Project Summary Report

EBC

Energy in Buildings and Communities Programme

EBC Annex 41

Whole Building Heat-Air-Moisture Response (MoistEng)

Hugo S.L.C. Hens

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About EBC

International Energy Agency

The International Energy Agency (IEA) was established in 1974 within the framework of the Organisation for Economic Co-operation and Development (OECD) to implement an international energy programme. A basic aim of the IEA is to foster co-operation among the twenty-eight IEA participating countries and to increase energy security through energy conservation, development of alternative energy sources and energy research, development and demonstration (RD&D).

Energy Conservation in Buildings and Community Systems

The IEA co-ordinates research and development in a number of areas related to energy. The mission of one of those areas, the EBC - Energy in Buildings and Communities Programme, is to develop and facilitate the integration of technologies and processes for energy efficiency and conservation into healthy, low emission, and sustainable buildings and communities, through innovation and research. (Until March 2013, the EBC Programme was known as the Energy in Buildings and Community Systems Programme, ECBCS.)

The research and development strategies of the EBC Programme are derived from research drivers, national programmes within IEA countries, and the IEA Future Buildings Forum Think Tank Workshop, held in April 2013. The R&D strategies represent a collective input of the Executive Committee members to exploit technological opportunities to save energy in the buildings sector, and to remove technical obstacles to market penetration of new energy conservation technologies. The R&D strategies apply to residential, commercial, office buildings and community systems, and will impact the building industry in five focus areas of R&D activities:

- Integrated planning and building design
- Building energy systems
- Building envelope
- Community scale methods
- Real building energy use

The Executive Committee

Overall control of the program is maintained by an Executive Committee, which not only monitors existing projects but also identifies new areas where collaborative effort may be beneficial. To date the following projects have been initiated by the Executive Committee on Energy in Buildings and Communities (completed projects are identified by (*)):

Annex 1: Load Energy Determination of Buildings (*)
Annex 2: Ekistics and Advanced Community Energy Systems (*)
Annex 3: Energy Conservation in Residential Buildings (*)
Annex 4: Glasgow Commercial Building Monitoring (*)
Annex 5: Air Infiltration and Ventilation Centre
Annex 6: Energy Systems and Design of Communities (*)
Annex 7: Local Government Energy Planning (*)
Annex 8: Inhabitants Behaviour with Regard to Ventilation (*)
Annex 9: Minimum Ventilation Rates (*)
Annex 10: Building HVAC System Simulation (*)
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Annex 13: Energy Management in Hospitals (*)
Annex 14: Condensation and Energy (*)
Annex 15: Energy Efficiency in Schools (*)
Annex 16: BEMS 1- User Interfaces and System Integration (*)
Annex 17: BEMS 2- Evaluation and Emulation Techniques (*)
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Annex 19: Low Slope Roof Systems (*)

Annex 20: Air Flow Patterns within Buildings (*)
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Annex 23: Multi Zone Air Flow Modelling (COMIS) (*)
Annex 24: Heat, Air and Moisture Transfer in Envelopes (*)
Annex 25: Real time HVAC Simulation (*)
Annex 26: Energy Efficient Ventilation of Large Enclosures (*)
Annex 27: Evaluation and Demonstration of Domestic Ventilation Systems (*)
Annex 28: Low Energy Cooling Systems (*)
Annex 29: Daylight in Buildings (*)
Annex 30: Bringing Simulation to Application (*)
Annex 31: Energy-Related Environmental Impact of Buildings (*)
Annex 32: Integral Building Envelope Performance Assessment (*)
Annex 33: Advanced Local Energy Planning (*)
Annex 34: Computer-Aided Evaluation of HVAC System Performance (*)
Annex 35: Design of Energy Efficient Hybrid Ventilation (HYBVENT) (*)
Annex 36: Retrofitting of Educational Buildings (*)
Annex 37: Low Exergy Systems for Heating and Cooling of Buildings (LowEx) (*)
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Annex 45: Energy Efficient Electric Lighting for Buildings (*)
Annex 46: Holistic Assessment Tool-kit on Energy Efficient Retrofit Measures for Government Buildings (EnERGo) (*)
Annex 47: Cost-Effective Commissioning for Existing and Low Energy Buildings (*)
Annex 48: Heat Pumping and Reversible Air Conditioning (*)
Annex 49: Low Exergy Systems for High Performance Buildings and Communities (*)
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Working Group - Energy Efficiency in Educational Buildings (*)
Working Group - Indicators of Energy Efficiency in Cold Climate Buildings (*)
Working Group - Annex 36 Extension: The Energy Concept Adviser (*)

(*) – Completed

General Information

Project leader: **Hugo Hens, Catholic University of Leuven, Belgium**
Project duration: **2003 - 2007**
Further information: **www.iea-ebc.org**

The project aimed to acquire better knowledge of whole-building heat, air and moisture (HAM) balance and their effects on the indoor environment, on energy consumption for heating, cooling, air humidification and air drying, and on building envelope durability. The research followed on from the EBC projects 'Annex 14: Condensation and Energy', 'Annex 24: Heat, Air and Moisture Transport in Insulated Envelope Parts' and 'Annex 32: Integral Building Envelope Performance Assessment'.

