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HAM-Tools – a whole building simulation tool in Annex 41

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SUMMARY. HAM-Tools is a building simulation software. The main task of this tool is to simulate transfer processes related to building physics, i.e. heat, air and moisture transport in buildings and building components in operating conditions. The scope of the ECBCS Annex 41 "Whole Building Heat, Air and Moisture Response" was of a high relevance for the testing, development, validation and promotion of the HAM-Tools. The majority of the numerical studies made by this programme were provided for Subtask 1 "Modelling principles and common exercises". This paper gives an overview of the modelling capabilities of HAM-Tools and some results provided for Subtask 1.

1. Introduction

HAM-Tools is a building simulation software. 'HAM' stands for *H*eat, *A*ir and *M*oisture transport processes in buildings and building envelopes that can be simulated by this program, and 'Tools' describes its modular structure. The main objective of this tool is to obtain simulations of transfer processes related to building physics, i.e. heat, air and moisture transport in buildings and building components in operating conditions.

Using the graphical programming language Matlab/Simulink®, the code was developed as a library of predefined calculation procedures (tools) where each supports the calculation of the HAM transfer processes in a building part or an interacting system. Thus, the tool can be used for the investigations of the above mentioned transfer mechanisms and for the analyses of the overall hygro-thermal response of buildings.

HAM-Tools was developed by Sasic (2004), within a PhD work that was conducted at the Building Physics research group at Chalmers University of Technology. The structure of the programme, it's interface and documentations provided are standardized according to the guidelines given in the International Building Physics Toolbox in Simulink (www.ibpt.org). IBPT is an open source of calculation tools for building physics application. It is a result of the cooperative work between Chalmers University of Technology and the Building Physics Department from Technical University of Denmark (see Weitzmann et. al 2003). As a part of IBPT, HAM-Tools is also an open tool and publicly available for free downloading.

Due to the complexity of the physics that is in-built in the programme, the need for an active development of the tools and to the costly modelling platform in Matlab/Simulink®, HAM-Tools is more suitable for research and education than for a commercial use. Some examples of the research applications can be found in Sasic and Mattsson (2005), Ramos (2006), Hagentoft and Sasic (2007), Essah et. al (2008), Nik and Nielsen (2008). A significant effort has been put on the validation of the existing modules. Results of the validation are presented in Hagentoft et. al (2002), Sasic (2004 b, 2007 b) and, as it is shown below, in the final reports from Annex 41.

1.1 HAM-Tools in IEA Annex 41

The scope of the ECBCS[1] Annex 41 "Whole Building Heat, Air and Moisture Response" (ECBCS, 2008) was of a high relevance for the testing, development, validation and promotion of the HAM-Tools.

The majority of the numerical studies made by this programme were provided for Subtask 1 "Modelling principles and common exercises" (Woloszyn and Rode, 2008), the working group who dealt with the modelling of heat, air and moisture transfer processes that take place in "whole buildings". HAM-Tools solutions were provided for five out of six calculation exercises that were presented in Subtask 1, as it is summarized in Table 1. All these cases present one of the three possible validation methods: analytical validation, e.g. the problem where an exact mathematical solution is known, comparison with other codes and empirical validation. In addition, in the frame of this Subtask, two numerical studies on the influence of air infiltration on the hygro-thermal states in buildings were performed by HAM-Tools and presented in Sasic and Mattsson (2005) and Sasic (2007 a).

TABLE. 1: HAM-Tools solutions provided to the calculation exercises in Subtask 1. The marker "•" denotes solutions from Chalmers University of Technology, "∗" are solutions from CSTB[2] using HAM-Tools and "X" marker denotes the skipped cases. Validation methods are indicated as: /A/-analytical, /C/-comparison with other codes, /E/-empirical.

CE 0 /C/	600	•	CE 2 /E/	Case 1-1	•,∗	CE 3 /E/	Step 1	•				
	900	•		Case 1-2	•,∗		Step 2	•				
	600 FF	•		Case 1-3	•,∗		Step 3	•				
	900 FF	•		Case 2-1	•,∗		Step 4	X				
CE 1 and 1B /A, C/	600-0A	•		Case 2-2	•,∗	CE 4 /C/		A	B	C	D	E
	600-0B	•		Case 2-3	•,∗		Step 1	•	•	X	X	X
	600-Open	•		Case 2-4	•,∗		Step 2	•	•	X	•	X
CE 1A /A/	0A	•		Case 2-5	•,∗		Step 3	•	•	X	•	X
	0B	•		Case 2-6	•,∗	CE 5 /A, E/	X					

Some results were also provided for Subtask 2 "Experimental analyses of moisture buffering" (Roels, 2008). These were the numerical solutions to the benchmark cases on moisture buffering in a layer of gypsum boards under transient conditions. As measured data are available for all benchmark cases in Subtask 2, they represent a set of problems for the empirical validation of one-dimensional hygro-thermal calculations in a wall. Table 2 gives the overview of the cases and the HAM-Tools solutions provided. Besides, Ramos (2006) presented a separate study on moisture buffering of coated gypsum boards under transient conditions. The study encloses the measured data from a small chamber test, supported by numerical investigations done by HAM-Tools.

TABLE. 2: HAM-Tools solutions provided within Subtask 2. The "X" marker denotes the skipped cases.

