

## INTEGRATED HEAT, AIR AND MOISTURE MODELING IN A SINGLE SIMULATION ENVIRONMENT

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**Summary:** The modeling and simulation of whole building heat air and moisture (HAM) responses in relation to human comfort, energy and durability are relevant. The paper presents the integration of the following lumped parameter models: whole building, HVAC and primary systems and distributed parameter models: indoor airflow, HAM transport in constructions and external airflow/driving rain into a single simulation environment. It is concluded that the presented simulation environment is capable of modeling and efficiently solving a large range of complex integrated HAM problems related with different time scales and lumped/distributed parameters.

**Keywords:** Modeling, simulation, heat air & moisture, HAM, buildings, systems]

### 1. INTRODUCTION

It is widely accepted that simulation can have a major impact on the design and evaluation of building and systems performances. Also, the modeling and simulation of whole building heat, air and moisture (further-on called HAM) responses in relation to human comfort, energy and durability are relevant. IEA Annex 41 [1] focuses on a holistic approach of HAM transfer between the outside, the enclosure, the indoor air and the heating, ventilation and air-conditioning (HVAC) systems. Therefore integrated HAM models capable of covering all these issues are sought-after. There is no single simulation tool that covers all of the issues (Augenbroe [2]). One option is the external coupling of tools (Hensen et al. [3]; Djunaedy [4]). Recent developments in general modeling and simulation tools give rise to another option: the use of a single computational environment. Important requirements for such a simulation environment are: (a) A lot of existing HAM models are based on Ordinary Differential Equations (ODEs) or Partial Differential Equations (PDEs). Therefore it should be relative easy to implement and couple such models in the simulation environment. (b)

The modeling and simulation results should be reproducible and accessible. This means that the relation between mathematical model and numerical model should be clear and people in the scientific community should have access to models (c) For practical use, a whole building model, capable of simulation the building response, should also be present. MatLab (including toolboxes) [5] has become the standard tool for scientific computations. The aim of this paper is to investigate whether the MatLab simulation environment, including SimuLink & Comsol, is capable of meeting all requirements. Over the past years hundreds of tools are developed (Crawley et al. [6]). The aim of this Section is not to obtain an exhaustive list of HAM models, but to obtain a representative group of HAM models that will be used in the next Section for identifying common HAM related modeling problems. The work in this paper is related to: (1) Annex 41 [1], (2) building energy programs, (3) modeling and simulation techniques; (4) Matlab/SimuLink related tools. For each of the four items, a summary of involved HAM models is presented now. First, in 2005, 14 different tools were used in an Annex 41 common exercise [1] about simulating the dynamic interaction between the indoor climate of a room and the HAM response of the enclosure. All tools model the indoor air and the enclosure. Six HAM models are stand-alone simulation tools and have promising capabilities for simulating HVAC systems: Bsim [7], IBPT [8], IDA-ICE [9], TRNSYS [10], EnergyPlus [11], and HAMLab [12]. The latter is presented in this paper. Second, the energy related software tools at the Energy Tools website U.S. Department of Energy U.S [13] has been used for several comparison studies. A recent overview is provided by Crawley et al. [6]. Furthermore, Schwab et al. [14] used the same website for a study on programs that might simulate whole building HAM transfer. The criteria were based on: moisture storage in building materials, calculate indoor climate, moisture exchange in

