Non-Isothermal Moisture Transfer in Porous Building Materials

Andreas Holm
Hartwig M. Künzel

Fraunhofer-Institut for Building Physics, Holzkirchen, Germany
(Director: Prof. Dr. Dr. h.c. mult. Dr. E.h. mult. Karl Gertis)

1. Introduction

In civil engineering there is an increasing demand for calculation methods to assess the moisture behaviour of building materials and components. Current tasks, such as preserving historical buildings are closely related to the moisture conditions in a building structure. In this context, questions regarding moisture behaviour and the related transport processes occurring under natural climatic conditions as well as the risks thus involved always occur. These questions can either be answered with the help of experiments or by numerical simulations. In view of the fact that experiments are often time-consuming and, in some cases, meteorologically both problematic and expensive, intensive work has been done over the past few years on the development of mathematical approaches and procedures to evaluate real thermal and moisture transfer processes. This paper gives a short summary of the physical fundamentals and shows that calculations performed with different validated computer programs will lead to adequate results. Finally some limitations of the models and possible future developments are shown.

2. Calculation model for the coupled heat and moisture transfer

In the last decades several theories have been developed, mostly based on fluid mechanics using the laws of mass (Fick and Darcy) and heat (Fourier) diffusion. Considering the calculation techniques of the past, the most common approaches used the water content and the temperature as driving potentials for moisture transfer (e.g. [1, 2]). Since neither of these potentials is a physical driving force for vapour or liquid transport – the water content is not even a continuous potential – the calculation models based upon them appear to be outdated. More advanced models, like [3, 4], used the moisture potential as driving force, but the required material data are difficult to determine.

An enquiry on calculation models in ref. [5] shows that while temperature is the only potential used for heat transfer, there is a great choice of possible potentials for moisture transport. It has been indicated in the introduction that potentials which are not physical driving forces, or which are not continuous in a multilayer building component are considered to be not appropriate for the modelling task. Of course, formulations using different potentials can be mathematically identical, but the derivation of the transport equations to fit into a model, using for example water content and temperature as potentials, entails among other problems latent numerical errors, which has been demonstrated in ref. [6]. In order to facilitate plausibility checks the driving potentials should be widely known quantities which are easily measurable.

The current state-of-the-art of the physical description is that moisture can migrate in porous materials either as vapour or liquid. The transport mechanism for vapour is molecular diffusion or effusion. In building practice temperature and total pressure induced diffusion are generally negligible. Thus the only relevant driving force for vapour diffusion is the vapour pressure gradient. Liquid transport takes place by surface diffusion or capillary flow. Surface diffusion in the absorbed water layer in the hygroscopic moisture range and capillary flow becomes important when the material gets into contact with water. The liquid driving force is in both cases the capillary pressure which can be related to the relative humidity. Due to the limited scope of this paper, the fundamentals are not described here in a more detailed way. A description of the transport and storage mechanisms can be found in [6, 10].

In recent years a rigorous simplification process of the numerical models validated by laboratory and field experimentation has led to very powerful and sufficiently accurate one- and two-dimensional simulation tools which have already gained a lot of attention from practitioners. In present models like [6, 7, 8, 9, 10] the relative humidity (respectively the corresponding capillary pressure) serve as driving force for the vapour and liquid transport. Here the required material data are easy to measure. Normally theses are: dry density, porosity, heat capacity, dry thermal conductivity and its moisture dependence (usually linear relationship), dry vapour diffusion resistance number as well as water retention function and liquid diffusivities for hygroscopic, respectively, capillary active materials.

Figure 1 shows the typical architecture of a program for calculating the heat and moisture transport. With the necessary input data the model calculates the resulting temperature and moisture fields and the corresponding heat and moisture fluxes. For these data additional post processing tools will be available that further analyze and process the hygrothermal performance results of the investigated construction. These modules are an energy module, a mould growth module, a damage assessment module, a corrosion module and an indoor air quality module.

