# Whole-Building Hygrothermal Modeling in IEA Annex 41

**Carsten Rode, PhD**
*Member ASHRAE*

**Monika Woloszyn, PhD**

**ABSTRACT**

*Annex 41 of the International Energy Agency's (IEA) Energy Conservation in Buildings and Community Systems program (ECBCS) is a cooperative project on "Whole-Building Heat, Air, and Moisture Response" (MOIST-ENG). Subtask 1 of that project set out to advance development in modeling the integral heat, air, and moisture transfer processes that take place in whole-buildings. Such modeling comprises all relevant elements of buildings: indoor air, the building envelope, inside constructions, furnishing, systems, and users. The building elements interact with each other and with the outside climate. The IEA Annex 41 project runs from 2004–2007, coming to conclusion just before the Thermal Performance of the Exterior Envelopes of Whole Buildings X conference. The Annex 41 project and its Subtask 1 do not aim to produce one state-of-the-art hygrothermal simulation model for whole buildings, but rather aim to stimulate the participants' own development of such models or advanced use of related existing models.*

*Subtask 1 deals with modeling principles and the arrangement and execution of so-called common exercises with the purpose of gauging how well we can succeed in the modeling. To direct the modeling, free scientific contributions have been invited from specific fields that need the most attention in order to better accomplish the integral building simulations.*

*This paper will give an overview of the advances in whole-building hygrothermal simulation that have been accomplished and presented in conjunction with IEA Annex 41, Subtask 1. In addition, the paper will give an overview of the Common Exercises that have been carried out in the subtask. Based on these two activities, some general experiences are reported about how well we are able today to carry out such advanced modeling, and some recommendations for future developments are indicated.*

## INTRODUCTION

Indoor air humidity is an important factor influencing air quality, energy consumption of buildings, and the durability of building materials. Indoor air moisture depends on several factors, such as moisture sources (human presence and activity, equipment), airflow, sorption to/from solid materials, and possible condensation. As all these phenomena are strongly interdependent, numerical predictions of indoor air humidity need to be integrated into combined heat-airflow simulation tools. Subtask 1 of the International Energy Agency's (IEA) Energy Conservation in Buildings and Community Systems program (ECBCS), Annex 41, has set out to advance development in modeling the integral heat, air, and moisture (HAM) transfer processes that take place in "whole buildings."

After discussing the state of the art and presenting the Annex 41 project, this paper gives an overview of the common exercises that have been carried out, as well as some of the advances that have been made and presented in conjunction with IEA Annex 41, Subtask 1.

### State of the Art

The past few decades have seen the development and professional use of tools that, for some of the processes or some of the building elements, describe the building's physical conditions. For instance, fairly comprehensive tools for

***Carsten Rode*** *is associate professor in the Department of Civil Engineering, Technical University of Denmark, Lyngby, Denmark.* ***Monika Woloszyn*** *is associate professor in Cethil, Thermal Science Centre of Lyon, Lyon, France.*

transient building energy simulation have been well established for more than a decade (see, for instance, www.eere.doe.gov/buildings/tools_directory). Such tools comprise the whole building with a granularity going from the suite of rooms that make up the building down to the individual building materials and individual parts and controls of the HVAC system. However, the building energy simulation tools are relatively poor tools for describing the moisture transfer processes in buildings.

Airflow simulation tools at the building level, e.g., COMIS (LBNL 2007) and CONTAM (NIST 2007), or at the room level, e.g., computational fluid dynamics (CFD) codes, such as FLUENT (FLUENT 2007) and STAR-CD (CD-adapco 2007), make good descriptions of air exchange between the zones of a building and the outer environment. Some of them deal with airborne moisture transport and even take into account moisture impact on the airflow. They also represent the heat transfer in the air and in the envelope. However, most of them do not take into account the moisture flow between the air and porous surfaces.

Detailed, transient tools for combined heat, air, and moisture transfer (HAM) were developed in conjunction with the IEA Annex 24 project, which ran from 1991 to 1995 (Hens 2002). The results of calculations with the building envelope HAM-tools may, however, be very dependent on the assumptions made about, for instance, the climatic boundary conditions. Many HAM tools for building envelopes have fairly good procedures to represent the outdoor environmental exposures, e.g., using weather data files, but the indoor environment would often have to be assumed and specified by the user. However, it should also be realized that the collection of building elements themselves form one of the most important factors to determine the indoor climate; thus, there is a mutual link between the envelope and room conditions.

For building envelopes, detailed tools exist for the multi-dimensional flow of heat, as for instance around thermal bridges. In some cases, models also exist for predicting multi-dimensional air or moisture flows in envelope constructions (BEESL [2007] and Fraunhofer [2007]).

Thus, there has been motivation 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 modeling. This has been the outset ambition for Subtask 1 of IEA Annex 41.

## Annex 41: MOIST-ENG

Annex 41 of IEA's ECBCS program is a cooperative project on "Whole Building Heat, Air and Moisture Response" (MOIST-ENG). The project seeks to deepen the knowledge about integrated HAM transport processes when the whole building is considered. To accomplish this, it is necessary to consider the building elements at different scales of size, ranging from the individual building materials to building assemblies to rooms of the building. It must be considered how users of the building, operation of building services, and the outdoor climate influence the hygrothermal condition of the building elements, and it should be considered how the different elements influence each other. Also, the nature of the transport processes for HAM make them depend on each other. While research projects in the past have focused only on some of these elements at a time, Annex 41 seeks to develop further understanding of how the elements function together. This has been done by concerted actions that aim to further and develop the common experiences in modeling and experimenting on the involved topics. Elementary processes that have also been studied in the past, such as moisture transport in materials or wind-driven rain on facades, are also studied in the Annex, but only with the objective to study how such processes influence whole-building performance.

The project is structured into the following four subtasks:

Subtask 1: Modeling principles and common exercises
Subtask 2: Experimental investigations
Subtask 3: Boundary conditions
Subtask 4: Long-term performance and technology transfer

The four-year project started in November of 2003 and has succeeded in gathering significant international contributions from researchers of four continents in the world. Altogether, researchers from some 39 institutions representing 19 different countries have participated in the project, which has the following two homepages: www.ecbcs.org/annexes/annex41.htm (hosted by the IEA ECBCS program) and www.kuleuven.be/bwf/projects/annex41/ (hosted by the project's operating agent, the Catholic University of Leuven, Belgium).

## BACKGROUND AND SCOPE FOR SUBTASK 1: MODELING PRINCIPLES AND COMMON EXERCISES

Modeling of different physical aspects of buildings (heat, air, and moisture) has been a very important part of Annex 41, involving most of the participants. A very large number of coupled phenomena were in the scope of the annex. The physical processes and their state variables (temperature, air pressure, and moisture content) have immense influences on one another. Some examples are:

- The air exchange of a building has an important effect on the energy consumption for thermally conditioning the building.
- Airflow through building envelopes tremendously affects the moisture conditions.
- Moisture conditions are strongly influenced by the temperature.
- Condensation or evaporation of moisture involves a significant conversion of energy.
- Thermal conditions within and around buildings incite airflow by stack effect.

Of course, such whole-building models should take into account location and orientation of the building (climate zone); various heating, ventilating, and air-conditioning systems; air infiltration or exfiltration; user behavior (number of people, activities, moisture and heat production, window ventilation, etc.); and type of room (bathroom, living room, office, etc.). Management of the overall physical processes for the whole is a matter not only of being able to describe the conditions in the different building elements, but also of mastering the interfacial transfers and balances.