Benchmark 1	Step - naked	•	Benchmark 2	Test 1	•
	Step - acryl	•		Test 2	•
	Step - latex	•		Test 3	•
	Cyclic-naked	•		Test 4	•
	Cyclic- acryl	•		Test 5	•
	Cyclic- latex	•		Hysteresis and 100 cycles	X

There were no particular contributions from HAM-Tools to Subtask 3 "Boundary conditions and whole building HAM analyses" (Kumaran and Sanders, 2008). However, the modelling of wind and wind pressure coefficients has been included in the above mentioned studies from Subtask 1, which deal with air

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[1] Energy Conservation in Buildings and Community Systems

[2] CSTB Centre de Thermique de Lyon, France

infiltration in buildings, (see for example Sasic 2007 a). Also, the modelling of the surface transfer coefficients has been addressed in the studies from Subtask 2.

One study based on numerical investigations by HAM-Tools was presented in the frame of Subtask 4 "Moisture-engineering application" (Holms, 2008). The study shows the moisture safety assessment in cold attics under different ventilation regimes. (Hagentoft and Sasic, 2007).

The HAM-Tools description and a selection of modelling issued from Annex 41 Subtask 1are presented hereafter.

2. Object oriented modelling approach in HAM-Tools

The general problem of HAM-Tools simulations is depicted in Figure 1, where main systems and transfer processes involved are indicated. These are: building enclosure (e.g. walls, windows, floor, ceiling, etc), building services (HVAC systems and components), occupants and appliances. The scope of the simulation is to find thermal and moisture states in a building enclosure and in enclosed air volumes, as the result of the building usage in specified operating conditions (in given climate conditions and internal activities). This knowledge enables a number of further analyses such as: calculation of energy consumption for heating and cooling in buildings, assessment of indoor comfort, analyses of risks for higher moisture content levels in a building construction and indoor air, functionality of HVAC systems, air flow distribution through openings on building enclosure, etc.

The main idea in HAM-Tools is to model a building as a system of cooperating objects. This approach is known as object-oriented programming (see for example Coyne et. al, 1989), as opposed to a traditional view in which a programme may be seen as a group of tasks to compute.
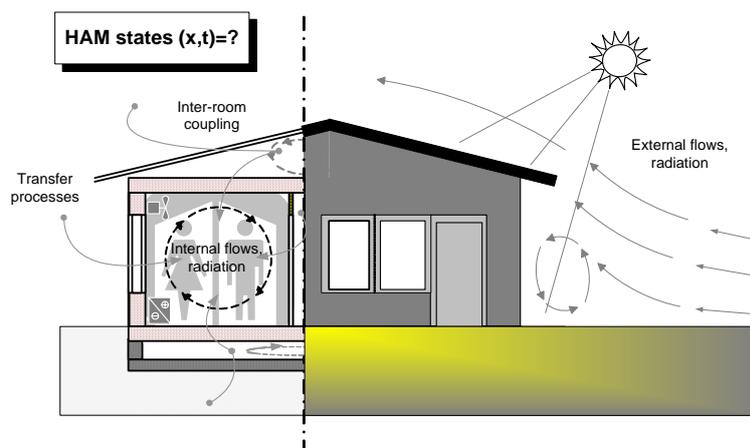

FIG.1 The general simulation problem in HAM-Tools.

2.1 Library

Using the graphical programming language Simulink® (Matlab), the code is developed as a library of predefined calculation procedures (tools) where each supports the calculation of the HAM transfer processes in a part of a building or in an interacting system. Tools are grouped according to their functionality into five sub-systems:

- Constructions   (building envelope parts),
- Zones   (air volumes and cavities),
- Systems   (HVAC systems),
- Helpers   (weather data and basic modelling tools) and
- Gains   (casual gains).

When all sub-systems are coupled together and solved simultaneously, the resulting simulation represents the highest level of integration in the HAM-Tools.

In the Simulink graphical approach, the HAM-Tools library appears as it is shown in Figure 2, where the above mentioned five subsystems appear as separate folders. Representatives of tools or blocks[3] from each of the subsystem are shown in the same figure below. Blocks can be modelled separately from each other, with different modelling techniques and with different levels of accuracy.
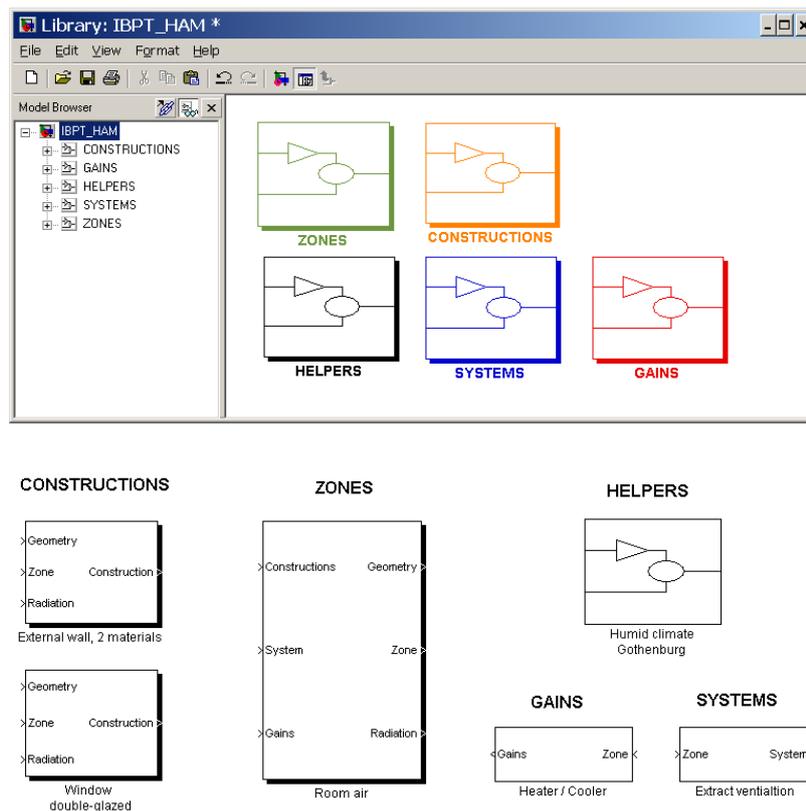

FIG.2 HAM-Tools library in Simulink, and some tools.

