EE13-2 DEVELOPMENT AND BENCHMARKING OF A NEW WHOLE BUILDING HYGROTHERMAL MODEL

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ABSTRACT

During design process, building engineers evaluate the performance of various design alternatives in terms of their durability, comfort and indoor air quality, as well as energy efficiency using building envelope, indoor and energy analysis tools, respectively. But, usually the analysis tools are in the form of stand-alone package, where there is no direct link among them but rather simplifying assumptions are made on the other two when designing for one. In this paper, the development and benchmarking of a newly developed whole building hygrothermal model are presented. The model considers the building as a system and accounts for the dynamic heat, air and moisture (HAM) interaction between building envelope components and indoor environmental conditions including HVAC systems, moisture and heat sources. The methodology adopted in this work is to develop and validate two primary models: building envelope and indoor models independently and couple them to form the whole building hygrothermal model. After successful integration of the models, the whole building hygrothermal model is benchmarked against internationally published numerical and experimental test results. The holistic model can be used to assess building enclosures durability, indoor conditions (temperature and relative humidity), occupant comfort, and energy efficiency of a building in an integrated manner.

NOMENCLATURE

A_c condensate surface area (m^2)
A_i surface area of surface i (m^2)
A_e water surface area (m^2)
Cv_m specific capacity of solid matrix (J/kg)
Cp_a specific capacity of air (J/kg)
Cp_v specific capacity of water vapor (J/kg)
D_l liquid conductivity (s)
$\vec{g}$ acceleration due to gravity (m/s^2)
$h_{t_i}^m$ mass transfer coefficient of surface I
h_i^h heat transfer coefficient of surface I
h_c^m mass transfer coefficient for condensate
h_{fg} latent heat of evaporation/condensation (J/kg)
h_e^m mass transfer coefficient for evaporation
k_a air permeability (m^2)
$\dot{m}$ mass flow rate of dry air (kg/s)
M molecular mass of water (0.018 kg/mol)
$\dot{Q}_s$ heat source (W/m^3)
P_v vapour pressure (Pa)
p zone vapour pressure (Pa)
$\hat{p}_e$ saturated vapor pressure of reservoir e

T temperature (^{o}C)
T_e outdoor air temperature (^{o}C)
T_i^s surface temperature of surface i (^{o}C)
$\tilde{T}$ set point temperature (^{o}C)
$\vec{u}$ air velocity (m/s)
$\tilde{V}$ volume of the zone (m^3)
w moisture content (kg/m^3)
Y_a mass fraction of air (-)
Y_l mass fraction of liquid water (-)
Greek letters
Θ sorption capacity (kg/m^3)
ϕ relative humidity (-)
δ_p vapor permeability (s)
ω humidity ratio (kg/kg air)
ω_e humidity ratio of exterior air (kg/kg)
$\tilde{\omega}$ set point humidity ratio (kg/kg)
ρ_w density of water (kg/m^3)
ρ_a density of air (kg/m^3)
ρ_m density of solid matrix (kg/m^3)
Δt time step (s)

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$\hat{p}_c$ saturated vapor pressure of condensate c λ_{eff} effective thermal conductivity (W/m.K)
P saturated vapor pressure (Pa) η dynamic viscosity (kg/ms)
p_i^s surface vapor pressure of surface i (Pa)
P_{atm} atmospheric pressure (Pa)
R universal gas constant (8.314 J/(K·mol))

1. INTRODUCTION

Buildings are designed to create an isolated space from the surrounding environment and provide desired interior environmental conditions for the occupants. In addition to fulfilling the function of creating a favorable indoor environmental condition, buildings are expected to be durable and energy efficient. These three functional requirements of the building should be optimized for a given climatic conditions. This optimization process is necessary: 1) to provide comfortable indoor environment to occupant since people spend most of their time in indoors and their productivity is dependent on how they perceive their indoor environment 2) due to the higher level of investment and maintenance cost involvement in the construction of new buildings and building failures repair 3) due to the high energy consumption of low energy efficient buildings which results high energy bills to maintain the desired building operating conditions. Dealing with one aspect of the building might lead to problems in the other aspects. For example, in early 1970's buildings were constructed and retrofitted to be more airtight and insulated (with more insulation) to reduce energy consumption. Although the energy efficiency of the buildings was improved, this new strategy created more problems in durability of the building envelope due to high moisture accumulation in the building structure. The indoor humidity level was also elevated due to the low air exchange, which resulted in low occupant comfort and health problems (Shaw and Kim, 1984; TenWolde, 1988).