HVAC system, access to source code. Three tools met all criteria: Bsim [7], TRNSYS [10] and EnergyPlus [11]. These tools are already mentioned. Third, Gough [15] reviews tools with the focus on new techniques for building and HVAC system modeling. In this study four simulation techniques were investigated. Proved techniques related with HAM modeling are the equation-based method techniques such as Neutral Model Format and IDA solver, which are included in IDA-ICE [9] and TRNSYS [10]. The other mentioned techniques of Gough [15] are simulation environments with limited HAM modeling capabilities for building simulation. Fourth, Riederer [16] provides a recent overview of Matlab/SimuLink based tools for building and HVAC simulation. The tools who are most related with the work in this paper are discussed now. SIMBAD [17] provides HVAC models and related utilities to perform dynamic simulation of HVAC plants and controllers. The toolbox focuses on thermal processes with limited capabilities for moisture transport simulation. In addition to this work, this paper presents how models that include moisture transport, can be simulated in SimuLink. The International Building Physics Toolbox (IBPT) [8] is constructed for the thermal system analysis in building physics. The tool capabilities also include 1D HAM transport in building constructions and multi-zonal HAM calculations. (Sasic Kalagasidis [18]). All models including the 1D HAM transport in building constructions are implemented using the standard block library of SimuLink. The developers notice the possibility to couple to other codes / procedures for 2D and 3D HAM calculations. In addition to this work, this paper shows how this can be done using Comsol. All HAM tools mentioned in previous Sections, face at least one limitation that cannot be solved by the tool itself. Either a problem occurs at the integration of HVAC systems models into whole building models, or a problem occurs at the integration of 2D and 3D geometry based models (for example airflow and HAM response of constructions) into whole building models. The first problem, a time scale problem, is caused by the difference in time constants between HVAC components and controllers (order of seconds) and building response (order of hours). This can cause inaccurate results and long simulation duration times (Gouda et al. [19] and Felsman et al. [20]). The second problem, a lumped/distributed parameters problem, is caused by the lack of lumped parameter tools to include internal 2D, 3D finite element method (FEM) capabilities (Sahlin et al. [21]). The key question is whether a single simulation environment is suitable for solving both the above-mentioned multi physics modeling problems concerning different time scales and lumped/distributed parameters. Our method was, first to develop, implement and validate the following modeling facilities into the simulation environment SimuLink: (1) a whole building (global) modeling facility, for the simula-

tion of the indoor climate and energy amounts; (2) an ordinary differential equation (ODE) solving facility, for the accurate simulation of HVAC systems and controllers; (3) a partial differential equation (PDE) solving facility, for the simulation of 2D/3D HAM responses of building constructions and 2D internal/external airflow. The second step was to evaluate our results with regard to the key question.

## 2. WHOLE BUILDING MODEL

The model originates from the thermal indoor climate model (ELAN) which was already published in 1987 (de Wit et al. [23]). Separately a model for simulating the indoor air humidity (AHUM) was developed. In 1992 the two models were combined (WAVO) and programmed in the MATLAB environment (van Schijndel & de Wit [24]). Since that time, the model has constantly been improved using newest techniques provided by recent MATLAB versions. Currently, the hourly-based model is named HAMBBase, which is capable to simulate the indoor temperature, the indoor air humidity and energy use for heating and cooling of a multi-zone building. The physics of this model is extensively described by de Wit [25].

### 2.1. Integration and the time scale problem

It is obvious that the hourly based approach of HAMBBase is not accurate enough if we want to integrate building systems with its relative small time scales (order seconds). Our major recent improvement is the development of a so called hybrid model that consists of both a continuous part with a variable time step as well as a discrete part with a time step of one hour. We adapted our HAMBBase model by splitting the energy and vapor flows into two parts. First, a discrete part was developed for modeling the transmittance through walls. Second, a continuous part was developed for the rest (admittance, ventilation, sources, etc.). We implemented this approach by using so-called S-Functions for SIMULINK (see also the Appendix). This new model, named HAMBBase\_S to avoid confusion, is able to simulate complicated HVAC installations and controls simultaneously with the building. We summarize the main advantages:

- a) The dynamics of the building systems where small time scales play an important role (for example on/off switching) are accurately simulated.
- b) The model becomes time efficient as the discrete part uses 1-hour time steps. A yearly based simulation takes less than 3 minutes on a Pentium 3.4 GHz, 2GB computer.
- c) The moisture (vapor) transport model of HAMBBase is also included. With this feature, the (de-) humidification of HVAC systems can also be simulated.

## 2.2. Verification

The thermal part of HAMBase has been subjected to a standard method of test (ASHRAE, [26]) with satisfactory results. For further details, see Table I. The hygric parts of both HAMBase and HAMBase\_S have been subjected to a new benchmark case developed by the IEA Annex 41 [1]. The geometry is identical to the one in the ASHRAE standard [26]. Further test conditions are as follows: (1) there is only one 1D construction type with linear properties; (2) the exposure is completely isothermal; (3) the outside relative humidity (RH) is 30%; (4) there are no windows; (5) the internal gains equal 500g/hour; (6) the ventilation rate is 0.5 ach. Bednar & Hagentoft [27] provide the analytical solution of this benchmark. Figure 1 shows the results of the a benchmarks representing moisture buffering by combined air and the construction. The figure provides three curves: the analytical solution of Bednar & Hagentoft [27], the hourly based HAMBase solution and the continuous HAMBase\_S solution. The results show a good agreement between all solutions.