Heating, ventilation and air conditioning (HVAC) systems are typically designed to keep indoor temperatures at comfortable levels under extreme outdoor weather conditions. Indoor relative humidity, however, is mostly free floating, as it is perceived to be less important. In addition, few take into consideration the whole heat, air, moisture balances between the building's interior, its envelope and the outside. This is unfortunate, as air pressure gradients may generate airflows that drastically change the heat, air and moisture response of the envelope and building. Moisture storage (or hygric buffering) in turn dampens indoor water vapor pressure fluctuations compared to outdoors. Air flows, rain penetration and moisture deposits in the envelope not only negatively affect energy consumption, but also may have a detrimental influence on the envelope's durability. Simultaneously, indoor relative humidity may affect the perceived indoor air quality and become a driving force for mould growth and dust mite proliferation.

Clearly, whole building heat, air and moisture response can have an impact on human comfort, indoor environment, energy consumption and envelope durability, and this was a reason for the project's initiation.

The project had two main objectives:

– A detailed exploration of the physics involved in whole building heat, air and moisture response (HAM-response). This included basic research, further development of existing and new models, measurement of the moisture storage function of materials, measurement of the air permeance of envelope parts as built, mock up testing, field testing and validation by inter-comparison of models through common exercises and confrontation with measured data.

This first objective aimed to foster a basic understanding of transient moisture storage in different finishing materials and moisture exchange with the indoor air. For this purpose material storage properties were measured. This has helped in the development of numerical models and backup experiments that link the heat and moisture storage and HAM-transfer in enclosures to the performance of the building and the HVAC system. Mock-up and field measurements have to prove the effectiveness of moisture storage under different weather conditions (cold, warm and dry, warm and humid and maritime).

– An analysis of the effects of the whole building HAM-response on comfort, enclosure durability and energy consumption. This included a literature review that aimed to increase the awareness for these effects and experimental testing. The air-tightness, moisture management, thermal insulation and moisture storage with possible negative impacts on comfort, enclosure durability and energy consumption were studied.

The research work was divided into four sections:

– **Modelling principles and common exercises**. This section focused on adapting existing energy models to include air and moisture, extending existing envelope HAM-models to include room moisture response and verifying and validating models through common exercises.

Participating Countries:

Austria
Belgium
Brazil
Canada
Denmark
Estonia
Finland
France
Germany
Japan
Netherlands
Norway
Portugal
Slovakia
Spain
Sweden
United Kingdom
USA

– **Experimental testing of moisture (hygric) buffering** in finishing materials, furniture and furnishings, a round robin experiment on the determination of the hygric properties of porous building materials combined with a transient heat and moisture transfer experiment to generate a data set for benchmarking numerical models

– **Boundary conditions.** This section concentrated on the indoor environment as measured, simple methodologies to evaluate indoor humidity excess, moisture sources, surface air pressures, surface film coefficients, wind driven rain and under-cooling, caused by celestial long wave radiation.

– **Long term performance and technology transfer.** Subjects tackled were: acceptable relative humidity levels, how to control the indoor climate, moisture tolerance and the impact of boundary condition assumptions on whole building heat-air-moisture simulation

A whole building heat-air-moisture approach should integrate these three knowledge tracks:

- building energy modelling,
- hygrothermal envelope modelling, and
- airflow modelling.

Definitions

Common exercises are experimental tests in which all of the willing participants simulate the same case and then compare the results.

Moisture buffer capacity can be defined as a material's ability to reduce variations within an enclosure.

Project Outcomes

Project leader: **Hugo Hens, Catholic University of Leuven, Belgium**
Project duration: **2003 - 2007**
Further information: **www.iea-ebc.org**

Introduction

The project aimed to acquire better knowledge of whole-building heat, air and moisture (HAM) balance and their effects on the indoor environment, on energy consumption for heating, cooling, air humidification and air drying, and on building envelope durability. The research work was divided into four sections:

– **Modelling principles and common exercises.** This section focused on adapting existing energy models to include air and moisture, extending existing envelope HAM models to include room moisture response and verifying and validating models through common exercises.

– **Experimental testing e.g. of moisture buffering** in finishing materials, furniture and furnishings, a round robin experiment on the determination of the hygric properties of porous building materials combined with a transient heat and moisture transfer experiment to generate a data set for benchmarking numerical models

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– **Long term performance and technology transfer.** Subjects tackled were: acceptable relative humidity levels, how to control the indoor climate, moisture tolerance and the impact of boundary condition assumptions on whole building heat-air-moisture simulation.

