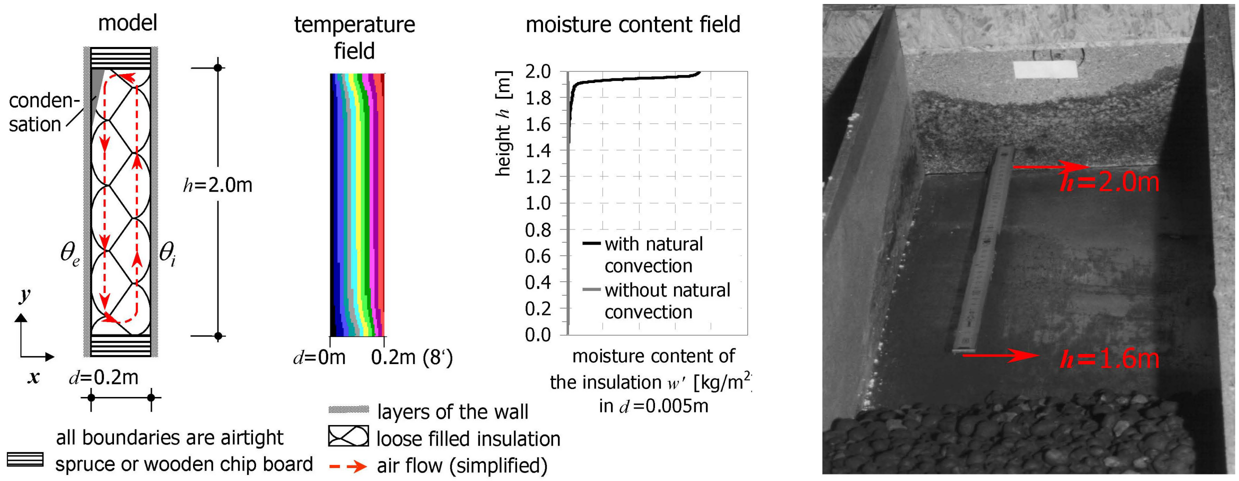


a) model of the investigation as well as the shape of the temperature and moisture redistribution in the insulation due to natural convection

b) mold growth on the chip board, photo of the upper cold edge

Figure 1 *Temperature and moisture redistribution as well as mold growth in the insulation of foamed clay spheres and wooden chipboard due to natural convection.*

Nevertheless, there is a need for further investigation with other building structures and with insulation materials considering workmanship. A causative factor is the very high sensitivity of convective moisture transport to changes in material properties, geometry, as well as climate conditions.

AIM AND RESTRICTIONS OF THE CASE STUDIED

The investigated subject is an airtight external wood-framed wall with a highly air-permeable, loose fill insulation within the cavity of the frame under a yearly climatic cycle of North Europe. The investigated air permeabilities of the insulations are in a range between $3 \cdot 10^{-10}$ m^2 and $500 \cdot 10^{-10}$ m^2. The dimensions of the insulation are $h \times d$ = 2.0 m × 0.2 m (6.56 in. × 0.656 in.). The tested materials do not have a mentioned capillarity (e.g., Künzel [1994]). Therefore, liquid transport is excluded. Radiation within the insulation between the particles is also not expected (Jonsson 1993; Riesner 2003). The investigated subject is only the vertical cavity filled with loose fill insulation. Note that:

- Moisture transport between the spruce and the insulation at the top and at the bottom is excluded by the simulation (see Figure 1).
- An ideal contact without air gaps between the insulation and the adjacent spruce at the top and at the bottom of the cavity is given.

The investigation is carried out with WINHAM2D, a numerical model to simulate the coupled heat, air, and moisture transport in building materials, especially in open-porous insulation materials. The convective moisture transport in loose fill insulation materials and the influence of the moisture capacity are of interest in simulations with WINHAM2D under a yearly climatic cycle. The aim of the first case study is to test the suitability of the common German method (GLASER method in combination with the standard DIN 4108-3:2001) when natural convection can be proved in several insulation materials of the investigated airtight external wall structures. This German method does not consider condensation risks due to natural convection, but damage due to local moisture accumulation as a result of natural convection could be avoided with the calculation by using the simple German method if:

- the condensation rate calculated with the simple German method would be higher than the moisture content simulated with WINHAM2D under the above-mentioned conditions, as well as
- the maximum allowed accumulated moisture content (upper limit) of the standard DIN 4108-3:2001 is higher than the simulated results of WINHAM2D.

In a second case study, the influence of the air permeability k_a and the water vapor diffusion resistances of the adjacent layers of the insulation Z_{pi} and Z_{pe} are investigated for different moisture capacities and heat capacities of insulations. Test results yield a first recommendation to avoid damages due to moisture redistribution caused by natural convection. The results are restricted to the investigated subject.

BASICS OF THE CASE STUDY

Large-scale experiments with nine loose fill insulation types in wood-framed external walls in a double climate chamber under a steady-state climate are a basis of the case study presented by Riesner (2003). The results give clear evidence of a redistributed temperature field and moisture field caused by natural convection dependent on the air permeability of the insulation. The shape of the temperature and moisture redistribution caused by natural convection in an insulated cavity of an external wall in the wood-framed structure is illustrated in Figure 1a. Furthermore, the investigations show a clear variation of the bulk density inside the loose fill insulation built in the structure with careful workmanship. This variation of the bulk density influences the heat and moisture transport caused by natural convection. In one experiment, mold growth within the insulation was evident near the cold top edge. The form of the condensation area with mold growth is typical for the form due to natural convection, shown in Figure 1b.

