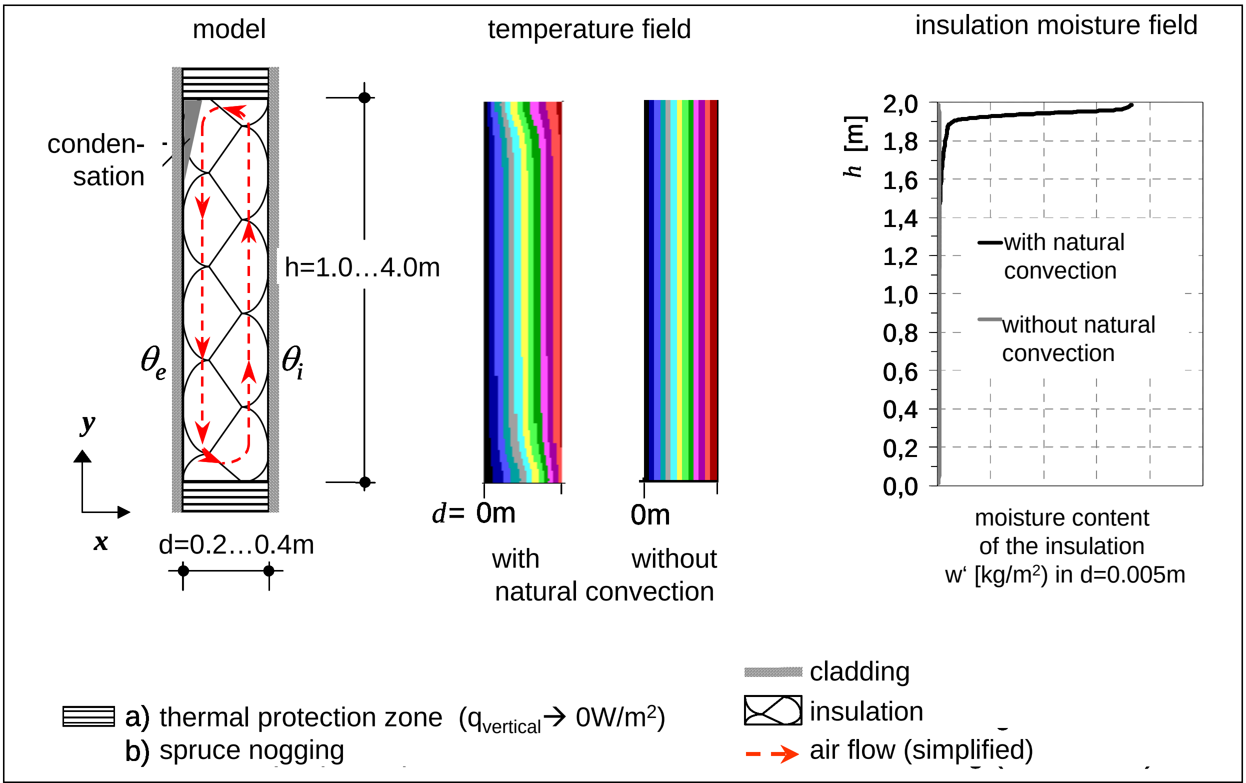
Results of the Research Project

Prevention of Condensation and Mould Growth Risks in Cavities of Thickly Insulated, Timber-Frame, Exterior Walls, due to Natural Convection in the Insulation