The current indoor, building envelope and energy analysis tools are in the form of stand-alone package, where there is no direct link among them but rather simplifying assumptions are made on the other two when designing for one. For example, the indoor models (Loudon, 1971; Hutcheon and Handegord, 1995; Tsongas et al., 1996; TenWolde, 2001) attempted to predict the indoor condition with a simplified or no coupling with the building components, which could have a moisture buffering effect. The building envelope models (Tariku et al., 2007; Tariku and Kumaran, 2006; Kuenzel, 1995; Burch, 1993; Pederson, 1990), on the other hand, usually use predefined indoor environmental condition in assessing the hygrothermal performance of a particular building component. However, in reality the indoor condition is determined by the heat and mass balance of the external and internal loading as well as the mechanical systems' outputs. Energy models usually ignore the moisture effect on the thermal transport and storage properties of materials. Incorrect prediction of indoor air condition and ignoring moisture in the energy calculation might lead to incorrect prediction of required ventilation rate, energy demand for heating/cooling as well as humidification/ dehumidification needed to maintain the intended building operating conditions. In this paper a holistic model called HAMFitPlus is developed to deal with these inter related and coupled effects. In this model various aspects of a building: building envelope enclosures, indoor environment, HVAC systems and indoor heat and moisture generation mechanisms will be integrated. The integrated model can be used to assess building enclosures durability, indoor condition, occupant comfort, and also energy efficiency of a building in an integrated manner.

2. MODEL DEVELOPMENT

In whole building hygrothermal modeling, the building is considered as an integrated system, which consists of building enclosure, indoor environment and mechanical systems. Thus the indoor environment conditions, more specifically, temperature and relative humidity, are unknown quantities, and have to be determined from the heat and mass balance at the zone considering the three mechanisms: 1) heat and

mass transfer across building enclosure 2) internal heat and moisture generated by occupants and their activities, as well as 3) heat and moisture supply by mechanical systems (heating, cooling, humidification, dehumidification and ventilation) depending on the mode of operation of the building. To deal with these inter related and coupled effects, an integrated and coupled modeling approach, which integrates the dynamic HAM transfer of the building envelope with the indoor environment and its components (HVAC system, moisture and heat sources) is necessary. Here, building envelope and indoor models are developed independently and coupled to form the whole building hygrothermal model, HAMFitPlus. The mathematical descriptions of these primary models are presented below.

2.1 Building envelope model
The building envelope 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 (PDEs) that govern the individual flows. The corresponding governing equations are as follow:

Moisture balance:

$$\Theta \frac{\partial \phi}{\partial t} = \nabla \cdot \left(D_\phi \nabla \phi + D_T \nabla T \right) - \nabla \cdot \left(D_l \rho_w \vec{g} + \rho_a \vec{u} C_c \widehat{P} \phi \right) \tag{1}$$

where $D_\phi = \left(\delta_v \widehat{P} + D_l \frac{\rho_w R}{M} \frac{T}{\phi} \right)$, $D_T = \left(\delta_v \phi \frac{\partial \widehat{P}}{\partial T} + D_l \frac{\rho_w R}{M} \ln(\phi) \right)$ and $C_c = \frac{0.622}{P_{atm}}$

Heat balance:

$$\rho_m C p_{eff} \frac{\partial T}{\partial t} + \nabla \cdot (\vec{u} T) \rho_a \left(C p_a + \omega C p_v \right) + \nabla \cdot \left(-\lambda_{eff} \nabla T \right) = \dot{m}_c h_{fg} + \dot{m}_c T \left(C p_v - C p_l \right) + \dot{Q}_s \tag{2}$$

where $C p_{eff} = C v_m + Y_l C p_l$ and $\dot{m}_c = \nabla \cdot \left(\delta_v \nabla P_v \right) - \rho_a \nabla \cdot (\vec{u} \omega)$

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

Momentum balance (Darcy equation)
$$\vec{u} = -\frac{k_a}{\eta} \nabla P \tag{4}$$

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

The governing partial-differential equations (PDEs) of the three transport phenomena (Equation 1, Equation 2 and Equation 5) are coupled and solved simultaneously for temperature, relative humidity and pressure using a finite-element based software called COMSOL Multiphysics[1]. This commercial software is found to be beneficiary for solving non-standard coupled-multiphysics problems because of its open provision for implementing user defined PDEs and its smooth interface with MatLab/SimuLink[2]. The model accommodates non-linear transfer and storage properties of materials, moisture transfer by vapor diffusion, capillary liquid water transport and convective heat and moisture transfer through multi-layered porous media. The transient HAM model is successfully benchmarked against published test cases (Tariku et al., 2008, Tariku, 2008). The test cases are comprised of an analytical verification, comparisons with other models and validation of simulation results with experimental data.