A further basis of numerical case studies is the experimental validation of the simulation program WINHAM2D used for some cases. WINHAM2D was developed at the Department of Building Physics, Chalmers University of Technology, by Wang and Hagentoft. The experimental validation contains investigations of loose fill insulation in wood-framed external walls for cases with large temperature differences and a clear dependence on natural convection. The results of the heat, air, and moisture transport in polystyrene spheres are presented by Riesner et al. (2001) and by Riesner (2003). These investigations contribute to knowledge of the thermal and moisture behavior for a better understanding of thermal and moisture effects of natural air convection in insulation materials. The steady-state experiments in a double climate chamber have just a few parameters that influence the results as a requirement to validate the numerical model of WINHAM2D in this kind of field. Further validation of WINHAM2D is given in Wang (2003). 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 of WINHAM2D can predict the moisture distribution fairly well in the cold upper edge (focal point), and the heat flows quantitatively in a good way.

THEORY

The combined heat, air, and moisture transport in open porous building materials is described in a mathematical model developed by Wang and Hagentoft (1999). The governing equations for air, moisture, and heat transport processes in two-dimensional Cartesian coordinates are as follows:

Mass conservation gives

$$\nabla \vec{q}_a = 0 .$$

The air mass flow (Darcy's law) is

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

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

Mass balance for the moisture flow gives

$$\frac{\partial w}{\partial t} = -\nabla \vec{q}_v .$$

The moisture flow is described by the Fick's law with an additional term due to moisture convection.

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

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

Energy conservation gives

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

The heat flow is given by Fourier's law, with an additional term due to convection.

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

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

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 for heat conduction.
4. Darcy's law is applicable to the air transport in porous building materials.
5. The Boussinesq approximation is valid in situations of interest.
6. Radiation effect inside the materials is neglected.
7. Moisture transport occurs only in gaseous phase by water vapor.
8. Thermal effect of the phase change between water vapor and liquid water is accounted for.

The first four assumptions are commonly made in building physics and give no important restrictions to the applicability of the mathematical model. Assumptions 5 through 7 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 has previously been presented by Wang and Hagentoft (1999).

The effects of coupled heat, air, and moisture transport are usually presented by nondimensional numbers. The heat transport within materials caused by natural convection are described by the Nusselt number when radiation within the insulation can be neglected.

$$\mathrm{Nu} = \frac{q_{cd} + q_{cv}}{q_{cd}}$$

The modified Rayleigh number, Ra_d^*, contains the essential parameter of influence of the coupled heat and air transport. In the first term, the equation implies the properties of the flowing fluid and, in the second term, the properties of the insulation—air permeability k_a and thermal conductivity λ_{por}—the air temperature difference $\Delta\theta_{i-e}$, as well as the thickness d are given.

$$\mathrm{Ra}_d^* = \frac{\beta g(\rho c_p)_L}{v} \cdot \frac{d \cdot k_a \cdot \Delta\theta_{i-e}}{\lambda_{por}}$$

SIMULATION PROGRAM "WINHAM2D"

The simulation program used—WINHAM2D—is based on the above-mentioned governing equations. The numerical model incorporated in the program is described by the developer (Wang and Hagentoft 2002; Wang 2003). Detailed numerical formulations of the model have been reported separately in Wang (1999). WINHAM2D calculates the combined heat, air, and moisture transport processes in materials and with or without natural convection and latent heat effects. The user has the option to calculate the following different combinations of the above-mentioned processes:

- heat conduction problems,
- 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),
- combined heat and moisture problems (for example, to evaluate the thermal and moisture effect of vapor diffusion),
- problems involving heat, air, and moisture processes simultaneously.

Defined orthotropic properties can be chosen for properties such as air permeability (k_{ax} and k_{ay}), thermal conductivity (λ_x and λ_y), and vapor permeability (δ_{px} and δ_{py}). The geometry of each part of a multilayer structure has to be rectangular. The climatic conditions can be chosen steady-state or transient by climate files. WINHAM2D calculates the fields of temperature, air pressure, moisture content, vapor pressure, and relative humidity and gives the results of the heat, air, and vapor flux and flow. The program user can also chose whether to account for some effects or not, such as latent heat effect, moisture contribution to heat capacity, etc. Detailed formulations are described in Wang (1999). WINHAM2D was validated for the investigated subject presented in Riesner et al. (2001), Wang (2003), and Riesner (2003).

INSULATION MATERIALS

The selection of the materials aimed at a wide spectrum of different material properties with an influence of heat, air, and moisture transport caused by natural convection. Those considered were:

- Different forms and different grain sizes (variation in air permeability)
- Various basic materials such as different organic and inorganic material and
- Different techniques to build the loose fill insulation (machine-driven blowing in or bulk in by hand)

The investigation includes bulk materials (expanded polystyrene spheres, foamed clay spheres, expanded cork granulate, and different expanded mineral bulk) as well as blown-in insulation, such as different mineral fibers as well as cellulose flakes.

The material properties such as air permeability $k_a = f(\rho)$, thermal conductivity $\lambda = f(\rho)$, moisture capacity $\xi = du/d\phi$ with $d\phi$ ~5% RH, water vapor diffusion resistance factor μ, bulk density ρ, and moisture content u are measured (Riesner et al. 2001; Riesner 2003). Isotropic properties are assumed and observed. The initial moisture content of the materials is chosen in balance to the relative humidity of 80%.

Loose fill insulation in an external wall has variations in bulk density ρ, which can cause a change of the air permeability $k_a = f(\rho)$. This effect was also demonstrated in our own tests with a high quality of workmanship. These tests in a double climate chamber verified a change in the air permeability by measurements of the temperature field and estimation of the local Nusselt numbers over the height at the interior surface Nu'_{si}. For instance, the temperature field inside the insulation measured at 52 locations (5 layers parallel at the isotherms and up to 12 different heights) was more strongly redistributed in the typical shape caused by natural convection than in the simulated results. A good agreement between measured and simulated results could be obtained when the measured air permeability k_a was adjusted to fit the simulated temperature field. Some of these adjustments are proved by measurements of density variations inside filled vertical cavities and a comparative measurement of the air permeability relating to a lower density. The results of these investigations are also used in the following simulations as corrected air permeabilities $k_{a,corr}$, shown in Table 1 (Riesner 2003).

