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Published in:
Proceedings of the IEA ECBCS Annex 41 Closing Seminar

Publication date:
2008

Document Version
Publisher's PDF, also known as Version of record

[Link back to DTU Orbit](#)

Citation (APA):
Janssens, A., Woloszyn, M., Rode, C., Sasic-Kalagasidis, A., & De Paepe, M. (2008). From EMPD to CFD – overview of different approaches for Heat Air and Moisture modeling in IEA Annex 41. In C. Rode, H. Hens, & H. Janssen (Eds.), *Proceedings of the IEA ECBCS Annex 41 Closing Seminar* (pp. 9-20). Technical University of Denmark, Department of Civil Engineering.

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From EMPD to CFD – overview of different approaches for Heat Air and Moisture modeling in IEA Annex 41

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KEYWORDS: *HAM, simulation, CFD, indoor environment.*

SUMMARY

This paper provides an overview of the recent developments of Heat, Air and Moisture modeling of Whole Buildings, which were carried out within a collaborative project of the International Energy Agency. The project has strived to advance the possibilities to calculate the integrated phenomena of heat, air and moisture flows while including the important interactions that take place in buildings between the various building materials, components, and room air, and how those conditions are influenced by occupants and HVAC systems. Principles and some applications of different levels of modeling are presented: simplified modeling of moisture buffering, whole building coupled models as well as more detailed contributions for airflow modeling, including CFD models.

1. Scope of IEA-Annex 41, subtask 1

Modeling of different physical aspects of buildings (Heat, Air and Moisture) has been a key element of Annex 41, involving most of the participants. Annex 41 of the International Energy Agency's (IEA) Energy Conservation in Buildings and Community Systems program (ECBCS) was a four-year cooperative project on "Whole Building Heat, Air and Moisture Response" (2004-2007). The project sought to deepen the knowledge about the integrated heat, air and moisture transport processes when the whole building is considered. Altogether researchers from some 39 institutions representing 19 different countries participated in the project.

The objective of one of the subtasks: *Subtask 1 - Modelling and Common Exercises* was to encourage the development and testing of new models that:

- integrate several physical aspects of buildings (Heat, Air and Moisture),
- operate on the various scales of a building: from porous materials, over composite building constructions to whole buildings with their furnishing, systems and users,
- consider indoor as well as outdoor climatic conditions, and
- adopt 1-, 2- and 3-dimensional aspects, or combinations, as appropriate.

The purpose of Subtask 1 has been to advance development in modeling the integral heat, air and moisture transfer processes that take place in "whole buildings". It is believed that a 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 presents an overview of different simulation tools and approaches that have been discussed and improved within the project.

2. Hygrothermal modelling approaches

2.1 Classification based on spatial discretization

Heat and mass transfer in buildings can be described by energy and mass conservation equations. Energy balances consider the flows of heat by conduction, convection and radiation. Mass balances for moisture include moisture flows by vapor diffusion, convection and liquid transport, and mass balances for air comprise air flows driven by natural, external or mechanical forces. The interactions between these phenomena are essential for the whole building (WB) Heat Air and Moisture (HAM) response. Figure 1 shows the main interactions between different transport phenomena to be considered in coupled HAM analysis.

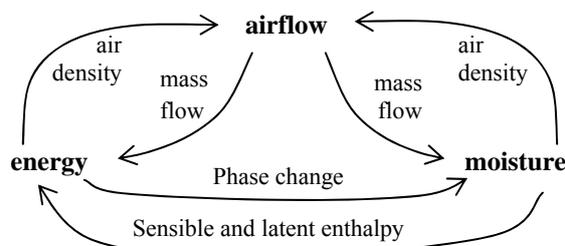


FIG. 1: Main interactions between heat and mass flows

Balance and interface equations may be implemented in simulation tools and solved using numerical methods for space and time discretization. Spatial discretization requires the division of the whole building into small computational cells. While some important transfer processes take place in narrow layers of air or building material, other processes in the same building do not require as finely discretized analyses. It is important to consider both heat and mass transfer processes 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. Whole building HAM-models may be categorized on the basis of the spatial discretization (further called granularity) of the room air volume, on the one hand, and the building envelope on the other.

Four principal levels of granularity can be distinguished for the air volume:

- *Very fine-grained models*: Computational fluid dynamic (CFD) modelling of room air, enabling detailed calculations of temperature, velocity and concentration fields in a room. Typically a room is divided into thousands to millions of control volumes and the conservation equations are solved for each control volume e.g. by using control volume or finite element techniques.
- *Fine-grained models*. In fine-grained models, the air in each room is subdivided into several control volumes (typically between ten and a few hundred). These *zonal* models can also be used to represent several adjacent rooms connected by openings.
- *Intermediate-grained models*: *multi-zone* models for a combination of well-mixed air volumes, that allow several rooms or groups of rooms, each with different characteristics, to be simulated. Therefore heat and mass transfer must be modelled not only between the indoor and outdoor environments but also between different zones inside one building. This includes transfer in walls and also air flows, that can be computed using for example pressure network modelling.
- *Coarse-grained models*: *mono-zone* models for air volumes, where the whole building is represented as one perfectly mixed zone and the same temperature and humidity are assumed for all rooms.