2.2 Indoor model

The indoor model is developed to predict the indoor temperature and humidity conditions based on the heat and moisture balance in a zone, by accounting all the heat and moisture fluxes which crosses the zone boundaries, and also the internal heat and moisture generation/removal from zone due to the operating condition of the building or occupant behavior. The basic assumption of the model is that the indoor air is well mixed and can be represented by a single node. Under this assumption, the following two linear first-order differential equations for moisture and heat balances are developed:

Indoor humidity balance:

The humidity balance equation developed in this work incorporates the moisture absorption/desorption of hygroscopic internal lining of building envelope components and furniture $\left(\dot{Q}_b^m \right)$, moisture supply and removal from the zone by airflow $\left(\dot{Q}_v^m \right)$, moisture addition and removal by mechanical systems $\left(\dot{Q}_m^m \right)$, moisture addition into zone due to occupant activities $\left(\dot{Q}_o^m \right)$, evaporation from sink or bath tub $\left(\dot{Q}_e^m \right)$, and moisture removal due to moisture condensation on surfaces $\left(\dot{Q}_c^m \right)$. The indoor humidity model is mathematically represented by Equation (6) below.

$$\rho_a \tilde{V} \frac{d\omega}{dt} = \dot{Q}_b^m + \dot{Q}_v^m + \dot{Q}_m^m + \dot{Q}_o^m + \dot{Q}_e^m + \dot{Q}_c^m \qquad (6)$$

where:

$$\dot{Q}_b^m = \sum_i A_i h_i^m \left(p_i^s - p \right); \qquad \dot{Q}_v^m = \dot{m} \left(\omega_e - \omega \right); \qquad \dot{Q}_m^m = \frac{\rho_a \tilde{V}}{\Delta t} \left(\tilde{\omega} - \omega \right);$$

$$\dot{Q}_e^m = \sum_e A_e h_e^m \left(\hat{p}_e - p \right); \qquad \dot{Q}_c^m = \frac{10^6}{6.22} \sum_c A_c h_c^m \left(\hat{\omega}_c - \omega \right)$$

Indoor energy balance:

The general energy balance equation for the indoor air considers the energy exchange between the building envelope internal surfaces and the indoor air $\left(\dot{Q}_b^h \right)$, the energy carried by the air flow into and out of the zone $\left(\dot{Q}_v^h \right)$, the heat supply and removal (heating/cooling) by mechanical systems to maintain

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[1] http://www.comsol.com

[2] http://www.mathworks.com

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the room in the desired temperature range $\left(\dot{Q}_m^h\right)$, and the internal heat generated due to occupant activities (e.g. cooking) and building operation (e.g. lighting) $\left(\dot{Q}_o^h\right)$. The governing equation for the indoor energy balance is given by Equation (7).

$$\rho_a \tilde{V}\left(Cp_a + \omega Cp_v\right)\frac{dT}{dt} = \dot{Q}_b^h + \dot{Q}_v^h + \dot{Q}_m^h + \dot{Q}_o^h \tag{7}$$

where:

$$\dot{Q}_b^h = \sum_i A_i h_i^h \left(T_i^s - T\right); \qquad \dot{Q}_v^h = \dot{m}Cp_a\left(T_e - T\right); \qquad \dot{Q}_m^h = \frac{\rho_a \tilde{V}}{\Delta t}\left(Cp_a + \omega Cp_v\right)\left(\tilde{T} - T\right)$$

The moisture and heat addition into zone due to occupant activities ($\dot{Q}_o^m$ and $\dot{Q}_o^h$) are usually independent of the indoor condition, but rather on the occupant behavior. To reflect their activities at various times, diurnal moisture and heat generation rate schedules are used in the indoor humidity and energy calculations. These coupled and non-linear indoor humidity and energy balance equations, Equation (6) and (7) respectively, are simultaneously solved for indoor humidity and temperature using SimuLink and MatLab.

2.3 Whole building hygrothermal model
The whole building hygrothermal model, HAMFitPlus, is developed on SimuLink simulation environment, which provides a smooth interface with the COMSOL Multiphysic and MatLab computational tools. The simulation environment allows full integration and dynamic coupling of the building envelope and indoor models using the special SimuLink block called S-Function. This user-developed block is written in MatLab programming language, and enables dynamic coupling between COMSOL Multiphysics (for building envelope model) and MatLab/SimuLink (for indoor and HVAC models) models.