SIMULATION OF THE YEARLY CONDENSATION RISK IN LOOSE FILL INSULATION

Introduction

Natural convection can be a cause for moisture accumulation in the upper cold edge of an insulated cavity in an external wood-framed wall. Qualitatively expressed, the amount of the moisture accumulation in the insulation increases when:

Table 1. Material Properties

No.	Insulation Material	Thermal Conductivity* $\lambda_{15°C}$ [W/(m·K)]	Bulk Density* ρ [kg/m^3]	Air Permeability* k_a, ($k_{a,corr}$) [10^{-10} m^2]	W. Vapor Diff. Res. Factor μ [-]	Heat Capacity† c [J/(kg·K)]	Moisture Capacity $\xi = du/d\phi$)‡ 100 · [kg/kg]						
							RH:10%	20%	50%	80%	90%	98%	100%
1a 1b	Cellulose	0.040	63	3 (75)	2**	1944	2.980	4.210	7.810	14.00	18.50	27.90	34.20
2a 2b	Mineral fiber	0.040	55	41 (110)	1**	850	0.070	0.100	0.165	0.243	0.317	0.505	0.561
3a 3b	Mineral fiber	0.038	66	15 (32.5)	1**	850	0.034	0.047	0.076	0.126	0.165	0.239	0.267
4a 4b	Glass fiber	0.036	26	35 (100)	1**	850	0.102	0.138	0.225	0.426	0.701	2.030	2.880
5	Exp. polystyrene spheres, 2/4 mm)††	0.037	22	125	3*	1470	0.040	0.060	0.220	0.400	0.581	0.980	1.120
6	Exp. cork granulate, 2/5 mm	0.041	80	205	3*	1880	0.715	1.140	2.210	3.190	3.570	4.080	4.250
7	Foamed clay spheres, 4/16 mm	0.084	440	500	5‡‡	1000	0.001	0.001	0.013	0.081	0.155	0.432	0.567
8a 8b	Exp. mineral granulate, 0/4 mm	0.079	390	60 (90)	3**	840	0.874	1.070	1.550	2.380	3.690	8.290	10.00
9	Exp. mineral granulate, 0/4 mm	0.053	145	5	3‡‡	1000	0.001	0.016	0.213	0.632	1.280	3.220	3.940

* own measurements
† IEA, Annex XIV, Vol. 3
‡ extrapolation to RH = 100%
** information of the producer
†† grain size
‡‡ Bauer et al. 2000

- a high moisture content within the insulation is caused by
  - a high input moisture u_A,
  - a high moisture capacity ξ,
  - a low water vapor diffusion resistance of the warm-side bounded layers of the insulation Z_{pi}, and
  - a low ratio of the water vapor diffusion resistances of the warm-side bounded layers of the insulation to the cold-side bounded layers of the insulation Z_{pi} / Z_{pe};
- a high convective airflow caused by
  - a high air permeability k_a,
  - a low ratio of height h / thickness d and
  - a high air temperature difference $\Delta\theta_{i-e}$ with a low middle temperature θ_m; as well as
- other potential hygrothermal conditions that create condensation, depending on the thermal conductivities of the insulation and of the adjacent materials as well as the heat capacity of insulation and of the adjacent materials for transient cases.

These factors influence each other. The risk of moisture accumulation can be minimized by variation of the parameter in case studies.

Description of the Investigated Cases

Two typical wall structures are investigated. The first wall structure has the following layers from inside to the outside:

- gypsum board (d = 0.0125 m, λ = 0.21 W/(m·K), ρ = 900 kg/m^3, μ = 8)
- vertical closed air layer (d = 0.03 m)
- vapor barrier ($\mu \cdot d$ = 0.5 m)
- wooden chipboard (d = 0.010 m, λ = 0.130 W/(m·K), ρ = 600 kg/m^3, μ = 100)
- loose fill insulation (d = 0.2 m), (see Table 1)
- wooden chipboard (d = 0.016 m, λ = 0.072 W/(m·K), ρ = 600 kg/m^3, μ = 8)

This structure has a water vapor diffusion resistance Z_{pi} = 9.11 10^9 m^2sPa/kg ($\mu \cdot d$ = 1.63 m) inside of the insulation and a value of Z_{pe} = 7.15 10^8 m^2sPa/kg ($\mu \cdot d$ = 0.128 m) outside of the insulation.

The second wall structure has on both sides of the insulation open vapor diffusion layers with inside and outside water vapor diffusion resistances of $Z_{pi} = Z_{pe}$ = 7.15 10^8 m^2sPa/kg ($\mu \cdot d$ = 0.128 m). The layers from inside to the outside are:

- wooden chipboard (d = 0.016 m, λ = 0.072 W/(m·K), ρ = 600 kg/m^3, μ = 8),
- loose fill insulation (d = 0.2 m), see Table 1,
- wooden chipboard (d = 0.016 m, λ = 0.072 W/(m·K), ρ = 600 kg/m^3, μ = 8).

Spruce ($d \times h$ = 0.2 m × 0.05 m) is on the top and on the bottom of the insulated cavity (h = 2.0 m) (see Figure 1a).

These two wood-framed wall structures are investigated by three calculation methods.

1. *German Standard DIN 4108-3:2001 (Glaser method)* with prescribed simplified climate conditions.

   Condensation period: 1440 hours, θ_e = –10°C (14°F), ϕ_e = 80%, θ_i = 20°C (68°F), ϕ_i = 50%;

   Evaporation period: 2160 hours, $\theta_e = \theta_i$ =12°C (53.6°F), $\phi_e = \phi_i$ =70%)

   The simplified standardized Glaser method is generally reliable and commonly used in practice. This method contains the moisture transport only by vapor diffusion. Sorption effects as well as liquid transport effects and vapor transport caused by convection are not considered. The result of the one-dimensional calculation is the condensation rate (kg/m^2) and the evaporation rate (kg/m^2) of the whole structure or between adjacent layers. Moisture damage is not expected when

   - the evaporation rate is higher than the condensation rate,
   - the condensation rate is less than 0.5 kg/m^2 after 1440 hours (condensation period), when a noncapillarity of adjacent materials is given, and
   - the condensation rate is less than 1.0 kg/m^2 after 1440 hours (condensation period), when a capillarity of adjacent materials is given.

