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The 11th International Conference on Durability of Building Materials and Components [Proceedings], pp. 1-8, 2008-05-11

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NRCC-50286

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A version of this document is published in / Une version de ce document se trouve dans:
11th International Conference on Durability of Building Materials and Components,
Istanbul, Turkey, May 11-14, 2008, pp. 1-8

Development and Benchmarking of a New Hygrothermal Model

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ABSTRACT

Building enclosures are subjected to a random climatic loading on the exterior surface and a relatively stable indoor condition on the interior. These loadings result in a transport of Heat, Air and Moisture (HAM) across the structure. Depending on the boundary conditions, a building envelope component may experience wetting or drying as it is exposed to real weather conditions that change by hours and seasons. In addition to the time varying external loading, the thermal and moisture storage characteristics of the layers, which constitute the enclosure component, make the HAM transport a complex non-linear process. HAM models, which take these complex interactions, have a significant benefit for evaluation of building envelope performance as they can provide detailed spatial and temporal conditions of the component.

In this paper, the development and benchmarking of a new hygrothermal model (HAMFit) are presented. First, a set of partial differential equations (PDEs) that govern the heat, air, and moisture transfer across building envelopes are formulated based on building physics. Then, these nonlinear and coupled PDEs are solved simultaneously for air velocity, temperature, and moisture distributions in the computational domain for a given outside environmental condition (weather data) and prescribed indoor conditions. The PDEs are solved using finite-element based commercial software called COMSOL Multiphysics and MatLab. The model is benchmarked using internationally published numerical model test cases. The good agreements obtained with the respective test cases suggest that the model can be used for products development and evaluations as well as hygrothermal performance assessment of different building envelope components.

KEYWORDS

HAMFit, HAM, hygrothermal modeling, Building envelope model

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1. INTRODUCTION

Building enclosures are subjected to a random climatic loading on the exterior surface and a relatively stable indoor condition on the interior. These loadings result in a transport of Heat, Air and Moisture (HAM) across the structure. The direction of flow of these entities depends on the gradient of the driving potential of the respective entity. In addition to the time varying external loading due to time varying weather conditions, the thermal and moisture storage characteristics of the layers, which constitute the enclosure component, make the heat and moisture transport in the building envelope a transient and complex process. The complex phenomena including the dynamic wetting and drying processes of the building envelope component can be captured using computer models. In various research projects, hygrothermal models are used to assess the performance of a wall system as it is exposed to climatic conditions of different geographical locations, or to select an appropriate building envelope system for a given geographic locations (Tariku et al. 2007; Tariku and Kumaran, 2006, 1999). The model presented here (HAMFit) is part of the recently emerging class of HAM models that use commercial software to solve building physics problems (Kalagasidis, 2004; van Schijndel, 2007). These models are more transparent and flexible for futures upgrades (for example to 2D or 3D), addition of new features and integration with other models.

2. MATHEMATICAL MODELS IMPLEMENTED IN HAMFit MODEL

2.1. Moisture transfer

The general equation for moisture transfer through a porous media is given by Equation [1]. This governing equation is based on conservation of mass, and accounts for moisture transfer by vapor diffusion, convection and liquid water conduction. The vapor diffusion and liquid conduction fluxes are given by Fick's and Darcy's law, respectively.

$$\frac{\partial w}{\partial t} + div\left(\rho_a V \omega\right) + div\left(-\delta_v \frac{\partial P_v}{\partial x_i}\right) + div\left(D_l\left(\frac{\partial P_s}{\partial x_i} + \rho_w g\right)\right) = 0 \qquad [1]$$