2.2 Interface

The blocks "communicate" with each other by exchanging data through communication ports. Input ports are usually grouped on a left-hand side of a block, while the output ports are placed on the right-hand side. The ports tolerate or provide the data that are organized in arrays or signals, which have predefined and rigid structures. In this way, the block communication is always ensured even then when they are developed by different users. The set of rules for the data exchange between the blocks is called interface.

For the highest level of integration in HAM-Tools, e.g. at the level where a model of a building is assembled, the set of seven signals is used. These are:

- Surface weather data

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[3] A "block" is a common term in Simulink for any kind of modelling elements – operations, routines, subsystems, etc.

- Construction array
- System array
- Geometry array
- Zone array
- Radiation array
- Gain array

The same interface is valid for all tools enclosed in IBPT (see Rode et. al 2002).

2.3 Building a model of a building

By combining different tools such as a single-layer wall in a multi-layer wall, a couple of different walls in a zone, several zones in a building, and finally together with climate load and HVAC equipment, it is possible to build a house as a system. Basically, all HAM-Tools models used in the common exercises of Subtask 1 were one-zonal models. A system with several air zones, a dwelling and two air cavities in a roof can be found in Sasic (2007a).

2.4 Granularity

Woloszyn and Rode (2008) use the term "granularity" to describe the size and the dimension of the numerical girds used in whole building simulation tools, e.g. the spatial discretization of air spaces and building envelopes in the numerical models. There are four levels of granularity: coarse, intermediate, fine and very fine. Coarse models assume well-mixed air in a zone and do not provide the hygro-thermal states in a building envelope. "Very fine" refers to the models that are, for example, based on computational fluid dynamics (CFD) calculations. Table 3 shows the classification of the models used in Annex 41 Subtask 1.

TABLE. 3: Typical associations of model granularities, from Woloszyn et.al (2008)

Air	Envelope			
	Coarse	Intermediate	Fine	Very fine
Coarse	X	X		X
Intermediate	X	X	X	X
Fine		X		
Very fine		X		X

These are the programming capabilities of HAM-Tools:
- 1D calculations of transient heat, air and moisture transfer through a building envelope
- Transient heat and moisture balances in air zones, assuming well mixed air. At the same time, the mass balance of air can be performed on a multi-zonal grid.
- Coupling between air zones, e.g multi-zonal calculations
- Modelling of wind and temperature induced air pressure differences around a building
- Moisture uptake by surface materials during rain
- Condensation of surfaces
- Modelling of the radiation heat exchange with surroundings based on a building orientation.
- Modelling of the radiation heat exchange within air zones based on exact view factors
- Detailed modelling of internal HAM gains and HVAC equipment
- Coupling to oher codes / procedures developed in Matlab, C++ and Femlab

According to Woloszyn and Rode (2008), HAM-Tools can be classified as an intermediate to fine-grained model. For example, HAM-Tools provides 1D calculations in a building envelope and thus it can be classified as intermediately-grained. But in terms of the represented physical processes, such as coupled HAM transfer in a building envelope, including liquid transport and temperature and moisture dependent material properties, the programme can be classified as "fine".

2.5 Limitations

The programme has following the limitations:

- Temperature should be in the range of –30 °C to +80 °C
- Effects associated with phase change liquid from/to ice, are neglected.
- Hysteresis is not considered.
- Gravity effects are not considered.
- Chemical reactions are not considered.
- Drainage between material layers is not considered.
- Ageing effects or changes in geometrical dimensions are neglected.

3. HAM-Tools calculation model for HAM transport in whole buildings

This chapter encloses the detail description of the governing equations for the calculation of heat, air and moisture transfer in a whole building, in HAM-Tools.

3.1 HAM states in a building enclosure – the model for the construction blocks

HAM states in a wall, e.g. temperature T (^{o}C) and moisture content w (kg/m^3) can be found from the following energy and mass balance equations:

$$c\rho \frac{\partial T}{\partial t} = -\frac{\partial q}{\partial x} \qquad\qquad 1.$$

$$\frac{\partial w}{\partial t} = -\frac{\partial g}{\partial x} \qquad\qquad 2.$$

Both the temperature and the moisture content are the functions of time t and the space coordinate x.

