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Hygrothermal Modeling of Aerated Concrete Wall and Comparison With Field Experiment

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ABSTRACT: A two-dimensional heat, air and moisture transport model called hygIRC is adapted to simulate a well-documented field exposure of an aerated concrete wall section. Difficulties are encountered due to a few missing information on boundary conditions of the exposure and hygrothermal properties of aerated concrete. The paper presents how these inadequacies were overcome to simulate the hygrothermal behavior of the wall section. Appropriate assumptions were made due to justifiable reasons. Then the model provides temporal and spatial distributions of temperature and relative humidity for an extended period that are in excellent agreement with the documented field data. The paper presents the justifications for the assumptions and the comparison of experimental and simulation results.

1 INTRODUCTION

Hygrothermal (Heat, Air and, Moisture Transport or HAM) models are gradually finding their ways into the hands of building practitioners. Researchers have made significant advances in the development of these models during the past two decades (Hens 1996; Trechsel 2001). Several computer models are now commercially or publicly available to the practitioners. Examples are MOIST, MATCH, WUFI, hygIRC, and DELPHIN. But the question always asked is: How reliable are these models?

In order to address the above question, a European Union project called HAMSTAD was launched. One of the outputs of that project was a set of benchmarking exercises (Hagentoft et al. 2004) that can judge the reliability of one-dimensional HAM models. This, though a major step forward to addressing the question, is still not the final solution. Well-controlled laboratory as well as field experiments with measurable hygrothermal effects shall be performed and these experiments shall be simulated using the models. Agreements between the measured and simulated results of these experiments at the very least shall be semi-quantitative. Quantitative agreements are desirable. Experience, however, shows that the latter is very challenging, due to a variety of reasons. The three-dimensional processes when captured by a HAM model that is at best a two-dimensional model is converted to a two-dimensional problem. This introduces several assumptions. Often factors that support full justifications for these assumptions will be missing from the experiments. Good examples are the actual path of airflows that may exist in typical wood-frame constructions or the model representation of the studs in the cavities of a wall. Lack of proper information on the boundary conditions has always been a problem. Information on the hygrothermal properties of the components is often incomplete or non-existing. Interfacial phenomena are not properly accounted for, in experiments and in simulations. Liquid water movement if it exists within the cavities or on the surfaces is not easy to model or quantify by experiments. So the best one can expect is a semi-quantitative agreement between the experiment and HAM model simulation. At the field level even this is hard to accomplish.

Zarr et al. (1995) have reported a set of experiments on wall specimens and corresponding HAM simulations. But the hygrothermal changes that were undergone by the test specimens were small in those experiments and hence the simulations were not challenging for a HAM model. Künzel & Kießl (1996) have reported a field experiment on brick and used the results from it to fine-tune their inputs to several hygrothermal simulations using WUFI. In a recently concluded ASHRAE project, experiments from laboratory and field measurements were used to benchmark a hygrothermal model (Burnett, in prep.).

At the Institute for Research in Construction, several small scale and full-scale laboratory experiments have been performed to benchmark hygIRC. Kumaran & Wang (2002) obtained nearly quantitative agreement with a drying experiment on a set of fully saturated 30 cm × 30 cm specimens of an exterior sheathing board. Tariku & Kumaran (2002) have reported good agreement between transient moisture distributions from a gamma spectroscopic investigation of a 10 cm × 10 cm × 10 cm aerated concrete specimen and corresponding hygIRC simulations, during the drying of the fully saturated specimen. Maref et al (2002a) have reported many experiments and hygIRC simulations on the drying process undergone by 1 m × 60 cm test specimens of OSB in contact with various types of membranes as well as full-scale wall specimens (2m × 2m) with semi-quantitative agreements (Maref et al 2002b).

In the present work hygIRC has been adapted to simulate a series of field experiments on many sections of wall specimens that was performed at the Norwegian Building Research Institute (Geving & Uvsløkk 2000). Geving et al. (1997) have reported some of the earlier attempts to compare the experimental results and HAM simulations. The agreements between the two were often poor and the authors have attempted to give some explanations, based on conjecture. The present work, which includes several parametric analyses, points out several challenges in comparing the results from the field experiments and corresponding HAM simulations using hygIRC. The scope of this conference paper does not allow the authors to present all the results from their study. Hence mainly a series of simulation results on the hygrothermal behavior of an aerated concrete wall section is presented here.

