Convective Moisture Transfer through Walls and Wall Components

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KURZFASSUNG. Feuchtigkeitstransporte vom Innenraum durch die Außenwände verursachen häufig Probleme und sollten daher vermieden werden. Generell gibt es zwei Möglichkeiten wie Feuchtigkeitstransporte ablaufen können: diffusiv und konvektiv. Die folgende Arbeit beschäftigt sich besonders mit dem konvektiven Feuchtigkeitstransport durch Leckagen in Außenwänden. Durch Druckdifferenzen zwischen Innenraum und Umgebung kann es zum Eintrag von Luftfeuchtigkeiten kommen, welche bei erreichen des Wasserdampfsättigungsdruckes zur Kondenswasserbildung führen. Folglich kann Schimmel- und Pilzbefall entstehen. Um das Problem des konvektiven Feuchtigkeitstransportes zu analysieren wurde ein Versuchsstand entwickelt. Mit diesem kann man einzelne Bauteilschichten und komplette Wandkonstruktionen mit verschiedenen Leckagen untersuchen. Erste Untersuchungen an Luftdichtheitsfolien zeigten, dass es bei Hohlräumen zwischen Dämmung und Folie zur Verformung der Folie und folgender Strömungsänderungen kommen kann.

ABSTRACT. Moisture transfer from inside a building in an exterior wall creates manifold problems and has to be prevented. In general two processes can produce a moisture transfer: diffusion and convection. The following investigation focuses on convective moisture transfer facilitated by leakages in the construction. Due to a pressure difference between inside and outside, air humidity may be transported to the exterior wall and condensed at the saturated vapour pressure of water. In consequence mould and mildew can arise. To analyse the problem of convective moisture transport an experimental setup was developed. With the setup it is possible to investigate each layer of a wall construction separately as well as the complete wall construction with different leakages. First results of investigation on vapour barriers show that cavities between insulation and foil can cause a deformation of foil with a changed flow.

Schlagwörter: convective moisture transfer, pressure differences, flow through leakages

1 Introduction

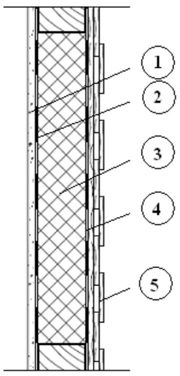
As a result of the world climate conference in Copenhagen in 2009 and the introduction of the EnEV (Energieeinsparungsverordnung = energy saving regulations for buildings) in Germany, the public focused increasingly on leakage of buildings. This is due to that leakages in the exterior wall construction of a building may cause increased energy consumption. This contradicts with the need for reduced consumption of primary fuel sources as well as reduction of energy cost and carbon dioxide footprint of buildings. In order to analyse the leakage rate of buildings, the Blower-Door-Test is usually used. A pressure difference of 50 Pa is applied and the air change rate is measured in 1/h. Based on these measurements, the energy loss due to existing leakages can be assumed [1].

Fig. 1: Mould, caused by convective moisture transport from interior to cold roof

However, not only energy losses occur due to leakages but humidity, transferred through leakages, may accumulate in exterior walls as well. The moisture which is transported into the wall construction precipitates at the saturated vapour pressure e.g. in the insulation. The amount of moisture that can be transferred by convection through leakages and precipitate in the wall is usually many times higher than that transported by diffusion controlled processes [2-5]. This may lead to thermal bridges in the insulation material and in extreme cases, when the insulation material dislocates, to thermal bridges in the construction. Beside the thermal problems, the moisture results in degradation of the construction and health risks for the user of the building due to mould and mildew (Fig. 1). Since a construction that was built according to relevant standards is usually considered air-tight, the problem of air flows transporting moisture through leakages was given only little attention. In order to be able to analyse the problem of convective moisture transport in buildings, an experimental setup was developed. With this experimental setup, it is possible to investigate each layer of a wall construction separately as well as the complete wall construction. First results have been determined on vapour barriers of wooden wall constructions.

2 Background

Existing as well as newly constructed buildings are often at least partly built by wood. The design varies between different countries. Basically, five different styles can be distinguished: (i) the wood frame construction, (ii) the wood truss construction, (iii) the wood skeleton construction, (iv) the solid wood construction and (v) the mixed construction. This work focuses on constructions like the wood frame or truss construction. However, these kind of constructions can be different due to the usage of varying materials. One possible construction is shown in Fig. 2 .



1 Gypsum plaster board
2 Air-tightness layer
3 Insulation
4 Wind-tightness layer
5 Weatherproof protective layer

Fig. 2: Wood frame construction, inside left and outside right.

