International Energy Agency

Heat, Air and Moisture Transfer In Highly Insulated Building Envelopes (HAMTIE)

Technical Synthesis Report
IEA ECBCS Annex 24

Energy Conservation in Buildings and Community Systems

Heat, Air and Moisture Transfer in Highly Insulated Building Envelopes (Hamtie)

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Annex 24 Synthesis Report based on the five final reports.
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Preface

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 program. A basic aim of the IEA is to foster co-operation among the twenty four 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 sponsors research and development in a number of areas related to energy. In one of these areas, energy conservation in buildings and community systems, the IEA is sponsoring various exercises to predict more accurately the energy use of buildings, including comparison of existing computer programs, building monitoring, comparison of calculation methods, energy management systems as well as air quality, studies of occupancy and in depth evaluation of impact on energy consumption of the building enclosure.

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 conservation in buildings and community systems (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 (*)
Annex 11: Energy Auditing (*)
Annex 12: Windows and Fenestration (*)
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 (*)
Annex 18: Demand Controlled Ventilation Systems (*)
Annex 19: Low Slope Roof Systems (*)
Annex 20: Air Flow Patterns within Buildings (*)
Annex 21: Thermal modelling (*)
Annex 22: Energy Efficient Communities (*)
Annex 23: Multi Zone Air Flow Modelling (COMIS) (*)
Annex 24: Heat, Air and Moisture Transfer in Envelopes (*)
Annex 25: Real time HEVAC 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
Annex 38: Solar Sustainable Housing
Annex 39: High Performance Insulation systems
Annex 40: Building Commissioning to Improve Energy performance
(*) - Completed Annexes

This summary report concentrates on Annex 24: Heat, Air and Moisture Transfer in highly insulated envelopes (*).

Summary

Combined heat, air and moisture (HAM) transfer heavily impacts the energy performance and durability of well insulated building enclosures. Hence, the main objectives of the annex were to study the physics involved in HAM-transfer and to analyse the consequences for thermal performance and durability. Activities covered:

- Modelling of combined heat, air and moisture transport;
- An in-depth study of the environmental conditions involved;
- Round robin testing and data gathering in relation to material properties;
- Experimental verification and an analysis of the HAM response of a collection of envelope parts;
- Performance formulation in relation to HAM-transport and practice.

Contents

1. A Short History

The idea to initiate an annex on heat, air and moisture transport (called HAM in this summary report) surfaced in 1990. That year, an enquiry was conducted in 10 IEA-countries, asking for the level of involvement in HAM-research and the way research results were implemented in standards and codes of practice. The results revealed an ambiguous situation. Many laboratories were very active in heat and moisture modelling and testing and applied the knowledge gained on building enclosures. Most national building codes and standards however remained notably silent on HAM-performance or treated the subject in a very elementary way. This situation convinced 14 countries, 12 as full members and 2 as observers, to join forces and to start a common research project named Heat, Air and Moisture Transfer in Highly Insulated Envelope Parts and was initiated by the Energy Conservation in Buildings and Community Systems Programme Executive Committee as Annex 24.

Participating Countries:

Full	Belgium, Canada, Denmark, Finland, France, Germany, Italy, Norway, Sweden, Switzerland, The Netherlands, United Kingdom
Observers	Slovakia, USA

The Annex advanced two main objectives:

- to study in a fundamental way the physics of **H**eat, **A**ir and **M**oisture **T**ransport in new and retrofitted, **H**ighly **I**nsulated **E**nvelope parts (**HAMTIE**);
- to analyse the consequences of HAM-response on thermal performance and durability.

At a 'Kick-Off Meeting' in Paris, April 1991, these two objectives were shaped into five subtasks:

Subtask	**Title**	**Leading Country**
1	Modelling	Belgium
2	Environmental conditions	United Kingdom
3	Material properties	Canada
4	Experimental verification	Germany
5	Performances	Sweden

Subtasks one to three concentrated on objective one, while subtasks four and five on objective two. During the four years of common research activity, nine working meetings of three days each were organised. Every meeting saw research results discussed, the latest common exercises analysed and common work for the next six months agreed. The last two meetings were devoted to intensive review and revision of the draft final reports. In addition, the leading countries met four times to check progress. The work was completed and the Annex was closed in 1995.

Annex Meetings:

Paris, France, April 1991 (Kick-Off)
Zürich, Switzerland, October 1991
Saskatoon, Canada, April 1992
Eindhoven, The Netherlands, October 1992
Glasgow, UK, April 1993
Holzkirchen, Germany, October 1993
Trondheim, Norway, April, 1994
Rome, Italy, October 1994
Leuven, Belgium, April 1995
Helsinki, Finland, September 1996

Leading Countries Meetings:

Holzkirchen, Germany, February 1993
Goteborg, Sweden, February 1994
Garston, UK, March 1995
Porto, Portugal, September 1995

During the operative phase, the Annex produced three small interim reports. At the end of the operative phase, four draft reports and the draft of one addendum with the results of the common exercises were ready.

The Annex officially closed on April, 30, 1995. However, it took another year before the reports were edited. They were presented to an international audience at the Nordic Building Physics Conference in Helsinki, Finland, in September 1996.

1.1 Annex Reports

Intermediate Reports:

- Hens H., A. Janssens, 1993, Enquiry on HamCat Codes, ACCO, Leuven, 23 pp.
- Sanders C., 1994, Design parameters used to Avoid Interstitial Condensation for a Range of Climates, ACCO, Leuven, 19 pp.
- Kumaran K., 1994, Symbols and terminology, ACCO, Leuven, 21 pp.