2. WINHAM2D—coupled heat and moisture transport in a yearly climate cycle.

   Two-dimensional simulation: transient heat transport, latent heat effects, vapor diffusion, sorption effects, but without natural convection, without liquid transport and without moisture transport between the adjacent layers – insulation and spruce – at the top and at the bottom.

3. WINHAM2D—coupled heat air and moisture transport (with natural convection) in a yearly climate cycle.

   Two-dimensional simulation: transient heat transport, latent heat effects, vapor diffusion, sorption effects, with natural convection, but without liquid transport and without moisture transport between adjacent layers—insulation and spruce—at the top and at the bottom.

A comparison of steps 2 and 3 depict the moisture accumulation within the insulation caused by natural convection only. The subject of interest is the insulation only, not the adjacent layers. A moisture transport between the adjacent layers—insulation and spruce—at the top and at the bottom is not considered. As a result of steps 2 and 3, the maximum moisture content w_{max} (kg/m^3) of the insulation is selected, located in a layer of 10 mm width of the cold surface and in an area of A = 10 mm × 10 mm. This maximum moisture content is converted into $w'_{max, local}$ (kg/m^2) with a distance of 5mm of the cold surface of the insulation.

The yearly climatic cycle for the outdoor climate is shown in Figure 1a. The climate of 1963 in Sweden was chosen as a reference year for moisture calculations (Hagentoft and Haderup 1993). The yearly indoor climate is given in Figure 1b. It is based on a high indoor moisture load. The indoor relative humidity depends on the outdoor air temperature (Künzel 1997, 1998).

Finally, a simplified parameter study shall estimate a limited value of the air permeability k_a for the investigated cavity of 2.0 m × 0.5 m × 0.2 m (6.56 in. × 1.64 in. × 0.656 in.) and climatic conditions seen in Figure 2 to avoid moisture damages due to natural convection. This study considers the influence of the moisture capacity by including the high hygroscopic cellulose (1) and the nonhygroscopic foamed clay spheres (7) (see Table 1), as well as the inside and outside water vapor diffusion resistances Z_{pi} and Z_{pe}.

Aim of the Simulations

Calculated results of nine insulation types described in Table 1 are interpreted with the following criteria.

- Is there moisture accumulation in the structure after one year?
- Will the local moisture content increase more than $w' \geq 0.5$ kg/m^2 and $w' \geq 1.0$ kg/m^2 temporary?
- Are hygrothermal conditions present inside the insulation to induce mold growth by using selected hygrothermal conditions of isopleths (Sedlbauer 2001) for the simulated cases with WINHAM2D?

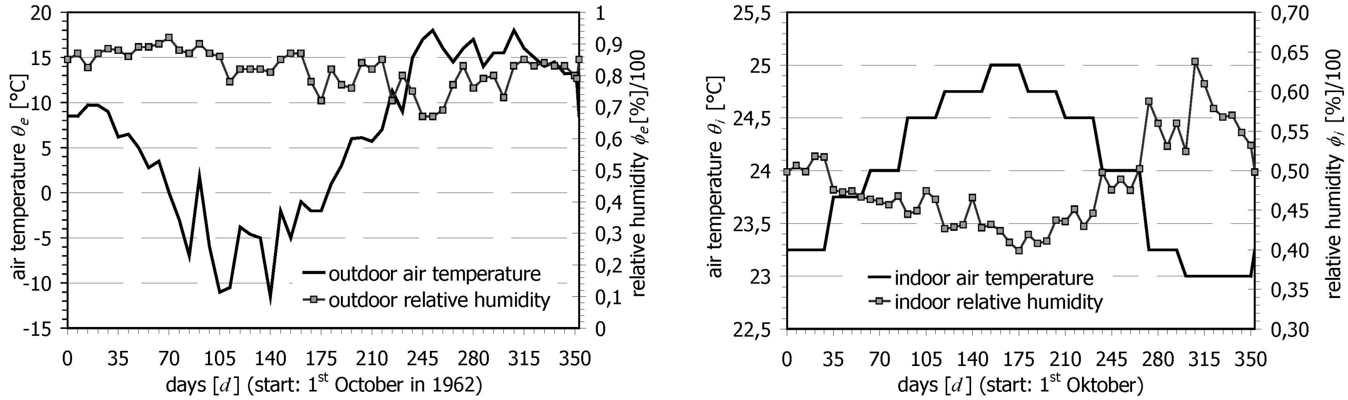


Figure 2 *Yearly climate cycle used for the simulations with WINHAM2D.*

So-called isopleth diagrams contain curves with the same mycelium growth rate or the same spore germination time. Isopleth diagrams are given for different species of mold. The mold species are divided into classifications, for instance (A) or (B). Mold species of the classification (A) are very harmful to health. These species of mold are not allowed in living rooms. Mold species of the classification (B) have an allergen potential and are very harmful to health when they are present for a long time. Further information is presented by Krus et al. (2001) and by Sedlbauer (2001).

The following conditions of the classification (A) and (B) are chosen of isopleths (Sedlbauer, 2001) and are used in this presented investigation.

(A) ≥ 8 days with $\theta \geq 5°C$ and $\phi \geq 98\%$,
(A) ≥ 16 days with $\theta \geq 5°C$ and $\phi \geq 96\%$,
(A) ≥ 8 days with $\theta \geq 10°C$ and $\phi \geq 87.5\%$,
(A) ≥ 16 days with $\theta \geq 10°C$ and $\phi \geq 86\%$,
(A) ≥ 32 days with $\theta \geq 5°C$ and $\phi \geq 92.5\%$,
(B) ≥ 8 days with $\theta \geq 5°C$ and $\phi \geq 86\%$.

The results of these questions allow an estimation of the following questions:

- Does natural convection cause a risk of moisture damage in well-insulated wood-framed walls under a usual yearly climatic cycle?
- Are the calculation results of German standard DIN 4108-3 based on the common Glaser method sufficient to prevent moisture damages due to natural convection?