Modelling principles and common exercises

This section of the project concentrated on whole building heat, air, and moisture (HAM) transfer process modeling with special emphasis on HAM transfer:

- between the outdoor and the exterior surface of the building envelope,
- in the envelope,
- between the interior surface of the envelope and indoors,
- from outdoors to indoors and vice versa through leakages, purpose designed ventilation grids and air in- and outlets,
- between the indoor air, furniture and furnishing, and
- between the different zones in a building.

The models that were verified and validated using common exercises took into account parameters such as location and orientation of the building, the HVAC-system, adventitious and user defined air flows, moisture response by hygroscopic finishes, furniture and furnishings, the type of room (bathroom, living room, etc.) and user behaviour (number of people, activities that released moisture and heat, frequency and duration of window ventilation).

Whole building heat-air-moisture modelling is based on the conservation axioms of energy, mass and momentum. These axioms state that for each system considered, be it a material volume, an envelope part, a room or a whole building, the resulting in- and outflow rate of the quantity considered, together with its rate of generation or absorption in the system, equals the storage rate in the system.

Heat flow in materials is largely diffusive, while it is governed by Fourier's law of conduction with equivalent thermal conductivity as a basic property and the change in temperature per unit length as the driving force (called a gradient). In cracks, joints, holes, cavities, rooms, outside and between the air and the building fabric, convection takes over part of the job, while long-wave radiation and short-wave radiation account for the rest. In open-porous materials some heat may also be transported through convection.

Moisture flow shows a similar picture: It is largely diffusive in porous materials where water vapour moves by equivalent diffusion with vapour permeability as a basic property and the partial water vapour pressure gradient as the driving force, while the liquid part is displaced by capillarity with moisture conductivity as a basic property and the suction gradient as the driving force. In cracks, joints, holes, cavities, rooms and outside, equivalent diffusion is completely dominated by a convective displacement. Even in open-porous materials, convection may substantially increase the water vapour flow rate.

The carrier allowing convective heat and moisture flow is the air. In porous materials, air movement is mainly laminar, which allows using a diffusion-like equation for the air flow rate with air permeability as a basic property and the air pressure gradient by wind, stack and fans as the driving force. In cracks, joints, holes, cavities, rooms and outside, air flows easily become transient and turbulent, which makes quantification much more complicated. In such cases, a good approximation of reality demands solving the Navier-Stokes equations for conservation of momentum, which computational fluid dynamics (CFD) achieves. Simple assumptions include considering preferential flow paths (as in cavities) or assuming ideal mixing (as in rooms).

Models

Altogether 17 simulation tools were used to provide solutions for different applications and common exercises. All of them were able to represent dynamic evolution of indoor temperature and relative humidity influenced by variable outdoor climate and hygrothermal loads, including the effect of moisture buffering by indoor materials.

The simulation tools included existing multi-zone models for building energy simulation, such as TRNSYS and EnergyPlus. The main focus of these models was to predict the temperature fluctuations and energy demands of individual rooms. As a result the moisture transfer models for the envelope had a coarse granularity in these tools. Also, in some cases the granularity differed, i.e. intermediate for heat and coarse for moisture analysis. Other tools also originated

Table 1. List of common exercises

Common Exercise	Description
Exercise 0	Validating the thermal aspects of the models by inter-model comparison. This was done by repeating the building energy simulation BESTEST of IEA SHC Task 12 and EBC Annex 21 (Judkoff and Neymark 1995).
Exercise 1	Extending the original BESTEST building case with moisture sources and material properties for moisture transport in order to predict the indoor relative humidity level in isothermal and transient conditions. Verification by inter-model comparison.
Exercise 2	Validating models by simulating experimental results at room level under isothermal conditions.
Exercise 3	Validating models by simulating experimental results at room level under non-isothermal conditions.
Exercise 4	Energy consumption in the room used for the non-isothermal measurements, assuming a humidity controlled ventilation system was applied. Verification by inter-model comparison.
Exercise 5	Real world case, evaluating the impact of adventitious infiltration flows that traverse the envelope on durability and energy consumption. Looking to the ability of the participants to handle a typical moisture damage case by using simplified models.
Exercise 6	Experimental work on a coupled room configuration under isothermal conditions.