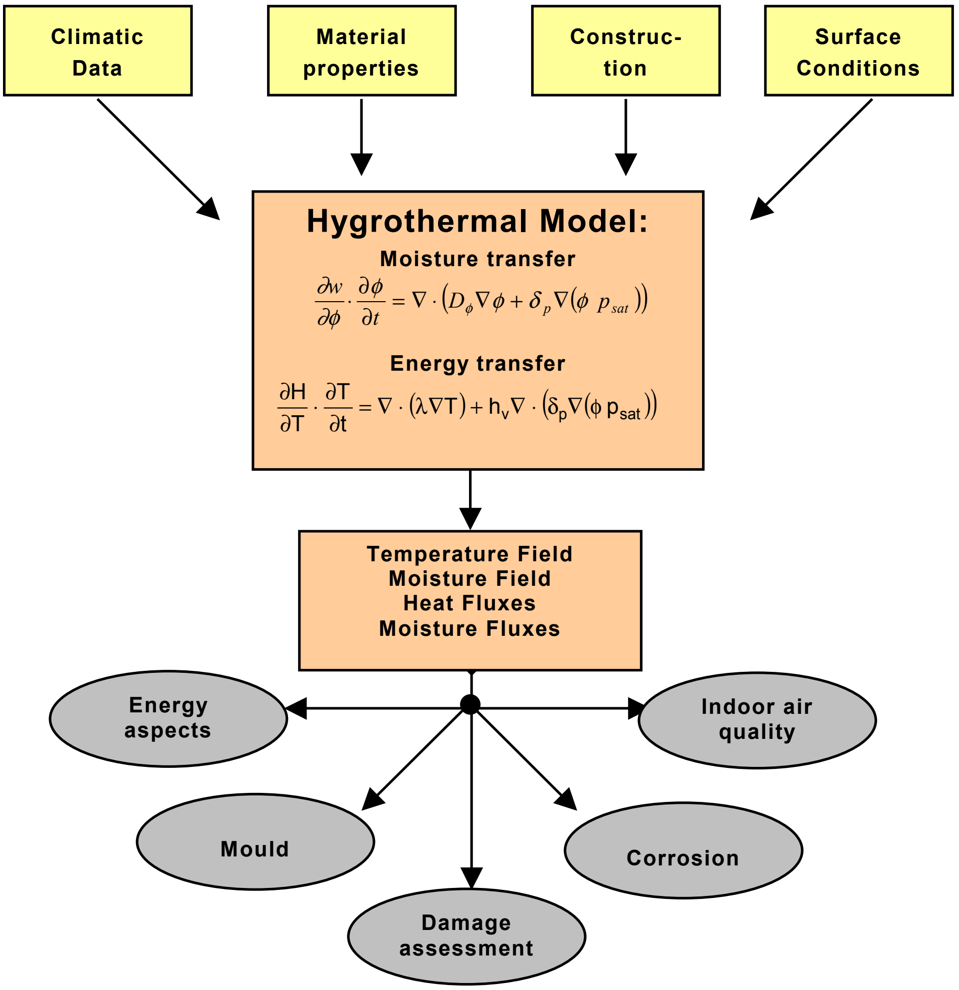

Figure 1: Typical software architecture and possible post-process moduls

3. Limitations

Any model has its share of limitations, requires a certain skill level and the user must be aware of what the model can do and cannot do. The models have been validated for several building materials and compounds. All these validations run well as long as the used materials show “normal behaviour”. If chemical interactions like carbonisation, salt transport phenomena, swelling or shrinkage processes are present, the models might fail. Thatmeans, that the results must be checked for plausibility. There are numerous circumstances that can degrade the quality of a calculation or even render it worthless.

Some materials do not lend themselves to the simplified transport equations. Wood and concrete may change their material properties as a function of their present and past moisture content. The consequences of this may be negligible or serious - depending on the component assembly and the boundary conditions. Only a comparison with samples exposed to natural weather can show whether the calculation results are reliable or not. As an example Figure 2 shows the course of the average water content over the entire thickness for a west-orientated concrete facade exposed to natural conditions. A comparison of calculated and measure results over a period of 6 months after commencement of weathering in Holzkirchen open-air site shows a good agreement. The measurements and the calculations, which coincide relatively well, show a rise in the moisture content of the building component due to driving rain interrupted by brief drying periods. The bottom section of Figure 2 shows the moisture profiles occurring in the facade prisms at two different times during the initial moisture-absorption phase. Here, too, there is a good correspondence of measurements and calculations.