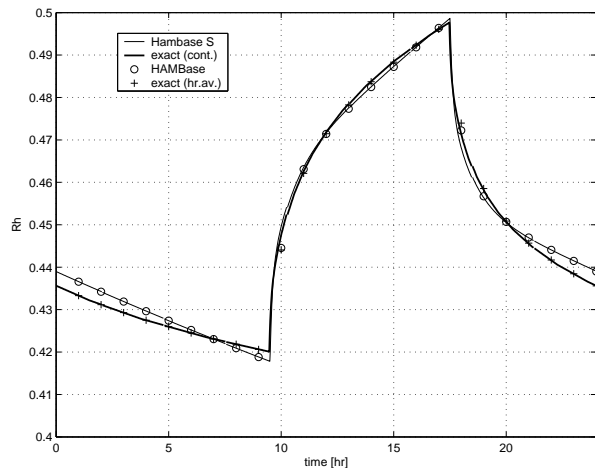


Fig. 1. Simulated RH of the indoor climate with moisture buffering by air and the construction

## 2.3. Validation

The intention of the following study, developed within the Annex 41, was to retrieve an experimental based and well defined benchmark for evaluating the involved HAM models. The experiment comprehends two real and almost identical rooms, which are located at the outdoor testing site of the Fraunhofer-Institute of building physics in Holzkirchen. During the winter of 2005-2006, tests were carried out. The walls and the ceiling of the test room were fully covered with aluminum foil. In the reference room 50 m<sup>2</sup> of the walls was not covered with aluminum providing more buffering capacity of the walls compared to the test room. The air temperature in both rooms was kept between 19.8 and 20.2 °C. The next results are presented: the measured and simulated RH in the reference

room (figure 2) and heating power to the reference room (figure 3).

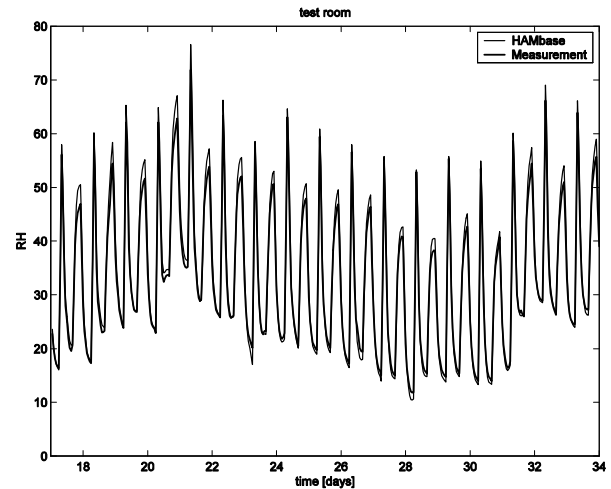


Fig. 2. The measured and simulated RH in the test room

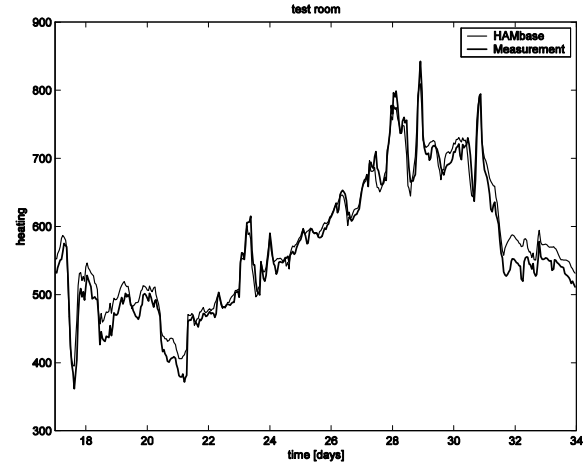


Fig. 3. The measured and simulated heating power in the test room

The results of the test room are similar to the reference room and are therefore left out. The results from figure 2 and 3 show a good agreement between measured and simulated results.

