The impact of leakage properties onto the flow-through of single leakages

Jens Schmidt, [1]
Oliver Kornadt, Professor [2]

[1, 2] Technical University of Kaiserslautern, Germany

KEYWORDS: *convection, leakage flow, discharge coefficient, air tightness, simulation*

SUMMARY
Leakages in the building envelope may lead to increase of primary energy demand and carbon footprint of buildings. Additionally, particle and bacteria infiltration or exfiltration are possible. Furthermore, the building shell may be damaged by hygric enveloping surface infiltration. For investigation of the impact of leakages in the building envelope, different measurements and simulations are used. The disadvantage of the both is that the knowledge on discharge coefficient of leakages in real buildings is limited. Therefore, the discharge coefficient is estimated or based on sharp edged, circular standard orifice. But real leakages are different, e.g. the shape is not comparable to a standard orifice. Due to these, the flow through different leakages in perforated air tightness layers of light-weight timber frame constructions was analysed. The applied pressure differences were real measured values of long term investigations on building shells. At these specific pressure differences, the flow profile through leakages is different to studies of standard orifice. The volumetric flow through leakages is significantly influenced by this difference. The results show the impact of the different leakage parameters onto the discharge coefficient. Thus, simulations should not be based on standard orifice investigations.

Introduction

In walls of new or refurnished buildings, it is common to integrate different insulation. Thus, a reduction of energy losses through the building envelope is possible. However this climate separation of interior and environment represents also a potential danger. If the water vapour diffusion resistance of the room side materials is too small, condensation may arise in the wall construction. For prevention, room-side diffusion inhibiting or blocking materials e.g. vapour barriers are arranged. According to (Schulze H. 2011), awareness regarding diffusive moisture transport processes has increased. Therefore, moisture problems caused by diffusion in constructions of new buildings are infrequent at present time. A far bigger problem is given by the deficient air tightness of the building envelope. According to (Biskop R. 2008), these leakages are caused by mistakes in planning and execution. Especially during the heating season, bacteria, particle and moisture may be transported by convection from the interior to the environment. This transport of matter may lead to deposits in the wall structure. This might result in growth of mould and mildew or the formation of heat bridges e.g. in case of condensation in non-capillary active components. Additionally, the convective heat exchange leads to increased energy losses. Light-weight timber constructions are particularly at risk concerning leakages. Damages in the air tight and protection layer are easily possible and the used insulation materials are frequently air permeable. In addition, the convective leakage flow is promoted by the non-obligatory air tightness of the weather protection layer. These findings led to the development of simulation software with the aim of analysing the disadvantages of leakage flows on buildings. The best-known algorithms are implemented in the software of Delphin and WUFI. These algorithms are based on leakage flows caused by density differences (Häupl P. et al. 1997, Künzel H.M. 2010). Only a few calculation models are developed for leakage flow analyses under real pressure difference conditions of wind and buoyancy. They are frequently based on the existing calculation approaches of Delphin and WUFI (Langmans J. 2013, de With G. et al. 2009, Zirkelbach D. 2009, Kurnitski J. et al. 2000). In these new approaches, the contraction influence on the leakage flow is either estimated or refers to unpublished references. Currently, standards and knowledge about the discharge coefficient are exclusively based on standard orifice and materials which are used in technical building equipment (ASHRAE 2009, DIN EN ISO 5167-2). However, leakages in buildings may differ e.g. in shape, compared to standard orifice. Nevertheless, for investigation of the equivalent leakage area with the pressure difference method, also a generalized discharge coefficient is used (DIN EN 13829, ASTM E779-10, ASTM E1186-03). Furthermore, the friction coefficient of pipeline materials for air and water transport is different, compared to the short channels which arise by perforation of the room-side layers e.g. in materials of light-weight timber frame constructions. Therefore, this work aims to analyse the impact of the leakage shape and size in air barriers onto the flow-through. Also, the influence of deformation of the air barriers onto the discharge coefficient was measured. Finally, a comparison of the volumetric flow through a single leak and several leakages of the same total leakage area and texture was carried out.

