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REVIEW ARTICLE

Tools for Performance Simulation of Heat, Air and Moisture Conditions of Whole Buildings

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Abstract Humidity of indoor air is an important factor influencing the air quality and energy consumption of buildings as well as durability of building components. Indoor humidity depends on several factors, such as moisture sources, air change, sorption in materials and possible condensation. Since all these phenomena are strongly dependent on each other, numerical predictions of indoor humidity need to be integrated into combined heat and airflow simulation tools. The purpose of a recent international collaborative project, IEA ECBCS Annex 41, has been to advance development in modelling the integral heat, air and moisture transfer processes that take place in “whole buildings” by considering all relevant parts of its constituents. It is believed that full understanding of these processes for the whole building is absolutely crucial for future energy optimization of buildings, as this cannot take place without a coherent and complete description of all hygrothermal processes. This paper will illustrate some of the modelling work that has taken place within the project and present some of the simulation tools used.

Keywords modelling, heat, air, moisture, whole building

1 Introduction

Humidity of indoor air is an important factor influencing energy consumption of buildings, durability of building components, and the perceived air quality. Indoor humidity depends on several factors, such as moisture sources, airflows, and moisture exchange with materials. As all these phenomena are strongly dependent on each other, numerical predictions of indoor humidity need to be integrated into combined heat and airflow simulation tools. During the past few decades there has been quite some development and increased professional use of tools to simulate some of the processes that are involved in analysis of whole building Heat, Air, and Moisture (HAM) conditions.

For instance, fairly comprehensive tools for transient building energy simulation have been well established for more than a decade. A list of such tools can be seen in www.eere.energy.gov/buildings/tools_directory/ and in Crawley et al. (2005). However, the building energy simulation tools have so far not been well suited to predict moisture transfer processes in buildings.

Airflow simulation tools and Computational Fluid Dynamics (CFD) codes are available which either at a bulk level or in fine volume elements can predict airflow within and between zones of a building, as well as air exchange with the outdoor environment. Some of the tools deal with airborne moisture transport and also represent the heat transfer in the air and in the envelope. However, in general these tools cannot be used to predict moisture exchange between the air in a zone and its adjacent porous walls.

Detailed, transient tools have been developed for combined heat, air and moisture transfer within individual constructions that form the building envelope (Hens 2002). Many HAM tools for building envelope simulations require that the indoor environment is specified by the user. However,

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in reality the assembly of building elements constitute one of the most important factors to determine the indoor climate, and thus there is a mutual link between the building envelope and room conditions.

Development, use and validation of whole-building simulation tools, which are able to represent various physical processes dealing with moisture, heat and air transfer, were greatly encouraged by Subtask 1 ("Modelling and Common Exercises") of the International Energy Agency project, ECBCS, Annex 41 ("Whole building heat, air and moisture response"). A central ambition has been to combine the capabilities of earlier tools in order to make it possible to describe all relevant hygrothermal processes in a composite building, i.e., to bring a holistic perspective to building physics modelling. The project ended in 2007, and this paper will render an overview of the different tools that have been used and improved.

1.1 Physical phenomena

In order to predict indoor environment and building energy consumption, important heat and mass flows must be described. Mass flows concern air as a whole, as well as some of its specific constituents—water vapour being one of them. For several applications, water vapour should be treated separately. Water vapour also has the particular feature that it may easily condensate or evaporate under conditions that may be found in buildings, and such processes may not only lead to undesired transformations of water, but they also involve a significant conversion of latent heat.

The moisture balance should therefore include both gaseous and liquid forms, e.g., by looking to vapour sources, transport by the air, diffusion and adsorption in solids. Water in its solid form (ice) may also appear in buildings, causing mechanical damages.

Figure 1 shows an example of a building with just some of the building components, loads and transport processes that should be taken into account when analysing whole-building hygrothermal processes. Most processes occur only locally, but they influence the adjacent building elements such as rooms or structures. The physical conditions also influence each other, such as when the temperature determines the severity of moisture influences. To describe a whole building, it is necessary to set up heat, air, and moisture balances in various elements of the building, e.g., materials, constructions, and rooms. The flows that pass over the interfaces are important.

1.2 Spatial representation of buildings

An ideal situation would be to describe the whole building in very small computational cells. However, this would in most cases not be needed and would not be computationally efficient. But while some important processes take place in narrow layers of air or building material, other processes in the same building do not require as finely discretized analyses. Figure 2 schematically illustrates heat and moisture accumulation in a building wall. Daily temperature variation on one side of the wall easily penetrates some 20cm into the material, while daily moisture penetration may be just a few millimetres. However, it is important to consider both heat and moisture accumulation in walls with the most appropriate accuracy and computational efficiency when the hygrothermal conditions in rooms and building assemblies are to be predicted. The computational procedures may therefore need to work on different levels of spatial resolution.

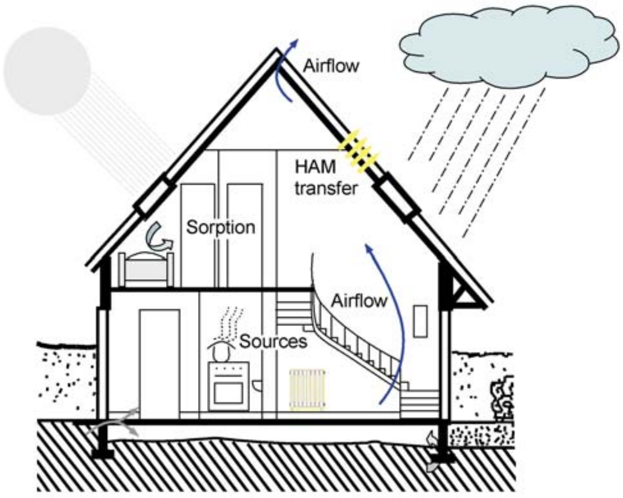

Fig. 1 Building with indoor and outdoor hygrothermal loads

1.3 Balances

The hyrothermal performance of a building can be assessed by analysing energy, moisture, and air balances. The hygrothermal balances consider the normal flows of heat by conduction, convection, and radiation; moisture flows by vapour diffusion, convection, and liquid transport; and airflows driven by natural, external, or mechanical forces. However, in whole building heat, air and moisture analyses, combined forms which involve advection heat flows and conversion of latent heat should also be considered. Likewise, the thermal conditions influence very strongly the moisture conditions and natural airflows.

The correct treatment of the interfacial flows at boundaries between control volumes of different type (interface between air and material) is a cardinal point in successful modelling. In practice the interfacial flows may be rather complex, as shown in Fig. 3 for heat transfer.

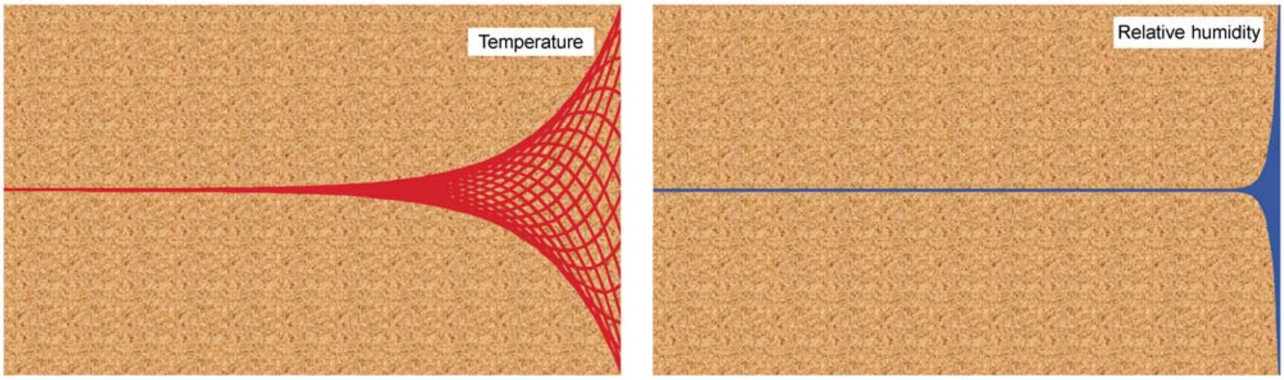

Fig. 2 Schematic illustration of temperature and moisture buffering in building materials. Hourly profiles resulting from daily excitations at the right-hand boundary