We may conclude that our approach of discrete/continuous modeling provide accurate results within acceptable simulation duration times and thus providing us a good solution to the mentioned time scale problem.

## 3. ODE BASED MODELING

### 3.1. Integration

A complete case study on how to integrate a model described by a system of ODEs into SimuLink is now exemplarily shown for a heat pump model. We start with a mathematical model of the heat pump, based on first principles, in the form of ODEs:

$$\begin{cases}
 COP = k \cdot \frac{0.5 \cdot T_{cin} + 0.5 \cdot T_{cout} + 273.15}{(0.5 \cdot T_{cin} + 0.5 \cdot T_{cout}) - (0.5 \cdot T_{vin} + 0.5 \cdot T_{vout})} & (1) \\
 C_c \frac{dT_{cout}}{dt} = F_{cin} \cdot c_w \cdot (T_{cin} - T_{cout}) + COP \cdot E_{hp} \\
 C_v \frac{dT_{vout}}{dt} = F_{vin} \cdot c_w \cdot (T_{vin} - T_{vout}) - (COP - 1) \cdot E_{hp}
 \end{cases}$$

Where  $T$  is temperature [ $^{\circ}\text{C}$ ], COP Coefficient of Performance [-],  $k$  heat pump efficiency [-],  $c_w$  specific heat capacity of water [ $\text{J/kgK}$ ],  $C$  heat capacity of the water and pipes in the heat pump [ $\text{J/K}$ ],  $t$  time[s],  $F$  mass flow [ $\text{kg/s}$ ],  $E_{hp}$  heat pump electric power supply [ $\text{W}$ ]. Subscript  $c$  means water at the condenser,  $v$  water at the evaporator,  $in$ , incoming,  $out$ , outgoing. The second step is to define the input-output definition of the model. The final step is to implement the mathematical model into a S-Function, a programmatic description of a dynamic system. It should be mentioned that the time scale problem seems less relevant in case of ODE based models because there are special designed solvers for this case. So-called stiff solvers can handle such a problem accurately and time efficient. On the other hand, simulating controllers for example (rapid) on/off switching can generate small time steps during simulation. Although accurate results are obtained in this case, it could still lead to relative long simulation duration times.

### 3.2. Validation

At a test site of the Eindhoven University, a configuration with a heat pump, an energy roof has been investigated with a focus on the convective heat recovery from ambient air. Also one of the goals of this project was to evaluate the modeling approach of previous Section applied to respectively a heat pump, an energy roof and a thermal energy storage. From this work, published in van Schijndel & de Wit [32], we show the validation results of the heat pump which are presented in figure 4.

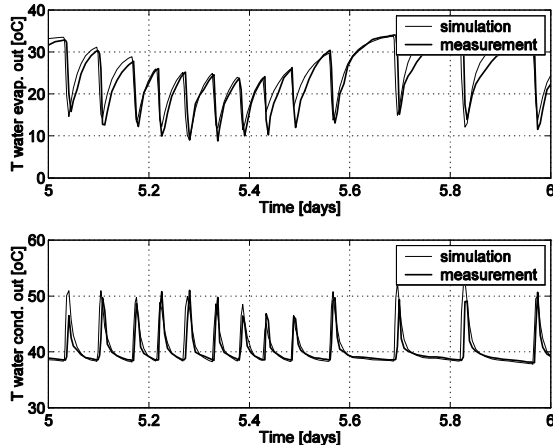


Fig. 4. The measured and simulated water temperature of the evaporator (top) and condenser (bottom).

In this figure the measured and simulated water temperatures of the outgoing flows at the condenser and evaporator are compared and show a good agreement. The other components: energy roof and thermal energy storage were validated with similar results. We may conclude that the presented ODE based modeling approach provide accurate results. In general it is expected that systems modeled as a system of ODEs can be relative easy and accurately simulated using the presented modeling approach.

## 4. PDE BASED MODELING

HAM responses of building constructions and internal/external airflow can be modeled and simulated with Comsol (formerly FemLab) [28]. This is an environment for modeling scientific and engineering applications based on partial differential equations (PDEs).

