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Common Exercises in Whole Building HAM Modelling

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SUMMARY:
Subtask 1 of the IEA Annex 41 project had the purpose to advance the development in modelling the integral heat, air and moisture transfer processes that take place in "whole buildings". Such modelling comprises all relevant elements of buildings: The indoor air, the building envelope, the inside constructions, furnishing, systems and users. The building elements interact with each other and with the outside climate. The Annex 41 project and its Subtask 1 has not aimed to produce one state-of–the-art hygrothermal simulation model for whole buildings but rather to stimulate the participants' own development of such models, or advanced use of related existing models.

Subtask 1 dealt with modelling principles and the arrangement and execution of so-called common exercises with the purpose to gauge how well we can succeed in the modelling. The paper gives an overview of the Common Exercises which have been carried out in the Subtask. Based on this activity, some general experiences are reported about how well we are able today to carry out such advanced modelling, and some recommendations for future developments are indicated.

1. 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 from/to 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 IEA Annex 41 has set out to advance the development in modelling the integral heat, air and moisture transfer processes that take place in "whole buildings".

The past few decades have seen the development and professional use of tools which, for some of the processes or some of the building elements, describe their building physical conditions.

For instance, fairly comprehensive tools for transient building energy simulation have been well established for more than a decade – see for instance http://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 heating, ventilation and air-conditioning system. However, the building energy simulation tools are relatively poor tools to describe the moisture transfer processes in buildings.

Air flow simulation tools at building level, e.g. COMIS, CONTAM, or at room level, e.g. CFD codes like Fluent, STAR-CD, 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) within individual building components 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. from 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, and thus there is a mutual link between the envelope and room conditions.

For building envelopes, detailed tools exist for the multidimensional flow of heat, as for instance around thermal bridges. In some cases, models also exist for predicting multidimensional air or moisture flows in envelope constructions.

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

2. 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 which have some of the desired performances.

The following Common Exercises (CE) have been carried out as part of Subtask 1 of Annex 41:

- Common Exercise 0. Validation of thermal aspects of the employed models.
- Common Exercise 1. Expanding on CE0 ase by considering moisture interactions..
- Common Exercise 2. Experimental climate chamber tests in the laboratory.
- Common Exercise 3. Double outdoor climatic chamber test.
- Common Exercise 4. Extension of CE3 with moisture management to reducing energy consumption.
- Common Exercise 5. Real life row house case.
- Common Exercise 6. Two-story test-hut data determeined in Environmental Chamber

2.1 BESTEST Case as Common Exercises 0 and 1

Both Common Exercise 0 and Common Exercise 1 have studied the IEA BESTEST building of IEA SHC Task 12 & ECBCS Annex 21 (Judkoff and Neymark, 1995). The building is shown in FIG 1. The building is superficial, so no measurement data exist.

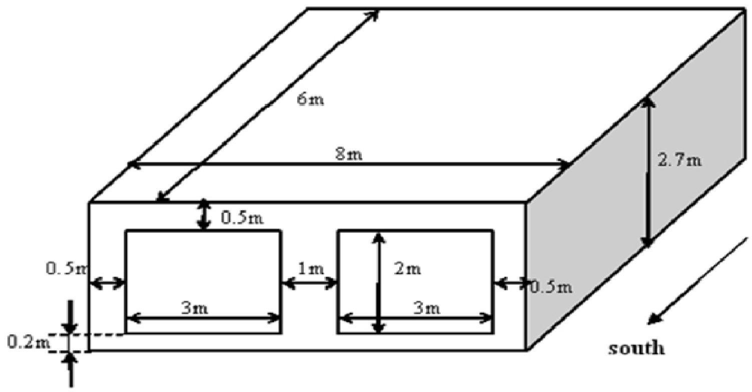

FIG. 1 BESTEST base case building.

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 intention to make comparisons between the different participants in this exercise.

2.1.1 CE 0 Thermal building simulation.

For the purpose of Annex 41, four cases were chosen from the original BESTEST procedure, appropriate for 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 the code "FF" indicates if the building was 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.

Table 1 Four cases tested as Common Exercise 0.

Case	Building structure	Heating and cooling
600 FF	plasterboard, insulation, wood	None
600	plasterboard, insulation, wood	
900 FF	concrete, insulation, wood	None
900	concrete, insulation, wood	20°C < Tint < 27°C

13 sets of results were collected coming from 10 institutions from 9 countries using 11 different programs (see Table 2). The programs participating in 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.

Table 2 Overview of the participating institutions and the used simulation tools in CE0 and CE1

Institution	Country	CE0 May 2004	CE 1 Oct 2004	CE 1A Jan 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	-

Some differences in the results could be expected because of the differences in the reconstruction of outdoor climate from meteorological data. Some programs use linear interpolation while others assume that the climate remains constant over the sampling interval.

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

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

Indoor temperature variation during one day is shown in FIG 2. The difference between heavy- and lightweight 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 noted that the results concerning heating and cooling loads mostly corresponded well with the original range of results from BESTEST.