Results of Three Calculation Methods for the First Wall Structure (with Vapor Barrier)

The results of the local and temporary highest moisture content inside the insulation types calculated with WINHAM2D and compared with calculations of DIN 4108-3 are shown in Figure 3. The location and the time of the maximum moisture content are different for the chosen insulation materials dependent on their material properties.

The results of the first wall structure (with a vapor barrier) show:

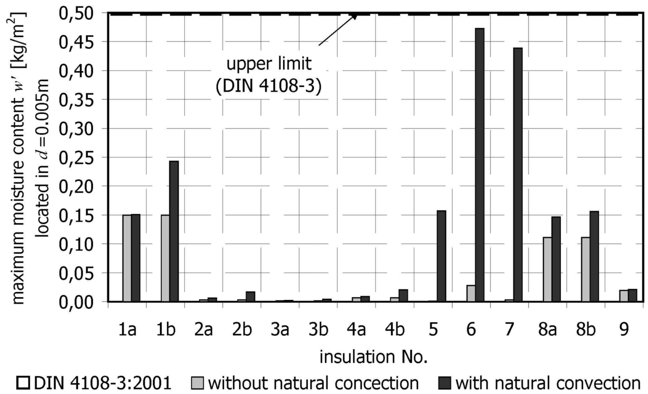


Figure 3 *Maximum moisture content in insulations no. 1-9 in the first wall structure (insulated cavity: h × d = 2.0 m × 0.2 m): calculations with DIN 4108-3 (Glaser method, no condensation is given in each insulation) and simulations with WINHAM2D (with/without natural convection).*

- The demands of DIN 4108-3:2001 (an upper limit of a restricted condensation rate and a higher evaporation rate than the condensation rate) are met for the wood-framed wall structure with all chosen loose fill insulation types. No condensation occurs by using the calculation method of DIN 4108-3:2001.
- Simulation results of WINHAM2D show a local and temporary condensation area near the upper cold edge for all investigated insulation materials. The amount of moisture content is less than the upper limit given by DIN 4108-3:2001 for boundaries of noncapillary materials. The maximum moisture content of the high hygroscopic cellulose, which has an air permeability of $k_{a,corr}=75\cdot10^{-10}m^2$ (1b), is clearly influenced by natural convection. The moisture content does not change because of natural convection when the cellulose has an

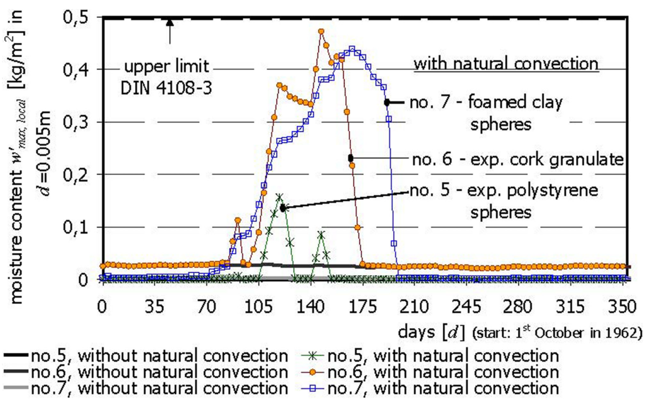


Figure 4 *Time-dependent maximum local moisture content in insulations no. 5, 6, and 7 in the first wall structure (with vapor barrier).*

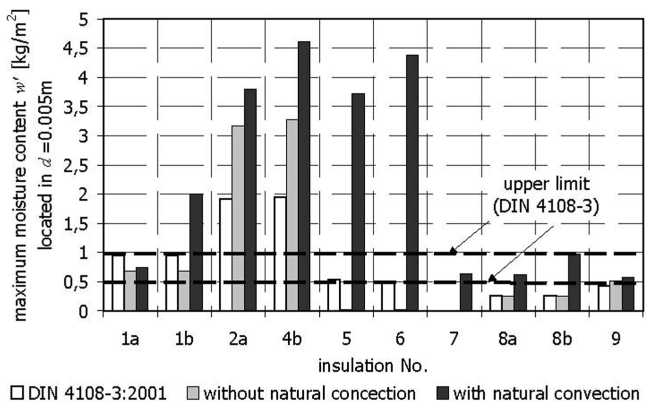


Figure 5 *Maximum moisture content in insulations no. 1-9 in the second wall structure (insulated cavity: $h \times d$ = 2.0 m × 0.2 m): calculations with DIN 4108-3 (Glaser) and simulations with WINHAM2D (with/without natural convection), the upper limit of DIN 4108-3 with $w' \leq 0.5$ kg/m² is for both sides noncapillary and that of $w' \leq 1.0$ kg/m² for both sides capillary bounded materials.*

air permeability of $k_a = 3{\cdot}10^{-10}\text{m}^2$ (1a). The convection caused moisture content is smaller in the middle hygroscopic mineral granulate (8a, 8b: $k_a \leq 90{\cdot}10^{-10}\text{m}^2$) than in the cellulose. A significant influence of natural convection occurs in all loose fill insulation with an air permeability $k_a \geq 125{\cdot}10^{-10}\text{m}^2$.

Results of Three Calculation Methods for the Second Wall Structure (without Vapor Barrier)

The results of the local and temporary highest moisture content inside the insulation types calculated with WINHAM2D for a year and compared with calculations of DIN 4108-3 are shown in Figure 5.