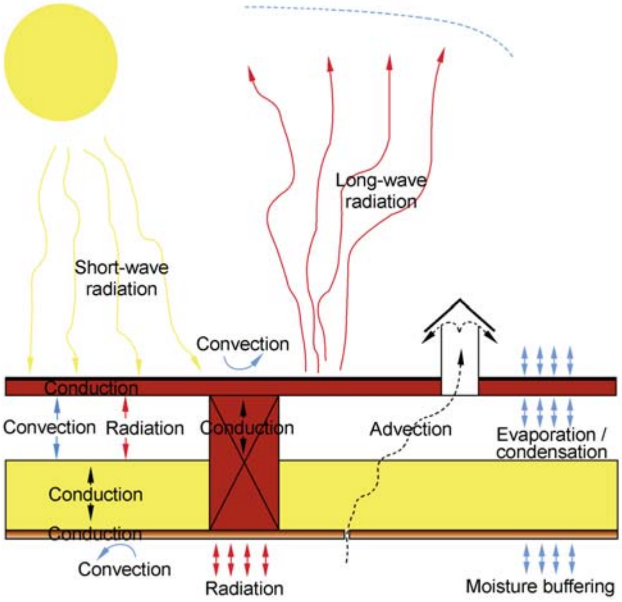

Fig. 3 Roof with different hygrothermal loads and transport processes

1.4 Numerical methods

All simulation tools presented later in this paper are based on some numerical methods for space and time discretization. Possible numerical methods are

- Finite Difference Methods (FDM)/Finite Control Volume (FCV) methods,
- Finite Element Method (FEM),
- Response Factor / Transfer Function method.

1.5 Granularity

Granularity is related to the size of the control volume. In buildings a large variation of granularity is available, from the simplest single-zone modelling (whole building = one zone, called coarse-grained) to CFD modelling (one room = thousands or millions of zones, called very-finely grained). Intermediate approaches use multi-zone modelling, dividing the building, and even sometimes a room, into a few zones with different air characteristics. Similar classification can apply for the granularity of envelope models: from the simplest transfer functions, through 1D, over 2D to 3D modelling using control volume or finite elements techniques.

Whole building tools mainly use two granularity classes:

- The intermediate-grained models (Fig. 4, left)
  - Multi-zone models for air volumes, where several rooms or groups of rooms are represented, each with different characteristics (each zone is supposed perfectly mixed)
  - 1D models for the envelope, using control volume or finite element techniques, with typical size of mesh between a few millimetres to several centimetres
- The coarse-grained models (Fig. 4, right)
  - Single-zone models for air volumes, where the whole building is represented as one perfectly mixed zone
  - Transfer function models for the envelope, where dynamic heat and possibly mass fluxes are represented without investigating conditions within the envelope

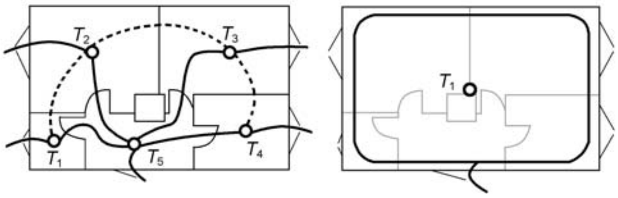

Fig. 4 Levels of granularity for room air

2 Development of whole building HAM models

The developments could take place by making entirely new models and tools (Tariku et al. 2006), or by extension of already existing tools, as for instance:

- Extending the existing building simulation tools (to account better for processes linked with the envelope), e.g., Rode and Grau (2003)
- Extending the building component simulation tools, e.g., Holm et al. (2003)
- A combination of both building simulation and building component simulation tools, e.g., Koronthályová et al. (2004)

Several engineering tools were under development during the period Annex 41 was running, improving their capacities to represent coupled heat, air and moisture response of buildings. Some of them are well known building energy simulation software, such as TRNSYS and EnergyPlus; some have more proprietary use, such as PowerDomus, Clim2000 and SimSPARK. Whole building models take into account location and orientation of the building (climatic zone), various heating, ventilating and air conditioning systems, air infiltration or exfiltration, user behaviour (number of people, activities, moisture and heat production, window ventilation, etc.), and type of room (bathroom, living room, office, etc.). They are mainly situated at the intermediate level of granularity. Some tools are able to support fine level of granularity, for example, by CFD extension of room air modelling. However, these possibilities were not tested in the benchmark cases of the Annex, and therefore are simply mentioned but not described in the following. Management of the overall physical processes for the whole is a matter of not only being able to describe the conditions in the different building elements, but also to correctly account for interfacial transfer and balances.

All tools calculate also moisture level in the indoor air and can account for vapour storage in hygroscopic materials. This last phenomenon is modelled either using simplified (coarse-grained) models or using a detailed description of the heat and mass transfer phenomena in the building envelope. In the last case, moisture level in building elements can also be assessed using the simulation tool.

2.1 General features of whole building HAM models

The following text presents the 17 simulation tools that have been used in Annex 41, which are able to simulate whole building HAM performance. This cannot be an exhaustive list of all whole building HAM simulation tools that may exist in different countries. However, as so many as 39 institutions from 19 countries participated in this project, the results give a good overview of today's simulation capabilities. Each participant was free to choose the tool he or she wanted to use. The choice was frequently based on beforehand knowledge of and experience with the tool. Often the tool was developed by the participant's institution, or it had been used there for several years. Moreover the tools were also benchmarked in so-called "Common Exercises" in the Annex, and some improvements were made to the tools during the project. Presentation and discussions of some of the benchmark cases can be found in Woloszyn and Rode (2007), Holm and Lengsfeld (2007).

First, a brief introduction is given for all the models, including relevant references and internet sites when available. Then their main features are contrasted in 8 tables. Evidently, it is impossible to give a full description of 17 simulation tools in a limited number of pages. The aim is to give a general overview of the main features, focusing more on moisture modelling and on the interactions between heat, air and moisture transfer mechanisms. The comparison is based on the descriptions given by the users of the tools with the Annex. As it can be seen in Table 1, the "user" is in some cases from the institution which developed the tool, or in some cases he or she is simply an experienced user.

It must also be stated that some of the models are still under active development. Therefore between the moments of writing this paper and using the information some more or less important improvements might have been made.

Table 1 gives the origin of the tool and main institutions working with it in Annex 41. It can be seen that eleven tools are used by the developers, and the six remaining by other institutions. Five tools are commercially available, and also five are freeware. Five are only research tools, and two are personal products. Eleven, i.e., the majority, of the tools are originally energy simulation tools, four tools were building envelope simulation tool, and the last two were directly developed as whole building simulation heat-air-moisture tools.

Table 2 gives a first overview of the whole building HAM models implemented in the tools. Most of them can simulate a multi-zone building and heat and mass transfer in the envelope. Four are single-zone tools, and five are able to describe intra-room flows using zonal models or CFD. Of course all of the thirteen multi-zone tools can represent single-zone buildings. Four tools represent in standard version 1-dimensional heat transfer in the envelope, nine 1-dimensional heat and moisture transfer in the envelope and three 1-dimensional heat, air and moisture transfer in the envelope. Finally, only three tools can deal with multi-dimensional coupled transfer at building level. The effect of furniture on indoor relative humidity and temperature is not represented as such, but can be approximated as interior building structures. Some tools use a coarse-grained (lumped) approach. Also, with two exceptions, the tools can represent most of the typical

HVAC systems. However, in most of the tools, the systems are represented in a rather simplified way, where the action of the system on the indoor conditions is represented without detailed description of the HVAC element itself.

The main elements of the thermal models are contrasted in Table 3. "Standard" window model means use of standard coefficients, such as *U*-value (heat loss), *g* (solar gain coefficient) and *SC* (shading coefficient). Such models also allow for calculations of heat gains according to the position of sun. "Detailed" window model means that the heat transfer is modelled including convection and radiation between and inside the glazing, etc. Some information is also given about the way in which the solar gain is treated. Also wall models are briefly described in Table 3, and especially if they are treated in 1 or 2 dimensions, and what is the main numerical method used (finite control volume—FCV, finite element method—FEM or transfer function). Also principles for computing convection and long-wave radiation are presented in Table 3.