Figure 1 shows the graphical representation of the HAMFitPlus whole building hygrothermal model. The hygrothermal responses of a building (indoor temperature and relative humidity, energy consumption and building enclosure hygrothermal conditions) are the consequences of the dynamic interactions of various elements shown in Figure 1. The building enclosure may constitute many layers of different thickness, which may have unique non-linear hygrothermal properties. A change in the building enclosure design, say painting the interior surface or addition of insulation, or changes in climatic conditions will affect the indoor air conditions, which in turn affect the HVAC system outputs, say dehumidification or heating demand. Likewise, a change in the indoor heat and moisture generations or HVAC system output affects the indoor air conditions, which in turn affect the hygrothermal performance of the building enclosure. The holistic model deals with these interrelated and coupled effects in a single platform, and simultaneously predicts the indoor temperature and relative humidity conditions, the moisture and temperature distributions in the building envelope components, as well as the heating and cooling loads.
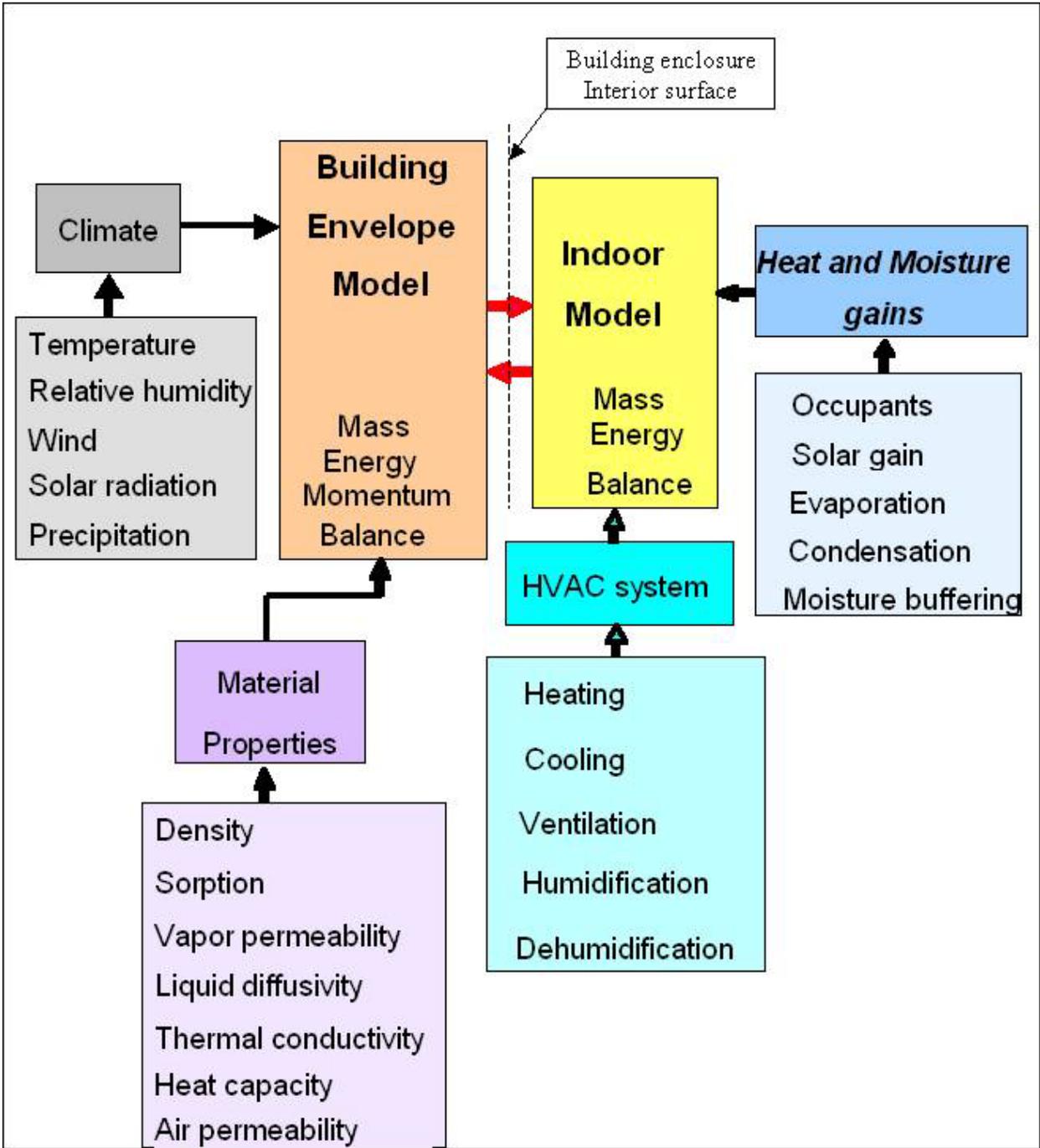
Figure 1 Schematic diagram of the whole building hygrothermal model, HAMFitPlus.

3. BENCHMARKING OF HAMFitPlus

In this section, the newly developed building envelope model, HAMFit, is benchmarked against published test cases. The complete benchmarking exercises that are undertaken to test the model are presented in Tariku (2008). Here, two of the seven benchmarking exercises, namely an analytical verification and comparison with experimental results are presented.

3.1 Analytical verification
An analytical verification of the whole building hygrothermal model, HAMFitPlus, is carried out using test cases for which analytical solutions are available. The test case was originally formulated in the IEA[3]/Annex 41 project (Ruut and Rode 2004, 2005) and later published by Rode et al (2006). In this exercise, the quasi-steady indoor humidity condition of the simplified building, shown in Figure 2, is calculated. The whole building components (i.e. walls, roof and floor) are constructed from a monolithic layer of 150 mm thick aerated concrete. The material properties of the aerated concrete, represented in a simplistic manner, are given in Table 1. The external surfaces of all building envelope components (walls, roof and floor) are covered with a vapour tight membrane to avoid vapour loss from inside to outside. However, the interior surfaces of all building envelope components are open, where moisture exchange between indoor air and building enclosure is possible (Figure 3). The mass transfer coefficient for the interior surfaces is 2E-8 m/s. Furthermore, the following assumptions are made: 1) the initial conditions (temperature and relative humidity) of the building envelope components (walls, roof and floor) and indoor air are at 20°C and 30%, respectively; 2) the outdoor temperature and relative humidity are also constant and have the same values as the initial conditions; 3) the indoor temperature is held constant at 20°C during the simulation period, which results in isothermal moisture absorption and desorption processes; 4) the building is assumed to operate with a constant ventilation rate of 0.5 ACH (air-exchange per hour), and 500 g/hr indoor moisture gain during the time between 9:00 to 17:00 h. The schematic diagram of the diurnal moisture production schedule is shown in Figure 4. The complete description of the exercises is given in Ruut and Rode (2004). For this test case, derivation of analytical solution is possible due to the various simplifying assumptions made in respect to the building geometry, boundary conditions, hygrothermal material properties, and also building operation.