Where w is moisture content (kg/m^3), ρ_a is air density (kg/m^3), V is air velocity (m/s) and ω absolute humidity (kg/kg-air), P_v and P_s are vapor and suction pressures (Pa), respectively, ρ_w is density of water (kg/m^3), g is the acceleration due to gravity (m/s^2), δ_v and D_l are the vapor permeability and liquid conductivity of the material (s). The moisture balance equation, Equation [1], comprises of various moisture driving potentials, P_v, P_s, w and ω. In the numerical method adapted here it is important to express the driving forces and flow variables with a single flow potential. The chosen flow potential in this work is relative humidity (ϕ) since it is continuous at interface of two layers of materials with different moisture storage properties (sorption and moisture retention), in the contrary to moisture content, which is discontinuous. Thus, the mathematical model implemented in HAMFit for moisture transfer through building envelope component is presented as shown in Equation [2], The full mathematical derivation of the moisture and heat transfer equations are given in Tariku's Ph.D. thesis (to be published in early 2008). In Equation [2] Θ is sorption capacity (kg/m^3), T is temperature (^{o}C), $C_c = \frac{0.622}{P_{atm}}$, $\hat{P}$ and P_{atm} are saturated vapor and atmospheric pressure (Pa), respectively, R and M are the universal gas constant (8.314 J.mol^{-1}) and molecular weight of water molecule (0.01806 kg.mol^{-1}), respectively

$$\Theta \frac{\partial \phi}{\partial t} = \frac{\partial}{\partial x_i}\left(D_\phi \frac{\partial \phi}{\partial x_i} + D_T \frac{\partial T}{\partial x_i} \right) - \frac{\partial}{\partial x_i}\left(D_l \rho_w \vec{g} + \rho V_i C_c \widehat{P} \cdot \phi \right) \qquad [2]$$

where: $D_\phi = \left(\delta_v \widehat{P} + D_l \frac{\rho_w R}{M} \frac{T}{\phi} \right)$ $\quad D_T = \left(\delta_v \phi \frac{\partial \widehat{P}}{\partial T} + D_l \frac{\rho_w R}{M} \ln(\phi) \right)$

2.2. Heat transfer

After some mathematical manipulations, the conservation equation for the total energy (sum of internal, kinetic and potential energy) can be expressed in terms of enthalpy, *h*, Equation [3] (Kuo, 1986).

$$\frac{\partial(\rho h)}{\partial t} + div(\rho V h) = -div(j_q) + \dot{Q}_s \qquad [3]$$

Where j_q is a diffusion term, which comprises heat transfer by conduction and enthalpy transport due to moisture transfer. Q_s is a heat source (or sink) term. The mathematical model that is implemented in the HAMFit model for heat transfer through building envelope component is obtained (Equation [4]) after substituting the transient, convection and diffusion terms with the corresponding mixture enthalpy (moisture, air and solid matrix), and carried out some mathematical manipulations.

$$\rho_m Cp_{eff} \frac{\partial T}{\partial t} + \rho_a (Cp_a + \omega Cp_v) div(VT) + div(-\lambda_{eff}\, grad(T)) = \dot{m}_c h_{fg} + \dot{m}_c T (Cp_v - Cp_l) + \dot{Q}_s \qquad [4]$$

Where ρ_m is density of material (kg/m^3), ρ_a is density of air (kg/m^3), Cp_a, Cp_v and Cp_l are the specific heat capacity of air, vapor and liquid water (J/(K.kg)), respectively. Cp_{eff} and λ_{eff} are the effective specific heat capacity and thermal conductivity (which take moisture effect into account), respectively. h_{fg} is the latent heat of condensation/evaporation (J/kg). $\dot{m}_c = div\left(\delta_v \frac{\partial P_v}{\partial x_i} \right) - \rho_a div(V\omega)$ is the amount of moisture condensation/evaporation (kg/s)

2.3. Airflow through porous media

Airflow through a porous media can be expressed by using Poiseuille's law of proportionality (Hens, 2007), which relates pressure gradient and flow velocity (Equation [5]).

$$V = -\frac{k_a}{\mu} div(P) \qquad [5]$$

Where k_a and μ are the airflow coefficient and dynamic viscosity, respectively. Combing the mass conservation equation for incompressible flow (in building physics applications, the air is considered as incompressible due to very low airflow speed, and low pressure and temperature changes) with Equation [5], gives the governing equation for airflow through porous media.

$$div\left(\delta_a div\left(P\right)\right) = 0 \qquad [6]$$

Where $\delta_a = \rho_a \frac{k_a}{\mu}$ is the air permeability of the porous media.