### 4.1. Already published models and validation data

van Schijndel [31] presents PDE models and validation data for: (1) 1D water absorption of several brick materials; (2) 2D combined heat and moisture transport of a brick specimen; (3) 2D incompressible flow using the Boussinesq approximation with constant properties for the Reynolds ( $Re$ ) and Grasshof ( $Gr$ ) numbers. Furthermore, a 3D combined heat and moisture transport model of a brick specimen is also provided but not validated. Two PDE models are developed as part of the benchmark study, concerning 1D HAM transport in constructions: HAMSTAD published by Hagentoft et al [29]. One model shows an excellent agreement with the solution of the analytical case. A second PDE model, simulating the insulated roof case, shows a good consensus with the other solutions. In addition to the above mentioned models, a new developed model concerning driving rain is presented now. The model is verified by another benchmark case of the mentioned IEA Annex 41 [1], on boundary conditions. The benchmark covers for several building geometries: (a) Simulated wind velocity profiles around buildings; (b) Simulated raindrop trajectories; (c) Simulated wind-driving-rain coefficients on the building facades. The solution of (a) is obtained by using the standard k-epsilon turbulence model of Comsol. Figure 5 shows the simulated wind profile around the lower building. The solution of (b) is obtained from the equation of motion of a raindrop [32], moving in a wind-flow field characterized by a velocity vector  $v$  (see equation 2).

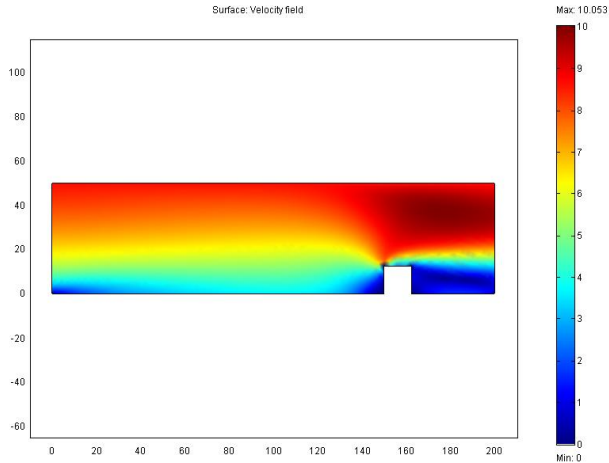


Fig. 5 The wind velocity profile: absolute value of the velocity [m/s] for each coordinate x, y [m].

$$g + f(Cd, Re) \cdot (v - \frac{dr}{dt}) = \frac{d^2 r}{dt^2} \quad (2)$$

where g is gravity, f is a function dependent on Re (Reynolds number) and Cd (drag coefficient), v is wind velocity, t is time and r is the position of raindrop. Equation 2 is solved with the ODE solver of MatLab providing raindrop trajectories. The result for the low building benchmark case is shown in figure 6.

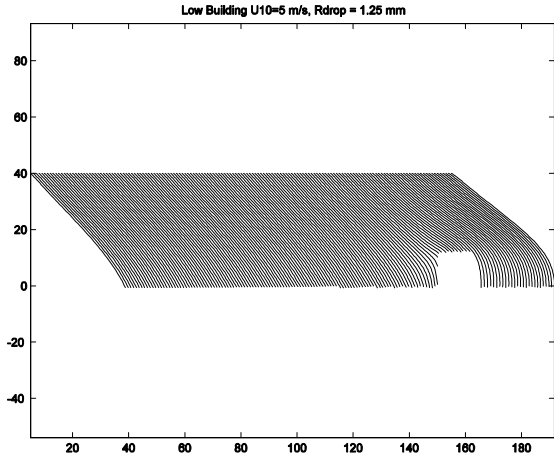


Fig. 6. The raindrop trajectories

The solution of (c) is obtained from the locations of raindrops hitting the building façade. The preliminary results are in good agreement with the results obtained by a reference solution. This is shown in figure 7.

#### 4.2. Integration and the lumped/distributed parameter problem

A second new development concerns the integration of a distributed parameter model and lumped parameter model in

SimuLink. In this case study, the 2D airflow model of van Schijndel [22] is implemented using the discrete part of an S-function..