For the building envelope the main difference in HAM-transfer modeling is made by the dimension of represented phenomena. Therefore, granularity refers here to the dimension of spatial discretization used:

- *Very fine-grained models*: *3D models* for the envelope, using control volume or finite element techniques to calculate the heat and mass fluxes, as well as the temperature and concentration fields in the envelope parts, including 3D thermal bridges or similar singular geometries.
- *Fine-grained models*: *2D models* for the envelope.

- *Intermediate-grained models: 1D models* for the envelope.
- *Coarse-grained models: transfer function models* for the envelope, where the dynamic heat and possibly mass fluxes are determined without investigating conditions within the envelope

2.2 Models used within IEA-Annex 41

Table 1. WB HAM simulation tools used in Annex 41

| Name | Web site / reference | Availability | Origin | Granularity | |
|-------------------|--|-----------------------|----------|---------------------------------|---|
| | | | | Air | Envelope |
| BSim | www.bsim.dk Rode & Grau, 2003 | Commercial | Energy | Intermediate | Intermediate Heat-Moisture |
| BUILD OPT-VIE | www.bph.tuwien.ac.at Sofic, Bednar 2007 | No | Energy | Intermediate | Intermediate Heat-Moisture |
| Clim2000 | Plathner and Woloszyn, 2002 | No | Energy | Intermediate | Intermediate Heat, Coarse Moisture |
| DELPHIN 4.5 | www.bauklimatik-dresden.de Funk & Grunewald, 2002 | Commercial | Envelope | Coarse | Fine Heat-Air - Moisture |
| EnergyPlus v1.2.1 | www.energy-plus.org Crawley et al., 2004 | Freeware | Energy | Intermediate | Intermediate Heat, Coarse Moisture |
| ESP-r | www.esru.strath.ac.uk Koronthályová et al., 2004 | Freeware | Energy | Intermediate | Intermediate Heat, (Moisture: see NPI) |
| NPI | ICA SAS (Slovakia) | No | Envelope | Coarse | Intermediate Heat-Moisture |
| IDA-ICE | http://www.equa.se Sahlín et al., 2004 | Commercial | Energy | Intermediate | Intermediate Heat-Air-Moisture |
| HAMFitPlus | Tariku, 2007 | No (Personal program) | WB HAM | Intermediate | Intermediate/Fine Heat-Air-Moisture |
| HAMLab | http://sts.bwk.tue.nl/hamlab van Schijndel, 2007 | Freeware | Energy | Intermediate /able of very fine | Coarse Heat-Moisture, able of very fine Heat-Air-Moisture |
| HAM-Tools | www.ibpt.org Sasic Kalagasidis, 2004 | Freeware | WB HAM | Intermediate | Intermediate Heat-Air-Moisture |
| PowerDomus | www.pucpr.br/LST Mendes et al., 2003 | No | Envelope | Intermediate | Intermediate Heat-Moisture |
| SPARK 2.01 | http://gundog.lbl.gov/ Wurtz et al., 2006 | Freeware | Energy | Intermediate / fine | Intermediate Heat-Moisture |
| TRNSYS 16.00 | sel.me.wisc.edu/trnsys/ Klein et al., 2004 | Commercial | Energy | Intermediate | Intermediate Heat, Coarse Moisture |
| TRNSYS ITT | www.tu-dresden.de Perschk, 2000 | No | Energy | Intermediate | Intermediate Heat-Moisture |
| WUFI-Plus | www.wufi.de Holm et al., 2003 | Commercial | Envelope | Coarse | Intermediate Heat-Moisture |
| Xam | Iwamae et al., 1999 | No (Personal program) | Energy | Coarse | Intermediate Heat-Moisture |

Altogether 17 tools were used to provide solutions for different applications and common exercises. All of them are able to represent dynamic evolution of indoor temperature and relative humidity influenced by variable outdoor climate and hygrothermal loads including the effect of moisture buffering by indoor materials. Table 1 shows the 17 simulation tools that have been used in IEA-Annex 41.

The simulation tools include existing multi-zone models for building energy simulation, such as TRNSYS and EnergyPlus. The main focus of these models is to predict the temperature fluctuations and energy demands of individual rooms. As a result the moisture transfer models for the envelope have a coarse granularity in these tools. Also in some cases the granularity is different for heat (intermediate) and moisture (coarse). This excludes the coupling of transfer phenomena in the envelope.