2 FIELD EXPERIMENT

With the objective of generating experimental data for verification of HAM models Geving and Uvsløkk (2000) performed a field experiment on a test house. The test house was built on an open field located at Voll, Trondheim, Norway, with a weather station beside it (16 m away from the test house). The temperature, relative humidity and moisture content of various walls and roof sections were instrumented and monitored. The test house was designed to have a total of sixteen instrumented walls and eight roof panels separated by polyethylene foil to avoid lateral airflow and moisture transfer. Eight of the walls were oriented in the east and the rest in the west. The detailed description of the configurations and materials used for the walls and roofs, as well as the experimental setup are discussed in Geving and Uvsløkk (2000) report.

In this paper, aerated concrete wall section is considered for verification and benchmarking of IRC's advanced hygrothermal model, hygIRC. The wall orientation is east, and has a dimension of 1200, 300 and 3250 mm for the width, thickness and height, respectively. It is exposed to the Voll weather condition at the exterior, and controlled temperature and relative humidity of 23^{o}C and 45%, respectively, at the interior. Although the wall is subjected to these boundary conditions since October of 1994, the actual measurement of temperature and relative humidity in the structure was started only in February of 1996. Three temperature and relative humidity sensors were positioned at a depth of 50, 150 and 260 mm from the interior to the exterior at a cross-section plane of 1100 mm from the top, Figure 1. A continuous measurement of temperature and relative humidity with one-hour time interval was recorded by the data acquisition system. The indoor climate (temperature and relative humidity) was logged in on an hourly basis as well. The weather station recorded the ambient temperature, relative humidity, wind speed, wind direction, rainfall, air pressure, global radiation, long-wave radiation and snow depth. For most of the parameters the average, minimum and maximum values for the hour are derived from every five-second (one second for wind) measurement.

3 DESCRPTION OF THE HYGROTHERMAL MODEL (hygIRC)

The two-dimensional version of the advanced hygrothermal model of IRC, hygIRC, is used in this work. The non-uniform loadings, which are applied along the height of the wall, caused by stack effect and wind-driven-rain may cause two-dimensional flows. The detailed description of the model[1] is published previously by Karagiozis (1993, 1997), Salonvaara & Karagiozis (1994) and Hens (1996). Here, a brief description of the mathematical model is presented. The model solves, simultaneously, the three interdependent transport phenomena of heat, air and moisture in a building component. The mathematical model is based on building physics and comprises a set of partial differential equations that govern the individual flows. The corresponding governing equations are as follow:

Moisture balance:

$$\frac{\partial w}{\partial t} + \nabla \cdot \left(\vec{u}\rho_v + K\rho_w \vec{g} \right) = \nabla \cdot \left(D_w \nabla w + \delta_p \nabla p_v \right) + \dot{m}_s \tag{1}$$

Heat balance:

$$c\rho_o \frac{\partial T}{\partial t} + \nabla \cdot \left(\vec{u}\rho_a c_{p,a} T \right) = \nabla \cdot \left(\lambda \nabla T \right) + L_v \left[\nabla \cdot \left(\delta_p \nabla p_v \right) \right] - L_{ice} \left(w \frac{\partial f_l}{\partial t} \right) + \dot{Q}_s \tag{2}$$

[1] In earlier development of hygIRC it is used to be called LATENITE

Air mass balance:

$$\nabla \cdot \left(\rho_a \vec{u} \right) = 0 \tag{3}$$

Momentum balance (Darcy equation)

$$\vec{u} = -\frac{k_a}{\eta} \nabla P \tag{4}$$

$$-\nabla \cdot \left(\rho_a \frac{k_a}{\eta} \nabla P \right) = 0 \tag{5}$$

where w =moisture content (kg/m^3); $\vec{u}$ =air velocity (m/s); ρ_v =water vapor density (kg/m^3); K =liquid water permeability (s); ρ_w =density of water (kg/m^3); $\vec{g}$ =acceleration due to gravity (m/s^2); D_w =moisture diffusivity (m^2/s); δ_p =vapor permeability (s); p_v =vapor pressure (Pa); $\dot{m}_s$ =moisture source (kg/m^3); c =effective heat capacity (J/kg.K); ρ_o =dry density of the material (kg/m^3); T =temperature (^{o}C); ρ_a =density of air (kg/m^3); $c_{p,a}$ =specific capacity of air (J/kg.K); λ =effective thermal conductivity (W/m.K); L_v =latent heat of evaporation/condensation (J/kg); L_{ice} =latent heat of freezing/melting (J/kg); f_l =fraction of water frozen (-); $\dot{Q}_s$ =heat source (W/s.m^3); k_a =air permeability (m^2); and η =dynamic viscosity (kg/ms).