Table 4 details the main characteristics of the moisture models. Thirteen tools include vapour diffusion through the envelope, eight also liquid transport. Moist air movement through the envelope, which is one-dimensional airflow through very permeable constructions excluding cracks, can be simulated by five tools (two more will be available soon), and hysteresis effect of sorption isotherm only by one tool. Also a rather large variety of driving potentials for moisture flow can be seen in Table 4. For example vapour pressure [Pa] is used in nine tools, moisture content [$\mathrm{kg_{moisture}/kg_{dry\_material}}$] in six, relative humidity [—] in four, and vapour concentration [$\mathrm{kg_{vap}/m^3}$] in two; some tools using more than one. Moreover, suction pressure [Pa], temperature [℃] and volumetric moisture content [$\mathrm{m^3/m^3}$] are also used. Some tools use only simplified (coarse-grained) models for moisture buffering.

Table 5 depicts the main characteristics of the airflow models in the 17 tools. Six have only lumped representation of the indoor air, eleven are able to use pressure network to represent more accurately interzonal flows and different ventilation systems, and one tool is a zonal model, where several control volumes are used to describe one room. Most of the multi-zone models and the zonal model include wind and buoyancy effect, also one-way flow through the cracks in the envelope and indoor partitions, as well as cross-flow through large openings. In most of the "lumped" models ventilation and infiltration flows can be defined by the user and added to the energy and moisture balances of the indoor air. Also some tools can be coupled with airflow simulation tools, such as COMIS or CFD, to enhance their modelling capacities.

The main couplings between heat, air and moisture models are represented in Table 6. Of course all tools represent both latent and sensitive contributions of internal sources. Latent heat due to vapour transfer and to condensation/evaporation process is taken into account in most of the codes; however, in most of them it is either in the envelope or in the HVAC system. Only seven tools are able to take both into account. Also most of the multi-zone models (thirteen) can take into account the impact of both humidity and temperature on air density and therefore on buoyancy. Some tools can also represent moisture and temperature impact on some of the material properties.

The numerical methods are contrasted in Table 7. Some of the simulation tools use an external solver, such as Matlab for HAMLab, HAM-Tools, and HAMFitPlus. Explicit and implicit methods, as well as constant or variable time-step methods are almost equally distributed. In the envelopes eleven tools use FCV method, four use transfer functions, and two use FEM. If a mesh is used, it is the same for all transfer process (heat, air, and moisture). Moreover in most of the cases (fourteen tools) all equations are simultaneously solved ensuring full coupling between different flows.

All the tools can use variable inputs from weather files; however, not all the information is used. From Table 8 it can be seen that only five tools are able to deal with wind driven rain and eight with heat and moisture transfer through the ground. Wind impact on outdoor convection and on infiltration is rather often represented (twelve tools), as well as the solar shadings from close neighbourhood (twelve tools).

2.2 Introduction of different software

2.2.1 BSim

Rode and Grau (2003 and 2004) present the program BSim2000 (www.bsim.dk), which is a computational design tool for analysis of indoor climate, energy consumption, and daylight performance of building, developed by the Danish Building Research Institute. The core of the system is a common building data model shared by the design tools, and a common database with typical building materials, constructions, windows, and doors. The software can represent a multi-zone building with heat gains, solar radiation through windows (with shadings), heating, cooling, photovoltaic, ventilation, and infiltration, but also transient moisture model for the whole building.

2.2.2 BUILDOPT-VIE

BUILDOPT-VIE is a simulation tool developed at Vienna University of Technology (www.bph.tuwien.ac.at) described in Sofic and Bednar (2007). Development of the first edition of the program started in 2002 and was carried out with

Table 1 General information about the software

Name	Developer	Main user in Annex 41	Availability	Origin	Possibility of adding new components	Remarks
BSim	Danish Building Research Institute (Denmark)	Technical University of Denmark	Commercial program	Energy	No	
BUILDOPT-VIE	Vienna University of Technology (Austria)	Vienna University of Technology	Research program	Energy	—	—
Clim2000 3.2.0	EDF (Electricité de France)	CETHL (France)	Research program	Energy	Yes	
DELPHIN	TU Dresden (Germany)	TU Dresden	Research program, commercial version available	Envelope	No	
EnergyPlus v1.2.1	Department of Energy (USA)	University College London (UK)	Freeware	Energy	Yes	
ESP-r	University of Strathclyde (UK)	ICA SAS	Freeware	Energy	Yes	
NPI	ICA SAS (Slovakia)	ICA SAS	Research program	Envelope	Yes	
IDA-ICE	EQUA Simulation AB (Sweden)	Tallinn University of Technology (Estonia)	Commercial program	Energy	Yes	The code is open
HAMFitPlus	Concordia University, NRC (Canada)	Concordia University	Personal program	HAM whole building	Yes	Requires Matlab/Simulink and COMSOL
HAMLab (Heat, Air & Moisture Laboratory)	Eindhoven University of Technology (the Netherlands)	Eindhoven University of Technology	Freeware	Energy	Yes	Requires Matlab/Simulink and COMSOL
HAM-Tools	Chalmers University of Technology (Sweden)	Chalmers University of Technology, CETHIL	Freeware	HAM whole building	Yes	Requires Matlab/Simulink
PowerDomus	PUCPR (Brazil)	PUCPR	Research program	Envelope	No	
SimSPARK 2.01	LEPTAB, University of La Rochelle (France)	LEPTAB	Freeware	Energy	Yes	Possible couplings with EnergyPlus
TRNSYS 16.00 (standard models)	University of Wisconsin-Madison (USA)	University of Gent (Belgium) PUCPR, CETHIL	Commercial program	Energy	Yes	Possible coupling with COMIS
TRNSYS ITT	University of Wisconsin-Madison (USA) TU Dresden (Germany)	TU Dresden	Research program	Energy	Yes	All features of TRNSYS available
WUFI-Plus	Fraunhofer-Institut für Bauphysik (Germany)	Fraunhofer-Institut für Bauphysik	Commercial program	Envelope	Yes	
Xam	Kinki University (Japan)	Kinki University	Personal program	Energy	No	Personal use by the author

Table 2 General features of whole building Heat, Air and Moisture models

Name	Granularity	Envelope	Air	Furniture (impact on moisture)	HVAC systems
BSim	Multi-zone, capable of zonal model	1D Heat+Moisture, airflow through envelope under development	Interzonal flows (including cross flow through large openings), natural and mechanical ventilation	Approximated as interior building envelopes	Most of the typical systems
BUILDOPT-VIE	Multi-zone	1D Heat+Moisture	Well mixed zone, interzonal flow	No	Some of the typical systems with ideal behaviour
Clim2000	Multi-zone, capable of zonal HA model	1D Heat, vapour diffusion through envelope under development	Interzonal flows (including cross flow through large openings), natural and mechanical ventilation	Lumped model for moisture buffering (rendering+furniture)	Most of the typical systems, with detailed representation of some systems
DELPHIN	1 zone	1D/2D Heat+Air+Moisture	1 well mixed volume	No	No
EnergyPlus	Multi-zone	1D Heat	Interzonal flows (including cross flow through large openings), natural and mechanical ventilation	Approximated as interior building envelopes	Some of the typical systems, with capabilities of detailed representation of most systems & controllers
ESP-r	Multi-zone, capable of CFD	Standard 1D Heat, capable of 1D/2D/3D Heat, or 1D Heat+ Moisture	Interzonal flows (including cross flow through large openings), natural and mechanical ventilation	No	Most of the typical systems, with detailed representation of systems
NPI	1 zone	1D Heat+Moisture	1 well mixed volume	Yes	No
IDA-ICE	Multi-zone	1D Heat+Air+Moisture	Interzonal flows (including cross flow through large openings), natural and mechanical ventilation	For moisture buffering: approximated as interior building envelopes	Most of the typical systems, with detailed representation. Possibility to create own systems
HAMFitPlus	Multi-zone	1D/2D Heat+Air+Moisture	Single zone: well mixed zone. Multi-zone: coupled with COMIS	Approximated as interior building envelopes	Some of the typical systems
HAMLab	Multi-zone, capable of CFD	Standard 1D Heat+Moisture capable of 1D/2D/3D Heat+Air+Moisture	Interzonal flows (including cross flow through large openings), natural and mechanical ventilation, CFD capabilities	One parameter for all moisture storage in each zone	Some of the typical systems, with capabilities of detailed representation of some systems & controllers
HAM-Tools	Multi-zone	1D Heat+Air+Moisture	Well mixed volumes, interzonal flows, natural and mechanical ventilation	Approximated as interior building envelopes	Most of the typical systems, 2D and 3D floor heating systems
PowerDomus	Multi-zone	1D Heat+Moisture, airflow through envelope under development	Well mixed volumes, natural and mechanical ventilation. Possible link with COMIS is under analysis	Approximated as interior building envelopes	Most of the typical systems, with detailed representation of systems
SimSPARK	Zonal model	1D Heat+Moisture	Zonal, represents airflows in one room and intra-rooms, including ventilation	Approximated as interior building envelopes	Some of the typical systems, including solar DEC
TRNSYS	Multi-zone	1D Heat	Interzonal flows, ventilation, extensions possible using COMIS	Lumped model for moisture buffering (rendering+furniture)	Most of the typical systems, including many solar components, with detailed representation of systems
TRNSYS ITT	Multi-zone	1D Heat+Moisture	Well mixed zone, zonal model or interactive coupling with CFD available	Lumped models for heat and moisture buffering	All of the TRNSYS modules
WUFI-Plus	1 zone	1D Heat+Moisture	1 well mixed zone	Approximated as interior building envelopes	Most of the typical systems, including heat recovering
Xam	1 zone	1D Heat+Moisture	1 well mixed zone	No	Hourly schedule of H&M gain/sink