Other tools also originate from building energy simulation but have implemented building envelope models with a higher level of granularity (eg BSim, IDA-ICE, ...). Most of these models are therefore situated at intermediate level of granularity for both air and envelope. Finally a smaller group of Whole Building HAM-models are the ones originating from detailed models for heat-, air and moisture transfer in building envelopes (eg Delphin, WUFI,...). Since HAM-models are capable of describing heat and mass transfer within the layers of the building envelope in a very precise way, the exchange of water vapour between the room air and the surrounding walls may be accurately defined. However in some of these tools the fine granularity for the building envelope model is associated with a coarse representation of the air volume. A more detailed comparison can be found in Woloszyn and Rode (2008).

2.3 Simulation problems studied in IEA-Annex 41, Subtask 1

The WB-HAM-models were used to study various problems. This was organised by means of several common exercises. They all involved simulations of the indoor hygrothermal response in a room or simple building exposed to variable indoor loads and outdoor conditions. Some of them were based on Bestest procedures, others on experimental data collected in climatic chambers and test rooms. Most of the exercises aimed to analyse the interaction between the moisture storage in walls and the room and envelope performance, like energy demand for heating and cooling, indoor temperature and humidity variations, critical moisture conditions in the envelope... In one exercise also the performance of humidity controlled ventilation systems was analysed and optimized. The exercises thus allowed for extensive testing of simulation tools, by inter-code comparison, comparison to experimental data and various sensitivity studies.

The 17 tools from table 4 proved their suitability for whole building hygrothermal simulation and to simultaneously predict indoor climate, as well as energy consumption. Tools situated at intermediate level of granularity for envelopes could also predict local hygrothermal conditions within the building elements. Clearly when the moisture level in constructions is of interest, the investigations require use of coupled heat and mass transfer models, of at least intermediate granularity, to describe the complex physics in walls. However when only the impact of moisture on whole building energy response is of interest, this can be done by using simplified coarse-grained models for moisture transfer and storage, such as the Effective Moisture Penetration Depth (EMPD) model.

Since airborne moisture transfer has an important influence on the whole building HAM-response, specific attention was given in IEA-Annex 41 to an improved modelling of convective flow fields both between zones (network models) and within zones (CFD-models). These models were applied to study the relation between convective heat and moisture transfer and whole building HAM-performance. Typical applications studied with multi-zone WB-HAM-models were dynamic insulation (Sasic 2007), ventilation drying of cavity walls (Stovall and Karagiozis 2004, Grau and Rode 2006), moisture problems due to air leakage or attic ventilation (Hens 2004, Sasic and Mattson 2005) and humidity controlled ventilation (Woloszyn et al. 2005).

In some applications the detailed knowledge of local conditions in air and envelope is important for evaluating local thermal comfort and for the assessment of the risk of moisture related damage to materials. This analysis is not possible with a coarse or intermediate level of granularity for the air volume. When a detailed field of moisture in the air or in the constructions is needed, Computational Fluid Dynamics (CFD) can help to get a precise prediction of the conditions.

All these approaches, from EMPD to CFD, are complementary, and are of interest in HAM simulations of buildings. In the following two examples are given of work performed within Subtask 1 of IEA-Annex 41. The first example deals with the choice of model parameter values in simplified coarse-grained models. The second example deals with CFD-studies of indoor humidity variations in a room.

3. Model parameters for simplified models

3.1 Governing equations

A full and coupled calculation of the impact of water vapor storage on the indoor climate is complicated. The detailed knowledge of geometry and properties of many indoor materials is needed, such as building materials, wall and floor finishing, furniture and even books and other hygroscopic objects. This information is often not available. Therefore the moisture exchange between the air and surrounding materials may be modeled in a simplified way.

Equation 1 gives the non-steady-state moisture balance for the indoor air in a room, in terms of the partial pressure of water vapor. This equation assumes that the air in a room is well mixed, such that the room conditions (temperature, humidity, air pressure) are equal in the whole zone.

$$m_p + m_{sys} + \frac{\dot{V}}{R_v T_i} (p_e - p_i) = \frac{V}{R_v T_i} \frac{dp_i}{dt} + \sum_j A_j \beta_j (p_i - p_{s,j}) \quad (1)$$

The left-hand side contains all moisture sources/sinks: indoor vapor production (m_p , kg/s), vapor addition/removal by the HVAC-system (m_{sys} , kg/s) and vapor gains/losses by ventilation and infiltration. The right-hand side contains the terms describing the vapor storage in the air and the convective vapor transfer from the air to the interior surfaces of the enclosure walls. The balance may also include interzonal airflow from adjacent rooms but is not taken into account here. Other symbols are: p_i and p_e for the partial water vapor pressures of the indoor and outside air (Pa), R_v the gas constant for water vapor (462 J/kg/K), T_i the indoor air temperature (K), \dot{V} the volume flow rate of outside air (m^3/s), V the room volume, m^3 , A_j the area of the interior surface of wall j , m^2 , β_j the convective surface film coefficient for vapor transfer (s/m) and $p_{s,j}$ the vapor pressure at the interior surface of wall j (Pa).

