Simulation of heat and moisture transfer in construction assemblies

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1. Introduction

Moisture in building components is mostly attributed to diffusion and condensation of indoor air humidity. Practitioners know that the Glaser-method is a steady state design tool to avoid interstitial condensation problems. There are, however, other moisture sources like rain water penetration, rising damp and construction moisture which may affect historic and also new buildings. These phenomena cannot be accurately dealt with by the Glaser-diffusion model because they include liquid transport as well as moisture retention. The same holds for transient effects like summer condensation, freeze and thaw cycles, humidity buffering and heat losses by water evaporation which can cause damage or higher energy consumption. In order to determine the real moisture behavior of building components hygrothermal simulation models have been developed and experimentally validated in recent years. One of the commercially available models widely used in Germany, Eastern Europe and the United States is the PC-program WUFI described in [1].

2. Moisture retention and transport phenomena

The application of hygrothermal simulation tools requires some basic knowledge about material properties. Most building materials are hygroscopic which means that they absorb water vapor from the environment until equilibrium conditions are achieved. This behavior can be described by sorption curves over a humidity range between 0 and ca. 95% R.H.. Because the equilibrium water content is not very sensitive to changes in temperature, these sorption curves are also called sorption isotherms. From 95% R.H. up to the capillary saturation at 100 % R.H. stretches the capillary water range. In this range the equilibrium water content of a material is still a function of relative humidity. However, this function can no longer be determined by sorption tests in climatic chambers. Here, a pressure plate apparatus is necessary in order to complete the sorption curve in the high humidity range. The resulting water retention curve is a prerequisite for simulations including liquid transport. Fig. 1 shows some examples of these curves for typical building materials with different sorption capacities. While wood has a similar moisture capacity in both humidity ranges, clay brick has a very low sorption capacity in the hygroscopic range but a high water retention in the capillary water range. For concrete the opposite is true. These differences have an important effect on the transient moisture behavior of the materials and may not be neglected. The water retention curves in Fig. 1 are based on sorption tests in climatic chambers and pressure plate measurements which extract water from capillary saturated material samples by applying pressure up to 10 Pa [2]. The experimental results of both tests are combined by using Kelvin's equation which links the relative humidity and the capillary pressure. This procedure to derive the water retention curve is shown in Fig. 2 for autoclaved aerated concrete.

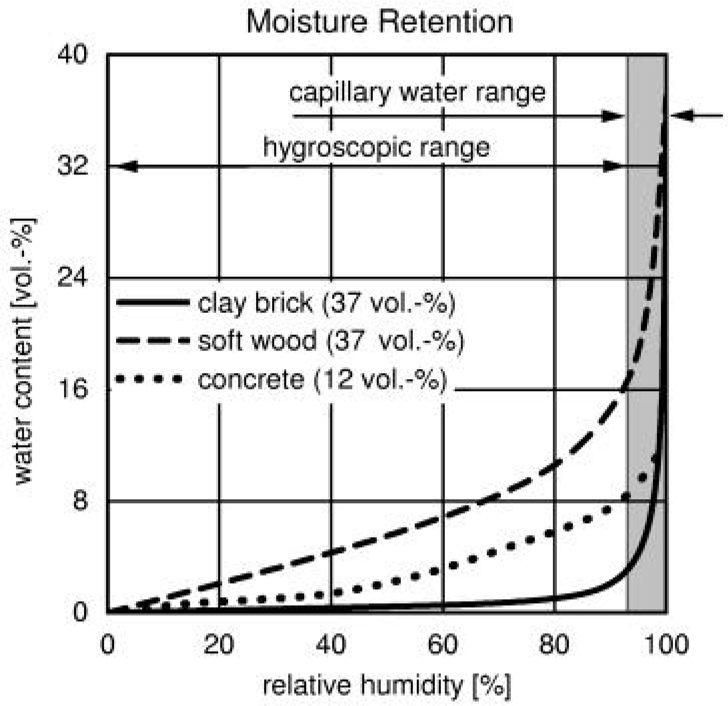

Fig. 1: Moisture retention curve for three typical building materials.