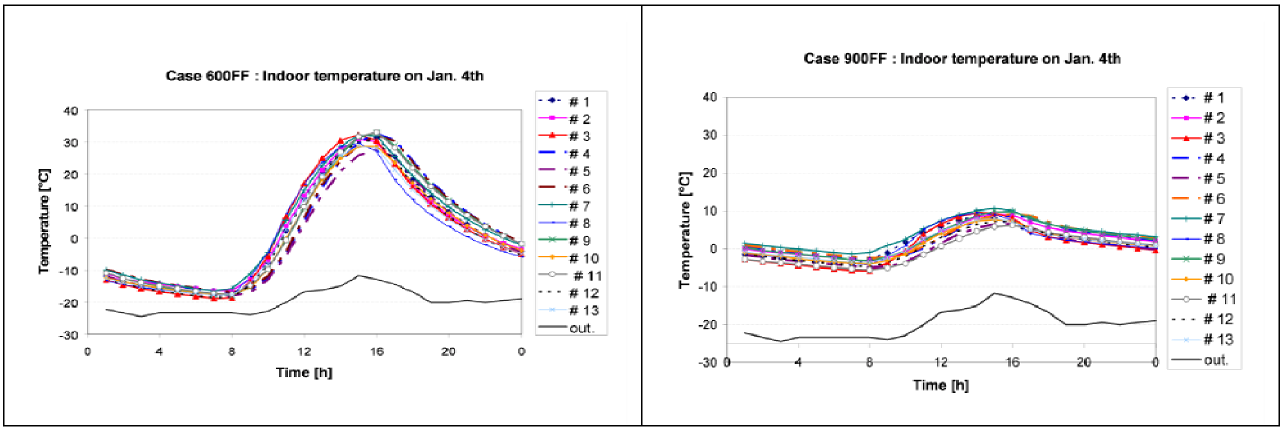

FIG. 2 Common Exercise 0: Indoor and outdoor temperature (°C) on Jan.4th, for both lightweight structure (left – 600FF) and heavyweight structure (right – 900FF for all 13 sets of results.

2.1.2 CE 1 Hygrothermal building simulation.

Common Exercise 1 extended on Common Exercise 0 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.

Table 3 Overview of variations of Common Exercise 1.

CE1 Numerical cases in principle like in CE0. Natural climate.	**CE1A** Monolithic walls w. simple material properties. Isothermal conditions. No internal or solar gains.	**CE1B** Monolithic walls with realistic properties. Natural climate.
- 600 0A Analytical, Vapor tight - 600 0B Analytical, Vapor open - 600 Open Numerical, vapor open - 600 Paint & VR Numerical, painted - 900 Open Numerical, vapor open	- 0A Tight Analytical, vapor tight - 0B Open Analytical, vapor open	- T_{indoor} 20°C no external radiation - T_{indoor} 20 - 27°C no external radiation - T_{indoor} 20 - 27°C with solar and long-wave radiation

The first results of the Common Exercise 1 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 Common Exercise 1A (an analytical case) and Common Exercise 1B (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 0.5 ach. The heating and cooling controls for all the non-isothermal cases kept the indoor temperature between 20 and 27ºC. 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 have used the same code for all the exercises – with or without modifications from case to case – while others have used 2 different codes or have not taken part in particular exercises.

Results from the original CE1. "CE1" was the original case of an exercise for simulations which include moisture exchange. It was posed with a relatively high degree of freedom for modelling 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 have been made on some of the input conditions both for energy and moisture modelling. Facing the difficulty to interpret such data, it was decided to review the exercise giving much more details on the input data and on the way of modelling the problem.

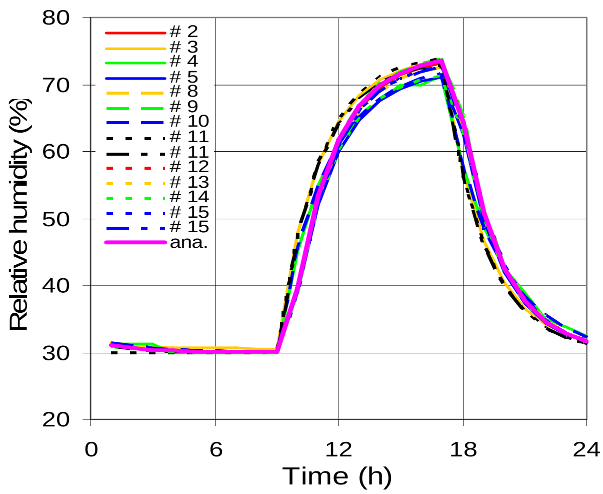

FIG. 3 CE 1A, Case 0A. Analytical test. Isothermal exposure. Construction surfaces are tight. The results are given as the numerical results compared with the analytical consensus solution of the indoor RH. The main deviation is due to the way the hourly values are given: either actual or mean hourly values.