This latter variable couples the enclosure moisture balance to the moisture conservation equations of materials surrounding the enclosure. Equation 2 describes the mass balance equation for 1D-transfer and storage of water vapor in a wall with porous building materials, the typical basis of HAM-models for the envelope:

$$\frac{\partial}{\partial x} \left(\delta(\varphi) \frac{\partial p}{\partial x} \right) = \frac{\partial w}{\partial t} = \rho \xi(\varphi) \frac{\partial}{\partial t} \left(\frac{p}{p_{sat}(T)} \right) \quad (2)$$

where δ is the vapor permeability (s), φ is the relative humidity (-), w is the moisture content by volume (kg/m^3), $\rho \xi$ is the moisture capacity in terms of relative humidity, derived from the material sorption isotherm (kg/m^3) and $p_{sat}(T)$ is the saturation water vapor pressure at temperature T (Pa). Vapor transfer and storage properties are typically a function of ambient humidity.

Finally the boundary condition at the interior material surface is:

$$\beta_i (p_i - p_s) = -\delta(\varphi) \frac{\partial p}{\partial x} \Big|_s \quad (3)$$

3.2 Classification of simplified models

3.2.1 Effective Moisture Penetration Depth Model.

The EMPD model is a simplified lumped approach to simulate surface moisture adsorption and desorption (Kerestecioglu et al. 1989). In the EMPD approach, Equation 2 and 3 are solved by assuming that only a thin layer near the interior surface interacts with the indoor air (the so-called sorption-active layer or humidity buffer). This implies that water vapor diffusion between the indoors and outdoors through exterior walls is neglected. The thin layer absorbs and releases moisture to the room air when exposed to cyclic air humidity variations. Temperature and vapor pressure are assumed to vary linearly in that layer.

The depth d_p of the sorption-active layer is related to the effective moisture penetration depth EMPD associated with the period of typical fluctuations in the vapor pressure at the wall surface:

$$\text{EMPD} = \sqrt{\frac{\delta \cdot p_{\text{sat}}(T) \cdot t_p}{\rho \cdot \xi \cdot \pi}} \quad (4)$$

In Equation 4 t_p is the period of the cyclic variation (s). For porous building materials the effective penetration depth for moisture exchange is typically in the order of millimeters for daily variations and in the order of centimeters for yearly fluctuations. It can be shown that at the depth of three times EMPD, the moisture variation is less than 5% of the variation at the surface.

With the assumption that the wall-air interaction occurs in a humidity buffering layer with thickness d_b , Equations 2 and 3 are reduced to a single equation:

$$\frac{p_i - p_b}{\frac{1}{\beta_j} + Z_b} = \rho \cdot \xi(\varphi_b) \cdot d_b \frac{d}{dt} \left(\frac{p_b}{p_{\text{sat}}(T_b)} \right) \quad (5)$$

where p_b is the average vapor pressure in the humidity buffering layer (Pa) and Z_b is the vapour diffusion resistance between the surface and the moisture storage centre of the layer (m/s).

The calculation of indoor humidity as a function of time now requires the numerical solution of the set of ordinary differential Equations 1 and 5. In a more complete approach, Equation 5 is applied to all wall surfaces. The number of equations to be solved per room is $j+1$, where j is the number of humidity buffering surfaces. Non-isothermal conditions are assumed: the temperature used in Equation 5 comes from the solution of the energy conservation equations for the individual walls. The moisture capacity of the intervening layer is a function of the relative humidity of the layer. This more complete approach is used in the computer code EnergyPlus (Crawley et al. 2004).

In a more simple approach, Equation 5 is applied to a single humidity buffering layer with properties representative of the average moisture storage properties of all room surrounding surfaces. Isothermal conditions are assumed when solving the buffering layer mass balance: the temperature of the humidity buffering layer is constant in time. Also, the moisture capacity is constant and independent of the layer humidity. This approach is used in the computer code TRNSYS. Isothermal, but time-varying conditions are assumed in the computer code Clim2000. With the assumption of isothermal conditions, the interaction between the heat transfer in the walls and the moisture balance in the enclosure is neglected. For some applications, however, this interaction has an important impact on the humidity variations in a room (Janssens et al., 2005).