The heat and moisture flows in a wall, q (W/m^2) and g (kg/m^2), are governed by the differences in temperature T (^{o}C), vapour pressure p_v (Pa) and suction pressure s (Pa):

$$q = \underbrace{-\lambda \frac{\partial T}{\partial x}}_{\text{heat conduction}} + \underbrace{g_a \cdot c_a}_{\text{heat convection}} + \underbrace{g_v \cdot h_e}_{\text{source due to evaporation}} \qquad\qquad 3.$$

$$g = g_v + g_a \cdot x_a + g_l = \underbrace{-\delta_p \frac{\partial p_v}{\partial x}}_{\text{vapour diffusion}} + \underbrace{g_a \cdot x_a}_{\text{vapour convection}} + \underbrace{\lambda_{m,l} \frac{\partial s}{\partial x}}_{\text{suction}} \qquad\qquad 4.$$

The air flow rate through a wall g_a (only one-dimensional, along x coordinate) is governed by the difference in air pressure across the wall. This flow is either prescribed in advance or calculated by another module.

The humidity ratio x_a (kg/kg) is approximated as:

$$x_a = 6.21 \cdot 10^{-6} \cdot p_v \qquad\qquad 5.$$

3.2 HAM states in a zone – Zone blocks

HAM states in a zone, e.g. air temperature $T_{a,in}$ (^{o}C), moisture content in the air v_{in} (kg/m^3) and air pressure $P_{a,in}$ (Pa) can be found from the energy and mass balance equations:

$$c\rho V \frac{dT_{a,in}}{dt} = \sum_i Q_i \qquad\qquad 6.$$

$$V \frac{dv_{in}}{dt} = \sum_j M_{v,j} \qquad\qquad 7.$$

$$0 = \sum_k M_{a,k} \qquad \text{8.}$$

The first two equations describe the storage of energy and water vapour in air. The last equation describes the mass conservation of dry air in a zone.

The HAM-Tools zone model is based on the assumption of a well-mixed air. This means that special variations of the air temperature and moisture content in air are neglected. i.e. the corresponding gradients are zero:

$$\nabla T_{a,in} = 0 \quad \text{and} \quad \nabla v_{in} = 0 \qquad \text{9.}$$

The right-hand sides enclose HAM flows to and from the zone, such as:

$$Q_1 = \sum_p h_p A_p \left(T_{surface,p} - T_{in} \right) + \qquad$$

Heat flows due to a convective heat exchange between the air and the adjacent surfaces   10.

$$Q_2 = \sum_q \dot{m}_{a,q} c \left(T_{inlet,q} - T_{in} \right) + \qquad$$

Heat flows due to ventilation and infiltration

$$Q_3 = \sum_r Q_{sources,r} \qquad$$

Heat sources due to eating/cooling/humidifying equipment, solar gains through windows, lighting, appliances, etc. Only the convective parts are of interest.

$$M_{v,1} = \sum_l \beta_l A_l \left(p_{surface,l} - p_{in} \right) + \qquad$$

Vapour flows due to convective moisture exchange with adjacent surfaces   11.

$$M_{v,2} = \sum_m \dot{V}_m \left(v_{inlet,m} - v_{in} \right) + \qquad$$

Vapour flows due to ventilation and infiltration

$$M_{v,3} = \sum_s M_{sources,s} \qquad$$

Vapour generated within a zone by cooking, evaporation from a water surface, etc.

Q_1 and $M_{v,1}$ are organized in the Construction array, Q_2 and $M_{v,2}$ are in the System array while Q_3 and $M_{v,3}$ are in the Gain array.

$$\sum_k M_{a,k} = \sum_k \rho_{a,inlet,k} C_k \left(P_{a,inlet,k} - P_{a,in} \right)^n \qquad$$

Air flows governed by mechanical ventilation systems, through openings and leakages in a building envelope   12.

Depending on the source of air, the flows $M_{a,k}$ can be either in the Construction or in the System array. The air pressure in a zone, $P_{a,in}$, can be found from equation 8 and 12 by iterations.

3.3 HAM balance at outdoor surfaces (external boundary conditions)

Heat balance at an outdoor wall surface is given as:

$$-\lambda \frac{\partial T_{surface}}{\partial x} = h_c \cdot \left(T_{a,ext} - T_{surface} \right) + q_{rad} + \left(g_a \cdot c_a + g_{rain} \cdot c_l \right) \cdot T_{a,ext} + g_v \cdot h_v \qquad \text{13.}$$

The first two terms on the right-hand side represent the convective and radiative heat exchange with the surrounding air. The third and the fourth parts refer to the specific enthalpy flows for air and water, when either an air ex-filtration or rain is taking place. The specific enthalpy flow for the water vapour is presented only by the latent part, the last term, while the sensitive part is neglected. The reference temperature for the sensible specific enthalpy is zero. In case of the air infiltration, the enthalpy of air is based on $T_{surface}$.

Net radiant energy absorbed by a wall surface originates from incoming solar radiation (direct and diffuse parts, I_{dir} and I_{diff}) and long-wave radiation exchange with surroundings:

$$q_{rad,ext} = \alpha_{sol} I_{sol} \cdot + \sum_k F_k \varepsilon_k \cdot \sigma \cdot \left(T_k^4 - T_{surface}^4 \right) \qquad\qquad 14.$$

Temperature of surrounding surfaces, T_k, view factors F_k and emissivities ε_k should be prescribed. Solar radiation intensity on a sloped (exterior) surface, I_{sol}, is calculated by the model presented in Perez (1986). Intensity of solar radiation through windows is a function of angle of incidence, number of panes and coatings.