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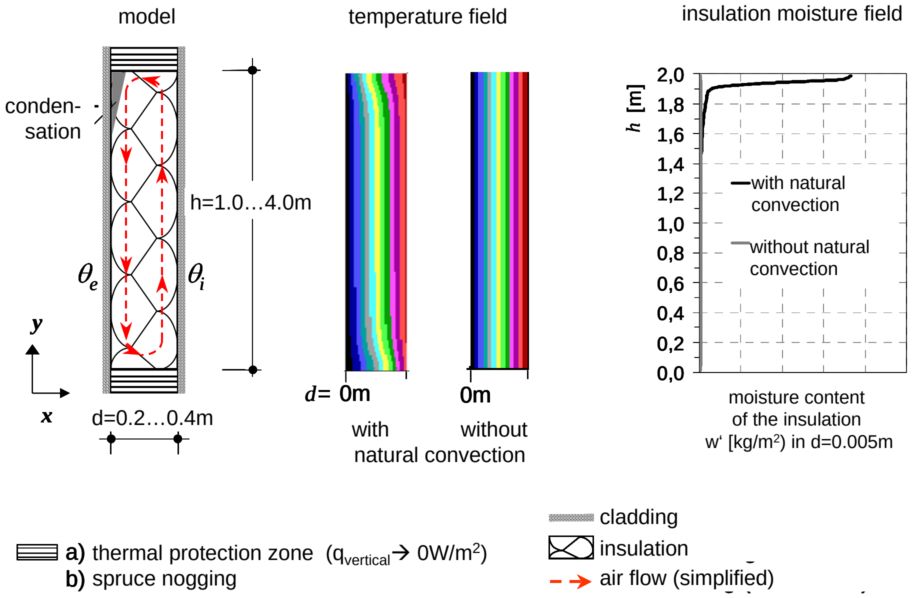
Introduction

Nowadays, insulation with depths of between 200mm and 400mm is installed in the cavities of thickly insulated, timber-frame, exterior walls. One area that has received little attention and which is not considered in the structural physics design of cavities within exterior, timber-frame walls is the risk of moisture damage due to natural convection. The driving force of natural convection is the pressure difference due to thermal buoyancy caused by high air-temperature variations between the internal and external boundaries of the building component. This results in a slowly moving circular air flow within open-porous insulation in cavities with air-tight cladding. An increase in the depth of the insulation increases the influence of the natural convection on heat- and moisture transport in the open-porous, cavity insulation.

The results of these building component tests and simulation calculations have shown that impermissibly high levels of material moisture and mould growth were present in the upper, cold corner of some cavities in thickly insulated, external, timber-frame walls - despite the fact that these installations complied with current building regulations. *This means:* An increase in the incidence of condensation and the ensuing mould growth is possible, despite compliance with DIN 4108-3:2001. This jeopardises the long-term durability of thickly insulated timber-frame constructions and can be avoided by the stipulation of limits for the s_d-values of the cavity cladding.



Picture 1 Object under investigation and the effects of natural convection on the heat- and moisture transport

a) Building component test in a double climate chamber

b) Practical test case in a window parapet area

Picture 2 The incidence of condensation and mould growth in the upper, cold corner of cavities in thickly insulated, external, timber-frame walls

Building upon the findings of Riesner (2003), this publication presents the scientifically-based correlations, illustrates the risks of condensation for practically-relevant structures and suggests constructive recommendations for their avoidance.

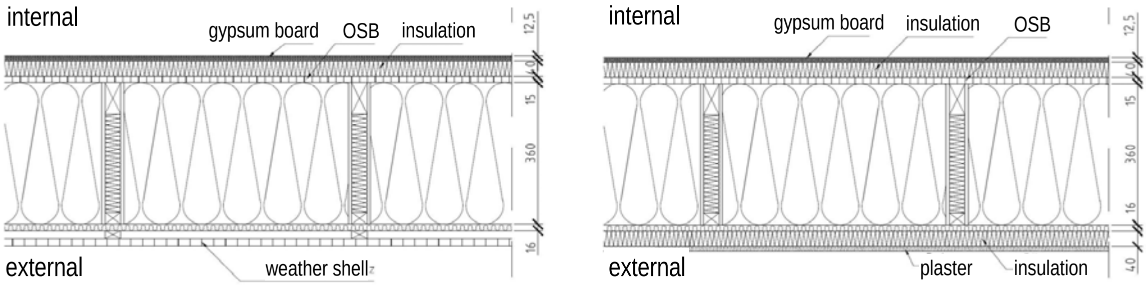
Factors influencing condensation through natural convection