Therefore, the initial objective of Subtask 1 was to encourage the development and testing of new models that:

- integrate several physical aspects of buildings (heat, air, and moisture);
- operate on various levels of buildings, from porous materials and overcomposite constructions to whole buildings with their furnishings, systems, and users;
- consider indoor as well as outdoor climatic conditions; and
- may adopt one-, two- and three-dimensional aspects, or combinations, as appropriate.

Objectives are met by theoretical analysis, computer model development, application of engineering tools (from MATLAB to CFD), benchmarking, and common exercises. Another important focus was put on parameter analysis and making considerations about which details are important (and which are not).

However, it has not been the intention that the subtask and Annex per se should be developing a unique integral tool. The intention was that the Annex by its common authority should stimulate and be a concerting forum for the development among individual researchers of tools that would take as many of the integral aspects into account as possible. The developments could take place by making entirely new models and tools or by extension of already existing tools, such 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); and
- combining both building simulation and building component simulation tools, e.g., Koronthalyova et al. (2004).

It is a long road to the full-fledged hygrothermal model for whole buildings, so it is natural that the path is taken in smaller steps. The ambition of the subtask has been to always encourage researchers to take such small steps, as long as they contribute to the progress of development. In practice, the work within Subtask 1 has been organized in two parts:

- Common exercises, in which all of the willing participants simulated the same case and the results where then compared.
- So-called “free papers,” which present the most recent developments of whole-building HAM modeling.

In the following, both aspects will be described.

## COMMON EXERCISES

The purpose of the common exercises being part of Subtask 1 of the Annex has been to test the current possibilities to use modeling as a means to predict the integrated hygrothermal behavior of buildings and to stimulate new development in this area. This could be done either by clever use of already existing models or by new modeling, where models were developed either from scratch or as extensions to already existing models that have some of the desired performances.

The following common exercises (CEs) have been carried out as part of Subtask 1 of Annex 41:

- **Common Exercise 0 (CE0).** This CE validates the thermal aspects of the employed models. This was done by repeating the building energy simulation BESTEST of IEA SHC Task 12 and ECBCS Annex 21 (Judkoff and Neymark 1995).
- **Common Exercise 1 (CE1).** This CE expands on CE0 and the BESTEST case by adding considerations about moisture interactions between building constructions and indoor climate.
- **Common Exercise 2 (CE2).** This CE was based on experimental data from climate chamber tests carried out at Tohoku University in Japan (the tests are similar in nature to those reported in Mitamura et al. [2004]). Two kinds of experiments were carried out. The first was run with different ventilation rates (either 0, 1, or 5 ach per hour) in a small room. The other variation dealt with the amount of hygroscopic surface that was facing the room, where either none, some, or all interior room surfaces were exposed to the building material, which was gypsum board, to test the effect of moisture buffer capacity. Detailed measurements of boundary conditions, as well as of indoor conditions at several points, were performed. This exercise was designed to test whole-building HAM models but can also be used to validate detailed airflow codes (such as CFD, for instance). Results from this CE were not available by the time of writing this paper.
- **Common Exercise 3 (CE3).** This exercise was based on a double climatic chamber test carried out by the Fraunhofer Institut für Bauphysik in Germany (a somewhat similar test is mentioned in the paper by Holm et al. [2003]). In this CE two identical chambers have been run with different cladding materials, and the experimental results were to be replicated by modeling.
- **Common Exercise 4 (CE4).** This CE is an extension of CE3 and was based on the same two real test rooms from CE3. The intent of this CE was to show that an appropriate management of the indoor moisture reduces the building’s energy consumption.
- **Common Exercise “X” (CEX).** This was an exercise with data from a real-life row house located in Belgium.

The house has been studied for some pronounced indoor climate/moisture problems that also involved some effects of adventitious airflow. The case is well documented, and gradually more issues from the study of the house have been dealt with as the Annex progressed (hence the name of the exercise: "X"). The objective of CEX was to simulate the airflow and hygrothermal conditions within a real house. The reports from this CE were not available by the time of writing this paper.

Besides being used for testing existing modeling possibilities and stimulating new developments, CEs also provide elements of validation of whole-building hygrothermal simulation tools. All three elements required by Judkoff and Neymark (1995) for code validation have been included in the CEs from Annex 41:

- Analytical verification (in CE1 and CEX)
- Empirical validation vs. experimental data (in CE2 and CE3)
- Comparative testing, which is the heart of all the CEs

More details about the completed CEs (CE0, CE1, CE3, and CE4) are given in the following.

## BESTEST Case as CE0 and CE1

Both CE0 and CE1 have studied the IEA BESTEST building of IEA SHC Task 12 and ECBCS Annex 21 (Judkoff and Neymark 1995). The BESTEST building is also referenced in *ANSI/ASHRAE Standard 140-2004, Standard Method of Test for the Evaluation of Building Energy Analysis Computer Programs* (ASHRAE 2004). The building shown in Figure 1 is superficial, so no measurement data exist.

The BESTEST case serves to provide comparison between different modeling results. For the thermal analyses of CE0 it would of course be possible to compare against the previous endeavors of IEA BESTEST, but otherwise, and due to the good participation in the exercises, it has been the intent to make comparisons between the different participants in this exercise. Each of the common exercises in IEA Annex 41 had more than ten participants, and it has seemed reasonable to define some consensus solutions based on a majority of the results. Along with files containing numerical results from the study, reports on the program and modeling choices were completed by the participants. These reports document the first state-of-the-art models that can be used for whole-building HAM transfer simulations.

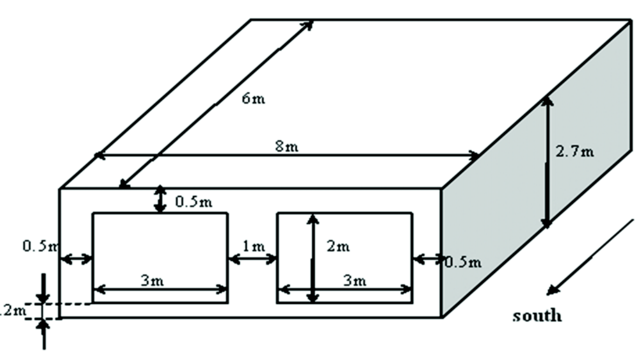


***Figure 1*** *BESTEST base case building.*

**CE0 Thermal Building Simulation.** For the purpose of Annex 41, four cases were chosen from the original BESTEST procedure, appropriate for the whole-building approach (see Table 1). The four cases are indicated by their BESTEST code, "600" for a building made of lightweight construction, "900" for a heavyweight building, and "FF" for buildings simulated under free-floating thermal conditions without heating or cooling systems. These four cases were chosen because they represent well the whole-building approach, according to the scope of Annex 41, without focusing too much on some very specific issues, such as solar shading or transfers to the ground.

The building presented in Figure 1 has a very simple structure with two windows facing south, constant ventilation of 0.5 ach per hour, and constant internal gains of 200 W of sensible heat. The weather file is for Denver, Colorado (altitude 1609 m, latitude 39.8° N, longitude 104.9° W), and is characterized by high-temperature amplitudes and important solar radiation. All of the data can be found in Judkoff and Neymark (1995.)