On the outside is a weatherproof protective layer on a substructure, followed by permeable layer which allows water vapour to move the interior to the exterior. Insulation, consisting of mineral fibre or ecological insulating material is situated in the centre of the construction, between the load bearing wood structure. Then an air-tightness layer (usually denoted vapour barrier), often PE-foil, is attached in order to prevent the ingress of moisture. The inside forms the interior protective layer on a substructure, for example gypsum plaster boards. Especially after building renovation, penetrations like floor joists or mounting parts like ventilation tubes represent an injury of the air-tightness layer. A flow connection between interior and exterior can be formed. Due to pressure differences between these regions, air exchange may occur. Such leakages can be visualised by means of thermal imaging. Depending on the flow direction of the air, exfiltration, when air flows because of higher inner pressure to the exterior and the opposite effect, infiltration, can be distinguished. In both cases, moisture and particles like germs and dust may be introduced into the construction. This is often referred to as enveloping surface infiltration. As already mentioned, the amount of moisture transported by convective moisture transfer can be many times higher than that transported by diffusion controlled processes [2-5]. Problems due to that type of moisture do occur often and therefore, research on moisture infiltration by quasi-stationary convective air streams will be done. A new experimental setup was developed, because the current level of awareness is, to the best of the authors' knowledge, limited [6]. This setup offers the opportunity to analyse the convective moisture transfer through leakages in layers or completely constructions of walls under variable differential pressure conditions.

2.1 Experimental setup

To be able develop this kind of experimental setup, it was necessary to analyse the reasons for convective moisture transfer. Convective moisture transfer has its origin in the formation of leakages within a construction which result in a connection between interior and exterior air. The shape, size and boundary profile of leakages can differ inside the layers of a wall and this may influence the flow rate [7–9]. The maximum size of a leakage was defined to be $10 cm^2$. The driving force of the air stream through a leakage is the pressure difference between inside and outside air. Both, static and dynamic air pressure (wind) do have influence on the pressure difference. Beside references [11; 12] and own initial calculations [13], long-time measurements were carried out in Rostock and Weimar. It appears that the maximum values from the references disagree with the analysed data. The influence of wind is a significant parameter (Fig. 3) [13; 10].

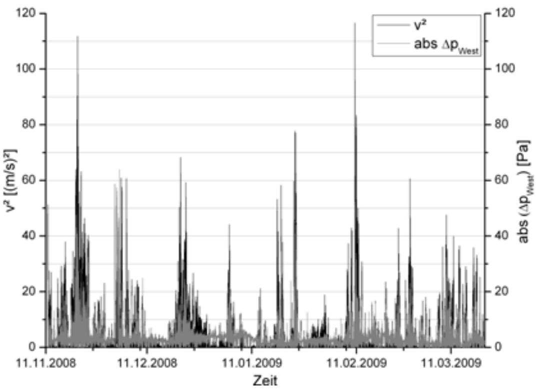


Fig. 3: Comparison of the wind speed to the power of two with the value of the force of pressure difference on a west facade in Weimar

Based on these measurements, a pressure difference of 0...350 Pa was realised in the experimental setup (Fig. 4). The setup consists of two equal pressure chambers and a specimen holder. An equidistant horizontal levelling of both chambers is given. The connection of both chambers is formed by the test specimen, in general a part of outer wall with a defined leakage. Special seals at the end of specimen holder and chamber 1 help to hold air-tight membranes as well as to seal specimen holder and chamber 1 against the other. Chamber 2 and specimen holder are attached similarly. Each chamber (inclusive specimen holder) is protected against exterior pressure and flow influences from outside the system. Influx and discharge opening are the only joints to the environment. The resistance of the material of the pressure chambers against liquid water and water vapour diffusion offers the possibility to take measurements at high levels of humidity. To analyse humidity enriched air streams under real thermal parameters, conditioning systems may be attached. Different fans arrange the pressure differences in the chambers, realistic parameters can be created in this way. The dimension of the chambers is chosen so that the fans respectively leaks have a free outflow in horizontal and vertical direction into the interior of the chambers [14; 15]. All fans are mounted into the front side plate of chamber 1. Only one fan may be used at once. The neighbouring resting pressure generators (fans) are sealed so that impacts on measurements can be excluded. A digital pressure differential meter is used to measure the pressure differences between chamber 1 and 2. The positions of the pressure meters are chosen to minimise errors [16; 17]. Temperature- and humidity meters are attached to measure these properties in the chambers, if required. To investigate the air flow through leakages, three different, independent, digital controlled measuring systems are included. The systems are tracer-gas-detection, mass flow and laser-doppler-anemometer (LDA). In chamber 1, there are five sampler tubes and at least one dosing tube integrated and sealed tight. They are positioned at distinctive points in chamber 1.