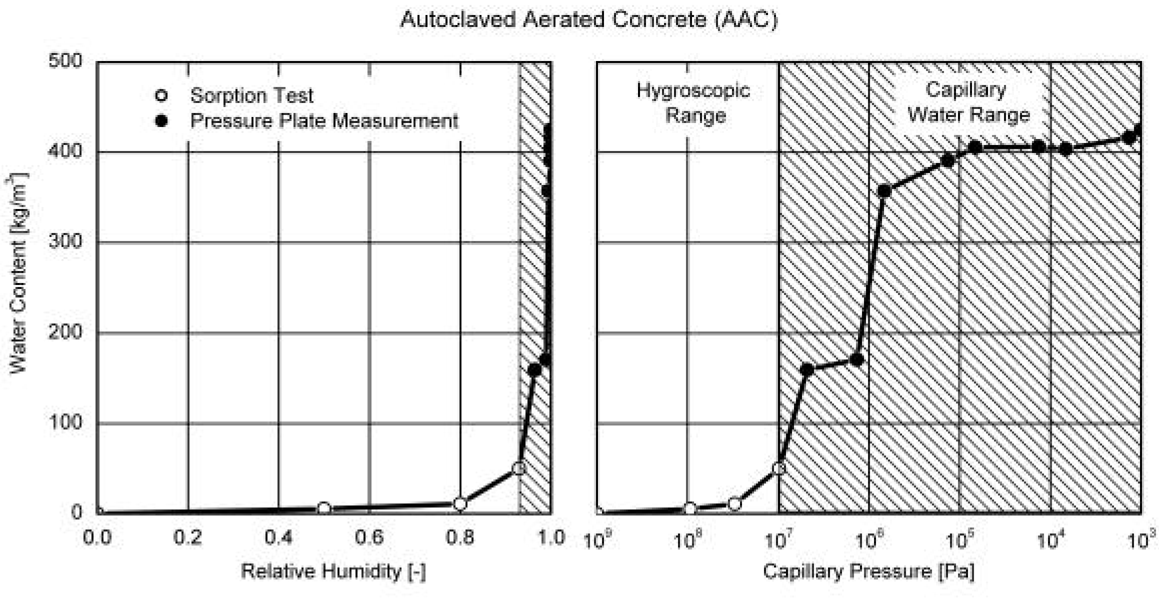

Fig. 2: Measured moisture retention curve for Autoclaved Aerated Concrete (AAC) as a function of the relative humidity (left) and the corresponding capillary pressure (right). The shadowed area represents the part of the capillary water range which is determined with pressure plate apparatus.

The moisture transport in porous materials is largely due to vapor diffusion, surface diffusion and capillary conduction. The coincidence of theses transport phenomena in practice will be explained by Fig. 3. Considered is a capillary in a masonry wall under winter conditions, when the vapor pressure indoors is higher than outdoors and the inverse is true for the relative humidity. In the dry state the vapor is driven outwards by the vapor pressure gradient. However such a dry state rarely exists and there is a layer of absorbed water at the inner surface of the pore. This layer has a higher molecular density (it is ‘thicker’) at the outdoor end compared to the indoor end of the capillary due to the gradient in relative humidity which is opposed to the vapor pressure gradient. By molecular motion in the surface film moisture is thus transported inwards. Vapor and surface diffusion can counterbalance each other to such an extend that the overall moisture transport and therefore also the amount of condensation are considerably reduced. In the case of wet conditions, e.g. after rain penetration, when the pores are filled with water, capillary conduction sets in. This very efficient moisture transport is governed by differences in capillary pressure. Since there is a direct relation between the capillary pressure and the relative humidity (Kelvin’s law) the latter can also be considered as driving force for capillary flow. In homogeneous materials also the water content can be used is driving potential. In this case the liquid transport coefficient which increses almost exponentially with the water content is called the liquid diffusivity D_w. Experience shows that the liquid flow within most building materials is higher during water absorption than during the subsequent drying process. This behaviour can be explained by the counterbalancing capillary forces once the water source is removed from the surface [2]. Thus, the liquid transport is best desribed by two different diffusivities, one for the suction process in contact with water (e.g. from precipitation or rising damp) and one for the drying or moisture redistribution process. These diffusivities can be derived from NMR scanning tests of material samples under transient conditions [2]. The results are depicted for autoclaved aerated concrete in Fig. 4.

