HAMBASE

Heat Air and Moisture model for Building And Systems Evaluation

Martin de Wit
Cover illustration: ‘boter kaas en eieren’ (tick-tack-toe)
Brammetje Cox, 1983

Cover Design: Ton van Gennip, tekenstudio Faculteit Bouwkunde

© 2006 Martin de Wit
Printed by the Eindhoven University Press, Eindhoven, the Netherlands
Published as issue 100 in the Bouwstenen series of the department of Architecture, Building and Planning of the Eindhoven University of Technology

ISBN 90-6814-601-7
My work is a game, a very serious game.

M. C. Escher

Dutch artist (1898 - 1972)

To
Tony
Sanne
Meike
Table of contents

Preface ................................................................................................................1

1 Introduction .................................................................................................3

2 The physical model ......................................................................................7

2.1 The heat and mass balance .................................................................7
2.2 The HAMBASE indoor climate model .......................................8
  2.2.1 The thermal indoor climate .......................................................8
  2.2.2 The hygric indoor climate .......................................................13
2.3 The HAMBASE envelope model ..................................................14
  2.3.1 The continuous thermal model .............................................14
  2.3.2 The continuous hygric model ...............................................18
  2.3.3 The finite differences model ...............................................20
2.4 Fenestration .......................................................................................22
  2.4.1 Incident solar radiation .........................................................22
  2.4.2 Heat flow through fenestration ............................................23
  2.4.3 Solar radiation absorbed in a zone .......................................24
  2.4.4 Airflow window ......................................................................26
2.5 Air Infiltration .....................................................................................28
2.6 Wall heating/cooling system .........................................................31

3 The computer program ...........................................................................33

3.1 Temperature and humidity controls ...............................................33
  3.1.1 The HAMBASE_S model .......................................................33
  3.1.2 The HAMBASE model ..........................................................35
3.2 General features ...............................................................................38
  3.2.1 The envelope ..........................................................................38
  3.2.2 The profiles .............................................................................39
  3.2.3 Exterior climate .................................................................40
  3.2.4 Output ......................................................................................41
3.3 Validation ..........................................................................................42
  3.3.1 Comparative testing: the ASHRAE Bestest .........................42
  3.3.2 Analytical verification of the hygric indoor climate model ....44
  3.3.3 Empirical validation of the hygric model ...............................47
  3.3.4 Comparison with data from monitored buildings ...............50

Conclusions ..................................................................................................53

References .................................................................................................55
Appendix A  Model development .................................................................63
  A.1  The temperature nodes of the indoor climate ....................................63
    A.1.1  The delta-star transformation of the radiation exchange network ....63
    A.1.2  The heat balance at an interior surface ........................................64
  A.2  The heat flow to a building element ..................................................65
    A.2.1  The continuous model, admittance and transmittance .................65
    A.2.2  The determination of the network components ..............................72
    A.2.3  The finite differences method ..........................................................75
  A.3  The moisture flow to a building element .............................................76
  A.4  Floor, wall or ceiling heating/cooling ..................................................78

Appendix B  HAMBASE help .................................................................83
  B.1  General structure of input .................................................................83
  B.2  The calculation period .................................................................84
  B.3  The building .................................................................85
  B.4  Profiles for internal sources and controls .........................................91
  B.5  Heating, cooling, humidification, dehumidification ...........................93
  B.6  Input check and changes .................................................................95
  B.7  Extra features of HAMBASE_R ..........................................................99
  B.8  Extra output in HAMBASE_R ............................................................103

Appendix C  IEA-annex41 common exercise ..............................................105
  C.1  ASRHAE BESTEST .................................................................105
  C.2  0A0B 'MOISTURE BESTEST' ..........................................................107
  C.3  Whole building heat and moisture analysis ......................................109
Preface

The model described in this report is the result of work that started in 1985. In that time there was a large gap between sophisticated transient models and the manual very popular degree days and degree hours models. For the latter models the computer was already often used so why not add some heat storage components for a better prediction of overheating? It started with a first order model that was successfully used for the simulation of district heating with many different dwellings. Comparison however with a state-of-the-art model showed that with two nodes and two thermal capacitances the accuracy increased significantly. The challenge was to base this model on physics instead of tuning it with results from a sophisticated transient model.

So the ball started rolling without stopping yet. The only constant in the process is that of change; improvements and extensions are always possible and sooner or later they will be implied. This report reflects the model at just a moment in time.

The first models were ELAN (heat) and AHUM (moisture) and programmed mainly by MSc students in Fortran. The model was used as a part of a ‘Computer Supported Methodological Design System’ (COSMOS) in design studios. For the successful use in a studio it appeared to be important that the model could deal with complex geometries in an easy way.

Then the development stopped for many years until Jos van Schijndel showed me Matlab. I couldn’t resist the temptation to program a combination of ELAN and AHUM in this environment, the model WAVO. At that time WAVO was unique because of this combined modelling of both temperature and indoor air humidity (accounting for the effect of hygroscopic storage) at a sufficient degree of accuracy for design decisions.
There are several reasons that I have spend more hours on the model than I ever could have imagined when I started: the use of the model by students, the use in research projects and the development of the Matlab environment.

Students forced me to make the model more robust in order not to loose too much time with strange bugs.

The successful research projects of my colleague Henk Schellen encouraged me to extend the model, improve it and to use model output as input for other software. Matlab was an ideal environment to for this.

Thanks to colleague Jos van Schijndel I kept track of all new possibilities of Matlab after every new release, we discussed them and I updated the model accordingly. The use of the model as an S-function for Simulink is his idea and the development of this combination is in his hands. We renamed the model: HAMBASE.

For me working on this model was a puzzle with matrices and vectors and I spend many late hours behind my PC wondering why it went wrong. I learned that one can never be sure that there are no bugs; every change can introduce new ones. This insight kept me too long from publishing this report.

Martin de Wit, March 2006
1 Introduction

HAMBASE is a simulation model for the heat and vapour flows in a building. With the model the indoor temperature, the indoor air humidity and energy use for heating and cooling of a multi-zone building can be simulated. A first version of this model (ELAN) was published in 1987 (Wit 1987, Wit 1988a, Wit 1988b). Separately a model for simulating the indoor air humidity (AHUM) was developed (Wit 1988c, Wit 1990, Pernot 1991, Laan 1994). In 1992 the two models were combined (WAVO) and programmed in the MATLAB environment. The choice of MATLAB turned out to be crucial for the further development. The powerful tools for matrix manipulation of MATLAB together with a very transparent code make it easy to implement improvements and extensions of the model. With the evolution of MATLAB capabilities e.g. the cell-arrays, also WAVO evolved. The approach of WAVO turned out to be excellent for making S-functions for MATLAB-SIMULINK and enabling the simulation of complicated HVAC installations and controls simultaneously with the building. This new development started recently (Schijndel 2002, 2003a, 2004) and will go on in future. In 2004 the model got a new name: HAMBASE.

The need for simplicity to get a short simulation time has changed very much in the last decades. The current version is not simple anymore. The intention however, to develop models of the different phenomena with a desired accuracy that is dependent on the impact it has on the overall accuracy is still valid. Apart from these objectives it is important for research to have a model of which the physics and the assumptions are well known instead of a black box. The model as a product has never been the objective; it is just a tool that evolves with the research questions to be solved. That is why we wanted a model that can be
adapted and extended easily. So to be able to master the code easily is a very important condition.

The model has been used in several research projects (Some of them are not published in international journals):

- The study of surface temperatures and humidity's on thermal bridges using the HAMBASE for generating the indoor and outdoor boundary conditions. Also the effect of thermal bridges on the total heat loss was studied.
- The study of the energy performance of a heat-pump installation with a solar roof at the evaporation side, a 'cold' storage and a boiler. The solar irradiation on the roof, the atmospheric radiation and the heat demand were calculated with ELAN. A second study with the use of 'grey' (waste) water for the evaporator was also done with this model (Jong 2000, Schijndel 2003a).
- Study of shadow in an existing neighbourhood with terraced houses and small gardens.
- Study of the thermal and hygric performance of an indoor swimming pool. As both the temperature and humidity are modelled the modelling of an indoor swimming pool is possible. The water surface is just a moisture and heat source that is dependent on the indoor humidity. A special m-file is made that gave each hour the evaporation and heat flow of the pool and the energy balance of the pool. Also a model for the installation and controls was added.
- Study of direct and indirect adiabatic cooling
- airflow windows
- hygrostatic humidity control in a museum
- indoor climate in churches and museums (Schellen 1999, Schellen 2000, Schellen 2002, Neilen 2003, Schijndel 2003b, Schijndel 2005a, Schijndel 2005c). For the research on existing buildings the model can be tuned with measured data before it is used for simulating design alternatives.
There are three versions of HAMBASE all with exactly the same input:
- The HAMBASE continuous model, solved with transfer functions.
- The HAMBASE research model with finite differences discretization and more special features (HAMBASE_R)
- The HAMBASE SIMULINK model that provides an S-function for SIMULINK (HAMBASE_S).

All models have as much in common as possible to make upgrading easier.
An intermodel comparison with a large model (Bruggen 1978, Hoen 1987, Wit 1987) was done earlier. Recently the model is subjected to the ASRHAE-test (ASHRAE 2001) and was well within the limits required. The simulation of indoor humidity is compared with measurements of a simple case (IEA-annex41 2005).

This report doesn’t treat the computer code with all its tricky matrix formulations but the ideas and physics of HAMBASE. Information about the input, output and the features of the computer model are given in a help-file (Appendix B).
2 The physical model

2.1 The heat and mass balance

In the model the smallest spatial entity of the building is a zone. A zone can be one room but also a number of adjacent rooms with more or less equal climatic conditions.

The model of a zone consists of two parts: a thermal model and a hygric model. The models are coupled as the saturation vapour pressure depends on the temperature and by condensation latent heat is released (the opposite by evaporation).

In order to calculate the heating or cooling needed in a zone it is necessary to determine the different terms of the heat balance:

\[
\Phi_l + \Phi_s = \Phi_g + \Phi_p
\]

The heat loss consists of transmission and ventilation (infiltration) losses through the building envelope. The heat gain is caused by incident solar radiation, casual gains from people, artificial lighting, domestic hot water and appliances.

Heat is stored and released by the building construction. Over a large time interval the total of this heat will be zero. However, the storage term has a great influence on the heat gain terms: e.g. the storage of an excess of solar energy increases the amount of solar energy that can be utilised. The auxiliary heat is supplied or extracted by the heating or cooling plant.
For the calculation of the air humidity in a zone the different terms of the mass balance need to be determined:

\[
G_l + G_s = G_g + G_p
\]

Vapour leaves the zone by diffusion and advection (ventilation air) through the envelope. The loss by diffusion through construction assemblies is negligible compared to the advective losses by air flows.

Vapour is produced by people, plants, appliances etc.

Vapour is stored as water in porous materials. Over a large time interval the total of this stored moisture will be zero. By the storage term however there is less variation in relative humidity just in the same way as by heat storage there is less temperature variation. Humidification or dehumidification is needed if there are requirements regarding the maximum and minimum acceptable relative humidity in the zone. The humidity is an important property both for people and for materials in zones. Also the latent cooling energy and energy needed for humidification can be important.

2.2 The HAMBASE indoor climate model

2.2.1 The thermal indoor climate

In many simulation models the indoor climate is described with one air temperature only and several radiant temperatures (the indoor surface temperatures). One can wonder however how much the detailed calculation of radiation exchange between the surfaces contributes in a realistic way to the accuracy of a model with no thermal stratification, uniform surface temperatures, grey radiator assumption and no furniture. With furniture surfaces will ‘see’ each other differently. The probably most serious error is the assumption of one air
node. In reality there is a temperature stratification that can have a great influence on energy loss and comfort. To calculate this stratification the airflow pattern has to be modelled and even with CFD only a rough approximation is obtained.

In HAMBASE the indoor climate is characterized by three properties that are assumed to be uniform in the room: a radiant temperature, an air temperature and a relative humidity:

- The view factors are approximated with the (corrected) integrating sphere values (the thermal radiation is equally distributed over the walls). In insulated buildings the internal surface temperatures of opaque walls are about equal compared with the temperature of the glazing; so radiation exchange between walls is small. By the integrating sphere approximation it is possible to get one radiant temperature for all walls and there is no restriction on the geometrical form of the room (no shoebox restriction)

- The zone air is perfectly mixed. So a zone has but one uniform air temperature ($T_a$) and one vapour pressure ($p_{va}$). This is an approximation that is very common in thermal models.

- The surface coefficients for convection and radiation are constant. Dependency on local temperature differences is hardly more accurate because the coefficients depend on the total flow pattern in a room.

- All radiant heat input (short-wave and emitted thermal radiation) ($\Phi_r$) is distributed in such a way that all surfaces with an exception for windows, absorb the same amount per unit of surface area. Shortwave radiation falling on a window directly or by reflection is, depending on its transmittivity, lost to the exterior.

If there is but one value for the surface coefficient for convection and one for radiation then one can derive (see chapter 4) that the indoor thermal model contains only two temperature nodes: an air temperature node ($T_a$) and a ‘resultant’ temperature node ($T_x$) (Danter 1973). This is the main approximation made in the HAMBASE models. The heat flows to these two nodes are:

- The convective heat losses (ventilation, interzonal airflows) are calculated with the air temperature ($T_a$).
The heat losses through the envelope are calculated with the ‘resultant’ temperature \( T_x \) (all the inner surfaces of the envelope of a zone will ‘see’ the same temperature). (A small correction on the surface coefficient for radiation is made, see chapter 4)

- The heat flow from the resultant temperature to the air temperature is determined with a coupling coefficient \( L_{xa} \): \( \Phi = L_{xa} (T_x - T_a) \)

- The radiant heat input \( \Phi_r \) is split between the air node and resultant node. The convective heat input \( \Phi_c \) flows completely to the air temperature node.

Remarks:

- **Different combined surface coefficients**
  The assumption that all surface coefficients are equal is needed for the derivation of the coupling coefficient but is abandoned for each model of an envelope part, i.e. the transmission heat loss through an envelope part can be calculated with different combined surface coefficients in order to get the right thermal transmittance (U-value).

- **Splitting into a convective and radiant part**
  The heat input by the heating or cooling plant \( \Phi_p \) as well as the casual \( \Phi_{cg} \) and solar gains \( \Phi_{sol} \) are split into convective and radiant parts by means of convection factors.

  The convective part is:
  \[
  \Phi_c = CF_p \Phi_p + CF_{cg} \Phi_{cg} + (\Phi_{sol})_c
  \]

  The radiant part is:
  \[
  \Phi_r = (1-CF_p) \Phi_p + (1-CF_{cg}) \Phi_{cg} + (\Phi_{sol})_r.
  \]
The convective part of the solar gains (eq. 2.28) consists of both the convective part of solar gain factor of the window system and the amount of solar radiation falling on furniture and not on the construction (section 2.4.3)

In figure 2-1 the room model is summarized.

\[ \Sigma \Phi_{xy} \rightarrow T_x \rightarrow L_{xa} \rightarrow T_a \rightarrow \Sigma \Phi_{ab} \rightarrow \Phi_r + h_{cv} \Phi_r / h_r \rightarrow \Phi_c - h_{cv} \Phi_r / h_r \rightarrow C_a \]

*Fig. 2-1. Thermal network for the air and resulting temperature node*

The equations describing this network are (see chapter 4):

\[
C_a \frac{dT_a}{dt} = L_{xa} (T_x - T_a) - \Sigma \Phi_{ab} + \Phi_c - \frac{h_{cv}}{h_r} \Phi_r
\]

\[
0 = L_{xa} (T_a - T_x) - \Sigma \Phi_{xy} + \Phi_r + \frac{h_{cv}}{h_r} \Phi_r
\]

In figure 2-1 $T_a$ is the air temperature and $T_x$ the ‘resultant’ temperature. $h_r$ and $h_{cv}$ are the surface weighted mean surface heat transfer coefficients for convection and radiation. $\Phi_r$ is the total radiant heat input (short-wave and emitted thermal radiation from casual and solar gains, heating and cooling) and $\Phi_c$ is the convective part. $C_a$ is the heat capacity of the air and $L_{xa}$ is a coupling coefficient:

\[
C_a = \rho_a c_p \text{ Vol} \quad \text{and} \quad L_{xa} = A_t h_{cv} \left( 1 + \frac{h_{cv}}{h_r} \right)
\]

where

- $\rho_a$ = density of the air (1.2kg/m$^3$)
- $c_p$ = specific heat of the air (1000kJ/kg)
- Vol = volume of the air
- $A_t$ = total interior surface area of a zone
Φ_{ab} is the heat flow caused by air entering the zone with an air temperature T_b. In case of ventilation T_b is the outdoor air temperature T_e. If the air comes from another zone (interzonal convection) T_b is the zone air temperature and the zone models are strongly coupled. So:

$$\sum \Phi_{ab} = L_a(T_a - T_e) + \sum L_{ab}(T_a - T_b)$$  \hspace{1cm} (2.3)

where $L_{ab}$ = heat loss coefficient for airflow from zone b to a

The coefficient is derived from the airflow from zone b to a. ($L_{ab} \neq L_{ba}$)

$T_b$ = air temperature of zone b

$L_a$ = ventilation heat loss coefficient (=C_{ach}/3600)

$ach$ = air change rate (h⁻¹)

$T_e$ = outdoor air temperature

Φ_{xy} is transmission heat loss through the envelope from T_x to the room with a ‘resultant’ temperature T_y. For external envelope parts T_y is the sol-air temperature including the effect of atmospheric longwave radiation.

$$T_y = T_e + aE_{\text{sol}}/h_e - \varepsilon L_{at}/h_e$$  \hspace{1cm} (2.4)

where $E_{\text{sol}}$ = total solar irradiance of the surface considered

a = absorptivity of the surface

$L_{at} = (\sigma T_e^4 - \text{atmospheric radiation})(\text{view factor ‘surface->sky’})$

$\varepsilon$ = emissivity of the surface

$h_e$ = total external surface coefficient

$T_e$ = the outdoor temperature

$T_y$ = the ‘resultant’ outdoor temperature for envelope part y

The sol-air temperature has to be calculated for each external surface and each hour. In hot climates with no insulation in the envelope the solar absorptivity of the surface is very important.
2.2.2 The hygric indoor climate

Consistent with a uniform air temperature also the vapour pressure is assumed to be uniform. So there is but one node in the hygric room model: the vapour pressure. Analogous to the heat storage in the room air there is moisture storage in the room air. Moreover moisture is stored in furnishing (textiles, paper and wood) and the zone envelope.