The driving potentials of moisture transport, Equation (1), are vapor pressure and moisture content. The advanced model includes two important moisture transport mechanisms, in addition to diffusion process: water vapor transport by convection and liquid water transport by gravity as expressed by the second and third terms of the left hand side of the equation, respectively. The model has also the capability of handling volumetric moisture source or sink as represented by the last term in the right hand side of the equation. Temperature is the driving potential for the heat balance equation, Equation (2). The transfer of heat by convection and diffusion are represented by second (l.h.s) and first (r.h.s) terms of the equations, respectively. The heat source/sink associated with phase changes are represented by the second (evaporation/condensation) and third (freeze-thaw) terms of the right hand side of the equation. Any other internal heat source/sink is given by the last term of the of the right hand side of the equation. The mass balance equation for incompressible fluid is given by Equation (3). In building physics application, the air is considered as incompressible due to very low airflow speed, and low pressure and temperature changes. Darcy equation, Equation (4), is a reduced form of Navier-Stokes momentum equation for flow in a porous media. Combing the mass balance, Equation(3), and momentum balance, Equation (4), equations gives Equation (5).

4 APPLICATION OF THE HYGROTHERMAL MODEL (hygIRC)

The two-dimensional version of hygIRC does a transient calculation on a geometrical model, which represents a building component with a number of layers of materials in a two dimensional domain. The model outputs a transient state of moisture content, temperature and airflow distribution in the calculation domain for the applied time varying boundary and given initial conditions. The application of hygIRC is demonstrated in a number of publications; Karagiozis et al. (1996), Djebbar et al. (2002), Mukhopadhyaya et al. (2003).

Geving (1997) and Geving et al. (1997) applied the model to reproduce the experimentally measured local moisture and temperature conditions on wood frame constructions. They found similar trends with some discrepancy and gave the following reasons for the discrepancy: uncertainty of measurements, existence of unforeseen phenomena—high air convection in the cavity, and influence of moisture sensors on the measurement. Maref et al. (2000a) benchmarked hygIRC with a well-controlled laboratory experiment. They carried out drying experiments of simplified wall assemblies in a constant boundary condition, and measured the total weight loss of the assembly during the drying process. The benchmark exercise, which was a comparison of the measured and computed gross weight (total weight of the wall sample), yielded good agreement. In this paper the model is benchmarked against a field-experiment. In this case, the aerated concrete wall shown in, Figure 1, is exposed to real weather conditions on the outside and controlled indoor conditions in the inside. Relative humidity and temperature, measured at specific locations are used to benchmark the model predictions.

