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Convection through Light Weight Timber Constructions with Mineral Wool

J. Schmidt, O. Kornadt

***Abstract*—**The major part of light weight timber constructions consists of insulation. Mineral wool is the most commonly used insulation due to its cost efficiency and easy handling. The fiber orientation and porosity of this insulation material enables flow-through. The air flow resistance is low. If leakage occurs in the insulated bay section, the convective flow may cause energy losses and infiltration of the exterior wall with moisture and particles. In particular the infiltrated moisture may lead to thermal bridges and growth of health endangering mould and mildew. In order to prevent this problem, different numerical calculation models have been developed. All models developed so far have a potential for completion. The implementation of the flow-through properties of mineral wool insulation may help to improve the existing models. Assuming that the real pressure difference between interior and exterior surface is larger than the prescribed pressure difference in the standard test procedure for mineral wool ISO 9053 / EN 29053, measurements were performed using the measurement setup for research on convective moisture transfer "MSRCMT".

These measurements show, that structural inhomogeneities of mineral wool effect the permeability only at higher pressure differences, as applied in MSRCMT. Additional microscopic investigations show, that the location of a leak within the construction has a crucial influence on the air flow-through and the infiltration rate. The results clearly indicate that the empirical values for the acoustic resistance of mineral wool should not be used for the calculation of convective transfer mechanisms.

***Keywords*—**convection, convective transfer, infiltration, mineral wool, permeability, resistance, leakage

I. Introduction

Convective transfer through leakages in the vapor barriers of exterior walls may lead among other things to primary energy losses and particle infiltrations. Additionally, moisture, which may be transported as vapour by the flow and condensate at the dew-point, becomes a major problem. This moisture condensates at the vapor barrier and can result in the growth of mould and mildew and the formation of heat-bridges (Fig. 1-2) [1]-[4]. Moisture problems due to diffusion are scarcer in buildings than the occurrence of convective moisture infiltration [5]. That can be explained by the initially mentioned reasons for leakage due to errors in planning, construction or use phase of buildings. When comparing the possible moisture infiltration into buildings due to diffusion and convection, the infiltrated amount of moisture by air flow through leakages is many times higher [6]–[9]. This aspect is the main reason why different researchers work on mathematical models describing the convective moisture transfer and infiltration [10]–[14]. However, the present models are not easily applicable to practice. In order to improve the connection between theory and practice, the measuring setup "MSRCMT" (**M**easurement **S**etup for **R**esearch on **C**onvective **M**oisture **T**ransfer) has been developed at the Bauhaus University Weimar. This setup offers the opportunity to analyze the convective moisture transfer through leakages in individual layers or complete wall structures under variable differential pressure conditions. Currently, the research is focused on the infiltration of exterior walls of light weight timber frame structures and the development of a moisture mass balance model [14]. Due to the observed differences between model and measurement, an intensive investigation was started. The initial assumption, that the observed differences were a result of an incorrect measuring setup, could be contradicted. It was found that the inhomogeneity of the insulation material, the main component in light-weight timber structures, is responsible.

J. Schmidt is with the Department of Building Physics, Bauhaus-Universität Weimar, Th. 99423 Germany (phone: +49 (0) 3643 584716; fax: +49 (0) 3643 584702; e-mail: jens.schmidt@uni-weimar.de).

O. Kornadt is with the Department of Building Physics, Bauhaus-Universität Weimar, Th. 99423 Germany (phone: +49 (0) 3643 584701; fax: +49 (0) 3643 584702; e-mail: oliver.kornadt@uni-weimar.de).

II. Background

A. Basics

Convective transfer is subdivided in free (or natural) and forced convection. Natural convection originates from a pressure difference between conflux area and efflux area which is based on thermal and hygrical density differences. In case of forced convection, next to density differences, the influence of forced ventilation e.g. the wind cannot be neglected. Exfiltration, the transport from the inside to the outside, occurs if the pressure level is higher on the interior side of the exterior wall. Wind suction may increase the transfer rate. The opposite effect is denoted infiltration. In both cases, moisture and particles like germs and dust may be introduced into the structure (Fig. 1-2). This has been referred to as enveloping surface infiltration [15]-[16]. Natural convection occurs mainly in all-side enclosed regions like bay sections [11]-[12]. Forced convection is only possible through leakages which form a connection between the different pressure zones e.g. holes in the vapor barrier. Depending on building location, direction, altitude and climatic region, measured pressure differences reach up to ±175 Pa [16]. The wind as basic actuation potential is able to influence the flow-through of leakages in exterior walls of buildings significantly. In light weight timber structures according to DIN 68800 [17], leakages are often concentrated in the bay section or connection points of bay and timber frame (Fig. 1-2). In case of convective moisture transfer through these structures, the insulation is penetrated frequently.