The moisture storage of the air volume is far more important than the storage in air. Also the moisture storage in furnishings can be much more important than in the building fabric because textiles and paper are very hygroscopic. This storage however depends on the relative humidity and not on the absolute one. So the solution of the air temperature is needed for this.

Storage in furnishings is modelled as a hygroscopic capacity parallel to the capacity of the air in the zone, defined by:

\[ G = \frac{d}{dt} C_f^i p_v \]  \hspace{1cm} (2.5)

where \( C_f^i = C_f p_{\text{sat}}(T_{\text{ref}})/p_{\text{sat}}(T_a) \) the hygroscopic capacitance of the furnishings

\( p_{\text{sat}}(T_a) \) = saturation vapour pressure at temperature \( T_a \)

\( T_{\text{ref}} \) = reference temperature (\( C_f \) is determined at this temperature)

The network for the hygric indoor climate is more or less analogous to the heat balance network shown in figure 2-1:

![Fig. 2-2. The hygric room model](image)

The equation is:
\[ C_{va} \frac{dp_{va}}{dt} + \frac{dC_v}{dt} p_{va} = -\Sigma G_{ab} - \Sigma G_{xy} + G_p + G_g \]  

(2.6)

where \( C_{va} \) = moisture storage coefficient = \( (0.62) \times 10^{-5} \rho_a \text{Vol} = (0.62) \times 10^{-5} C/v/c_p \)

\( t \) = time

\( p_{va} \) = vapour pressure (Pa) of zone a

\( G_{xy} \) = vapour flow to the envelope (kg/s)

\( G_p \) = humidification (or dehumidification)

\( G_g \) = vapour sources (sinks)

\( G_{ab} \) = vapour transfer by airflow from zone b to a

Analogous to the convective heat transfer equation the vapour transfer by airflow from zone b to a is:

\[ G_{ab} = L_{vab}(p_{va} - p_{vb}) + L_{va}(p_{va} - p_e) \]  

(2.7)

where \( p_{vb} \) = vapour pressure (Pa) of zone b

\( L_{vab} \) = vapour transfer coefficient. \( L_{vab} = (0.62) \times 10^{-5} L_{ab}/c_p \)

\( L_{va} \) = ventilation vapour transfer coefficient, \( L_{va} = (0.62) \times 10^{-5} L_a/c_p \)

\( p_e \) = outdoor vapour pressure (Pa)

2.3 The HAMBASE envelope model

2.3.1 The continuous thermal model

With the assumption that all material properties of a building component and also the surface coefficients are constant the governing differential equations for heat flow with boundary conditions are linear. For this linear system the heat flow density to a multi-layered wall can be written as:

\[ q_x = S_{xy}T_x - M_{xy}T_y \]  

(2.8)

where S and M are mathematical operators working on the resulting temperatures on either side of the wall.
In the frequency domain S and M are admittances. In the z-transform domain S and M are the transfer functions. We write this in a different way:

\[ q_x = q_{lx} + q_{lxy} \quad (2.9) \]
\[ q_{lx} = (S_{xy} - M_{xy}) T_x = Y_{xy} T_x \quad \text{and} \quad q_{lxy} = M_{xy} (T_x - T_y) \quad (2.10) \]

It can be shown that \( M_{xy} = M_{yx} \) or that at the opposite side of the wall:

\[ q_{lx} = -q_{lxy} = M_{xy} (T_y - T_x) \quad (2.11) \]

This approach is depicted in figure 2-3. In the frequency domain the components of this \( \pi \)-network are the (modified) admittance \( (Y_{xy}) \) and cyclic transmittance \( (M_{xy}) \) for each frequency.

The transmittance and the (modified) admittance behave very different for different cyclic frequencies \( (\omega) \):

\[ \lim_{\omega \to 0} M_{xy} = U_{xy} \quad \lim_{\omega \to \infty} M_{xy} = 0 \quad 0 \leq \arg(M_{xy}) < \infty \]
\[ \lim_{\omega \to 0} Y_{xy} = 0 \quad \lim_{\omega \to \infty} Y_{xy} = 1/R_i \quad 0 \leq \arg(Y_{xy}) < \pi/4 \quad (2.12) \]

with \( R_i \) = the thermal resistance between the indoor node and the first capacitive layer in the wall.

The different behaviours in the frequency domain are illustrated in figure 2-4 where an example of the values \( |M_{xy}/U_{xy}| \) and \( |Y_{xy} R_i| \) for a lightweight and a heavyweight wall are given.
Fig. 2-4. The cyclic transmittance and admittance for two different walls

The phase shift of the transmittance can have any value. This turns out to give a time lag for a step function. The ‘heavier’ the wall the longer the delay time is. The admittance doesn’t cause a time lag. Its phase shift is at maximum 1/8th of the period time.

The splitting into a cyclic transmittance and the admittance as proposed here has advantages:

− The interior admittances can all be added. The effect of this total room admittance on indoor temperature variations is usually (in insulated buildings) much higher than that of the transmittance.
− The relation $q_{yx} = -q_{xy}$ is convenient for programming.
− For adiabatic walls and walls within a zone the transmission heat flow $q_{yx}$ is always zero and only the interior admittances remains.

The heat flow through a multilayered wall turned out to fit excellent with the solution of the second order equation with a time delay below ($q_{yx} = q_{xy1} + q_{xy2}$):

$$ q_{xy1} + \tau_1 \frac{dq_{xy1}}{dt} = \frac{\tau_1}{\tau_1 - \tau_2} U_{xy} \Delta T_{xy} (t - t_d) $$

$$ q_{xy2} + \tau_2 \frac{dq_{xy2}}{dt} = \frac{\tau_2}{\tau_2 - \tau_1} U_{xy} \Delta T_{xy} (t - t_d) $$

(2.13)

where $\Delta T_{yx}$ = the temperature difference ($T_y - T_x$)
The $U_{xy}$ is the U-value and $A_{xy}$ the surface area of the construction.

The coefficients $\tau_1$, $\tau_2$ and $t_d$ (= time lag) coefficients to be determined.

One can easily see that the steady state condition ($q_{\text{steady state}} = U_{xy} \Delta T_{xy}$) is always fulfilled. Thermal bridges and windows are modelled as ‘steady state’ components.

The total room (interior) admittance can also be modelled as a second order differential equation with 4 coefficients $C_{x1}$, $C_{x2}$, $L_{x1}$ and $C_{x2}$ (see figure 2-5):

\[
\Phi_{x1} \frac{d\Phi_{x1}}{dt} = C_{x1} \frac{dT_x}{dt} \quad \text{and} \quad \Phi_{x2} \frac{d\Phi_{x2}}{dt} = C_{x2} \frac{dT_x}{dt} \quad (2.14)
\]

For a steady state situation the solution of these equations is zero.

A graphical representation of this equation in given in the thermal network below:

Fig. 2-5. The HAMBASE indoor thermal model

In this figure $L_{yx}$ denotes a normal conductance (no storage nor delay).
The unknown coefficients are found by minimizing (MATLAB tool) the error function of the exact solution with the model solution. The exact solution in the frequency domain can easily be found with the well-known matrix method (Pipes 1957). Instead of taken the solution of an arbitrary linear combination of cyclic signals we used the Fourier transform of a temperature consisting of one normalized triangle pulse with a base of two hours each 24 hours. With such a function all temperature profiles with a period of 24 hours can be composed. The results for the interior admittance (see chapter 4) turned out to be excellent. The accuracy for this signal was better than 1%.

For the transmittance a period of 24 hours is often too short as the cyclic transmittance can be already very small for a 24-hour period. So instead of 24 hours we used nx24 hours where 'n' depends on an estimated time-constant of the wall. Here the accuracy for very heavyweight walls is less (8%) but it is 8% from a very small variation (large amplitude attenuation). We found that this had a negligible effect on the overall accuracy of the building model.

Some inaccuracy for the admittance is allowable as the time-constant of the indoor air \( \frac{C_a}{L_a}=1/\text{ach} \) is often of the order of one hour, so indoor temperature variations are already attenuated. Also the indoor furnishings contribute to attenuation of variations.

### 2.3.2 The continuous hygric model

The approach is the same as in the thermal case. As the vapour transfer through a wall by diffusion can be neglected compared to the vapour transfer by ventilation only the moisture storage of the walls needs a model. So only an indoor hygric model is needed. The governing equations are similar to the temperature equations with some important differences:

- the equations are not linear
- there are two potentials: the absolute and the relative humidity

In order to simplify the equations are linearized, i.e.:

- The retention curve is linear between 20% and 80% RH
- The vapour permeability is constant (dry cup value)
- The linearization limits the validity of the model. However a RH less than 20% is rare and if the surface-RH rises often above 80% there will be a problem indoors (moulds).

With the linearization it is possible to derive a hygric second order network in the same way as the thermal second order network.

The dependency of moisture storage on relative humidity is taken care of by a temperature dependent moisture storage capacitance in the hygric network: \( C_v^1 = C_v p_{\text{sat}}(T_{\text{ref}}) / p_{\text{sat}}(T_m) \). This means that the storage capacity of the wall is dependent on the wall temperature. As the thickness of the layer responsible for hygroscopic moisture storage is only several millimetres (Wit 1990) the surface temperature is considered a good approximation. We decided to correct the hygroscopic capacitances with the average surface temperature of the opaque walls and not with the different surface temperatures to be able to add all hygric admittances as we did in the thermal case. The average surface temperature is calculated with:

\[
T_m = T_s - \frac{\sum_y \Phi_{xy} + \Phi_x + \Phi_{x1}}{\sum_y A_y (h_r + h_{cv})}
\]  \( (2.19) \)

where \( \sum' \) = summation over the opaque constructions

This temperature couples the hygric model to the thermal model.

The approximations needed for the hygric model look much cruder than the ones for the thermal model. Hygric modelling is less accurate by the hardly known input data:
- The influence of furniture (e.g. textiles) on the storage capacity is very high and can be much larger than the influence of the fabric.
- Vapour transfer depends mainly on advection. Airflows however are not well known. Especially not through constructions.
Hygric properties of materials are not well known and have a wide range of values for the same material. They also change in time by ageing.

The way \( L_{v1}, L_{v2}, C_{v1}, C_{v2} \) and \( C_{va} \) are determined is given in chapter 4.

The equations for the flow to the envelope are:

\[
G_1 + \frac{1}{L_{v1}} \frac{dC_{v1}^i}{dt} G_1 = \frac{dC_{v1}^i}{dt} + \frac{dC_{va}^i}{dt} \quad \text{and} \quad G_2 + \frac{1}{L_{v2}} \frac{dC_{v2}^i}{dt} G_2 = \frac{dC_{va}^i}{dt} (2.20)
\]

The way the components of this network are determined is described in sec.2.3.1 and in detail in sec.4.2.2.

### 2.3.3 The finite differences model

In this model (the research version HAMBASE_R) the diffusion equations for heat and moisture transfer in the walls are modelled with a finite difference scheme and solved with an implicit method.

The degree of implicitness can be defined by the user. (e.g. Crank Nicolson: 0.5)

The time step is one hour and the place step of each layer is determined by the Fourier number of the layer (Fo~1). The thermal network of the construction is given in figure 2-7.
In this figure the symbols represent the following quantities:

\[ \Delta R_1 = \text{the thermal resistance of a place step} \]
\[ \Delta C_1 = \text{the thermal capacity of a place step} \]
\[ h_i = \text{the combined surface coefficient} \]

Similar to the heat diffusion equation the vapour diffusion equation is discretized. The problem is that the Fourier number is very different: the vapour diffusivity is much smaller than the thermal diffusivity. The place steps for vapour flows have to be much smaller than for thermal flows. This problem is solved by linear interpolation of the temperature. As calculation time would be very long by the small steps the interpolation is only applied to the layers near the surface and in such a way that from the surface to the inside each next step is twice the previous one until the same step-size is reached as the temperature step-size. In the model the first step is split into 3 (see figure 2-8). This turned out to be reasonable accurate (Laan 1994). Note that in this model the wall temperatures are used to account for the relative humidity dependence of the storage and not the mean surface temperature as in section 2.3.2
In figure 2-8 the symbols represent the following quantities:

\[ \Delta Z_1 = \text{the vapour resistance of a (temperature) place step} \]

\[ \Delta C_{v1} = \text{the moisture capacity of a (temperature) place step} \]

\[ \beta_1 = \text{the surface coefficient for vapour transfer} \]

By the linearization and by considering only vapour flow (no water) this model is not really accurate. Linearization has a great advantage however: only a minimum of data for the material properties is needed. Compared to the standard HAMBASE where the same linearization is used, the discretized version should be more accurate. In future non-linear equations will be programmed to get better predictions for high and very low indoor relative humidity.

### 2.4 Fenestration

#### 2.4.1 Incident solar radiation.

The incident solar irradiance on the building envelope is calculated from the normal and diffuse radiation with the Perez diffuse irradiance model (Perez 1987). For atmospheric longwave radiation the sky is assumed to be isotropic. For calculation of the shading on windows by overhangs, by buildings, trees or far away blocks the sky is divided into a large number of grid cells. Also the window surface is divided in small grid cells and for each window grid cell is determined whether it is shaded or not by the radiation coming from a sky grid cell. So far the obstructions that are modelled can be made up of any combination of blocks, cylinders and spheres (figure 2-9). The fraction of the window that is shaded by the radiation coming from a sky grid cell is the shading factor. This factor is corrected for the dependence of the transmittivity of glazing on the angle of incidence. This was the most convenient. With these factors the incident solar irradiance can be calculated for any solar position and for diffuse sky radiation (e.g. CIE overcast sky) as well.
2.4.2 Heat flow through fenestration

The transmission heat flow is calculated with the U-value (no thermal storage is assumed in the fenestration):

\[ q = U(T_x - T_e + \varepsilon L_{at}/h_e) \]  \hspace{1cm} (2.21)

If a shading device is used the U-value of the combination must be known. The shading device is used when both the irradiance on the window and the indoor control temperature are above given threshold values. If the indoor air temperature is above this threshold and the outdoor temperature is lower than this threshold also the ventilation rate can be increased simulating the effect of e.g. open windows (free cooling).

In order to investigate surface condensation on glazing in the ventilated cavity, the thermal resistances between the critical glazing surface and the interior/exterior must be known. These resistances are defined as \( \Delta R_i + 1/h_i \) and \( \Delta R_e + 1/h_e \) where \( h_i = h_r + h_{cv} \) and \( h_e \) are the surface coefficients of the inner and outer surface. The surface temperatures are (at night):
\[ T_{si} = T_k - q \left( \frac{1}{h_i} + \Delta R_i \right) \]
and
\[ T_{se} = T_e - \varepsilon L_a e / h_e + q \left( \frac{1}{h_e} + \Delta R_e \right) \]  

If the saturation vapour pressure at one of these surface temperatures is lower than the vapour pressure of the air close to the surface, condensation will happen. For the interior side the amount of condensation is calculated with:

\[ g = \frac{\beta (p_{va} - p_{sat}(T_u))}{1 + 15.10^4 \beta p_{sat}(T_u)(1/h_i + \Delta R_i)(1 - U(1/h_1 + \Delta R_1))} \]  

where \( \beta \) = vapour transfer surface coefficient

A similar formula holds for the exterior side. The denominator accounts for the small increase of surface temperature by latent heat of condensation.

### 2.4.3 Solar radiation absorbed in a zone

The solar heat entering the zone by window \( k \) can be written as:

\[ \Phi_{solk} = \text{SGF}_k (A_{gk}E_k) \]  

where \( \Phi_{solk} \) = the solar heat entering the zone by window \( k \)

\( \text{SGF}_k \) = solar gain factor of window \( k \)

\( A_{gk} \) = glazing area

\( E_k \) = incident solar irradiance The incident irradiance depends on orientation, slope of the glazing area and the shadow factor.