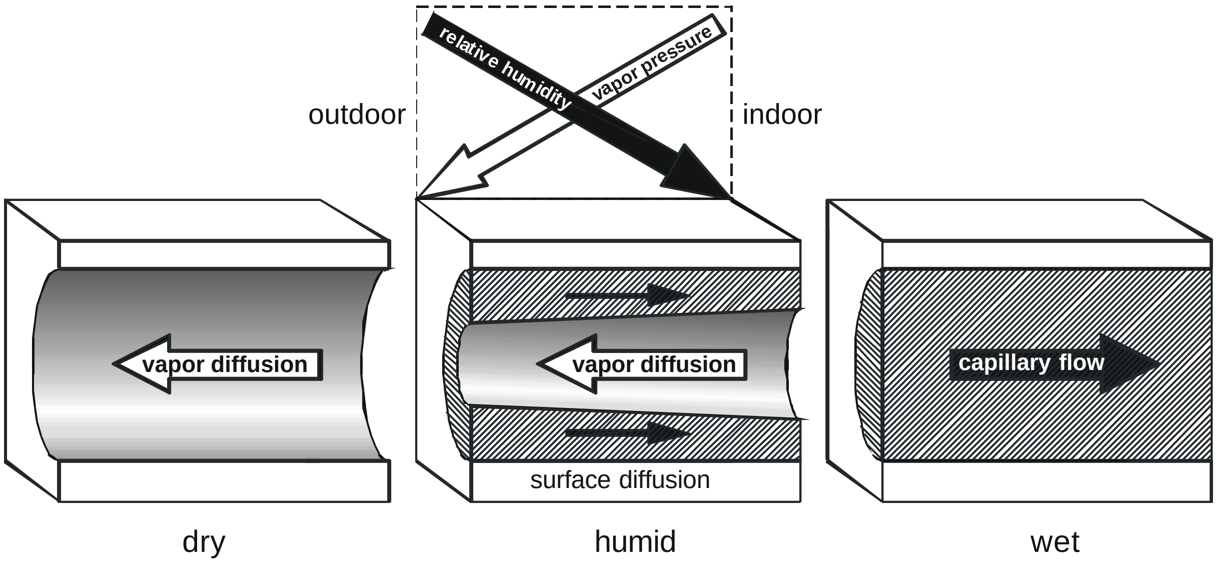

Fig. 3: Schematic diagram of the different moisture transport mechanism inside a porous hygroscopic building materials media with the gradients of vapour pressure and relative humidity running in different directions (winter conditions)

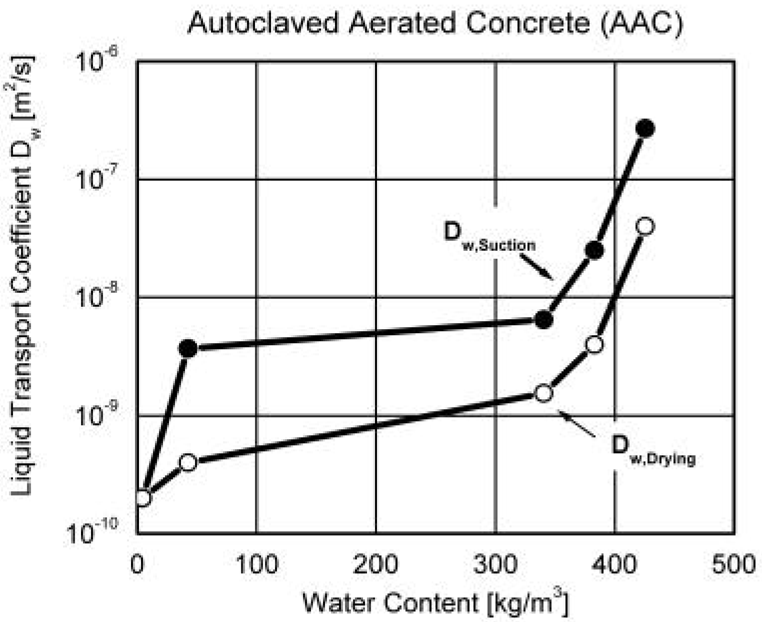

Fig. 4: Liquid transport coefficients for suction and drying of AAC. The values were determined by NMR-scanning.