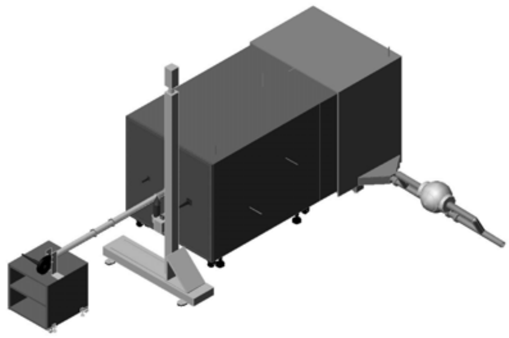


Fig. 4: Experimental setup for analysis of convective moisture transfer through leakages.

One additional sampler is located next to the experimental setup in the laboratory in order to measure and consequently avoid negative tracer-gas-effects and leakages of the chamber. All of these tubes are connected to the tracer-gas-monitor respectively sampler / doser unit and may be individual controlled. A mixing fan inside chamber 1 ensures an even distribution of tracer-gas in the air. The waste of the non toxic tracer-gas which is detected by photo-acoustic infrared spectroscopy and the tracer-gas which streams through the sample will be drained from chamber 1 naturally by a pipe or by a bypass with a fan to the outside air. With the help of a shutter, a defined draining is possible. That way, errors can be minimised and safety standards may be abided. Additionally to tracer-gas, e.g. water vapour can be detected which is very important in analysis at high humidity. By means of concentration decay method [18], the volume flow respectively mass flow through the leakage can be determined from the air change rate. The volume flow through a defined leakage can be ascertained with a precision of ± 2% FS at a detection rate smaller than 0.01ppm. To validate the values, diffusors can be attached to the front of the intake opening of the pressure generators [8; 9]. The diffusors scale the intake cross section of the fans and enable the establishment of compatibility with the mass flow meters. This is capacitive measurement method and it is calibrated for air stream measurements of 0.05...450 nl/min. The precision of the mass flow measurement is 1.5% FS. Due to the continuity equation in steady state, influx is equal to outflow at all times, the mass flow system is a good comparison to the tracer-gas-system. For the validation of particularly large leaks (≥ 5cm²) at higher pressure ranges, it is necessary to realise fewer outflow openings with reduced influences. The diffusors will be dismantled for such investigations. In front of chamber 1 is a detachable perspex pipe in connection with one of the pressure generators to measure these high flows with the LDA. A rectifier in the pipe aligns the stream in one direction at a maximum pressure loss of 25% [19]. The length of the pipe was determined according to the relevant standard [19]. A measuring point before and behind the rectifier allows for analysis of pressure losses [19]. The LDA measures at 10.5 d (d = diameter of pipe) [20] through the perspex pipe with the gravity line method [21; 22]. A coupled 2-D traversal supports this process. To measure the velocity of flow in the pipe, nanoparticles are added into the air flow. The precision of this analysis is 0.067% FS. Special filters protect the parallel measurement systems. The volume- or mass flow may be calculated subsequent using the cross section of pipe. The perspex pipe for measurements has to be sealed with a smaller fan, therefore the pipe and the coupled pressure generator is mounted on a movable substructure. This substructure may be levelled for use and is separated with special gaskets from chamber 1.

2.2 Calculation model

On the basis of conservation of energy and continuity, a stationary calculation model has been developed. Due to a sudden reduction of the cross-section at the leak, the air flow contracts, which can be expressed by the factor ψ. Additionally, there are influences on the velocity of the flow, expressed by the factor φ. Both factors are restricted by the viscosity of the fluid and the properties of the leak. If a dimensionally stable material is assumed, contraction and velocity factor operate contrary to the theoretical volume flow. Both factors cannot be resolved individually [7–9]. They are summarized as the discharge coefficientζ. Assumed that there is an ideal gas, the following equation (1) can be deduced for the volume flow:

$$\dot{V}_{Leak} = A_{Leak} \cdot \zeta \cdot \sqrt{\frac{2 \cdot \Delta p}{\rho \cdot (1 - n^2)}} \qquad (1)$$

$\dot{V}_{Leak}$ → volume flow through the leak (volume outflow)