Figure 2 Schematic diagram of simplified building

Figure 3 Typical building envelope component.
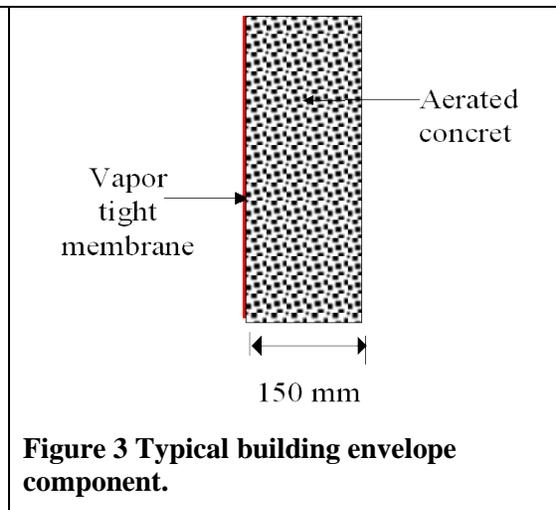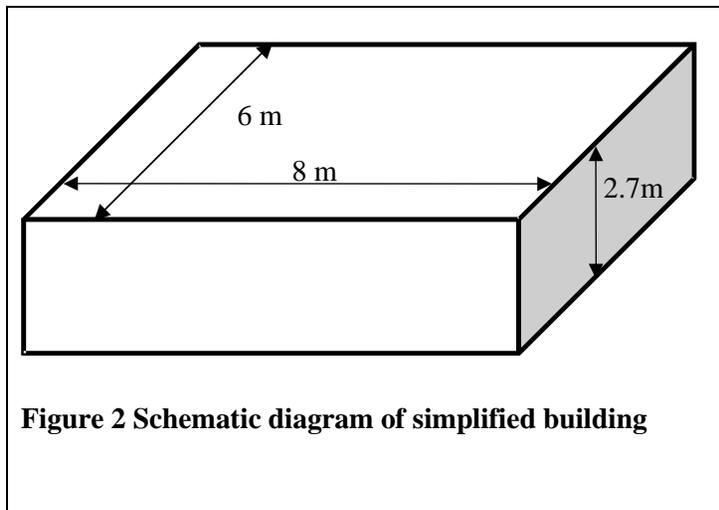
Table 1. Simplified material properties of aerated concrete.

Thickness (m)	Density (kg/m³)	Conductivity (W/mK)	Heat capacity (J/kgK)	Water vapour permeability (kg/m.s.Pa)	Sorption curve (kg/m³)
0.15	650	0.18	840	3E-11	$w = 42.965\phi$

Figure 4 Diurnal moisture production schedule.
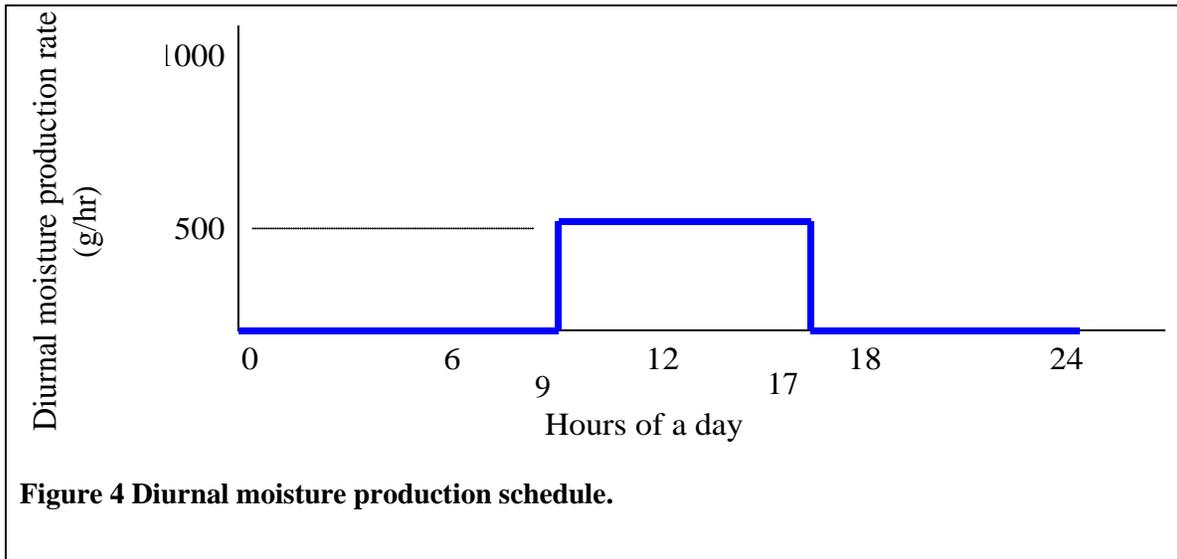
Figure 5 shows the hourly average relative humidity of the indoor air after a quasi-steady state condition is reached. The numerical prediction of HAMFitPlus is in excellent agreement with the analytical solution provided by Bednar and Hagentoft (2005). The indoor relative humidity steadily increases from 41.5% to 49% during the moisture generation period (9:00-17:00 h), and then decreases and completes the cycle (reduced to 41.5%), which is due to the presence of ventilation (0.5 ACH) and absence of moisture generation.