Final Reports:

- Hens H., 1996, Modelling, ACCO, Leuven, 90 pp.
- Anon., 1996, Modelling, Addendum, ACCO, Leuven
- Sanders C., 1996, Environmental Conditions, ACCO, Leuven, 96 pp.
- Kumaran K., 1996, Material Properties, ACCO, Leuven, 135 pp.
- Hagentoft C.E., 1998, Performances and Practice, ACCO, Leuven, 56 pp.

The final reports may be purchased from:

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2. The Situation before Annex 24

The enquiry organised in 1990 has been mentioned previously. The results of that enquiry reflect the situation before Annex 24.

On the one hand, the research community had a rich tradition in studying combined heat and moisture transport. The first software tools that allowed the analysis of heat and moisture ingress in composite walls were available. However, much effort was directed either to moisture or to heat. The term 'combined' in fact was used to indicate that temperature induced moisture flow was considered when analysing moisture mitigation or that moisture effects were included when analysing heat exchanges. Looking at both phenomena simultaneously was not common practice. Also, albeit Canada and the Nordic countries had already built air flow into their HAM-models for lightweight construction and a few studies underlined the impact of air displacement on the thermal performance of timber framed walls, most research teams did not realise the twin heat and moisture should be enlarged to a triplet consisting of heat, air and moisture.

On the other hand, practice, as reflected in standards and building codes, gave a more frustrating picture. Most countries had to admit the way HAM-related performances were treated remained largely unsatisfactory. Old fashioned rules survived the evolution in building technology introduced by thermally insulation. Advanced standards did not go beyond the combination of a U-value check and a steady state vapour diffusion control on the dry part, as if climate is an averaged reality, as if wind driven rain does not interfere, as if capillary suction does not exist, as if building enclosures are airtight, as if heat, air and moisture do not interfere, as if built in moisture does not exist, and so on.

3. The Annex Results in a Nutshell

3.1 Modelling

3.1.1 In General

HAM-modelling is based the three conservation axioms of classical physics: i.e. conservation of mass, conservation of energy and conservation of momentum. All three axioms state that the resultant in- and outflow rate per elementary material volume of the quantity involved, together with the local rate of generation or absorption of that quantity, equals the storage rate of the quantity in the elementary material volume. While heat and mass conservation both intervene in all HAM-models in their full amplitude, conservation of momentum instead is replaced by a set of simple diffusive and convective transport equations for moisture and air. The format these equations take reflects the way heat is transported: by conduction, which is the equivalent of diffusion, and enthalpy flow, which is the equivalent of convection.

Diffusive equations assert proportionality between the displacement of heat, moisture and air and the change per unit meter of a driving force. The proportionality coefficient these equations introduce acts as a material property. It differs between materials and may be a function of the driving forces involved. Typical examples of diffusive equations are:

- Fourier's law of heat conduction, introducing thermal conductivity λ in W/(m.K) as a material property and temperature T in K or temperature θ in °C as driving force;
- Fick's law of diffusion, introducing vapour permeability δ_v in kg/(Pa.m.s) as material property and water vapour pressure p in Pa as a driving force.

Bulk or convective equations apply when a fluid, such as water or air, acts as a carrier for heat and a carrier for other mass components or when the displacement of the fluid is macroscopically visible. In that case, the term diffusion-like equation instead of bulk equation is used. Typical examples of diffusion-like transport equations are:

- Darcy's law for water flow in a porous system, introducing water permeability k_w in kg/(m.s. Pa) as a material property and capillary suction s or water pressure P_w as a driving force;
- Darcy's law for air flow in a porous system, introducing air permeability k_a in kg/(m.s.Pa) as a material property and air pressure P_a as a driving force;

The combination of full heat and mass balances and simple diffusion, diffusion-like and bulk transport equations results in a set of three partial differential equations (PDE's), one for heat transport, one for moisture transport and one for air transport.

Solving these PDE's demands knowledge of the equations of state. These relate the storage terms in the balance equations to the driving forces, they interrelate some of the driving forces and they introduce two storage related material properties: the specific heat capacity c in J/(kg.K) and the specific moisture content ξ in kg/(kg.Pa). Examples of equations of state are:

- The ideal gas law;
- The relation between water vapour saturation pressure, temperature and curvature of the water surface;
- The enthalpy equation;
- The sorption isotherm, as shown in Figure 1;
- The water retention curve.

Also, the initial conditions, the boundary conditions, the contact conditions and the geometry of the envelope part to be analysed should be known. Initial conditions give the HAM-situation in the part at the moment the solution starts. Boundary conditions describe the environmental situation at both sides of the part during the time interval spanned by the solution, while contact conditions fix the way the different surfaces between the separate material layers make contact with each other in the part. Finally, geometry is almost every time replaced by a simplification. For example: a flat roof is represented by one m^2 of its surface, which puts forwards the assumption that all remaining m^2 are identical to the one chosen!