Thirteen sets of results were collected from ten institutions from nine countries using eleven different programs (see Table 2).

The programs used by participants of CE0 were both public domain and commercial software, and their common feature is continuous development of physical models.

For numerical resolution, different solution methods were used, such as explicit and implicit finite difference algorithms or response factor methods. Both fixed and auto-adaptive time steps were equally represented.

Some differences in the results could be expected because of the differences in the reconstruction of the outdoor climate from meteorological data. Some programs use linear interpolation while others assume that the climate remains constant over the sampling interval. The used energy models include the following features:

- outdoor heat transfer, including convection and radia-

**Table 1. Four Cases Tested as CE0**

| Case | Building Structure | Heating and Cooling |
|---|---|---|
| 600 FF | plasterboard, insulation, wood | None |
| 600 | plasterboard, insulation, wood | Heating if $T_{int} < 20°C$,<br>Cooling if $T_{int} > 27°C$ |
| 900 FF | concrete, insulation, wood | None |
| 900 | concrete, insulation, wood | Heating if $T_{int} < 20°C$,<br>Cooling if $T_{int} > 27°C$ |

**Table 2. An Overview of the Participating Institutions and the Used Simulation Tools in CE0 and CE1**

| Institution | Country | CE0 May 2004 | CE 1 October 2004 | CE 1A January 2005 | CE 1B May 2005 |
|---|---|---|---|---|---|
| CETHIL | France | Clim2000, TRNSYS | Clim2000 | — | — |
| CTH | Sweden | HAM-Tools | HAM-Tools | HAM-Tools | HAM-Tools |
| DTU | Denmark | BSim | BSim | BSim | BSim |
| FhG | Germany | Wufi+ | Wufi+ | Wufi+ | Wufi+ |
| KIU | Japan | — | Xam | Xam | Xam |
| KUL | Belgium | TRNSYS, ESP-r | — | — | — |
| KYU | Japan | — | Original Code | Original Code | Original Code |
| ORNL | USA | EnergyPlus | EnergyPlus | — | — |
| PUCPR | Brazil | — | — | PowerDomus 1.0 | PowerDomus 1.0 |
| SAS | Slovakia | — | Esp-r+Wufi+NPI | NPI | Esp-r + NPI |
| TTU | Estonia | IDA ICE | IDA ICE | IDA ICE | IDA ICE |
| TUD | Germany | — | TRNSYS ITT | TRNSYS ITT DELPHIN | TRNSYS ITT DELPHIN |
| TUE | Netherlands | HAMLab | HAMLab | HAMBase | HAMLab |
| TUW | Austria | ESP-r | HAM-VIE | HAM-VIE | HAM-VIE |
| UCL | UK | EnergyPlus | EnergyPlus | EnergyPlus, Canute_beta | EnergyPlus |
| UG | Belgium | — | (analytical solution) | TRNSYS | 1DHAV+, TRNSYS 16 |
| ULR | France | — | — | TRNSYS, SPARK | — |

tion, using global exchange coefficients in most of the cases

- indoor heat transfer, including convection and long-wave radiation (all except one); however, different methods are used to compute the heat transfer: constant coefficients, detailed computations, with or without linearization
- perfect mixing of the air zone in all the cases
- one-dimensional heat transfer assumed in envelope parts
- some differences can be seen in the treatment of windows and solar gains: transmitted radiation distribution can be fixed by the user or calculated as a function of solar position; different possibilities are used to calculate the short-wave radiation transmitted through the windows
- heating and cooling systems represented are, in general, "perfect": no dynamics, purely convective, controlled by air temperature

All models used include moisture in the balance of the air zone, but at the time of executing CE0 only a few programs represented moisture transfer through the envelope.

The results gathered comprised indoor air temperatures and heating and cooling loads (for cases 900 and 600) as well as solar radiation descriptions (incident radiation at all the walls and gains through the windows). Both detailed hourly values and global results (annual loads, mean temperature, etc.) were collected.

Indoor temperature variation during one day is shown in Figure 2. The difference between light- and heavyweight structures can be clearly seen. Similarly, a spread of several degrees between different sets of results can be seen on the graph. The differences are mainly due to different modeling capabilities of the codes and especially to differences in calculating solar gains through windows. However, it should be stressed that in all the cases most of the results concerning heating and cooling loads corresponded well with the original range of results from BESTEST.

**CE1 Hygrothermal Building Simulation.** CE1 expanded on CE0 by adding some analysis of the indoor and building envelope moisture conditions for the BESTEST building used in CE0. The original plan for CE1 was to add the moisture problem parts directly to the problem from CE0. The first results of CE1 showed, however, that the original case had too many uncertainties even within the thermal calculation, e.g., the presentation of the material data, window models, etc. Therefore, a step back was taken with CE1A (an analytical case) and CE1B (a more "realistic," numerical case). The constructions were monolithic, the material data were given as constant values (CE1A) or as functions (CE1B), and the solar gain through windows was modeled simplified. An overview of these variants is given in Table 3.

For all cases there was an internal moisture gain of 500 g/h from 9:00–17:00 every day. The air change rate was always

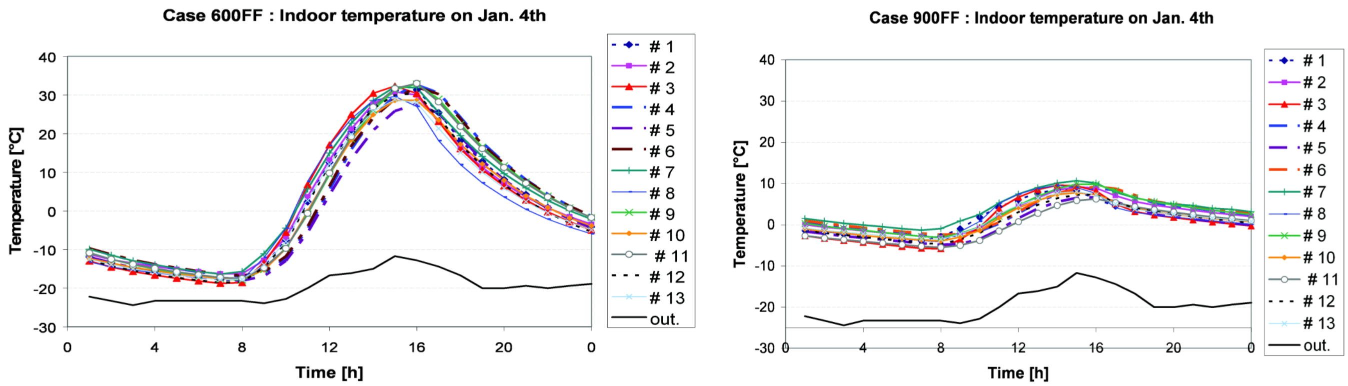


***Figure 2*** *CE0: indoor and outdoor temperature (°C) on Jan. 4 for both a lightweight structure (left) and a heavyweight structure (right) for all 13 sets of results.*

**Table 3. Overview of Variations of CE1**

| CE1 | CE1A | CE1B |
|---|---|---|
| Numerical cases in principle like in CE0; natural climate | Monolithic walls with simple material properties; isothermal conditions; no internal or solar gains | Monolithic walls with realistic properties; natural climate |
| *600 0A* Analytical*,* vapor tight surfaces<br>*600 0B* Analytical, vapor open surfaces<br>*600 Open* Numerical, vapor open surfaces<br>*600 Paint & VR* Numerical, painted surfaces<br>*900 Open* Numerical, vapor open surfaces | *0A Tight* Analytical, vapor tight surfaces<br>*0B Open* Analytical, vapor open surfaces | $T_{indoor}$ 20°C no external radiation<br>$T_{indoor}$ 20°C–27°C no external radiation<br>$T_{indoor}$ 20°C–27°C with solar and long-wave radiation |

0.5 ach. The heating and cooling controls for all the nonisothermal cases kept the indoor temperature between 20°C and 27°C. The system was a 100% convective air system and the thermostat was on air temperature.