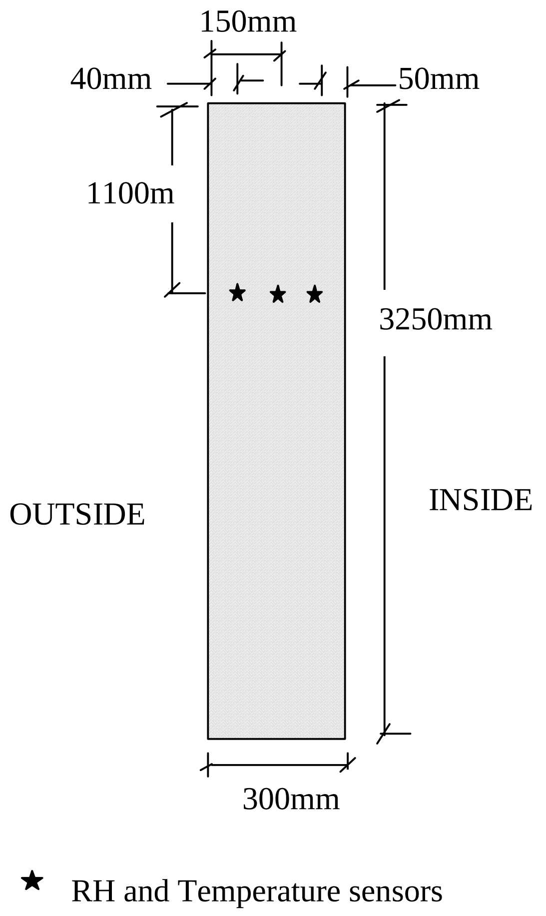

Figure 1 Aerated concrete wall

Modeling with hygIRC involves a number of input data processing, such as creating a two-dimensional representation of the wall, generating the indoor and outdoor boundary conditions, establishing initial conditions, and preparation of the hygrothermal properties of materials involved in specific formats.

4.1 Wall geometry

Assuming the temperature and moisture gradients in the third directions are negligible, the wall is represented in two-dimension by a vertical cross-section at the centerline of the wall. As shown in Figure 1, the cross-section has a dimension of 3250 mm height and 300 mm thickness. The three temperature and relative humidity sensors were positioned at a depth of 50, 150 and 260 mm from the interior to the exterior at a horizontal cross-section plane of 1100 mm from the top. In the computational domain, the wall cross-section is discretized into a number of control volumes and the mathematical models are applied at each control volume to arrive at a solution that satisfies all the balance equations described above.

4.2 Boundary conditions

In the experiment the indoor conditions were controlled, and the set temperature and relative humidity were 23°C and 45%, respectively. As shown in Figure 2-3 the actual measurements (in daily average) deviated from the set values. In summer of 1997 the indoor temperature rose above 30°C, and in the wintertime of the same year went below 20°C (Figure 2). A significant drop of relative humidity in the house occurred in April 1997, when the ventilation system was adjusted to create over pressure condition in the house (Figure 3). The indoor pressure before and after April 1997 were 2 Pa negative pressure and 0.5 Pa overpressure, respectively. In the modeling, the measured indoor temperature, relative humidity and pressure conditions are applied as indoor environmental conditions. The indoor boundary conditions for heat and moisture balance equations are applied as Neumann boundary conditions, where the fluxes are calculated using the corresponding surface transfer coefficients and change in the driving potentials. In this work constant values of 8 W/m^2.K and 5.08E-8 s/m are used for the indoor surface heat and mass transfer coefficients, respectively.
The outside surface of the wall is exposed to Voll weather. Voll is located at 63.25° latitude and 10.28° longitude. The outdoor environmental conditions which are required for hygIRC simulation are: hourly temperature, relative humidity, wind speed, wind-direction, global, diffuse and reflected radiations, rain and cloud index. The model incorporates solar radiation, radiation heat exchange with the surrounding and sky, and moisture load due to wind-driven rain. In the field experiment since March 1995 the outdoor weather conditions were measured and recorded by an automated weather station. In some occasions the measurements were not complete; there were missing data of rain, global radiation and in some cases the whole weather parameters.