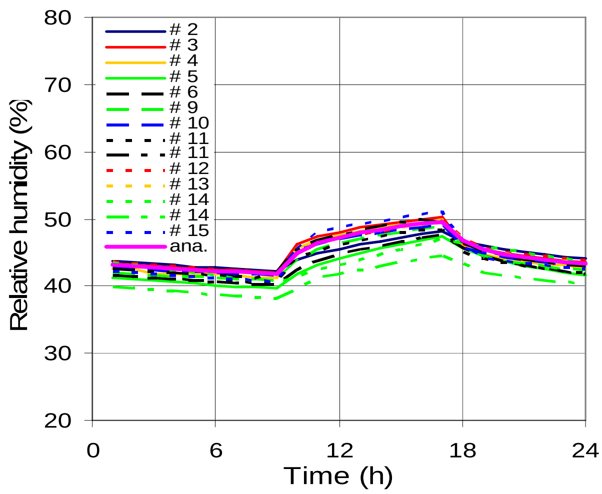

FIG. 4 CE 1A, Case 0B. Analytical test. Isothermal exposure. Construction surfaces are open. The results are here given as the numerical results compared with the analytical consensus solution of the indoor RH.

Results from CE 1A Analytical cases. This exercise applied the simplest conditions in terms of material properties and boundary conditions and used properties which 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 vapour from the building by transport all the way through the walls. The exposure was completely isothermal, i.e. the same temperature outside as inside the building. The building had no windows. The initial conditions were given, an dthe calculagtoins were run until quasi-steady conditions..

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

Results from CE1B "Realistic" cases. This exercise was the second part of the revised CE 1: 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 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 non-isothermal conditions, and the non-isothermal conditions were run either with or without solar gains in the building. The results were again given as the indoor relative humidity. 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 Common Exercises 2 and 3 where measured data give target solutions and help to validate the modelling approach.

2.2 Common Exercise 2 - Small climate chamber test

In order to design residential spaces for indoor humidity control, it is important to investigate the influence of ventilation rate and hygrothermal materials. The objective of this common exercise was to simulate the small chamber (called "THU test room") which is located in a climate chamber. Two kinds of experiments were carried out. The first examined the influence of ventilation rate, while the second examined the influence of both the quantity and location of the hygrothermal materials within the chamber. The moisture buffering material investigated was gypsum board (the same gypsum board used in the round robin test of Anbex 4's Subtask 2).

Experimental settings. Each experiment consisted of a preconditioning period followed by 6 hours of humidification and 12 hours without humidification, during which variations of indoor temperature and humidity within the small chamber were evaluated.

A schematic view of the test chamber is shown in FIG. 5. The test chamber was located in the climate room at the Akita Prefectural University. In the climate room, it is possible to control indoor temperature in a range from 10 °C to 40 °C. and humidity from 30 %RH to 90%RH. This test chamber is approximately half the size of a typical residential room. The internal volume of the test chamber is 4.60 m^3 and the area of interior surfaces is 16.62 m^2. The walls, ceiling and floor of the chamber consist of an internal surface of 12.5 mm of gypsum board behind which is 100 mm of polystyrene. In order to keep vapour- and airtight conditions in the chamber, an aluminium sheet is installed between the polystyrene and the gypsum board. The inlet and outlet for mechanical ventilation are located at the bottom and top of two opposite walls respectively. A small ventilation duct is connected to the outlet of the chamber to measure the ventilation rate accurately.