3. Material properties and boundary conditions

The accuracy of simulation results depends largely on the availability of consistent material properties. The lack of reliable material data has been the main handicap for the large-scale application of modern simulation tools. Therefore a material database is included in WUFI-program. The minimum parameters required for each material are specific heat capacity c, thermal conductivity λ, bulk density ρ, total porosity ε and the vapor diffusion resistance factor μ. If hygroscopicity and capillarity should be accounted for the moisture retention curve (see Fig.1) and the liquid diffusivity functions D_w have to be added.

All building components interact with their hygrothermal environment. This means that the ambient conditions influence the building component and vice versa. This reciprocal influence which is mainly confined to the interior environment may have to be considered for the formulation of the boundary conditions. For most applications an annual sine wave for indoor temperature and humidity is appropriate. The formulation of the exterior climate conditions is more complex. As a minimum monthly mean values of temperature and relative humidity are required. If solar radiation or precipitation should be accounted for, hourly weather data become necessary. Those data, however without precipitation, can be found in the European Test-Reference-Years. A complete data set (including precipitation) for Holzkirchen (a location close to Munich) is delivered with WUFI or may be downloaded from www.wufi.de.

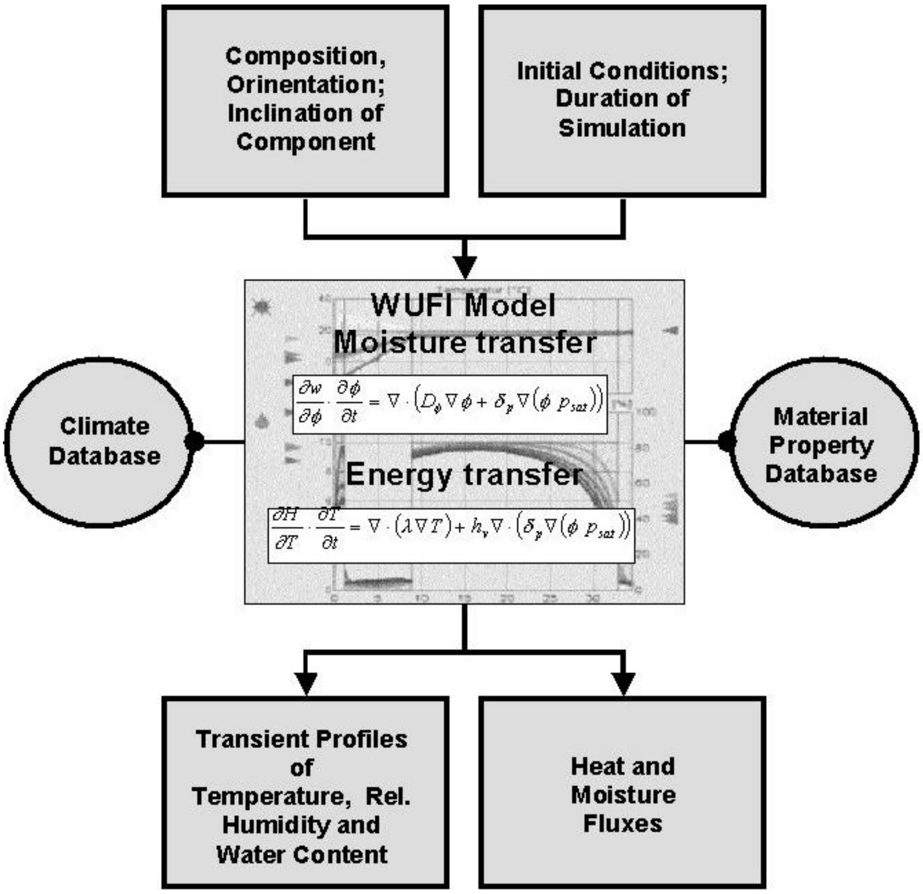

Fig. 5: Flow Chart of WUFI

4. Calculation procedure

The transient calculation procedure of the WUFI model is outlined by the flow chart in Fig. 5. The necessary input data include the composition of the examined building component, its orientation and inclination as well as the initial conditions and the time period of interest. The material parameters and the climate conditions can be selected from the attached database or from other available sources. Starting from the initial temperature and water content distributions in the component, the moisture and energy balance equations have to be solved for all time steps of the calculation period. Both equations contain the storage terms on the left and the transport terms on the right