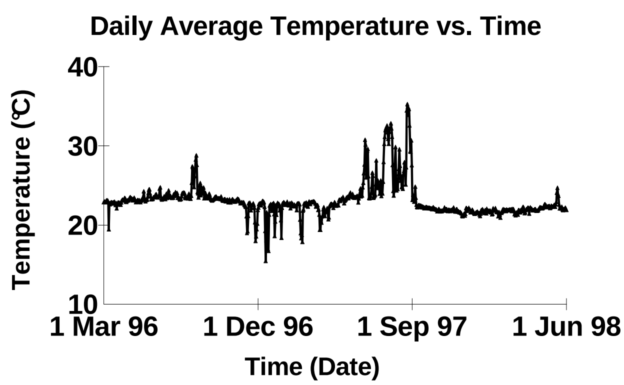

Figure 2 Daily average indoor temperature

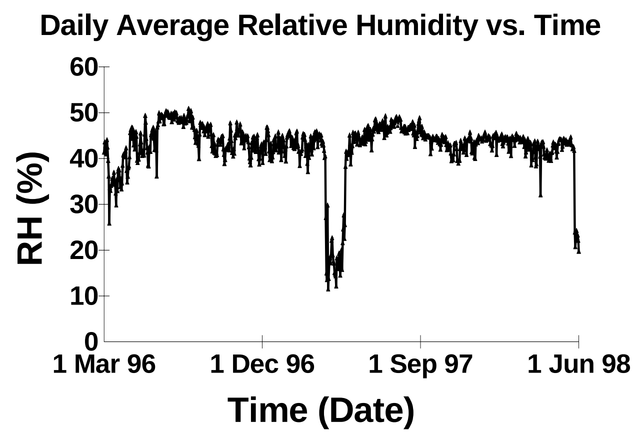

Figure 3 Daily average indoor relative humidity

In these cases extrapolation from adjacent data were performed. The boundary conditions on the outdoor surface are applied as Neumann conditions with variable surface transfer coefficients. The heat transfer coefficient is a function of wind speed, and the mass transfer coefficient is deduced from the heat transfer coefficient using Lewis relation.

The boundary conditions for heat and moisture transfer at the top and bottom surfaces are assumed to be adiabatic since the area of interest (measuring points) are relatively far from the end surfaces.

Even though the test house was monitored since October 1994, the actual measurement on the aerated concrete wall was started in March 1996. The later date marks the beginning of the hygrothermal simulation, and therefore, the relative humidity and temperature measured at that time by the sensors in the wall are used as initial conditions. To apply the initial conditions the wall cross-section is divided vertically into three sections with each section of 100 mm thickness. The measured temperature and relative humidity are assigned to the corresponding sections throughout the wall height. These assumed initial temperature and relative humidity were: on the outer section of the wall 3^{o}C and 88% RH, on the middle section 11^{o}C and 75% RH and on the inner section 18^{o}C and 61% RH, respectively.

4.3 Material properties

To solve the mathematical models of heat, air and moisture balance equations described above, the properties of the material layer that define the storage and the flow of the appropriate entity have to be known. The heat and moisture storage capacity of a material are given as heat capacity and specific moisture capacity respectively (Kumaran 1996). The two flow coefficients for moisture transfer are vapor permeability and liquid diffusivity, which characterize the vapor and liquid water flow in the material. Thermal conductivity and air permeability are the heat and airflow coefficients, respectively. Both storage capacities and flow coefficients are function of temperature and moisture content. The material properties measured and reported for aerated concrete by Bergheim et al. (1998) were: dry material density, water vapor permeability at a 72% relative humidity and adsorption and de-sorption data for the hygroscopic range. Since these reported material properties were not enough and complete for hygIRC simulation, a matching aerated concrete from hygIRC database is chosen based on the given material properties. As shown in Figure 4-5 the sorption isotherm and vapor permeability curves are close to the measured values. The heat capacity and air-permeability are assumed to be constant, and have values of 840 J/kg.K and 6.9E-14 m^2, respectively. The density and thermal conductivity at dry state of the material are 460 kg/m^3 and 0.122 W/m.K, respectively. The latter is adjusted based on the available moisture content.