Figure 5 The diurnal indoor relative humidity profile of the building.
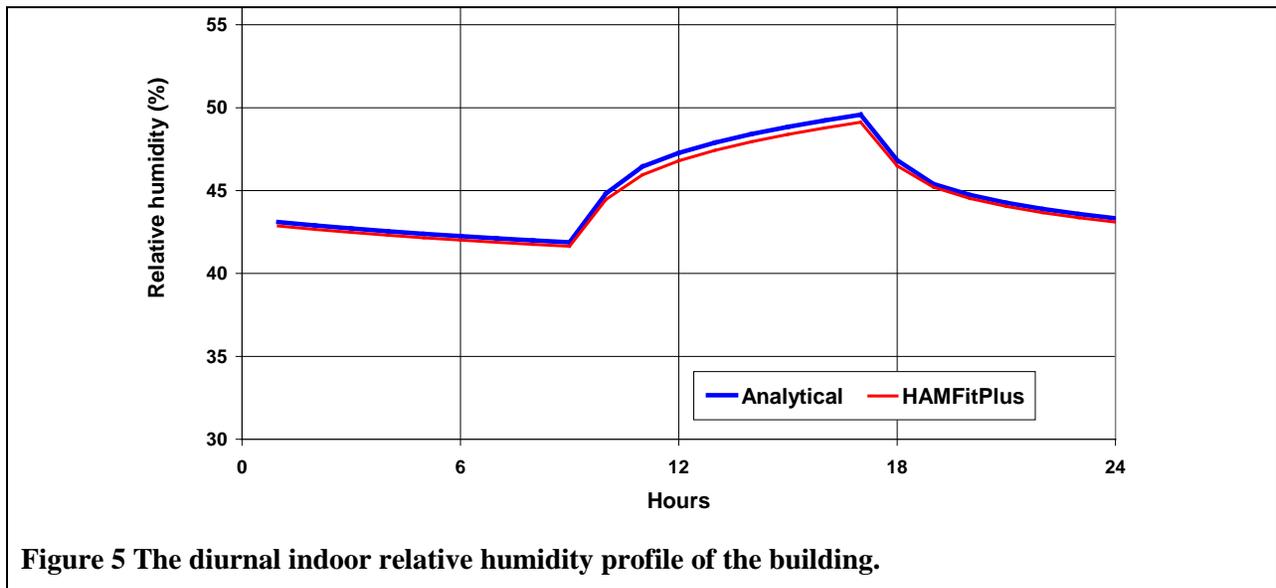
3.2 Experimental validation—A room with real climatic exposure

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In this section HAMFitPlus is benchmarked with the field experimental data that is published in Holm and Lengsfeld (2007). In this experiment, two rooms that have identical geometry, dimensions, orientation as well as boundary conditions but with interior furnishing layers with different moisture buffering capacities. Each room has a floor area of 19.34 m^2 and volume of 48.49 m^3. In this paper the room, which is referred as a "test room" in the experiment, is considered. The interior surfaces of the test room are unpainted, whereas the ceiling is covered with aluminum foil. The approximate vapor diffusion thickness of latex paint and aluminum foil are 0.15 m and 10000 m, respectively. The exterior surfaces of the room are exposed to real weather conditions of Holzkirchen, Germany. Holzkirchen is located at 47.88° north latitude and 11.73° east longitude, and has an elevation of 600 m. During the experiment the outdoor as well as adjacent rooms climatic data are recorded. This data are used in the whole building hygrothermal simulation as the boundary conditions of the respective surfaces. The type, dimension and hygrothermal properties of each layers of the room's enclosure material are provided. Furthermore, the following model input parameters were prescribed: 1) ground temperature is 2°C, 2) the emissivity and absorptivity of the exterior and interior surfaces of the building components are 0.9 and 0.4, respectively, 3) the exterior surface heat transfer coefficients of the exterior walls and floor are 18 and 100 W/m^{2}K, respectively, and 4) a heat transfer coefficients of 8 W/(m^{2}K) is assumed for all interior surfaces.