The transport of moisture in open-porous insulation materials by means of natural convection is chiefly intensified by the following interacting factors:

- a high initial moisture level in the insulation material due to high input moistures u_A, high insulation material thicknesses d, a high moisture capacity of the insulation material, a high diffusion-equivalent air-layer thickness s_{di} of the adjacent building component layers and a low ratio of s_{di} / s_{de}
- high air-permeability in the insulation material through natural convection. These are chiefly influenced by a high insulation material air-permeability k_L, and a low cavity dimension ratio ($h/ d \rightarrow 1$)
- a cold, exterior climate; a low, solar radiation yield and a high, night-time, radiation exchange between the cloudless sky and the wall surface.
- a low water vapour diffusion resistance factor μ of the insulation material
- layered constructions which may promote the development of condensation

Object under investigation

The object under investigation is a cavity within an external, timber-frame wall. The open-porous, cavity insulation was installed between the external and room-side cavity cladding and enclosed from above and below by timber noggins. The insulation depths ranged from 200mm to 400mm. The cavity insulation materials employed were loose-fill insulation (organic granulates, organic and inorganic fibres) and insulation mats (mineral-fibre, wood-fibre, sheep's wool, hemp). The cavity cladding was composed of OSB-boards and gypsum boards on the internal, room side and wood-based boards (chip/particle boards, vapour-permeable wood-fibre boards and an OSB- board as a bearer board for an external thermal insulation composite system (ETICS)).



Picture 3 Horizontal section of the external, timber-frame wall

Investigation methods

The investigations were performed in ***4 stages***:

- ***Stage 1***: Simulation calculations relating to the influences on the moisture transport by means of natural convection within insulated, external, timber-frame walls within the framework of a parameter study.

- ***Stage 2***: Simulation calculations on the convective moisture transport for practically-relevant, timber-frame, exterior wall constructions in a complex presentation of all building component layers (no substitution of the non-relevant individual components by WINHAM2D modelling)
- ***Stage 3***: Tests in a double climate chamber on 8 cavities within timber-frame, exterior walls using certified insulation materials for a winter-spring climate cycle
- ***Stage 4***: A comparison of the investigation results with those of the simulation calculations which replicated the practical tests.

Simulation software WINHAM2D

The simulation calculations were performed using WINHAM2D. The heat-, air- and moisture transport within the insulation materials, elicited by the natural convection, can be simulated using this 2D-WINDOWS-program employing standard, measurable material properties. This program was developed at the TU Chalmers / Sweden. This software has been validated for external wall insulation (Riesner, 2003). Very long calculation periods were required using this scientific software – often several days. Furthermore, due to numerical limitations, it was not possible to calculate all climatic factors or all types of building component constructions. As WINHAM2D allows the selection of individual heat- and moisture transport mechanisms to be calculated, the influence of natural convection within the individual wall constructions in combination with the insulation to be investigated was determined by calculating the difference between two simulations with and two simulations without natural convection. The WINHAM2D calculation results were evaluated for evidence of impermissible increases in material moisture levels and the presence of hygrothermal climatic conditions that promote mould growth as per SEDLBAUER (2001).

Climate

In stage 1, comparative simulation calculations were performed for the moisture reference year in Sweden (MRY - 1962/63) as well as for the external climate for Holzkirchen (1991), Davos (1996) and Wismar (2006). The external climates for Holzkirchen (1991) and Davos (1996) refer to a north-facing wall (N-wall) with diffuse radiation and radiation absorption on a light-coloured surface with an absorption coefficient of a=0.4. The analysis of the climate data showed that the most significant influence of natural convection on the transport of moisture was associated with the climate from Davos 1996.

The building component tests were performed in a double climate chamber over a period of 12 weeks. The simulated internal climate conditions in the warm chamber were 23 ± 3°C at 55± 5% RH. The transient external climate conditions in the cold chamber corresponded almost exactly to those of a natural climate in a winter-spring period. During the 6-week winter period the material moisture level in the cavity increased continuously due to the vapour pressure difference. During the 6-week spring period, the drying-out potential of the building materials in the wall construction could be demonstrated. No mould growth was observed in the winter period due to the low temperatures. In the spring, local increases in material moisture levels caused by natural convection take longer to dry out. The effects of natural convection may lead to mould growth in the insulation material and to impermissibly high levels of moisture in the timbers and wood-based materials.