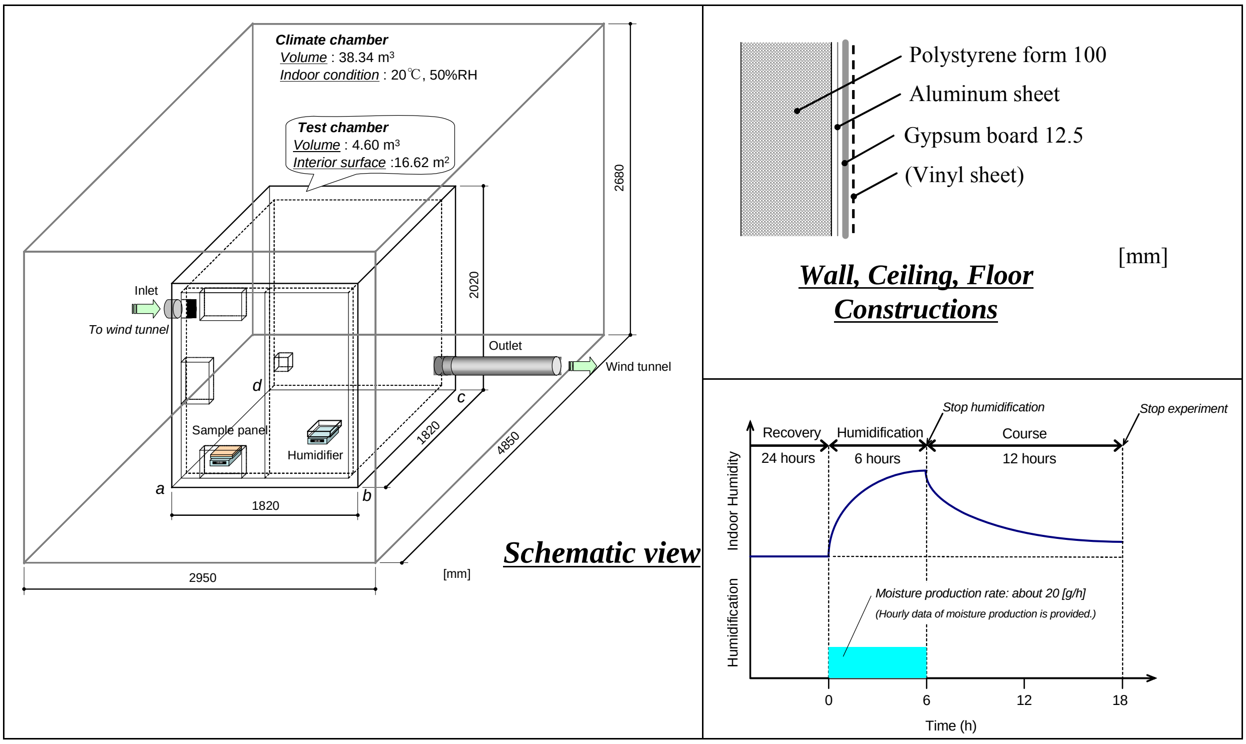

FIG. 5 Schematic view of the test chamber, the construction, and the schedule

Constructions Wall, ceiling and floor constructions are shown in FIG. 5. The gypsum board on the walls, ceiling and floor is covered with the vinyl sheet according to the experimental cases in order to prevent moisture absorbing and desorbing from the surface. Gypsum board is not installed on the door of the chamber in any of the experimental cases.

Internal Gains and schedules Humidification took place by evaporating moisture from two water reservoirs that were heated by an electric heating element. The water reservoir tray was weighed by an electric balance to measure the quantity of humidification water. The target moisture production rate was about 20 g/h. The experimental schedule is shown in FIG. 5.

Comparison between simulation and experimental results. In all the cases there was a rise of approximately 1.5-2°C in the air temperature, due to vapour production. It was correctly represented by all the models except one, which assumed almost isothermal conditions. As the power used to heat the water in the reservoirs was not known, the participant did not want to "guess" the size of heat source.

Experimental data were higher than simulated values in all the cases. Moreover:

- Experimental values agreed well with simulated values in cases which focused on: *High ventilation*, *One hygroscopic surface on the wall*, and *No hygroscopic surfaces*.
- The simulation tools underestimated the peak absolute humidity by approximately 1g/kg in cases with: *five hygroscopic surfaces*, *three hygroscopic surfaces on the wall*, and 2-5 *one hygroscopic surface on the ceiling*.
- The simulation tools underestimated the peak absolute humidity by approximately 2g/kg in cases with *five hygroscopic surfaces and no ventilation*, and *one hygroscopic surface on the floor*.

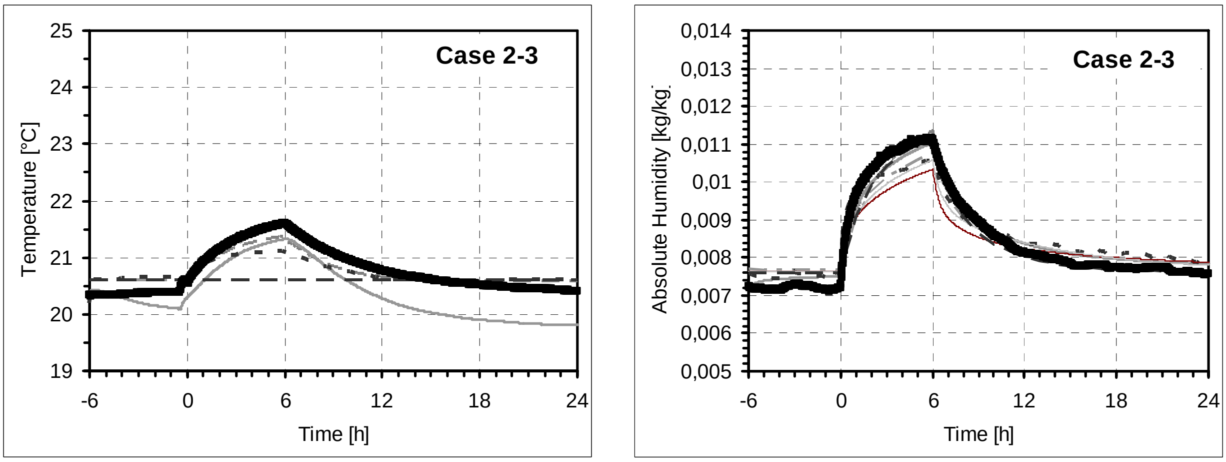

FIG. 6 Comparison between measured values and simulation results (Case 2-3)

The agreement was better when the impact of moisture buffering is lower (high ventilation and no hygroscopic surfaces). The biggest differences occurred in cases with no ventilation and with hygroscopic surface on the floor. It may indicate that besides moisture adsorption on hygroscopic surfaces there was some stratification of the indoor air. Indeed with no ventilation the air was very still in the test chamber, so there was no mixing. Moreover water vapour is lighter than dry air, so it has a tendency to rise, which is a factor to be considered when the hygroscopic material is on the floor.