Table 2 shows the used simulation codes. Some of the institutions used the same code for all the exercises—with or without modifications from case to case—while others used two different codes or did not take part in particular exercises.

**Results from the Original CE1.** CE1 was the original case of an exercise for simulations that include moisture exchange. It was posed with a relatively high degree of freedom for modeling a realistic building, based on the descriptions for thermal BESTEST cases. The results from different participants showed a very large spread. Big differences in results were coming from different assumptions that were made on some of the input conditions for both energy and moisture modeling. Facing the difficulty to interpret such data, it was decided to review the exercise giving much more detail on the input data and on the way of modeling the problem.

**Results from CE1A Analytical Cases.** This exercise applied the simplest conditions in terms of material properties and boundary conditions and used properties that facilitate the possibility to solve the case analytically. Compared to the original CE1, the following changes were made: constructions were supposed to be made of monolithic aerated concrete with constant/linear properties. Tight membranes on the outside, and in case 0A also on the inside, prevented loss of vapor from the building by transport all the way through the walls. The exposure was completely isothermal, i.e., there was the same temperature outside as inside the building. The building had no windows. The initial conditions were given.

The calculations were run for as many days as it was necessary to achieve quasi-steady conditions. The results were reported for the last day of calculation.

It was possible also to solve the cases by using numerical tools. The numerical results are shown in Figures 3 and 4 for tight and open surfaces, respectively, together with an analytical consensus solution developed by Bednar and Hagentoft (2005). For this simple case, all models used showed a very good agreement with the analytical consensus solution.

**Results from CE1B "Realistic" Cases.** This exercise was the second part of the revised CE1—the constructions were still more simple than in the original CE1 and a more humid location, which is also close to sea level, was chosen: Copenhagen. All of the envelope constructions were made of monolithic aerated concrete and faced outdoor air. There were no coatings or membranes on any sides, not even for the roof. Variations were run either for isothermal or nonisothermal conditions, and the nonisothermal conditions were run either with or without solar gains in the building. The results were again given as the indoor relative humidity (Figures 5 and 6). Given the important spread between different numerical solutions, judging the results in terms of "correct" or "not correct" was very difficult. It was then preferred to go to CE2 and CE3, where measured data give target solutions and help to validate the modeling approach.

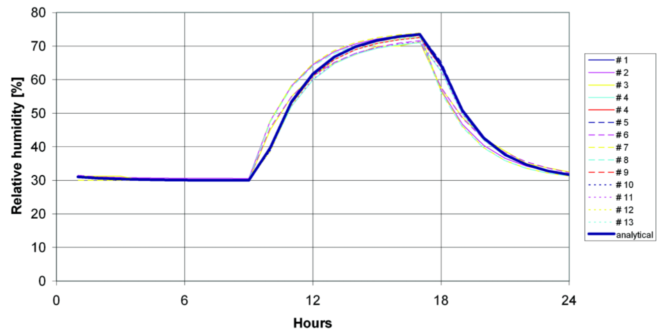


***Figure 3*** *CE1A, Case 0A: Numerical results of indoor relative humidity for isothermal exposure. Construction surfaces are tight. The results are compared with an analytical consensus solution.*

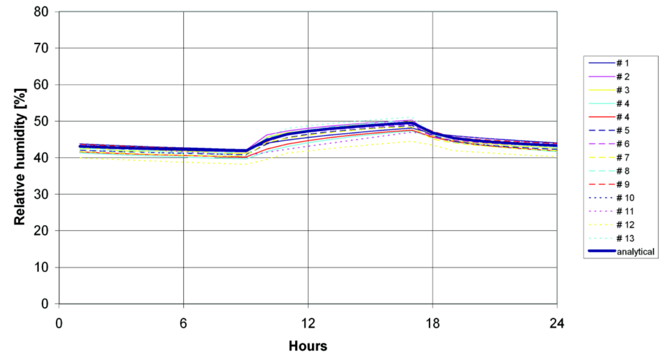


***Figure 4*** *CE1A, Case 0B: Numerical results of indoor relative humidity for isothermal exposure. Construction surfaces are open. The results are compared with an analytical consensus solution.*

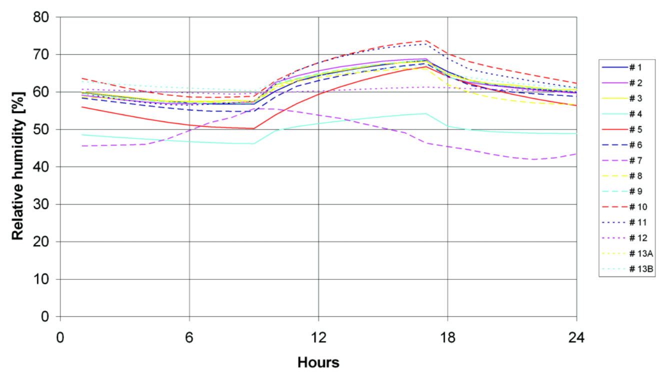


***Figure 5*** *CE1B, Case 1, "20°C, no external radiation": simulation results of indoor relative humidity for a day in July where the influence of the solar radiation is neglected and where constant indoor temperature conditions emphasize the deviations in moisture calculations.*

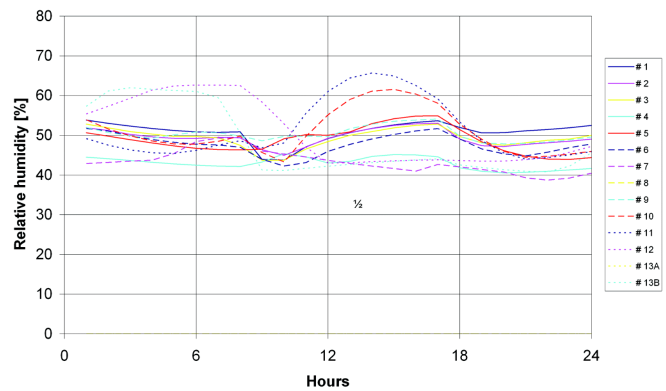


***Figure 6*** *CE1B, Case 3, "20°C to 27°C, with solar and long-wave radiation" through the windows and on the external opaque surfaces: simulation result of indoor relative humidity for a day in July with dynamic indoor temperature conditions.*

## Common Exercise 3

The intent of this common exercise was to simulate two real test rooms that are located at the outdoor testing site of the Fraunhofer Institut für Bauphysik in Germany (see Figure 7). Tests were carried out during winter and spring with the aim of comparing the measurements with the models developed with the Annex 41 project. Gypsum board served as moisture buffering material (the same gypsum board was used as was tested in a round robin test from Subtask 2 of the Annex 41 project).