Fig. 1 Convective moisture ingress through a leakage at the connection point of bay and timber frame

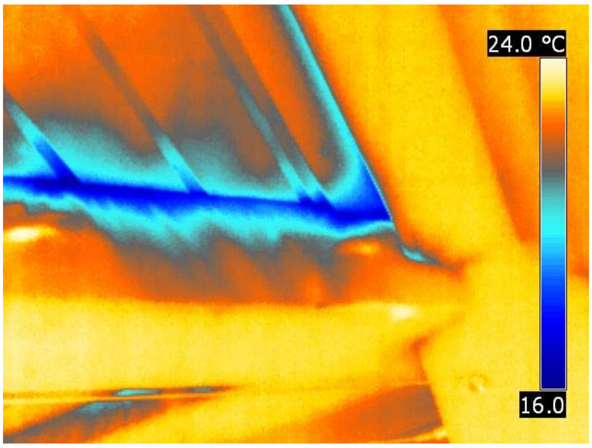

Fig. 2 Thermal image of the leakage zone in Fig.1

Present numerical models for convective heat and mass transfer are using the parameter "K", the permeability, to describe the flow-through of insulation materials [18]. This parameter is associated with the length related flow resistance "r" of the insulation.

$$\frac{\dot{V} \cdot x \cdot \eta}{A \cdot \Delta p} = K \quad (1)$$

$\dot{V}$ ⇒ volumetric flow through the insulation [m³/s]
x ⇒ thickness of the insulation [m]
η ⇒ dynamic viscosity of the air [Ns/m²]
A ⇒ investigated area of insulation [m²]
Δp ⇒ pressure difference between the material sides [Pa]
K ⇒ Permeability of the material [m²]

The basic rule of the permeability was descried by Henry Darcy in the 19th century [19]-[20] using (1).

According to ISO 9053 / EN 29053 "materials for acoustical applications" [21] the permeability of a material may be calculated using the length related flow resistance in (2) [11].

$$\frac{\eta}{r} = K \quad (2)$$

η ⇒ dynamic viscosity of the air [Ns/m²]
r ⇒ length related flow resistance [Ns/m^4]
K ⇒ permeability of the material [m²]

B. Determination of permeability according to ISO 9053

Two methods are defined in ISO 9053 to determinate the permeability of acoustic materials like insulation, the "continuous air flow-through current method (A)" and the "alternating air flow-through current method (B)". Measurement setups for both methods are presented in ISO 9053 [21]. It is possible to analyze circular or rectangular specimens. The minimum length of rectangular specimens should be ≥ 90 mm and the minimum diameter of circular specimens should be ≥ 95 mm. To reduce leakages next to the frame, fibrous materials like insulating materials should be slightly bigger than the specimen holder.

"Due to the increase of the specific air flow resistance of sound absorbing materials with increasing air stream velocity in a certain range, the air flow resistance should be measured at the smallest possible flow velocity. The linear flow velocity is defined by a lower limit of $u = 0.5 \cdot 10^{-3}$ m/s. This value of sound particle velocity corresponds to an acoustic pressure 0.2 Pa (80 dB in relation to 20 µPa) [21]".

That implements that the flow resistance in method (A) and (B) must be determined at exactly $u = 0.5 \cdot 10^{-3}$ m/s. Investigations using this target value revealed a different permeability in parallel and vertical direction of mineral wool insulation materials [22]-[23].