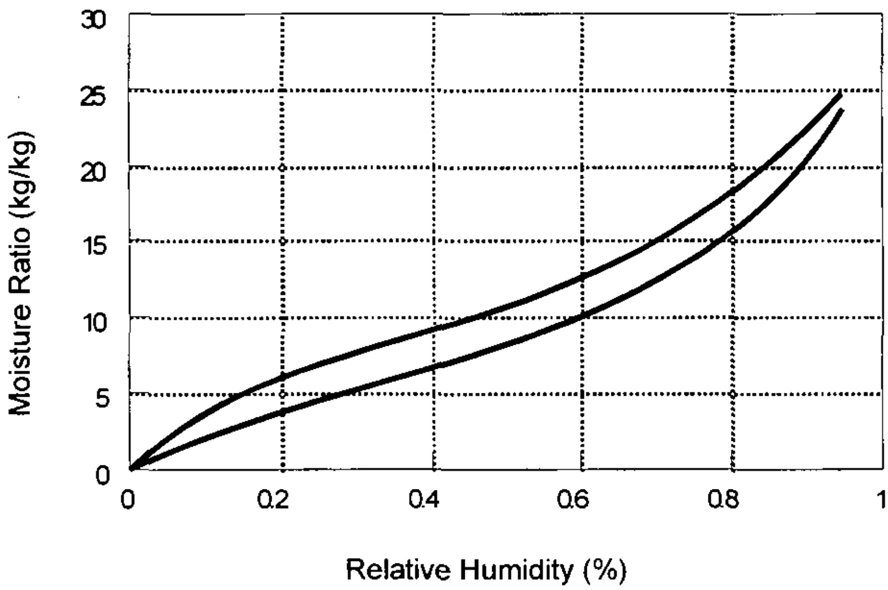


Figure 1 The sorption isotherm for pine. The lower curve stands for adsorption, the higher curve for desorption. The surface in-between indicates the magnitude of the hysteresis between wetting and drying.

3.1.2 Computer Codes

Since the coefficients in the three PDE's depend on temperature and moisture content, no analytical solution can be produced in any case. Applying a numerical approach based on control volumes or finite elements is the only possibility. As computers handle numerical calculations in a fraction of the time as manual calculations, the development of computer codes and computer tools to solve the HAM-models constructed was a logical next step. At the start of the Annex, twenty-nine codes could be documented. At the end, that number reached a total of thirty-seven. Most codes were classified as 'transient heat, vapour and liquid', i.e. the type of code needed for an in-depth study of heat conduction, vapour diffusion and capillary water transport in envelope parts. A few codes analysed HAM in its overall complexity, while others were based on highly simplified HAM-transport approaches.

The main difference between the codes considering combined transient heat and moisture transfer concerned the driving forces used. Temperature was commonly accepted as the reference driving force for heat transfer. On the contrary, moisture transport was linked to various sets of driving forces, such as moisture content and temperature, suction and vapour pressure, generalised relative humidity and vapour pressure, suction and temperature, etc. That disparate picture obliged the Annex participants to formulate rules on 'how to use driving forces for moisture transfer'. In an attempt to classify the mix of code based tools, the Annex defined three levels of comprehensiveness:

Level of comprehensiveness	
1	Simple engineering tools
2	Simplified models
3	(Nearly) full models

Simple engineering tools respect conservation of mass and energy but reduce the physics involved drastically. Time as an independent variable is skipped, bulk flows deleted (air, suction driven capillary flow), vapour saturation pressure versus temperature kept as the only equation of state, material properties set constant, and so on.

A well known example is the *Glaser method*. Glaser restricts moisture mitigation to steady state diffusion and heat transfer to steady state conduction only, leaving interstitial condensation of vapour as the only cause of moisture deposit. Figure 2 illustrates the method graphically.

The *Convection/Diffusion method*, also takes air in- and exfiltration and related bulk heat and vapour flow into account (Figure 3). Infiltration eliminates winter interstitial condensation in cool climates. Exfiltration instead may aggravate the condensation deposit. This is shown in Figure 4.

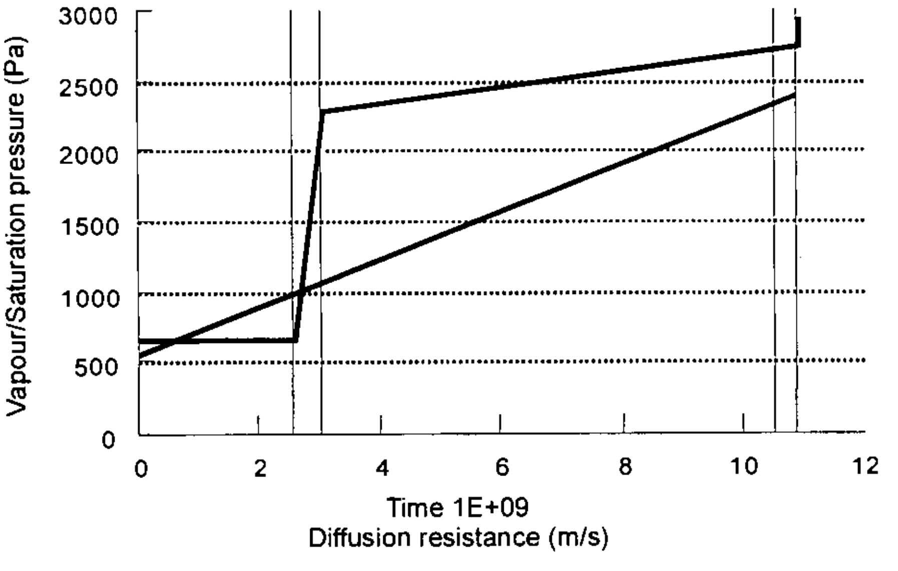
Simplified models not only respect the conservation of energy and mass axioms, they also keep track with the overall complexity of the physics involved. Material properties however are imposed as predefined functions, while boundary conditions, initial conditions, contact conditions and the geometry are kept as simple as possible. Typically an envelope part is reduced to a one-dimensional geometry. Contacts between materials are assumed ideal, with continuity of the heat and moisture flows and continuity of all driving forces. The initial moisture content is kept uniform for all capillary porous layers and expressed in terms of relative humidity for all non-capillary-porous layers. Moisture loads that are handled include initial moisture content, vapour ingress by diffusion and convection from inside and from outside and capillary suction of wind driven rain.