It is clear that representing moisture adsorption by a single sorption active layer means that only moisture variations with a single well-defined cycle, e.g. daily fluctuations, can be modeled. To overcome this limitation, the EMPD-approach has been elaborated further in the TRNSYS and Clim2000 codes by dividing the humidity buffer into a surface layer and a deep layer (Abadie et al, 2005, Plathner and Woloszyn, 2002). With this representation, both short-term exchanges (between the air and the surface buffer) and mid-term exchanges (using the deep buffer) can be modeled.

3.2.2 Effective capacitance model.

The previous approach is further simplified by assuming that the thermal and humidity conditions in the humidity buffering layer are the same as in the room air, and so the moisture capacities of walls, furniture and room air are combined into a single room moisture capacity (the so-called effective capacitance or air mass multiplier). Hence the vapor pressure of the wall layer is eliminated from Equation 1, and the set of 2 equations reduces to a single differential equation, Equation 6. This simplest approach is also incorporated in most building simulation codes (effective capacitance humidity model). The factor C on the right-hand side is then treated as a constant capacitance, independent of temperature. It aggregates the influence of room air and of different materials and objects present in a room, each characterized by a buffering layer thickness and volumetric moisture capacity.

$$m_p + m_{\text{sys}} + \frac{\dot{V}}{R_v T_i} (p_e - p_i) = C \frac{dp_i}{dt} \quad (6)$$

3.3 Definition of model parameters

One of the problems with simplified models is that it is difficult to correctly evaluate the model parameters based on the materials that compose the envelope and are in contact with the room air. Janssens et al. (2005) and Abadie et al. (2005) give some guidance on the choice of the buffering layer thickness (d_p) to be used in simplified humidity models. They compare simulations of the humidity variation in a room with homogeneous walls of aerated concrete. The comparison shows a good agreement between predictions with the simplified EMPD-model and a WB-HAM-model when the buffering layer thickness is taken equal to the effective moisture penetration depth defined in Equation 4. The diffusion resistance Z_b in Equation 5 is taken equal to half the diffusion resistance of the buffering layer. This is based on the assumption of a linearly varying vapor pressure in the layer.

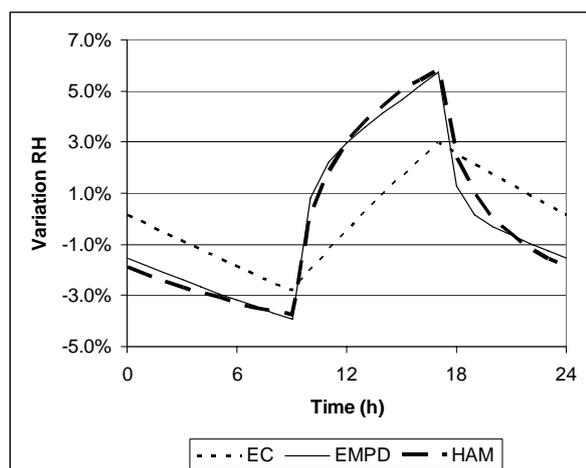


FIG. 2: Periodic state solution of three models: relative humidity variation around the daily average for effective capacitance model (EC), effective penetration depth model (EMPD) and HAM-model.

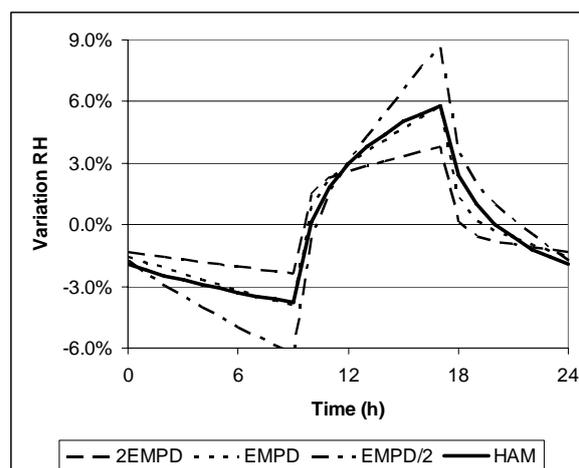


FIG. 3: Periodic state solution of two models: relative humidity variation around the daily average. The figure shows the sensitivity of the EMPD-model to the choice of the buffering layer thickness d_p

Figure 2 makes this more clear: it shows a comparison between periodic state solutions of the indoor humidity variation predicted with the simplified models described above, and a state-of-the-art HAM-model (Janssens et al., 2005). For the model comparison, room geometry was adopted from a hypothetical base case building used in the Annex 41 Common exercise 1 (Woloszyn and Rode, 2008b). The building walls, roof and floor are made of monolithic aerated concrete with thickness 15 cm and a vapor tight exterior finishing. The analysis is performed for constant boundary conditions: indoor and outdoor temperature 20°C, outdoor relative humidity 50% and air exchange rate 0.5 ach. Only the release of water vapor is variable: it is released in the room from 9.00h until 17.00h at a constant rate of 0.5 kg/h.