However, pressure differences of Δp = 0.2 Pa seem to be too low for the determination of the permeability under conditions of forced convection. Even very small changes of the temperature lead to a pressure change of several Pa, given by the second rule of Gay-Lussac alternatively the isochoric change of state of an ideal dry gas, see (3).

$$\frac{p_1}{p_2} = \frac{T_1}{T_2} \quad (3)$$

p_1, p_2 ⇒ absolute pressure at section 1 or 2 [Pa]
T_1, T_2 ⇒ absolute temperature at section 1 or 2 [K]

Considering wind influence as well, the pressure difference between interior and exterior may be many times higher and increase the air change rate. Deformations of the fibers in the mineral wool may occur and contribute to changes of the permeability. In order to improve the understanding of possible effects, the fabrication method and certain test methods for mineral wool should be investigated.

C. Fabrication of mineral wool

Mineral wool is an insulation material, consisting of manufactured, disorganized silicate fibers. The basic components for rock wool are diabase, basalt, lime rock and feldspar or recycled glass, sand, lime rock and soda (glass wool). The basic materials are molten at 1200-1600 °C and then fiberized. To fiberize the material, the blowing method, nozzle blowing method, rotation method, cascade centrifugation method, cylinder centrifugation method or the centrifugation blowing method can be used [24]. The most efficient production method is the centrifugation blowing method. In the centrifugation blowing method alternatively the nozzle centrifugation method, the molten mass is poured into a rotating vertical cylinder [24]-[26]. The centrifugal force presses the molten mass through nozzles in the spinning cylinder, resulting in monofilaments. The diameter of the filaments depends on the size of nozzles, on the viscosity of the molten mass, the rotation velocity of the cylinder and the surface tension of the molten mass. To get a nearly uniform filament cross-section of 3-6 µm, the monofilament are re-heated by flame jets and redirected at an angle of 90 ° downwards. The process results in a nearly completely fiberized product [24]. Depending on the process of the producing company, the filaments are coated with an aqueous solution, an emulsion, a suspension and oil during or after the fiberization process. Afterwards, the coated filaments are accumulated and compressed, resulting in an unstructured mesh of fiberized mineral wool. The achievable degree of compaction is influenced by the amount of material that is accumulated. Then, the compressed material is reheated to 200-250 °C, allowing the coating to harden and thus bind the fibers tighter. Finally, the mineral wool will be cut into shape, tested, packed and shipped [27].

D. Selected tests of mineral wool

The homogeneity of insulation material is regulated by note 1 in the EN 12086 [28]: "Insulation is homogeneous in respect of the mass distribution, if the density is nearly constant. That means that each measured value of the bulk density hardly differs from the average value". A test method or the maximum allowed deviation is not defined. Given values of density and deviation for insulation materials are therefore individually defined by the manufacturer of the material. That means that the structural homogeneity of mineral wool is not regulated. Different flow-through properties can be expected for different batches of similar materials. Most producers use visual spot-checks to test for textural inhomogeneity of their product. Classification into different qualities depends on the experience of the person performing the visual test. Measures how to react on observed structural inhomogeneities of produced mineral wool insulation materials are not regulated. However, EN 13162 [29] specifies the determination of the air flow resistance according to ISO 9053 [21]. Still, the question remains how and if forced convection through mineral wool affects the air flow resistance and the permeability of the material.

III. Experimental setup and Investigations

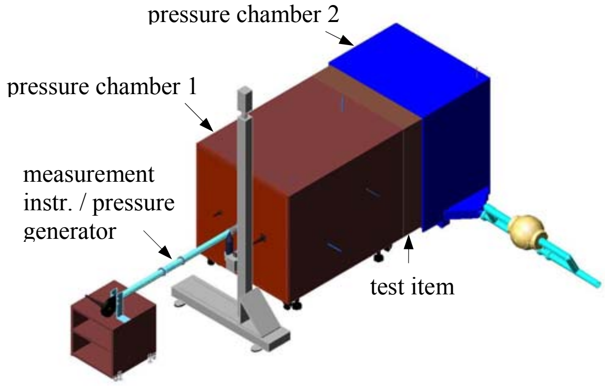

Fig. 3 Experimental setup "MSRCMT"

The **M**easurement **S**etup for **R**esearch on **C**onvective **M**oisture **T**ransfer "MSRCMT" (Fig. 3) consists of two pressure chambers which are divided by a specimen holder. Parts or complete wall structures of about 1 m² may be subjected to convective transfers. Different measuring methods for the research of convective moisture transfer can be used [15], [30]. In this investigation, a double layer timber frame structure according to DIN 68800 [17] was tested.