Finally, Full models not only respect the conservation of heat and mass axioms in their overall complexity, but they also handle the physics involved in their full amplitude and implement all material properties, the boundary conditions, the initial conditions, the contact conditions and the geometry in a way that stands as close as possible to reality. The two and three dimensionality of enclosure details is respected. Predefined material property functions are exchanged for measured curves. Real contacts between layers are implemented, including a thin air layer in-between; partial suction, a mix of local suction alternated with local air layers; an additional contact resistance as a consequence of chemical or physical interactions between materials poured together. Contrary to simplified models, which can be used as practice related tools, full models mainly form research tools for in-depth analysis of all phenomena involved.

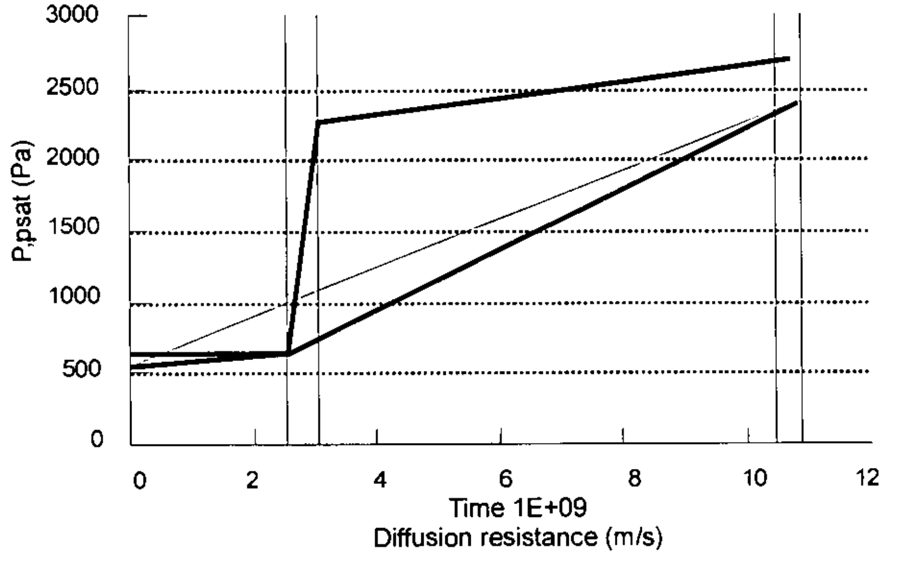
More information about modelling and codes can be found in the final report on Modelling.

3.1.3 Common Exercises

Physical models, translated into computer tools, must be validated. Normally, a full validation demands a combination of experimental verification, comparison of the code results with analytical solutions and inter-model evaluations. Such overall validation could not be done within the limited timeframe of the Annex. The activity therefore was restricted to an inter-model comparison and some experimental verification.



(a) Vapour pressure intersects vapour saturation pressure physically impossible



(b) Correct solution: in- and outgoing p-tangent to the p_{sat}-curve

Figure 2 The Glaser method. Graphical solution for the vapour pressure and the condensation interface. The moisture deposit equals the difference in slope between the in- and the outgoing vapour pressure tangent.

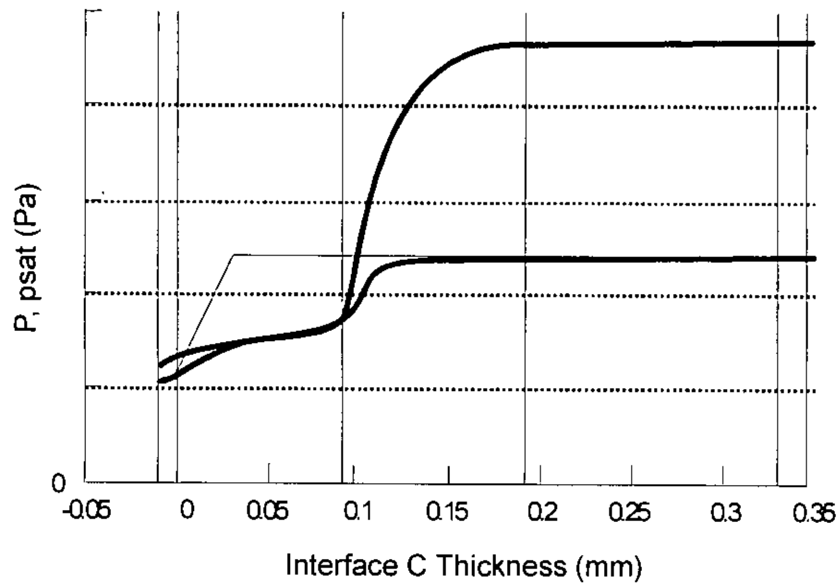


Figure 3 Convection/diffusion model, saturation pressure, vapour pressure, interstitial condensation in interface C.