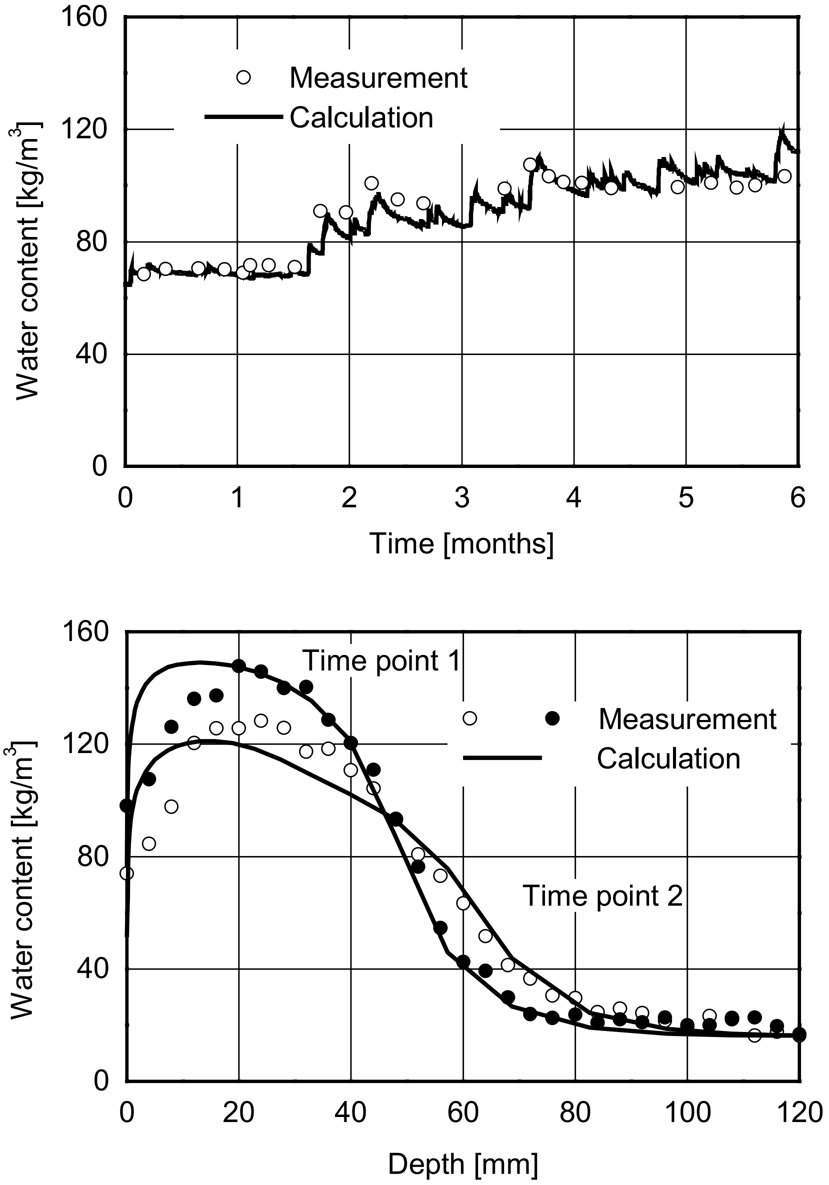

Fig. 2 Measured and calculated water contents of a sample weathered on one side over the first six months of the observation period.
Top: Measured and calculated moisture course.
Bottom: Measured and calculated moisture profiles.

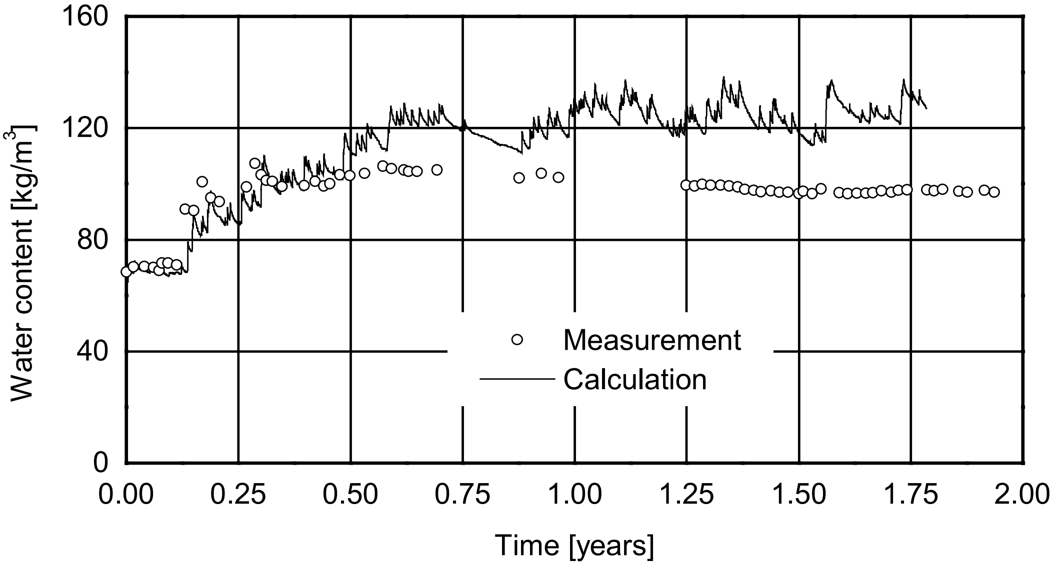

Fig. 3 Measured and calculated moisture course over the entire 2-year observation period.