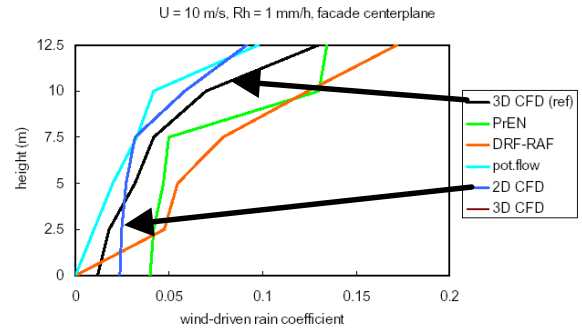


Fig. 7. Wind-driven rain coefficient at the centre of the building (reference solution: 3D CFD, our solution: 2D CFD)

After each time step (in this case 1 sec) the solution is exported. Dependent on the controller, different boundary values can be applied. Furthermore, the airflow at the inlet is now controlled by an on/off controller with hysteresis (Relay) of SimuLink. The sensor temperature (lumped parameter) is calculated as mean of a several air temperature nodes (distributed parameter). If the temperature of the sensor above 20.5 °C the air temperature at the inlet is 17 °C if the air temperature is below 19.5 °C the inlet temperature is 22 °C. Initially the inlet temperature is 18 °C. Figure 8 gives an overview of the results.

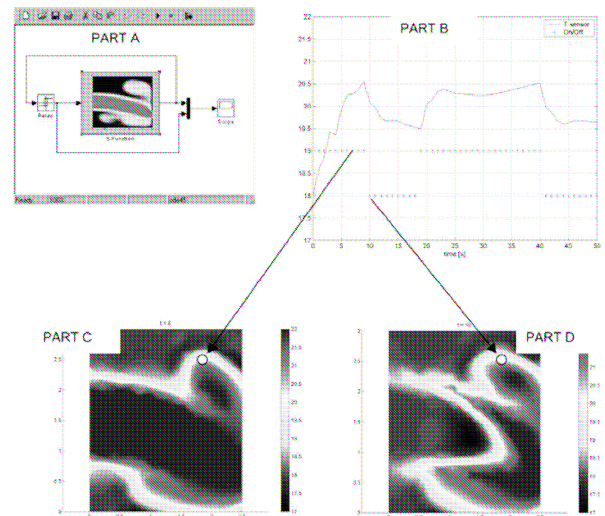


Fig. 8. Part A, The SimuLink model including the S-function of the Comsol model and controller (Relay), Part B, the temperature of the sensor (-) and the output of the on/off controller (+) versus time, Part C, the air temperature distribution at 8 sec. (hot air is blown in) and Part D, the air temperature distribution at 10 sec. (cold air is blown in) (o = sensor position).

From figure 8, it is clear that the controller has a great impact on the indoor airflow dynamics and temperature distribution. Many researchers perhaps overlook this phenomenon because most of the time, quasi steady airflow is assumed. This also shows the need of integrated models as presented here. Furthermore, we compared the amount of computational time used for solving the airflow problem to the rest of processes including calculation of the lumped parameter and the on/off controller. It turned out (as expected) that in this case most of the time (>98%) was consumed for solving exclusively the airflow problem.

## 5. CONCLUSIONS

It is concluded that the presented simulation environment Matlab/SimuLink/Comsol is capable of solving a large range of integrated HAM problems. Furthermore, it seems promising in accurately solving modeling problems that are caused by the presence of different time scales and/or lumped/distributed parameters. However, there are some limitations: (1) some specific solvers such as time-dependent k-epsilon turbulence solvers are not available yet. This means that, for example, time dependent 3D airflow around buildings cannot be integrated without external coupling; (2) Although it is possible to construct a full 3D integrated HAM model of the indoor air and all constructions in the simulation environment, the simulation duration time would probably be far too long to be of any practical use; (3) The modeling of radiation is not included in this research. The main benefits of our modeling approach are: (1) it takes advantage of the facilities of the well maintained Matlab/SimuLink and Comsol simulation environment such as the state-of-art ODE/PDE solvers, controllers library, graphical capabilities etc; (2) all presented models in this paper are public domain; (3) although not explicitly shown in this paper, compared to other HAM models, it is relative easy to integrate new models that are based on ODEs and/or PDEs. (4) the simulation facilitates open source modeling and if desired, models can be compiled into stand-alone (web) applications.

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