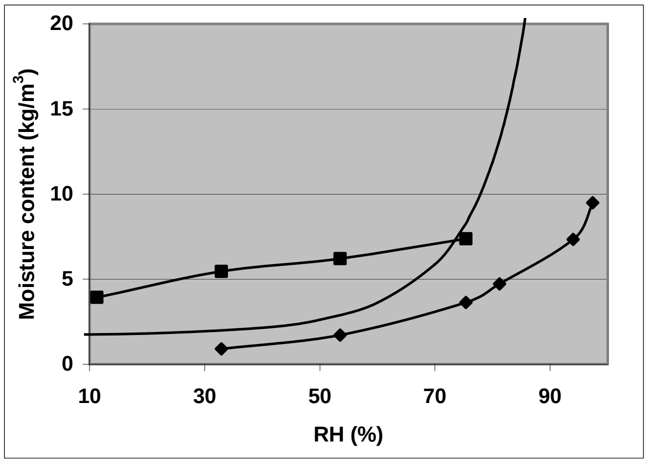

Figure 4 Sorption isotherm of Aerated concrete

Measured desorption absorption
hygIRC Database

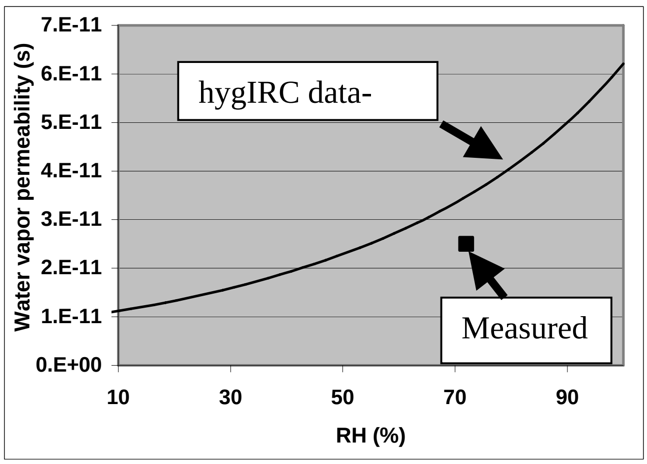

Figure 5 Water vapor permeability of Aerated concrete

5 RESULTS AND DISCUSSION

The dynamic response of the aerated concrete wall exposed to the outdoor weather on the exterior and controlled indoor conditions on the interior surfaces are presented below. The simulation started on March 1st 1996 and ran for a continuous period of two years and five months. The temperature and relative humidity at the sensor locations are extracted for comparison with the field measurement. Figure 6 shows the measured and calculated daily average relative humidity at the inner section of the wall (50 mm). The simulation has the same trend as the measurement but is systematically under-predicted. As it is close to the indoor environment, the values are highly influenced by the indoor relative humidity condition. This is clearly shown in April 1997, where the calculated relative humidity shows steep decreases as the indoor relative humidity goes down (see Figure 3). In the middle section (150 mm), Figure 7, as well the simulation under-predicts the relative humidity. However, a good agreement between the measured and computed values is obtained in the outer section of the wall (260 mm), Figure 8. The computed values closely follow the trend and magnitude of the measured relative humidity. Moisture condition at this point is strongly influenced by the outdoor environmental conditions, specially the wind-driven rain and solar radiation. Knowledge of liquid diffusivity of the material is very important in this section of the wall as it is exposed to rain load and moisture transport at high moisture content is dominant.

In the middle and inner sections of the wall the relative humidity is relatively constant, where as in the outer section, the wetting and drying pattern during the winter and summer season are noticeable. Taking into consideration the constant deviation of the inner point measurement from the computed values, and a better agreement on the outer section of the wall, and also the fact that Geving (1997) reported in his thesis that one of the uncertainties of the experiment is boundary conditions measurement, additional set of simulation was performed. The new simulation employed the same material properties and outdoor weather condition, but with modified indoor environmental condition. At this time the indoor surface of the aerated concrete is exposed to a relative humidity of 10% higher than the previous case, but with the same temperature. The simulation results are shown in Figure 9-11 for the inner, middle and outer section of the wall, respectively. As it can be seen from the figures, very good agreement of computed and measured relative humidity values for all three locations are obtained. As mentioned earlier, the inner and middle section of the wall are highly influenced by the indoor environmental condition. Figure 12-14 show the transient temperature responses of the three monitored locations. As the figures shows the computed and measured temperatures values agree very well in all three sections of the wall. Moreover, the temperature responses in the modified relative humidity case were not different from the corresponding values of the previous simulation.

Validation of hygrothermal models with experiment requires complete information on the four major input parameters, which are construction details, boundary conditions, initial condition and hygrothermal properties of the materials used. In this validation exercise some difficulties were faced in the last three input parameters, and appropriate assumption were made, as discussed below.

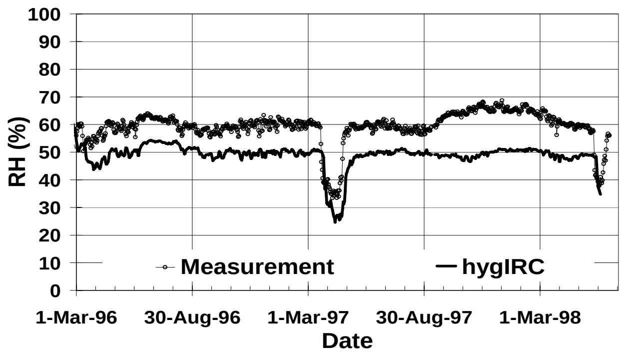

Figure 6 Comparison of measured and computed relative humidity at the inner section