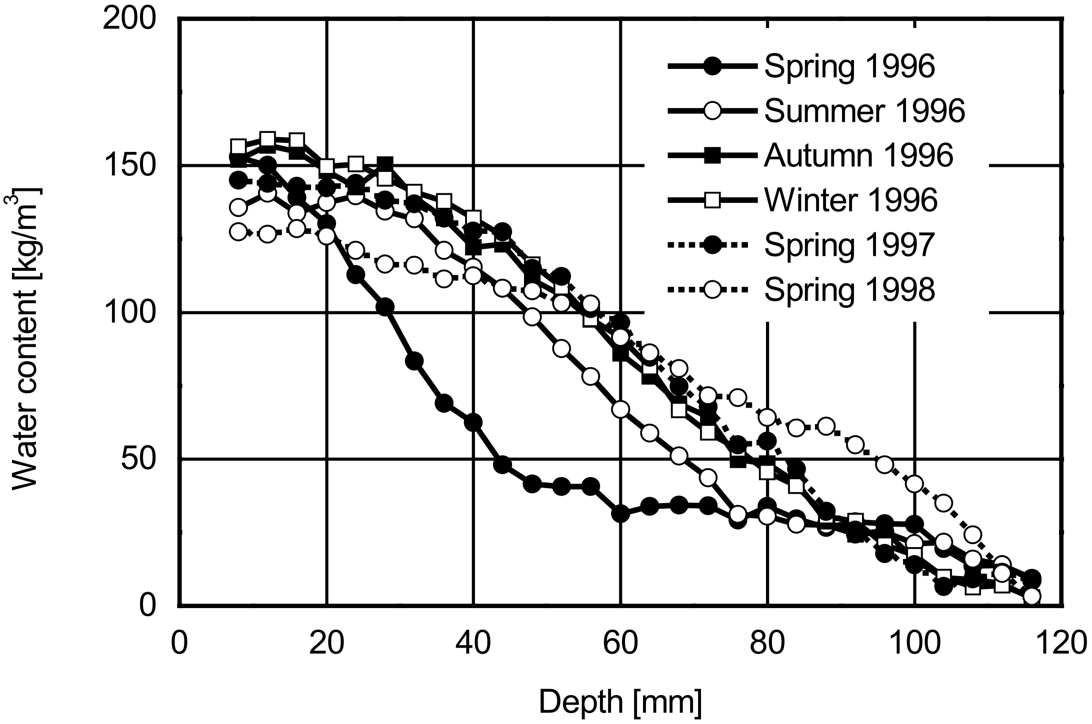

Fig. 4 Moisture profiles measured with the help of NMR at various times during the entire observation period.

However, if observation is continued beyond the first 6 months, calculation and measuresment begin to deviate as shown in Figure 3 for the entire 2-year period. One striking feature is the behaviour of the concrete facade sample after approx. 6 months, which, seems to become inert. The average water content measured scarcely alters whatever the external conditions are, remaining constant at approx. 100 kg/m³. The calculated course in contrast continues to rise. A similar behaviour is observable in the moisture profiles. The profiles at various points of time during the entire observation period are depicted in Figure 4. Here an apparent "freeze" of the moisture distribution can be seen. A similar behaviour is also observable in the case of other types of concrete.

For further clarification of this “unnormal” behaviour, the capillary water-absorption behaviour is measured across the weathered surface of one of the field-weathered samples with an "apparently" unchangeable moisture front. The development of the moisture profiles obtained with the help of the NMR equipment is presented in Fig. 5. The specimen of concrete fills with water slowly, the moisture front does not, however, continue to wander further into the interior of the sample. After over 450 hours, only approx. the first 50 mm of the sample are saturated, after which the concrete has "sealed" itself. If the same experiment is subsequently carried out across the back of the same sample, one would expect that no further moisture enrichment would be possible at the same point where water was absorbed on the front. The moisture profiles measured (Fig. 6) show, however, that even after only approx. 50 hours the sample is almost completely penetrated with moisture. Here the unnormal behaviour of concrete is obvious. Existing heat- and moisture transport models do not include this effects. In this case the obtained results have to be treated with caution.