hand side. The moisture balance includes the derivative of the moisture retention curve (l.h.s.), the liquid transport the vapor diffusion which are related to gradients in relative humidity and vapor pressure respectively. The enthalpy of solid and moisture forms the storage of the energy balance. The energy flux consists of the thermal transmittance and the latent heat due to condensation and evaporation of moisture. The coupled transfer equations are solved numerically by an implicit finite volume scheme. The resulting output contains the calculated moisture and temperature distributions and the related fluxes for each time step. The results may be presented as animated moisture and temperature profiles over the cross-section of the building component or as plots of the temporal evolution of the variables.

5. Application and validation

The program was validated with experimental results in many cases. The validation of a numerical model requires reliable experimental investigations with well documented initial and boundary conditions, as well as accurate material properties. The following example meets these criteria moisture behavior of natural stone wall. In order to investigate the hygrothermal behavior and the durability implications of natural stones, sandstone samples were thoroughly examined in the laboratory to obtain reliable material parameters for the numerical simulations. Afterwards the samples were dried and exposed to the natural climate in a field test. During this test the exact climate conditions were recorded and the moisture behavior of the samples was determined by NMR-profile measurements. The material parameters and the recorded weather data (hourly values of indoor and outdoor temperature, relative humidity, driving rain and solar radiation) served as input for the calculations. Fig. 6 depicts the measured and the calculated course of the total water content after exposition of the initially dry wall samples moisture and moisture profiles for different times of exposure. The excellent agreement proves the practical suitability of the WUFI-simulations.

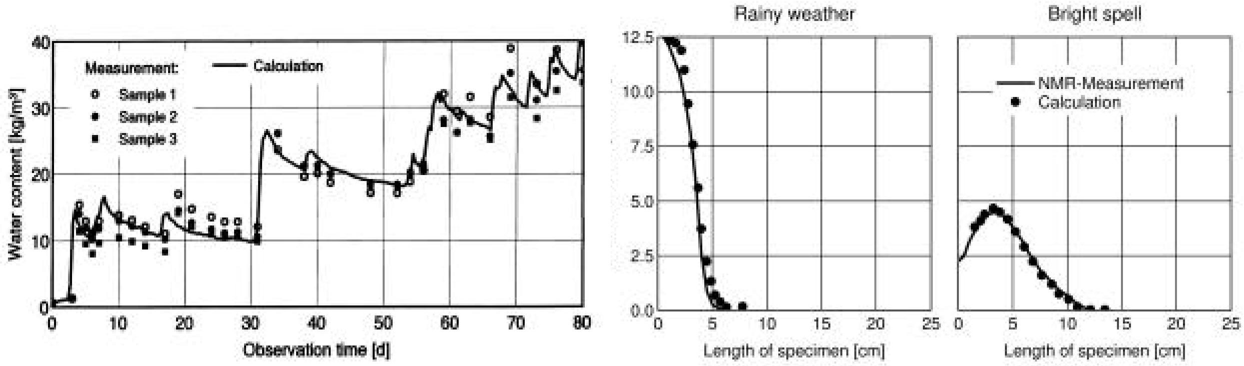

Fig 6: Comparison between measurement and WUFI-calculations.
Left: Time curves of the water content of a natural stone masonry, western exposure
Right: Moisture profiles at two significant time points