Basics

The pressure difference between interior and the surrounding area is the potential of flows through leakages in the building envelope. In naturally ventilated buildings, these are influenced by wind and buoyancy. The change of pressure differences occurs in intervals of seconds (Schmidt J. et al. 2010b). According to the Bernoulli equation, the leakage flow is from the higher to the lower pressure level. In order to analyse and simulate the exfiltration flow through a room-side layer with a single leak and adjacent permeable insulation in a light-weight timber structure, knowledge on the pressure loss caused by the leak is required. Commonly, the cross-section of a leak in the building shell is much smaller than the cross-section area of the room, which forces a constriction of the exfiltration flow. This results in contraction and velocity losses. The contraction factor Ψ is affected by the ratio of stream and leakage cross-section. In addition, the shape of leakage edge is crucial (fig. 1, 2). Ψ of e.g. sharp edged standard orifice is 0.61 … 0.64 (Bohl W. et al. 2005). The velocity coefficient Φ of the leakage flow is influenced by the macroscopic and microscopic geometry of the opening, the viscosity and the surface tension (if not air) of the fluid. Φ is in case of sharp edged standard orifice 0.97 (Bohl W. et al. 2005). The product of Ψ and Φ gives the discharge coefficient ζ. “Caused by the difficulty to investigate Ψ and Φ experimentally separated from each other, values of these coefficients are only scarcely documented in the literature.” (Bohl W. et al. 2005) Theoretical considerations were already carried out by Torricelli and Borda in 17^{th} and 18^{th} century (Borda J. C. 1769).

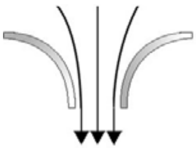

FIG 1. Circular opening

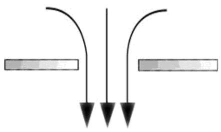

FIG 2. Sharpe edged opening

By comparison of pressure and impulse force, they determined a theoretical contraction coefficient of 0.5 (Bohl W. et al. 2005). Later, investigations of the discharge coefficient of standard orifice by E. Buckingham (1931) and J. Unger (1979) have resulted in the values given in (DIN EN ISO 5167-2). The discharge coefficient ζ of the air flow through a horizontal leak may be derived by the Bernoulli and continuity equation according eq. (1):

$$A_L \cdot \zeta \cdot \sqrt{\frac{2 \cdot \Delta p}{\rho \cdot \left(1 - N^2\right)}} = \dot{V}_{real} \tag{1}$$

In eq. (1) A_L represents the leakage area, Δp the pressure difference and ρ the density of air. The ratio between room and leakage cross-section is given by N. Corresponding to eq. (2), it is possible to determine the discharge coefficient by experimental investigations. In this context represents $\dot{V}_{real}$ the measured and $\dot{V}_{theo}$ the undisturbed, theoretical volumetric flow.

$$\frac{\dot{V}_{real}}{\dot{V}_{theo}} \cdot \sqrt{(1 - N^2)} = \zeta \tag{2}$$

According to (DIN EN ISO 5167-2), the parameter N is powered by 4. An explanation of the exponent is missing in DIN EN ISO 5167. Due to the fact that N approaches to 0 the root expression is negligible. In contrary to the Darcy-Weisbach formulation in eq. (3), according to the (ASHRAE 2009) it is possible to investigate ζ without knowledge about channel friction, profile and velocity of the leakage flow through perforations of layers. Furthermore, the influences of inlet and outlet losses for integration in eq. (3) are scarcely documented (Langmans J. 2013). The impacts of these losses are integrated in ζ.

$$\left(\frac{f \cdot L}{d_h} + \Sigma C \right) \cdot \left(\frac{\rho \cdot \bar{u}^2}{2} \right) = \Delta p \tag{3}$$

In eq. (3) ΣC is representing the sum of local losses. f is the Darcy-Weisbach friction factor. In case of fully developed laminar flow it is equal 96/*Re* (Langmans J. 2013). The other parameters in eq. (3) are L the length, d_h the hydraulic diameter and the mean square velocity $\bar{u}^2$ in the channel. *Re* denotes the Reynolds number, which defines the stream profile (laminar, $Re \leq 2300$). DIN EN ISO 5167 provides additional opportunities for estimation of ζ under conditions of $0.05 \leq N \leq 0.64$ and $5 \cdot 10^4 < Re < 10^7$. A tabulation of some ζ-values of standard orifice is implemented in this standard. Furthermore the Reader-Harris/Gallagher equation may be used for estimation under knowledge of *Re* at $N \geq 0.1$ (Böswirth L. 2007). It is only applicable to pipes with circular standard orifice. Caused by the approach of $N \rightarrow 0$ and the laminarity of flows through common leakages in buildings, (Langmans J. 2013) values that these models are unsuitable for forecasts of pressure losses. Hence, the discharge coefficient was analysed using eq. (2).