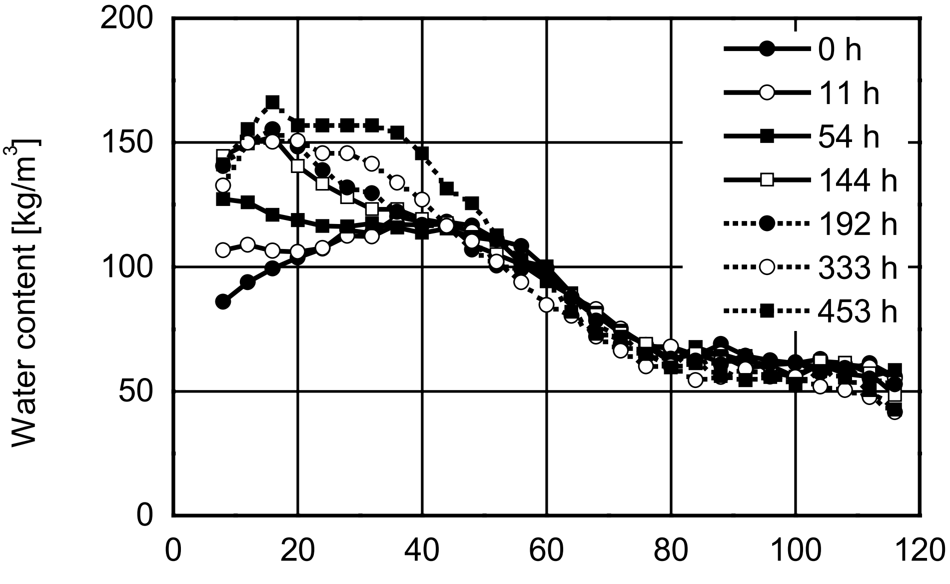

Fig. 5 Development of moisture profiles for capillary water intake via the weathered surface of a concrete sample following a two-year weathering period.

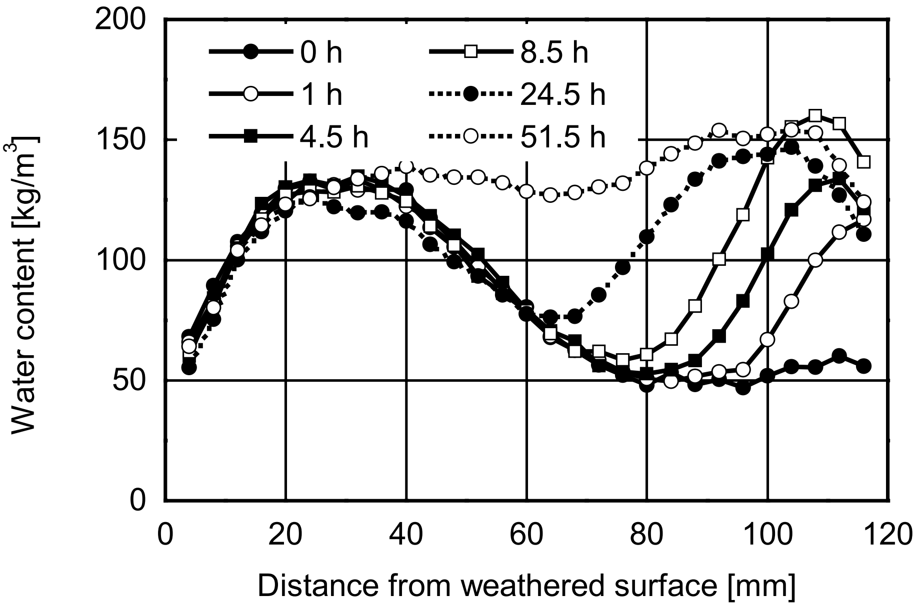

Fig. 6 Development of moisture profiles for capillary water intake through the back of the concrete prism in Fig. 5.

This example shows, that up to now the current models are limited to the “normal” behaviour in capillary water absorption. The deviation from that behaviour in the example of a concert facade could be explained in terms of swelling processes. The capillary pores, very small in any case, are made smaller by swelling so that water absorption is impeded. This is also indicated by experiments of water and hexane absorption of hardened cement paste [12]. The hexane is sucked up in accordance with the √t behaviour, but not the water. Simultaneous measurements of hygric swelling show that the hardened cement paste does not swell when absorbing hexane, by contrast with water.