The radiant part of the solar energy entering the zone is:

\[ \Phi'_\text{sol} = \sum (1 - \text{CF}_{solk}) \Phi_{solk} \]  

where \( \text{CF}_{solk} \) = fraction that is convective (convection factor) of window \( k \)

The value of this convection factor depends on:
- The fraction of the solar heat entering the zone that is absorbed in the window system (glazing + solar blinds) and released by convection: the glazing convection factor CF\text{glaz}

- The fraction of the solar radiation into the zone that is absorbed by furnishings in the room and released as a convective heat flow: CF_f. This can be important.

- The airflow rate leaving a window cavity and entering the room, e.g. airflow windows. This has to be calculated separately (sec. 2.4.4).

If only the first two causes are present the convection factor CF\text{solk} is:

\[
\text{CF}_{\text{solk}} = \text{CF}_{\text{glaz}} (1 - \text{CF}_f) + \text{CF}_f \tag{2.26}
\]

It is obvious that for Venetian blinds at the interior side of the glazing the gain factor SGF_k and the convective fraction CF\text{glaz} are much higher than if the shading device is at the exterior side. If it is not known this can be calculated (Wit 1989).

With more windows a part of the radiation that enters by one window can leave by the other ones. Also a fraction will leave the zone after reflection at the opaque zone walls. In a first approximation the transmittivity of each window equals (1-CF\text{solk})SGF_k. In this expression the thermal radiation resulting from absorbed solar radiation in the window system is neglected. If the solar energy is equally distributed over the inner surfaces the fraction of the total solar energy leaving the zone by the windows is estimated to be:

\[
\text{corr} \approx \sum A_{gk} (1 - \text{CF}_{\text{solk}}) \text{SGF}_k / A_t \tag{2.27}
\]

where \(A_t\) = the total inner area of the zone.

Of course this is not ‘exact’, but the correction is expected to be small. The advantage is that no extra input data is needed.

So the radiant solar heat gain of the zone is calculated with:

\[
(\Phi_{\text{sol}})_r = (1 - \text{corr}) \sum (1 - \text{CF}_{\text{solk}}) \Phi_{\text{solk}} \tag{2.28}
\]

and the convective part remains the same

\[
(\Phi_{\text{sol}})_c = \sum \text{CF}_{\text{solk}} \Phi_{\text{solk}}
\]
2.4.4 Airflow window

As an example the case of three plane parallel panes will be described (e.g. triple glazing or double glazing with solar blinds). It is assumed that the panes have the same optical properties at both sides, that the distance is small compared to the surface dimensions.

![Fig. 2-10. Transmission of solar radiation through triple glazing](image)

In figure 2-10 the irradiances are denoted. The irradiance $E_{1r}$ is the result of reflection of $E_{1i}$ and the transmission of $E_{2i}$. In the same way $E_{2r}$ is the result of transmission of $E_{1i}$ and the reflection of $E_{2i}$. The equations between these irradiances can be written in a matrix form (Wit 1989) as:

$$
\begin{pmatrix}
E_{1i} \\
E_{1r}
\end{pmatrix}
= \begin{pmatrix}
\frac{1}{\tau_i} & -\frac{\rho_i}{\tau_i} \\
-\frac{\rho_i}{\tau_i} & \tau_i - \frac{\rho_i^2}{\tau_i}
\end{pmatrix}
\begin{pmatrix}
E_{2i} \\
E_{2r}
\end{pmatrix}
= A_i \begin{pmatrix}
E_{2i} \\
E_{2r}
\end{pmatrix}
$$

(2.29)

where $\tau_i$ = transmittivity of first pane
$\rho_i$ = reflectivity of first pane

For the other panes similar equations can be derived. So for the whole system:

$$
\begin{pmatrix}
E_{3i} \\
E_{3r}
\end{pmatrix}
= A_3 \begin{pmatrix}
E_{4i} \\
0
\end{pmatrix} ;
\begin{pmatrix}
E_{2i} \\
E_{2r}
\end{pmatrix}
= A_2 A_3 \begin{pmatrix}
E_{4i} \\
0
\end{pmatrix} ;
\begin{pmatrix}
E_{1i} \\
E_{1r}
\end{pmatrix}
= A_1 A_2 A_3 \begin{pmatrix}
E_{4i} \\
0
\end{pmatrix}
$$

(2.30)
So all irradiances equal a factor times $E_{4i}$. The total transmittivity is the inverse of this factor for $E_{ii}$: $E_{4i}/E_{1i}$. This calculation can be repeated for different incident angles of the direct solar radiation and for diffuse radiation.

In order to calculate the amount of absorbed radiation entering the building a thermal network of the system with the absorbed solar radiation as heat flows at the temperature nodes of the system has to be solved. The absorbed solar radiation at the front surface of e.g. pane 1 is calculated with:

$$E_{abs1\text{front}} = \{1 - \rho_i - \sqrt{\tau_i (1 - \rho_i)}\}E_{ii} + \{-\tau_i + \sqrt{\tau_i (1 - \rho_i)}\}E_{2r}$$ \hspace{1cm} (2.31)

At the backside with:

$$E_{abs1\text{back}} = \{1 - \rho_i - \sqrt{\tau_i (1 - \rho_i)}\}E_{2r} + \{-\tau_i + \sqrt{\tau_i (1 - \rho_i)}\}E_{ii}$$ \hspace{1cm} (2.32)

A particular problem is a solar shade device in the ventilated cavity. Usually air can flow through the device and by this ventilation the air temperatures in the adjacent cavities are almost equal. This is a special case of an airflow window. In this window air from either the interior or exterior enters a cavity with or without solar blinds and leaves to either the interior space or to the outside.

The thermal network of the ventilated cavity is shown in figure 2-11.

*Fig. 2-11. Ventilated cavity without and with a shading device*
In figure 2-11 $R_{\text{flow}} \approx 1/(2c_p Q_m)$ where $c_p$ = specific heat of air and $Q_m$ the air mass flow (kg/m³) in the cavity. The other resistances are $1/A_h$ (radiation) or $1/A_{hv}$ (convection), with $A =$ the surface area. The temperatures are averaged along the height of the cavity. If the air is fully mixed (no vertical temperature gradient) $R_{\text{flow}} = 1/(c_p Q_m)$ (ventilation efficiency=0.5).

It is a simplified model of a very complicated system. The real problem however is not the simplification but the uncertainty about input quantities as there are: the airflow rate, the surface coefficients at the cavity surfaces and at the solar protection, the optical properties of the different layers. Moreover there are many combinations possible with the HVAC installation. With this model the solar gain factor, the convection fraction and U-values of the system with and without solar shading can be calculated. Additionally factors are calculated for the heat added to the airflow leaving the cavity by solar irradiation and heat recovery. Care is taken as well for the opaque part of the window as is shown in figure 2-11.

The room between an exterior glazed construction and the façade behind it can also be modelled as a zone. If the air is not mixed the ventilation efficiency is higher. This can be accounted for with a fictitious higher ventilation rate (maximum the double). The solar gain by a window in the façade between the unconditioned room and the building behind it can also be calculated. It will often be important to take care of shading. If transient effects by walls and floor are negligible it can be much easier to consider this room as an airflow window.

2.5 Air Infiltration

The simulation of the airflows by natural ventilation caused by wind pressures and stack effects is very inaccurate. There are several reasons for that. Firstly wind pressures cannot be predicted accurately for all wind directions and velocities at a complex geometry as a building with its surroundings, even not
with a complex CFD model. The pressure at the building surface by the wind is described with:

\[
\Delta p_e = C_p 0.5 \rho_a v_{wind}^2
\]  \hspace{1cm} (2.33)

where \( \Delta p_e \) = dynamic pressure of the wind
\( C_p \) = wind pressure coefficient
\( v_{wind} \) = reference wind velocity. The reference is often the undisturbed wind velocity at the roof height.

The pressure coefficient is assumed to be independent of the wind speed but varies according to wind direction and is affected very much by neighbouring obstructions. To find reliable values is a problem. Also a problem is the reference wind speed or the relation between this speed and the data supplied by meteorological stations. The models for that are very rough by the complexity of the upwind terrains in a city and of a height often inside the internal surface boundary layer. Moreover turbulent fluctuations will also affect the infiltration especially when the wind speed is low.

The second cause of inaccuracy are the air leakage characteristics adventitious and/or purpose provided leakage openings of the cracks, openings etc. The mass flow rate is described in a very simple way by two parameters:

\[
Q_m = \rho_a C(\Delta p)^n
\]  \hspace{1cm} (2.34)

where: \( Q_m \) = air leakage (mass flow) rate (kg/s)
\( C \) = flow coefficient
\( n \) = flow exponent (0.5<\( n \)<1)
\( \Delta p \) = pressure difference

There are many formulas to calculate \( C \) and \( n \) with the geometry of the opening. For intentional openings they might be known but for cracks however the geometry is seldom well known. One would also expect a flow direction dependency of \( C \) and \( n \) but usually this is not taken into account.
The third cause of inaccuracies is the stack effect. The pressure in a room is dependent on the temperature and the vertical distance to a reference height e.g. the top of the roof:

\[ p_i(h) = p_i - 0.043hT_i \]  \hspace{1cm} (2.35) 

where:  
- \( T_i \) = room air temperature or ambient temperature (°C)  
- \( h \) = distance (= positive) to top of the roof  

\[ 0.043 \approx 1.28g/(T_i+273) \approx 1.28x9.81/291 \]

The stack effect is not a problem when the room is perfectly mixed but is when there is temperature stratification. In particular openings with a large vertical dimension as open doors, windows staircases etc. are a real problem. These openings have to be divided vertically into more small openings with a better defined \( h \). If a door is always open between two rooms the alternative is to consider the two rooms as one zone (equal air temperature).

The equations simply follow from the mass balance. Let:

\[ H(p_1, p_2, \ldots) = \sum_k \frac{C_k}{n_k + 1} \left( \text{abs}(p_i - 0.043h_k(T_i - T_j) - p_j) \right)^{(l+n_k)} + \sum_i \frac{C_i}{n_i + 1} \left( \text{abs}(p_i - 0.043h_i(T_i - T_j) - C_{pi}0.5\rho_{i}v_{wind}^2) \right)^{(l+n_i)} + \]

\[ + \sum_{i,j} p_i(Q_{mi\rightarrow j} - Q_{mj\rightarrow i})/\rho_{i} + \sum_{i} p_i(Q_{mi\rightarrow e} - Q_{me\rightarrow i})/\rho_{i} \]  \hspace{1cm} (2.36) 

with:  
- \( k \): the number of an opening between two zones: \( j \) and \( i \)  
- \( l \): the number of an opening between a zone (\( i \)) and outdoors (\( e \))  
- \( Q_{ni} \): mass flow rates (extract and supply) by mechanical ventilation from zone \( i \) to zone \( j \) and from zone \( i \) to zone \( e \) (outdoors)

The mass balance for each room follows from:

\[ \frac{\partial H}{\partial p_i} = 0 \]  \hspace{1cm} (2.37)
One can easily show that for all $p_i : H \geq 0$ and $\frac{\partial^2 H}{\partial p_i^2} \geq 0$. So by minimizing the function $H$ (MATLAB has a very quick tool for it) the pressures are found and then the calculation of the airflows is straightforward. Some very small corrections are applied to get a 100% correct mass balance.

### 2.6 Wall heating/cooling system

HVAC systems and controls can be modelled in a detailed way with HAMBASE_S and SIMULINK (Mathworks 1997) (section 3.1). These systems will not be treated here; it could only be possible for some designs. Only the way the heat is supplied to the zones (convective or radiant) is needed for HAMBASE as it affects the indoor climate and energy demand, e.g. for air heating and cooling the convection factor is 1, for radiators 0.7/0.8 and for radiant heating 0.5.

In HAMBASE_R a wall floor or ceiling can be modelled for heating or cooling. There are several reasons to model these systems in more detail.

- The heat is supplied by a building component. The transient behaviour of the system can have a large effect on the indoor climate and energy demand.
- In the case of cooling the relative humidity at the surface can be critical high and is important for the control. The advantage of modelling the humidity in HAMBASE_R is obvious for this problem.

If it is assumed that material properties and surface coefficients are constant; so the system is linear. This means that the heat input into the room can be calculated by superposition of two systems (see figure 2-12): a system with no heat input (this is modelled as the other envelope parts) and a system with bordering temperatures zero and a heat input. For the latter system transfer coefficients are calculated with a 2D discretized model. The coefficients relate the extra (by the heating/cooling system) outgoing heat flow ($\Phi_{fl}$) and the accompanying temperature increase at the inlet of the system to the temperature increase and heat flows supplied by the system ($\Phi_{in}$-$\Phi_{out}$) at previous time steps. The extra heatflow is divided between the two zone temperature nodes of the zones adjacent to the
wall/floor. The surface coefficients for this part of the model can be chosen differently from the other part to get a more realistic value.

The maximum power of the heat supplied to the floor depends on the maximum permitted water temperature in the floor heating tubes and the maximum the plant can supply.

Fig. 2-12. Superposition for floor/wall heating
3 The computer program

3.1 Temperature and humidity controls

3.1.1 The HAMBASE_S model

SIMULINK (Mathworks 1997) is a software package for modelling, simulating, and analyzing dynamical systems. It supports linear and non-linear systems, modelled in continuous time, sampled time or a combination of the two. SIMULINK includes a block library of sinks, sources, linear and non-linear components and connectors. Algorithms in MatLab or C can be implemented in S-functions. The main advantage of using S-functions is that users can build general-purpose blocks that can be used many times in a model. SIMULINK makes repeated calls during specific stages of simulation to each routine in the model, directing it to perform tasks such as computing its outputs, updating its discrete states, or computing its derivatives.

Models of HVAC installations with controls require very small time steps. As the installation is linked to the building also the building model is subjected to these small steps. To solve for these small steps the large amount of coupled differential equations that describe a building (each layer of an envelope part is already a differential equation) is not practical. The HAMBASE continuous model however offers a splendid opportunity to make an efficient and accurate block for a multi-zone building in SIMULINK.

In the continuous model the heat flow $\Sigma\Phi_{xy}$ (see figure 4) is split into two parts: a part that will change by the calculations in a certain time step $\Sigma L_{yx}(T_x-T_y)$ and the part that is left: $\Phi_{xy}-L_{yx}(T_x-T_y)$. Once the temperatures at the zone nodes are
known at the end of a time step this part is calculated for the next time step (mdlUpdate). As this part represents the heat flow through the constructions they vary only slowly and a time step of one hour is usually sufficient small. Together with the calculated heat gains $\Phi_{g1}$ and $\Phi_{g2}$ and vapour source $G_g$ it is the discrete part of the HAMBASE_S (SIMULINK) model.

The part with the network (see figs 2-5, 2-6 and 2-11) is the continuous part described with differential equations for each zone (2.1), (2.14), (2.6) and (2.20) (mdlDerivatives). The necessary values of the various model parameters: $L_{yx}$, $L_{xa}$, $L_{ab}$, $C_a$, $L_{x1}$, $C_{x1}$, $L_{x2}$, $C_{x2}$ and $C_{va}$, $C_f$, $L_{v1}$, $C_{v1}$, $L_{v2}$, $C_{v2}$ for each zone are also calculated in the building model block.

The main advantages of the model are:

a. the dynamics of the building systems of time scales less than one hour are accurately simulated. (e.g. on/off switching),

b. the model becomes time efficient as slowly varying heat flows are modelled with 1-hour time steps

c. the moisture (vapour) transport model of HAMBASE is also included. With this feature, the (de-) humidification of HVAC systems can also be simulated.

In SIMULINK continuous models of system components and control strategies can easily be included. Examples so far are: a heat pump, an energy roof and a TES (Thermal Energy Storage). Future models will include more advanced control strategies in order to get more realistic simulation results and to validate the complete model.

Fig. 3-1 A model scheme in SIMULINK.
3.1.2 The HAMBASE model

In the standard version also the differential equations mentioned in section 3.1.1 are discretized. The final equations are very similar to the ones that can be obtained with the fully discretized (research) version HAMBASE_R. For each zone there are three equations with the heat/cooling power, the two room temperatures the humidification/dehumidification and the air humidity as unknown variables:

\[ f_p \Phi_p = C_a(Ta - Ta^*)/\Delta t - L_x(T_x - Ta) - \sum L_{ab}(T_{ab} - Ta) - \Phi_{g1} \]

\[ (1-f_p)\Phi_p = L_x T_x - \Phi_0 - L_xa(T_a - T_x) - \sum L_{yx}(T_y - T_x) - \Phi_{g2} \]  (3.1)

\[ G_p = [a_1(C_{va} + C_f f_a) + a_2 C_v f_m]p_{va}/\Delta t - G_0 - \sum L_{vab}(p_{va} - p_{va}) - G_6 \]

where most symbols are defined in figure 2-5 and figure 2-6

\[ f_p = \Phi_{p1}/\Phi_p \]

\[ \Delta t = \text{time-step} \]

\[ Ta^* = \text{air temperature of the previous time-step} \]

\[ L_x T_x - \Phi_0 = \text{total heat flow to the zone enclosure. } \Phi_0 \text{ depends on quantities calculated in previous time steps and on the outdoor climate within the same time step.} \]

\[ [a_1(C_{va} + C_f f_a) + a_2 C_v f_m]p_{va}/\Delta t - G_0 = \text{total heat flow to the zone enclosure, furniture and room air. } G_0 \text{ depends on quantities calculated in previous time steps and on the outdoor climate within the same time step.} \]

\[ f_a = p_{sat}(T_{ref})/p_{sat}(T_a), \quad f_m = p_{sat}(T_{ref})/p_{sat}(T_m) \]

\[ a_1, a_2 \text{ and } C_v \text{ constants calculated at reference temperature.} \]

The two missing equations are defined by the control strategy relating the temperature and humidity in a zone to \( \Phi_p \) and \( G_p \). For control temperature of the heating or cooling plant any linear combination of the resulting temperature and air temperature can be used. With a certain combination of the resulting
temperature and air temperature the control temperature $T_c$ equals the operative temperature (chapter 4).

\[ T_c = C_F^0 T_a + (1 - C_F^0) T_r \quad \text{So:} \quad (3.2) \]
\[ T_c = f_c T_a + (1-f_c) T_x \quad \text{(3.3)} \]
with \[ f_c = (1+h_{cv}/h_r) C_F^0 - h_{cv}/h_r \]

The terms that link the zones complicate the solving of the equations. Above all it is difficult by the unlimited number of zones one can define in HAMBASE. The easiest way is to solve the system is by iteration, estimating the link term by a previous calculated value. Without airflows between zones 2 iterations are usually sufficient, otherwise 5 iterations can be necessary.