The simplified models are the EMPD-model and the EC-model (effective capacitance). In these two models, the diffusion resistance and moisture capacity of the humidity buffer are taken constant and evaluated at average indoor humidity conditions. The HAM-model takes the dependency of moisture properties with relative humidity into account. The material properties used in the analysis may be found in the references given above. As Figure 2 shows, the effective capacitance model gives a reasonable estimate of indoor humidity variations. However, this simple model is not able to predict the initial fast response of indoor humidity to changes in moisture production, compared to the HAM- and EMPD-model.

The humidity variation predicted by the EMPD-model is very sensitive to the choice of the buffering layer thickness. Figure 3 shows this by comparing the previous simulation results to calculations where the buffering layer thickness is taken double and half the value of the EMPD of the wall material. Clearly the humidity variation is underestimated and overestimated, respectively, when the model parameters are not properly defined.

In case where the humidity absorbing walls are not homogeneous but multi-layered, the model parameters should be calculated from the properties of the finishing layers and one or more of the layers behind. If the thickness of a wall finishing (d_1) is larger than its effective moisture penetration depth ($EMPD_1$), then the

influence of the other layers is not taken into account. If its thickness is smaller (for instance a wall paper), then the whole finishing layer is considered sorption active and the effective moisture penetration depth of the layer behind is added (Hens, 2005). The model parameters in Equation 5 are calculated as follows (suffix 1 refers to the wall finishing, 2 to the layer behind):

$$\begin{aligned} \text{EMPD}_1 > d_1: & & (7) \\ \rho \xi d_p &= \rho \xi_1 d_1 + \rho \xi_2 \text{EMPD}_2 \\ Z_b &= 0.5 \left(Z_1 + \frac{\text{EMPD}_2}{\delta_2} \right) \end{aligned}$$

4. Modelling humidity distribution within a room

4.1 Developments within IEA-Annex 41

The assumption of well-mixed air in a zone or in an air cavity is typically used in building simulations with a coarse or intermediate level of granularity of the air volume. The air volume is treated as homogeneous and air circulation, caused by temperature and concentration gradients within it or by mechanical devices, is neglected.

In reality, the air in a zone is never perfectly mixed. HAM models based on the well-mixed air assumption may lead to erroneous results in situations where there exist regions with low air circulation, such as in corners or spaces behind furniture. This is because the wall partitions, which are well-flushed with air, experience at least one order of magnitude larger surface transfer coefficients and different heat and moisture transfer driving potentials than those in a hidden position. As a result, only a part of the wall appears active in the HAM transfer investigated, while the other part is practically inactive. Models based on very-fine spatial discretization of an air volume and on the detailed conservation equations of mass, momentum and energy in the air are needed for such problems.

The difficulties associated with modeling convective flow fields have led to the development of specialized Computational Fluid Dynamics (CFD) tools. In the past few years CFD has been playing an increasingly important role in building design, following its continuing development for over a quarter of a century. The areas in building design where CFD has been used are widespread: HVAC-design, ventilation design, fire and smoke control, draft comfort, etc... A good overview of recent developments is given by Zhai (2006). It is interesting to note that whole building heat, air and moisture modeling does not appear in this overview. Most of the existing CFD-tools can represent water vapor diffusion and transport in air, however they do not take into account mass transfer at the interface of the air and the building envelope. Some extended modeling was needed in order to include both heat and moisture transfer in CFD codes. During Annex 41 several approaches were formulated in order to solve coupled mass transfer in air and building envelopes in very fine-grained models for the air volume.

Hedegaard et al. (2004) proposed a method using the existing diffusion equations in a CFD code mainly because it is a method where no programming of user defined functions is needed. As diffusion is computed only in fluid domains, the walls need to be defined as fluids. The building envelope was therefore modeled as immobile fluids with ordinary building material characteristics as material properties. This enables the modeling of moisture diffusion within the walls.

Steeman et al. (2005, 2008) programmed a user defined function using the EMPD-model in order to describe moisture transfer in the building envelope. The main advantage of this approach is a better flexibility of the model. This model was further expanded by using user defined scalars in Fluent containing the mass transfer equations in the solid porous material. This way the solver of the CFD code can be used to solve the mass transfer in the material. This model was successfully validated with experimental data.

Neale et al. (2006) programmed a moisture transfer model in Matlab and made an external coupling with Fluent in order to solve heat and mass transfer in air and porous materials. This approach was also compared to the experimental data.