Measurements

The investigations were carried out on vapour barrier foils of about 1 x 1 m in the “Measurement Setup for research on convective moisture transfer (MCMT)” (Schmidt J. et al. 2010a). Every investigated leakage was sharp edged by use of special tools. The climate conditions between the over and under pressure chamber were equal at all measurements. The perforated vapour barrier was the separation of these two connected chambers. For the early investigations, the foil was stiffened without influencing the flow. The volumetric flows through the leaks were measured parallel by use of Tracer-gas-system “TGS” and calorimetric flow meter “MSD”. According to (Böhle M. et al. 2002, Leick Ph. 2008), the flow-through was under open outflow wherein the air flow after overcoming the obstacle could open conically. First, the pressure difference between the inflow and outflow-side were calculated by weather data of a German test reference year (Christoffer J. et al. 2004). Later, these values were arranged based on long term measurements at real building facades. According to the design of the MCMT (Schmidt J. et al. 2012), the maximum total leak size was 10 cm^2, at a maximum pressure difference of 350 Pa. Under real measured pressure differences (Schmidt J. 2013) the leakage flow is usually laminar. Due to poor execution of real buildings, cavities between the insulation and airtightness layer may occur. In order to analyse their influence on the leakage flow of perforated vapour barrier foils, double chamber measurements were carried out under free arching of foils like before. Additionally, the deformation of 4-sided clamped, perforated vapour barrier foils was investigated in single chamber tests with onesided over pressure. For this, a 2D- traversal with rangefinder was installed behind the leakage at the under-pressure side.

Results

The first part of the study related to the analysis of the flow of differently shaped leaks. Therefore, leakages of the same cross-section and shape of edge were investigated in stiffened PE-foil.

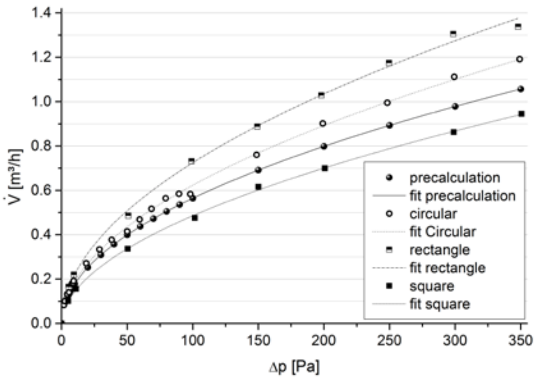

FIG 3. Volumetric flow through different shaped leaks, A_L = 0.2 cm²

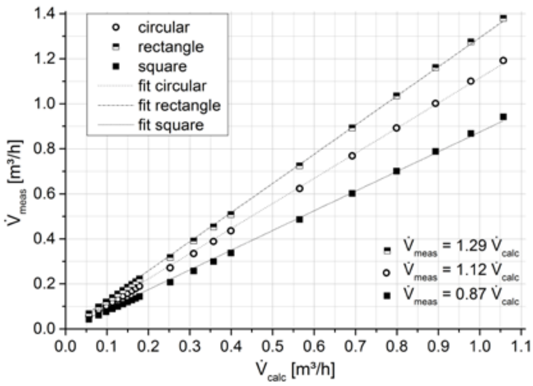

FIG 4. Comparison of volumetric flow through different shaped leaks to the calculated leakage flow, A_L = 0.2 cm²

Figure (3) shows the leakage flow through 0.2 cm² leakages of different shape at different pressure differences. In this context, the flow may be approximated by a leak according to (DIN EN 13829, ASTM E779-10, ASTM E1186-03) as a function of the applied pressure difference by an exponential function. As leakages in figure (3, 4) were used: an edged rectangular leak (0.1 x 2 cm), a squared leak (0.45 x 0.45 cm) and a circular leak (d = 0.5 cm). The measurement error between the carried out parallel measurements was about 3%. The association for air tightness in the building trade "Flib" (2008) suggests using a ζ-value of 0.61 to analyse the equivalent leakage area of a building. Calculated flows, using this ζ-value, were compared with the measurement results, see figure (3, 4). According to figure (4), the calculated flows had an average difference of about 20 % compared to the measured flows. When using the hydraulic diameter to calculate the flow rate, the error would increase further. For e.g.the rectangular leak, it would yield d_h = 0.19 cm. Thus, a much smaller calculation cross-section would be given.