Conclusion from Common Exercise 2. Simulation results of humidity in Case 1-3, Case 2-3 and Case 2-6 indicated comparatively good agreement with the experimental values. When comparing the results of the simulation programs, a spread in the range of predicted humidity was noted. The reasons for the differences between the experimental and simulation results were not clear but could be due to measurement error and the influence of the distribution of indoor temperature

2.3 Common Exercise 3. Double outdoor climatic chamber test

The intention of this common exercise was to simulate two real test rooms which are located at the outdoor testing site of the Fraunhofer Institute of building physics in Holzkirchen. Tests were carried out during winter and spring period with the aim to compare the measurements with the models developed within this Annex 41. As moisture buffering material served gypsum boards (the same gypsum board was used as was tested in a round robin test from Subtask 2).

The results of the measurements showed the influence of different materials in comparison to the relative humidity in the rooms. In the reference room was used a standard type of gypsum board with a latex paint (s_d = 0.15 m). The walls and the ceiling of the test room were fully coated with aluminium foil. For the experiments the test materials can be 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 only with aluminium 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 reference room and the test room with aluminium foil where no sorption effects were possible.

2. Reference room – Test room with gypsum boards on the walls. In the second step gypsum boards were attached on the surface of the walls with aluminium foil in the test room so that it covered the area of the walls, this experiment was run for a period of 35 days. For the test were used gypsum boards with or without paint.

3. Reference room - Test room with gypsum boards on the walls and the ceiling. For this experiment additional gypsum boards were installed in the room with aluminium foil, so also the ceiling was covered (in total now approximately 65 m²). The test was carried out for a period of 26 days. For this test were again used gypsum boards with or without paint.

4. Same as the previous tests but now also with solar gains in the rooms. In Step 4 the influence of solar radiation through the windows are considered and additionally the indoor climate conditions are measured with and without a heating system. The test room was empty and only covered with aluminium foil.

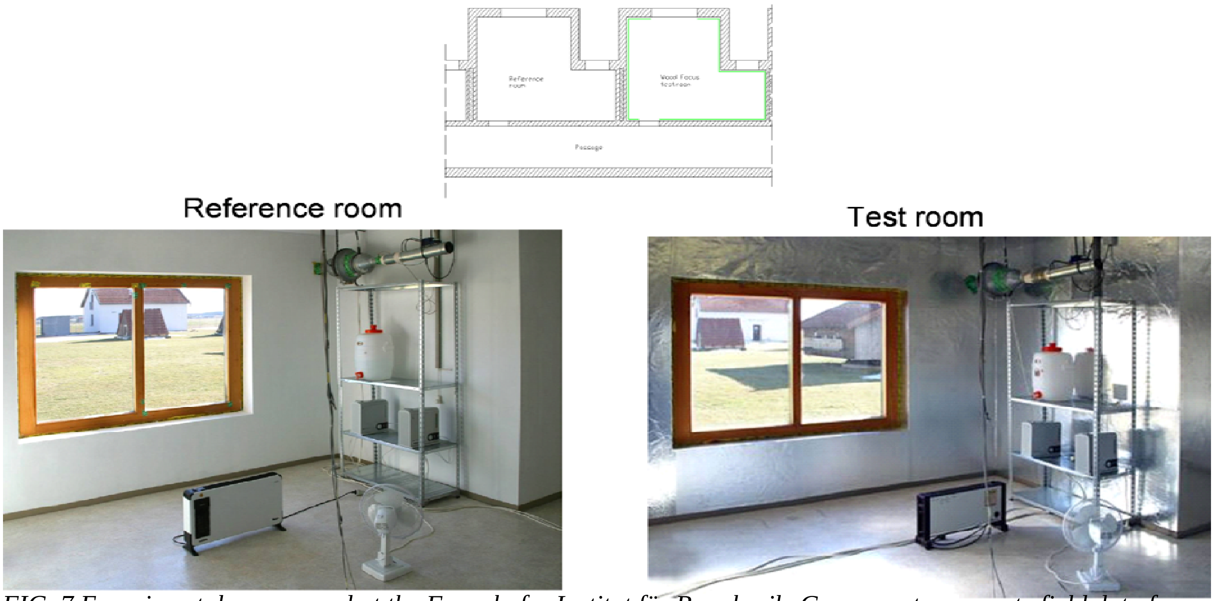

FIG. 7 Experimental rooms used at the Fraunhofer Institut für Bauphysik, Germany, to generate field data for Common Exercise 3. "Reference room" (left): The surfaces of the walls and the ceiling are coated with common gypsum plaster and paint (s_d=0.15m). "Test room" (right): Surfaces of the walls and the ceiling are completely coated with aluminum foil.