Table 3 Some details of the thermal models

Name	Windows	Walls	Indoor interfaces
BSim	Standard available. Solar transmission and gains can be calculated in detail for all surfaces	1D Heat, Finite Control Volumes, mesh defined by user, ventilated cavities	Combined constant coefficient for convection and long-wave radiation, optional separated calculations
BUILDOPT-VIE	Detailed model. Solar gains are calculated from angle dependent glass properties	1D Heat+Moisture, Finite Control Volumes, mesh defined by user	Constant coefficient for long-wave radiation and convection
Clim2000	Standard and detailed available. Solar gains on the floor	1D Heat, Finite Control Volumes, mesh defined by user	Combined constant coefficient for convection and long-wave radiation, optional separated calculations with constant and temperature-dependent convection and view factors for long-wave radiation
DELPHIN	No	2D Heat+Moisture, Finite Control Volumes, mesh defined by user	Combined constant coefficient for convection and long-wave radiation
EnergyPlus	Standard or detailed available. Solar gains calculated in detail for all surfaces	1D Heat, Transfer functions	Separated calculations with constant or temperature-dependent convection and view factors for long-wave radiation
ESP-r	Detailed model. Solar gains are calculated from angle dependent glass properties	1D Heat, Finite Control Volumes, mesh defined by user, capable of 1D/2D/3D Heat, or 1D Heat+Moisture	Separated calculations with constant or temperature-dependent convection and view factors for long-wave radiation, capable of including furniture effect on radiation computations and of timestep-by-timestep CFD calculations of heat convection
NPI	No	1D Heat+Moisture, Finite Control Volumes, mesh defined by user	Combined constant coefficient for long-wave radiation and convection
IDA-ICE	Standard and detailed available. Distributed solar gains	1D Heat+Air+Moisture, Finite Control Volumes, mesh defined by user	Separated calculations with temperature and slope-dependent convection and view factors for long-wave radiation
HAMFitPlus	Standard. Solar gains: uniformly distributed	1/2D Heat+Air+Moisture, Finite Elements, mesh defined by user	Combined constant coefficient for convection and long-wave radiation
HAMLab	Standard or detailed available	1D Heat, Transfer functions, capable of 1/2/3D Heat+Air+Moisture using Finite Control Volumes	Separated calculations with convection and integrating sphere approximation for long-wave radiation
HAM-Tools	Standard. Gains distributed by user or calculated (the first bounce only)	1D Heat+Air+Moisture, Finite Control Volumes, mesh defined by user	Combined constant coefficient for convection and long-wave radiation or separated calculations with constant or temperature dependent convection and exact view factors for long-wave radiation
PowerDomus	Standard and detailed. Solar gain on the floor	1D Heat+Moisture, Finite Control Volumes, mesh defined by user. Possible extension with 3D Heat+ Moisture model through the ground	Separated calculations with constant and temperature-dependent convection. The program ViewFactor-LST is being integrated to get precise values of view factors, considering obstructions for calculation of long-wave radiation
SimSPARK	Standard or detailed available. Detailed solar gains for all surfaces	1D Heat+Moisture, Finite Control Volumes, mesh defined by user	Separated calculations for convection and long-wave radiation (fictitious enclosure method)
TRNSYS	Standard or detailed available. Solar gains can be distributed	1D Heat, Transfer Functions	Combined constant coefficient for long-wave radiation and convection or separated calculations with temperature-dependent convection
TRNSYS ITT	Embedding of the WINDOW5 library possible	1D Heat+Moisture, Finite Elements, mesh defined by the program	Separated calculations with constant or temperature-dependent convection (or delivered by CFD) and with view factors for long-wave radiation
WUFI-Plus	Standard, with solar gains	1D Heat+Moisture, Finite Control Volumes, mesh granularity defined by user (coarse, medium, fine)	Combined constant coefficient for long-wave radiation and convection
Xam	Standard. Solar gains: divided on the floor and the space	1D Heat, Transfer Functions	Combined constant coefficient for long-wave radiation and convection

Table 4 Main characteristics of the moisture models

Name	Lumped	Diffusion through the envelope			Hysteresis	Driving potentials for moisture transfer
		Vapour	Liquid	Moist air		
BSim	No	Yes	No	Under development	Yes	Vapour pressure [Pa]
BUILDOPT-VIE	No	Yes	No	No	No	Vapour pressure [Pa]
Clim2000	Duforestel & Dalicieux	Under development	No	No	No	Moisture content [kg_{vap}/kg_{dry_air}] for airborne flow, vapour density for buffering effect [kg_{vap}/m^3] and vapour pressure [Pa] for 1D HM envelope under development
DELPHIN	No	Yes	Yes	Yes	No	Vapour pressure [Pa] for vapour diffusion, moisture content [$kg_{vap}/kg_{dry\_material}$] or water pressure [Pa] (choice between the 2 models) for liquid water
EnergyPlus	EMPD	No	No	No	No	Relative humidity [—]
ESP-r	—	No	No	No	No	Relative humidity [—]
NPI	No	Yes	Yes	No	No	Relative humidity [—]
IDA-ICE		Yes	No	Yes	No	Vapour density [kg_{vap}/m^3]
HAMFitPlus	No	Yes	Yes	Yes	No	Relative humidity [—]
HAMLab	Transmittance & admittance	Yes	No	Yes	No	Vapour pressure [Pa]
HAM-Tools	No	Yes	Yes	Yes	No	Vapour pressure [Pa] for vapour flow, suction pressure [Pa] for liquid flow and moist air pressure for airflow [Pa]
PowerDomus	No	Yes	Yes	Under development	No	Temperature and volumetric content [m^3/m^3] or vapour pressure [Pa] (choice between different models)
SimSPARK	No	Yes	Yes	No	No	Moisture content [$kg_{moisture}/kg_{dry\_material}$] and temperature
TRNSYS	Capacitance “buffer storage”	No	No	No	No	Moisture content [$kg_{moisture}/kg_{dry\_material}$]
TRNSYS ITT	No	Yes	Yes	No	No	Vapour pressure [Pa] for diffusion, water content [$kg_{moisture}/kg_{dry\_material}$] for liquid transport
WUFI-Plus	No	Yes	Yes	No	No	Vapour pressure [Pa] and moisture content [$kg_{moisture}/kg_{dry\_material}$]
Xam	No	Yes	No	No	No	Moisture content [$kg_{moisture}/kg_{dry\_air}$]