It consists of two 6/20 posts of the typical distance of 62.5 cm [31] and an intermediate rock wool insulation of 20 cm thickness. The insulation was installed with a length and width of 1.5 cm larger than the specimen holder. A vapor barrier with a central perforation was attached, facing the interior of the measuring setup (Fig. 4).

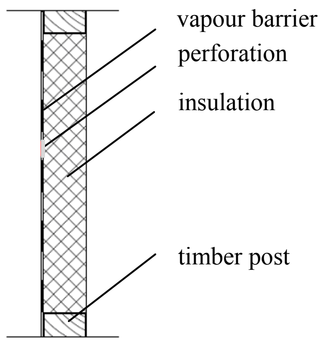

Fig. 4 Schematic layout of the double layer wall specimen

First, the aim was to determine the volumetric flow through a single centered circular leakage with edge boundary. Two independent measurements were used to obtaine reliable results, tracer gas (accuracy 2 %) and calorimetric measurements (accuracy 1.5 %) were performed simultaneously. The discharge coefficient ζ for vapor barriers with leakages of different shape, size and boundary conditions were studied prior to this investigation [15]-[16]. In order to generalize the research of the described double layer system, the insulation material was changed after each measurement.

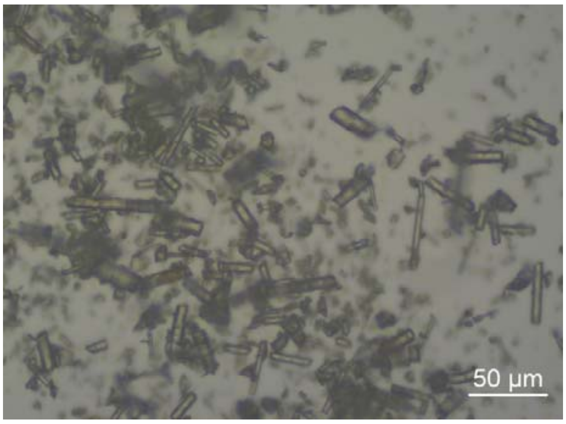

Fig. 5 Keyence-microscopy of the fine ground rock wool insulation

The obtained values did not reflect the expectations, therefore an installation error with a leakage between timber frame and insulation was assumed, see also [32]. However, the results were confirmed, using leakages of different size but similar shape. Therefore, the variation of the bulk density "ρ_{bu}"of rock wool insulation material with λ = 0,035 W/mK from a single manufacturer was tested according to EN 12089 [28]. The bulk density was calculated from the dimensions of the specimens and the weight. Then, the rock wool was ground to a grain size of ≤ 63 µm (Fig. 5) and the true density "ρ_{tr}" was determined with a Quantachrome Ultrapycnometer 1000 [33]. Using the obtained values for bulk density and true density, the percentage pore volume was calculated using (4):

$$V_p = \left(1 - \frac{\rho_{bu}}{\rho_{tr}}\right) \cdot 100 \tag{4}$$

By these means, the homogeneity of the mineral insulation material according to standard requirements can be assessed. However, statements regarding the structural inhomogeneity are not possible. Therefore, the measuring setup of the MSRCMT was slightly altered. The chamber simulating the outer environment of the insulation was removed and the general specimen holder was replaced by a special insulation holder. Insulation material specimens of the size 46.2 cm x 50.2 cm x 10 cm could be tested (Fig. 6). The contraction of the air flow could be neglected due to the small ratio of cross section of specimen to cross section of measuring chamber. The dimensions of the specimen were 1.5 cm larger than the dimensions of the specimen holder in order to achieve tight fit. Behind the insulation, a 2-D positioning system (accuracy ± 0.05 mm) was attached. A hot-wire anemometer (accuracy ± 0.001 m/s) was attached at a distance of 1 cm behind the insulation (Fig. 6). The determination of the air velocity was carried out at 529 monitoring points following a grid of 2 cm x 2 cm. The temperature in the laboratory was kept at 22 ± 1 °C and air movement was kept at a minimum. Prior to all experiments, the air velocity in the laboratory was determined using the hot-wire anemometer. The obtained values were used to correct the test results. In order to reduce the influence of the measuring system on the determined air velocities, the moving speed of the positioning system was reduced and a waiting period before taking a measurement was introduced.