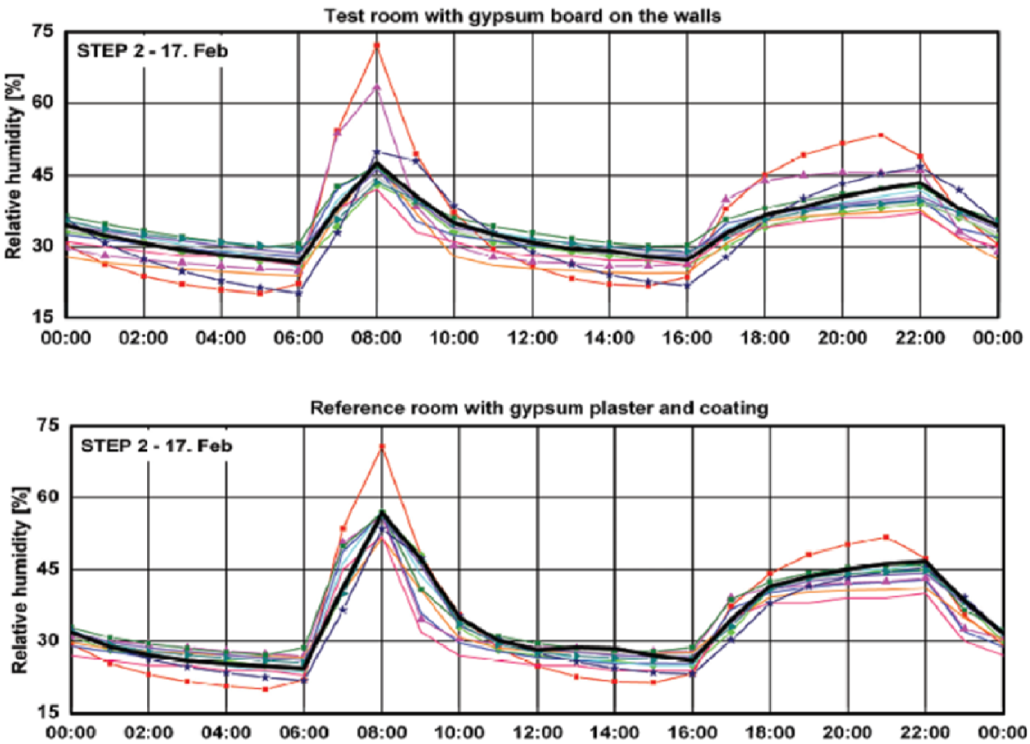

FIG. 8. Results of simulations for Common Exercise 3. Rooms with gypsum boards on the walls which were either untreated (top graph) or painted (bottom). Bold line represents the measured values and the thin lines represent 12 computed solutions.

Output from the investigations . For each calculation hourly averaged air temperatures and relative humidity was 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 *FIG. 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 reported some misunderstanding of the input data. Improving of overall results between CE1 (2004/2005) and CE3 (2006) are an encouraging proof that some progresses in whole building HAM modelling were accomplished within the Annex 41.

2.4 Common Exercise 4. Moisture management for reducing energy consumption

The intention of this common exercise was to show that an appropriate management of the indoor moisture conditions could reduce 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 which were 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 15251:2007 for class A buildings.

The participants were asked to perform 5 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 Relative Humidity Controlled ventilation system,
- Run C: using original finishing materials and a Relative Humidity Controlled 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 RH.

The simulations were run for a period from January to April covering cold and mild periods. 6 solutions were provided by 6 diffrerent participants. Even if some differences in results were noticed, an overall good agreement was found for the different simulations. FIG. 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 the maximum values of relative humidity. It was also found that the use of and RHC system could reduce the mean ventilation rate of 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 with 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 (~2%), mainly because of the higher moisture content outside. It was also confirmed by the participants that the use of moisture buffering materials enables a significant reduction of the amplitude of daily moisture variations.

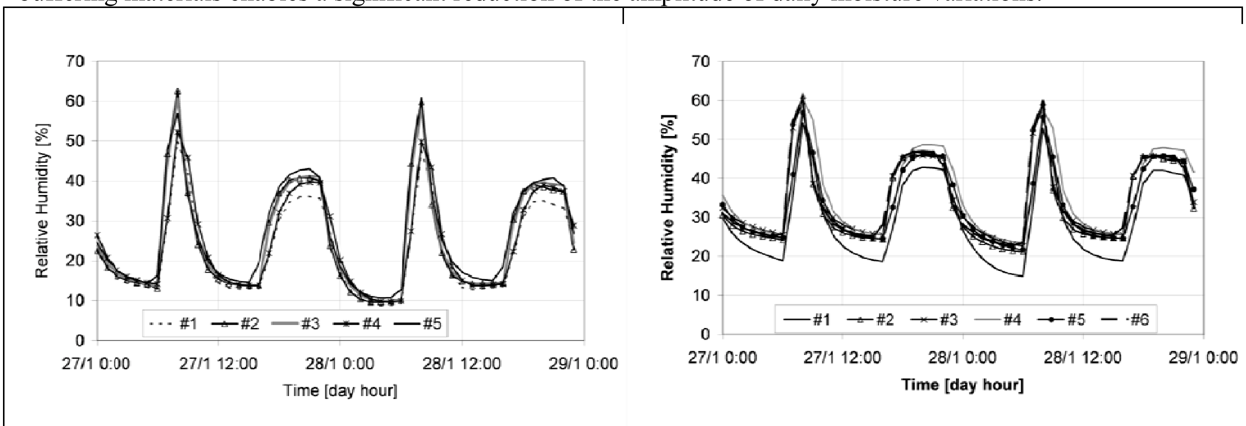

FIG. 9. Common Exercise 4: Indoor relative humidity as computed by all the participants.
(a) constant ventilation rate *(b) relative humidity controlled ventilation*