Investigation results

Material properties

In order to conduct the investigation, it was necessary to take measurements of the material properties. The air-permeability of the insulation materials are in the region of 3E-10m^2 (cellulose) to 359E-10m^2 (organic granulate 1). The water vapour diffusion resistance factor μ of the insulation materials lies between 1 and 3. The choice of insulation materials allowed a large range of the moisture capacities to be encompassed.

- non-hygroscopic mineral fibres,
- five organic insulation materials with $u_{90\%}$ ~ 3.6 -11M.-%,
- three organic insulation materials with $u_{90\%}$ ~ 17 – 18.5M.-% and
- a highly hygroscopic organic insulation material with $u_{90\%}$ = 51M.-%.

The air-permeability k_L of the cavity cladding was determined using values from literary sources and from the investigation measurements. The analysis of the measurement results gained from literary sources revealed, in certain cases, a margin of deviation of one to two orders of magnitude for the same types of materials. The values, for all the cladding materials investigated, lie well below the upper limit of $q_{50} = 3.0m^3/(m^2h)$ as specified in DIN 4108 T.7 and they may therefore be employed as air-tight layers for external, timber construction components. As an example, the influence of joints between cladding boards was investigated using MDF-boards with a combined surface area of $0.09m^2$.If the air-permeability of the MDF-board without joints is taken as 100%, then the air-permeability increases to 215% for tightly-fitting 'tongue and groove' joints which are not glued and gives a value of 160% when employing additional bonding with air-proof adhesive tape.

The measured water vapour diffusion resistance factors μ of the wood-based boards deviate in some cases significantly from those contained within the official Building Inspectorate approvals. This influences the s_d-values of the cavity cladding and can lead to increased risks of moisture damage, especially in vapour-permeable timber-frame exterior wall.In the case of unplanned moisture load levels or through the transport of moisture due to natural convection (which should ideally be accounted for during the planning phase), the risks of moisture damage are increased additionally. Therefore it is recommended that *a safety factor for the* s_{di}/s_{de} *ratio is introduced* which takes the variations in the water vapour diffusion resistance factors μ of the boards into account.

Stage 1 Parameter study

The main focuses of the parameter study are the cavity internal dimensions, the material properties of the cavity boundaries, the insulation material properties, the moisture transport to and from the timber noggins (above and below) and the annual climate. These were investigated in ca. *270 Simulation calculations using WINHAM2D*. In a number of simulations an air barrier was installed at the boundary between the insulation material and the timber noggins in order to measure the convectional moisture transport in the insulation and to exclude an interaction with the moisture transportation between adjacent layers. The following conclusions were drawn from the results of the simulations:

1. The water vapour diffusion resistance factor μ of the insulation materials: Customary water vapour diffusion resistance factors μ of open-porous insulation materials increase the risks of moisture damage through natural convection in timber-frame external walls with vapour-permeable internal cladding. This risk can primarily be reduced by the s_{di}/s_{de}-ratio. An s_{di}/s_{de}-ratio of 10 is recommended.

2. Insulation dimensions: Depth d and Height h: The depth d is one of the main factors influencing the risk of moisture damage through natural convection (comparable to the insulation air-permeability k_L and s_{di}/s_{de}). The height h has little influence.

3. The air-permeability of adjacent layers at Δp=5Pa (without air leaks):

The air-permeability of adjacent layers is less important than the air-permeability of the insulation k_L, s_{di}/s_{de} and the moisture capacity of the insulation. In extremely vapour-permeable timber-frame walls with low s_{di}/s_{de}-ratios, the risk of moisture damage through natural convection is increased far more by the practically-relevant air-permeability than, for example, the climate and the solar radiation (North-wall). The air-permeability of the cavity cladding has a greater influence on the risk of moisture damage through condensation in hygroscopic insulation materials than in non- hygroscopic insulation materials. The choice of claddings should ensure air flow resistance levels of $R_{Li} >> R_{Le}$.