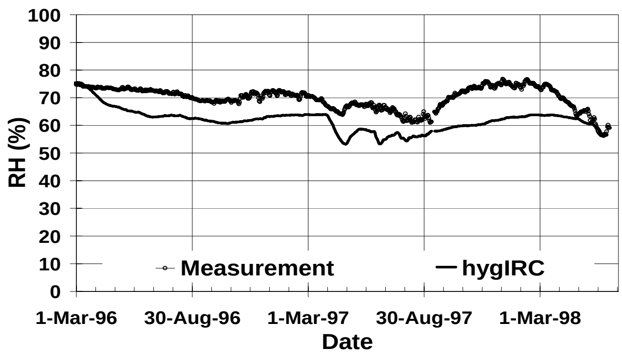

Figure 7 Comparison of measured and computed relative humidity at the middle section

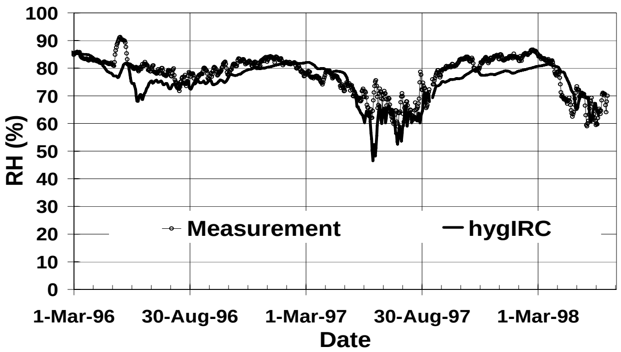

Figure 8 Comparison of measured and computed relative humidity at the outer section

Problem with boundary and initial condition: During the field experiments, mainly before March 1996, there were periods when the weather station was not working and missing data for the whole or some of the parameters. Because of this reason (unreliable boundary condition) the simulation had to start in March 1996 instead of the time when the test house was built (October 1994). This shift in the starting time of the simulation due to missing information on boundary conditions gave rise a problem in setting up the initial condition. The initial condition had to be different from the initial condition reported during the constriction (60% relative humidity and 23^{o}C temperature).

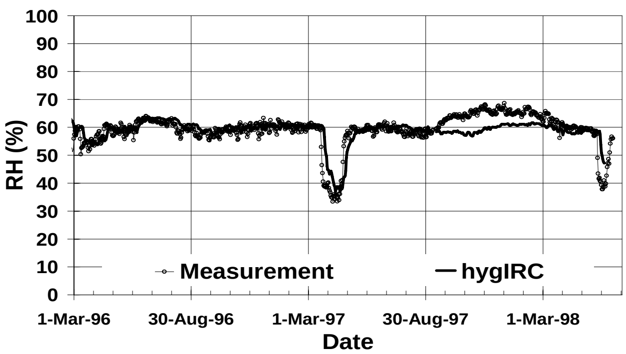

Figure 9 Relative humidity comparison with modified indoor relative humidity at the inner section

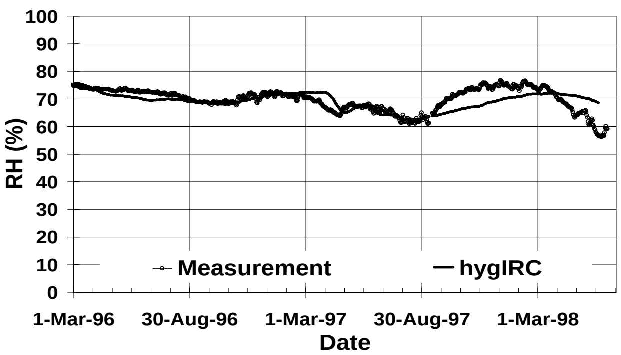

Figure 10 Relative humidity comparison with modified indoor relative humidity at the middle section

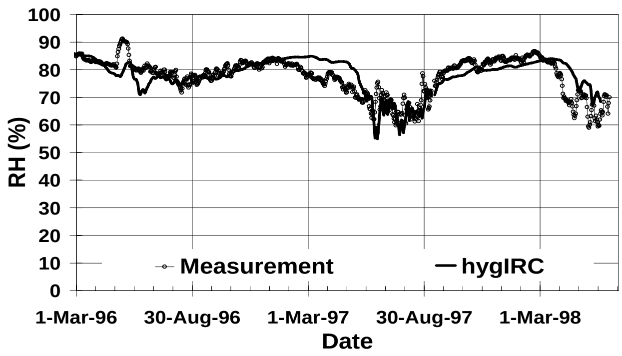

Figure 11 Relative humidity comparison with modified indoor relative humidity at the outer section

Consequently, the assumptions for boundary and initial conditions described earlier are implemented. These are extrapolation of missing data from the adjacent recorded values, and adaptation of the measured temperature and relative humidity at the start of simulation, respectively.