A_{Leak} → cross section of the leak

Δp → pressure difference between inner room an environment

n → ratio between leak and cross section of the room

The outflow factor ζ was assumed to be 0.61 for precalculations, which is similar to Blower-Door-calculations [23; 24]. First investigations of moisture exposure of buildings by envelope surface infiltration have been done on different leaks in the air-tightness layer (vapour barrier) in reference to their streaming behavior. The results show that different shapes may result in different volume flow values [10], even for identical cross section of the leakages. The increase of the volume flow in accordance to the differential pressure change followed a similar exponential trend as it is shown in [23]. Due to special additional arrangements, neither a deformation of the leak border sections nor the whole membrane was possible.

2.2 Results

When oversized insulation boards are forced into place on building sites, cavities between the insulation and the air-tightness layer may occur. These cavities can, in combination with pressure differences, lead to deformations of the air-tightness layer. Based on the in [10] shown leak cross-sections of 0.2 cm² and leak shapes, measurements were done on this type of damage of a vapour barrier. The material of the membrane (polyethylene-foil) was similar to the material used in the first test set-up [10]. First, the deformation of the membrane with a circular sharp-edged leak was investigated. The membrane was marked with a uniform 3cm grid. Chamber 2 was removed from the experimental rig and replaced by a traversing with laser-distance measurement equipment. The laser instrument was able to measure the distance between measurement point and membrane by accuracy of 0.1mm. The equidistant allocation of the grid points, beginning from the centre, allowed measuring only one quarter of the membrane and transferring the results to the rest of the whole foil. Depending on the pressure difference, different deformations in z-direction were determined. At a differential pressure of 350 Pa, the deflection of the membrane was almost 7cm (Fig. 6).

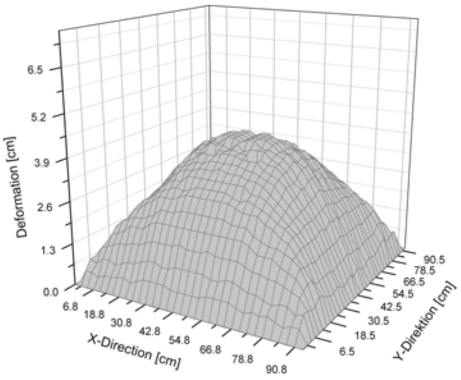


Fig. 5: Curvature of PE-foil under 50 Pa with a leak of 0.2 cm²

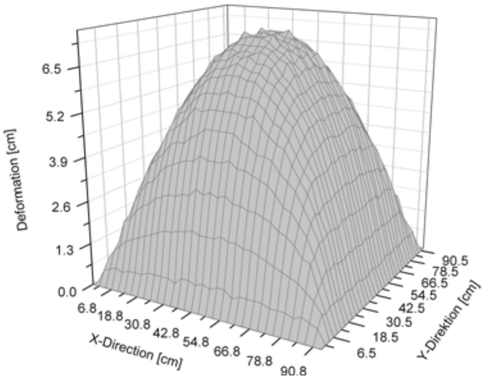


Fig. 6: Curvature of PE-foil under 350 Pa with a leak of 0.2 cm²

The results in figure 5 and 6 show that measured values can be simulated with a 2D-approximation. The deformation of the foil implicates the effect of a confusor in direction of the lower pressure level. The influence of this aspect became apparent when comparing the volume flows through leakages in deformable and stiff materials [10]. The deviations of the results from tracer-gas flow and mass flow method for analyzing the volume flow showed a value of 3 %, using no perspex glass tube with straightened flow.

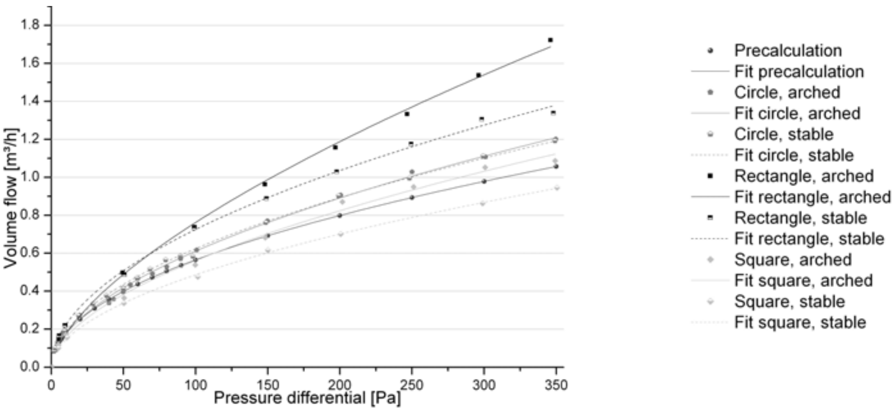
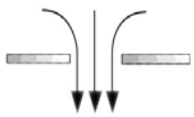