Table 5 Main characteristics of the airflow models

Name	Air network	Included effects	Airflow between zones	Airflow through the wall	Possible extensions
BSim	Pressure network	Buoyancy and wind effects	Yes, multi-zone model	1D flow	
BUILDOPT-VIE	Flow-network or pressure network	Buoyancy and wind effects	Yes	No	
Clim2000	Pressure network	Buoyancy effect, effects of ventilation systems	1 way ex/infiltrations; cross-flow in large openings	No	
DELPHIN	Lumped	—	No	1D/2D flow + crack flow (flow path model)	
EnergyPlus	Pressure network	Buoyancy and wind effects, plus pressure effects of mechanical system on natural flows	1 way ex/infiltrations; cross-flow in large openings	No	
ESP-r	Pressure network	Buoyancy and wind effects, effects of ventilation systems	1 way ex/infiltrations; cross-flow in large openings	No	CFD
NPI	Lumped	—	No	No	
IDA-ICE	Pressure network	Buoyancy and wind effects	1 way ex/infiltrations; cross-flow in large openings	1D flow	
HAMFitPlus	Lumped, capable of pressure network	Buoyancy and wind effects	1 way ex/infiltrations; cross-flow in large openings	Capable of 1D/2D flow in porous media and cracks (flow path model)	CFD
HAMLab	Lumped, capable of pressure network	Capable of buoyancy and wind effects	Capable of 1 way ex/infiltrations	Capable of 2D/3D flow in cracks and porous media	CFD with COMSOL
HAM-Tools	Lumped or pressure network	Buoyancy and wind effects, effects of ventilation systems	1 way ex/infiltrations; cross-flow in large openings	1D flow	Airflow model can be used as stand-alone application
PowerDomus	Lumped	Buoyancy and wind effects	No	1D flow under development	
SimSPARK	Intra-room pressure network	Buoyancy and wind effects, also empirical laws for jets and plumes	1 way ex/infiltrations; cross-flow in large openings	No	
TRNSYS	Lumped	—	Possible defined by user	No	Coupling possible with COMIS
TRNSYS ITT	Pressure network by Type157 (based on COMIS)	Capable of buoyancy, wind effects and detailed simulation of ventilation systems	1 way ex/infiltrations; cross-flow in large openings	No	CFD (Fluent, PNS)
WUFI-Plus	Lumped	—	No	Infiltration in cracks	
Xam	Lumped	—	Possible defined by user	No	

Table 6 Main couplings between Heat, Air and Moisture models

Name	Latent heat	Airflow	Material properties depending on temperature	Material properties depending on relative humidity
BSim	In envelopes	—	None	Water vapour permeability
BUILDOPT-VIE	—	T & RH impact on air density and airflow	None	None
Clim2000	In HVAC systems	T & RH impact on air density and airflow	None	None
DELPHIN	In envelopes	—	Thermal conductivity and vapour diffusivity	Yes
EnergyPlus	In HVAC systems	T & RH impact on air density and airflow	None	None
ESP-r	In HVAC systems	T impact on air density and airflow	Thermal conductivity	None
NPI	In envelopes	—	Water vapour permeability + moisture diffusivity	Water vapour permeability; moisture diffusivity + thermal conductivity (using sorption isotherm)
IDA-ICE	In envelopes, in HVAC systems	T & RH impact on air density and airflow	By default: no	Water vapour permeability
HAMFitPlus	In envelopes, in HVAC systems	T & RH impact on air density and airflow	Only vapour permeability	Yes
HAMLab	Capable of latent heat in envelopes and in HVAC-systems	T & RH impact on air density and airflow	Possible using COMSOL	Possible using COMSOL
HAM-Tools	In envelopes, in HVAC systems	T & RH impact on air density and airflow	All	All
PowerDomus	In envelopes, in HVAC systems	T & RH impact on air density and airflow	Possible	All properties by means of specific tables
SimSPARK	In envelopes, in HVAC systems	T & RH impact on air density and airflow	Conductivity, Heat capacity for phase change materials	Transport coefficients
TRNSYS	In HVAC systems	T & RH impact on air density and airflow (in COMIS)	No	No
TRNSYS ITT	In envelopes and HVAC systems	T & RH impact on air density and airflow	Yes	Yes
WUFI-Plus	In envelopes	T & RH impact on air density and airflow	None	Water vapour permeability, thermal conductivity, liquid, transport coefficients, Heat capacity
Xam	In envelopes, in HVAC systems	T & HR impact on air density and airflow	No	No

Table 7 Numerical methods used in the tools

Name	Transfer in building elements (method and typical mesh size)	Time integration	Coupling	External solver
BSim	FCV (HM), mesh can be defined by user, typical size: few cm per CV (control volume)	Implicit, constant time-step	Intermittently between the different types of flow	
BUILDOPT-VIE	FCV, mesh can be defined by user	Explicit, variable time-step	All the equations solved simultaneously	
Clim2000	FCV (H), mesh is user defined, typical size: few cm per CV	Implicit, variable time-step	All the equations solved simultaneously, if convergence problem appear an iterative block method can be used	ESACAP
DELPHIN	FCV (HM) typical mesh size: (1D 100…200 Elements / 2D <10.000 elements)	Variable time-step	All the equations solved simultaneously	CVODE Solver
EnergyPlus	Transfer function for heat transfer	Constant time-step		
ESP-r	FCV (H), maximum 24 volumes per element in standard version	Can be chosen: explicit, implicit or Crank Nicholson, constant time-step	All the equations solved simultaneously	
NPI	FCV (HM), same mesh for heat and moisture, about 1mm size	Implicit (Crank Nicholson), constant time-step	All the equations solved simultaneously	
IDA-ICE	FCV (HAM), mesh can be defined by user, same mesh for heat, air, and moisture	variable time-step	All the equations solved simultaneously	Yes
HAMFitPlus	FEM (HAM), mesh can be defined by user, typical size: 1 to 5 mm per element	Explicit, variable time-step	All the equations solved simultaneously	MATLAB COMSOL
HAMLab	Transfer function for heat transfer, capable of FEM (HAM)	Combinations of implicit, explicit, constant time-step, capable of variable time-step	Different solutions for heat and moisture or air and envelope	MATLAB
HAM-Tools	FCV (HM), mesh can be defined by user. No limits in number of elements. Typical size: 1cm per CV, 0.0001mm at contact surfaces when liquid flow is present	Explicit, variable time-step	All the equations solved simultaneously	Standard ODE solvers included in MATLAB
PowerDomus	FCV (HM), mesh can be defined by user, typical mesh size: 1volume/mm	Implicit, constant time-step from 1s to 24h is user defined	All the equations solved simultaneously (MTDMA – MultiTriDiagonal Matrix Algorithm)	
SimSPARK	FCV (HM), mesh can be user defined	Implicit, variable time-step	All the equations solved simultaneously	
TRNSYS	Transfer function for heat transfer	Constant time-step	All the equations solved simultaneously	
TRNSYS ITT	FEM (HM), user defined mesh size, typical mesh size: 50 layers for each wall (distributed with a nonlinear function)	A combination of implicit and explicit methods with variable time-step	All the equations solved simultaneously	
WUFI-Plus	FCV (HM), expanding and contracting mesh	Implicit, constant time-step	All the equations solved simultaneously	
Xam	Transfer function	Explicit, constant time-step, capable of variable time-step	All the equations solved simultaneously	

NOTE: 1) When ESP-r + NPI are coupled, results of energy simulations (as indoor air temperature, calculated by ESP-r) are used as inputs for NPI calculation.
2) FCV: Finite Control Volume; FEM: Finite Element Method; HAM: Heat – Air – Moisture.