The discharge coefficient is calculable by use of eq. (2) and neglecting *N*. According to figure (5), a linear relationship exists between theoretical and measured volumetric flow. The inclination of the linear fit defines the correlation between the two flow rates. Thus, the inclination resembles a resistance coefficient respectively the discharge coefficient. The properties of the ζ-value were investigated on sharp edged, circular leaks of different cross-section. As shown in figure (6), the discharge coefficient ζ is hyperbolic, approaching a limit value. This relationship can be approximated by an exponential function. The result for circular holes was similar (figure 7). Both, figure 6 and 7 show that the discharge coefficient approaches the theoretical, calculated contraction coefficient according to Torricelli and Borda (1769) with increasing leakage size. This suggests that the influence of the velocity on Φ decreases when the leakage area increases.

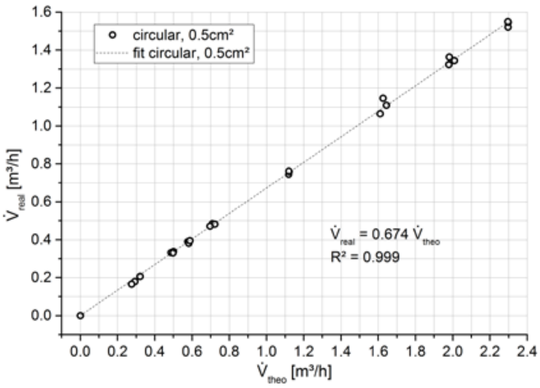

FIG 5. Linear relationship of theoretical and measured volumetric flow A_L = 0.5 cm², sharp edged, circular leak

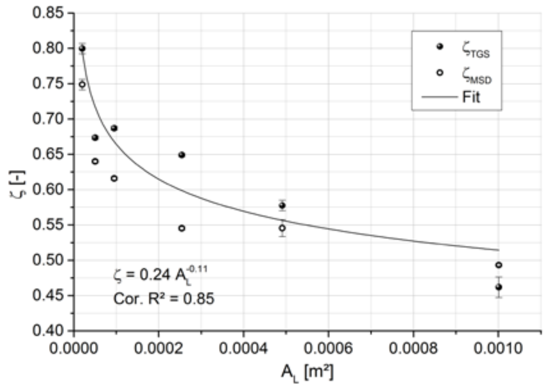

FIG 6. Change of the discharge coefficient in comparison of the change of the leakage area of circular, sharp edged leaks

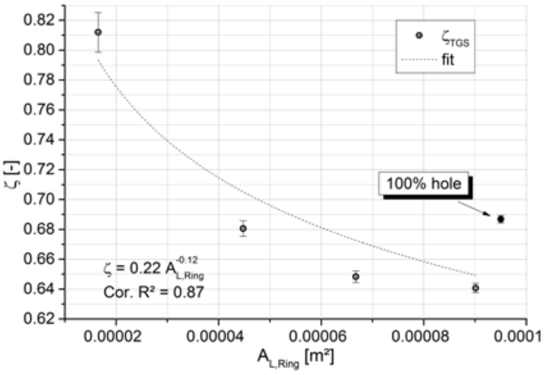

FIG 7. Change of the discharge coefficient in comparison of the change of the leakage area of annular, circular, sharp edged leaks

In the next step of this investigation, the deformation behaviour of a 1 m² large, 0.2 mm thick, perforated PE-foil was examined. In figure (8) is shown that the PE-foil is arching like a nozzle due to the one-sided pressure load. The maximum of arching was 7.4 ± 0.1 cm at a leak size of 0.2 cm² and 350 Pa of pressure difference (figure 9).