Project Outcomes

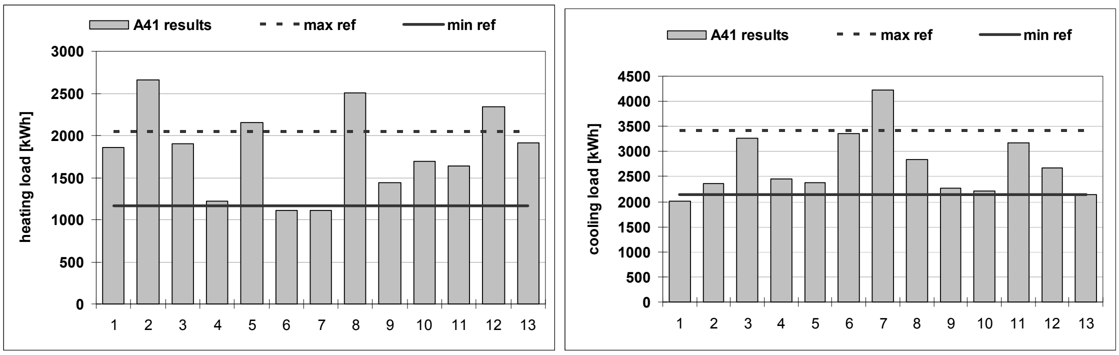


Figure 1. A comparison of annual net energy demand for heating and cooling for heavyweight structure building between various models in Common Exercise 0. The dotted and the full lines give the simulated maximum and minimum values from Annex 21.

from building energy simulation, but had implemented building envelope models with a higher level of granularity (e.g. BSim, IDA-ICE). Most of these models were therefore situated at an intermediate level of granularity for both air and envelope. Finally, a smaller group of whole building HAM models originated from detailed models for heat, air and moisture transfer in building envelopes (e.g. Delphin, WUFI).

Common exercises

The purpose of the common exercises was to test the possibilities to use modelling as a means to predict the integrated hygro-thermal behaviour of buildings. Six different common exercises were carried out in the project to make inter-model comparison and to validate the results with experimental data. A short description of the common exercises is presented in Table 1.

An objective of Exercises 0 and 1 was to verify models. The results were to some extent disappointing, especially when humidity was added. An example of results for Exercises 0 is shown in Figure 1. The results present the annual net energy demand in case of a heavyweight structure building. One of the reasons why they varied was the differences between the solar gain modelling applied. However, all models predicted the trend correctly, i.e. higher net energy demand and larger temperature amplitudes with a lightweight fabric building, compared to a heavyweight one.

Exercises 2 and 3 were conceived to validate the models. During Exercises 2, an isothermal testing small chamber was used that allowed the ventilation rate and wall finish to vary. Figure 1 shows the experimental set-up used for this exercise and Figure 2 gives an example of validation results. From the results it was learned that common assumptions, such as ideal air

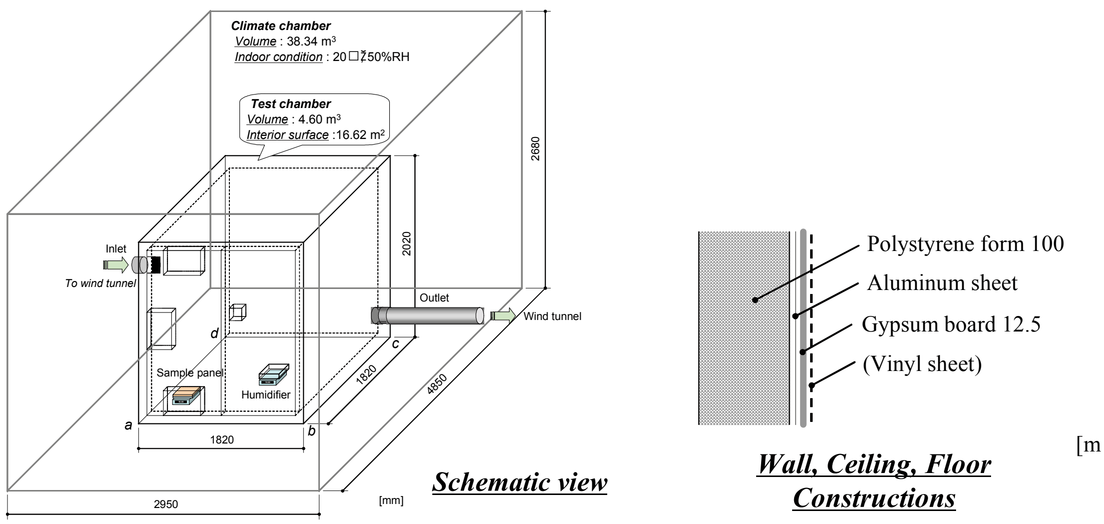
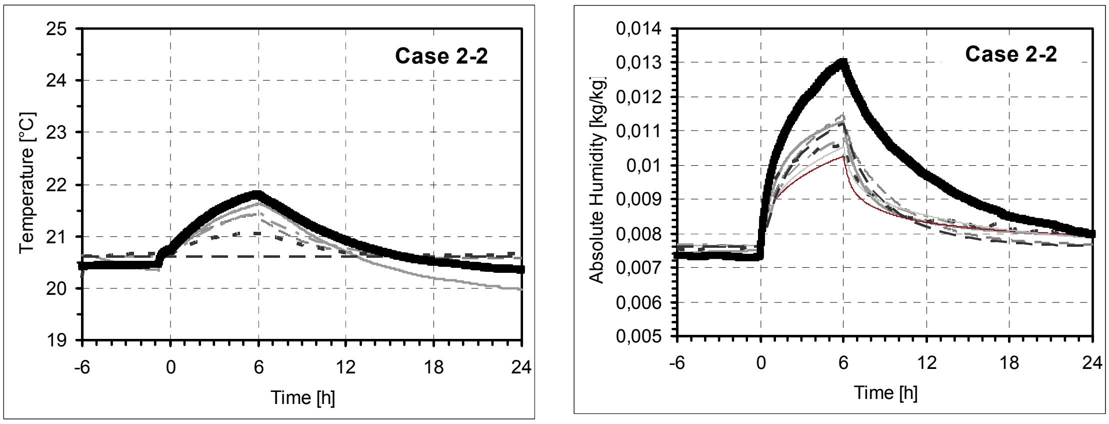
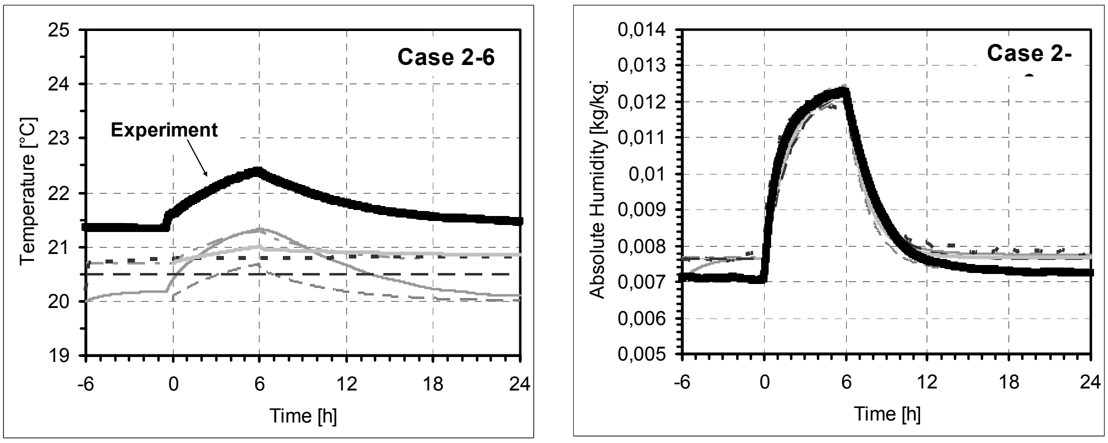