3. DEVELOPMENT OF A NUMERICAL TOOL FOR HAM ANALYSIS (HAMFit)

3.1. Numerical tool

The governing equations implemented in the building envelope model (HAMFit) are Equation [2], [4], and [6] for moisture, heat and air transport, respectively. To obtain the airflow velocity, temperature and relative humidity fields across the computational domain (building envelop component), the coupled and nonlinear partial differential equations (PDEs) need to be solved simultaneously. Here, a finite-element based computational tool called COMSOL Multiphysics and MatLab (Mathworks) are used to solve these three equations. COMSOL Multiphysics has a library of predefined models to solve familiar engineering problems such as convection diffusion problems, fluid dynamics, heat transfer and other similar problems. Also it has a provision to create and solve user-developed models, which may not be solved by the standard modules. In fact, HAMFit model is developed using this equation based modeling technique "PDE Modes", where the formulated HAM governing PDEs are directly implement it in the COMSOL Multiphysics working environment. The solver is based on an explicit scheme with variable time stepping. The user can predefine the maximum time step so that it will match with the boundary condition change period. It is possible to solve any one of the three or all equations simultaneously. In addition to its efficient solver it has a graphical user interface (GUI) to create computational domain geometry, automatic and user controlled mesh generator, and also has an integrated post processing capability for plotting, interpolating and integrating simulation results.

3.2. HAMFit model

The newly developed building envelope model, HAMFit, has two versions, HAMFit-1D and HAMFit-2D. HAMFit-1D is used for one-dimensional heat, air and moisture analysis of building envelope components. And HAMFit-2D is used to solve two-dimensional HAM problems that are caused by the geometry of the region of interest such as wall-floor junction, two-dimensional corner section, and also in cases where the physical process itself has three-dimensional nature but can be approximated in two-dimension (for example airflow and gravitational moisture flow in the structure). The models take advantage of the smooth interfaces of COMSOL Multiphysics, MatLab and SimuLink computational tools, which all are from the same development environment. In fact COMSOL Multiphysics is one of the blocks in the SimuLink model library, and it is also possible to call MatLab functions from COMSOL Multiphysics working environment. Making use of these flexible simulation environments, HAMFit model is developed in such a way that a number of functions are created in MatLab; and these functions are called by COMSOL MultiPhysics multiple times during solving the HAM equations, which are caste in COMSOL MultiPhysics "PDE Modes". The "PDE Modes" data structure of the problem including the geometry, mesh, PDEs and boundary conditions are embedded in the SimuLink S-function. Finally, the hygrothermal simulation (S-function) is run in the SimuLink simulation environment where the overall simulation parameters including outputs of the simulation results are controlled. S-function is a user-developed SimuLink block written in MatLab or C programming language, and where the developer sets the block's tasks, inputs and outputs. One of the advantages of this modeling technique is that it allows simulation of HAM transfer in any building envelope detail with no geometric (shape) restriction.

4. BENCHMARKING OF HAMFit

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 Ph.D. Thesis (to be published in early 2008). Here, two of the five benchmarking exercises that are designed in the European HAMSTAD (Hat, Air and Moisture Standards Development) project are used for assessing the accuracy of the model through inter model comparison. The objective of the HAMSTAD project was to develop test cases by which the accuracy of the existing and newly developed hygrothermal models will be evaluated (Hagentoft, 2002).

4.1. Comparative Analysis 1—HAMSTAD Benchmark Exercise #3

In benchmark #3, the effect of airflow (exfiltration and infiltration) on the wetting (accumulation of moisture) and drying of a lightweight structure of 200 mm thickness is analyzed. Although the main moisture transfer mechanism in this exercise is by airflow, moisture transports due to temperature and moisture gradient across the monolithic wall layer. The pressure gradients across the wall, which causes heat and moisture transfer by convection, in both infiltration and exfiltration periods are 30 Pa, Figure 1. The exterior surface of the structure is vapor tight (painted), where as the interior surface is open. Accordingly the mass transfer coefficients of the exterior and interior surfaces are 7.38E-12 and 2E-7 s/m, respectively. The heat transfer coefficients for both surfaces are 10 W/(m^2K).