In IEA-Annex 41 CFD has proven to be a promising tool to get detailed information of the air flows in buildings and over building components. It also may provide the users with local values of heat and mass transfer coefficients which can be used in whole building simulation programs. Additional possibilities for applying CFD simulations in practice are envisioned through the further integration with building simulation tools.

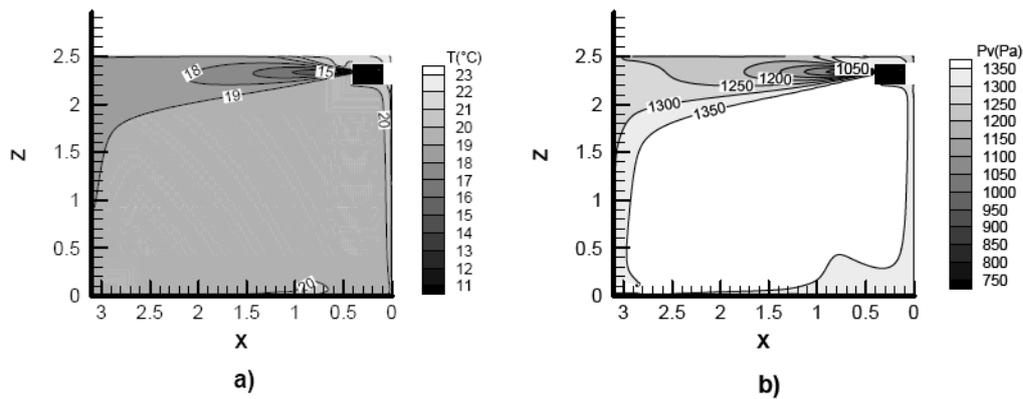


FIG. 4: Air temperature (a) and water vapour pressure (b) distribution in the symmetry plane after 8 hours.

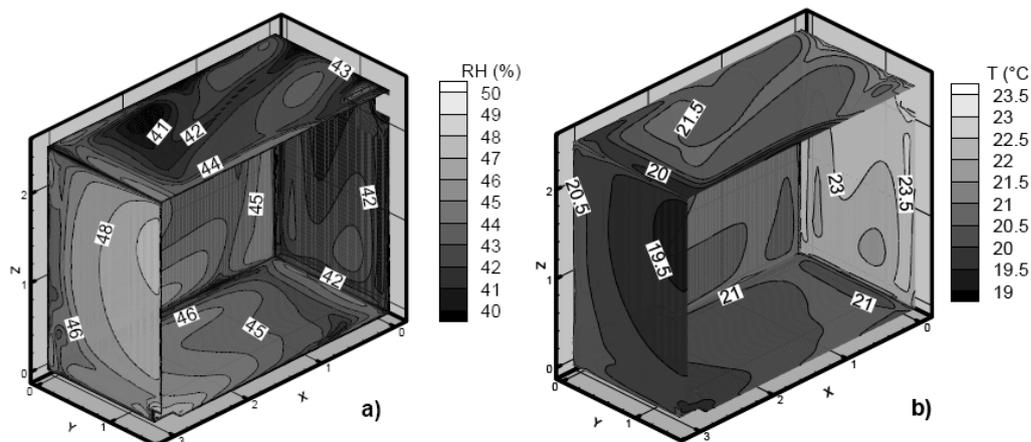


FIG. 5: Distributions after 8 hours: a) Relative humidity inside the walls, b) Temperatures at the wall surface

In spite of the important advances in this field, two major limits are still imposed for such a detailed approach. One is the computational time: even though computing power has risen and is rising significantly every year, annual simulations of whole building using CFD are still far beyond the capabilities of current computers. The second and very important limit consists in the problem of validation. Such detailed tools require very detailed description of the room (geometry and material properties) and a very experienced user in order to provide realistic results.

4.2 Example of a coupled HAM-CFD approach (Steeman et al. 2008)

In this example, the standard CFD model Fluent® is used to solve the heat and mass balance for a room. Therefore, the room is discretized in a number of ‘air’ control volume elements. The heat conduction in the wall is solved by the CFD solid model. Therefore, the wall is discretized in a number of ‘heat’ control volume elements. For moisture transport in the porous material, the EMPD-model is used, which only requires a discretization of the surface layer of the wall into one layer of ‘hygric’ control volume elements (Equation 5). The dimensions of the ‘hygric’ control volume element are defined by the corresponding air control volume element and the penetration depth. For the moisture balance of the air control volume adjacent to the sorption active surface, all the terms in Equation 1 are considered. The EMPD-model is implemented in the CFD code by means of user defined functions.