In case the measurement of the air velocity implemented the presence of inhomogeneities, digital microscopy (Keyence VHX-600 Gen II) was used to visualize these.

Then the flow resistance of 46.2 cm x 50.2 cm x 10 cm rock wool insulation panels of different batches was tested. The test should give information about the interaction of forced flow-through and material properties of the insulation material. Therefore the pressure difference was increased to 5-10 Pa compared to the value stipulated in ISO 9053 [21]. For this measurement, the MSRCMT was used in basic setup. Using (2), conclusions regarding the permeability of the mineral wool insulation can be made.

Fig. 6 Research on air flow-through velocity of mineral insulation by Experimental setup

IV. Results

The convective flow through a single circular leakage with edge boundary in a light weight timber construction was investigated. Every leakage was placed in center of the vapor barrier. A perforated vapor barrier and 20 cm rock wool in front of timber posts were placed in the specimen holder. The flow was directed from the inside of the structure to the outside.

$$\dot{V} = C_L \cdot \Delta p^n \tag{5}$$

C_L ⇒ leakage coefficient in [m³/hPa^n]
n ⇒ flow exponent

Fig. 7 shows the relationship between volumetric flow at identical conditions but different pressure differences. It can be approximated by a potential function, see (5) [34]-[36]. Additionally, Fig. 7 shows that the deviation between measured and calculated values is small, the average was determined to be 0.08 m³/h. The systematic error of the measurements can be estimated using the parallel measurements with tracer gas and calorimetry. The maximum deviation was determined at 5 % for all investigated leakage areas (0.2, 0.5, 1.0, 2.5, 5.0, 10 cm²), see Fig. 8.

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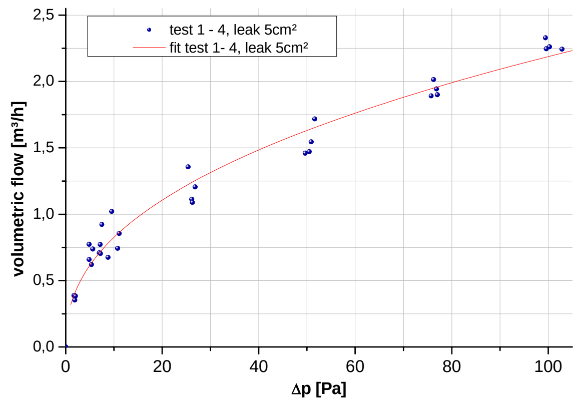

Fig. 7 Volumetric flow through a double layer timber frame construction with 5 cm² leakage in the vapor barrier

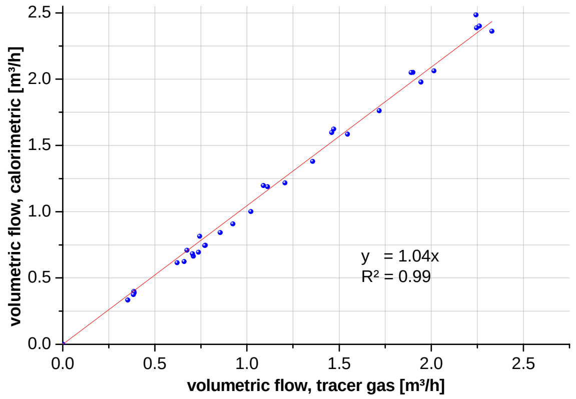

Fig. 8 Comparison between tracer gas and calorimetric measurement at leakage size of 10 cm²

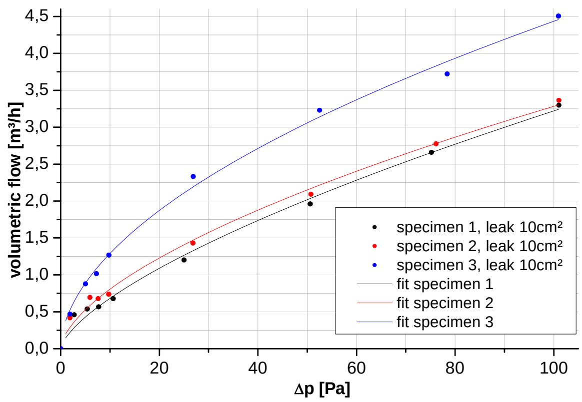

Fig. 9 Volume flow through a double layer timber construction with a leakage size of 10 cm² and the same type of insulation from different batches