4. Moisture transport from/to the upper and lower timber noggins:

hygroscopic insulation materials: no significant influence

median range moisture storage capacity of the insulation: A reduction in the insulation moisture level through the transport of moisture to the adjacent timbers.

non-hygroscopic insulation materials: An increase in the insulation material moisture level through the moisture transport from adjacent timbers.

5. The coefficient of thermal resistance of the internal and external cladding:

extremely vapour-permeable claddings and $s_{di} = s_{de}$*:* no influence by the internal insulation layers; a marked decrease in the maximum local insulation material moisture level due to natural convection at increasing external insulation depths

$s_{di}/s_{de} = 10$*:* a negligible influence

6. The coefficient of thermal resistance of the upper and lower cavity boundaries (bordering the noggins): Thermal bridges reduce the local moisture proportion from natural convection in the upper, cold corner of the cavity but with a comparably small influence however.

7. Annual climate and solar radiation: If the solar radiation is disregarded, then there are only small differences between the investigated climates in central and northern Europe. The solar radiation (North-wall) reduces the risk of moisture damage through convection. For the convective transport of moisture, it is recommended that the climate from Davos (1996) be used as the moisture reference year for central and northern Europe.

Stage 2 – WINHAM2D-Simulations on wall constructions

Calculations were performed for typical, exterior, timber-frame wall constructions and several insulation types within a seasonal climate cycle using a realistic model for the wall constructions. The dimensions of the insulation in the cavities are h x d = 2m x 0.36m. The proportional increase in the moisture levels due to natural convection in the insulation materials, the noggins and in the cold-side cavity cladding was determined by comparing the results from simulations with and without natural convection influences. The following findings are based upon the results of the calculations:

- *Wall 1a* with $s_{di} / s_{de} = 55$ ($s_{di} = 2.2$m; $s_{de}=0.04$m) and the ratio of the air flow resistances of the internal cladding R_{Li} and the external cladding R_{Le} where $R_{Li} >> R_{Le}$;
  - sufficient protection against condensation and no risk of hygrothermal mould growth
- *Wall 1b* with $s_{di} / s_{de} = 11$ ($s_{di} = 2.2$m; $s_{de}=0.2$m); $R_{Li} = R_{Le}$
  - sufficient protection against condensation in the cavity (insulation, cavity cladding and noggins) with insulation materials where $k_L \leq 100$E-10m^2 and $u_{23°/80\%} \leq 10$M.-% and
  - no risk of hygrothermal mould growth with insulation materials where $k_L \leq 180$E-10m^2 and $u_{23°/80\%} \leq 10$M.-%
- *Wall 2* with $s_{di} / s_{de} = 4$ ($s_{di} = 2.2$m; $s_{de}=0.6$m); $R_{Li} = R_{Le}$
  - sufficient protection against condensation in the cavity (insulation, cavity cladding and noggins) with insulation materials where $k_L \leq 100$E-10m^2 and $u_{23°/80\%} \leq 10$M.-% and
  - no risk of hygrothermal mould growth with insulation materials where $k_L \leq 180$E-10m^2 and $u_{23°/80\%} \leq 10$M.-%
- *Wall 3a* with an ETICS: $s_{di} / s_{de} = 4$ ($s_{di} = 10$m; $s_{de}=2.3$m); $R_{Li} < R_{Le}$ and $R_{Li} = R_{Le}$
  - sufficient protection against condensation in the cavity (insulation, cavity cladding and noggins) with non-hygroscopic insulation materials where $k_L \leq 70$E-10m^2 and $u_{23°/80\%} \leq 0.5$M.-% and
  - a high risk of hygrothermal mould growth with all the investigated open-porous insulation materials
- *Wall 3b* with an ETICS: $s_{di} / s_{de} = 1.3$ ($s_{di} = 3$m → consideration of typical air leaks as per KÜNZEL, 2003 and TenWolde, 1999) ; $R_{Li} < R_{Le}$