The coupling between the CFD and the EMPD numerical model is explicit in time. Hence small time steps have to be used in the CFD-EMPD model. It is noted that the transport processes in the walls are much slower than in the air. Hence by choosing a time step of the same order of magnitude as the time constant of the air transport the accuracy of the coupling is guaranteed. In this example a time step of 5s is chosen.

The coupled model is used to study the temperature and water vapour pressure distribution in a room with hygrothermal wall interaction. The geometry of the rectangular room considered in the example is based on an experimental setup for the validation of CFD models for indoor air flow (Hohota 2003). The room is ventilated through an air inlet located at the top of one wall, and an air outlet at the bottom of the opposite wall. The walls consist of cellular concrete, with a thickness of 0.1 m. The room response is studied after a period of 8h moisture production with a uniformly distributed moisture source of 0.5 kg/h, starting from a steady state situation without moisture source. All the time a cold and dry air flow is supplied to the room at a flow rate of 55 m³/h, temperature of 11°C and water vapour content of 4.3 g/kg. The temperature at the outside of the inlet wall is 27°C, and at the outside of the other walls 22°C. This leads to a non-uniform temperature distribution.

Figure 4 shows the predicted temperature and water vapour pressure distributions in the symmetry plane of the room after 8 hours. The figures clearly show that the jet hits the opposite wall (called outlet wall) forming a distinct zone of air with lower temperature and water vapour pressure sticking to the ceiling and outlet wall. The jet does not penetrate into the occupied zone of the room. Figure 5 shows the RH distribution in the walls and the distribution of the wall surface temperature corresponding to the air conditions in Figure 4. The higher surface temperatures at the inlet wall are related to the higher temperature (27°C) as boundary condition at the outside surface of this wall. For the outlet wall, the surface temperatures are lower compared to the temperatures in the occupied zone, as a result of the cold jet hitting the outlet wall. The locally higher RH values in the outlet wall are explained by the colder surface temperatures of the wall, resulting in lower water vapour saturation pressures and thus higher RH values and moisture contents.

The predicted variation of temperature and humidity conditions over a wall surface shows that, when an accurate prediction of the local relative humidity in the wall is required, the use of a fine-grained model which can take into account local temperature and humidity distributions in the indoor air, is necessary.

5. Conclusions

5.1 HAM-modelling in IEA-Annex 41

Many models and simulation tools are available to represent the HAM behavior of buildings at different levels of granularity and complexity. The models are ranged from simplified (coarse-grained) approaches where analytical solutions can be found, to detailed CFD simulations (very finely-grained). According to the objectives of Annex 41, all of them are complementary and help to understand better how a whole building works in terms of its hygrothermal conditions. All tools involve modeling of several physical processes pertaining to coupled flow of heat, air, and moisture. They represent 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.

Simplified modeling for moisture buffering showed its usefulness in many situations, especially when detailed calculations of coupled heat and mass transfer through the envelope are not needed, but rather correct estimations of indoor air relative humidity are of interest. The main problem pointed out was how to correctly evaluate the model parameters based on the materials that compose the envelope and that are in contact with the room air.

Whole building models, mainly situated at intermediate level of granularity, demonstrated that they can correctly predict indoor climate, energy performance, together with hygrothermal conditions within the envelope.

Fine and very-fine-grained models have proven to be a useful tool to get detailed information of the air flows in buildings and over building components, and on local hygro-thermal fields within multi dimensional building elements. They also provide the users with local values of heat and mass transfer coefficients, or hygrothermal bridges, which can be used in whole building simulation programs at intermediate and coarse levels of granularity.

5.2 Future development of HAM tools for buildings

The actual challenge in whole building HAM modeling is to ensure a good balance between 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 modeled, then the energy model is rather simple; or if energy is rather well calculated, then moisture behavior 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. For example, some interesting modeling approaches of air flows through envelopes were proposed.

Also a correct balance should be ensured between different granularities for air volume and for the envelope. Multi-dimensional effects, both in air spaces and in construction elements, need more analysis. The challenge is to have a fully coupled multi-dimensional model of both: the building element and the indoor space, in order to better capture the interactions. Mainly due to modeling and computational difficulties, relatively little attention has been given until now to the problems of air which is not well mixed, and to specification of the cases when it is acceptable to treat the air in a zone as one bulk. Also the influence of possible 2D or 3D HAM transfer through the envelope parts, and the possible variability in space and time of the surface film coefficients, have not been greatly investigated.

To link different levels of modeling, whole building performance with problems of mould behind furniture for example, some adapted approach should be employed – such as multi-scale, reduced order or zonal models. It is not possible to calculate the whole space in the building by a grid whose size is in the order of millimeters, such as those which may be used for calculation of the transport in building materials. Rather than having one tool that calculates everything, a suite of separate, specialized tools should be developed which are able to work together synchronously (distributed calculations).

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