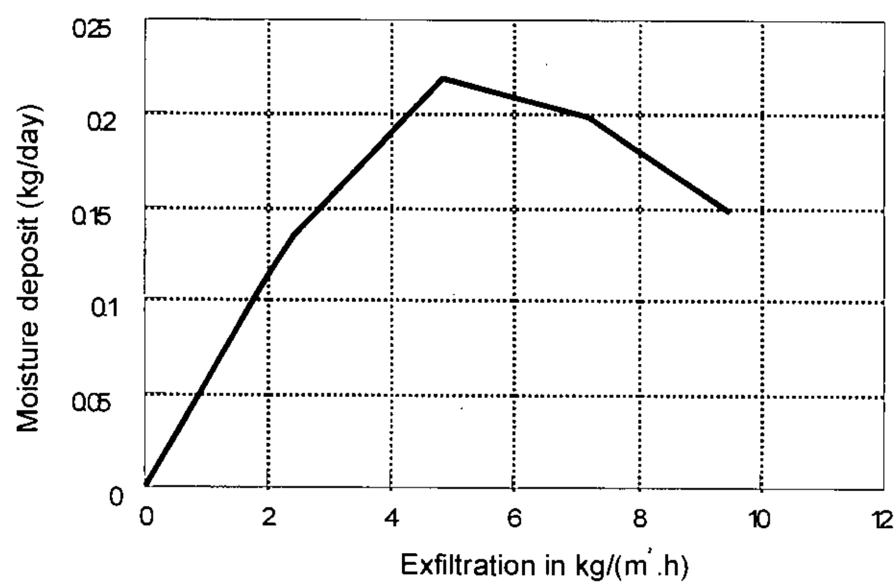


Figure 4 Condensation deposit in C as a function of the exfiltration rate.

For that purpose, six common exercises were solved by the participating countries, using their own HAM-software. The exercises concerned several envelope parts and focused on different aspects of the HAM-reality: initial moisture, solar gain, wind driven rain, air transport, heat losses by exfiltration, drying and two-dimensional capillary suction.

COMMON EXERCISES

- Heavy weight flat roof with built in moisture
- Air permeable timber framed wall

- Cavity wall (wind driven rain, 2-D)
- Air permeable lightweight metallic roof (validation)
- Timber casette roof with a water permeable vapour retarder
- Crawl space (2-D and 3-D modelling)

Let us consider the cavity wall: The geometry of the walls, all material properties, the outside environmental conditions, included driving rain, and the inside environmental conditions were known. All participating countries had to calculate the evolution of the moisture content in the outside leaf between July 1991 and June 1992 and had to tabulate the monthly mean heat flux through the filled wall for each of the 12 months considered. No experimental investigations were available at the time the exercise started. Five countries completed the calculations. Their results on moisture content are summarised in Figure 5. Two countries predicted the same evolution. One country gave lower values, while two countries proposed a result that showed much higher changes in moisture content than the others predicted. One of the two even ended with a moisture content in the outside leaf beyond vacuum saturation, which is physically impossible. One common feature however was reassuring: all countries predicted bad drying in wintertime. Experimental data collected years after the exercise confirmed that result, as can be seen in Figure 6. As far as heat flux was concerned, the percentages of influence that an increase in thermal conductivity of the outside leaf and latent heat transport had on the flux shifted respectively from 1.6% to 4 % and 3.8% to 8%. Total driving rain impact was guessed to be situated between 5.4% and 13%.

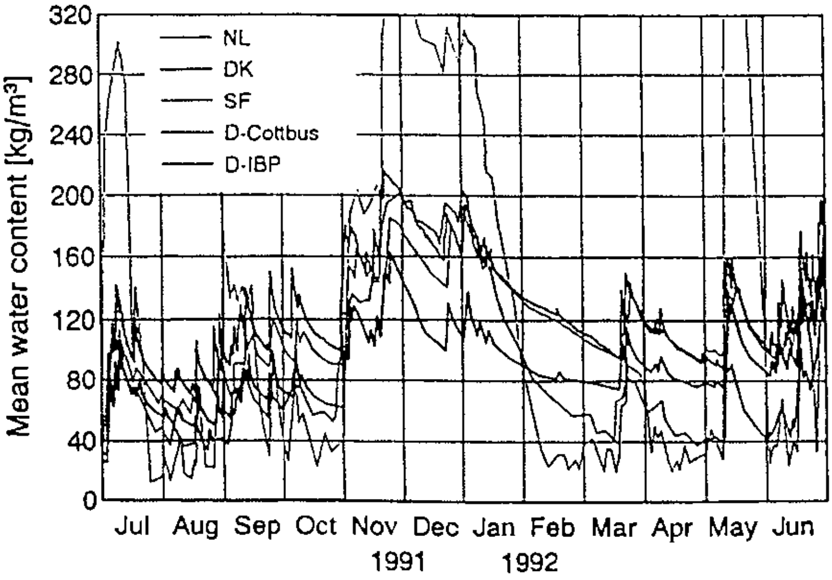


Figure 5 Moisture content in the outside leaf of a filled cavity wall, calculated results.