The results of the measurements show the influence of different materials in comparison to the relative humidity in the rooms. In the *reference room* a standard type of gypsum board with a latex paint ($s_d = 0.15$ m) was used. The walls and the ceiling of the *test room* were fully coated with aluminum foil. For the experiments, the test materials were attached to the walls and ceiling of the room.

The tests in the rooms were made for the following four steps:

1. Reference room—test room with only aluminum foil
2. Reference room—test room with gypsum board on the walls
3. Reference room—test room with gypsum board on the walls and the ceiling
4. Same as the previous tests but now, unlike in the previous cases, also with solar gains in the rooms

## Investigations in the Rooms

**1. Reference and Test Rooms with Only Aluminum Foil.** During the first test stage, no material was attached to the walls in the test room and measurements were run for a period of 17 days. This test showed the difference between the

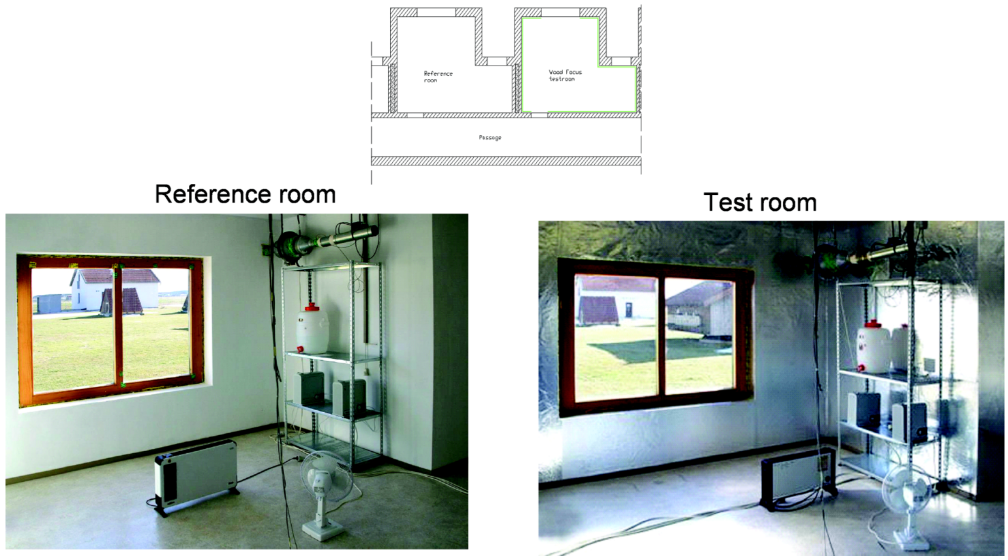


*Figure 7* *Experimental rooms used at the Fraunhofer Institut für Bauphysik in Germany to generate field data for CE3. Reference room (left): the surfaces of the walls and the ceiling are coated with common gypsum plaster and paint ($s_d$ = 0.15 m). Test room (right): surfaces of the walls and the ceiling are completely coated with aluminum foil.*

reference room and the test room with aluminum foil where no sorption effects were possible.

**2. Reference and Test Rooms with Gypsum Boards on the Walls.** In the second step, gypsum boards were attached on the surface of the walls with aluminum foil in the test room so that it covered the area of the walls (approximately 50 m). This experiment was run for a period of 35 days. For the test, gypsum boards with or without paint were used.

**3. Reference and Test Rooms with Gypsum Boards on the Walls and Roof.** For this experiment, additional gypsum boards were installed in the room with aluminum foil; the ceiling was also covered (in total now approximately 65 m). The test was carried out for a period of 26 days. For this test, gypsum boards with or without paint were again used.

**4. Reference and Test Rooms with Solar Gains.** Results from this part of the CEs were not available by the time of writing this paper.

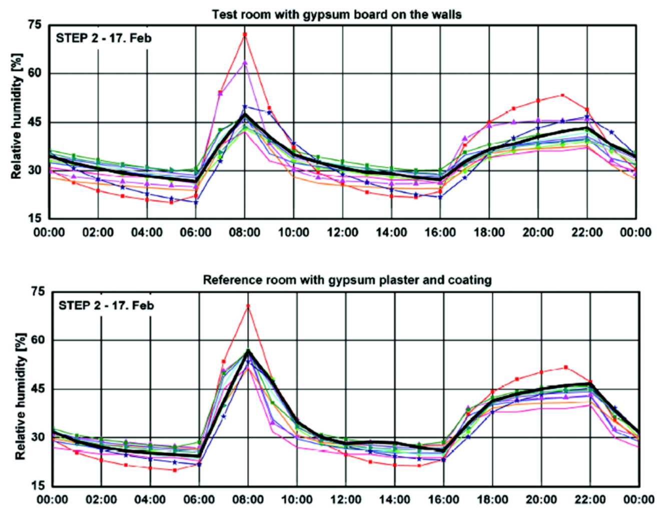


*Figure 8* *Results of simulations for CE3. Rooms with gypsum boards on the walls, which were either untreated (top graph) or painted (bottom). The bold line represents the measured values and the thin lines represent 12 computed solutions.*

### Output from the Investigations

For each calculation, hourly averaged air temperatures and relative humidity were reported for the air in each of the rooms. In addition, the required energy to maintain the desired temperature in the rooms was reported. The results of relative humidity predictions and measured results for a day of Step 2 are shown in Figure 8. In comparison with CE1, a rather good agreement between different solutions was obtained. It should be noticed that the authors of the "extreme" numerical solutions (the highest/lowest values) reported some misunderstanding of the input data. The improvement of the overall results between CE1 (2004/2005) and CE3 (2006) are encouraging proof that some progresses in whole building HAM modeling were accomplished with the Annex 41 project.

### Common Exercise 4

CE4, entitled "Moisture Management for Reducing Energy Consumption," was an extension of CE3. The intent of this common exercise was to show that an appropriate management of the indoor moisture conditions could reduce

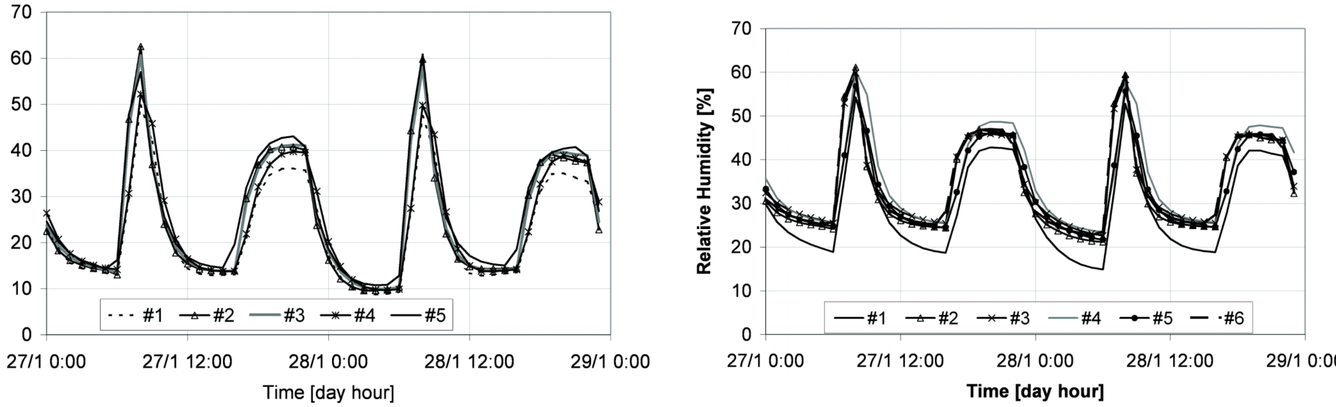


***Figure 9*** *CE4: indoor relative humidity as computed by all the participants—constant ventilation rate (left) and relative humidity controlled ventilation (right).*

the building's energy consumption. The objective of the exercise was to use a relative humidity controlled (RHC) ventilation system combined with the effects of moisture buffering materials in order to reduce the energy consumption and improve the indoor climate.