As an example for a two-dimensional calculation figure 7 shows the moisture distribution in the vicinity of a mortar joint between two differently orientated anisotropic sand stones (layer structure results in directionally depending water absorption) of an exposed masonry wall. The results show the rapid water absorption of the mortar during driving rain impact. This is due to the higher porosity of the mortar compared to the sand stone which facilitates the water infiltration but also the drying by vapor diffusion. Therefore the mortar dries faster than the adjacent stone which retains moisture spots at its flanks even after long periods without rain. It is exactly at these locations that frost or salt induced damage is observed in practice. The profiles also show that the exterior surface dries fast after a rainfall leaving the highest water content in a region some centimeters beneath. In many heritage buildings this region is often more damaged than the surface layer, resulting in the typical spalling effect of the surface crust. The degradation of natural sandstone is mainly due to moisture related weathering or damage processes. Therefore facades are often treated with water repellent or reinforcing chemicals which may not always be beneficial. Such a treatment not only reduces the water absorption but also the drying rate.

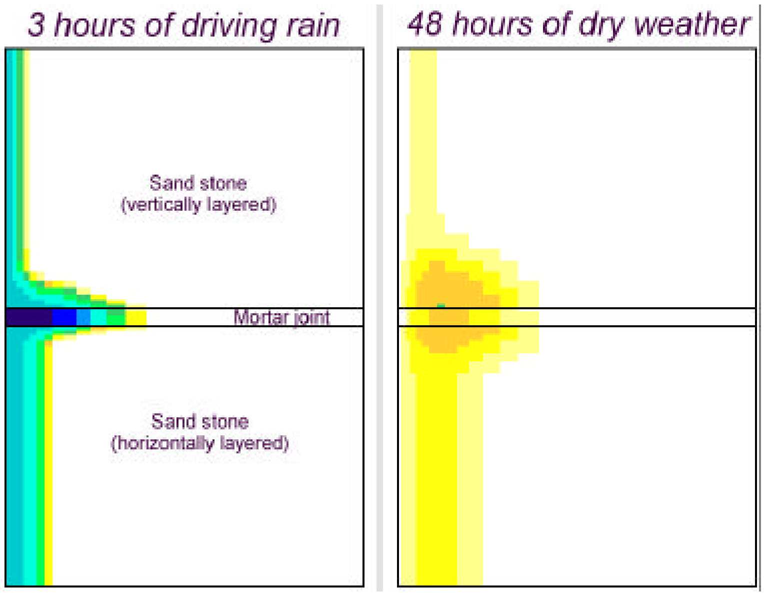

Fig 7: Moisture distribution in the vicinity of a mortar joint between two differently orientated anisotropic sand stones (layer structure results in directionally depending water absorption) of an exposed masonry wall.

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6. Conclusions

The deficiencies of the Glaser-method and the advantages of hygrothermal simulations has been recognized by the CEN committee TC 89. Therefore a new task group was formed in order to overcome the lack of official guidelines for modern simulation tools. Since many manufactures are prepared to have their products tested more thoroughly in order to provide the necessary material data a more wide-spread application of hygrothermal simulations will be feasible in future. In order to convince an increasing number of practitioners to use simulation tools, the user-interface has to become simple and foolproof. This has been the emphasis for the development of the third version of WUFI which is available since November 2000 (Demo and further information www.wufi.de).

The simulation results help to understand the hygrothermal processes in building assemblies. However, the interpretation of the results requires practical experience. In order to quantify moisture related effects, such as mold or algae growth, corrosion, frost or salt damage post-process models have to be developed which derive the damage probability from the hygrothermal simulation results.

7. References

[1] Künzel, H.M.: Simultaneous Heat and Moisture Transport in Building Components; one- and two-dimensional calculation using simple parameters. IRB-Verlag, Stuttgart 1995, ISBN 3-8167-4103-7.

[2] Krus, M.: Moisture Transport and Storage Coefficient of Porous Mineral Building Materials; theoretical principles and new test methods. IRB-Verlag, Stuttgart 1996, ISBN 3-8167-4535-0