Uncertainty Approaches for Hygrothermal Building Simulations—Drying of AAC in Hot and Humid Climates

Andreas H. Holm

Hartwig M. Kuenzel
Member ASHRAE

Jan Radon

ABSTRACT

This paper presents approximation techniques that allow estimation of the moisture retention curve and capillary transport coefficients needed for computer calculations of the hygrothermal behavior of building components.

INTRODUCTION

In Europe, prefabricated building flat roofs are often made out of an autoclaved aerated concrete (AAC). However, elements of AAC often have a very high construction moisture content. Values around 20 vol % are quite normal. Under moderate Central European climates, those roof elements have almost reached hygrothermal equilibrium after two years, and moisture-related failures, such as mold growth, are normally unknown. During previous years, several European manufacturers have tried to open their markets and have introduced European building technology to North America. Unfortunately, under hot and humid climates, such as in Florida, severe damage was observed. In order to find out whether an unvented flat roof of AAC works, field tests or computational simulations can be made. Experimental investigations are expensive and of limited transferability. An alternative is the use of validated models to assess the hygrothermal behavior. The main advantage of modeling is that if the building envelope system has been carefully characterized, modeling can predict the long-term hygrothermal performance of the system under different climatic conditions, the effect of changes in the interior conditions (HVAC), and the effect of various energy retrofits on building durability (hygrothermal performance). Moisture load tolerances of various envelope designs can also be investigated with respect to the drying potential and the total system effect on various design alternatives by use of modeling.

Until now, the uncertainty of input data was left out of hygrothermal modeling because the understanding of the individual physical processes and their impact on the component assembly was the first priority. In the following work, the necessary input data for hygrothermal calculations are described with a specific uncertainty, and its influence on the calculation results is considered.

The uncertainty approach for the hygrothermal component was carried out with the help of a sensitivity analysis. With this technique, one can study how sensitive is the solution of a problem based on the data confidence input and its reaction to a single parameter of uncertainty.

NUMERICAL APPROACH

This paper considers the hygrothermal behavior of a 100 m² dwelling, 2.5 m high, with a 20-cm-thick AAC flat roof. First, the drying-out potential of a 200-mm-thick AAC flat roof with built-in moisture under natural climatic conditions is studied. The roof is sealed from outside with a vapor-tight bituminous membrane. On the interior surface, a gypsum plaster with an s_d value of 0.1 m is applied. Hourly weather data measured for a typical year in Miami (USA) represent the climatic conditions for a hot and humid climate. The room climate was set at a constant 25°C with 65% relative humidity. The heat transfer coefficient at the external surface is 17 W/m^{2}K, and it is 8 W/m^{2}K on the inside. The shortwave absorption coefficient of the bituminous felt is 0.6. Rainwater absorption is neglected. The starting point is the beginning of

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Andreas H. Holm is senior hygrothermal group manager and **Hartwig M. Kuenzel** is research director at Fraunhofer Institute for Building Physics, Holzkirchen, Germany. **Jan Radon** is a senior researcher at the University of Krakow, Poland.

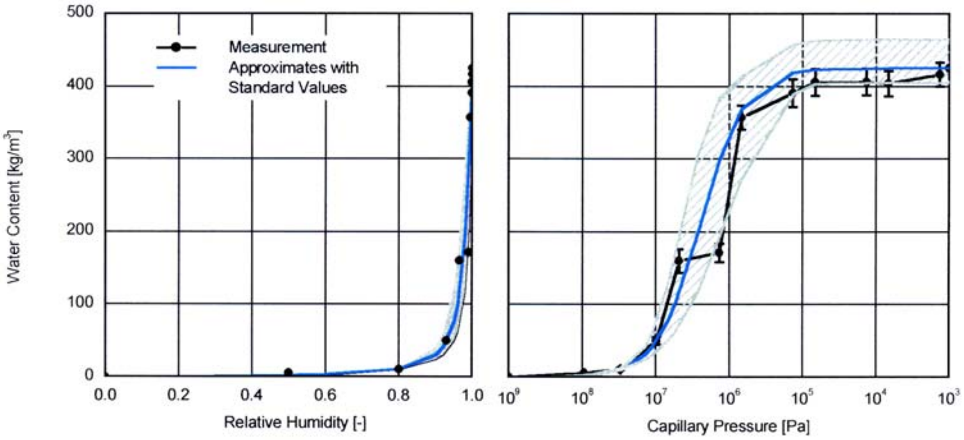

Figure 1 *Measured and approximated moisture storage function for the AAC (density 600 kg/m^3) as function of the relative humidity (left) and the capillary pressure (right). The measured values, including the observed derivation determined by vapor absorption experiments and pressure plate measurements, are shown as dots. The shadowed area in both graphs represents the possible range of the approximated moisture storage function given by the uncertainty of the material parameters as shown in Table 1.*