Figure 2. Experimental set-up used in Common Exercise 2.

Figure 3. An example of results from Common Exercise 2.



Measured values and simulation results (ventilation rate: 0.62 ach, ambient temperature 20.6°,ambient relative humidity 51%, floor covered with gypsum board)



Measured values and simulation results (ventilation rate: 0.64 ach, ambient temperature 20.5°,ambient relative humidity 51%, all walls non-buffering)

mixing, could produce predictions that deviated substantially from the measured data.

Exercise 4 examined the ability of whole building HAM models to predict net energy demand. Exercise 5 offered the participants the possibility to explain a real life problem and to propose solutions, while Exercise 6 produced a set of very interesting measured data that could be useful for future validation of new models, included CFD-based tools. In Exercise 5, 48 identical two storey dwellings were investigated concerning the problem of condensing moisture on a cathedral ceiling. It was found that air egress through pitched roofs was the main cause of this problem. Figure 4 shows one of the dwellings and the amount of condensate in the roof for the case when only the ground floor was heated. The black line shows the limit of the moisture quantity that could be absorbed by the fibre-cement corrugated roof cover.

All common exercises showed the complexity of the whole building combined HAM modeling. Although a consensus among the solutions with different calculation models was found only for an extremely simple case, these exercises showed the importance of testing existing codes, developing new codes, including further development of existing ones to be able to handle moisture transfer modelling. Moreover, the presented results confirmed that the whole building HAM simulation tools were able to simultaneously predict indoor climate, as well as energy consumption, together with local hygrothermal conditions within the building elements.

Project Outcomes

Experimental analysis of moisture buffering

Investigations of moisture buffering in finishing materials, furniture and furnishings was the main objective in this part of the project. For this purpose, round robin testing on vapor permeability and hygroscopic adsorption / desorption of painted and unpainted drywall samples was organized. The data produced created confusion, as large differences in measured vapour permeability were noted between the many participating laboratories, which could not be explained otherwise than by measurement errors. One of the conclusions was that future standards on vapour permeability measuring techniques should include more precise and restrictive information on how to prepare the samples, how to vapour tighten the joint between the sample and the cup and how to perform the tests (duration, number of measuring moments, time interval between measurements, etc). Also, the adsorption / desorption data showed quite some variation. From that point of view, gypsum is a difficult material, as chemical bound water molecules are easily released when dried at too high temperatures.