2.5 Common Exercise 5

With exercise 5, a practice-related case was introduced within the Annex 41 common exercises. First, the case study dwelling is described, then its translation into a common exercise is explained, ending with the reference solution and a comparison with the results introduced by the participants.

FIG. 10 The dwelling considered

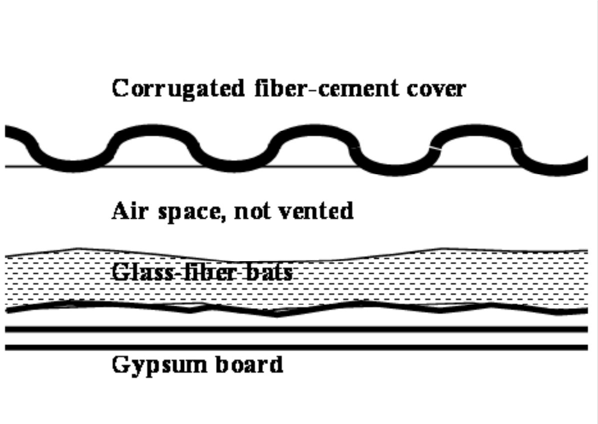

FIG. 11 Roof section

The case concerns a low income estate of 48 two storey houses built in the 1970s (FIG 10). The only difference between the 48 dwellings is the orientation of the main façade: 9 NW, 4 NNW, 16 NE, 5 E, 5 SE and 8 SW. All had a non-insulated floor on grade, non insulated cavity walls, double glazed aluminium windows on the ground floor, single glazed aluminium windows on the first floor and a cathedral ceiling composed of (from inside to outside) (1) gypsum boards mounted with open joints, (2) 6 cm thick glass-fibre bats with a vapour retarder on the underside, (3) an un-vented air space and (4) corrugated fibre cement plates as roof cover (FIG 11). The two floors were linked by an open staircase in the living room. The dwellings were adventitiously ventilated, while purge ventilation was provided by opening windows.

85% of the dwellings showed traces of moisture on the cathedral ceiling, while a large number of inhabitants complained about dripping moisture in the bedrooms after cold nights. A detailed inspection of some roofs revealed poor installation of the glass-fibre bats, abundant traces of condensation at the underside of the corrugated fibre-cement plates, mould on the rafters and traces of condensate at the back of the internal lining.

The suggested solution was: (1) retrofit the roof in accordance to the better solution; (2) upgrade the overall poor insulation quality of the dwellings; (3) equip the dwellings with a purpose designed ventilation system.

The exercise. The objective of the exercise was not comparing software-based solutions, but evaluating if the Annex 41 participants could solve an engineering problem using simplified approaches. For that reason, the exercise was kept as a eady state problem, based on a cold week.

The exercise was split in three successive steps:

- Step 1: ground floor and first floor heated, daily vapour release constant over the week, air leakage through the façade distributed proportional to the surface
- Step 2: ground floor heated, first floor not, vapour release on both floors given on an hourly basis, air buffering only, air leakage through the façade distributed proportional to the window perimeter lengths
- Step 3: as step 2 plus moisture buffering by the fabric included

Conclusions from Common Exercise 5. The exercise proved that solving real life problems, using simplified methods, is not as simple as expected. One has to know a lot about what could happen before the calculations. The simple models used should be physically correct. Nodes for air balance calculations must be chosen carefully. Hand calculations of these balances are hard to perform as iteration is needed. Modelling in a spreadsheet programme anyhow is easily done. The material or system property values used should be realistic. Mass balances for air and vapour must fit. Heat balances should be correctly constructed and solved. And, finally, the results have to be interpreted correctly.

2.6 Common Exercise 6. Two-story test-hut data from Environmental Chamber

The objective of the experimental study was to generate reliable datasets that will serve first to advance the understanding of the whole building response to heat, air, and moisture (HAM), and secondly to validate ongoing and future numerical models. For this objective, tests were carried out in a two-story test-hut that was assembled inside the Environmental Chamber at Concordia University.

In the first stage, the test rooms were isolated and the HAM transfer and moisture buffering parameters were monitored. Each room was tested independently to study the moisture buffering capacity of two finishing materials and furniture, and to study airborne moisture distribution within a room. These tests are referred herein as the "single room" tests. In the second stage, the upper and lower rooms were coupled by a horizontal opening to study the inter-zonal HAM transport through this opening and the resulting airborne moisture distribution in both rooms. These tests are referred herein as the "two-room" tests.