One demand of DIN 4108-3 to limit the calculated condensation rate to $w' \leq 1.0$ kg/m² after the condensation period is not met in this structure in case of two types of mineral fiber. Further demand to $w' \leq 0.5$ kg/m² for both sides of noncapillary bounded materials is not kept in the case of cellulose, polystyrene spheres, and cork granulate. The WINHAM2D simulations without natural convection and with the input of the moisture capacity show a significantly higher local condensation rate in two mineral fibers than in the calculation with the simplified method of DIN 4108-3. The simplified calculation of DIN 4108-3 shows a higher calculated condensation rate only in case of cellulose with the lowest air permeability ($k_a = 3{\cdot}10^{-10}\text{m}^2$) investigated in this study. That means the simplified method of DIN 4108-3 (Glaser) is not enough for a well-insulated structure without a vapor barrier. Natural convection increases the local moisture accumulation in all investigated cases. Figure 6 shows a condensation duration of ≤ 230 days a year in high permeable insulation due to natural convection when a vapor barrier is not provided. A local moisture accumulation with $w'_{second\ year} > w'_{first\ year}$ is not estimated in all investigated cases.

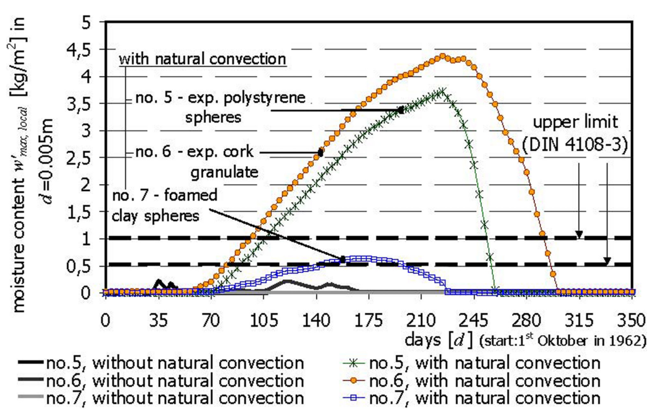


Figure 6 *Time-dependent maximum local moisture content in insulations no. 5, 6, and 7 in the second wall structure (without vapor barrier).*

The Risk of Mold Growth in the Insulation of the Investigated First and Second Wall Structures

The mold growth risk was estimated for the location of the maximum moisture content inside the investigated insulations within the distance of 0.005 m from the cold side under the above-mentioned selected mold growth conditions. The simulation results for both wall structures are shown in Figure 7.

The results in Figure 7 show a local increase of mold growth risk when natural convection is given inside the insulation of wood-framed wall structures with or without a vapor barrier. The presented mold growth risk is located near to the upper cold edge. This corresponds with the occurrence of

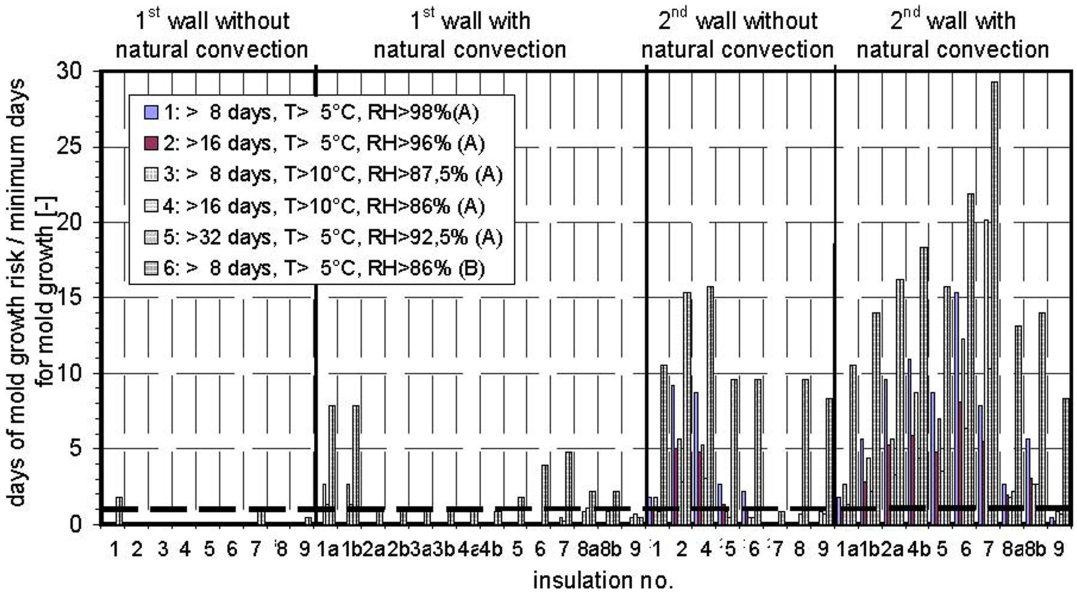


Figure 7 *Local mold growth risk within loose fill insulation of two wall structures at the area of the maximum local moisture content near the upper cold edge, described by a factor given by the quotient of days of mold growth risk/minimum days for mold growth.*

mold in experiments (see Figure 1). The hygrothermal mold growth risk increases when the insulation has a high air permeability k_a and when a vapor barrier is not at the warm side. Besides, an insulation with a high moisture capacity ξ has a retarded drying period after the winter. This also promotes a hygrothermal mold growth risk inside the insulation. There is also a risk of mold growth in nonhygroscopic insulated vertical cavities due to running down of condensed water caused by gravity, which could promote the soaking of the wood frame. Further investigations are necessary to assess the above-mentioned mold growth risks of high hygroscopic and nonhygroscopic insulation materials inside vertical cavities.