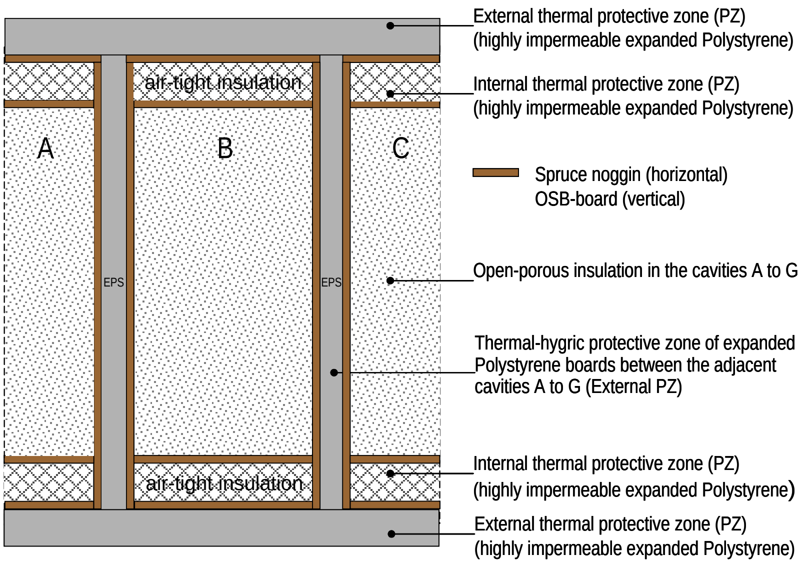
- insufficient protection against condensation in the cavity (insulation, cavity cladding and noggins) for all the investigated insulation materials as the natural convection must be taken into consideration, and
- a high risk of hygrothermal mould growth with all the investigated open-porous insulation materials

- *Wall 3c* with an ETICS: s_{di} /s_{de} =15,7 ($s_{di,}$=3,14m; $s_{d,\ plaster}$=0,2m; $s_{d,\ ETIC\text{-}insulation}$=0,3m); $R_{Li} = R_{Le}$
  - sufficient protection against condensation and against hygrothermal mould growth with a open-porous insulation material in the cavity where $k_L \le$ 31E-10m^2 and $u_{23°/80\%} \le$ 10M.-%

The results of this investigation have indicated that wall 1a with s_{di} / s_{de} = 55 and s_{de}= 0.04m and with a cavity insulation depth d = 360mm as well as that wall 3c with s_{di} / s_{de} = 16 and s_{de}= 0.2m provide sufficient protection against condensation damage. A high risk of condensation damage is to be expected within the cavities of north-facing, exterior, timber-frame wall constructions with a cavity insulation depth d > 300mm and with an ETICS employing polystyrene boards mounted on a bearer board (s_{de}=2.3m) where $s_{di} \ge$ 10m and with standard, constructional, air-leakage levels as approved in DIN4107-7: $n_{50} \le 3h^{-1}$.

Stage 3 – Building component tests

The object of the tests was to show if natural convection in open-porous, cavity insulation with a depth of 400mm leads to risks of condensation damage. These tests were performed using eight air-tight, test cavities. This involved the investigation of the material moisture levels in the cavity insulation, the timber noggins and the cavity cladding as well as the mould growth levels and the incidence of condensation at the boundary between the insulation material and the adjacent, cold-side, cladding board over the entire test period. The construction configuration of seven cavities differed from one another in the combinations of one of four types of certified insulation (high, medium and low levels of moisture capacity) and one of three different types of cladding. The remaining test cavity was divided into 6 smaller cavities with a height of 0.5m in order to investigate further types of insulation.