Other reasons for iterations can be e.g. the control of sunshade or ventilation with the indoor temperature as a criterion.

In the simplest case the control strategy involves three situations (figure 3-2):

a. **No heating or cooling:**

a1. The control temperature without heating or cooling is between the desired minimum temperature ($T_{\text{min}}$) and the desired maximum temperature ($T_{\text{max}}$).
   
   In this case the heat gains provide sufficient heat.

a2. No heating or cooling system is present in the zone.

b. **Heating:**

b1. The control temperature is kept at the desired minimum temperature ($T_{\text{min}}$). The maximum heating load of the plant ($\Phi_{\text{maxh}}$) is larger than the heating demand.

b2. The zone is heated with the maximum heating load. In this case the maximum load ($\Phi_{\text{maxh}}$) is less than the heating demand and the control temperature will be lower than the desired minimum temperature ($T_{\text{min}}$) (e.g. after a period of night set-back).
Cooling:
c1. The control temperature is kept at the desired maximum temperature ($T_{\text{max}}$). The maximum cooling load of the plant ($\Phi_{\text{max}}$) is larger than the cooling demand.
c2. The zone is cooled with the maximum cooling load ($\Phi_{\text{max}}$). In this case the control temperature is higher than the desired maximum temperature ($T_{\text{max}}$).

![Fig. 3-2. Temperature control strategy](image)

The power of the heating system can be input but also be estimated by the program.
In HAMBASE_R the speed of heating up can be limited by a given maximum temperature increase per hour. Also a time constant for the heating system can be defined. Then the maximum heating up power is dependent on the increase per hour of the heating up power (differential control).

\[
\Phi_{\text{maxh}} = \Phi_h^* + (\Phi_{\text{maxmaxh}} - \Phi_h^*)\tau(1-e^{-\tau/\Delta t})/\Delta t
\]  

(3.4)

where 
- $\Phi_h^*$ = heat supplied during the previous time step 
- $\Phi_{\text{maxmaxh}}$ = maximum heat power that can be supplied 
- $\tau$ = time constant for heating 
- $\Delta t$ = time step, e.g. one hour
A similar control function can be given for the vapour pressure. A maximum humidification and dehumidification must be known together with desired range of the indoor relative humidity (bounded by a minimum and a maximum value). The latent heat needed for humidification and dehumidification is calculated separately.

The relative humidity can also be controlled with the indoor air temperature: the so-called hygrostatic temperature control. In practice it means extra heating to lower the relative humidity or less heating to increase the humidity. If the humidity calculated is lower than the allowed humidity the temperature to reach this lower limit is calculated and compared with the lowest allowed temperature. The maximum of both is taken as the set temperature. For the upper limit of the relative humidity the opposite procedure is applied. Another constraint used is the limiting value for the power of the heating or cooling plant.

### 3.2 General features

#### 3.2.1 The envelope

The building is divided into zones which consists of rooms with more or less the same indoor climate, e.g. it is not obvious to combine a room with a large window facing south with a room facing north. However if the door is always open between these rooms it might be a good choice. In spite of the fact that the model has no limitation regarding the number of zones it might be convenient as it reduces the number of input items and will also reduce the time needed to calculate the heating or cooling load of a building.

As the model is almost irrespective of the geometry of a room only global input data are needed:

- The area for internal walls, floors, external walls, roofs, floors
- The area, orientation and slope of glazing and exterior constructions
For each surface the user has to specify a certain construction type. An m-file with a long list of material properties is available.

Three types of external constructions are distinguished:
- exterior constructions,
- constructions with identical environmental conditions at either side (adiabatic),
- constructions adjoining zones with a constant temperature.

Internal constructions are constructions between two zones and the ones that are completely in one zone.

3.2.2 The profiles

Input data related to the function of the building (profiles) are stored in a profile library. A profile is defined by a set of properties related to the use of the zone for predefined periods of a day with a maximum of 24 hourly values. For each zone and each day of the week a different profile can be given.

The profile properties are:
- casual gains
- vapour production
- ventilation regimes
- threshold temperature for free cooling
- maximum and minimum set temperatures and set relative humidity's
- threshold solar irradiance for the control of solar protection (one value).
  This is used in combination with the threshold for free cooling.

Other needed input per zone is:
- convection factors (per zone) for casual gains
- the room convection factor (fraction of solar radiation not falling on constructions is supposed to enter as convective heat)
- hygroscopic capacitance of furniture
- air temperature threshold for the air to air heat recovery unit
- efficiency of the air to air heat recovery unit
- power of the heating or cooling system
- convection factor (type) of the heating or cooling system
- weighing factor for air temperature contribution in set temperature

If air infiltration is calculated a profile must be added for the net mechanical ventilation per zone (flow rate in - flow rate out).

The easiest (not most accurate) way to account for ‘free cooling’ is to estimate the ventilation rate and input this value as maximum ventilation. Above the threshold temperature this maximum will be used. With a maximum ventilation that is equal to the minimum one there is no free cooling.

Solar blinds are used only when both the indoor temperature exceeds the temperature threshold and the solar irradiance is above the irradiance threshold.

The use a heat recovery unit is modelled straightforward with a constant efficiency given as input. The unit is controlled by the indoor air temperature: above a threshold value the heat recovery is by-passed.

An hourly file is made of this profiles input in order to be able to change data for particular hours: e.g. Xmas-day etc.

3.2.3 Exterior climate

Standard Dutch hourly meteorological data from 1970 till 2005 are used. Of course also other data can be used, if written in the right format, e.g. hourly METEONORM data (Meteonorm 1999) were used already for projects in Africa and Asia.

In the model the data for the European summer saving time are modelled. This can be changed.

Default the calculation starts three days in advance of the first day to account for the heat and moisture storage in the building envelopes. If there are no previous days available these days are assumed to be the same as the first day. For building with much thermal mass more days are needed.
3.2.4 Output

In the output all calculated hourly properties are present. The user can select at
wish, e.g.:

- only total heating or cooling loads
- peak loads for heating or cooling
- the values of the air, resulting, or control temperature for each hour
- the values of the relative humidity for each hour
- the number of hours the minimum or maximum temperatures are exceeded

For design the effect on comfort and energy demand of changing one input
parameter (e.g. the window size) is important. This can be done easily by making
a loop around the program.
The graphic features of Matlab allow the user in an easy way to make the plots he
wants or to make movies for presentation.

\[ \text{heating}=5206 \text{ kWh} \quad \text{cooling}=22 \text{ kWh} \]

\[ \text{zone1 T}>25 \text{ C}=466 \text{ hours} \]

\[ \text{RH air} \]

\[ \text{energy (W)} \]

*Fig.3-3. Typical output*
3.3 Validation

3.3.1 Comparitive testing: the ASHRAE Bestest

The test described here was presented in an IEA annex 41 working group (IEA annex 2005). For this test 4 cases were selected from the ASHRAE Bestest. The Bestest (ASHRAE 2001) is a set of well documented test cases for software-to software comparisons and program diagnostics. Good results make it likely that there are no severe internal (programming) errors and that the assumptions made are justified. Of course it not a proof because by chance errors can cancel each other out.

The cases were:
- Case 600FF: lightweight structure, base case, free floating temperature,
- Case 900FF: heavyweight structure, base case, free floating temperature,
- Case 600: lightweight structure, base case, heating and cooling system,
- Case 900: heavyweight structure, base case, heating and cooling system,

The test building is represented in figure 15 (windows are facing south). Details of the construction are given in the appendix.

Fig. 3-4. Bestest base case building
The weather data supplied with this test are from a site at 39.8° latitude with cold clear winters (min. 24.39 °C) and hot dry summers (max. 35 °C) with often a clear sky. So this is very different from the Dutch climate. In free floating situations (neither heating nor cooling) the simulation results are very sensitive for the modelling of surface coefficients, longwave sky radiation and air density. This explains the range of the results from the main models in this field (ESP, BLAST, SRES/SUN, SERIRES, S3PAS, TRNSYS, TASE).

The simulation is run for the period of one year. The model is not changed to get better results, although in the MATLAB environment it is easy to ‘tune’ the model.

Results:

<table>
<thead>
<tr>
<th>Nr. test</th>
<th>Simulation of</th>
<th>HAM-BASER</th>
<th>HAM-BASE</th>
<th>ASHRAE 2001</th>
</tr>
</thead>
<tbody>
<tr>
<td>600</td>
<td>annual sensible heating [MWh]</td>
<td>5.3</td>
<td>5.4</td>
<td>4.3……5.7</td>
</tr>
<tr>
<td>600</td>
<td>annual sensible cooling [MWh]</td>
<td>6.7</td>
<td>6.8</td>
<td>6.1……8.0</td>
</tr>
<tr>
<td>600</td>
<td>peak heating [kW]</td>
<td>4.1</td>
<td>4.1</td>
<td>3.4……4.4</td>
</tr>
<tr>
<td>600</td>
<td>peak sensible cooling [kW]</td>
<td>6.3</td>
<td>6.3</td>
<td>6.0……6.6</td>
</tr>
<tr>
<td>600ff</td>
<td>mean indoor temperature [°C]</td>
<td>24.8</td>
<td>24.8</td>
<td>24.2…25.9</td>
</tr>
<tr>
<td>600ff</td>
<td>minimum indoor temperature [°C]</td>
<td>-19.0</td>
<td>-19.1</td>
<td>-18.8…-15.6</td>
</tr>
<tr>
<td>600ff</td>
<td>maximum indoor temperature [°C]</td>
<td>64.5</td>
<td>64.7</td>
<td>64.9…69.5</td>
</tr>
<tr>
<td>900</td>
<td>annual sensible heating [MWh]</td>
<td>1.9</td>
<td>1.9</td>
<td>1.2……2.0</td>
</tr>
<tr>
<td>900</td>
<td>annual sensible cooling [MWh]</td>
<td>2.6</td>
<td>2.6</td>
<td>2.1……3.4</td>
</tr>
<tr>
<td>900</td>
<td>peak heating [kW]</td>
<td>3.7</td>
<td>3.7</td>
<td>2.9……3.9</td>
</tr>
<tr>
<td>900</td>
<td>peak sensible cooling [kW]</td>
<td>3.4</td>
<td>3.4</td>
<td>2.9……3.8</td>
</tr>
<tr>
<td>900ff</td>
<td>mean indoor temperature [°C]</td>
<td>24.8</td>
<td>24.8</td>
<td>24.5…25.9</td>
</tr>
<tr>
<td>900ff</td>
<td>minimum indoor temperature [°C]</td>
<td>-5.1</td>
<td>-5.5</td>
<td>-6.4…-1.6</td>
</tr>
<tr>
<td>900ff</td>
<td>maximum indoor temperature [°C]</td>
<td>43.2</td>
<td>43.1</td>
<td>41.8…44.8</td>
</tr>
</tbody>
</table>

Table I. Comparison of the room model with some cases of the standard test
The results of HAMBASE and HAMBASE_R are also quite similar and fall mostly within the range given in the BESTEST document (ASHRAE 2001). The peak loads and extreme temperatures appear also at the same time (hour, day and month). This might be surprising as:

- The distribution of solar radiation in the room is by the integrating sphere and not by the BESTEST prescribed distribution
- The free-floating cases are sensitive for the interior surface coefficient for convection which is constant in HAMBASE and also independent of the heat flow direction.
- The exterior surface coefficient is the default HAMBASE value and not the wind dependent coefficient of the BESTEST
- The dependence of the glazing absorptance on the incident angle is not modelled (only the reflectivity).

In conclusion:

- Internal programming errors are very unlikely
- For the Bestest cases the (simplifying) assumptions made are justified.

3.3.2 Analytical verification of the hygric indoor climate model

In this test a simple case for which an exact solution of the equations can be calculated is compared with the simulation model solution. Two FEM simulation tools (FEMLAB and FLEXPDE) were used to retrieve independently exact solutions. (Annex41 2005).

In IEA annex41 two cases were proposed for analytical solution and solution of the building model:

**Case 0A.** Isothermal exposure. Construction surfaces are tight.

**Case 0B.** Isothermal exposure. Construction surfaces are open.

We compared the ‘exact’ results with the numerical solutions of HAMBASE, HAMBASE_R and of HAMBASE_S.

Compared to the BESTEST cases the following changes are made for the new cases:
- Constructions are made of monolithic aerated concrete with constant/linear properties.
- Tight membranes on the outside, and in case 0A also on the inside, prevent loss of vapour from the building by transport all the way through the walls.
- The exposure is completely isothermal, i.e. the same temperature outside as inside the building. However, if solutions consider the latent heat of condensation/evaporation this may generate some (local) temperature changes.
- The building has no windows (figure 3-4 with windows that should be neglected).

Outside and initial indoor conditions are: Temperature is 20°C and relative humidity is 30% RH. These are also the initial conditions of materials in the constructions.
Below the floor is outside air (i.e. no ground).
Internal moisture gain = 500 g/h from 9:00 - 17:00 every day. No moisture gains outside these hours. No heat gains at any time. Constant ventilation of 0.5 ach.

Figure 3-5 Case0A, no hygroscopic material
In figure 3-5 the results for case0A are presented. The difference with the exact solution is not visible. This means that the solution of the second order equation (the mass of the room air is the only hygric capacitance) is very close to exact and no errors are made in the three HAMBASE models.

![Figure 3-6 Case0B, hygroscopic walls](image)

In figure 3-6 the results for the case with the monolithic aerated concrete construction is presented. The HAMBASE_R model solves the differential equations for the wall. So the result should be ‘exact’ if no internal errors are made and the time-step is small enough. With a timestep of 15min the result is almost the same, although it took almost a year of calculation for the thick walls to arrive at a constant mean daily humidity. In HAMBASE and HAMBASE_S a second order network is derived from the diffusion equations of the walls, so there is an approximation. The difference of HAMBASE and HAMBASE_S results from the timestep: very small in SIMULINK and one hour in HAMBASE. One can see that these two models deviate slightly from the exact solution. In conclusion, the inaccuracy introduced by the second order network approximation of the walls introduces but a small error. The amplitude of the variation is slightly
smaller. In view of the uncertainty of the hygroscopic material that is present in real furnished rooms it is negligible.

In this analytical test the retention curve was assumed to be linear, so the effect of linearization in the HAMBASE models is not be evaluated.

### 3.3.3 Empirical validation of the hygric model

In the framework of IEA annex41 simulation results are compared with measured data from two test rooms which are located at the outdoor testing site of the Fraunhofer-Institute of building physics in Holzkirchen. Geometry and construction of both rooms is identical. The geometry of the rooms is shown in figure 3-7.

The front façade is oriented south. The back wall, the walls separating the test rooms and the roof can be considered adiabatic.

One room (the reference room) is plastered with a common used gypsum plaster and in the other rooms (the test room) the walls and ceiling are covered with aluminium foil (the concrete floor is covered with linoleum and has a small influence on the air humidity). In the test room hygroscopic material can be fixed on top of the aluminium foil at the walls and ceiling.
The rooms were heated by an electric heating and controlled on 20°C air temperature. The airchange rate was determined with a blower door test: 0.65±0.05 h\(^{-1}\). This is not really accurate because of infiltration. The moisture production is 2.4kg/day: 25gr/hour from 6 to 8 am and 400 gr/hour from 4 till 10p.m.

The measurements were carried out in winter. The measured data of the hourly mean indoor relative humidity and the hourly mean total energy demand (sum of heating and energy for evaporation) were obtained from the Fraunhofer Institut für Bauphysik (IEA annex41 2005).

In figure 3-8 the measured and simulated results of the reference room are presented.

![Figure 3-8 Reference room](image)

The hygroscopic plaster has an important influence on the amplitude of the variation as can be seen from the results of the test room in figure 3-9. The results of simulation agree well with the measurements. In the reference room the amplitude of the simulation is slightly smaller. This was also concluded in the
analytical test. The HAMBASE network is damping a bit more. Also the linearization of the sorption curve and the constant vapour permeability introduce some errors.

In the test room the amplitude of HAMBASE is slightly larger. A reason could be that although aluminium is not hygroscopic it has some influence. The change of the thickness of the surface layer with absorbed water molecules with relative humidity might be part of the explanation.