Environmental Chamber and test-hut construction The Environmental Chamber was used to provide the desired outdoor temperature. The temperature condition in this large chamber was controlled by two cooling systems and two electric heaters. A blower (5.7 m3/s) and small portable fans provided the air circulation in the large chamber.

A two-story test-hut was built inside the Environmental Chamber (FIG 11A). The test-hut consisted of two rooms with internal dimensions of 3.62m x 2.44m x 2.43m each (FIG 11b). The test-hut represents typical wood-framed construction of Canadian houses. In each floor, a small foyer was built adjacent to the north wall to reduce disturbance to the test rooms when doors were opened to set new conditions inside the rooms and to house part of the data acquisition system.

The east and west walls (see FIG 11b) were used to study the moisture buffering capacity of two different finishing materials, uncoated gypsum board and pine paneling. The rest of the indoor surfaces were covered with aluminum sheets (0.8 mm thickness) to avoid any additional moisture buffering effect. For the non-hygroscopic cases, the east and west walls were covered with polyethylene sheets (0.15 mm thickness).

Materials used in this study were generic. Hygrothermal properties of similar materials were tested at IRC (NRCC). Also, surface mass transfer coefficients for uncoated gypsum board and pine paneling were measured at the University of Saskatchewan.

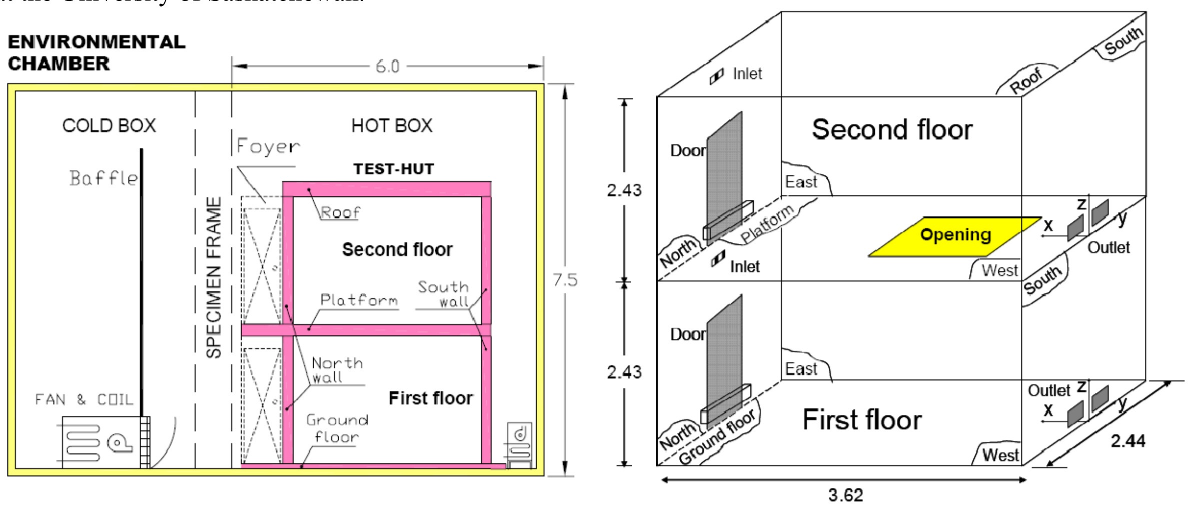

FIG. 12 a) Schematic drawing of the two-story test-hut inside the Environmental Chamber. b) Interior dimensions of the two-story test-hut and name of the test-hut components (dimensions are in meters)

Air leakage of the test-hut was measured at operating conditions. Air leakage varied from 0.014 to 0.044 h^{-1} for single room tests, and from 0.018 to 0.027 h^{-1} for two-room tests.

Conclusions from Common Exercise 6. Full-scale tests in single rooms and two rooms coupled vertically by a horizontal opening were carried out in an environmental chamber. The aim of these tests was to generate complete datasets that allow the study of the moisture buffering capacity of two finishing materials and furniture, airborne moisture distribution within the rooms and inter-zonal HAM transport through horizontal openings. In total, 20 datasets are provided in electronic format, which may be used to validate ongoing and future Whole Building HAM and CFD models.

A complete report with further details and explanations of the experimental setup, test conditions, details of the constructions, specifications of sensors and instruments, and the contributions from the University of Saskatchewan (Experimental determination of the convective mass surface transfer coefficients for gypsum board and pine paneling) and from IRC (Moisture buffering capacities of five North American building materials) are provided in the electronic appendix.

3. Some conclusions to draw from all common exercises

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

But the Common Exercises 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 modelling was enhanced in more energy oriented tools. The improvement of the models was noticed in CE3, when the obtained agreement was much better that in CE1.

All common exercises showed that there is a need for some consensus data concerning heat and moisture properties of the materials, and more generally about all the input data. 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 modelling all elements are very important: For example some differences in the indoor relative humidity may be induced by modelling of solar gains or long wave radiations, 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 modelling; they can lead to numerical divergence.

A crucial question was raised during the discussion: how can we evaluate if 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 Common Exercises 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 "H", "A" or "M".
- 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.

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