Vapour balance at an outdoor surface is given as:

$$-\delta_p \frac{\partial p_{v,surface}}{\partial x} = \beta_p \cdot \left(p_{v,a,ext} - p_{v,surface} \right) + \begin{cases} g_a \cdot x_{a,ext}, & \text{for air ex - filtration } (g_{air} > 0) \\ g_a \cdot x_{a,surface}, & \text{for air infiltration } (g_{air} < 0) \end{cases} \qquad 15.$$

In case of rain, the suction of water takes place for capillary active surface materials. The liquid inflow becomes the minimum of

$$\lambda_{m,l} \frac{\partial s_{surface}}{\partial x} \quad \text{and the prescribed flow } g_{rain}. \qquad\qquad 16.$$

The rain load from a wind driven rain should be supplied from other calculations – there is no a specific calculation procedure for it.

3.4 HAM balance at indoor surfaces (internal boundary conditions)

Heat balance at an interior wall surface is given as:

$$-\lambda \frac{\partial T_{surface}}{\partial x} = h_c \cdot \left(T_{a,in} - T_{surface} \right) + q_{rad,in} + g_a \cdot c_a \cdot T_{a,in} + g_v \cdot h_e \qquad\qquad 17.$$

when indoor air is flowing into the construction (infiltration). For the case of air flowing out from the wall, the enthalpy of air is based on $T_{surface}$.

Long-wave radiation exchange between internal surfaces can be modelled either in a simplified way, by using the so called "star model" or in an exact way, using additional modules for the calculation of exact view factors between the surfaces in an enclosure. In the first model, the net radiation that is coming to a surface is calculated as

$$q_{rad,i} = \frac{\Phi_r}{\sum_i A_i} + h_r \cdot \left(T_{star} - T_i \right) \qquad\qquad 18.$$

where the first part on the right-hand side, Φ_r, represents a sum of all radiative heat sources in the zone, e.g both short wave and emitted long wave. The second part presents the radiative heat flow from the surrounding surfaces. The temperature of the "star", T_{star} represents the mean surface temperature of all surfaces in an enclosure. In this way, all opaque surfaces absorb the same amount of energy per unit of surface area. The part that reaches a transparent surface (a window) is counted as a loss (see de Wit, 2000).

3.5 Gains and Systems

HAM sources in a zone, such as those originating from HVAC equipment or gains from transmitted solar radiation, people, appliances, wind and temperature induced air flows through intentional and unintentional openings, can be modelled in details by using the standard Simulink library tools.

3.6 Numerical model and solvers

The system of energy and mass balance equations presented above is solved numerically using the control volume technique and explicit time discretization scheme. The space discretization is done on a non-uniform stationary discretization mesh. As a part of the Matlab package, Simulink has built-in state-of-the-

art ordinary differential equation (ODE) solvers, which are automatically configured at run-time of the model. Thus, time discretization is done by the solver, and not by user. More details about the numerical model can be found in Sasic (2004 a)

4. Modelling issues in Subtask 1 that were exclusively addressed by HAM-Tools

As shown in Table 1, HAM-Tools was used in five of the six modelling exercises that were presented in the frame of Subtask 1. This section includes a selection of additional numerical studies that were made by HAM-Tools.

4.1 Thermal problem in Common Exercise 0

Common exercise 0 considered rather standard thermal problems - energy consumption for heating and cooling in lightweight and heavyweight test buildings (cases 600 and 900 in Table 1), and free-running indoor temperatures (cases FF in Table 1). All cases are based on the testing procedure that is known as BESTEST (Judkoff and Neymark, 1995).

As in BESTEST, the results obtained within Annex 41 for this exercise fairly diverged from one programme to another (see Woloszyn and Rode, 2008). In order to investigate some possible causes for the differences found, Sasic (2004 c) made a sensitivity analysis on one modelling aspect in energy calculations – modelling of a long-wave radiation heat exchange inside the test building. The analysis was done by HAM-Tools.

Two options can be found in HAM-Tools for the calculation of a long-wave radiation heat exchange in an enclosure: by using the approximate model that is given in equation 18 or by using a procedure for the calculation of exact view factors between surfaces. For the latter, the view factor between surfaces i and j is found from the following expression:

$$F_{ij} = \frac{1}{A_i} \int_{A_i} \int_{A_j} \frac{cos(\theta_i)cos(\theta_j)}{\pi r^2} dA_i.dA_j \qquad 19.$$

where A_i and A_j are the areas of the surfaces i and j; θ_i and θ_j are the view angles between the surfaces; r is the distance between the surfaces.

The view factor F_{ij} gives the fraction of radiation that leaves A_i and is intercepted by A_j (see for example Hagentoft, 2001). The integration in equation 19 can be performed numerically; in HAM-Tools this is done by a separate module that is presented in Karlsson and Hagentoft (2005). In this way, instead of using a common radiative heat transfer coefficient for all surfaces, h_r, an exact amount of radiative heat flow is calculated for each surface.

Results of energy calculations for CE 0 in respect to the model used for long-wave radiation exchange are summarized in Table 3. As it can be seen, the exact model for the long-wave radiation gives substantially lower annual average free-running temperatures (up to 3 ^{o}C) and lower energy demands for cooling (around 5 %).

4.2 Moisture-buffering capacity of finishing materials in Common Exercise 3

The simulation problem in Common exercise 3 is based on a real one storey test building with two rooms, which are located at the outdoor testing site of the Fraunhofer Institute of Building Physics in Holzkirchen, Germany. The internal surfaces in the reference room were covered by standard gypsum boards with a latex paint. The walls in the test room were firstly fully coated with aluminium foil and then, in further tests, covered with gypsum boards. The indoor air temperature in both rooms was kept at 20 ^{o}C. The moisture production in both rooms was also the same: a high production of 0.4 kg/h in the morning, from 6-8 a.m., and moderate but longer production in the afternoon - 0.2 kg/h from 4-10 p.m. The rooms were exposed to the outdoor climate conditions in Fraunhofer.