![Figure 3-9 Test room](image)

For a better comparison of the simulated hourly heat supply and the measured one the heat needed for the moisture production was subtracted from the measured total heat supply.

The result of the comparison is shown in figure 3-10. Differences can be expected by the infiltration, the one-dimensional approach of the heat flow through the construction, the variation of the indoor temperature and the model approximations. Nevertheless the agreement is excellent and the mean difference is only 10W.
3.3.4 Comparison with data from monitored buildings

HAMBASE has been used in many projects about old buildings: buildings without insulation, with a huge volume (e.g. churches) and a lot of thermal mass. As the humidity in these buildings is a key issue for the conservation of the building and its interior HAMBASE is very well suited for studying the best heating and humidification strategy. The model is ‘tuned’ with the results of a small period of monitoring (as least as possible and within acceptable physical boundaries) and after that used to predict the behaviour over a longer period.

Example 1
The annual use of heating energy in the St. Martinus church in Weert (NL) was recorded for some years. The church has a very floor heating system. The system is very slow due to the heavy ground floor. HAMBASE predicted the energy effects of the introduction of a new temperature setting and the installation of a protective glazing within 5 percent.
Figure 3-11 The long term (one-year) simulated and measured air temperature and humidity in the St. Martinus Church in Weert.

The long term behaviour of measured and calculated air temperatures and relative humidity's in the church is shown in figure 3-11. The agreement of both air temperature and relative humidity is rather good, except for the hours from about 5000 to 5500. In reality the gas burning device broke down, and this was not accounted for in the simulation.

Example 2

In figure 3-12 the results of the measured and simulated air temperature and relative humidity in a church of one month (December 2000) are shown.
The results show an agreement well enough to have confidence in the model.
Conclusions

Below the main conclusions are summarized.

The proposed approximations for the radiation exchange appear to have but a very small influence on the accuracy. The advantage of being able to model complicated geometries far outweighs this disadvantage.

With linearized equations the accuracy of the continuous HAMBASE model is comparable with the fully discretized model. Further developments with non-linear equations will be confined to HAMBASE-R.

The combined modelling of heat and moisture transfer is required for many research projects in building physics. So far it is the main reason for the successful application of HAMBASE.

The choice of the MATLAB environment is the main reason that the development keeps going on:
- Improvements and extensions are easily implemented
- Models in the MATLAB environment can easily be linked

The continuous model offers an ideal possibility for modelling HVAC designs with SIMULINK. The splitting in a part with large time constants and one with small ones enables an efficient simulation. This part will be explored much more in future.
References

Bruggen, R.J.A. van der

*Energy consumption for heating and cooling in relation to building design.*


Danter, E.

*Heat exchanges in a room and the definition of room temperature*

IHVE symposium, 1973

Hoen, P.J.J.

*Energy consumption and indoor environment in residences.*


Pipes, L.A.

*Matrix analysis of heat transfer problems.*

J. Franklin Institute 623, 195-206, 1957

Wit, M.H. de; Driessen, H.H. and Velden, R.M.M. van

*ELAN, a Computer Model for Building Energy Design, Theory and Validation.*

Eindhoven University of Technology, 1987

Perez, R, et al:

*A new simplified version of the Perez diffuse irradiance model for tilted surfaces.*

Solar Energy vol. 39, 1987 pp. 221-231

Wit, M.H. de

*ELAN - a Multizone Simplified thermal Simulation Model.*

Proc. sixth intern. PLEA Conference Porto, Portugal, 1988a, pp. 725-729

Wit, M.H. de; Driessen, H.H.

*ELAN- A Computer Model for Building Energy Design.*
Wit, M.H. de

A second order model for the prediction of indoor air humidity.
Rapport 88.27.K., FAGO, TUE, 1988c, pp. 11.

Wit, M.H. de; Zonneveldt, L.:

Chapter 9, European Reference Book on Daylighting.
i.o.v. NOVEM, FAGO-TNO-TPD, 1989, pp. 37.

Wit, M.H. de; Donze, G.J.

A model for the prediction of indoor air humidity.

Pernot, C.; Wit, M.H. de

Modelling: Combined heat, air and moisture transport.
Sourcebook, IEA-annex: condensation and energy, vol.1, chapter 5, March 1991, pp. 5.36-5.46, University of Technology Eindhoven, The Netherlands

Laan, M.J. van der

A model for the combined heat and moisture transfer in building constructions.
Rep 94-CBO-R0331 Centrum Bouwonderzoek TNO-TUE Eindhoven, April 1994


Schijndel, A.W.M. van.; Wit, M.H. de.

A Building Physics Toolbox in Matlab.
5th Symposium on Building Physics in the Nordic Countries. Gothenburg, Sweden, 1999

Schellen, H.L.; Wit, M.H. de

Heat- and Moisture Modelling of a Monumental, Massive Building
5th Symposium on Building Physics in the Nordic Countries. Gothenburg, Sweden, 1999

Meteonorm,
Global meteorological database for solar energy and applied climatology
Meteotest, Swiss Federal Office of Energy, CH-3003 Bern, Sept. 1999
Jong, J de; Schijndel A.W.M. van; Pernot, C.E.E.
Evaluation of a low temperature energy roof and heat pump combination,
Schellen, H.L.,
Building physical impact of heating systems on monumental buildings and their interior.
ASHRAE,
Standard method of test for the evaluation of building energy analysis computer programs,
Schellen, H.L.; Diepens J.F.L.; Schijndel A.W.M. van:
Building Physical Impact of Infrared Gas Heating on Monumental Churches and their Interior.
Proceedings 6th Symposium Trondheim, 2002
Schijndel, A.W.M. van;
Advanced HVAC modeling with FemLab/SIMULINK/Matlab,
Schellen, H.L.,
Heating Monumental Churches, Indoor Climate and Preservation of Cultural Heritage
Schijndel, A.W.M. van, M.H. de Wit
Advanced simulation of building systems and control with SIMULINK
Proc. of 8th IBPSA Conference, Eindhoven 2003a, pp1185-1192
Schijndel, A.W.M. van; Neilen, D.; Schellen, H.L.; Aarle, M.A.P. van,
Optimal setpoint operation of the climate control of a monumental church,
Neilen, D.; Schellen, H.L.; Aarle M.A.P. van

*Characterizing and comparing monumental churches and their heating performance*

2nd International Conference on Research in Building Physics_Leuven, 2003b pp777-784

Schijndel, A.W.M. van,

*Advanced HVAC modeling with FemLab/SIMULINK/MatLab,*

Building Serv. Eng. Technol. 24, 4 2004 pp289-300

Schijndel, A.W.M. van; Schellen H.L.

*Application of an integrated indoor climate & HVAC model for the indoor climate performance of a museum.*


Schijndel, A.W.M. van; Hensen J.L.M.

*Integrated heat, air and moisture modeling toolkit in Matlab.*

Proc. of 9th Int. IBPSA Conference, Montreal, August 15-18, 2005, pp 1107-1114

Schijndel, A.W.M. van,

*Indoor climate design for a monumental building with periodic high indoor moisture loads*

Proceedings of the 26TH AIVC Conference in Brussels, 2005, pp301-313

IEA annex41
### Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>surface area (m²)</td>
</tr>
<tr>
<td>a</td>
<td>thermal diffusivity λ/(ρc) (m²/s)</td>
</tr>
<tr>
<td>a</td>
<td>solar absorptivity (-)</td>
</tr>
<tr>
<td>ach</td>
<td>air change rate (h⁻¹)</td>
</tr>
<tr>
<td>C</td>
<td>flow coefficient</td>
</tr>
<tr>
<td>Cp</td>
<td>wind pressure coefficient (-)</td>
</tr>
<tr>
<td>CF</td>
<td>convection factor (-)</td>
</tr>
<tr>
<td>Cק</td>
<td>Cp_sat(T_ref)/p_sat(T_a) hygroscopic capacitance (kg/Pa)</td>
</tr>
<tr>
<td>Ca</td>
<td>heat storage coefficient (capacitance) of indoor air (= ρ_acpVol) (J/K)</td>
</tr>
<tr>
<td>Cva</td>
<td>moisture storage coefficient (= (0.62)10⁻⁵C_p/c_p) (kg/Pa)</td>
</tr>
<tr>
<td>cp</td>
<td>specific heat of the air (1000 kJ/kgK)</td>
</tr>
<tr>
<td>c</td>
<td>specific heat (J/kgK)</td>
</tr>
<tr>
<td>d</td>
<td>thickness of the slab (m)</td>
</tr>
<tr>
<td>E_s, E</td>
<td>solar irradiance (W/m²)</td>
</tr>
<tr>
<td>Gᵢ</td>
<td>moisture loss (kg/s)</td>
</tr>
<tr>
<td>Gₛ</td>
<td>moisture stored (kg/s)</td>
</tr>
<tr>
<td>G₉</td>
<td>vapour production (sources, sinks) (kg/s)</td>
</tr>
<tr>
<td>Gxy</td>
<td>vapour flow to the envelope (kg/s)</td>
</tr>
<tr>
<td>Gp</td>
<td>humidification (or dehumidification)</td>
</tr>
<tr>
<td>G_ab</td>
<td>vapour transfer by airflow from zone b to a (kg/s)</td>
</tr>
<tr>
<td>hᵢ</td>
<td>the combined surface coefficient hᵢ =hᵢₐ+hᵢᵥ (W/m²K)</td>
</tr>
<tr>
<td>hᵢₐ</td>
<td>surface heat transfer coefficient for radiation. (W/m²K)</td>
</tr>
<tr>
<td>hᵢᵥ</td>
<td>surface heat transfer coefficient for convection (W/m²K)</td>
</tr>
<tr>
<td>hₑ</td>
<td>total external surface coefficient (W/m²K)</td>
</tr>
<tr>
<td>h</td>
<td>distance (= positive) to top of the roof (W/m²K)</td>
</tr>
</tbody>
</table>
\[ j^2 = -1 \]

- \( \mathcal{L}_{xa} \): coupling coefficient (W/K)
- \( \mathcal{L}_{ab} \): heat loss coefficient for airflow from zone b to a (W/K)
- \( \mathcal{L}_a \): ventilation heat loss coefficient (=C\(\varphi\)ach/3600) (W/K)
- \( \mathcal{L}_{at} \): \(\sigma T_e^4\) - atmospheric radiation). (view factor) (W/m²)
- \( \mathcal{L}_{va} \): ventilation vapour transfer coefficient, \( \mathcal{L}_{va} = (0.62)10^{-5} \mathcal{L}_a/c_p \) (kg/sPa)
- \( n \): flow exponent (0.5<\(n<1\))
- \( p_v \): vapour pressure (Pa)
- \( p_e \): exterior vapour pressure (Pa)
- \( p_{sat(Ta)} \): saturation vapour pressure at temperature \( T_a \) (Pa)
- \( Q_m \): mass flow (kg/m³)
- \( R_i \): thermal resistance \( R \) (m²K/W)
- \( R_x \): surface resistance of surface \( x \) (=1/(h\(_e\)+h\(_c\)) or 1/h\(_e\)) (m²K/W)
- \( R_{flow} \): \( \approx 1/(2c_pQ_m) \) (K/W)
- \( RH \): relative humidity (%)
- \( SGF \): solar gain factor of window (-)
- \( T_a \): indoor air temperature (°C)
- \( T_x \): ‘resultant’ temperature (°C)
- \( T_e \): outdoor air temperature. (°C)
- \( T_m \): average surface temperature (°C)
- \( T_{ref} \): reference temperature (\( C_l \) is determined at this temperature) (°C)
- \( t \): time (s)
- \( t_d \): time lag (s)
- \( U\)-value: total thermal transmittance (W/m²K)
- \( u \): moisture content (kg/kg)
- \( Vol \): volume of the air in a zone (m³)
- \( v_{wind} \): reference wind velocity (m/s)
- \( x \): absolute humidity (kg/kg)
- \( x \): distance (m)
- \( \beta \): surface coefficient of vapour transfer (s/m)
- \( \delta_a \): vapour permeability of air (1.8 \(10^8\) s)
\( \varepsilon \) emissivity of the surface (-)

\( \lambda \) thermal conductivity (W/mK)

\( \mu \) vapour resistance number (-)

\( \xi \) specific differential moisture storage coefficient (kg/m\(^3\))

\( \sigma \) Boltzmann constant

\( \rho_a \) density of the air (1.2 kg/m\(^3\))

\( \rho \) density (kg/m\(^3\))

\( \Phi_i \) heat loss (W)

\( \Phi_s \) heat stored (W)

\( \Phi_g \) heat gains (W)

\( \Phi_p \) auxiliary heat (W)

\( \Phi_r \) total radiant heat input (W)

\( \Phi_c \) convective heat input (W)

\( \Phi_{cg} \) heat input by the heating or cooling plant (W)

\( \Phi_{eg} \) casual gains (W)

\( \Phi_{sol} \) solar gains (W)

\( \Phi_{ab} \) convective heat flow from \( T_a \) to \( T_b \) (W).

\( \Phi_{xy} \) transmission heat loss from \( T_x \) to \( T_y \) (W)

\( \phi \) relative humidity (= \( p_v / p_{sat} \))

\( \omega \) \( 2\pi \) times the frequency of heat input (1/s)
Appendix A  Model development

A.1  The temperature nodes of the indoor climate

A.1.1  The delta-star transformation of the radiation exchange network

The calculation of the amount of radiation each surface will receive by radiation exchange with the other surfaces demands a great number of data about geometry, reflectivity etc. and is not suited for our purpose. Therefore an approximation of the physical reality is needed in order to reduce the required data considerably.

The total surface radiation is equal to:

$$\sum_j A_j \varepsilon \sigma T_j^4$$

where $A_j$ = surface area of j-th surface

$\varepsilon$ = emissivity (assumed equal for all surfaces)

$\sigma$ = Boltzmann constant

$T_j$ = absolute temperature of each surface j

It is assumed that this sum is equally spread over all inner surfaces (The received radiation is per unit of surface area equal for each surface). As each surface also emits radiation the first approximation for the net radiation exchange is:

$$H_i = \frac{\sum_j A_j \varepsilon \sigma T_j^4}{A_i} - \varepsilon \sigma T_i^4 = \frac{\sum_j A_j \varepsilon \sigma (T_j^4 - T_i^4)}{A_i}$$

One can show easily that this involves an approximation for the view factor:

$F_{ij} = A_j / \sum_i A_j$

This kind of approximation is known as a delta-star transformation.
The problem is that $F_{ii} \neq 0$ e.g. for a cavity bounded by two parallel planes the view factor should be $F_{12} = F_{21} = 1$ so: $F_{ii} = 0$ and for $i \neq j$ $F_{ij} = 2A_j / \sum_j A_j$.

In a cube the view factors are also about equal and one can show that $F_{ii} = 0$ and for $i \neq j$ $F_{ij} = 1.2A_j / \sum_j A_j$. So for a better approximation a factor between 1 and 2 has to be introduced. A good compromise seems to be 1.2.

For the radiation exchange the total factor is: $A_j / A_t(1/\varepsilon - 1 + 1/1.2) = \varepsilon A_j / (1-\varepsilon/6)$.

$$H_i = \frac{\sum_j A_j \varepsilon \sigma (T_j^4 - T_i^4)}{A_i (1 - \varepsilon/6)}$$

In a linearised form:

$$H_i = \frac{h_r \sum_j A_j T_j}{A_i} - h_r T_i$$

where $h_r$ = surface heat transfer coefficient for radiation.

The coefficient $h_r$ is assumed to be $5/(1-\varepsilon/6) \approx 6 \text{ W/m}^2\text{K}$ for all surfaces.

**A.1.2 The heat balance at an interior surface**

We assume that $\Phi_r$ is equally spread over the surfaces; so the heat balance at an opaque surface is:

$$\Phi_{xi} = A_i H_i + A_i h_{cv} (T_a - T_i) + A_i \Phi_r / A_i$$

where $\Phi_x$ = heat flow directed to the wall

$H_i$ = net radiation exchange

$T_a$ = air temperature of the room

$A_i$ = surface area

The surface heat transfer coefficient $h_{cv}$ is assumed to be $2.6 \text{ W/m}^2\text{K}$ for all surfaces. The air temperature is the same near all surfaces. (This is a similar approximation as the one for radiation).

The heat flow $\Phi_x$ can be written as:

$$\Phi_{xi} = A_i (h_{cv} + h_r) (T_x - T_i)$$

where: $T_x = \frac{h_r \sum_j A_j T_j + \Phi_r + h_{cv} A_t T_a}{A_i (h_r + h_{cv})}$
For each surface the resulting temperature $T_x$ has the same value. $T_x$ is similar to the concept of ‘environmental temperature’ (Danter 1973).

The heat balance of the air is:

$$C_a \frac{dT_x}{dt} = \sum \Phi_{ab} + \Phi_c + \sum_j A_j h_{cv}(T_j - T_a)$$

Elimination of the surface temperature with the expression for $T_x$ leads to the following equation:

$$C_a \frac{dT_a}{dt} = \sum \Phi_{ab} + \Phi_c + L_{xa}(T_x - T_a) - \frac{h_{cv}}{h_r} \Phi_r$$

where 

$$L_{xa} = A_x h_{cv} \left(1 + \frac{h_{cv}}{h_r}\right)$$

The equation for the ‘resulting’ temperature node with the same heat flow from $T_x$ to $T_a$ is easily derived from the expression for $T_x$:

$$A_x h_r \left(T_x - \frac{\sum_j A_j T_j}{A_t}\right) + A_x h_{cv}(T_x - T_a) = \Phi_r$$

or

$$\sum_y \Phi_{xy} + L_{xa}(T_x - T_a) = \left(1 + \frac{h_{cv}}{h_r}\right) \Phi_r$$

In figure 2-1 the equations for the air temperature node and the ‘resulting’ temperature node are represented by a thermal network.