Table 8 Representation of outdoor boundary condition

Name	Wind driven rain	Wind	Neighbourhood	Ground
BSim	No	Impact on outdoor convection, impact on infiltrations	Shadows for solar radiation, local pressure coefficients for wind	Simple representation HM possible
BUILDOPT-VIE	No	Impact on infiltrations	Shadows for solar radiation (detailed)	Simple
Clim2000	No	Impact on outdoor convection, capable of impact on infiltrations	No	No
DELPHIN	Yes	No	No	No
EnergyPlus	No	Impact on outdoor convection, impact on infiltrations	Shadows for solar radiation	Heat transfer
ESP-r	No	Impact on outdoor convection, impact on infiltrations	Shadows for solar radiation, local pressure coefficients for wind	Heat transfer
NPI	No	No	No	No
IDA-ICE	No	Impact on infiltrations and on outdoor convection	Shadows for solar radiation	Heat transfer
HAMFitPlus	Yes	Impact on outdoor convection, impact on infiltrations	Shadows for solar radiation, adjustable coefficients for wind profile, wind driven rain load	Heat and moisture transfer
HAMLab	Yes	Capable of wind impact on infiltration/ventilation	Shadows for solar radiation, local pressure coefficients for wind	Heat transfer
HAM-Tools	Possible with simplified models	Impact on outdoor convection, impact on infiltrations	Shadows for solar radiation, local pressure coefficients for wind, local temperature for radiation	Heat and moisture transfer
PowerDomus	No	Impact on outdoor convection, impact on infiltrations	Shadows for solar radiation	Heat and moisture transfer
SimSPARK	No	No	Shadows for solar radiation	Heat and moisture transfer
TRNSYS	No	No. In COMIS impact on infiltrations available	Shadows for solar radiation	Heat (ground temperature as a boundary condition)
TRNSYS ITT	No	Impact on outdoor surface coefficients (heat and moisture), impact on airflow network (Type 157)	Shadows for solar radiation	1D heat and moisture transfer
WUFI-Plus	Yes	Impact on outdoor convection, impact on infiltrations	Shadows for solar radiation (simplified)	Simple representation with adjusted T&RH
Xam	No	No	Shadows for solar radiation	Calculated as a very thick wall

the focus to optimize the building design for low energy houses. During Annex 41 the tool was further developed to include vapour transfer. It is a multi-zone model which can be used with several hundreds interacting zones. Special attention has been put to prepare the calculation of solar gains through each single window and on the outside of walls by considering the shading by other buildings, overhangs, etc. Transfer in building constructions are calculated in one-dimension, based on a FCV method with explicit time integration.

2.2.3 Clim2000

Clim2000 simulation environment has been developed by Electricité de France (Bonneau et al. 1993; Woloszyn et al. 2004). An important feature of Clim2000 is its open structure, allowing combinations of existing components with elements created by the user. A lot of work has gone into validate different Clim2000 models (Lomas et al. 1997; Plathner and Woloszyn 2002). The standard model library includes airflows in multi-zone spaces, energy and moisture sources, and heat transfer through the building envelope. Moisture buffering effect of materials is modelled using a coarse-grained model by Duforestel and Dalicieux (1994).

2.2.4 DELPHIN

The numerical simulation program DELPHIN4 has been developed at the Dresden University of Technology (TUD, www.bauklimatik-dresden.de) as part of research in the field of transport processes in porous building materials. The computer code allows performance analysis of building components under transient climatic boundary conditions and considering moisture and temperature depending material functions. The included material database represents the current research results in material modelling. The new integrated room model allows the calculation of indoor climate in a simplified room as boundary condition for 1D and 2D wall (details see Grunewald 2000; Häupl et al. 2004).

2.2.5 EnergyPlus

EnergyPlus (www.energy-plus.org) is primarily a simulation engine—with a relatively simple user interface, which does not allow the user to input building geometry graphically. More complete interfaces are available from independent third-party developers. Some key capabilities of the simulation engine include variable time steps, configurable modular systems integrated with heat balance-based zone simulation, multiple comfort models, daylighting and advanced fenestration, multi-zone airflow, displacement ventilation, flexible system modelling, photovoltaic and solar thermal simulation, and moisture sorption by building materials using coarse-grained EMPD model (see Crawley et al. 2004; Henninger et al. 2004; Hong et al. 2003).

2.2.6 ESP-r

ESP-r (Clarke 1985 and www.esru.strath.ac.uk) is an integrated modelling system for the assessment of the environmental and energy performance of buildings. It is capable of modelling the heat, power, and fluid flows, within combined building and plant systems when subjected to control actions, as well as visual and acoustic performance of buildings. The package comprises a number of interrelating program modules addressing project management, simulation, results analysis and client report generation. The problem definition exercise is achieved interactively and with the aid of pre-existing databases offering standard construction materials, glazing systems, event profiles, and plant components. Modelling of heat, air, moisture, and electrical power flows can be performed at user determined levels of granularity.

2.2.7 NPI

NPI is a 1D heat and moisture transport model for a system of structures with ideally mixed and time variable ventilated indoor air space (Koronthályová 1998 and 1997). It was developed at the Institute of Construction and Architecture of Slovac Academy of Sciences and is applied in case studies connected mainly with diagnostics of moisture induced damage problems. NPI involves also the dependency of material parameters on moisture content. The current version of NPI gradually couples the indoor space only with one type of structure and afterwards, the resulting course of indoor air relative humidity (RH) development is calculated as the weighted mean of the previously calculated indoor air RH developments, in order to ensure fast calculations.

2.2.8 Coupling ESP-r and NPI

An original way of computing whole building energy behaviour is to integrate several simulation tools. Koronthylova et al. (2004) present coupling of NPI and ESP-r, to simulate whole building heat and air transfer, zone airflows, as well as zone heat and moisture transfer in the adjacent building structures (1D) linked with the air and moisture balances in the zone.

The coupling between the tools has been accomplished by the following sequential step algorithm realised in each coupling time (hourly) interval at different levels:

- The whole building level—simulation of the 3D heat and air transfer consisting of the modelling of radiation and conduction transfer, together with the air and moisture flows balance of a zone, without hygric inertia (ESP-r)

- Zone level—simulation of heat and moisture transfer in the adjacent envelope structures (1D) linked with the air and moisture balance of the zone (NPI)

Post-processing or coupling of the ESP-r and NPI enables to exploit the capabilities of both particular tools.

2.2.9 IDA-ICE

IDA Indoor Climate and Energy (www.equa.se) is a tool for simulation of building energy consumption. The indoor air quality (IAQ) and thermal comfort is presented by Kalamees (2004) and Sahlin et al. (2004). IDA-ICE covers a large range of phenomena, such as the integrated airflow network and thermal models, CO_2 and moisture calculation, vertical temperature gradients and daylight predictions. To calculate moisture transfer in IDA-ICE, the common wall model RCWall should be replaced with HAMWall, developed by Kurnitski and Vuolle (2000). The moisture transfer is modelled by one moisture-transfer potential, the humidity by volume.

2.2.10 HAMFitPlus

HAMFitPlus is developed during the Annex 41 project by Tariku et al. (2006). This whole building hygrothermal simulation tool is used to assess the durability, indoor conditions (occupant comfort), and also energy efficiency of a building in an integrated manner. The model includes heat, air and moisture transfer across building envelope components and the indoor air taking into account the indoor heat and moisture generations, HVAC system, and dynamic HAM interaction with building envelope components.

2.2.11 HAMLab

A new integrated heat, air and moisture modelling toolkit in MATLAB named HAMLab (sts.bwk.tue.nl/hamlab) has been presented by van Schijndel (2007) and de Wit (2006). The implemented numerical model consists of a continuous part for the HVAC system and the indoor climate, solved with a variable time step, and a discrete part, solved with a time step of one hour for the external climate. Combining the MATLAB/Simulink modelling toolkit with COMSOL allows comprehensive modelling of a room with 2D/3D HAM transport in constructions or 2D airflow.

2.2.12 HAM-Tools

HAM-Tools (www.ibpt.org), presented by Sasic Kalagasidis (2004) and Sasic Kalagasidis et al. (2007), is a modular building simulation software, developed in Sweden by Chalmers University of Technology in collaboration with Technical University of Denmark. The main objective of this tool is to obtain simulations of transfer processes related to building physics, i.e., heat and mass transport in buildings and building components in operating conditions. The model solves heat, air and mass balance equations in an air zone (supposed to be fully mixed) and in the building enclosure, considering air, vapour and liquid transport in one dimension.

2.2.13 PowerDomus

PowerDomus (Mendes et al. 2003; Mendes and Philippi 2005; www.pucpr.br/LST) solves heat and moisture transfer in walls simultaneously according to a method developed by Mendes et al. (2002). The model has an integrated simulation of HVAC systems (Barbosa and Mendes 2007). Seven levels of calculation complexity in HAM models are possible (e.g., with or without moisture transfer, constant or variable material hygrothermal properties, vapour pressure or moisture content driving potentials).

2.2.14 SimSPARK

SimSPARK (Wurtz et al. 2006; Mora et al. 2004; Mendoca et al. 2005) uses zonal models to represent intra-room airflow as well as different models to describe heat and moisture transfer across the building zone envelope, with two of them taking into account moisture adsorption / desorption by building materials. The resulting set of non-linear coupled equations is solved simultaneously by the object-oriented simulation environment, SPARK (gundog.lbl.gov). SimSPARK is suited to parametric studies and complex problems, and can be linked to other simulation tools like EnergyPlus.