Room's operating conditions

During the experiment, the indoor temperature of the room is maintained at 20 ± 0.2^{o}C using thermostatically controlled radiator heater. The reported air exchange rates per hour due to both infiltration and mechanical ventilation system is 0.68. The room is subjected to an indoor moisture load of 2.4 kg per day. The moisture load is distributed according to the diurnal moisture production schedule shown in Figure 6. According to this schedule, the occupants' morning activities (such as taking a shower) generates a peak moisture production rate of 400 g/hr for two hours (6:00-8:00 h). Whereas, their evening activities (such as cooking and washing dishes) result in a moderate moisture production rate of 200 g/hr for six hours (16:00-22:00 h). For the rest of the day a 25 g/hr moisture production rate, which represents moisture generation by other than the occupants' activity (such as pets or plants), is assumed.
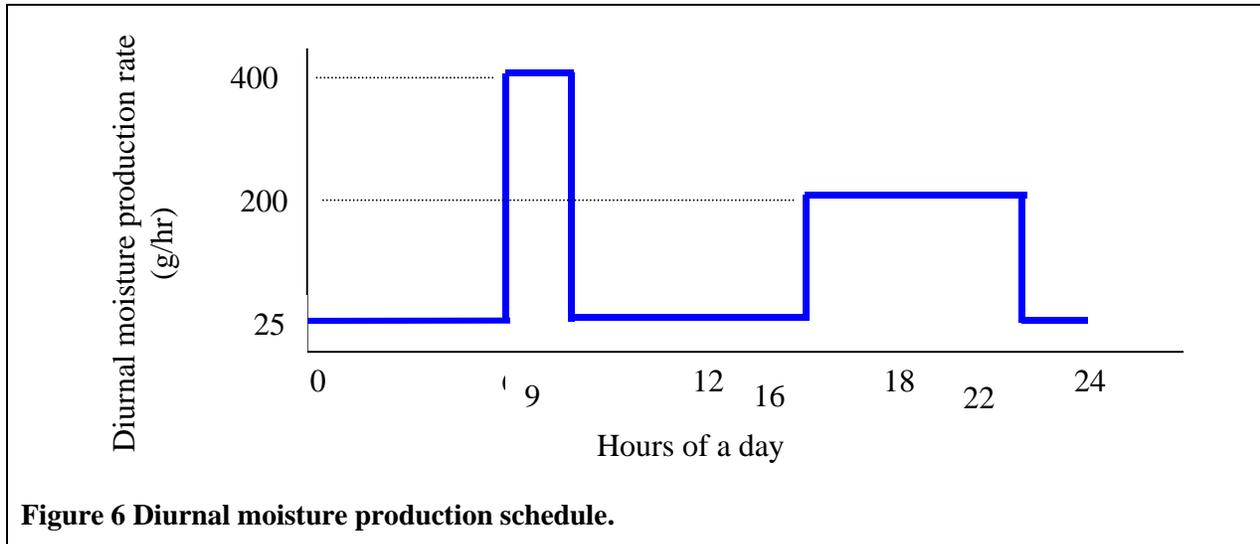
Figure 6 Diurnal moisture production schedule.

Comparison of simulation and measured results

In this model validation exercise, HAMFitPlus predicts the indoor relative humidity condition of the "test room" by taking into account the moisture buffering effect of interior furnishing layer through dynamic simulation of building envelope components and indoor air interactions. Figure 7 shows the indoor relative humidity of the "test" room for the measurement period of February 14 to March 20 2005 along with HAMFitPlus simulation result. The indoor humidity profile of the room on a typical day for clarity, in this case February 17th, is presented in Figure 8. As can be seen in these figures, the simulation result of HAMFitPlus is in good agreement with the corresponding measured data. The good simulation results obtained here are attributed to the model's capability of handling the dynamic indoor air and building envelope heat and moisture interactions.

Figure 7 Measured and simulated indoor humidity of the Test room.