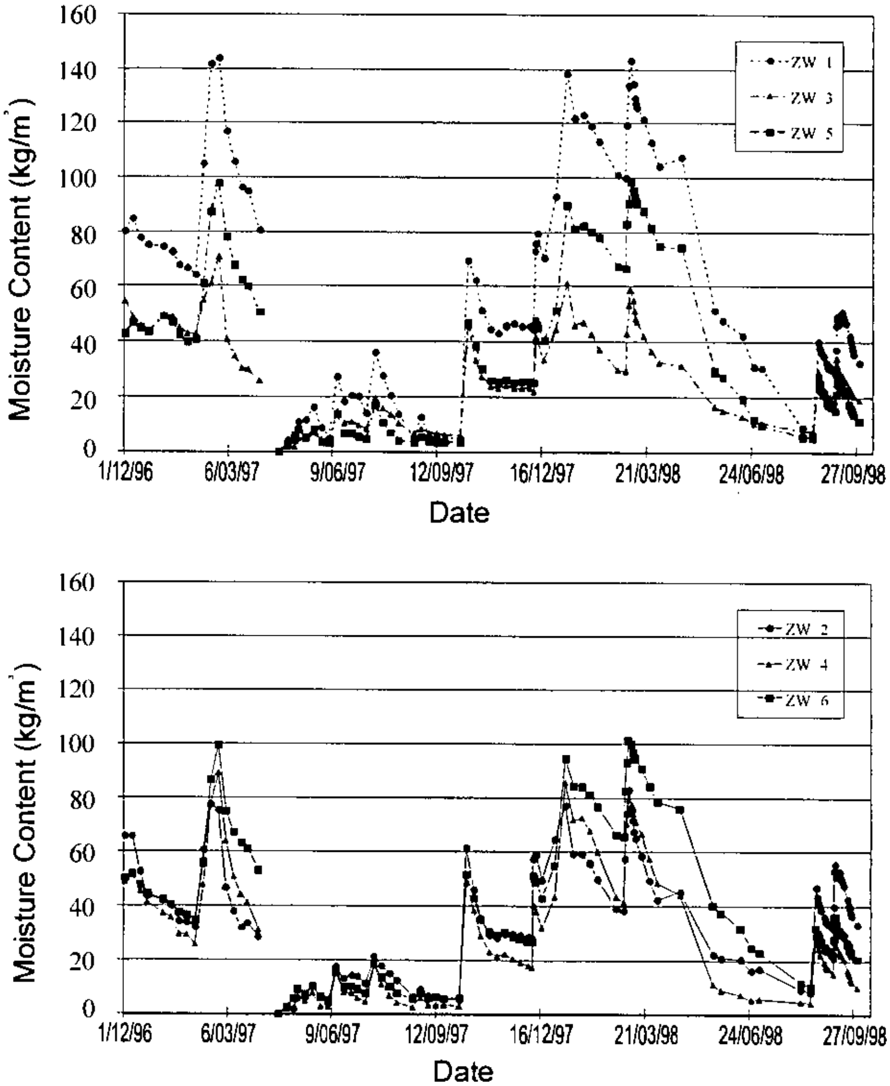


Figure 6 Moisture content in the outside leaf of several filled cavity walls, experimental data.

Conclusions gained from the six common exercises were:

- Simple engineering tools have a restricted capability as design instruments. In many cases, they do not succeed in formulating a correct answer to the question 'is a design acceptable or not?'
- The exercises confirmed the following order of importance of the different mechanisms that define the hygrothermal load: (1) air exfiltration, (2) initial moisture, (3) latent heat, (4) wind driven rain.
- In most cases, simplified and full models produce a correct qualitative picture of the hygrothermal response.
- Large differences anyhow exist between the numerical results, i.e., the amplitude of the moisture deposit, the shape of the moisture profiles and the specific time evolution. The main reasons for that are the use of simplified material properties, a different formulation of the boundary conditions and differences in the chosen simplification to represent the real geometry.

More information about these common exercises may be found in the Addendum to the final report on Modelling

3.2 Environmental Conditions

Measured indoor climate data were compiled and analysed. This resulted in a series of interesting data for dwellings, swimming pools and non-domestic buildings. A comparison between countries showed that sleeping rooms in the UK are fairly cold. Canada in turn struggles with a very low relative humidity indoors during wintertime when no humidifier is used. Italian dwellings on the contrary demonstrate quite a high relative humidity during wintertime.

The concept of Indoor Climate Classes (ICC) was elaborated, starting from the observation that the indoor-outdoor vapour pressure excess intervenes as a major factor in all vapour diffusion and vapour convection related moisture problems. Two pilot constructions were chosen to check the relation between vapour pressure excess and interstitial condensation:

- a north oriented well insulated lightweight wall with a vapour-tight cladding and no vapour retarder at the inside;
- a lightweight unprotected well insulated flat roof without vapour retarder at the inside.

Both constructions were considered as being airtight. The vapour pressure excess pivot between ICC1 and ICC2 was defined as being the highest excess possible that did not cause interstitial condensation in the wall at the end of January. The pivot between ICC2 and ICC3 coincided with the value that just initiated annual accumulation of condensing water in the wall. Finally, the pivot between ICC3 and ICC4 caused annual accumulation of condensing water to start in the flat roof. These pivots were calculated for Europe and North America and the lines of equal indoor-outdoor vapour pressure excess mapped for both continents. These maps determine that in hot climates, mould, surface condensation and reversed interstitial condensation impose more severe constraints on the vapour pressure excess than 'winter' interstitial condensation does.

Table 3.1 Indoor Climate classification

Indoor Climate Class PIVOTS			
City	ICC1-ICC2 January	ICC2-ICC3 year	ICC3-ICC4 year
London	170	352	717
Rome	210	591	no limit
New York	268	647	1239
Winnipeg	44	439	1037

The indoor climate class concept is a very attractive tool when performance requirements and design solutions have to be formulated for building enclosures.

CONSEQUENCES FOR DESIGN

- ICC1 imposes no severe constraints on the building envelope, except that it should be airtight.

- ICC2 and ICC3 demand more precautions to avoid interstitial condensation related damages: air-tight, a minimum vapour retarding quality at the warm side of the thermal insulation. What vapour resistance should be realised depends on the type of outside cladding, the vapour retarding quality of all layers at the warm side of that cladding and moisture sensitivity of the layer that accumulates the condensing water.

- ICC4 imposes a correct moisture design. If not, neither durability nor thermal performance can be guaranteed.