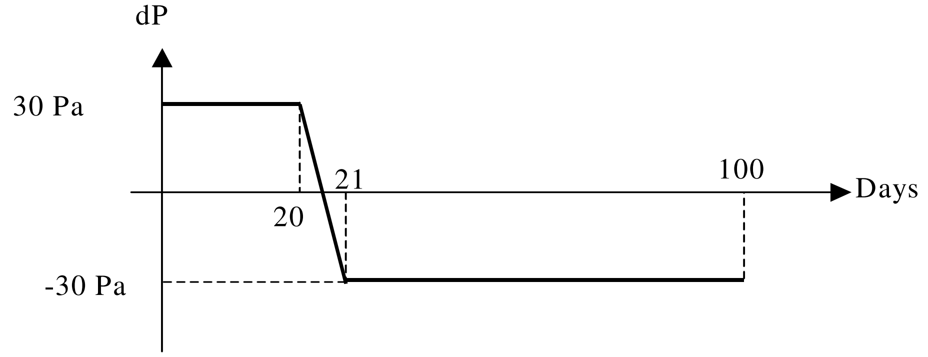
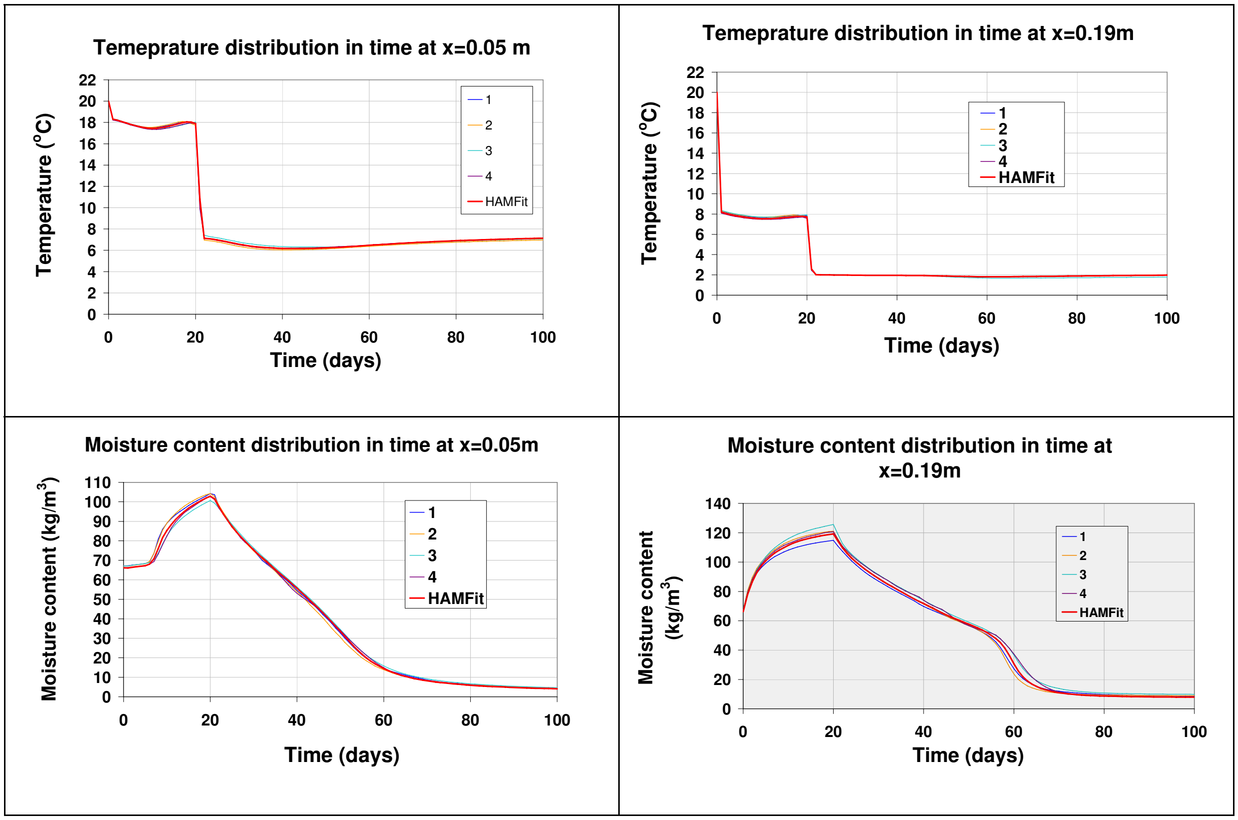