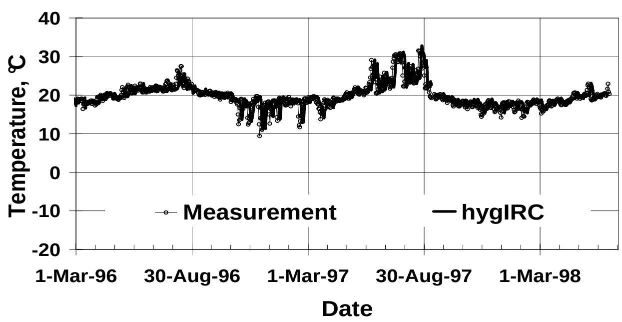

Figure 12 Comparison of measured and computed temperature at the inner section

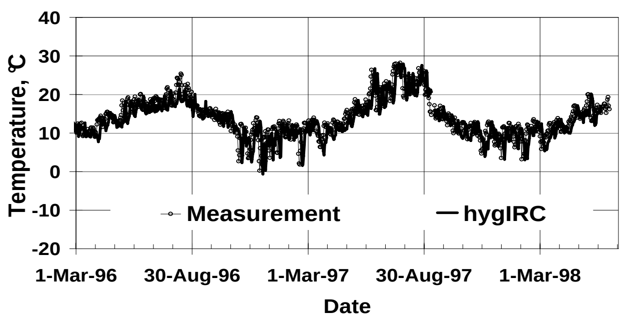

Figure 13 Comparison of measured and computed temperature at the middle section

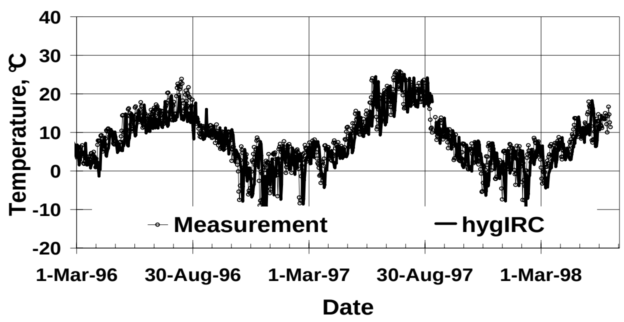

Figure 14 Comparison of measured and computed temperature at the outer section

Problem with material properties: The heat capacity, thermal conductivity, air-permeability, and liquid diffusivity of aerated concrete were not provided. Particularly, the latter property is very important for rain absorption and distribution of moisture at high moisture content. Moreover information on the two important hygrothermal properties of aerated concrete were incomplete: the capillary range of the moisture storage curve, and vapor permeability dependency on relative humidity. During the simulation it is assumed that the material properties used from hygIRC database (see Figure 4-5) represent the hygrothermal properties of the actual aerated concrete used in the test house. By implementing the above assumptions validation of hygIRC with field experiment was possible.

6 CONCLUSION

Hygrothermal models are useful tools to assess the hygrothermal conditions of new and/or existing buildings. Advanced hygrothermal models give more detailed information and cover a wider monitoring area compared to experiments. The additional advantages of computer modeling are: running models is less expensive in terms of labor, time and cost, and enables to simulate both realistic and hypothetical scenarios. However, the usefulness of the simulation result depends on the mathematical model, which describes the underling physics, and the numerical method used to solve the mathematical model. Moreover user's understanding of the physical problem, and adaptation of the problem in the numerical modeling are equally important. For the model to be relevant it has to be validated with experimental results. At the same time, the benchmark experiment must contain complete information on construction details, boundary conditions, initial conditions and hygrothermal properties of the materials used, in addition to measured variables in the structure. In this paper, the difficulties encountered in benchmarking of hygrothermal model with a field experiment, and the appropriate assumptions made to overcome the missing information were discussed. The excellent agreement of the simulation and the field experiment results validated the IRC's advanced hygrothermal model, hygIRC, and demonstrated its capability.

7 ACKNOWLEDGEMENT

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