Two additional tests and exercises were organized, one looking at buffering by the same drywall used in the round robin testing in response to stepwise and sinusoidal changes in relative humidity in the air and the other looking at the humidity build-up in a pile of drywall boards in response to a sudden change in relative humidity in the air. Simulation of the first test by several participants again gave rather disappointing results, with large spreads between the different solutions. The second test was, however, quite well reproduced by the different models used by the participants. Some participants also tried to use CFD as a simulation tool, in combination with a materials model. The first trials showed large differences between the measured data and the CFD data, though follow-up trials did quite well.

Apart of the testing and validating activity, a new track in simplified modeling was explored, using a short-term (1 hour) and medium-term (8 hours) moisture buffering values (MBV). It gives the humidity uptake per percentage change in relative humidity when 1 m² of a surface is exposed to a succession of 1 hour (short) or 8 hours (medium) at 75% relative humidity, followed by 23 (short) or 16 hours (medium) at 33% humidity. The MBV-value is quite easily measurable for all types of substrate, finishes, furniture and furnishings. The project successfully extended the concept from the 1 m^2 and one object level to the room level.

Boundary conditions

This phase of the project was mainly devoted to measuring temperature and relative humidity in residential buildings, student accommodation and schools. In addition, a literature review was carried out of moisture production and building usage schedules and simple indoor humidity calculation tools were evaluated.

During the project, several data sets with measured values for temperature, relative humidity, vapour pressure and vapour pressure

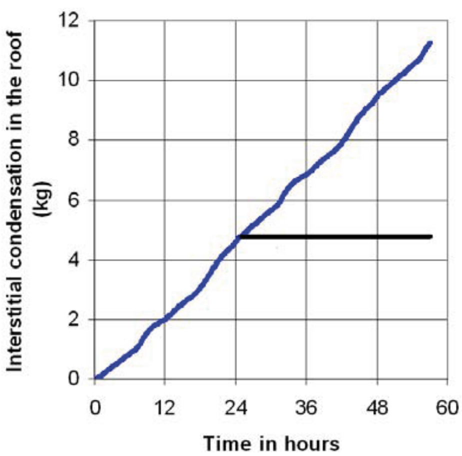


Figure 4. One of the low income houses (left) with the condensation deposit in the cathedralised ceiling pitched roof for the case when only the ground floor is heated (Exercise 5).

Table 2. Moisture production rates.

Cooker	Food	Quantity of Food	Time for cooking, min	Production rate g/h
Iron pot	Rice	0.09 m^3	30	270
Milk boiler	Milk	0.036 m^3	5.5	90
	Fried vegetable	66 g	10	396
Frying pan	Fried egg	10 g	3.5	168
	Pancake	184	28	396
BBQ	Grilled fish	47 g	11	258
Toaster	Two slices bread	7 g	3	144

excess were gathered from Finland, Estonia, Belgium, Canada, Slovakia, Germany and the UK. These were then analysed and compared with standards. Moisture sources, daily and weekly building usage patterns were also recorded and numerical values of moisture production rates were tabulated, in addition to the data included in the Annex 14 reports. As an example, Table 2 shows data measured by the participants from Japan.

Long term performance and technology transfer

Four main topics were investigated in this part of the project:

- acceptable indoor relative humidity levels,
- indoor climate control,
- moisture tolerance, and
- the impact of boundary conditions on whole building heat-air-moisture simulations.

Acceptable relative humidity levels

Comfort and health

High relative humidity in combination with high air temperature causes a stuffy feeling, which humans perceive as unpleasant. The effects on human health, however, are rather indirect. High relative humidity favours the growth of micro-organisms. Especially sensitive people may get distressed by their presence. Typical complaints are headache, tiredness, loss of concentration, etc. A relative humidity below 15%, on the other hand, may give a feeling of dryness, though this is not believed to be due to relative humidity alone. Rather, this in combination with other pollutants, such as volatile organic compounds (VOCs), may be the real cause of complaints. In fact, studies with test subjects have shown that the humidification capacity of the nasal track is sufficient to compensate for lack of humidity in the air.

Furnishing and objects

This is an important subject, particularly looking at cultural heritage, museums and historic churches. The problem is that each object demands specific conditions. Too high relative humidity may favour corrosion of metals, degradation of glass and will activate biological attack by moulds and bacteria. Changes in relative humidity cause swelling and shrinking, especially of wood-based materials, and induce tensile stresses with cracking as one of the consequences.

This negative picture previously convinced the International Council of Museums to impose very strict climate schedules in museums, with a dry bulb temperature of 20±1°C and a relative humidity of 50±3%. Today, more relaxed conditions are accepted and made dependent on the importance of the museum and the value of the pieces present, though tough rules remain in place for short term fluctuations (less than ±2°C for the dry bulb temperature and less than ±2% for relative humidity). In historic churches, the most critical and valuable indoor parts determine the climate conditions to be maintained, with limited change rates in temperature and relative humidity as one of the requirements.