TABLE 1
List of Hygrothermal Material Properties

Hygrothermal Material Properties for the AAC	Default Values	Standard deviation
Bulk density (kg/m^3)	600	5 %
Heat capacity (kJ/kgK)	0.85	5 %
Heat conductivity (W/mK)	0,14	5 %
Moisture-related supplement (%/M %)	3.7	5 %
Water content at RH of 80% (±2 %) (vol %)	1.07	10 %
Water content at RH of 93% (±2 %) (vol %)	5.0	10 %
Free saturation (vol %)	42.5	10 %
Porosity (vol %)	72.0	5 %
Vapor diffusion value	8.3	15 %
A-value (kg/m^2/√s)	0.094	20 %
$D_{w,\ Surface\ Diffusion}$ at RH of 71.5 % (±10 %) (m^2/s)	2.0e-10	10 %
$D_{w,\ Suction}$ at free saturation (m^2/s)	1.6e-7	10 %
$D_{w,\ Suction}$/$D_{w,\ Drying}$	3	30 %

April with an initial moisture content of 20 vol % in the roof element.

The study was carried out in two steps. During the first step, both single and multiple differential sensitivity analysis methods were used. Both types of analysis of the input data were included in the computer program WUFI, which allows the calculation of transient one-dimensional heat and moisture transport in building assemblies (Künzel 1994; Holm). WUFI has repeatedly been validated by comparison with experimental data. The aim of this step was to find the set of material parameters that allows the fastest and the slowest drying. These two critical data sets were then used in the second step. Within this step, the transient moisture and temperature conditions inside a dwelling were calculated with the new hygrothermal building simulation tool called WUFI-Plus (Radon et al.). These results also give information on the energy consumption needed for keeping a constant and comfortable climate.

SENSITIVITY ANALYSIS OF THE MATERIAL PROPERTIES

The aim of the first step is to find the set of material parameters that allows the fastest and the slowest drying. The technique applied in this case is the differential sensitivity analysis. Therefore, a base case simulation is needed in which the input parameters are set to the best estimates of the parameters under consideration. Then the simulation is repeated with one input parameter changed from P to P + ΔP and from P to P – ΔP, respectively, and the effect on the amount of dried-out moisture after one year noted. This is done for each material parameter of Table 1, which, in turn, gives a total of 32 simulations. The hygrothermal behavior is simulated over a period of one year. As a criterion for the influence of the different input parameters, the amount of dried-out moisture after one year is chosen.

The hygrothermal material parameters required for AAC, including their observed standard derivation, are listed in Table 1. The moisture retention curve and the liquid transport coefficients were approximated and used for the sensitivity analysis of the material input data. A detailed description of the determination of the liquid transport coefficients and the moisture retention curve from simple material properties can be found in Holm (2001). Figure 1 shows both the measured and approximated moisture storage function for the AAC as function of the relative humidity (left) and the capillary pressure (right). The measured values, including the observed derivation determined by vapor absorption experiments and pressure plate measurements, are shown as dots. The shadowed area in both graphs represents the possible range of the approximated moisture storage function given by the uncertainty of the material parameters as shown in Table 1.

For transient calculations of moisture behavior, the liquid transport has a particular influence on the moisture behavior of envelopes, especially if built-in moisture wants to dry out. The drying process is a superposition of liquid transport and vapor diffusion. The correct determination of the transport coefficients for liquid transport is thus of decisive importance. As discussed in Künzel (1994), a distinction must be made between wetting and drying (i.e., these two boundary conditions produce different liquid transport coefficients). The determination of these transport coefficients, which are highly dependent on water content, is made possible by the measurement of water-content profiles in the building material using a special apparatus. Such precise but time-consuming and cost-intensive determination is, however, often not always available for a practitioner. For this reason, the corresponding moisture transport coefficients are approximated according to Holm and Krus (1998, 1999). They are obtained from basic hygric parameters already known for most building materials or from simple additional experiments. With uncertainty of the material parameters as shown in Table 1, the liquid transport coefficients for both suction and drying approximated from these values also have a certain confidence range, which is shown in Figure 2. The shadowed range represents the envelope of all possible approximated coefficients. For the following sensitivity analysis, the described approximated material properties with observed uncertainty were used.