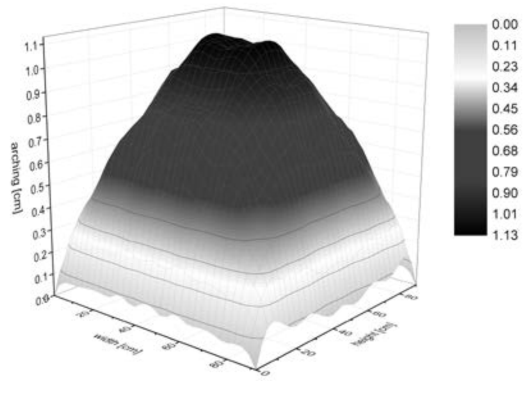

FIG 8. Arching of perforated PE-foil at Δp = 2Pa, A_L = 0.2 cm², circular, sharp edged leak

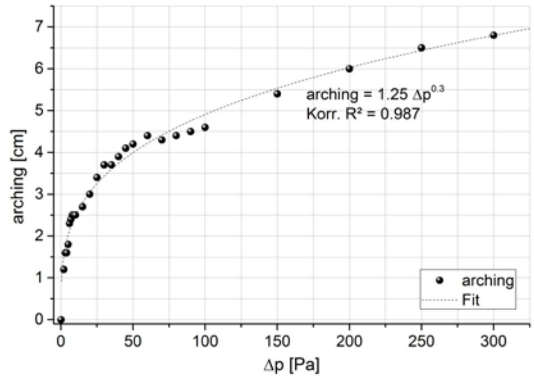

FIG 9. Maximum of arching of perforated PE-foil at different Δp, A_L = 0.2 cm², circular, sharp edged leak

The values for the volumetric flow through the holes in an arched and stiffened PE-foil were compared with the calculated flows for ζ = 0.61 according to (Flib 2008). As can be seen in figure (10), the formation of a nozzle in the air tightness layer may lead to a change of the leakage flow at different pressure differences.

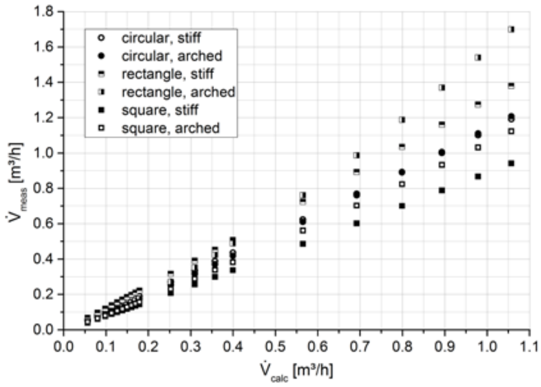

FIG 10. Impact of foil arching onto the leakage flow compared to calculated flow with ζ =0.61, A_L = 0.2 cm², circular, sharp edged hole

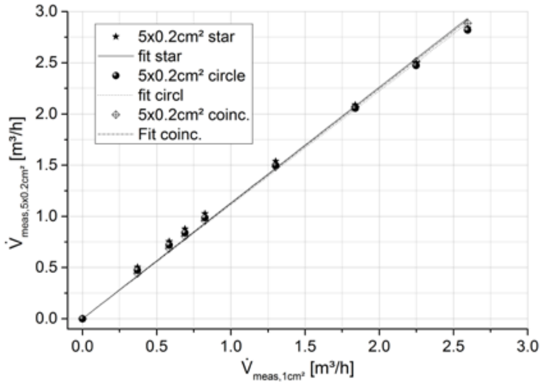

FIG 11. Comparison of leakage flows through a single leak with the total cross-section of 5 small leaks of the same properties in deformable PE-foil

In figure (10) is shown that the smallest variation between the flows through arched and stiffened PE-foil occurs for circular leaks. The difference of leakage flow between deformed and undeformed foil increases with increasing pressure difference (figure 10) for leakages of non-circular shape. The ratio between calculated and measured volumetric flows was never 1 for all measurements (figure 10). These results show that only one value for ζ is not generally valid for every single leakage.

Further investigations should clarify if the ζ-value of the volumetric flow of one leak is equal to the ζ-value of several leakages of the same total cross-section and properties. For the experiment, a leakage area of 1 cm² was chosen. The reference was the flow through a single, sharp edged, centred leakage in deformable PE-foil. The total flow at different pressure differences for the single leak was compared to 5 leakages of A_L = 0.2 cm² (total 1 cm²) with different positions.