Figure 1 Pressure gradient across the wall

The initial hygrothermal conditions of the structure are 20°C and 95% temperature and relative humidity, respectively. In the first 20 days the airflow is from inside to outside (exfiltration) and the airflow is reversed in the next 80 days (infiltration). The interior temperature and relative humidity conditions are 20°C and 70%, respectively. Where as the exterior temperature and relative humidity conditions are 2°C and 80%, respectively. These boundary conditions are maintained constant for the 100 days of simulation period. The density and specific heat capacity of the monolithic layer are 212 kg/m^3 and 1000 J/(kg.K), respectively. The full description of this benchmark exercise is given in Hagentoft (2002). Here, the temperature and moisture content time history of the left and right section of the wall, 0.05 and 0.19 m respectively, are presented in Figure 2 below. For comparison purpose, the HAMFit simulation results are superimposed on the solutions provided by the HAMSTAD participants. The top two figures are the temperature and the bottom two figures are the moisture content profiles of the left and right sections of the walls. As can be seen in these figures, the HAMFit simulation results agree very well with the other models solutions (labeled 1 to 4).


Temeprature distribution in time at x=0.05 m

Temeprature distribution in time at x=0.19m

Moisture content distribution in time at x=0.05m

Moisture content distribution in time at x=0.19m

Figure 2 Temperature and moisture content time history of the wall at 0.05 and 0.19 m depth

4.2. Comparative analysis 3—HAMSTAD Benchmark Exercise #4

The second comparative analysis deals with heat and moisture transfer in a two-layer wall system exposed to realistic internal and external boundary conditions. The wall system is composed of a load-bearing layer on the exterior and finishing layer on the interior. The load-bearing is 100 mm thick and has a density of 2050 kg/m^3, and specific heat capacity of 840 J/(K.kg), where as the finishing layer has a thickness of 20 mm, density 790 kg/m^3 and specific heat capacity of 870 J/(K.kg). The full description of this benchmark exercise is given in Hagentoft (2002). The test case is more challenging (Hagentoft et al., 2004) as it involves severe climatic load that causes surface condensation on the exterior surface due to nighttime cooling (low equivalent temperature), and frequent occurrences of wetting and drying of the wall due to the alternating rain and solar radiation loads. Moreover, the problem involves rapid rainwater absorption at the interfaces and fast moisture movement within the layers due to the extremely high liquid water absorption property of the load-bearing layer. For comparison purpose, the simulation results of HAMFit are superimposed on the corresponding HAMSTAD project participants' solutions. In Figure 3 the surface moisture content and temperature, as well as the moisture and temperature profiles across the wall sections at 96 hours are presented. As can be seen in these typical results presented here, the simulation results of HAMFit agree very well with the other six models solutions (labeled 1 to 6).