Simplified Parameter Study for the Estimation of Recommendations

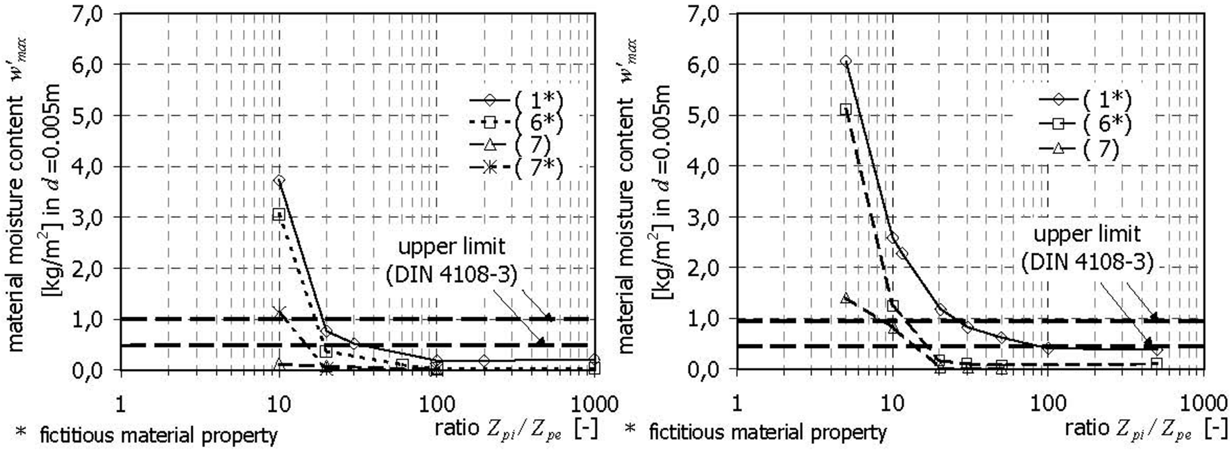
Based on the investigations of the first wall and the second wall, a simplified parameter study is carried out to estimate a maximum value of air permeability k_a with respect to avoiding moisture damages due to natural convection under the used climatic conditions. This study considers the influence of the moisture capacity of the high hygroscopic cellulose (1), the hygroscopic cork granulate (6), and the nonhygroscopic foamed clay spheres (7), as well as the variation of the inside and outside vapor diffusion resistances Z_{pi} and Z_{pe}. The used insulation properties are shown in Table 1. It is investigated as follows:

- a fictitious air permeability in the range of $500 \cdot 10^{-10}$m^2 to $1 \cdot 10^{-10}$m^2 differing of the measured value
- a ratio of Z_{pi} / Z_{pe} in a range between 10 and 1000 with steady-state values for the outside water vapor diffusion resistance of $Z_{pe} \in \{5.05 \cdot 10^8$ m^{2}sPa/kg; $1.09 \cdot 10^9$ m^{2}sPa/kg$\}$
- the vapor diffusion factor $\mu = 3$ [-] for cellulose (1*) and expanded cork granulate (6) and partially for foamed clay spheres (7*) as well as $\mu = 5$ [-] for foamed clay spheres (7).

When a fictitious material property was used in the simulation, the number of the insulation is signed with "*" in the diagrams, for instance (7*). Results of the simplified parameter study are shown in Figures 8 and 9. The investigation indicates that local moisture accumulation caused by natural convection could be avoided by limiting a

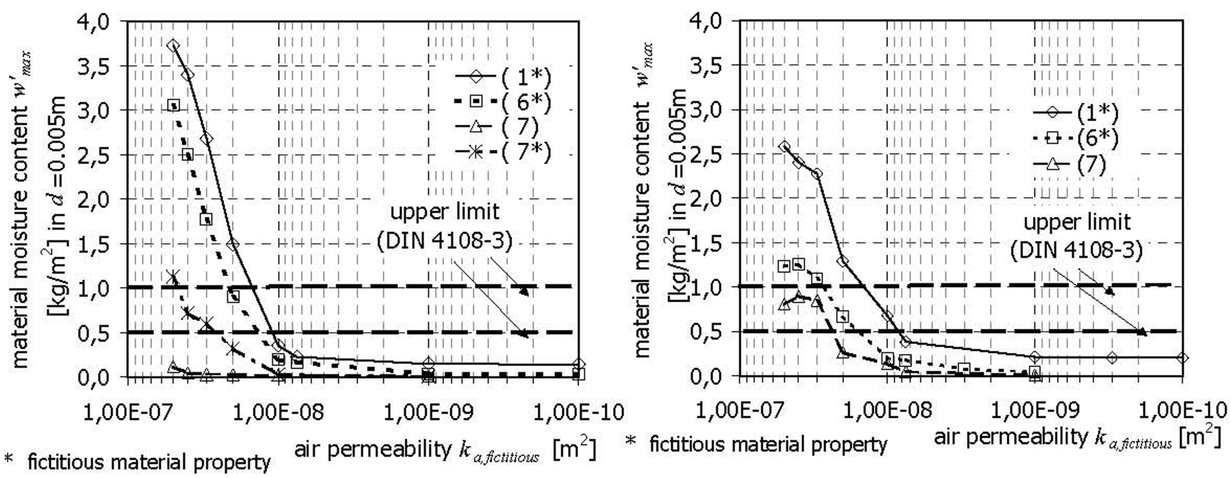
- maximum air permeability of $k_a \leq 1 \cdot 10^{-9}$m^2 in building insulation materials and / or
- minimum ratio of the inside and outside water vapor diffusion resistances Z_{pi} / Z_{pe} with a high value for Z_{pi}.

A reduction of the air permeability k_a decreases the airflow speed within the open porous insulation. That leads to a lower amount of humid air pumped in the upper cold edge with the result of a lower local condensed amount. A high ratio of inside and outside water vapor diffusion resistances Z_{pi} / Z_{pe} guarantees a high drying capacity of the insulation. Reduction of vapor diffusion within the insulation by a high inside water vapor diffusion resistance Z_{pi} is useful to avoid local moisture accumulation due to natural convection. The moisture capac-



a) $k_{a,fictitious} = 500{\cdot}10^{-10}$ m², $Z_{pe} = 5{,}05{\cdot}10^{8}$ m²sPa/kg   b) $k_{a,fictitious} = 500{\cdot}10^{-10}$ m², $Z_{pe} = 1{,}09{\cdot}10^{9}$ m²sPa/kg

Figure 8 *Local maximum moisture content w' of cellulose (1), expanded cork granulate (6), and foamed clay spheres with an air permeability* k_a *or* $k_{a,fictitious}$ *of* 500×10^{-10} m^2 *and dependent on the ratio of* Z_{pi}/Z_{pe}.