2.2.15 TRNSYS

The TRNSYS program (TRaNsient SYstems Simulation, sel.me.wisc.edu/trnsys) is a building energy performance simulation tool with a modular structure. Some other tools (COMIS, Matlab/Simulink, etc.) can be directly linked to the software. The TRNSYS library includes many of the components commonly found in thermal and electrical energy systems, such as solar systems (solar thermal and photovoltaic systems), low energy buildings and HVAC systems, renewable energy systems, cogeneration, fuel cells, etc. It also allows for predictions of the indoor relative humidity, including some buffering effect of materials, using the penetration depth model (Klein et al. 2004).

2.2.16 TRNSYS ITT

TRNSYS ITT is a tool for building simulation that is based on the framework of TRNSYS 14.1 (Klein et al. 2004; Perschk and Meinhold 2007). The wall-model in “Type 56” (module for a multi-zone building) is replaced by a new one (Type 158). The new type is able to consider coupled heat and moisture transfer in the envelope. Diffusion, liquid water transport, phase changing and ice formation are taken into account, as well as a geometrical model for realistic representation of shading and long-wave radiation.

2.2.17 WUFI-Plus

Holm et al. (2003) describe a holistic model called WUFI-Plus (www.wufi.de) based on the hygrothermal envelope calculation model WUFI (Künzel 1994). WUFI-Plus combines a model for heat and moisture transfer in the building envelope with a whole building simulation model for energy calculations. It takes into account moisture sources and sinks inside a room, moisture exchange with the envelope due to capillary action, diffusion and vapour absorption and desorption as a response to the exterior and interior climate conditions, as well as the thermal parameters.

2.2.18 Xam

Xam is a heat and moisture simulation program which has been developed by Iwamae (Iwamae et al. 1999; Iwamae 2004). It calculates the annual variations of temperature and humidity in a building and the energy needed for heating and cooling. The numerical model depends on the simultaneous heat and moisture (humidity ratio) transport in porous 1D wall. The user can get information about the sensitivity of the properties of materials on the temperature and humidity variations.

3 Common exercises

Six different common exercises were carried out in the project to make inter-model comparison and to stimulate the participants to extend the capabilities of their models. In some common exercises, it was attempted to model the results from experimental investigations, such as climate chamber tests (for example Lenz 2006). In Common Exercise 1, it was attempted to model the so-called BESTEST building of IEA SHC Task 12 & ECBCS Annex 21 (Judkoff and Neymark 1995), see Fig. 5. The original BESTEST building was extended with moisture sources and material properties for moisture transport and is described more in details in Rode et al. (2006). Constructions were altered so they were monolithic, the material data were given as constant values or as functions, and the solar gain through windows was modelled in a simplified way.

For all cases there is an internal moisture gain of 500g/h from 9:00 – 17:00 every day. The air change rate was always 0.5ach. The heating and cooling control for all the non-isothermal cases specified that the indoor temperature should be between 20 and 27℃, and that the heating and cooling systems had infinite power to ensure this. The system was a 100% convective air system, and the thermostat was regulating on the air temperature.

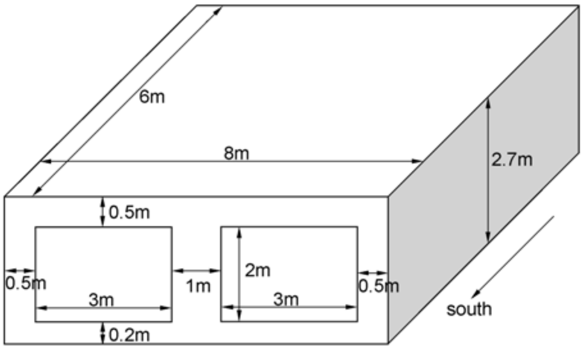

Fig. 5 BESTEST base case building

The first cases were very simple, so analytical solutions could be found. The results from 14 different simulation tools are plotted against the analytical solution in Figs. 6 and 7, showing good agreement between solutions. These results gave an increased belief that it was possible to predict the indoor RH with whole building hygrothermal calculations.

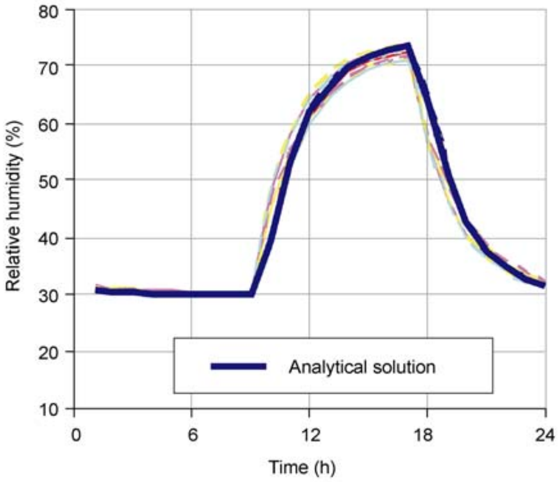

Fig. 6 Indoor relative humidity from analytical predictions with isothermal exposure. Construction surfaces are tight

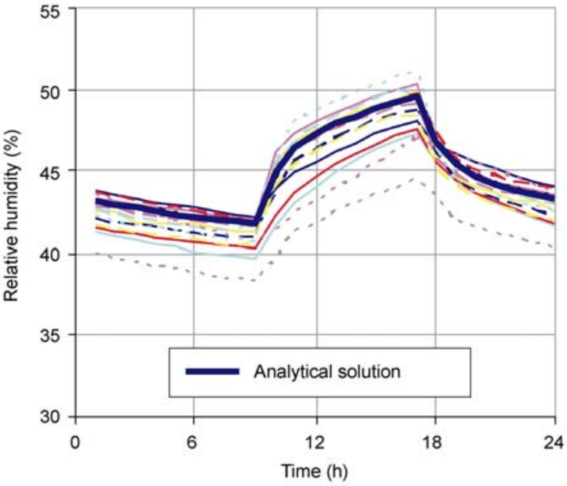

Fig. 7 Indoor relative humidity from analytical predictions with isothermal exposure. Construction surfaces are open

In the second and the more realistic part of the exercise the building was exposed to a real outdoor climate as represented by the test reference weather of Copenhagen, and a simplified modelling of radiation was adopted. The results shown in Figs. 8 and 9 illustrate the difficulty of carrying out the whole building hygrothermal modelling, as some deviations were quite significant. The differences in the thermal simulation could not explain all the deviation, as it was present also for the case with constant indoor temperature. Some deviations seemed to be the result of how well the solar gains were calculated. Thanks to whole building HAM modelling, some local results for moisture conditions could also be compared: Fig. 9 shows the relative humidity inside the roof structure. For most of the tools, the results agreed with one another, which indicate that the simulations perform correctly when it comes to the calculation of moisture transport in the building enclosure.

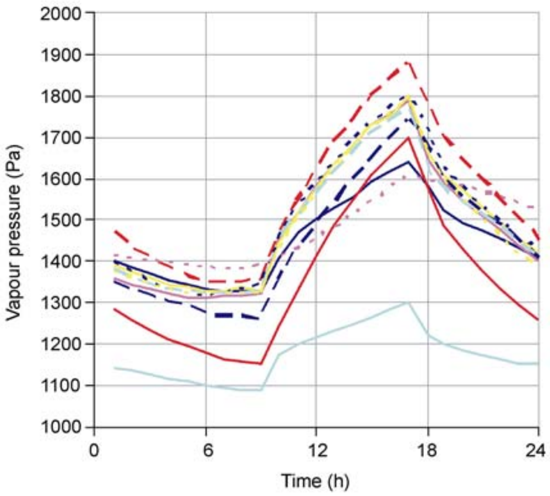

Fig. 8 Indoor vapour pressure from numerical calculations with varying indoor temperature in the range 20 to 27℃, but no external radiation

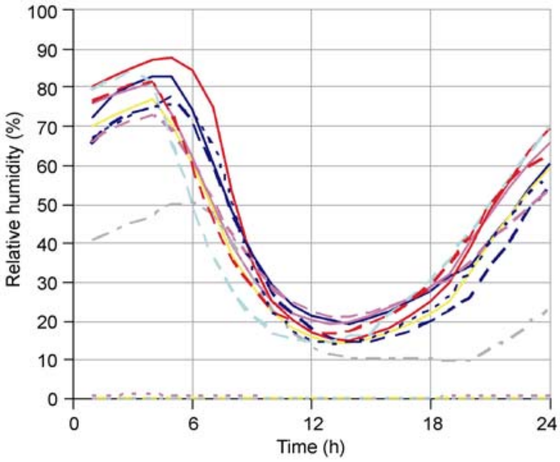

Fig. 9 Relative humidity in the top of the roof from numerical calculations with varying indoor temperature in the range 20 to 27℃. Solar and long-wave radiation is included

All Common Exercises executed as part of Annex 41 Subtask 1, illustrated the complexity of the whole building hygrothermal modelling: it was possible to find a consensus among the solutions with different calculation models only for an extremely simple case.