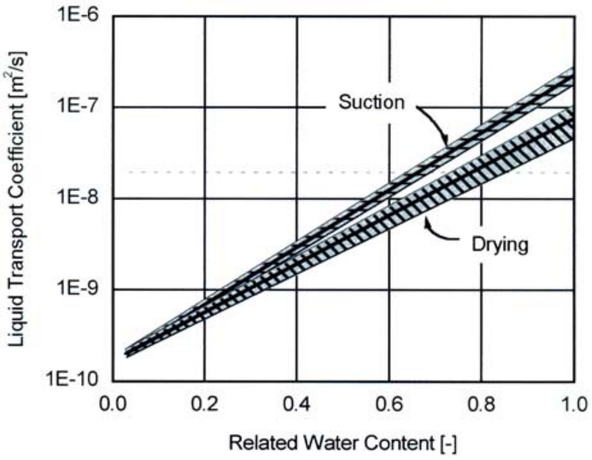

Figure 2 *With uncertainty of the material parameters as shown in Table 1, the shadowed area represents the possible range of the approximated liquid transport coefficients for suction and drying.*

Figure 3 shows the course in time of the water content for the examined variants of the AAC flat roof under hot and humid conditions. The hatched area represents the envelope of the 32 resulting variations. The thick dashed line is the corresponding average course in time of the sensitivity analysis. It can be concluded that within one year, the AAC has lost most of its construction moisture and is reaching its hygroscopic

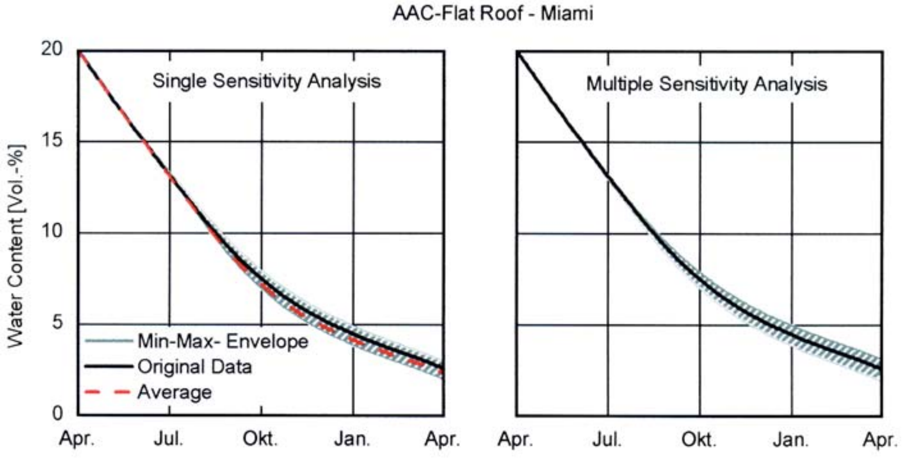

Figure 3 *Material sensitivity analysis for the transient drying-out behavior of the AAC flat roof under typical climatic conditions for Holzkirchen.*
Left: Each material parameter was changed from P *to* P + ΔP *and* from P *to* P – ΔP, *respectively, giving a total of 32 simulations.*
Right: Each material parameter was changed from P *to* P + ΔP *and from* P *to* P – ΔP, *respectively.*

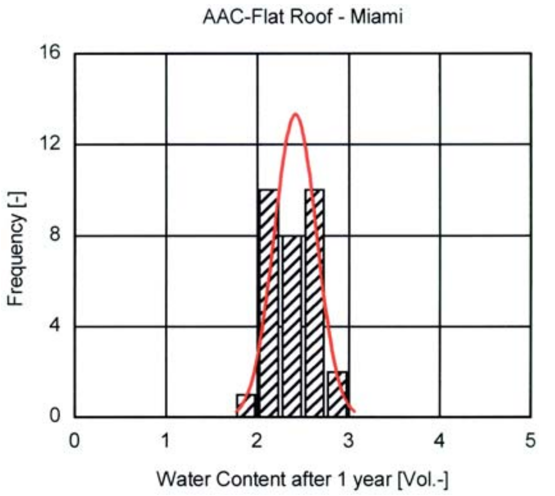

Figure 4 *Frequency distribution of the change of water content since the beginning after the first year (interval width: 0.5 kg/m^3).*