Building fabric durability

Relative humidity may affect the building fabric in two ways: first by inducing biological attack with mould and algae as typical phenomena and secondly by causing decay and corrosion. Biological attack may happen on

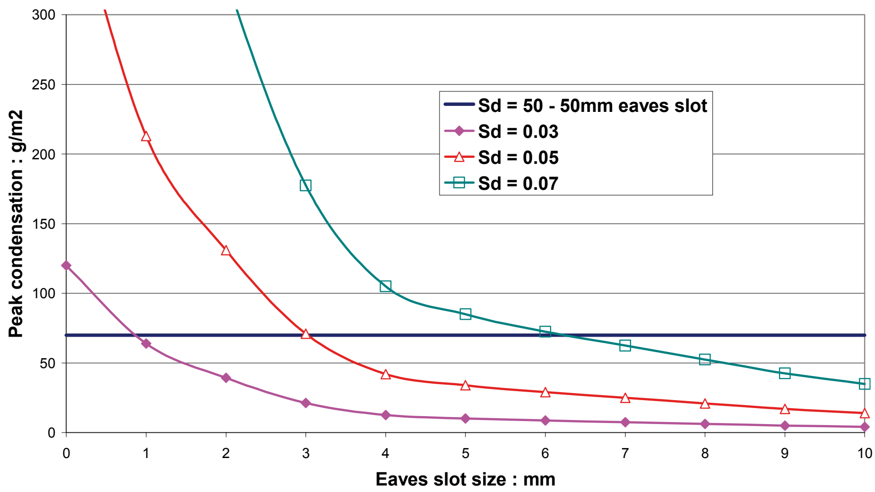


Figure 5 . peak accumulated condensate as a function of eaves gap and underlay resistance.

any substrate while decay is typical for timber based constructions and corrosion for metallic materials.

The project examined the recent literature on mould and found the Viitanen and the bio-hygrothermal model as the two most recent mould growth approaches. The Viitanen model calculates the mould growth index for wood as a function of time on the condition that the temperature, relative humidity, wood species and drying surface quality are known. The bio-hygrothermal model in turn starts from defining three material classes, each with their isopleths. The assumption is then that mould only germinates above a critical relative humidity and, once germinated, behaves as a buffer layer characterized by a vapour permeance and a sorption isotherm.

Wood decay is mainly a biological process, with bacteria as the first colonizers, decomposing the sugars in the sap. At relative humidities beyond 85% to 90% moulds take over, while fungal deterioration and rot only starts at high moisture ratios.

Finally, progressive corrosion is an electro-chemical process that starts when four conditions are met: water present, oxygen available, metal giving up electrons and corroded layer not protective. Important parameters are the time of wetness (relative humidity beyond 80% and temperature above zero in hours per year) and the climate with relative humidity, sulphur dioxide and chlorides as the main factors.

Algae require sufficient surface water to grow. They profit from the condensate deposited on exterior surfaces by night under-cooling. As the severity of the temperature decrease and condensate deposit drops with increasing thermal inertia of the exterior layer, algae formation is most likely on thin finishes such as EIFS. Also, suction helps in moderating their growth. That and its excellent thermal inertia explain why algae hardly colonize masonry.

Minimizing energy consumption

Two elements explain the increase in energy consumption when a buffering building fabric contains water: latent heat flow and a higher thermal conductivity. Rain suction may be responsible for that, although a specific problem is built-in moisture. Buildings are typically wet at the start of their service lives. That wetness must disappear, which demands energy. If the drying process takes too long, or through wetting insulation layers by condensation, favourable conditions for mould growth are created. Particularly buildings constructed with aerated concrete are vulnerable from a built-in moisture point of view, as the fresh material contains up to 200 litres of water per m^3.

Table 2. Air tightness criteria to prevent interstitial condensation in sloped roofs (Belgium, Δp = 4 Pa)

Indoor climate class (ICC)	Maximum allowable air permeance (10^{-4} $m^3/(m^2.s.Pa)$) Underlay μd = 2.0 m	Underlay μd = 0.02 m
ICC 1-2: $\Delta pv = 159 - 10.\theta e$	< 0.6	< 1.1
ICC 2-3: $\Delta pv = 436 - 22.\theta e$	< 0.2	< 0.3
ICC 3-4: $\Delta pv = 713 - 22.\theta e$	< 0.1	< 0.2

Indoor climate control

Ventilation based
The most important instrument to control indoor humidity in cold and mild climates is outside air ventilation. In fact, buffering may dampen the water vapour pressure swings inside and cause a time shift with the swings outside, but, buffering cannot change the mean value inside over longer periods. Only ventilation and vapour release are able to do that.

A question posed by the project was if relative humidity controlled ventilation has benefits in mild climates. Measurements showed that such systems did better than stack ventilation in terms of limiting energy use and moderating mould and surface condensation risk. An alternative system tested used a so-called artificial thermal bridge to create a reference surface for condensation. A dew point sensor on the thermal bridge activated fan assisted ventilation each time condensation was formed on it.