In order to be able to generalize the obtained results, the rock wool was changed to a sample with identical specifications and dimensions of a different batch from the same manufacturer. Fig. 9 shows that the volume flow through a leakage of 10 cm² differs in average with a factor of 0.6 between the different batches. Similar results were obtained using other leakage dimensions (Fig. 10).

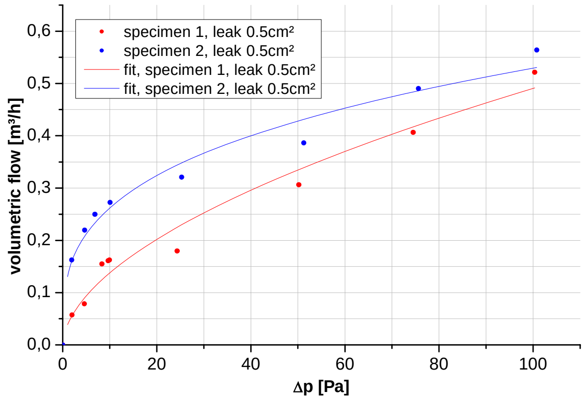

Fig. 10 Volume flow through a double layer timber construction with a leakage size of 0.5 cm² and the same type of insulation from different batches

These deviations, which represent a volume flow of up to 1.2 m³/h (Fig. 9), triggered the following investigations of the homogeneity of the insulation material.

The bulk density of different batches of rock wool panels with λ = 0.035 W/mK made by one manufacturer was determinated. The values are given in table 1. The standard deviation was ± 1.05 kg/m³. In accordance with EN 12086 [28], this is a variation of only 2 % from the average value. This result alone would imply the assumption of a very homogenous material. Additionally, the pore volume was calculated using (5). An average value of 98.19 ± 0.03 % was determined. Again, the initial assumption of homogenous material properties seems to be confirmed.

TABLE I
BULK DENSITY OF ROCK WOOL PANELS FROM DIFFERENT BATCHES

test	l [cm]	w [cm]	t [cm]	m [g]	V [m³]	ρ_{bu} [kg/m³]
1	120.3	62.4	9.5	3687.8	0.071	51.71
2	120.2	62.3	9.7	3779.7	0.073	52.03
3	120.4	62.3	10	3875.7	0.075	51.67
4	120.3	62.3	9.9	3726.3	0.074	50.22
5	120.7	62.2	9.8	3653.3	0.074	49.65

However, the upper results do not reveal information about the size distribution of the open porosity which may enable convective transport trough an exterior wall. Therefore, the distribution of the air velocity at constant flow-through was measured behind selected specimens of the insulation material. The pressure difference between front and back side of the material was 25.3 ± 0.3 Pa. Fig. 11-14 show that leakages between specimen holder and sample did not occur. Errors in the measurements due to incorrect installation of the samples can be excluded. The figures illustrate clearly that the convective flow through the specimens was not homogeneous. For example, the average flow-through velocity of specimen two (Fig. 12) was calculated to 0.018 ± 0.013 m/s. But the deviation between minimum and maximum value was determined to be 0.168 m/s.

The occurrence and position of a single leakage in a mineral wool insulation plate may influence the convective transfer through this material essentially.