**A.2 The heat flow to a building element**

**A.2.1 The continuous model, admittance and transmittance**

From section A.1.2 it follows that the unidirectional heat flow through the construction depends on the ‘resulting’ temperatures on both sides of the construction and its thermal properties (including surface coefficients).
The resulting temperatures outdoors will be the air temperature for glazing, the sol-air temperature for opaque walls and weighed average of soil temperature and external temperature for the ground floor.

The calculation of the heat flow is simplified by demanding correctness only for:
- steady state transfer (thermal transmittance)
- steady-cyclic transfer for a triangular shaped temperature with a base of 2 hours and appearing once a day

The temperature distribution through a homogeneous slab subject to one-dimensional heat flow is given by:

\[
\frac{\partial^2 T}{\partial x^2} = \frac{1}{a} \frac{\partial T}{\partial t}
\]

where

- \( t \) = time
- \( x \) = distance
- \( T \) = temperature
- \( a \) = thermal diffusivity \( \lambda/(\rho c) \)
- \( \rho \) = density
- \( c \) = specific heat
- \( \lambda \) = thermal conductivity

For sinusoidal variations of temperature the solution to this equation for a homogeneous slab can be written as:

\[
\begin{pmatrix}
\tilde{T}_o \\
\tilde{q}_o
\end{pmatrix} =
\begin{pmatrix}
A & B \\
D & A
\end{pmatrix}
\begin{pmatrix}
\tilde{T}_i \\
\tilde{q}_i
\end{pmatrix}
\]

where: \( \tilde{T}_o, \tilde{T}_i \) and \( \tilde{q}_o, \tilde{q}_i \) are the cyclic variations of the temperature and heat flow density on both sides of the slab.

and

\[
A = \cosh (1 + j) \psi
\]

\[
B = \frac{R}{(1+j)\psi} \sinh(1+j)\psi
\]

\[
D = \frac{(1+j)\psi}{R} \sinh(1+j)\psi
\]
\[ \Psi = \left( \frac{\omega d^2}{2a} \right)^{0.5} \]

\( R \) = thermal resistance of the slab = \( \frac{d}{\lambda} \)

\( \omega \) = \( 2\pi \) times the frequency of heat input

\( d \) = thickness of the slab

\( j^2 = -1 \)

If \( \Psi << 1 \) (no capacitance) the matrix becomes:

\[
\begin{pmatrix}
A & B \\
D & A
\end{pmatrix} = \begin{pmatrix}
1 & R \\
0 & 1
\end{pmatrix}
\]

In this way also boundary layers or air layers can be modelled.

So the relation between the resulting temperatures and the heat flow rates through wall assemblies with homogeneous layers can be written as a product of matrices:

\[
\begin{pmatrix}
\tilde{T}_x \\
\tilde{q}_x
\end{pmatrix} = \begin{pmatrix}
1 & R_x \\
0 & 1
\end{pmatrix} \begin{pmatrix}
A_1 & B_1 \\
D_1 & A_1
\end{pmatrix} \cdots \begin{pmatrix}
A_n & B_n \\
D_n & A_n
\end{pmatrix} \begin{pmatrix}
1 & R_y \\
0 & 1
\end{pmatrix} \begin{pmatrix}
\tilde{T}_y \\
\tilde{q}_y
\end{pmatrix}
\]

where

\( R_x \) = surface resistance of surface \( x \) (=1/(h_r+h_{cv}) or 1/h_c)

\( R_y \) = surface resistance of surface \( y \)

\( A_1, \ldots, D_n \) are the complex elements for \( n \) layers including air gaps.

So the following equation holds for sinusoidal variations:

\[
\begin{pmatrix}
\tilde{T}_x \\
\tilde{q}_x
\end{pmatrix} = \begin{pmatrix}
M_{xx} & M_{xy} \\
M_{yx} & M_{yy}
\end{pmatrix} \begin{pmatrix}
\tilde{T}_y \\
\tilde{q}_y
\end{pmatrix}
\]

It can be proved that the determinant of the matrix always equals 1 so:

\( M_{xx} M_{yy} - M_{xy} M_{yx} = 1 \)

By manipulating the system of equations one can derive for the heat flows:
\[ \tilde{q}_x = Y_{xy} \tilde{T}_x + (U_{xy} \tilde{g}_{xy})(\tilde{T}_x - \tilde{T}_y) \]
\[ \tilde{q}_y = -Y_{yx} \tilde{T}_y + (U_{yx} \tilde{g}_{xy})(\tilde{T}_x - \tilde{T}_y) \]

where: \( Y_{xy} = \frac{M_{yx}^{-1}}{M_{xy}} \) = admittance
\( Y_{yx} = \frac{M_{xx}^{-1}}{M_{xy}} \) = admittance
\( U_{xy} = \) U-value of the construction
\( g_{xy} = \frac{1}{U_{xy} M_{xy}} \) = normalized cyclic transmittance

The first term on the right hand side represents the heat flow if there is no resultant temperature difference across the wall (heat flow ‘into’ the construction or ‘stored’ heat flow). In the steady state approximation this part is zero.

The second term represents the transmission (heat flow ‘through’ the construction or transmitted heat flow). For a steady state approximation \( g_{xy} = 1 \).

All the admittances of a zone envelope together with the admittances of partitions within a zone and admittance of other heat-storing objects can be added. The total admittance of a zone is:

\[ Y = \sum A_y Y_{xy} \]

\( Y \) depends on the frequency. This dependency is very similar to the admittance of a second order thermal network with constant components (resistances and capacitances). In HAMBASE the stored heat flow is approximated by the solution of a second order network (see figure below).
The equations are given in eq2.14. Written in a different way:

\[
\frac{C_{x1}C_{x2}}{L_{x1}L_{x2}} \frac{d^2\Phi_x}{dt^2} + \left(\frac{C_{x1}}{L_{x1}} + \frac{C_{x2}}{L_{x2}}\right) \frac{d\Phi_x}{dt} + \Phi_x = \left(L_{x1} + L_{x2}\right) \frac{C_{x1}C_{x2}}{L_{x1}L_{x2}} \frac{dT_x}{dt} + \left(C_{x1} + C_{x2}\right) \frac{dT_x}{dt}
\]

The admittance of the model (fig. A-1) is:

\[
Y_{model}(\omega) = \frac{j\omega C_{x1}}{1 + j\omega C_{x1} / L_{x1}} + \frac{j\omega C_{x2}}{1 + j\omega C_{x2} / L_{x2}}
\]

The way the components of this network are determined is described in sec.A.2.2

After (time) discretization of the equations (only for the standard HAMBASE) the heat flow to the wall storage can be written as:

\[
\Phi_{x1} = \alpha_1 C_{x1}(T_x - T_{x1}) / \Delta t \quad \text{and} \quad \Phi_{x2} = \alpha_2 C_{x2}(T_x - T_{x2}) / \Delta t
\]

where: \(T_{x1} = T_{x1}^* - \alpha_1(T_{x1}^* - T_x^*)\) and \(T_{x2} = T_{x2}^* - \alpha_2(T_{x2}^* - T_x^*)\)

* denotes the value at the previous timestep

\(\alpha_x = 1 - \exp(-\Delta t L_{x1} / C_{x1})\) and \(\alpha_x = 1 - \exp(-\Delta t L_{x2} / C_{x2})\)

Note that \(T_{x1}\) is not the temperature at the capacitance but a help-variable

\[\equiv T_x^* - \Delta t \frac{1 - \alpha_x}{\alpha_x C_{x1}} \Phi_{x1}^*\]
The transmitted heat flow density $q_{txy}$ is also modelled by a second order differential equation. The main condition is that the solution is correct for steady state i.e the U-value is correct and the cyclic transmittance for very low frequencies is almost zero with a large delay time (the phase-shift can be more than $90^\circ$).

The second order model (eq 2.13) for the heat flow through the wall and a delay time $(\Delta t=\text{delay})$ can be written as:

$$\frac{\tau_1 \tau_2}{2} \frac{d^2 q_{txy}}{dt^2} + (\tau_1 + \tau_2) \frac{dq_{txy}}{dt} + q_{txy} = U_{xy} \Delta T_{xy} (t - t_d)$$

With initial conditions:

$$t = 0 : \quad q_{txy} = \frac{dq_{txy}}{dt} = \frac{d^2 q_{txy}}{dt^2} = 0$$

The normalized cyclic transmittance of this model is

$$g_{\text{model}}(\omega) = \exp(-j\omega t_d)/(1+j\omega (\tau_1 + \tau_2) - \omega^2 \tau_1 \tau_2)$$

Once $\tau_1$, $\tau_2$ and $t_d$ are determined (sec.A.2.2) the transfer function coefficients can be calculated. If $t_d = n + \Delta t_d$ where $n$ is a round number and $0 < \Delta t_d < 1$ (time-step=1 hour) the heat flow density can be written as:

$$q_{xy}(t_i) = a_1 U_{xy} \Delta T_{xy}(t_i) + \Delta q_{xy}(t_{i-1})$$

$$\Delta q_{xy}(t_i) = U_{xy} \sum_{i=2}^{n+4} a_i \Delta T_{xy}(t_{i-i+2}) + \sum_{k=1}^{2} b_k \Delta q_{xy}(t_{i-k})$$

where: $\Delta q_{xy}(t_i)$ are values at discrete times $t_1, t_2$ etc.

the coefficients $a_1..a_{n+4}$ and $b_1, b_2$ are given below

The way the coefficients are calculated is somewhat complicated:

$$a_1 = \delta_1; \quad a_2 = \delta_2 + \delta_1 b_1; \quad a_3 = \delta_3 + \delta_1 b_2; \quad i>3: \quad a_i = \delta_i;$$

and

$$b_1 = b(\tau_1) + b(\tau_2)$$
\[ b_2 = -b(\tau_1)b(\tau_2) \]
\[ \delta_i = 0 \text{ for } 1 \leq i \leq n \]
\[ \delta_{h+1} = \left( a_0(\tau_1) \tau_1 - a_0(\tau_2) \tau_2 \right)/(\tau_1 - \tau_2) \]
\[ \delta_{h+2} = \left( -a_0(\tau_1)b(\tau_2) + a_1(\tau_1) \right) \tau_1 - \left( -a_0(\tau_2)b(\tau_1) + a_1(\tau_2) \right) \tau_2 )/(\tau_1 - \tau_2) \]
\[ \delta_{h+3} = \left( -a_0(\tau_1)b(\tau_2) + a_1(\tau_1) \right) \tau_1 - \left( -a_0(\tau_2)b(\tau_1) + a_1(\tau_2) \right) \tau_2 )/(\tau_1 - \tau_2) \]
\[ \delta_{h+4} = \left( -a_0(\tau_1)b(\tau_2) + a_1(\tau_1) \right) \tau_1 - \left( -a_0(\tau_2)b(\tau_1) + a_1(\tau_2) \right) \tau_2 )/(\tau_1 - \tau_2) \]

The functions \( a_0(\tau), a_1(\tau), a_2(\tau) \) and \( b(\tau) \) are given below:

\[ a_0(\tau) = 1 - \Delta t_d - \tau + \tau \exp\left(-\frac{1 - \Delta t_d}{\tau}\right) \]
\[ a_1(\tau) = \Delta t_d + \tau - (1 - \Delta t_d - \tau) \exp\left(-\frac{1}{\tau}\right) - 2\tau \exp\left(-\frac{1 - \Delta t_d}{\tau}\right) \]
\[ a_2(\tau) = -(\Delta t_d + \tau) \exp\left(-\frac{1}{\tau}\right) + \tau \exp\left(-\frac{1 - \Delta t_d}{\tau}\right) \]
\[ b(\tau) = \exp\left(-\frac{1}{\tau}\right) \]

Remarks:

- One can easily see that there are only 5 independent factors as:
  \[ \Sigma a_i - a_1(b_1 + b_2) = 1, \text{ i.e. the steady state heat loss is correct.} \]
- For glazing, thermal mass is neglected: \( U_{yx} = U_{\text{glazing}} \) and \( a_0 = 1, a_1 = a_2 = a_3 = b_1 = b_2 = 0 \)
- If \( y \) is a different zone (not outdoors) the conductance \( a_1U_{xy} \) couples the zones (in the same way as interzonal airflows) by their resultant temperatures and an iterative solution for a multizone building is necessary.
- Adiabatic walls, internal partitions and other objects that can store heat in a room don’t contribute to this transfer heat flow

By adding the two heat flows to the construction the total heat flow is found:

\[ \Sigma \Phi_x = a_1C_{x1}(T_x - T_{x1}) + a_2C_{x2}(T_x - T_{x2}) + \Sigma a_1A_{xy}U_{xy}(T_x - T_y) + \Sigma \Delta \Phi_{xy}^* \]

where \( * \) means the previous time-step.
A.2.2 The determination of the network components

We try to find the coefficients of a second order model that gives the same heat flow with a cyclic temperature approximating a triangle with base of two hours each 24 hours. Any cyclic temperature with a period of 24 hours is a linear combination of this standard signal shifted 1 to 23 hours.

An approximate Fourier transform of this triangular pulse is:

\[
\begin{align*}
\hat{h}(t) &= 1/24 + \text{Re}\left(\sum_{i=1}^{23} w(\omega_i) \exp(j\omega_i t)\right) \\
\text{where: } w(\omega_i) &= \frac{\sin(\omega_i/2)}{\omega_i \sum_{k=1}^{23} ((-1)^k \sin(\omega_k/2)/\omega_k)} \quad \text{and} \quad \omega_i = 2\pi i / 24
\end{align*}
\]

Note that the unit of time is one hour here, so the capacitances are in [Wh/K].

The total stored heat flow resulting from this temperature pulse is:

\[
\tilde{\Phi} = \text{Re} \sum_{i=1}^{23} (w(\omega_i) \exp(j\omega_i t) Y(\omega_i))
\]

The unknown components of the network are found by minimizing the error function with respect to \(L_{x1}, L_{x2}, C_{x1}, C_{x2}\),

\[
F = \sum_{i=1}^{23} \left[ w_i^2 \cdot (Y(\omega_i) - Y_{\text{mod el}}(\omega_i)) \cdot (Y(\omega_i) - Y_{\text{mod el}}(\omega_i)) \right]
\]
where ‾ is the complex conjugate.

The main difference with the methods found in literature is that it uses a weighed sum of errors and not just the errors.

Another difference is that in the error function the model solution with unknown factors in the nominator as well as the denominator is subtracted from the exact solution instead of subtracting the nominator from the product of denominator and exact solution. We found that our method gives much better results.

The components of the model for the transmitted heat flow are determined in a similar way. Also here a triangular pulse is used to find the three unknown variables of the equation. For thick massive walls the cyclic transmittance can be very small. In that case a much longer period is used for the triangular pulse: 24*d_per hours where d_per>1 depends on the time-constant of the wall.

The pulse is:

\[
h(t) = \frac{1}{24} + \text{Re}(\sum_{i=1}^{23} w(d_{\text{per}}, \omega_i) \exp(jd_{\text{per}}, \omega_i, t))
\]

where:

\[
w(\omega_i) = \frac{\sin(\omega_i/2)}{\omega_i \sum_{k=1}^{23} (-1)^k \sin(\omega_k/2)/\omega_k}
\]

and \( \omega_i = \frac{2\pi i}{24d_{\text{per}}}, \) and the exact solution is:
\[ g_{xy} = \text{Re} \sum_{i=1}^{i_{\text{max}}} \left( w(d_{\text{per}}, \omega_i) \exp(jd_{\text{per}}\omega_it)g_{xy}(\omega_i) \right) + 1/24 \]

The normalized cyclic transmittance of the model is
\[ g_{\text{model}}(\omega_i) = \exp(-jd_{\text{per}}\omega_i\Delta t)/(1+j\omega_i(\tau_1 + \tau_2) - \omega_i^2\tau_1\tau_2) \]

The function to minimize is:
\[ F(\Delta t, \tau_1, \tau_2) = \sum_i w_i^2 (g_{xy}(\omega_i) - g_{\text{model}}(\omega_i)) (g_{xy}(\omega_i) - g_{\text{model}}(\omega_i))' \]
where: ‘ means the complex conjugate
\[ w_i = w(d_{\text{per}}, \omega_i) \]

Instead of the above function we used a simpler one to minimize:
\[ f(t_d, \tau_1, \tau_2) = \sum_i w_i^2 (g_{xy}(\omega_i) - g_{xy}(\omega_i)^2/g_{\text{model}}(\omega_i)) (g_{xy}(\omega_i) - g_{xy}(\omega_i)^2/g_{\text{model}}(\omega_i))' \]

Note that when \( \tau_1 \) is complex, \( \tau_2 \) is always its complex conjugate.