In figure (11), circle means a uniform distribution of the small holes with a 30 cm radius around one central leak. The definition star describes a hole distribution with one centre leak and 4 leaks in a distance of 5cm on the ordinate and abscissa. Coincidence “coinc.” denotes a freely chosen, non-definable distribution of the small leakages. Figure (11) shows, that the total leakage flows are similar for all 5-leak-tests. The relationship of the flow through the single leak and the 5 holes of the same total cross-section is linear. However, the inclination of the flow fit between the 5 small to the one large leak shows a deviation of 11 to 13 %. In order to be able to define only one discharge coefficient for existing leakages in the building envelope, e.g. in Zone models or to determine the equivalent leakage rate, accurate knowledge about the existing leaks is essential. Even the size of the leakage can be critical.

Conclusions

The investigations of leakage flows through PE-foil show that the volumetric flow through a leak in lightweight timber structures and the adjacent layers is significantly influenced by the discharge coefficient ζ of the room-side leak (exfiltration). It is shown, that the assumption of a discharge coefficient of standard orifices to describe a leakage flow under real pressure differences (wind + buoyancy) may contain errors. The ζ-values of building leakages deviate to ζ-values of standard orifice in pipes due to the ratio of usual leakage area and room cross-section that approaches zero. Furthermore, leakage flows through building structures under real pressure differences are mainly laminar, in deviation to studies of standard orifice. The investigations show that the discharge coefficient of building leaks is significantly influenced by size, shape and edge properties of a leak. Additionally, leakage edge deformations may influence the ζ-value for PE-foil. Furthermore, caused by poor workmanship, cavities between airtightness and insulation layer may affect the flow through the leakages. In case of PE-foil as air tightness layer, arching of the foil is possible. Depending on the shape of leakage and the applied pressure difference, this may affect the leakage flow in various ways. Only for circular holes were similar volumetric flows for stiffed and deformable foils detected. The theoretical value of $\zeta = 0.61$ for the discharge coefficient (based on shape-independent, stable standard orifices at $N \geq 0.1$) could not be measured for stiffened or deformable foils with single leaks. Furthermore, the discharge coefficient of a single leakage and several leakages with the same properties and the same total cross-section did not match. The obtained results demonstrate that the assumption of only one ζ-value for the whole variety of leakages in the building envelope, e.g. in zone models and for the determination of the equivalent leakage area in differential pressure tests, may be incorrect. The findings of this study can help to optimize simulation models of convective transports through leaks in the building envelope of lightweight timber constructions. However, the study refers only to the leakage flow through perforated air tightness foils. Therefore, the presented measurements should be continued for multi-layered, room boundary layers. It can be assumed that non-negligible factors will be the channel roughness, the material thickness and the propagation behaviour of the air stream in the leak channel.

References

ASTM E1186-03, 2009, Standard Practices for Air Leakage Site Detection in Building Envelopes and Air Barrier Systems.

ASTM E779-10, 2010, Standard Test Method for Determining Air Leakage Rate by Fan Pressurization.

ASHRAE Standards Committee, American National Standards Institute, 2009, ASHRAE Handbook - Fundamentals. Atlanta: ASHRAE Customer Service.

Biskop R., 2008, Bauphysikalische Probleme - Fallbeispiele aus der Praxis des mo-dernen Bauens, 1. Workshop InnoProfile / nuBau, CD, Bauhaus-Universität Weimar (editor), Germany.

Bohl W. & Elmendorf W., 2005, Technische Strömungslehre, Stoffeigenschaften von Flüssigkeiten und Gasen, Hydrostatik, Aerostatik, inkompressible Strömungen, kompressible Strömungen, Strömungsmesstechnik, 13.th ed., Vogel, Würzburg, Germany.

Böhle M., Etling D. et al., 2002, Prandtl - Führer durch die Strömungslehre, Grundlagen und Phänomene, 11th ed., Vieweg, Braunschweig, Germany.

Borda J. C., 1769, Mémoire sur l'Ecoulement des. Fluides par les Orifices des Vases, Mémoires de l'Académie, Royale des Sciences, Paris, France.

Böswirth L., 2007, Technische Strömungslehre: Lehr- und Übungsbuch, 7th ed., Vieweg, Braunschweig, Germany.

Buckingham E., 1931, Beitrag zur Berechnung der Kontraktionszahl, Mitteilung des Bureau of Standards, Washington, Rundschau, Forschungsband, vol. 2., 5th ed., Fritz W. (editor), Berlin, Germany, pp. 185–192.