Fig. 7: Volume flow at stable and arched membranes

Comparing the effusion of the fluid between the form stable to the free deformable material, there are influences for almost all shapes of leaks recognizable (Fig. 7). For example for a rectangular leak, an increase of 25% of the volume flow can be noticed at pressure differences above 150 Pa. When the pressure differences are small, the material deformation has a reducing effect on the volume flow with this shape of the leak. It is nearly 35% lower than the value for the undeformed material. Quadratic leaks in deformable material show a continuous, exponential increase of the influence by 4.5...20%. The volume flow is proportionally higher in comparison to form stable materials. An anomaly can be observed for deformable circular leaks. While they produce at low pressure differences nearly 10 % less volume flow, the measurement results equalizes (difference around 1 %) at pressure differences above 150 Pa, compared to the undeformed samples. Thus the creation of the confusor affects, depending on the shape of the leak, the volume flow through the leak. In areas of low differential pressure, the surface roughness and additional contractions of the nearly perpendicular converging boundary layers of the air causes negative influences on the flow. If the differential pressures increases, the deformation these air layers converge by a flat angle and the volume flow rises. Furthermore, boundary strains have an influence. The lower the boundary strains at the leak, the larger will the deformations become at higher differential pressure.



Transition
Increase in pressure

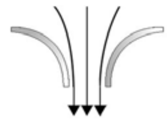


Fig. 8: Shape edged opening

ζ = 0.59...0.62

Fig. 9: Circular opening

ζ = 0.97...0.99

The boundary strains at the leak depend on the shape of the leak, the elasticity of the material, the temperature of the material and the differential pressure. The flow through the leak is influenced positively if there are large boundary deformations in direction of the flow (Fig. 8). Unlike mentioned in [9], transition regions can be expected between the extremes shown in fig. 8 and 9. Using different measurement methods, it was investigated if an enlargement of the opening for circular leaks occurred. The results show that this aspect can be excluded or is not detectable, respectively. However, it has been determined that the visco-elastic deformability of membranes [25] affects the formation of a confusor in the direction of the lower pressure level positively. Once a membrane has been deformed plastically, it can not be re-deformed to the initial state. Repeated loading of pre-deformed material will not result in similar deformation as unaffected material.

3 Summary

Any leakage in an exterior wall may result in an air-exchange between interior and environment. The driving force of the mass flow is the differential pressure between interior and exterior. This differential pressure depends on the pressure of the static air layers in both regions as well as the influence of the wind. The territorial position of the building and the direction of the walls are factors that have to be considered. Enriching the air with water vapour and fine particles like germs and dust, envelope face infiltration may take place, depending on the pressure level between inner room and exterior. To examine that problem in detail, a new experimental setup was developed at the department of building physics at the Bauhaus-University Weimar to analyse the convective humidity transport through walls and constructive elements. Quasi-stationary series of measurements are used to approach the instationary convective moisture ingress. The experimental setup consists of two chambers which are separated by a wall construction or a constructive element. The test setup was designed to analyse leaks with a cross-section from 0 cm² up to 10cm². For pressure differences between 0…350 Pa, the volume and mass flow can be determined. A validation of the measured results is possible by parallel analysis with different measurement systems. The first research on the discharge factor of air-tightness membranes showed that deformations of the membrane in direction of the lower pressure level may occur if free deformation is possible (often caused by faulty installation of insulation materials). This deformation is comparable to the formation of a confusor and has, in addition to potential border deformations, an influence on the volume flow. Depending on the shape of the leakage and the deformation of the membrane, air layers close to the boundary layer can converge and increase the contraction of the free exhausting air beam. The volume flow is increased by border deformations of the leakage, depending on differential pressure. In comparison to dimensionally stable materials, the ζ-value of deformable materials changes with the degree of deformation caused by the air flow. In a next step the aim is to analyse the air flow through realistic leakages in vapour barriers such as cracks, cuts, hammer holes and leakages around mounting parts. The gained knowledge will be used for further research on the convective moisture transfer through leakages in successive layers of wall constructions and finally the complete wall construction. The support of the Ministry for Education and Research is gratefully appreciated.

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