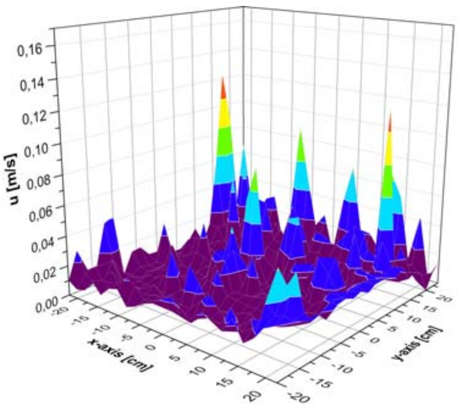

Fig. 11 Distribution of air velocity for rock wool at flow-through, specimen 1

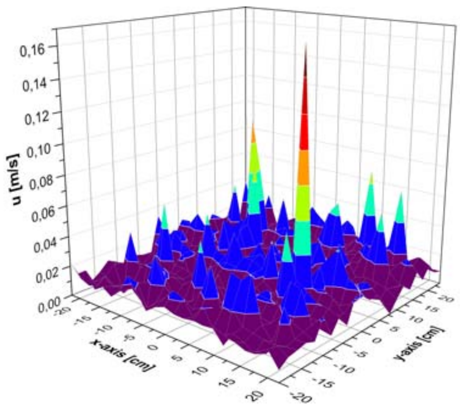

Fig. 12 Distribution of air velocity for rock wool at flow-through, specimen 2

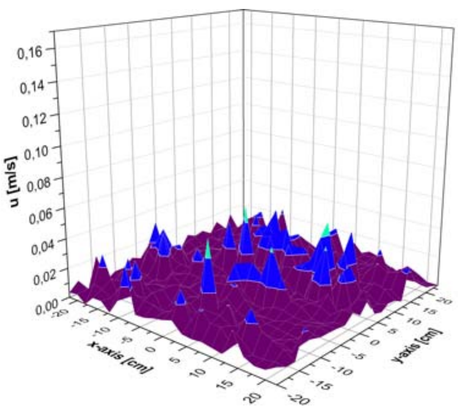

Fig. 13 Distribution of air velocity for rock wool at flow-through, specimen 3

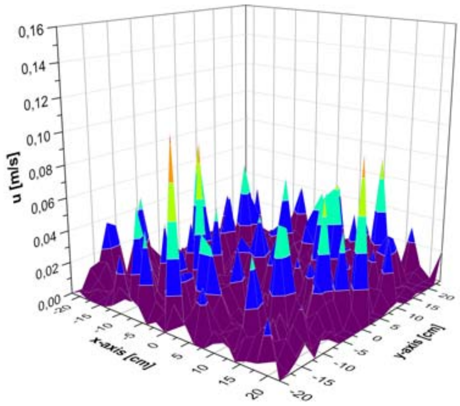

Fig. 14 Distribution of air velocity for rock wool at flow-through, specimen 4

Comparison of the individual measurements reveals that inhomogeneity in the insulation material is more frequent than the apparent homogeneity shown in Fig. 13.

Inhomogeneities were shown in the individual panels and between different panels. The tested insulation panels have an average flow-through velocity of 0.014 m/s with a standard deviation of 0.013 m/s.

Fig. 15 Curling of mineral fibers with discontinuities in the center

A standard deviation with 90 % order of magnitude of the average value implies inhomogeneous material properties. The convective moisture flow through double layer structures of light weight timber structures with penetrated vapor barrier and mineral wool insulation may vary strongly, depending on the position of the leakage. This can be explained by inhomogeneities in the mineral wool insulation, caused by the manufacturing process. Microscopy revealed curling of mineral fibers with discontinuities in the material. These areas with curled mineral fibers represent spots with reduced air flow resistance, compared to the rest of the insulation panel. Leakages in the vapor barrier in front of such spots in the insulation would result in higher volumetric or mass flow-through rate than in other insulation sections. In order to investigate the consequences on forced convection flow through rock wool insulation, samples of rock wool were tested in the MSRCMT. The pressure difference used in these experiments was 5-10 ± 1.0 Pa. According to Kloos in [12], who measured the permeability according to ISO 9053, the permeability of the used rock wool insulation material should be $1.054 \cdot 10^{-9}$ m² for the actual insulation density.