Christoffer J., Deutschländer Th. et al., 2004, Testreferenzjahre von Deutschland für mittlere und extreme Witterungsverhältnisse TRY, Selbstverl. des Deutschen Wetter-dienstes, Offenbach a. Main, Germany.

de With G., Cherry N. et al., 2009, Journal of Building Physics, Thermal Benefits of tiled roofs with above-sheathing ventilation, vol. 33, 2nd ed., pp. 171–194.

DIN EN 13829, 02/2001, Bestimmung der Luftdurchlässigkeit von Gebäuden, Differenzdruck-verfahren.

DIN EN ISO 5167-2, 01/ 2004, Durchflussmessungen von Fluiden mit Drosselgeräten in voll durchströmten Leitungen mit Kreisquerschnitt-Teil 2: Blenden.

„FLIB" Fachverband Luftdichtheit im Bauwesen e.V. (editor), 2008, Gebäude-Luftdichtheit, vol. 1, Kassel, Germany.

Häupl P., Grunewald J. et al., 1997, International Journal of Heat and Mass Transfer, Coupled heat air and moisture transfer in building structures, vol. 40, 7th ed., pp. 1633–1642.

Künzel H.M., 2010, Holzbau die neue quadriga, Trocknungsreserven schaffen, Ein-fluss des Feuchteeintrags aus Dampfkonvektion, 1st ed., pp. 28–32.

Kurnitski J. & Vuolle M., 2000, Simultaneous calculation of heat, moisture, and air transport in a modular simulation environment, Proceedings of the Estonia Academy of sciences / Eesti Teaduste Akadeemia Toimetised, Engineering / Tehnikateadused, vol. 1, Aben H. & Kurnitski V. (editors), The Academy, Tallinn, Estonia, pp. 25–47.

Langmans J., 2013, Feasibility of exterior air barriers in timber frame constructions, PhD Thesis, KU, Building Physics Section, Leuven, Belgium.

Leick Ph., 2008, Quantitative Untersuchungen zum Einfuss von Düsengeometrie und Gasdichte auf den Primärzerfallsbereich von Dieselsprays, Dissertation, Technischen Universität Darmstadt, Fachbereich Maschinenbau, Germany.

Schmidt J., 2013, Konvektiver Feuchtetransport, Schlussbericht zum InnoProfile Forschungsvorhaben: Methoden und Baustoffe zur nutzerorientierten Bausanierung, Vogel A., Völker C. et al. (editors), Universitätsverlag, Weimar, Germany, pp. 39–41.

Schmidt J. & Kornadt O., 2010a, Verfahren und Untersuchungsvorrichtung zur Untersuchung eines konvektiven Feuchtetransports in einem Bauwerkelement, Bauhaus-Universität Weimar (applicant), 09.07.2010, publication number: DE102010031141.3.

Schmidt J. & Kornadt O., 2010b, Konvektiver Feuchtetransport durch Bauteilleckagen in Bestandsgebäuden, Nutzerorientierte Bausanierung, vol. 1., 1st ed., Völker C. & Kornadt O. (editors), Universitätsverlag, Weimar, Germany, pp. 109–116.

Schmidt J. & Kornadt O., 2012, Der Bausachverständige, Konvektiver Feuchtetrans-port durch die Gebäudehülle – neuartiges Messsystem zur Klärung relevanter Fra-gen, 4th ed., pp. 29–33.

Schulze H., 2011, Feuchtebedingte Schäden an Wänden, Decken und Dächern in Holzbauart, Schadenfreies Bauen, vol. 5, 2nd ed., Fraunhofer IRB Verlag, Stuttgart, Germany.

Unger J., 1979, Forschung im Ingenieurwesen, Strömungen in zylindrischen Kanälen mit Versperrung bei hoher Reynolds-Zahl, vol. 45, 3rd ed., pp. 69–80.

Zirkelbach D., 2009, Dampfkonvektion wird berechenbar-Instationäres Modell zur Berücksichtigung von konvektivem Feuchteeintrag bei der Simulation von Leichtbaukonstruktionen, 4th International Symposium on Building and Ductwork Air tightness, Berlin, Germany, pp. 1–8. www.hoki.ibp.fhg.de, last call 19.01.2012.