TABLE. 3 HAM-Tools results for Common Exercise 0 in respect to the model used for the long-wave radiation heat exchange in enclosure

	Equation 18	Equation 19	Equation 18	Equation 19
	Case 600 FF		Case 900 FF	
Annual mean indoor temperature	27.8	24.2	27.8	24.3
Maximum indoor temperature	69	62.2	46.4	44.7
Minimum indoor temperature	-15.3	-15.7	-1.4	-4.6
	Case 600		Case 900	
Annual energy for heating, kWh	4700	4700	1700	1800
Annual energy for cooling, kWh	5800	5600	2400	2300
Peak effect in heating, W	3800	3800	3400	3400
Peak effect in cooling, W	5700	5500	3000	2800

The scope of this exercise was to investigate the influence of moisture-buffering capacity of different finishing materials on the indoor relative humidity. The set of measured data collected in the test and the reference room during January-April 2005 was used for the validation of the simulation tools. The exercise was organized in four steps (see Table 1). The results for the first step, obtained by HAM-Tools, are presented hereafter.

During the first step, the walls in the test room were covered by aluminium foil and the indoor relative humidity was completely controlled by ventilation. As it was found from the tracer gas measurements, the ventilation flow rate was 0.66 1/h. As it is shown in Figure 3, the HAM-Tools results for the test room and for the first step are in excellent agreement with the measured data.
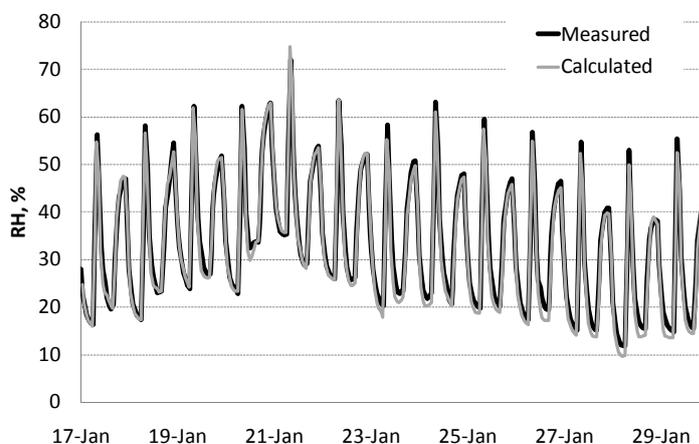

FIG. 3. Common exercise 3, Step 1: relative humidity in the test room. Black line shows the measured values, the grey line shows the calculated values with the ventilation flow rate of 0.66 1/h.

For the reference room, the ventilation flow rate was 0.63 1/h and the vapour resistance of the latex paint on the gypsum boards was specified to 0.15 m (s_d value). HAM-Tools simulations, however, point to a higher vapour resistance of the gypsum boards in the reference room than specified. As it can be seen in Figure 4, the calculated peaks in relative humidity are always lower than the measured ones. When a higher vapour resistance for the paint was used, $s_d = 0.4$ m instead of 0.15 m, a very good agreement with the measurements was achieved.

In HAM-Tools, the vapour resistance of the latex paint was incorporated in equivalent surface flow coefficient as:

$$\beta_{equivalent} = \beta_p + \delta_{p,air}/s_d$$ 20.

where β_p is the surface vapour transfer coefficient in air and $\delta_{p,air}$ is the vapour diffusivity in air. The equivalent surface transfer coefficient is than used in the model (see equation 11).

None of the participants in this exercise reported the similar observations. And it is not even certain that the calculations can be corrected in this way. However, there are indications that the moisture buffering capacity in the reference room could be lower than it is expected. Lengsfeld et. al (2005) reported similar observations during the measurements for the step 4, where the relative humidity in the test room was lower than in the reference room. For this step, the walls in the test room (area 45 m^2) were covered by painted gypsum boards, with the resistance of the paint s_d=0.34 m. At the same time, the walls and the ceiling in the reference room were covered by the latex-painted gypsum boards (area 67 m^2), the same as in the step 1. Another reason for the discrepancies between the HAM-Tools simulations and measurements can be the non-uniformity of air inside the reference room. Similar indications can be found in the results for Common exercise 2 of Subtask 1.
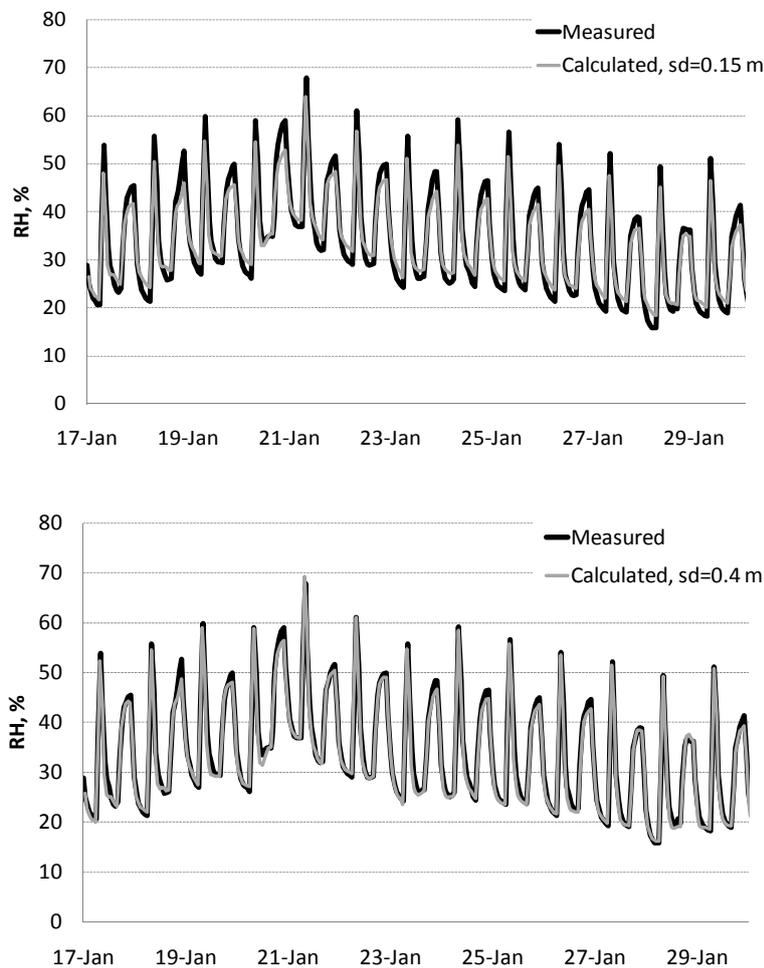