The exercise was based on the two real test rooms that are located at the outdoor testing site of the Fraunhofer Institut für Bauphysik in Germany and used in CE3. The RHC ventilation adapts the flow rate to the indoor relative humidity. The target relative humidity values of the indoor air were between 40% and 50%, as proposed by *EN Standard 15251: Indoor Environmental Input Parameters for Design and Assessment of Energy Performance of Buildings Addressing Indoor Air Quality, Thermal Environment, Lighting and Acoustics* (EN 2007) for class A buildings.

The participants were asked to perform five simulations changing ventilation system data and moisture buffering capacity of the envelope:

- Run A: the original results from CE3, with constant ventilation
- Run B: using original finishing materials and the RHC ventilation system
- Run C: using original finishing materials and the RHC ventilation system with maximum and minimum airflow values modified by the participants
- Run D: using the original RHC ventilation system from Run B but changing the moisture buffering capacity of materials by using different material properties and different surfaces
- Run E: combining both the ventilation and the materials in order to reduce the energy consumption and improve indoor relative humidity

The simulations were run for a simulation period from January to April covering cold and mild periods.

Six solutions were provided by six participants from different countries. Even if some differences in results were noticed, an overall good agreement was found for the different simulations. Figure 9 shows the indoor relative humidity in the cold period for two ventilation systems. It can be noticed that RHC ventilation reduces the spread between the minimum and maximum values of relative humidity. It was also found that the use of an RHC system could reduce the mean ventilation rate about 30% to 40% in the cold period and generate 12% to 17% of energy savings. It should be stressed that the energy savings are done keeping the peak RH values at the same level, therefore without raising the risk of condensation. However, during the mild period the savings were much lower (only about 2%), mainly because of the much higher moisture content outside. It was also confirmed by the participants (see Figure 10) that the use of moisture buffering materials enables a significant reduction of the amplitude of daily moisture variations.

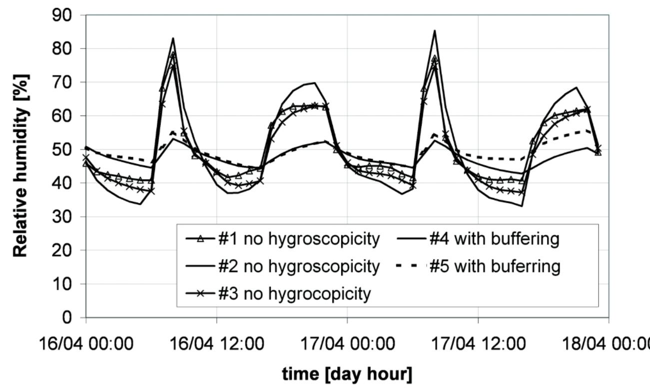


***Figure 10*** *Indoor relative humidity in a mild period with and without hygroscopic materials.*

## Some Conclusions to Draw from the CEs

The CEs have illustrated the complexity of whole-building hygrothermal modeling. It was possible to find some consensus among solutions only for an extremely simple isothermal case: a monolithic building without windows and with no contact with the ground.

But the CEs have stimulated some developments of different software as well as some original use of already existing programs. Mainly, in CE0 some energy models were improved in more moisture-oriented programs, and in CE1 moisture modeling was enhanced in more energy-oriented tools. The improvement of the models was noticed in CE3, when the obtained agreement was much better than in CE1.

All CEs showed that there is a need for some consensus data concerning heat and moisture properties of the materials and more generally about all of the input data. The same remark concerns the outputs: as energy and moisture are closely influenced by each other, some spread in relative humidity values can be easily explained by the spread in temperature values. Therefore, moisture content should be preferred over relative humidity for comparison purposes.

Also in such an integrated model, all elements are very important: for example, some differences in the indoor relative humidity may be induced by modeling of solar gains or long-wave radiation, and not at all by the differences in the moisture model. Moreover, some participants stressed the importance of wall discretization. Differences are important for energy vs. moisture modeling; they can lead to numerical divergence.

A crucial question was raised during the discussion: how can we evaluate whether the solution is *good* or *bad*? This is especially important when there are no measured data. In such cases, could one say that the consensus solutions are good? The question remains open.

Globally, the most encouraging results of all the CEs are:

- Existing models have been "tested" for their suitability for the whole-building hygrothermal simulation.
- New models have been created, including upgrading and developing existing models to be able to handle also new aspects in heat, air, and moisture.
- Several existing computational tools were found to be able to deal with coupled heat, moisture, and ventilation problems at the whole-building level—they all give similar results.

## NEW RESEARCH/FREE PAPERS

In addition to CEs, the researchers were encouraged to present the recent developments in the field of whole-building HAM modeling as so-called "free papers." The idea is to promote new developments in this field and to encourage discussion among researchers in order to improve existing tools and propose new concepts.

Free papers were received in different areas, from convective models and multidimensional effects to integrational aspects, simplified models, and critical analysis of simulation model limits. Some work dealt with sensitivity analysis, verification, and validation of whole-building simulations. There was a general presentation of all the free papers. Some of their interesting concepts are presented in the following.

### Papers and Presentations

Over the first six working meetings of Annex 41 (2004–2006), about 90 papers and presentations were proposed in Subtask 1, reflecting a high level of scientific activity of annex participants. About one-third of the papers deal with the CEs, and the remaining two-thirds represent the "free papers": the input of participants to the development of computational tools for whole-building hygrothermal conditions.

Within this group of about 60 free papers, 4 were "state-of-the-art" papers and 13 presented the capabilities and recent developments of computational tools used by participants, such as HAMLab, HAM-Tools, Wufi+, IDA ICE, BSim, Domus, Clim2000, and some others still being improved.

Also, 12 papers presented the applications of comprehensive simulations tools to case studies. It is interesting to note that four papers analyzed condensation problems in roofs and cold attics, whereas other papers dealt with very different applications, such as in a church, an office building, a massive wood construction, etc.

The remaining 30 papers described different aspects of holistic heat, air, and moisture modeling, from analytical solutions to the interactions between three-dimensional airflow and construction using CFD codes. Simple models and their intercomparison were presented in six papers and envelope model improvements in eleven papers (all presenting coupled heat and moisture transfer, some of them including convective airflow through the envelopes as well). Also, five papers were devoted to validation aspects, including benchmark tests, sensitivity studies, and intercode comparison.

### Advances in Three-Dimensional Modeling

Some of the interesting advances in whole-building heat, air, and moisture modeling concern the room modeling using CFD codes. Based on the equations of fluid mechanics, CFD codes are able to describe the airflow in a room in a very detailed way. Most of the existing tools can represent water vapor diffusion and transport in the air; however, they do not take into account mass transfer at the interface air-envelope.