Picture 4 Diagram of the structure of a test object and the installation in the test frame

Using s_d-values from product data sheets, it was planned that for the building component tests the s_{di}/s_{de}-ratios should lie within a range from 9.1 to 1.3. In addition to the building component tests, the s_d-value measurements exhibited significant deviations to those stated in the product data sheets. The s_{di}/s_{de}-ratios actually lay in a range from 4.3 to 2.3.

The results of the building component tests show:

The natural convection related material moisture distribution in each investigated cavity was determined through measurements in the insulation, in the cold-side cladding and the upper and lower noggins

The results of the measurements of the relative humidity in the insulation material, the material moisture levels and the incidence of condensation exhibit a plausible correlation to each other. The moisture transport due to natural convection during the condensation period (winter) led, in some cases, to impermissible increases in the building material moisture levels in the upper, cold corner of the cavities, which

- in the case of hygroscopic insulation materials then decreases again, after a time lag, during the evaporation period (spring and summer) due to increasing external air temperatures and
- in the case of non-hygroscopic insulation materials leads to an increase in the run-off of condensed water at the layer boundary to the cold-side cavity cladding.

Therefore, during the spring, there is an increased propensity for the development of mould and possibly wood destroying fungi in the aforementioned cavities with insulation depths of 400mm.

It has been shown in the tests that

- the risk of condensation damage due to natural convection is mainly influenced by the moisture capacity of the insulation, followed by the s_{di} / s_{de} -ratio.
- in a cavity with an insulation

with an air-permeability k_L = 70E-10m^2 and

with a similar moisture capacity to the cavity cladding and the noggins

that even at a ratio of s_{di} / s_{de} = 4 and in which $s_{de} \leq 0.5$m, there is no risk of condensation damage due to natural convection.

- in a cavity with a ratio of s_{di} / s_{de} = 3.2, in which $s_{de} \leq 0.3$m for the cold-side cavity cladding and with a high liquid transport coefficient, that an accumulation of moisture was present in the upper, cold corner of the cavity but that there was no evidence of condensation damage.
- there is a high risk of condensation damage in the cavity with an ETICS in which s_{de} = 0.9m and s_{di} / s_{de} = 2.3.
- the level of natural convection and the risk of condensation damage in the cavity are increased greatly due to vertical, enclosed air gaps between the insulation and the cladding.
- insulation materials with high moisture capacities and with high air-permeabilities at a ratio of s_{di} / s_{de} = 4.3 and a cavity depth d = 400mm should not be deployed as, in this case, this led to the occurrence of impermissible levels of material moisture in the upper noggin, the cold-side cavity cladding and the insulation material.
- in the tests, higher intensities of mould growth were discovered in the cladding boards than in the insulation materials or the noggins.

Stage 4 – Comparison of the WINHAM2D-simulation calculations to the building component tests

The results of the simulation and the building component tests display a principal correlation. In some cases they correspond very well but in other case there are clear differences. Reasons for the differences between the building component tests and the WINHAM2D-Simulations:

- no calculation of the capillary transport in WINHAM2D
- delays of up to a maximum of two days in the removal of the test object and in the removal of the insulation sample to determine the material moisture level using the Darr-Wäge-Procedure
- varying material properties

- local deviations between the sampling locations of the insulation material samples in the building component tests and the selected coordinates (regions) from the WINHAM2D-results and
- local effects relating to the moisture transport at the boundaries of the materials

The simulation program WINHAM2D calculated the risks of moisture damage from the coupled heat-, air- and moisture transport in insulation materials very well and those to the adjacent capillary building component layers (noggins, the cold-side cavity cladding) delivered results within the expected range.

In a further step, the suitability of the test climate cycle was investigated by using WINHAM2D-simulation comparisons with the climate from Davos (1996). In both cases, the calculated maximum timber moisture levels lay within the same range. This comparison was performed for three of the test cavities. These results therefore proved the suitability of the test climate cycle developed for this project.

Conclusions

In the cold period of the year, natural convection was present in the cavity insulation of thickly insulated, external, timber-frame walls. Dependent upon the type of insulation, the cavity dimensions and the type of cladding, natural convection in open-porous cavity insulation over a period of several weeks can lead to the development of high levels of locally confined condensation and therefore to moisture damage within the cavity. The cavities of thickly insulated, external, timber-frame walls, with and without condensation damage through natural convection, were investigated.