FIG. 4. Relative humidity in the reference room. Black line shows the measured values, the grey line shows the calculated values with sd=0.15 in the upper figure and 0.4 m in the lower figure. The ventilation flow rate is 0.63 1/h in all cases.

4.3 Convective heat and moisture flow through walls

As discussed in Woloszyn and Rode (2008), temperature and pressure gradients across a wall may lead to the onset of air convection inside air permeable materials and cavities, or to air filtration through the wall. Depending on the magnitude and direction of the air flow, the convective transport of heat and moisture, induced in this manner, may become a dominant transfer mechanism in comparison to heat conduction and vapour diffusion.

Air filtration through a wall has sometimes positive effects as, for example, when it is used for the heat recovery of the energy losses due to ventilation of a building. When passing through the insulation layer, the air is partly pre-heated by the heat that would be otherwise lost from a wall by heat conduction. The effective or the dynamical U-value of the wall is thus reduced and the overall efficiency of the insulation is improved.

Sasic (2007 a) investigated the energy efficiency of such concept and the hygro-thermal response of a house in relation to the overall air tightness of the house. The numerical investigation was made by HAM-Tools, on the model house from Common exercise CE 1- 600-Open (see Table 1). The original conventional roof in the test house was replaced by the roof with dynamical insulation. The airtightness of the building envelope was varied from 2 to 0.1 1/h airflow rates at 50 Pa pressure difference; in this way, the house can be classified as considerably airtight, according present standards, to extremely airtight. All other data were the same as in CE 1.

The coupled convective-diffusive heat and moisture transfer in the dynamical insulation was studied by using one-dimensional approach (see for example equations 3 and 4). The air flow through the house was studied by taking into account temperature and wind-induced pressure differences across the building envelope, as well as the action of an exhaust fan. For the calculation of the pressure distribution inside the house, the original one-zone model was upgraded with a quasi multi-zone model. Thus, the modelling equation 12 was extended for 12 more nodes (two pressure nodes in front of each internal surface).

Results of this study are summarized in figures below. As it can be seen in Figure 5, the energy efficiency of the dynamical insulation in the roof is directly correlated to the airtightness of the house. The maximum savings for heating, 17 % in comparison to the reference case from CE 1- 600-Open, are achieved for the extremely airtight house. For this case, the cooling energy demand is increased for 3 % in comparison to the reference case. In other two cases, the energy savings for heating and cooling are in the range of 2-4 %.
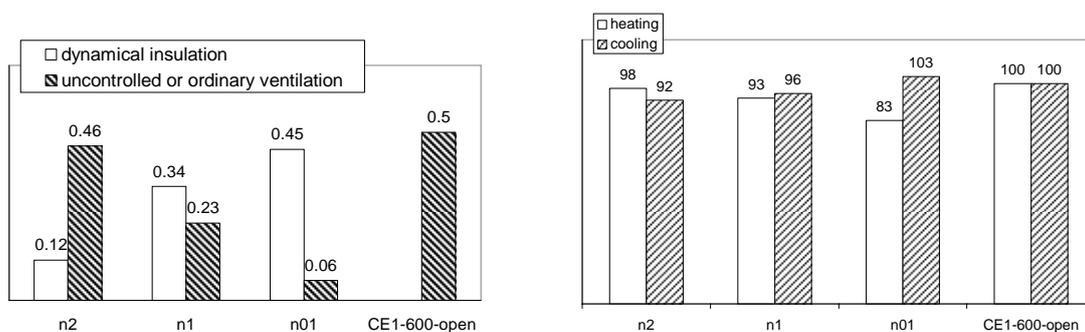

FIG 5. Left: Airflow rates (annual averages) through the dynamical insulation in the roof and thorough the air leakages in the building envelope, in relation to the overall airtightness of the building envelope. n2 stands 2 1/h at 50 Pa pressure difference, etc. The case CE1-600-open refers to the calculation exercise CE 1, with a lightweight and vapour-open construction. Right: Annual energy consumption for heating and cooling in kWh, for the cases from the figure to the left.