On the other hand, these results also underline the importance of this type of exercises: the existing codes are tested for their suitability for whole building hygrothermal simulation, and new codes have been created, including upgrading and further development of existing codes to be able to handle the moisture simulation. Moreover, the presented results underline some strong points of whole building HAM simulation tools: they are able to simultaneously predict indoor climate, as well as energy consumption, together with local hygrothermal conditions within the building elements.

4 Conclusion and perspectives

An overall ambition of IEA Annex 41 has been to stimulate the development of information and analytical tools about how a whole building works in terms of its hygrothermal conditions. This has involved modelling of several physical processes pertaining to coupled flow of heat, air, and moisture. And it has involved different building elements at various levels: its spaces, the building envelope with its materials, the interior building structures and furnishing, the system for heating, ventilating and air conditioning, occupants and equipment, and finally the exposure to the exterior environment. The actual challenge in whole building HAM modelling is to ensure a good balance between the many different physical phenomena which interact with each other, rather than to develop models that focus too much on mainly one phenomenon. For example, in most of the existing programs, if moisture is well modelled, then the energy model is rather simple; or if energy is rather well calculated, then moisture behaviour is treated in a simplified way—if not neglected. In this field a lot of progress has been made and encouraging outcomes resulted from this collaborative project.

The state-of-the-art of existing HAM models and tools at whole building levels, as well as the five Common Exercises designed and performed throughout the course of the Annex, are the major outcome of this collaborative work. The common exercises are well documented and can be successfully used by the scientific community as benchmark tests for model validation and development.

4.1 Specific developments in the used whole building HAM tools

As stated before, one of the purposes of IEA Annex 41 has been to enhance existing building simulation tools to be better able to predict the moisture behaviour of buildings. Common Exercises contributed to the validation of 17 tools. Besides this, one completely new tool was developed during the Annex (HamFitPlus). The most straightforward outcome is the enhancement of moisture transfer modelling for building envelopes:

- Coupled heat and vapour transfer models for 1D flow have been developed in energy simulation tools (Clim2000, BUILDOPT-VIE), and also a new module for coupled heat-air-moisture transfer is under development and testing in EnergyPlus.
- The dependency of water vapour permeability on moisture content was introduced in NPI.
- An additional model based on vapour pressure was included in PowerDomus.
- Modelling of multi-layer walls was achieved in SimSPARK.

Common Exercises have demonstrated the importance of correct evaluation of heat and airflow balances for moisture calculations. Indeed, relative humidity is highly temperature dependent, and airflows are significant for the transport of moisture. Therefore heat and air transfer models were enhanced in some tools. Long-wave radiative heat exchange between internal surfaces using exact view factors was introduced in HAM-Tools and PowerDomus. Moreover in PowerDomus the modelling of heat transfer through complex glazing was improved as well as computations of convective heat transfer and central HVAC system model. Models were introduced in BSim for outdoor ventilated cavities, and for 1D airflow through building envelopes. Pressure network modelling was introduced in BUILDOPT-VIE and HAMLab.

Extensive use of simulation tools encouraged optimisation of numerical methods for NPI and WUFI-Plus.

Concerning representation of intra-room airflow, a lumped model was introduced into the building envelope model DELPHIN. CFD modelling was tested within HAMLab, and two other building envelope models were coupled with more detailed room air simulations (NPI with ESP-r, for whole building aspects, and Xam with STREAM for CFD distribution).

4.2 Main results in whole building HAM modelling

As a general principle about the impact of moisture on whole building energy response, different researchers agree that the first and essential step is to correctly represent the moisture balance, including vapour absorption and desorption from hygroscopic surfaces. In some practical applications, when only an estimation of the indoor climate is of interest, this can be done using simplified models for moisture buffering.

However, when the moisture level in constructions is of interest, the investigations require use of coupled heat and mass transfer models to describe the complex physics in walls. An encouraging fact is that different potentials for moisture transfer can be successfully used (relative humidity, vapour pressure, moisture ratio by volume, etc.). Also models that represent heat and simple vapour diffusion in envelope parts, without considering liquid migration or hysteresis in sorption isotherm, can give correct estimation of hygrothermal building response in many practical applications. Indeed their results were similar to those of more complex tools in the common exercises performed. The importance of interactions in whole building HAM response was also shown. The levels of relative humidity in the indoor air were strongly dependent not only on the moisture transfer between air and construction and moisture sources, but also on the correct analysis of airflows and of temperature levels, depending upon proper energy balances.

Nevertheless, correct estimation of the initial conditions and good choice of mesh size and of time step size can have significant impact on the predicted solutions.

4.3 Outlook for the future

The experience from the Common Exercises, as well as parameter study performed and some of the free papers presented by partners of the project indicate that there is still a lot to do. The future work in the field of whole building HAM modelling should concentrate on two complementary issues:

- Consolidate and apply the existing knowledge
- Improve and extend the comprehension of physical phenomena and their modelling

As described in this paper, many models and simulation tools exist, which are able to represent the HAM behaviour of buildings at different levels of granularity and complexity. However, there is still a need to execute more validation cases, possibly as a comparison with measurement data, experiences from practice and field tests. Such validation should be complemented with extensive sensitivity studies. The objective would be to consolidate the knowledge on the limits of the models and to better point out difficulties in existing models, such as the choice of parameters in simplified modelling, or correct grid size.

The models are valuable tools to better understand real problems and to provide correct solutions. Therefore some effort should also be done in “bringing simulations into applications” in this field, and promote the use of whole building HAM modelling in building practice. For example, tools can be used to harvest on the energy benefit while maintaining good IAQ, or to explain and solve problems related to moisture in real constructions.

As the models will never give better results than the input data, analysis of the relationship between the variation of inputs and outputs will enable to define some generally applicable expert rules and principles.

While consolidating and applying the recent knowledge, further understanding of physical interactions and their modelling should also be developed. One of the ways forward is to add new elements to existing models in order to improve their scope and be able to study more complex situations. The final report of IEA Annex 41, Subtask 1 (Woloszyn and Rode 2007) contains a comprehensive list of possible extensions to the capabilities of models that were already presented in the Annex. The list includes

- correct modelling of indoor materials, which are not part of the building envelope, e.g., furniture, books, and textiles;
- HAM modelling of HVAC systems that should be integrated into whole building HAM modelling;
- more detailed representation of phenomena for building envelopes, for example, sub-models of building elements can be extended to include liquid moisture flow, air cavities within building envelopes, etc.;
- additional environmental conditions, which have an impact on whole building HAM response, such as wind driven rain, wind pressure distribution, coupling with ground, etc.;
- multi-dimensional effects, both in air spaces and in construction elements;
- development of adapted modelling approaches, such as multi-scale, reduced order, zonal models or distributed calculations, in order to link whole building performance with problems of condensation behind furniture.

Of course, modelling is not the only activity needed to further analyse coupled heat, air and moisture response of whole buildings. Extensive measurements are needed as well, both to validate the models and to provide reliable database of material properties—and this is discussed in other subtasks of Annex 41.

The list of future possible extensions shows that there is still a lot to do before the scientific community is able to fully manage all facets of hygrothermal modelling of whole buildings. But it should not be concealed that many developments in modelling have been successfully accomplished, and that Subtask 1 of Annex 41 has had a very important role in stimulating this activity.

Acknowledgement

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