Finally, the Annex developed a well documented methodology to construct a Moisture Durability Reference Year (MDRY) for a given location. The MDRY is a 1 on 10 year, meaning that 9 years on 10 are less severe from a moisture load point of view. The year is composed of monthly average air temperatures, monthly average relative humidity, monthly average vapour pressures and the monthly total solar gain on a horizontal surface. The MDRY allows assessment of the moisture response of any envelope part that has a HAM-response not impacted by wind driven rain.

Table 3.2 Moisture Durability Reference Year (MDRY) for LONDON (UK)

Month	Temperature (°C)	Relative humidity (%)	Vapour pressure (Pa)	Solar gain (horizontal) (W/m²)
January	5.0	85	740	23.1
February	3.4	80	620	45.1
March	7.6	71	740	105.3
April	9.4	73	860	155.1
May	11.3	76	1010	163.2
June	16.2	75	1370	178.2
July	16.7	74	1400	165.5
August	16.6	81	1530	121.5
September	15.2	83	1420	106.5
October	13.7	87	1360	62.5
November	7.5	87	900	27.8
December	3.4	90	700	17.4

For more information about these ICC's and MDRY's, see the final report on Environmental Conditions.

3.3 Material Properties

Symbols and terminology were clarified. A net distinction was made between the storage properties, transfer properties and combined properties.

Table 3.3 Clarified Terminology and Symbols

General	Dry density ρ (kg/m^3)			
Heat	Storage	Specific heat capacity Volumetric specific heat capacity	c ρc	J/(kg·K) J/(m^3·K)
	Transport	Thermal conductivity Thermal resistance	λ R	W/(m·K) m^2·K/W
	Combined	Thermal diffusivity	a	m^2/s
Moisture	Storage	Specific moisture capacity Volumetric moisture capacity	ξ $\rho\xi$	kg/(kg·Pa) kg/(m^3·Pa)
	Transport	Vapour permeability Vapour resistance factor Vapour diffusion thickness Moisture permeability Thermal moisture diffusion coefficient	δ μ μd k_m D_T	kg/(m·Pa·s) - m kg/(m·Pa·s) kg/(m^2·K·s)
	Combined	Moisture diffusivity	D_w	m^2/s
Air	Storage	-		
	Transport	Air permeability	k_a	kg/(m·Pa·s)

In the frame of a Round Robin on measuring moisture profiles in spruce and calculating the moisture diffusivity, samples of the same joist were mailed to four laboratories that had the equipment to scan moisture profiles (γ-ray or NMR). In a first round, profiles were measured and the moisture diffusivity calculated by each lab. In a second round, a set of measured data was distributed. The four labs used it to calculate the moisture diffusivity. The results revealed a large scatter in results between individual laboratories. One of the main reasons for that was that each lab used its own mathematical methodology to derive the diffusivity. However, the average diffusivity over the whole moisture interval hardly differed.

The last step taken was the production of an extended database of measured material properties, containing values for the heat-, moisture- and air-related properties of thirty-two building, insulation and finishing materials. Storage, transport and combined properties were listed as a function of temperature, moisture content and relative humidity. No transformation with the aim of obtaining calculation values was performed. Table 1 gives an example of the type of information the database offers.

Table 3.4 A selection of air permeability's k_a and air permeance coefficients and exponents.

Layer	Thickness (m)	Weight (kg/m²)	Air permeability (s)	Permeance a (kg/(m².s·Pa^b))	b
Mineral fibre	-		$2\ 10^{-2}\rho^{-1.5}$		
Glass fibre	-		$4.3\ 10^{-3}\rho^{-1.3}$		
Gypsum board	0.0125	8.6		$3.1\ 10^{-5}$	0.81
Lath ceiling	0.01	4.0		$4.1\ 10^{-4}$	0.68
Ceramic tiles, double lock	0.01	30.0		$9.6\ 10^{-3}$	0.68
Slates		30.0		$1.4\ 10^{-3}$	0.70
Brick veneer, no open perpends	0.09	135		$0.4\ 10^{-4}$	0.81
Hollow brick wall, perpends poorly filled	0.14			$2.8\ 10^{-3}$	0.59
Concrete block wall, perpends well filled	0.09			$2.4\ 10^{-4}$	0.86

For more information, see the final report on Material Properties

3.4 Experimental Verification and Practice

HAM-transport has a direct impact on building performance in terms of thermal quality and durability.

Thermal quality is primarily fixed by the U-value of the envelope part or the mean U-value of the complete enclosure. The property indicates how much heat is transferred through a unit surface of a part during a unit interval of time, if the difference in temperature over the part is one degree centigrade. Practitioners consider U to be a design related constant. A lowering of the U is realised by inserting a thicker insulation layer.

Hence, any HAM-analysis determines that U is badly affected by air mitigation, evaporation and moisture storage. Air entrains heat in the part. That may augment the heat flow considerably. Increases up to 300% are not exceptional. Air also disrupts the link between heat transfer and conduction. Simultaneously, each m² may experience different heat flows and different surface temperatures. Evaporation becomes a heat consuming mechanism, especially when it takes place at the warm side of the thermal insulation. In that case, it may increase the heat transfer with a percentage up to 100%. Moisture storage finally augments the thermal conductivity of the materials that serve as a storage volume. The effect is large if an insulation material is affected.