a) $Z_{pi} = 5{,}05{\cdot}10^{9}$ m²sPa/kg, $Z_{pe} = 5{,}05{\cdot}10^{8}$ m²sPa/kg   b) $Z_{pi} = 1{,}09{\cdot}10^{10}$ m²sPa/kg, $Z_{pe} = 1{,}09{\cdot}10^{9}$ m²sPa/kg

Figure 9 *Local maximum moisture content w' of cellulose (1), expanded cork granulate (6), and foamed clay spheres (7) dependent on the fictitious air permeability (range:* $1{\cdot}10^{-10}$ m^2 *to* $500{\cdot}10^{-10}$ m^2*) when* $Z_{pi}/Z_{pe} = 10$.

ity of loose fill insulation has a significant influence on the local moisture accumulation due to natural convection when $\mu = 3$ is given, as well as

- $k_a > 10{\cdot}10^{-10}$m² and $Z_{pi} / Z_{pe} \in \{1.09{\cdot}10^{10} / 1.09{\cdot}10^{9}$ [m²sPa/kg]; $5.05{\cdot}10^{9} / 5.05{\cdot}10^{8}$ [m²sPa/kg]$\}$ or
- $k_a = 500{\cdot}10^{-10}$m² and $Z_{pi} / Z_{pe} \leq 20$.

An increase of the vapor diffusion resistance factor μ of the open porous insulation will decrease the maximum moisture content of the insulation strongly when the results of foamed clay spheres in curve (7) with $\mu = 5$ and in curve (7*) with $\mu_{fictitious} = 3$ of Figure 8a and Figure 9a are compared.

CONCLUSIONS

Natural convection within an open porous insulation of a wood-framed external wall can be a cause of moisture damage due to condensation and mold growth, depending on the material properties, the geometry, and the boundary conditions. Natural convection induces a moisture redistribution within insulated wood-framed wall cavities with the effects of condensation and a mold growth risk at the upper cold edge.

The convective moisture transport is very sensitive for changes in parameter values and usually requires a numerical model of the coupled heat, air, and moisture transport inside materials. The isolated determination of the insulation moisture content caused by natural convection is possible by using the numerical model WINHAM2D. This tool was developed by Wang and Hagentoft and is suitable for investigation of noncapillary open porous insulations without liquid transport. The presented numerical results are based on an experimental validation of WINHAM2D (Riesner et al. 2001; Riesner 2003; Wang 2003).

The presented investigations make clear the variation of maximum insulation moisture content due to natural convection depending on parameter values. At first the moisture damage risk is estimated for a vertical insulated cavity by investigation of up to nine types of loose fill insulations in two typical wall structures (with and without a vapor barrier at the warm side of the wall) under a North European yearly climate cycle and are compared with the results of a common and simple German method (Glaser method in combination with the standard DIN 4108-3:2001). The results show the necessity of a warmside vapor barrier when a moisture flow caused by natural convection is expected. The German method is not sufficient to prevent moisture damage due to natural convection in wall structures without a warm-side vapor barrier.

Further, a simplified parameter study explains the influences of the insulation properties—air permeability k_a, moisture capacity ξ, and water vapor diffusion resistance factor μ—and the water vapor diffusion resistances Z_{pi} and Z_{pe} of the inside and outside bounded layers on condensation risk. As a result, a first recommendation could be derived to avoid moisture damage caused by natural convection in well-insulated wood-framed walls. The moisture damage risk can be prevented, and the German method is sufficient when

- $k_a \leq 10 \cdot 10^{-10}$ m^2
- $k_a \leq 50 \cdot 10^{-10}$ m^2 and $Z_{pi} / Z_{pe} \in \{1.09 \cdot 10^{10} / 1.09 \cdot 10^9$ [m^{2}sPa/kg]; $5.05 \cdot 10^9 / 5.05 \cdot 10^8$ [m^{2}sPa/kg]$\}$ or
- $k_a = 500 \cdot 10^{-10}$m^2 and $Z_{pi} / Z_{pe} \geq 30$.

Further risk assessments are necessary for material properties, other structures, other climatic conditions, and *should consider the capillarity of adjacent materials as well as the moisture transport between adjacent layers in y-direction*.

NOMENCLATURE

c	=	specific heat capacity of material, J/(kg·K)
c_a	=	specific heat capacity of air at atmospheric pressure, J/(kg·K)
d	=	thickness, m
g	=	gravitational acceleration, m/s^2
h	=	height, m
h_v	=	latent heat of water vaporization, J/kg
k_a	=	air permeability, m^2
$k_{a,corr}$	=	corrected air permeability, m^2
Nu	=	Nusselt value Nu = $q_{conduction+convection} / q_{conduction}$
p	=	water vapor pressure, Pa
P_a	=	atmospheric air pressure, Pa
P^a	=	deviation of air pressure from the hydrostatic one at reference temperature, Pa
p_{max}	=	maximum water vapor pressure, Pa
q	=	heat flux, W/m^2
q_a	=	air flux, kg/(m^2·s)
q_v	=	moisture flux, kg/(m^2·s)
R	=	thermal resistance, (m^2·K)/W
Ra_d^*	=	modified Rayleigh number
t	=	time, s
T	=	temperature, K
T_0	=	reference temperature, K
T_{ref}	=	an arbitrary reference temperature, K
u	=	moisture content of material mass by mass, kg/kg
w	=	moisture content of material mass by volume, kg/m^3
w'	=	moisture content of material mass by plane, kg/m^2
x, y	=	Cartesian space coordinates
Z_p	=	water vapor diffusion resistance, m^2·s·Pa/kg
α	=	the angle between x-direction and direction of gravity
β	=	thermal expansion coefficient of air, 1/K
δ_p	=	water vapor permeability, kg/(m·s·Pa)
φ	=	relative humidity of air, %
λ	=	thermal conductivity of material, W/(m·K)
μ	=	water vapor diffusion resistance factor
μ_a	=	dynamic viscosity of air, kg/(s·m)
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
ξ	=	moisture capacity of material, kg/kg
ξ_a	=	specific water vapor capacity of air, kg/(kg·Pa)

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