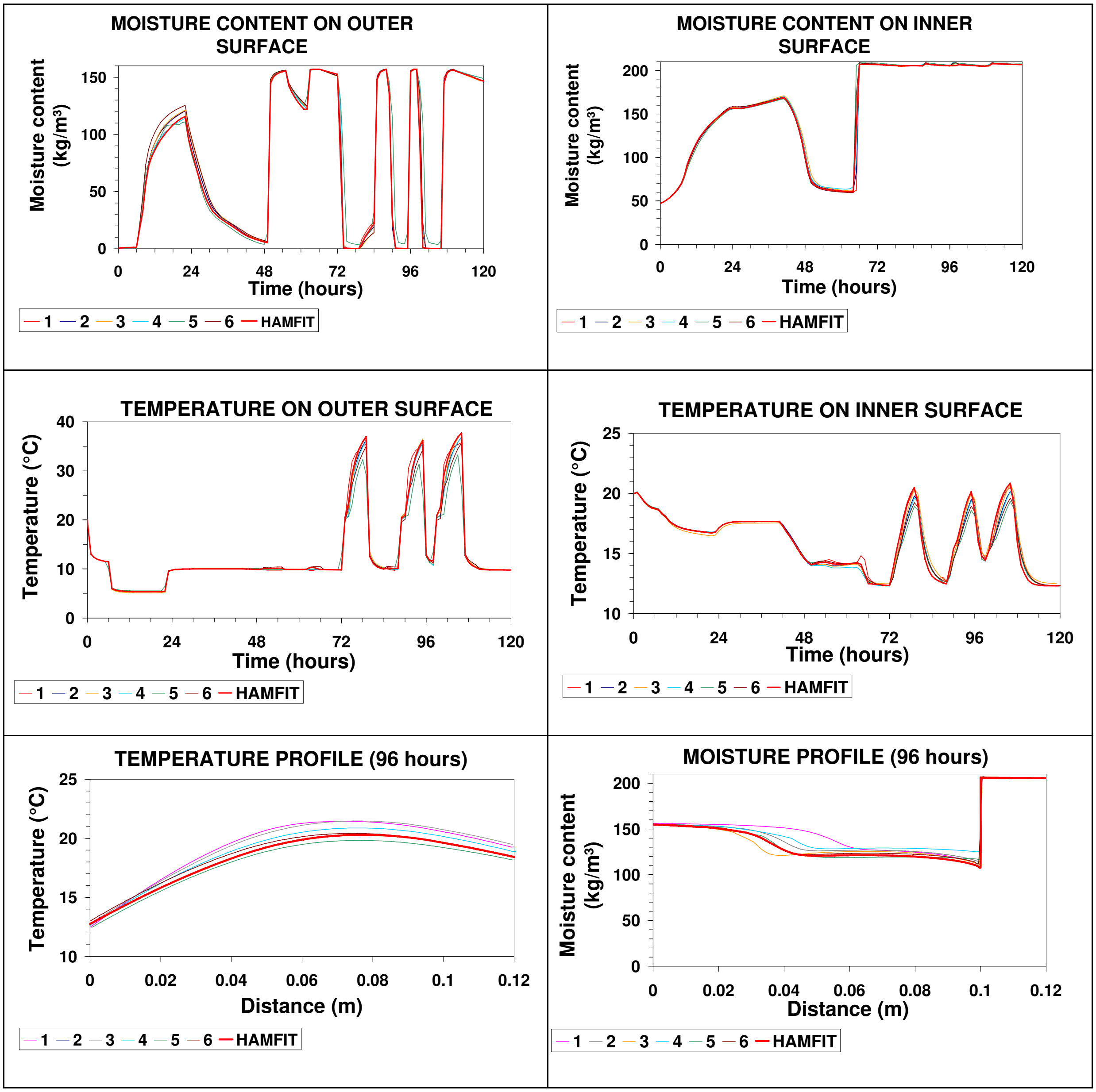


Figure 3 The moisture and temperature conditions of the surfaces and the wall at 96 hours

5. CONCLUSION

Heat, Air and Moisture (HAM) models are useful for hygrothermal performance assessment of building envelope components, new building materials and systems. In this paper, a new hygrothermal model, which utilizes equation based modeling technique, is developed. The model takes advantage of the smooth interfaces of commercial software of the same family, namely COMSOL Multiphysics, MatLab and SimuLink. The equation based modeling technique provides high transparency and flexibility of modeling HAM problems. Moreover, with this modeling technique addition of new feature and maintaining the software are relatively easy and less time consuming. The accuracy of HAMFit model is tested by carrying out two internationally accepted test cases. In both benchmarking exercises, the HAMFit simulation results are in very good agreement with other models' respective solutions, and consequently the model can be used with great confidence. In general, the model can solve airflow through a building component and the associated heat and moisture transfer, and accounts for simultaneous vapor and liquid capillary flow, and also has a capability of solving multi-dimensional HAM problems.

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