Durability is threatened by moisture through:

1	Biological attack
2	Chemical attack
3	Mechanical degradation

Examples of (1) are mould, mildew, bugs and rot. An example of (2) is corrosion. Examples of (3) are thermal and hygric stress and strain, salt attack and frost. A difficult element when discussing durability concerns the definition of projected service life. The Annex agreed projected service life is achieved when an envelope part keeps its designed performance level during a life span that equals or passes the span adopted as preferable. Typical preferences depend on the consequences of a failure and the costs of repair. Of equal importance is the perception that durability is not a deterministic but a stochastic concept. This is illustrated by Figure 7, which gives the risk related to the amplitude of the condensation deposit in an air permeable roof.

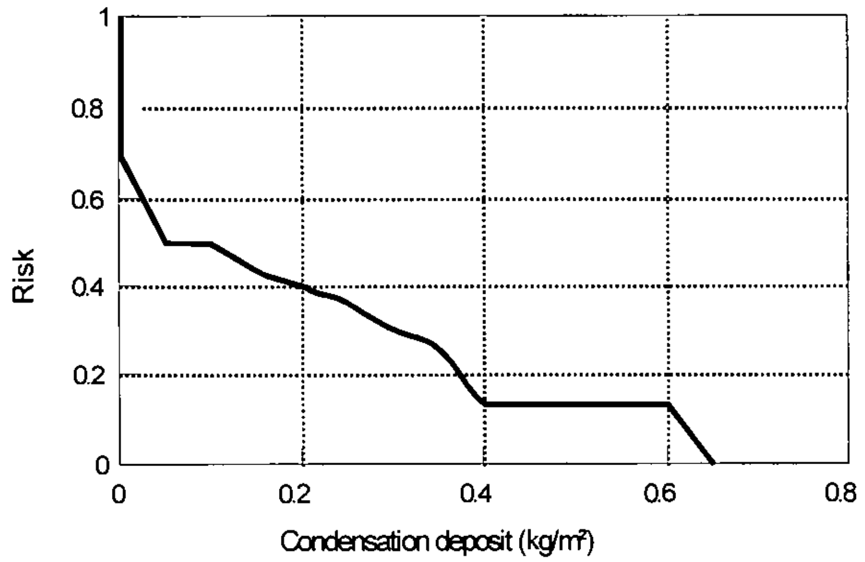


Figure 7 Risk related to the amplitude of the condensation deposit in an air permeable pitched roof. Hidden variables are building orientation and air leakage distribution over the enclosure.

HAM-response, the related energy and durability deficiencies and the design rules that HAM-tools generate were analysed for a number of reference envelope parts.

REFERENCE ENVELOPLE PARTS

1. Crawl spaces
2. Timber framed walls
3. Massive walls with inside insulation
4. Massive walls with outside insulation
5. Filled cavity walls
6. Flat roofs
7. Protected membrane roofs
8. Pitched roofs
9. Cathedral ceilings
10. Metal clad roofs
11. Ventilated PV-roofs

The studies produced some very interesting conclusions:

- Air-tightness is the most important performance requirement. If not achieved, no guarantee can be given in relation to thermal performance and durability.
- A sufficient vapour retarder at the warm side of the thermal insulation is a second order requirement. Only in case air-tightness is realised and the indoor climate is rather severe (ICC3 and ICC4), vapour diffusion may become a real threat in terms of unacceptable moisture accumulation by interstitial condensation.
- In case of built in moisture, a vapour retarder may harm the durability of an envelope part. In such cases, the retarder may prevent the part from drying or induce an unwanted moisture redistribution.

To obtain more about HAM, energy and durability, see the final report on Performances and Practice

4. The Situation since Annex 24

The achievements of the Annex can be summarised as follows:

- A group of researchers, some of them young and then not experienced, gained a broad common knowledge in the domain of combined HAM-transport and its consequences for thermal efficiency and durability. All became convinced that air is a most important item within the triplet of heat, air and moisture. Everyone agreed that the actual standards on HAM are obsolete.
- Environmental conditions were formulated in such a way that they can be used for performance formulation and evaluation. On the outside, the MDRY (Moisture Durability Reference Year) definitions allow a moisture reference year to be constructed for any meteorological station. On the inside, the ICC' s (Indoor Climate Class) integrate vapour load and ventilation in one number - the inside-outside vapour pressure excess.
- A Round Robin on the measurement of moisture profiles and the calculation of the moisture diffusivity of a piece of pine determined this is a very difficult task. If standardisation of that type of testing is planned, it will require a very clear procedure on how to measure and how to calculate.
- HAM experimental work has been given a better basis.
- The analysis of the so-called reference enclosure parts revealed that air-tightness in terms of eliminating infiltration, exfiltration, wind washing, ventilation and air rotation is the most important performance requirement in relation to HAM.
- More detailed information was produced on the impact of HAM on thermal performance and durability.

Although the sum of achievements is impressive, an answer to the question 'where are we today in terms of HAM-knowledge and better understanding of the HAM-impact on energy efficiency and durability' is not straightforward. Many of the results of Annex 24 will be lost if the knowledge gained is not embedded in an upgrade of existing national codes of practice and improved standardisation. As long as simple engineering tools, such as the Glaser method, form the ultimate proof for moisture tolerance, no changes should be expected in every days practice.

The International Energy Agency (IEA) Energy Conservation in Buildings and Community Systems Programme (ECBCS)

The International Energy Agency (IEA) was established as an autonomous body within the Organisation for Economic Co-operation and Development (OCED) in 1974, with the purpose of strengthening co-operation in the vital area of energy policy. As one element of this programme, member countries take part in various energy research, development and demonstration activities. The Energy Conservation in Buildings and Community Systems Programme has sponsored various research annexes associated with energy prediction, monitoring and energy efficiency measures in both new and existing buildings. The results have provided much valuable information about the state of the art of building analysis and have led to further IEA sponsored research.