Hohota et al. (2004) presented a development with a commercial CFD code used to extend the capacity of the existing model and especially to represent vapor condensation on cold faces. This was done by adding source and sink terms to energy and mass balance equations for each cell of computational domain that is in contact with a solid surface. As soon as the surface temperature drops under the dew point of the inside air, liquid occurs on the surface. Vapor pressure against the surface remains at the saturation value as long as the surface is moist. Latent heat released during the condensation process is injected into the energy network. The comparison with the experimental work showed that the numerical model was able to correctly predict the regions where condensation appeared. This was confirmed as long as vapor injection in the inlet was kept homogenous and stable (Hohota 2003).

The next step in improving model possibilities is to represent the moisture flow between air and materials. Indeed, most building materials are porous and interact with indoor air by absorbing or releasing moisture.

Existing CFD tools focus on airflow movement and have only some simple models of transfer phenomena in solids. Therefore, some extended modeling was needed in order to include both heat and moisture transfer. Basically there are two ways to represent moisture transfer in the envelope:

- *Use an existing model for heat transfer in a solid material and enhance it for moisture transfer.* In this case, vapor diffusion in the wall needs to be programmed by the user.
- *Use an existing diffusion equation.* As diffusion is computed only in fluid domains, the walls need to be defined as fluids.

Both approaches were used by Annex 41 project participants. The second approach was chosen by Hedegaard et al. (2004) mainly because it limits the use of user-defined functions, which decrease the performance of the numerical solver. The constructions were therefore modeled as immobile fluids with ordinary building material characteristics as material properties. This enables modeling of moisture diffusion within the walls. The diffusion model simply has two boundary vapor contents and then performs a linear regression between the values.

The first approach was as proposed by Steeman et al. (2005). Here, moisture transfer between the air and the envelope, as well as moisture transfer in the solids, was programmed as a user-defined function. The main advantage of this approach is better flexibility of the model.

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 if the computing power is rising significantly every year, annual simulations of whole buildings using CFD are still far beyond computer capabilities. The second and very important limit consists of the problem of validation. Such detailed tools require very detailed descriptions of the room (geometry and material properties) and a very experienced user in order to provide realistic results.

### Analysis of Simplified Models

A full calculation of the impact of water vapor storage on the indoor climate is very complex. Thermo-hygroscopic properties and detailed geometries of many indoor materials, such as building fabric and furniture, but also newspapers, books, and carpets, should be taken into consideration. Such a task is of course very difficult. Therefore, use of simplified models can give a realistic estimation of the indoor climate and help in understanding the phenomena involved. All simplified models assume perfect mixing of the room air and some different simplifications of coupled HAM transfer in materials. However, it is very important to know the limitations of such simplified tools.

For example, Hens (2005) presented two methods, one based on the lumped parameter approach and one, using the Fourier analysis, based on harmonic solution. In both cases, constant material properties were assumed. The lumped approach is based on a “sorption active layer,” with thickness depending on the time period considered. In the presented example, daily variations were considered. The second simple model, based on harmonic analysis of isothermal conditions, represented long-term variations. Both models have their applications to predict the indoor climate. The lumped approach was used to calculate indoor relative humidity for daily cycles for intermittent vapor sources. It shows a short-term effect in a sense that peaks in indoor partial water vapor pressure dampen substantially when the inside part of walls, furniture, etc., are sorption-active. The second approach, harmonic analysis, was used to calculate annual excess of indoor water vapor pressure and showed an effect of longtime inertia, which has also been seen in experimental field data. Indeed, buffer capacity also introduces effects on an annual basis in terms of a hysteresis between autumn and springtime.

Hokoi (2005) used Fourier analysis to investigate mass balance in a room. The conditions were isothermal, and heat and mass transfer in walls were written for semi-infinite material. Using an admittance matrix, the model was solved and used to investigate the amplitude decrement (output/input) as a function of period. The analysis showed that at high frequency (minutes) moisture capacity of the room air is dominant and at low frequency (days) the amplitude of the humidity fluctuation becomes small, mainly due to the absorption by the wall material.

Another simplified approach, the Effective Moisture Penetration Depth (EMPD), was presented by Karagiozis and Gu (2004). The EMPD model is a simplified, lumped approach to simulate surface moisture adsorption and desorption. It assumes that a thin layer close to the wall surface behaves dynamically and exchanges moisture with the air domain when exposed to cyclic air moisture pulses. For short periods where the cyclic integral of the total moisture adsorption and desorption is near zero (i.e., there is no net moisture storage), the EMPD concept has been shown to be a reasonable approximation of reality (Kerestecioglu et al. 1989). The EMPD model is implemented in EnergyPlus software and improves indoor climate predictions in energy simulations.

Another interesting paper by Janssens and De Paepe (2005) compares three different numerical models: a lumped capacity model, which lumps the moisture inertia in a single capacity for the room; a two-node model, which differentiates between the room air humidity and the representative humidity of an equivalent humidity buffering material; and finally a room-wall model, which describes the water vapor transfer and storage in the building fabric through a continuum model. Some deviations between calculation results of the various models were found. They can be related to different assumptions in modeling. The results of the simplified models appeared sensitive to the choice of the thickness of the humidity buffering layer. If the buffering layer thickness in simplified models is taken to be equal to the effective moisture penetration depth, the order of magnitude of the daily variation predicted by the simplified models corresponds to the variation predicted by the detailed HAM model. Moreover, the simplified models neglect the transmission of water vapor through the exterior walls, which may introduce significant changes in some cases.

## Developments and Use of Engineering Tools and Simulation Software

Several engineering tools were under development during the Annex 41 project, improving their capacities to represent the coupled heat, air, and moisture response of buildings. Some of them are well-known building energy simulation programs, such as TRNSYS and EnergyPlus, and some have more proprietary use, such as Domus, Clim2000, and Spark. They are all able to simulate the energy behavior of a building and of simple heating and ventilating systems in dynamic conditions. All of them also calculate the moisture level in the indoor air and can account for vapor storage in hygroscopic materials. This last phenomenon is modeled either using simple lumped models or using a detailed description of the heat and mass transfer phenomena in the building envelope. In the latter case, moisture levels in building elements can also be assessed using the simulation tool. Five examples of models and software are described in the following.

HAM-Tools, presented by Sasic Kalagasidis (2004), is a modular building simulation software developed in Sweden by Chalmers University of Technology. 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. Using the graphical programming language Simulink, the code is developed as a library of predefined calculation procedures (modules) where each supports the calculation of the HAM transfer processes in a building part or an interacting system. Simulation modules are grouped according to their functionality into five subsystems: constructions, zones, systems, helpers, and gains. The model solves a heat, air, and mass balance equation in an air zone (supposed fully mixed) and in a building enclosure, considering air, vapor, and liquid transport in one dimension. By combining different modules such as a single-layer wall in a multi-layer wall, a couple of different walls in a zone, several zones in a building, and, finally, together with climatic load and HVAC equipment, it is possible to build a house as a system. It should be noticed that HAM-Tools has a user-friendly interface and can be downloaded as freeware and was successfully used by other participants of the Annex 41 project.