Figure 8 Measured and simulated indoor humidity of the Test room on February 17th .
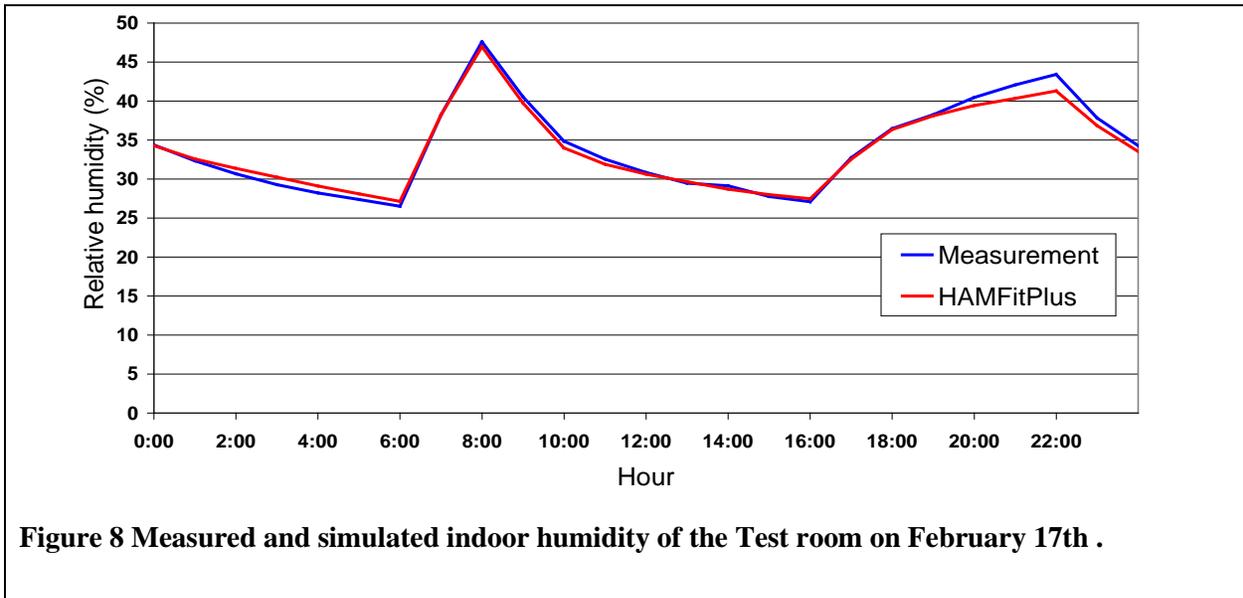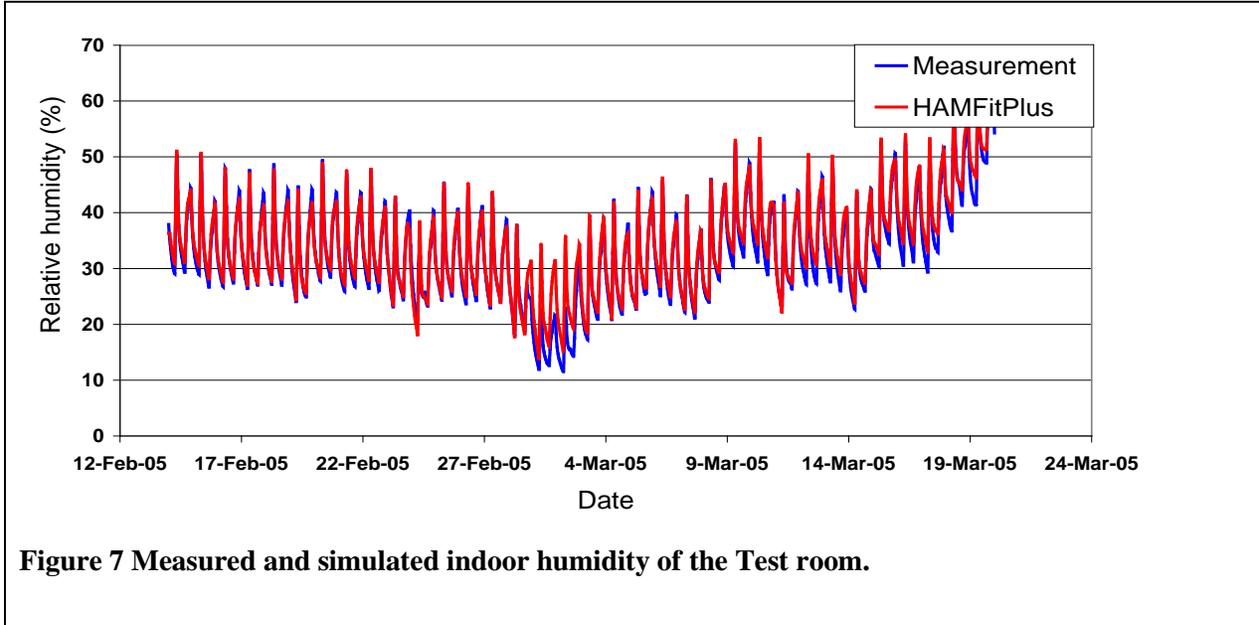
4. CONCLUSION

The three aspects of building design: durability, indoor condition, and energy performance, are interrelated. These three building performance parameters have to be considered simultaneously for optimized building design. Otherwise, there will be ambiguity of indoor boundary conditions for building envelope model; lack of information on moisture source and moisture buffering effects of interior materials for indoor model; and inaccurate operative temperature control, energy consumption and ventilation rate for HVAC systems. In this paper an integrated approach is proposed to deal with these inter related and coupled effects. The newly developed whole building hygrothermal model is developed by integrating building envelope and indoor models. The integrated model is successfully benchmarked against internationally published analytical and experimental test cases. The excellent agreement obtained between HAMFitPlus simulation results and the respective reference solutions of the test cases confirm the robustness of the model and its usefulness in an integrated whole building performance analysis. In future publications, the practical application of the model for holistic assessment of building enclosures moisture performance, indoor conditions (temperature and relative humidity) and energy efficiency of a building will be presented.

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