The transport of moisture in the insulation due to natural convection can be limited through correct structural planning limits for the s_{di} / s_{de}-ratio of the cavity cladding with reference to the moisture capacity and the air-permeability of the insulation material and to the insulation depth. For this reason, condensation damage is avoidable through correct planning. The required provisions for the s_{di} / s_{de}-ratio of the cavity cladding exceed those of the current stipulations of DIN 4108-3 and DIN 68800-2.

In so far as no other investigation or test results are available, the following requirements for the s_{di} / s_{de}-ratio are proposed,

- dependent upon the insulation depth

  $\boldsymbol{s_{di} / s_{de} \geq 30\ (50)}$ ***at*** $\boldsymbol{s_{de} \leq 0.2m}$ ***and:*** $\boldsymbol{k_L \leq 500E\text{-}10m^2}$***,*** $\boldsymbol{d \leq 200mm}$***,*** $\boldsymbol{u_{23°/80\%} \leq 14M.\text{-}\%}$

  $\boldsymbol{s_{di} / s_{de} \geq 50\ (100)}$ ***at*** $\boldsymbol{s_{de} \leq 0.2m}$ ***and:*** $\boldsymbol{k_L \leq 500E\text{-}10m^2}$***,*** $\boldsymbol{d \leq 400mm}$***,*** $\boldsymbol{u_{23°/80\%} \leq 14M.\text{-}\%}$

- in the case of insulation with a very high moisture capacity (high salt content within the insulation material) and high air-permeability

  $\boldsymbol{s_{di} = 100m}$ ***and*** $\boldsymbol{s_{de} \sim 0.1m}$ ***for:*** $\boldsymbol{k_L \leq 200E\text{-}10m^2}$***,*** $\boldsymbol{d \leq 400mm}$ ***and*** $\boldsymbol{u_{23°/80\%} \leq 29M.\text{-}\%}$

It is recommended that safety factors relating to the risks of moisture damage should be included in the standardised calculation procedures for the protection against condensation. This increases the dependability of planning decisions e.g. for varying material properties in vapour-permeable constructions.

In accordance with the current investigative findings, it is recommended that the following combinations are avoided:

- insulation materials with a high moisture capacity and non-hygroscopic insulation materials each with an air-permeability k_L> 100E-10m^2 coupled with
- high insulation depths d > 0.2m at
- a low s_{di}/s_{de}-ratio of s_{di}/s_{de} < 10 and
- a ratio of the air flow resistances of $R_{L,i} \sim R_{L,e}$ or of $R_{L,i} < R_{L,e}$

Further investigations may lead to a reduction in these requirements.

The transport of moisture due to natural convection in the cavities of thickly insulated, external, timber-frame walls can also be reduced by

- room-side cavity cladding with a high air flow resistance R_{Li} combined with cavity insulation with a high level of air-permeability k_L
- a vapour-permeable and capillary-active, cold-side, cavity cladding between the insulation and the weather-proofing layer
- the use of insulation materials which exhibit almost the same moisture capacity properties as the adjacent cladding boards and/or timber noggins
- the avoidance of enclosed air gaps between the cold-side, cavity cladding and the exterior wall insulation and between the upper noggin and the cavity insulation (the subsequent settling of loose insulation materials)
- vapour-permeable, external thermal insulation composite systems (ETICS) with s_d ~ 0.5m (for comparison: the results of both the tests and the simulations have shown a high risk of condensation damage exists in wall constructions with a cavity insulation depth of >200mm and an ETICS with $s_{d, ETICS}$ ~0.9m and for $s_{d, ETICS}$ ~2.3m in the simulations)

The inclusion of the values of the air-permeability of the insulation and the cladding boards in the product data sheets and also within the official certification process is fundamentally important for the avoidance of structural planning errors which may lead to risks of condensation damage due to natural convection.