4. Summary and Future Development

In many cases the detailed knowledge of the hygrothermal performance is not sufficient enough in order to predict the assessment of building materials or building assemblies. The interaction of heat and moisture with the material is often unknown. Here the existing theories require novel approaches. This will be the main focus of the model developers in the future. Three main directions can be observed. First of all it is important to integrate the hygrothermal modeling of single building components into a whole building simulation system. This is necessary because the interaction between indoor climate, user and surface conditions can't be neglected. A parallel development will be the introduction of chemical reactions, ageing functions and salt transport processes into the model. Today some models are available to simulate the coupled salt and moisture transport, but they are still limited to one salt and very simple boundary conditions. But the first steps are done. Another very important development direction will be the implementation of pre- and post processing tools. Here first steps are done by implementing stochastical methods, because the hygrothermal conditions within a construction depend on a large numbers of factors such as outdoor and indoor climate and material properties. Many of these factors are incompletely know or random in nature. This may introduce significant uncertainties in the results. Also first approaches to include damage and probability assessment modules into existing models are done. Figure 1 shows some possible post processing modules planned for the PC-Program WUFI. Especially the prediction of mould and algae growth is desirable [13].

With the new high-speed computers and the easy to uses graphical interfaces the acceptance of these heat and moisture transfer models will increase. Today more and more building component manufactures, engineers, educators, students, architects and other interested in moisture problems are using hygrothermal simulation tools.

5. Literature

[1] Luikov, A.V.: Systems of differential equations of heat and mass transfer in capillary-porous bodies. International Journal of Heat and Mass Transfer (1975), H. 18, S. 1-14.

[2] DeVries, D.A.: Simultaneous transfer of heat and moisture in porous media. Trans. Am. Geophys. Union, 39 (1958), Heft 5, 909-916.

[3] Kiessl, K.: Kapillarer und dampfförmiger Feuchtetransport in mehrschichtigen Bauteilen. Dissertation Universität-Gesamthochschule Essen 1983.

[4] Garrecht, H.: Porenstrukturmodelle für den Feuchtehaushalt von Baustoffen mit und ohne Salzbefrachtung und rechnerische Anwendung auf Mauerwerk. Dissertation Universität Karlsruhe 1992.

[5] Hens, H.: IEA ANNEX 24 - HAMTIE – Final Report, Volume 1, Task 1: Modelling, 1996.

[6] Künzel H.M.: Verfahren zur ein- und zweidimensionalen Berechnung des gekoppelten Wärme- und Feuchtetransports in Bauteilen mit einfachen Kennwerten; Dissertation Universität Stuttgart 1994.

[7] Grunewald, J.: Diffuser und konvektiver Stoff- und Energietransport in kapillarporösen Baustoffen. Dissertation an der TU Dresden 1997.

[8] Burch, D.M., Chi, J.: MOIST – A PC Program for Predicting Heat and Moisture Transfer in Building Envelopes, Release 3.0, NIST Special Publication 917 (1997).

[9] Rode Pedersen C.: Combined Heat and Moisture Transfer in Building Constructions. Dissertation an der Technischen Universität Dänemark 1990.

[10] Bednar, Th.: Beurteilung des feuchte- und wärmetechnischen Verhaltens von Bauteilen und Gebäuden. Weiterentwicklung der Meß- und Rechenverfahren. Dissertation Technische Universität Wien 2000.

[11] Krus, M.: Feuchtetransport- und Speicherkoeffizienten poröser mineralischer Baustoffe. Theoretische Grundlagen und neue Meßtechniken. Dissertation Universität Stuttgart 1995.

[12] Holm, A., Krus, M. und Künzel, H.M.: Grenzen der Feuchtetransportberechnung bei Betonaußenbauteilen. Tagungsband 5. Internationales Kolloquium – Werkstoffwissenschaften und Bauinstandsetzen – MSR '99, Esslingen, S. 405-414.

[13] Sedlbauer, K.; Oswald, D.; König, N.: Schimmelgefahr bei offenen Luftkreisläufen. Vorstellung einer Prognosemethode auf der Basis von Fuzzy-Algorithmen. Gesundheits-Ingenieur, Heft 5 (1998), S. 240 - 247.