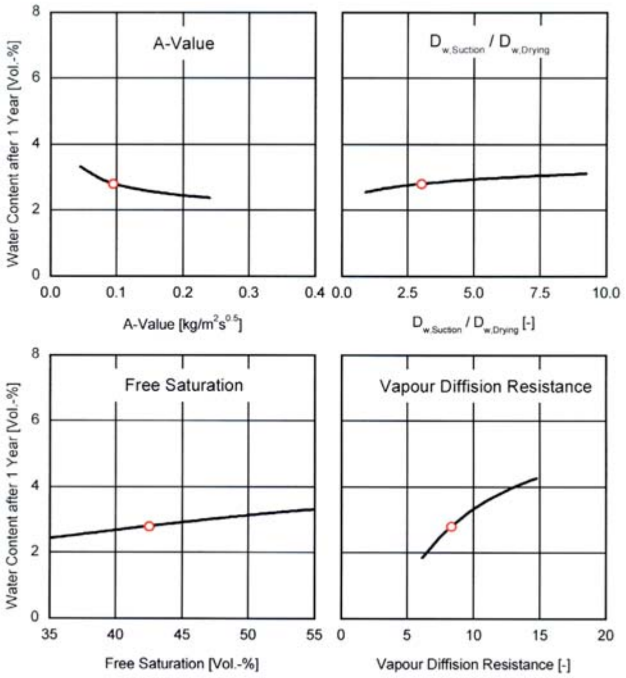

Figure 5 *Differential sensitive analysis for the AAC roof.*

equilibrium. This is nearly two-and-a-half times faster than in moderate climates, such as New York or Central Europe (Krus 1996).

In order to emphasize the influence of the different material properties, the frequency distribution of the change of water content since the beginning is plotted in Figure 4. After the first year, the average moisture content was reduced from the initial 20 vol % to 2.4 vol %, with a variation of ±0.2 vol %. The main influence is given by the A-value, vapor diffusion resistance, and the free saturation. All other parameters, such as density, porosity, and heat conductivity, have a minor effect on the result.

For the A-value capillary saturation factor between the two liquid transport coefficients and the vapor diffusion resistance, a singe sensitivity analysis for both climates was performed. For each calculation, only the studied material parameter was changed step-by-step in a possible range of ±50% of its original value (the observed deviations are shown in Table 1). The results show that in the range of typical expected measurement uncertainty, the maximum resulting error in the simulation is about 5% to 10%. For hot and humid climates, the influence of the vapor diffusion resistance variations has to be considered. Other studies showed, on the other hand, that for a central moderate climate situation, its variation could be neglected (Holm 2001).

HYGROTHERMAL SIMULATION

The results from the one-dimensional sensitivity analysis are now used in the second stage of these investigations. Both extreme data sets for the drying behavior of an AAC element serve as input for a new hygrothermal building simulation tool called WUFI-Plus. The results give information on the required energy consumption for keeping comfortable climatic conditions. The software takes into account the main hygrothermal effects, such as moisture sources and sinks inside a room, moisture input from the envelope due to capillary action, diffusion and vapor absorption/desorption as a response to the exterior and interior climatic conditions, heat source and sinks inside the room, heat input from the envelope, the solar energy input through walls and windows, and hygrothermal sources and sinks due to natural or mechanical ventilation.

Here, the necessary dehumidification rate and the heating/cooling rate of a 100 m², 2.5-m-high dwelling with a 20-cm-thick AAC flat roof and 20-cm-thick AAC wall elements was studied during a period of one year. The roof is sealed from outside with a vapor-tight bituminous membrane, and a lime cement plaster is applied at the facades. On the interior surface, a gypsum plaster is applied. On the south-orientated facade, windows with a total area of 8 m^2 and all other orientations with 5 m^2 each are integrated. It is assumed that the room is occupied from 8 a.m. to 7 p.m. During this time, the minimum temperature allowed is 20°C (otherwise 16ºC), the moisture production rate in the room is 0.5 kg/h, and the internal sources are 2 kW. The comfortable range for the interior RH lies between 40% and 60%. The maximum temperature allowed is 25°C. The results are compared for a dwelling with and without construction moisture.