The maximum indoor relative humidity in CE 1-600-Open was 66 %, as calculated by HAM-Tools. When the dynamical insulation is used, the maximum relative humidity is around 70 % as it is shown in Figure 6. The highest value is reached for the extremely airtight house, while it is just the same as in the reference case for other airtightness classes. Note, however, that the internal wooden cladding provides very efficient

moisture buffering here. If a more vapour tight cladding is used, indoor relative humidity may be much higher in the house with the dynamical insulation (more details can be found in Sasic, 2007 a).
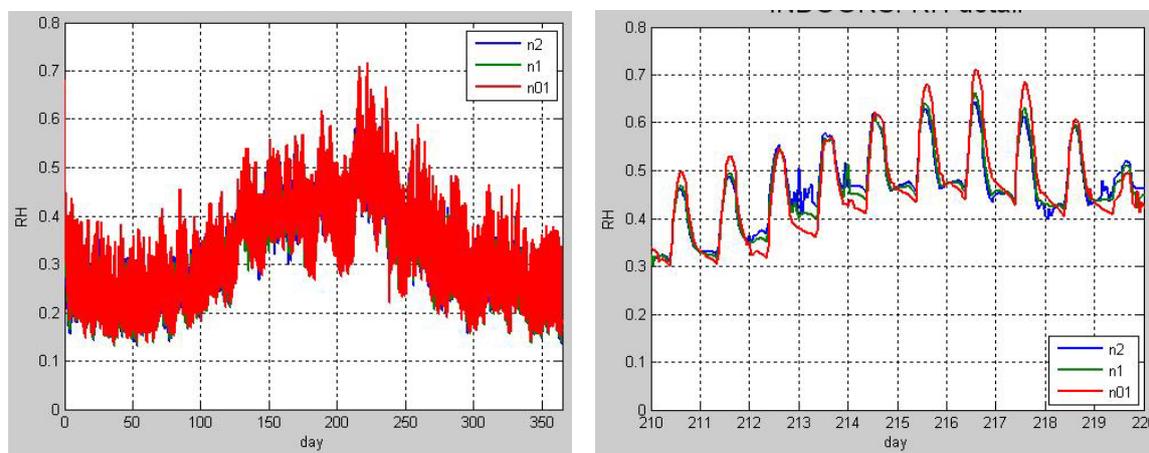

FIG. 6. Left: relative humidity in the indoor air, over a year. Right: the indoor air relative humidity reaches maximum in the middle of August (detail from the figure to the left).

5. Outlook

Annex 41 gathered around 15 building simulation tools that were capable for the calculation of combined heat, air and moisture transfer in whole buildings. The paper presents one of them, the building simulation program HAM-Tools, which participated in the most of the benchmark cases that were presented within Subtask 1 and 2.

The main quality of HAM-Tools is that it has been developed from a beginning as a whole building heat, air and moisture simulation tool. The programming environment of the Matlab/Simulink and the modelling approach used – the object oriented development of the calculation modules, enable a variety of the modelling possibilities in HAM-Tools. Some of them are presented in this work.

Though successfully validated and used in the exercises and topics that were enclosed within Subtask 1 and 2, HAM-Tools provides rather limited information on the hygro-thermal states in buildings – one dimensional distribution of temperature and moisture in the building envelope parts and "one-node" hygro-thermal states for the air zones. Therefore, the future development of this programme will be directed towards the refinement of the special granularity in air zones and building envelopes.

Nomenclature

A	Area, m^2	h_c	Convective surface heat transfer coefficient, W/m^2K
C	Flow characteristic, $m^3/s/Pa^n$	h_e	Heat of evaporation, J/kg
F	View factor	h_r	Radiative surface heat transfer coefficient, $W/m^2/K$
I_{sol}	Intensity of solar radiation, W/m^2	m_a	Density of mass flow of air, $kg/m^2/s$
M	Mass flow to a zone, kg/s	n	Flow exponent in equation 12
P_a	Air pressure, Pa	p	Partial pressure of vapour in air, Pa
Q	Heat flow to a zone, W	q	Density of heat flow, W/m^2
T	Temperature, ^{o} C	s	Suction pressure, Pa
V	Volume, m^3	s_d	Vapour resistance of a coating, m
V	Volumetric flow rate, m^3/s	t	Time, s

c	Specific heat capacity, J/kg/K	v	Humidity by volume, kg/m^3
g	Density of mass flow, kg/m^2/s	w	Moisture content in material, kg/m^3
g_{rain}	Intensity of rain, kg/ m^2/s	x	Space coordinate, m

Greek letters   Subscripts

α_{sol}	Absorptivity for solar radiation	a	Air
β_p	Vapour surface transfer coefficient, m/s	$inlet$	At inlet
δ_p	Vapour permeability, kg/smPa	l	Liquid
ε	Emissivity	rad	Radiative
λ	Thermal conductivity, W/mK	$surface$	At surface
$\lambda_{m,l}$	Liquid moisture conductivity, s	v	Vapour
σ	Stefan-Boltzmann constant W/m^{2}K^4	i,j,k,p,q,r	indices
θ	Angle, deg	ext	Exterior, outdoor
Φ_r	Radiative source of heat in a zone, W	in	Interior, indoor

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