A study of the ventilation needed to avoid mould in buildings with different thermal characteristics found that higher mean rates or more peak airing periods are needed in badly insulated buildings compared to well insulated buildings. In an analogous way, different ventilation strategies for residential buildings and classrooms were analysed, while for office buildings the effect of a passive enthalpy wheel in the HVAC-system on indoor relative humidity, perceived air quality and energy consumption for cooling was evaluated.

Passive control
The dampening effect of moisture buffering was analysed in detail with possible energy benefits. In mild climates, buffering improved the performance of cool ceilings, as higher cooling temperatures could be maintained during more operating hours. But, the relative humidity increase was moderated in a hotel room that was unconditioned during the day in a hot and humid climate, but the energy consumption hardly changed compared to a hotel room without buffering.

Moisture tolerance

The two topics studied under moisture tolerance were cathedralized sloped roofs and attic ventilation. Cathedralized roof design typically takes as starting point the assumption that in cold and mild climates air-tightness is the main performance requirement demanded to avoid interstitial condensation from inside. However, measurements over the years in buildings, test buildings and laboratory set-ups have proved that perfect air-tightness is not achievable. The question is therefore what level of air permeance should be achieved to keep the roof moisture-safe. Table 2 shows the recommendations that resulted from the study.

The attic ventilation debate focused on the use of a vapour permeable underlay instead of venting and the need, in colder climates with extremely well insulated ceilings, to use controlled ventilation coupled to a relative humidity sensor as controlling device. The answer to the first problem was that a more vapour permeable underlay allows minimizing the eaves gap for venting, see Figure 5. As far as the second problem is concerned, venting alone in fact did not work properly, on the contrary. Condensation by under-cooling and inside air ingress could not be avoided. Instead, a ceiling with low air permeance in combination with controlled attic ventilation worked well.

Impact of boundary conditions on whole building air and moisture (HAM) simulations

The last part of the project looked at the climate-related impact in terms of measured moisture response of a building and its fabric over successive years. The effects wind driven rain may have on indoor relative humidity and energy

Project Outcomes

consumption were considered. Also, the impacts that real world indoor heat and vapour release and ventilation schedule data may have on the moisture response of a building and its fabric were studied in comparison with indoor humidity boundary conditions as specified in standards.

Differences between successive years in terms of peak temperatures indoors were large. The annual trend in relative humidity inside, however, did not change. This was higher in summer than in winter. But, the day on day variation amounted to almost 30%.

If a building is massive in nature and its walls suck rain, then wind driven rain has quite an impact on the relative humidity inside. Also the net heat demand changes. For the case studied, winter heating increased with 11%. In addition, the mould growth risk increases.

Indoor humidity boundary conditions as specified in different standards (e.g. EN ISO 13788, EN ISO 15026, WTA-6-2-01/E) gave results that deviate between one another for the same class of building. They also differ quite substantially from those found when using real world indoor heat and vapour release and ventilation schedule data. EN ISO 15026 and WTA-6-2-01/E showed an embedded safety margin when used for residential buildings.

Project conclusions

The overall project conclusions were as follows:

- A number of existing simplified and more complete whole building heat-air-moisture software tools were verified and validated and used to obtain results for some specific applications.
- Sets of data were produced that can be used for validation of future upgrades to whole building heat-air-moisture software.
- Round robin testing on bare and painted gypsum board was carried out. The results showed that quite some uncertainty on the properties tested should probably be taken for granted, although also the testing methods require a thorough review.
- An in depth study of moisture buffering phenomena was brought to a good conclusion.
- Sets of measured indoor climate data were collected.
- Evidence was obtained that CFD / droplet trajectory modelling works well for predicting wind driven rain impact on buildings.
- A deeper analysis of the under-cooling phenomenon and its consequences was presented.
- A range of whole building heat, air, moisture applications were assembled, from acceptable relative humidity levels under indoor climate control and moisture tolerance aspects to the impact of boundary condition assumptions on simulation results.

However, many subjects are still open for a deeper exploration. Air flow models and CFD should be better integrated as the coupling between the building and fabric is still too simplistic. The energy consequences of air and moisture flow in different climates wait for being analysed. The effect of buffering on HVAC choices and design are not clarified in full detail. More testing in mock-up rooms and real buildings is needed.

Above all, it should be kept in mind that building up knowledge in such a complex field as whole building heat-air-moisture demands a combination of modelling, testing and field experience. One should never forget that reality is much more complex than any model may presume. Good experience and a sense of risk analysis are therefore important assets.

In fact, real world problems are always loaded with a probability that something is incorrect with more or less severe consequences of what may happen as a result. Buildings are also becoming more complex. That and the demands for much better insulation, higher air-tightness, more responsive building elements, smarter solar shading systems, better indoor air quality, high-level comfort, and complex mechanical, electrical and IT systems are also increasing risk. This demands much more refined analyses of expected, probability based heat-air-moisture responses and the corrections needed to achieve enough tolerance in real buildings.

Further Information

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