Figure 6 shows the resulting dehumidification rate for both cases. In order to smooth the results, only 24-hour averages are plotted in this graph. Due to the very high construction moisture content (20 vol %) of the AAC elements, the dehumidification rate during the first ten months is nearly twice as high as in the case without construction moisture. The corresponding cooling load is shown in the same picture at the bottom. The difference between both cases is not as pronounced. The cooling rate is mainly influenced by the exterior conditions. The influence of construction moisture is marginal. Only during the first two months is the cooling rate lower for the dwelling with construction moisture.

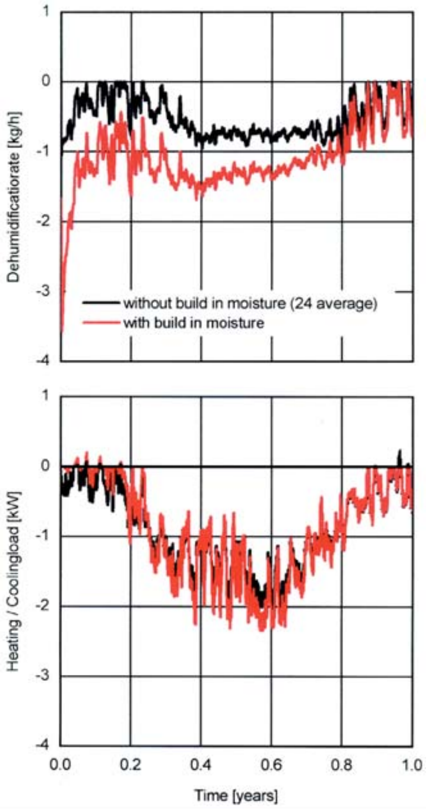

Figure 6 *Dehumidification rate and heating res. cooling rate (24-hour averages) for the dwelling during the first year.*

The different material parameters chosen for the AAC have only a small influence on the total amount of energy needed for cooling (see Table 2). The difference is less then 2%. For the first year, an average of 7900 kWh is needed for cooling if construction moisture is taken into account. This is about 5% less than in a later stage of the service life of a building (dry construction). This can be explained by the effect of surface cooling due to evaporation during the drying of the AAC elements. On the other hand, the construction moisture leads to an annual dehumidification rate of about 9250 kg water, which is nearly twice as high as in the dry case. The consequences are that if the HVAC system is only designed for the "dry" state of the dwelling, the surplus moisture during the first years can cause problems.

RESULTS AND CONCLUSIONS

Computer calculations are of increasing importance for assessing the hygrothermal behavior of building components since modern calculation methods achieve good agreement with measurements. A broader application of these methods is hampered, however, by the laborious measurements needed to determine the moisture retention curve and the capillary transport coefficients essential for the calculations. The approximation techniques presented, which allow estimating these material parameters from basic and often well-known parameters (free capillary saturation, practical moisture content, and water absorption coefficient), show only moderate and acceptable deviations from reality. By using these methods, the hygrothermal behavior of building components can be treated not only in a deterministic way. The very important stochastic approach is almost impossible without these approximation methods. An important technique to evaluate these influences from the input uncertainties is a combination of single and multiple differential sensitivity analysis. This was shown here with the example of the drying behavior of an AAC flat roof. Its behavior is mainly influenced by sources of uncertainty, such as material properties due to an inhomogeneous pore structure and production processes and weather data. The main influencing material properties are the moisture retention curve and the liquid transport coefficients in Holzkirchen and vapor permeability in Miami. Other parameters, such as density, porosity, and heat conductivity, can be neglected.

The sensitivity analysis served as an input for the hygrothermal building simulation tool WUFI-Plus. With this

TABLE 2
Energy Consumption for Cooling and Total Dehumidification During the First Year in Different Drying Cases

	With construction moisture		**Without construction moisture**	
	Fastest drying	**Slowest drying**	**Fastest drying**	**Slowest drying**
Energy consumption for cooling (kWh)	7920	7887	7670	7694
Dehumidification (kg)	9196	9596	4360	4552

program, the energy consumption, including hygrothermal effects, and the indoor climatic conditions were calculated. The results showed that the total energy needed for cooling is, under hot and humid conditions, nearly independent from the moisture content of the AAC. On the other hand, the initial high moisture content of AAC elements can cause serious problems if the dehumidification system is not adequately designed for these extreme conditions during the first year. Here the dehumidification rate is nearly twice as high.

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