A second new integrated HAM modeling toolkit in MATLAB named HAMLab, developed by the Technical University of Eindhoven in The Netherlands, was presented by van Schijndel (2005). The model, based on ELAN (de Wit, 1988), a computer model for building energy design and an analogue hygrothermal model, was implemented in a Building Physics Toolbox in MATLAB (van Schijndel and de Wit 1999) and was named WaVo. A major recent improvement is the development of a WaVo model in Simulink (HAMBase) (de Wit 2004). 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. HAM responses of building constructions and internal/external airflow were modeled and simulated with FEMLAB, an environment for modeling simulations of partial differential equations (PDEs). Combining a MATLAB/Simulink modeling toolkit with FEMLAB allows comprehensive modeling of a room with two-/three-dimensional HAM transport in constructions or two-dimensional airflow. It should be noted that HAMLab models are available for free on the Internet, and the simulation environment is open. It is relatively easy to integrate new models that are based on ordinary differential equations and/or partial differential equations.

Holm et al. (2004) described a holistic model called WUFI Plus (Holm et al. 2003) based on the hygrothermal envelope calculation model WUFI (Künzel 1994). The coupled heat and mass transfer for vapor diffusion, liquid flow, and thermal transport in the envelope parts is a strong feature of the model. A stable and efficient numerical solver had to be designed for the solution of the coupled and strongly nonlinear equations. Indeed, the conductive heat flux and the enthalpy flux by vapor diffusion with phase changes in the energy equation are strongly dependant on the moisture fields. The vapor flux is simultaneously governed by the temperature and moisture fields due to the exponential changes of the saturation vapor pressure with temperature.

Rode and Grau (2004) presented the program BSim2000, which is a computational design tool for analysis of indoor climate, energy consumption, and daylight performance of buildings developed in Denmark by the Danish Building Research Institute. At the core of the system are 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 multizone building with heat gains, solar radiation through windows (with shadings), heating, cooling, ventilation and infiltration, steady-state moisture balance, and condensation risks. A new transient moisture model for the whole building—its indoor climate and its enclosure—was also developed as an extension of BSim2000. Simultaneously, calculations of transient moisture conditions are carried out for all interior and exterior constructions of the building using a full model for humidity balance for zone air and a model for vapor diffusion in the constructions. Also, furnishings may be considered interior building constructions that face the same zone on both sides.

IDA Indoor Climate and Energy (IDA ICE), a tool for building simulation of energy consumption, indoor air quality, and thermal comfort was presented by Kalamees (2004). IDA ICE is commercially available and marketed by the Swedish company EQUA Simulation AB (www.equa.se). IDA, on which IDA ICE is based, is a general-purpose simulation environment, which consists of the translator, solver, and modeler, developed in Sweden by the Royal Institute of Technology in Stockholm (KTH) and the Swedish Institute of Applied Mathematics (ITM). The mathematical models of IDA ICE, written in the Neutral Model Format (NMF), have been developed at the Royal Institute of Technology in Stockholm and at the Helsinki University of Technology. IDA ICE covers a large range of phenomena, such as the integrated airflow network and thermal models, carbon dioxide 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 modeled by one moisture transfer potential, the humidity by volume. The liquid water transport is not modeled, and hysteresis is not taken into account. Many different cases in whole-building HAM transport can be simulated with IDA ICE; however, for comprehensive moisture simulations the computational time is rather high compared to only energy simulations, and the interface is not very user friendly.

The whole-building HAM models like those described above help to improve energy simulations because latent heat loads and their temporal patterns can be calculated more accurately. Moreover, complete transient calculations are performed of the moisture conditions within the envelope constructions of buildings and the indoor air. Since the moisture conditions in building constructions depend very much on the indoor humidity, and since the building constructions also influence the indoor humidity, the simulations of moisture conditions both for the indoor air and for the building constructions are therefore improved.

All of the models were validated using inter-code comparisons and some confrontations with experimental data. In addition, all five models were used in the CEs of the Annex project, and some improvements were made to them during the project's duration.

## RELATIONS WITH PRACTICE

Improving simulation codes improves the engineer's capacity to better design and control buildings. From a practical point of view, two main improvements to simulation tools were proposed in the Annex 41 project. First was the improvement of the capacity of existing models to simulate simultaneously the issues related to moisture, energy, and airflow. The second important point was the validation of several simulation tools done within the CEs.

As an example of practical applications (which are more developed in Subtask 4 of Annex 41), we should refer to the results from CE4, showing that optimizing the ventilation rate and buffering materials for target indoor moisture levels can lead to energy savings and to more stable indoor climates in terms of relative humidity.

Moreover, participants reported as practical applications the use of whole-building HAM models to investigate moisture problems in attics (for example, Sasic Kalagasidis and Mattsson [2005]) but also to study the performance of moisture-controlled ventilation (for example Woloszyn et al. [2005]).

An interesting practical application of one of the models was reported by Rode and Grau (2004). During autumn of 2001, the moisture model in BSim2000 was tested on real building design projects by three major consulting engineering firms. In one of the projects a study of the relative humidity of the air in an office building was performed, taking into account the ability of the building materials to buffer the air humidity. The aim was to estimate the risk of condensation on the chilled ceiling and in general to estimate the indoor air quality. Another project was an analysis of the moisture conditions of a planned museum repository. The consulting firms' main conclusions after the testing were that including a moisture model provided the possibility to analyze energy consumption and indoor climate in relation to construction moisture in building elements and to perform more realistic analysis leading to reduced cost of the building.

## CONCLUSION AND OUTLOOK FOR THE FUTURE

An overall ambition of the IEA Annex 41 project has been to stimulate the development of information and analytical tools about how a whole building works in terms of its hygrothermal building physics conditions. This involves several physical processes: flows of heat, air, and moisture. And it involves different building elements at various levels: its spaces; the building envelope with its materials; the interior building structures and furnishings; 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 heat, air, and moisture modeling is to ensure a good balance between the many different physical phenomena that interact on 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; if energy is rather well calculated, then moisture behavior is treated in a simplified way, if not neglected altogether. In this field, a lot of progress has been made and encouraging results are seen from the common exercises.

Concerning some general principles about the impact of moisture on whole-building energy response, different researchers agree that the first and essential step is to represent correctly the moisture balance, including vapor absorption and desorption from hygroscopic surfaces. In some practical applications, when only an estimation of the moisture in the indoor climate is of interest, this can be done using simplified lumped models (Hens 2005; Hokoi 2005; Woloszyn et al. 2005). However, when the moisture level in constructions is needed, the investigations require use of coupled heat and mass transfer models to describe complex physics in walls. An encouraging fact is that different potentials for moisture transfer can be successfully used (relative humidity, moisture ratio by volume, etc.). However, correct estimation of the initial conditions and a good choice of mesh size and of time-step size seem to have significant impacts on the predicted solutions (Hagentoft 2006; Abadie et al. 2005). When a detailed field of moisture in the air or in the construction is needed, CFD can help to get a precise response (Steeman et al. 2005); however, CFD requires an experienced user and a detailed description of the room.

The experience from the common exercises so far, as well as some parameter studies performed and some of the free papers, tells us that there is still a lot to do. There is a need to execute more validation cases, possibly as a comparison with measurement data. Some other aspects have to be considered as well, e.g., adding furniture and considering the airflows. Detailed consideration of the airflow should be done with detailed representations of HAM transfers in building elements: to link whole-building behavior with condensation problems behind a piece of furniture, some adapted approach should be studied—such as, for example, multiscale, reduced order, or zonal models.

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