Fig. A-4. The heat flow resulting from a cyclic triangle temperature pulse

For heavyweight walls the second order approximation with time delay cannot give an accurate phase shift and amplitude for all frequencies. The high frequencies however don’t need a very accurate modelling as the amplitude of the heat flow is almost zero. The model presented is optimised for low frequencies as the heat flow can have larger amplitude. We found that provided the model gives
the correct thermal transmittance (U-value) and a more or less correct absolute transmittance for variations with periods larger than 24 hours the sensitivity on the overall results of the building model is very small. For the transient behaviour of the building the heat flow to the admittance has a dominating influence.

Fig. A-5. *The relative error (24xΔq) of the second order model for a heavy wall*

### A.2.3 The finite differences method

The temperatures on the capacitances in this network follow from the boundary conditions and the temperatures of the previous time-step:

\[
C_q(T-T^*) = -frLT+ - (1-fr)LT^* + h_Tx e_1 + h_Ty e_n
\]

\[
T = (1-1/fr)T^* + (1/fr) MM^{-1}C_qT^* + h_Tx (MM^{-1} e_1) + h_Ty (MM^{-1} e_n)
\]

where: \(MM = C_q + fr L_q\)

- \(fr\) = degree of implicitness (Crank Nicholson \(fr=0.5\))
- \(C_q\) = diagonal matrix
- \(L_q\) = tridiagonal matrix (with \(1/ΔR\))

So the heat flow to each construction is:

\[
Φ_{xy} = h_i(T_x - frT_1 - (1-fr)T_1^*)
\]

or

\[
Φ_{xy} = Φ_{i0}^* + c_{ie}(T_x - T_y) + c_i T_x
\]

where: \(Φ_{i0}^* = A_i h_i (MM^{-1}C_qT^*)_1\)

\[
c_{ie} = A_i fr h_i (MM^{-1}e_1)_n = A_i fr h_i h_n (MM^{-1}e_n)_1 \quad (MM \text{ is symmetric})
\]
\[ c_i = A_i h_i \{1 - fr_h(MM^{-1}c_t)\} - c_{ie} \]

The solution of the network follows from:

\[ C_{nx}(T_a - T_{a*}) = L_{xa}(T_x - Ta) + \Phi_{p1} + \Phi_{g1} - \Sigma \Phi_{ab} \]

\[ L_{nx}(T_a - T_x) + \Sigma \Phi_{xy} = \Phi_{p2} + \Phi_{g2} \]

where: \( T_{a*} \) = air temperature of the previous time-step

### A.3 The moisture flow to a building element

The moisture distribution through a homogeneous slab subjected to one-dimensional vapour flow is given by:

\[ \frac{\delta_a}{\mu} \frac{d^2 p_v}{dx^2} = \xi \frac{d \varphi}{dt} \]

where:
- \( \delta_a \) = vapour permeability of air (1.8 \( 10^{-8} \) s)
- \( \mu \) = vapour resistance number \( \delta_p = \delta_a / \mu \)
- \( \xi \) = specific differential moisture storage coefficient
- \( \varphi \) = relative humidity (= \( p_v / p_{sat} \))

With the boundary condition e.g.:

\[ x = 0: \quad - \frac{\delta_a}{\mu} \frac{d p_v}{dx} = \beta (p_{va} - p_v) \]

where:
- \( \beta \) = vapour surface coefficient
- \( p_{vj} \) = vapour pressure at the surface

For isothermal transport the equation is analogous to the heat diffusion equation with diffusivity \( a = \lambda / (\rho c) \) replaced by \( \delta_a p_{sat} / (\mu \xi) \) and \( T \) replaced by \( p_v \).

Also boundary conditions are similar. Instead of \( h_i \) and \( h_e \) the vapour surface coefficient is used (\( \beta_i \) and \( \beta_e \)). This coefficient is according to Lewis related to the surface convective surface coefficient:
\beta = 1.1(0.62)10^{-5} \frac{h_{cv}}{c_p}

This is the default value in the computer program. It can be changed at the input.

In the same way as treated for the thermal case a hygric second order network can be derived (sec.2.3.2). As the vapour diffusion through walls is very small compared with the vapour flow by advection there is no need for the calculation of this part.

![The second order hygric network](image)

**Fig. A-6. The second order hygric network**

The components for the second order hygric network are determined in the same way as the thermal components. \(C_{v1}\) and \(C_{v2}\) are the values at \(T=T_m\)

The way the network is solved is very similar to the way the thermal network was solved. The main difference is the dependency of the capacitance on the temperature. So (*)=previous timestep):

The vapour flow is:

\[
G_1 = \alpha_1 \left( \overline{C_{v1} p_{va}} - \overline{C_{v1} p_{vl}} \right) / \Delta t, \quad G_2 = \alpha_2 \left( \overline{C_{v2} p_{va}} - \overline{C_{v2} p_{vl}} \right) / \Delta t
\]

With:

\[
C_{v1} p_{vl} = C_{v1}^{t*} p_{vl}^{*} + \alpha_1 \left( C_{v1}^{t*} p_{va}^{*} - C_{v1}^{t*} p_{vl}^{*} \right), \quad C_{v2} p_{vl} = C_{v2}^{t*} p_{vl}^{*} + \alpha_2 \left( C_{v2}^{t*} p_{va}^{*} - C_{v2}^{t*} p_{vl}^{*} \right)
\]

\[
\alpha_1 = 1 - \exp(-\Delta t \frac{L_{v1}}{C_{v1}}), \quad \alpha_2 = 1 - \exp(-\Delta t \frac{L_{v2}}{C_{v2}})
\]

\[
\overline{C_{va} p_{va}} = \gamma \overline{C_{va} p_{va}}^{*} + (1-\gamma) \overline{C_{va} p_{va}}^{*}
\]

\[
\gamma = 0.6 \text{ and}
\]
The discretized moisture balance (eq2.6) of the room air is:

\[
\frac{\bar{C}_{\text{vat}}}{\bar{C}_{\text{va}}} = \left(1 F_i p_{\text{sat}}(T_{\text{ref}}) / p_{\text{sat}}(\bar{T}_a) \right)
\]

(A.4) Floor, wall or ceiling heating/cooling

In a floor heating system heat is supplied to the floor by tubes in the floor with hot water. It can also be done with electrical wiring. The temperature distribution is in fact three-dimensional. The water temperature in the tubes can be controlled within a certain temperature range, e.g. for heating the maximum value is typically about 50 °C.

We assume that the temperatures in the floor can be calculated with a linear equation and linear boundary conditions with respect to the unknown temperature. In that case superposition of solutions is possible: the solution without the heat input by the floor heating tubes and the solution with the heat input and boundary temperatures of 0 °C.

The first problem is already part of the HAMBASE-model without floor heating and is considered as a one-dimensional problem. The more complicated second problem remains.

In fact the problem is not linear as the surface coefficient for convection increases with an increasing temperature difference between floor and indoor environment. To take this into account the first one-dimensional problem is solved with the ‘normal’ surface coefficient for convection and the second more-dimensional problem with an increased coefficient \(h_{\text{cvfl}}\). Although not correct the result is a kind of average coefficient when heat is coming from the heating system and is the ‘normal’ coefficient when the heating system is off for a long time. The convection factor of the heating system is \(h_{\text{cvfl}} / (h_{\text{cvfl}} + h_r)\)
The heat leaving the floor by the system in a time-interval is the weighed sum of the heat input in the same time-interval and of the previous ones. This can be written with transfer coefficients. With 5 factors a very good result is possible:

\[
\Phi_n = F_1 \Phi_h + \Delta \Phi^*
\]

with \[\Delta \Phi = F_2 \Phi_h + F_3 \Phi_h^* + F_4 \Phi_h^{**} + F_5 \Phi_h^{***}\]

and \[\sum_{j=1}^{5} F_j \left(1 - \sum_{j=1}^{5} F_j \right) = R_2 / (R_1 + R_2)\]

Where \(\Phi_n\) = heat flow from the floor to the room [W] (*) previous interval etc.

\(\Phi_h\) = heat flow from floor heating tubes to floor

\(F_i\) = transfer coefficient

\(R_2\) = the thermal resistance between the plane through the centres of the tubes and the boundary below (e. g. ground temperature)

\(R_1\) = the thermal resistance between the plane through the centres of the tubes and the indoor environment

The fraction \(R_2/(R_1 + R_2)\) accounts for the heat loss to the exterior

In HAMBASE these transfer coefficients are determined with a special routine.

Also measured values can be used.

---

**Figure A-7.** The heat flow at the top surface of a floor resulting from a heat flow of 1 W during 1 hour delivered by the heating plant.
Because there is a maximum permitted water-temperature this temperature has to be determined too. Also here transfer function coefficients are used. This is done in two steps.

The first step is the determination of the transfer function coefficients for the case that the in- and outlet-temperature of the water in the piping system are equal. The ‘room’ temperature at both sides is zero. So:

\[ \Delta T_{\text{mean}} = F_{t10} \Phi_h + F_{t20} \Phi_h + F_{t30} \Phi_h + F_{t4} \Delta T_{\text{mean}} + F_{t5} \Delta T_{\text{mean}} \]

and
\[
\sum_{j=1}^{3} F_{tj0} / \left(1 - \sum_{j=4}^{5} F_{tj}\right) = 1/R_{\text{sst}}
\]

where: \( \Delta T_{\text{mean}} = \) mean water temperature – temperature without heating

\( F_i = \) transfer function coefficient

\( R_{\text{sst}} = \Phi_h / \Delta T_{\text{mean}} \) for a constant \( \Delta T_{\text{mean}} \) (steady state)

*Figure A-8. The mean temperature increase in water of a floor heating system resulting from a heat flow of 1 W during 1 hour delivered by the heating plant.*

The second step is to account for the difference between in and outlet temperature.

\[ \Phi_h = c q_m (T_{in} - T_{out}) = 2 c q_m (\Delta T_{in} - \Delta T_{\text{mean}}) \]

where: \( c = \) heat capacity of the water
\[ Q_m = \text{mass flow (kg/s)} \]
\[ T_{in}, T_{out} \text{ in and outlet temperature} \]

So the corrected transfer function coefficients are:

\[ R_{\text{flow}} = \frac{1}{2cQ_m} \]
\[ F_{T1} = F_{T10} + R_{\text{flow}}, \quad F_{T2} = F_{T20} - F_{T4} R_{\text{flow}}, \quad F_{T3} = F_{T30} - F_{T5} R_{\text{flow}} \]

The mass flow depends on the design conditions. Suppose the design conditions of the system are: the difference between in and outlet temperature is \( \Delta T_{\text{design}} \) and the heat flow is \( \Phi_{\text{fl}} = \Phi_{\text{fl,design}} \). As \( \Phi_{\text{h,design}} = (R_1 + R_2) \Phi_{\text{fl,design}} / R_1 \):
\[ cQ_m = (R_1 + R_2) \Phi_{\text{fl,design}} / (2R_1 \Delta T_{\text{design}}) \]

If instead of \( \Phi_{\text{fl,design}} \) the design surface temperature \( T_{s,\text{design}} \) is known this heat flow can easily be determined with the design indoor temperature and the combined surface coefficient:
\[ \Phi_{\text{fl,design}} = A_h \rho c v_f (T_{s,\text{design}} - T_{i,\text{design}}) \]

An alternative without transfer function coefficients is depicted in figure A-9. The resistance \( R_x \) is added to account for the difference between inlet temperature and the temperature in the floor found with this one-dimensional approximation. One can show that this resistance is:
\[ R_x = R_{\text{stat}} + R_{\text{flow}} - R_1 R_2 / (R_1 + R_2) \]

---

**Fig. A-9. Simplified thermal network for floor heating**

HAMBASE offers panel heating/cooling the following options:
- Heating/cooling of a floor or wall between two zones. The control is done by just one zone.
- Additional heating or cooling with a chosen system (with given convection factors and power) when the floor/wall system has a limited capacity.
- Heating/cooling of a floor or wall with a constant inlet temperature and an additional system.
- Calculation of relative humidity's and temperatures in the system.
Appendix B  HAMBASE help

B.1 General structure of input
B.2 The calculation period

1 PERIOD

The available climate data of De Bilt are of the years 1971 till 2000. An average Dutch year is e.g. 1 May 1974 till 30 April 1975. A cold Dutch winter (242 days) started 1 September 1978. A hot Dutch summer (123 days) started 1 May 1976. 9 hot days started 1 at July 1976 and 9 cold days started at 30 Dec. 1978.

BASE.Period = [yr, month, day, ndays]

yr = start year, month = start month, day = start day, ndays = number of days simulated

For other locations than De Bilt yr = -1 and data for the location are needed

BASE.station = [latitude, longitude (east is negative), time zone (east is negative), albedo of the place].

Moreover load the climate file of the location here. The file must start at 1 Jan 0h. and should have at maximum 365 days. A longer period than 365 days can be simulated; the year is repeated. In leap years the last day is used twice.

BASE.meteofile(1:365*24, 1:8) = [year, Diffuse solar radiation [W/m²], 10*exterior air temperature [°C], Direct solar radiation (plane normal to the direction) [W/m²], cloud cover(1...8), 100*relative humidity outside, 10*wind velocity, wind direction(degrees north)]

Example

BASE. Period = [-1, 1, 1, 370];
load('Nairhour.dat');
BASE.meteofile = Nairhour;
BASE.station = [-1.18, -36.45, -3, 0.2];
2 **DAYLIGHT-SAVINGS TIME**

If BASE.DSTime = 1 the EU daylight-savings time is taken into account. It starts on the last Sunday of March and ends on the last Sunday of October (the total duration is 30 or 31 weeks). Without a daylight-savings period BASE.DSTime = 0

If the daylight-savings period is different from the EU the starting and ending day must be given:

BASE.DSTime(1, :) = [year, starting month, day, ending month, day];

BASE.DSTime(2, :) = [year+1, starting month, day, ending month, day]; etc.

### B.3 The building

3 **ZONES, NUMBERS & VOLUMES**

A zone consists of one room or several adjacent rooms with about the same temperature and relative humidity and the same climate control e.g. a dwelling might have three zones: the ground floor (living room etc), the first floor (sleeping) and the attic (not heated). There is no limit in the number of zones that can be simulated. All zones get a zonenumber (zoneNo).

Example: 3 zones: BASE.Vol{1} = …; BASE.Vol{2} = …; BASE.Vol{3} = …;

If alone zone with number 2 (zone2): define only BASE.Vol{2}. The air mass in the zone is 1.2*volume. If the density is very different from 1.2kg/m³ e.g. at a high altitude location, the volume should be corrected to get the correct air mass (lower density is corrected by a lower volume).

BASE.Vol{zoneNo} = volume [m³];

4 **CONSTRUCTION COMPONENTS DATA**

A construction component usually consists of different layers. The order of the input of the properties of these layers is standard from indoors to outdoors and for construction components between zones from the zone with the lowest zone-
number to the highest so: 1->2, 1->3, 2->3 etc.. The material properties of the
component layer are inserted by a material ID-number. By typing 'help matpropf'
a list of materials appears with a material ID-number.

Example:

```
help matpropf
```

```
matID Material Lambda Rho C Eps Mu Ksi bv.10^-7source
...... ..............................................................
422 mineral wool 0.04 60 850 0.9 1.3 1 0 annex41
423 Fiberglass quilt 0.04 12 840 0.9 1.3 1 2.6 annex41
...... ..............................................................
```

Also each different construction component gets a different construction ID-
number: conID = 1, 2, ....

```
BASE.Con{conID} = [Ri, d1, matID,..., dn, matID, Re, ab, eb];
d1..dn = material layer thickness [m], matID = material ID-number,
Ri = internal surface heat transfer resistance
Re = surface heat transfer resistance at the opposite site
ab = external solar radiation absorption coefficient
eb = external longwave emisivity [-]
```

e.g. Ri = 0.13 [Km^2/W]); Re = 0.04 [Km^2/W]); light colour: ab = 0.4; dark colour:
ab = 0.9; eb = 0.9.

Optional: For vapour transfer two hygric surface resistances can be defined: Zvi
and Zve [m^2/kg]. Default the values are calculated from Ri and Re with the
Lewis relation: Zvi = 1000/(1/Ri-5) and Zve = 1000/(1/Re-5*eb/0.9);
Changing these values might be necessary if Zv is very different, e.g. if the
surface is very irregular (Zv is smaller). New values are obtained by inserting:

```
BASE.Zvi{conID} = new value
BASE.Zve{conID} = new value
```
5  GLAZING SYSTEMS DATA

The solar gain factor of glazing depends on the incident angle of the solar radiation. The properties below are independent of this angle but if one wants to account for the incident angle this can be done (see the shadow section below). In that case the solar gain factor at normal incidence should be inserted here. Each different glazing system gets an ID-number: glaID = 1, 2,.

BASE.Glas\{glaID\} = \{Uglas, CFr, ZTA, ZTAw, CFrw, Uglasw\};

- Uglas  = U-value without sunblinds [W/m²K],
- CFr   = convection factor without sunblinds [-],
- ZTA   = Solar gain factor [-] without sunblinds,
- ZTAw  = Solar gain factor [-] with sunblinds,
- CFrw  = convection factor with sunblinds [-],
- Uglasw = U-value with sunblinds [W/m2K].