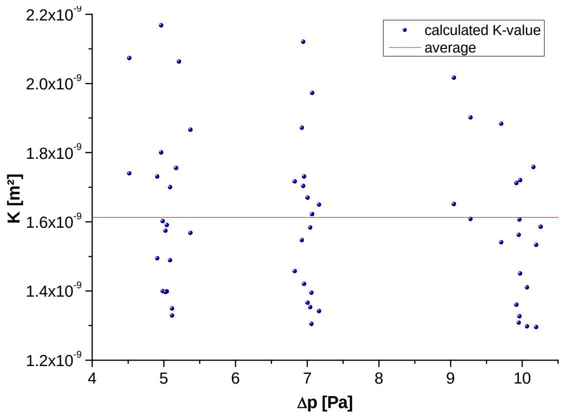

Fig. 16 Permeability of rock wool at forced flow-through

Due to the higher applied pressure difference of 5-10 Pa in the MSRCMT measurements, the flow-through of the mineral wool insulation resulted in a K-value of $1.613 \cdot 10^{-9}$ m² $\pm 2.251 \cdot 10^{-10}$ m² (Fig. 16). This means that the permeability according to Kloos differs more than 1/3 from the results under forced flow-through conditions. The obtained results imply that the length related air flow resistance, tested according to EN 13162 at 0.2 Pa alternatively $u = 0.5 \cdot 10^{-3}$ m/s, and calculated permeability from these tests are not suitable for calculation of convective transport mechanisms. Due to inhomogeneities of mineral wool insulation, there is a large scatter of the obtained K-values. That could have a negative influence on measurements done to validate calculations of convective transports. For predictive calculations, the use of K-values, determined on rectangular specimens with a length of at least 90 mm under flow-through conditions at realistic pressure differences (> 0.2 Pa), is recommended.

V. Conclusion

Leakages in vapor barrier of light weight structures may lead to flow-through of the mineral insulation. Due to enveloping surface infiltrations, formation of heat bridges and growth of health endangering mould and mildew are possible. A cost effective and typical insulation material in these types of buildings is mineral wool. It consists of non structured mineral fibers which hinder air flow. Only the open pore volume represents space where flow-through may occur. The permeability of a material describes these properties and is used in present calculation models for convective transfers. H. Darcy defined the parameter permeability in the 19th century. So far, the permeability of insulation material is calculated from the measured length related air flow resistance according to ISO 9053 / EN 29053. This is a standard test for insulation materials but the focus of the standard lies on acoustic properties. The length related air flow resistance is measured at a pressure difference of 0.2 Pa between the front and backside of the insulation. For convective transfer through the exterior walls of buildings, this pressure difference is untypical low. Deviations between calculations (existing models and models under development) and measurements of the convective moisture transfer through exterior walls of light weight timber structures can be related to the permeability of the mineral wool insulation. In the models, a homogenous material with constant permeability is assumed. When testing mineral wool according to EN 12086, the small scatter in density and porosity seems to verify homogenous material properties. Statements about the presence of discontinuities in the insulation material could be made after the investigation of the air velocity distribution behind samples subjected to flow-through. It was shown that uniform flow-through velocity was not measured within a single specimen or within a group of samples. This can be explained by curled mineral fibers which form imperfections in the material. Following investigations of the length related air flow resistance at realistic pressure differences of 5-10 Pa showed the influence of these imperfections on the permeability. The measured average K-value under realistic conditions differs more than 30 % from the value determined according to ISO 9053 / EN 29053. Due to the inhomogeneities in the mineral wool, there is a large scatter of the results. For predictive calculations of enveloping surface infiltration and convective energy loss, the use of values determined on larger specimens under flow-through conditions at realistic pressure differences is recommended.

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J. Schmidt was born in Meerane, Germany on the 29th of December, 1977. In 1996 he got his A-level in Altenburg, Germany. After school he was in the army until August 1997, in Kümmersbruck, Germany. He has reached the degree of journeyman in roofing and roof plumbing in 1999 in Altenburg. After some years of work as roofer and roof plumber in Germany he started his study of teacher for building technologies and sports in Weimar. This he finished with the first state examination in 2006. In the time between 2006 and 2008 he studied the second state examination in the same fields. He finished with the degree of Studienrat in September of 2008 in Gera, Germany. Since this time he is with the Department of Building Physics at the Bauhaus-Universität Weimar. He is a scientific assistant at the project of “Methods and materials for user-oriented refurbishment (nuBau)” and PhD student. Interesting publications of him are “Convective Moisture Transfer through Walls and Wall Components” [15] and “Konvektiver Feuchtetransport durch Bauteilleckagen in Bestandsgebäuden” [16].