Example:

Double glazing with exterior blinds
BASE.Glas\{1\}= \[3.2, 0.03, 0.70, 0.0.15, 0.07, 3 \];

Double glazing with interior blinds
BASE.Glas\{1\}= \[3.2-3.4, 0.03, 0.70, 0.30-0.45, 0.4-0.6, 2-2.5\];

6  ORIENTATIONS

For each surface of the building envelope (exterior walls) the tilt and the orientation with respect to the south has to be known. Each different orientation gets a different orientation-ID-number orID.

BASE.Or\{orID\} = \{tilt azimuth\};

- Tilt: vertical = 90, horizontal = 0;
- Azimuth: east  = -90, west = 90, south = 0, north = 180

7  SHADOWING
For each vertical window the shadow by exterior obstacles can be accounted for. The obstacles can have any combination of blocks, cylinders and spheres, provided some limitations regarding the positioning: The position of the blocks is such that two planes are horizontal, two vertical and perpendicular to the window pane and two parallel. The axis of the cylinder must be vertical. E.g. a tree is a cylinder and a sphere. If two equal windows with the same orientation and zone have a different view they cannot be added to one window (with the sum of the surface areas) anymore. Each shadow situation gets a shadow ID-number: shaID.

\[ \text{BASE.shad}\{\text{shaID}\} = [\text{typeno}, \text{size1}, \text{size2}, \text{size3}, \text{x}, \text{y}, \text{z}, \text{extra};
\ldots, 
\ldots, 
\ldots, 
\ldots, 
\ldots, 
\ldots, 
\text{typeno}, \text{size1}, \text{size2}, \text{size3}, \text{x}, \text{y}, \text{z}, \text{extra};] \]

\(\text{x}, \text{y}, \text{z}\) are Cartesian coordinates where \(z\) is vertical and \(x\) is horizontal and perpendicular to the window plane. Left and right are defined by facing the window from outside. The dimensions are always positive numbers.

- typeno = 1 (window): size1 = depth (= distance glazing to exterior surface), size2 = width, size3 = height of the window, \([x, y, z]\) = the coordinates of the lowest window corner at the left side, extra = elevation-angle in degrees of viewed horizon to account for far-away obstacles.

- typeno = 2 (block): size1 = width (in x-direction), size2 = length (in y-direction), size3 = height (in z-direction), \([x, y, z]\) coordinates of the left block corner closest to the window, extra = solar transmission factor (0 for opaque)

- typeno = 3 (tree): size1 = radius crown, size2 = radius trunk (e.g. 1/20*radius crown), size3 = height of the centre of the crown, \([x, y, z]\): coordinates of the bottom of the trunk, extra = solar transmission factor of crown (0 for opaque). In winter (120<\text{day}<304) this is higher than in summer. E.g. winter extra = 0.8, summer extra = 0.35

- typeno = 4: input for incident angle dependency of transmittivity of glazing. Perpendicular (angle = 0) always 1 and for 90 degrees (parallel) always 0. So there is no need for an input for these angles! First row [4, incident angle1,\ldots, incident angle7], second row [5, transmittivity1,\ldots,transmittivity7]
Example

BASE.shad{1} = [
  4  20  30  40  50  60  70  80;
  5  787/789  784/789  775/789  754/789  700/789  563/789  302/789];

In order to check if the input is correct a drawing of the obstacle geometry with number shaID (e.g. shaID = 1) can be made (see fig 2-9) by inserting the lines below:
shaID = 1;
figure (1)
shaddrawf1101(BASE.shad, shaID);

8 BUILDING COMPONENTS

A building is an assembly of different construction components. The input is about the size, place in the building and ID of these different components (for convenience called walls and windows, so also the doors, floors and roofs). They are divided into 5 groups: EXTERNAL WALLS (9): Constructions separating a zone from the exterior climate; Windows in external walls (10); CONSTANT TEMPERATURE WALLS (11): Constructions separating a zone from an environment with a constant temperature e.g. the ground; ADIABATIC EXTERNAL WALLS (12): Constructions separating a zone from an environment with the same conditions; INTERNAL WALLS (13): Constructions between and inside zones.

For external walls and constant temperature walls the heat loss by thermal bridges can be accounted for if the steady state heat loss in Watt per 1K temperature difference of these bridges is known. These values can be obtained by thermal bridge software or approximate methods. Use '0' if not known.

9 EXTERNAL WALLS

For each wall ID-number exID = 1, 2,...

BASE.wallex{exID} = [zoneNo, surf, conID, orID, bridge];
zoneNo = select zonenum from ZONES section(3),
surf = total surface \([m^2]\) the windows surface area is included,
conID = select construction ID-number from CONSTRUCTION section(4),
orID = select orientation ID-number from ORIENTATIONS section(6),
bridge = the heat loss in W/K of the thermal bridges

10 WINDOWS IN EXTERNAL WALLS
Each external wall can have one or more windows. The surface area is the area of
the transparent part. If the surface is curved the effective area for solar radiation is
needed. The U-value must be increased in such a way that the heat loss per 1K
temperature difference equals the one for the curved glazing, e.g. a glazed dome
in a flat roof has an orientation with tilt = 0, surface area 'pi*r^2' and U-value
Uglazing*2*pi*r^2/pi*r^2.
If a wall has 100% glazing use an EXTERNAL WALL that is slightly larger than
the window area. Each window gets an ID-number winID = 1, 2,...

window\{winID\} = [exID, surf, glaID, shaID];
exID = select external construction ID-number from CONSTRUCTIONS
section(4),
surf = surface area of the glazing \([m^2]\), glaID = select glass ID-number from
GLAZING section (5),
shaID = select ID-number of shadow from SHADOW section (7), no shadow:
shaID = 0.

11 CONSTANT TEMPERATURE WALLS
Each constant temperature wall gets an ID: i0ID = 1, 2,...

walli0\{i0ID\} = [zoneNo, surf, conID, temp];
zoneNo = select zone number from ZONES section(3), surf = total surface area
\([m^2]\)
conID = select construction ID-number from CONSTRUCTION section (4),
temp = constant temperature [°C], e.g. ground = '10', bridge = the heat loss in W/K of the thermal bridges (0 if unknown).

12 ADIABATIC EXTERNAL WALLS
Each adiabatic wall gets an ID: iaID = 1, 2,....

wallia{iaID} = [zoneNo, surf, conID];
zoneNo = select zone number from ZONES section(3),
surf = total surface area in m²,
conID = select construction ID-number from CONSTRUCTION section(4).

13 INTERNAL WALLS BETWEEN AND IN ZONES
All different internal walls get an ID-number: inID. If there are 3 different walls (or floors) between zone1 and zone2 the input is BASE.wallin{1} = [1, 2,....] through BASE.wallin{3} = [1, 2,....]. If the 4th construction is completely in zone2 the input is consequently: BASE.wallin{4} = [2, 2,....]
The first layer (Ri) of the construction component is in the zone that is defined in the first column. If instead BASE.wallin{3} = [2, 1,.... is used the construction is reversed and Ri is in zone2. The surface area is the surface area of one side of the wall, also for walls that are completely in the same zone.

wallin{inID} = [zone1, zone2, surf, conID];
zone1 = select zone number from ZONES section(3),
zone2 = select zone number from ZONES section, surf = total surface area [m²],
conID = select construction number from CONSTRUCTION(4) section.

B.4 Profiles for internal sources and controls

14 PROFILES TYPES
Profiles are related to the use of a zone: office, living room, school etc. on a certain day. This day can be divided in a maximum of 24 different periods (1 hour periods): period1: start time = hrnr1 and end time = hrnr2; period2: start time = hrnr2 and end time = hrnr3; last period: the hours that are left on the same day. For example [1, 8, 18] means period1: 1h till 8h, period2: 8h till 18h, period 3: 24h(==0h) till 1h and 18h till 24h. The inserted hours are the clock time.

For each period data are needed.

The profile allows for free cooling i.e. above a certain threshold Tfc the ventilation air change rate per hour (ach) is increased from minimum to a maximum value (vmin to vmax: e.g. vmax = 3*vmin). So if vmin = vmax there is no free cooling.

The temperature Tfc is also used for the control of sunblinds: if the solar irradiance on the window is higher than Ers and the indoor temperature higher than Tfc the blinds will be used. This means that if there is no free cooling the temperature Tfc is still necessary for the control of sunblinds.

Ers is the same for all zones. A number often encountered for Ers is 300W/m².

BASE.Ers{proID} = irradiance level for sun blinds [W/m²]
BASE.dayper{proID} = [hrnr1, hrnr2, hrnr3], the starting time of a new period
BASE.vvmin{proID} = [. . . ], the ach [1/hr] for each period
BASE.vvmax{proID} = [. . . ], the maximum ach [1/hr] in case of free cooling
BASE.Tfc{proID} = [. . . ], threshold [°C] for free cooling for each period
BASE.Tsetmin{proID} = [. . . ], setpoint [°C] switch for heating, (in case of no heating choose -100)
BASE.Tsetmax{proID} = [. . . ], setpoint [°C] switch for cooling, (in case of no cooling choose 100)
BASE.Qint{proID} = [. . . ], casual heat gains [W]
BASE.Gint{proID} = [. . . ], water vapour sources [kg/s]
BASE.RVmin{proID} = [. . . ], setpoint relative humidity [%] switch humidification, (in case of no humidification choose -1)
BASE.RVmax{proID} = [. . . ], setpoint relative humidity [%] switch dehumidification, (in case of no dehumidification choose 101)
THE PROFILES OF THE BUILDING

Each day of a week can have a different profile (profile ID-number: proID.) e.g. weekends are ID-number: proID.) e.g. weekends can be different.

BASE.weekfun{zoneNo} = [pnrmon, pnrtue, pnrwed, pnrthu, pnrfri, pnrsat, pnrsun]

For each zone zone = 1…etc. select the proID-numbers(14) for each day of the week: pnrmon = proId of Monday, pnrtue = proId of Tuesday, Wednesday: pnrwed, Thursday: pnrthu, Friday: pnrfri, Saturday: pnrsat, Sunday: pnrsun

B.5 Heating, cooling, humidification, dehumidification

HEATING AND COOLING PLANT

If the maximum heating capacity (W) is known then that value can be used. If it is unknown the value '-1' means an infinite capacity. The value '-2' can be used for a reasonable estimate of the maximum heating capacity. If there is no cooling the dehumidification capacity (kg/s) is '0' Cooling and dehumification are negative!

For each zone:

BASE.Plant{zoneNo} = [heating capacity, cooling capacity,... humidification capacity, dehumidification capacity];

CONVECTION FACTORS

The simulation program treats radiant heat and convective heat differently. For each zone:

BASE.convfac{zoneNo} = [CFh CFset CFint ];

CFh = Convection factor of the heating system: air heating CFh = 1, radiators CFh = 0.8 floor heating CFh = 0.5, cooling usually CFh = 1
CFset = Factor that determines whether the temperature control is on the air temperature (CFset = 1), or comfort-temperature(CFset = 0.6), Tset = CFset*Ta+(1-CFset)*Tr
CFint = is the convection factor of the casual gains (usually CFint = 0.5)

18 HEAT RECOVERY
If heat recovery from ventilation air is used the effective temperature efficiency 'etaww' and the maximum indoor air temperature 'Twws' above which the heat exchanger will be by-passed must be known. In summer with cooling on this temperature is used to switch the device on, e.g Twws = 22°C

BASE.heatexch{zoneNo} = [etaww, Twws];

19 FURNISHINGS
Real rooms are furnished. Furnishings are important moisture storage. Moisture is released dependent on the change in relative humidity. Especially in zones with a lot of paper of textiles this can easily outweigh the moisture storage of the building. A value of '1' means that about the same amount is stored as in the air that fills the volume of the zone.
The heat storage of furnishings is less important but by absorbing solar radiation and releasing that to the indoor air more solar energy enters the zone in a convective way. A value for the convective fraction of 0.2 can be considered as reasonable. For each zone:

BASE.furnishings{zoneNo} = [fbv, CFfbi];
fbv = Moisture storage factor
CFfbi = convection factor for the solar radiation due to furnishings.
Optional: If there is a known airflow between the zones (the same all the time) this can be inserted here. Airflows (dm³/s): Linkv(j, i): from zone i to zone j

BASE.Linkv(1:max(zoneNo), 1:max(zoneNo)) = [...]
B.6 Input check and changes

The input above is stored in the structured array BASE. By typing BASE in the command window, the input can be checked.

In the command window behind the input must be typed

\[
\text{[Control, Profiles, InClimate, InBuil] = Hambasefun5(BASE)};
\]

Output = Wavox1205(Control, Profiles, InClimate, InBuil); or if HAMBASE_R is used:

\[
\text{Xwavoextra1}
\]

\[
\text{[Output]=Xwavox1204(Profiles, InClimate, InBuil, Control)};
\]

20 HAMBASEFUN

In Hambasefun is checked whether input data are missing or wrong. If a warning is given it might be correct e.g. 'There is a zone without glazing' but it can also be forgotten. With an error the execution is stopped, e.g. because a material number is used for which no data are available in matpropf.

In order to shorten the files only the data needed for the calculations are selected from the input BASE array with exception of orientations, shadowing and glazing data.

In InClimate only the hours needed for the simulation are stored. The file InClimate.kli contains the hourly values of the weather data for the whole calculation period.

\[
\text{InClimate.kli(:, 1:7) = [Diffuse solar radiation \([W/m^2]\), 10*air temperature outside, Direct solar radiation (plane normal to the direction)[W/m^2], cloud cover(1...8), 100*relative humidity outside, 10*wind velocity; wind direction(degrees north)].}
\]

InClimate.LAT = latitude;
InClimate.SMLON = difference local longitude and Local Standard time Meridian;
InClimate.gref = albedo of environment;
InClimate.idag1 = number of days preceding the calculation date till Sunday 1 Jan
1968, 0h;
InClimate.date = [year, month, day, weekday(1==Monday), hour (when daylight-
savings time starts hour = 24 and is followed by hour = 2 and when it ends
hour = 1 is followed again by hour = 1]
InClimate.aantaldagen = number of days calculated; InClimate.nin; number of
extra days calculated before starting the calculation period.

If the climate file of the Bilt is mt1970(:, :) then:
InClimate.kli = mt1970(:, [1, 2, 3, 9, 6, 4, 5])

In the output of Hambasefun only the zones for which a volume is defined can be
found. The used zones also get a new number. The old number is stored in the
array: InBuil.zone(1, 2, etc) = (zone1, zone2, ...).

Also only the needed constructions can be found in the files with a new conID.
The old conID can be found at the last column of the arrays: InBuil.wandex,
InBuil.wandi0, InBuil.wandia, InBuil.wandin. The numbers of the walls (exID,
inID etc.) are also changed.

Material properties are stored in InBuil.con{i}.matprop
They are obtained with the function: matprop = matpropf(l, matID);
l = thickness (meter), matID = number of the material
matprop = [thickness, heat conductivity, density, heat capacity,
emissivity, diffusion resistance factor, vapour capacity*10^7] or
[l, lambda, rho, C, eps, mu, ksi, bv*10^7].
In case of an air cavity (matID = 2 or 3 or 4) the apparent thermal conductivity is
calculated with lambda = thickness/Rcav.

If l and matID are vectors the function returns a matrix. Each row of the matrix
corresponds with a layer.
Example

\[ l = [0.1, 0.5, 0.4]; \]
\[ \text{matID} = [205, 301, 501]; \]
\[ \text{matprop} = \text{matpropf}(l, \text{matID}) \]
\[ \text{matprop} = \]
\[ 1.0e+003 * \]
\[ 0.0001 \ 0.0006 \ 1.3000 \ 0.8400 \ 0.0009 \ 0.0075 \ 0.0020 \ 0.0015 \]
\[ 0.0005 \ 0.0001 \ 0.5000 \ 0.8400 \ 0.0009 \ 0.0050 \ 0.0300 \ 0.0072 \]
\[ 0.0004 \ 0.0002 \ 0.8000 \ 1.8800 \ 0.0009 \ 0.0300 \ 0.0400 \ 0.0034 \]

The file in matpropf can be extended with materials that are not yet in the file.

The file Profiles contains the hourly values of the profiles for each zone with a new zone number of the whole calculation period. The names are about the same as in BASE except that 'u' is added.

Useful files:
Profiles.periode(zone, hour): contains the period column number for each hour and zone, e.g. with 3 periods numbers 1, 2, 3..
Profiles.weekfun(zone, hour): contains the proID for each hour and zone
Profiles can be changed for each hour of the calculation period. An example how to do that is given below.

Example
If the value of Tset has to be changed in zone 2°C to the value 19°C on 11 dec from 12 till 17hour. (See below for the contents of InClimate.date and Profiles).
Insert the lines:

\[ k\text{zone} = \text{find(InBuil.zone==2)}; \]
\[ k = \text{find(InClimate.date(:, 2)==12&InClimate.date(:, 3)==11 & (InClimate.date(:, 5) > 12 & InClimate.date(:, 5)<= 17))}; \]
\[ \text{Profiles.Tsetu(1, k\text{zone})} = 19; \]
In Hambasefun some properties get default values. They can be changed afterwards.

- **InClimate.nin = 3** number of extra days calculated before starting the calculation period. For heavy constructions this value should be larger.

- **Control.etaintst = 100**; This is the efficiency of the plant.

- **InBuil.glas.Ri(i) = 0.13; InBuil.glas.Riw(i) = 0.13; InBuil.glas.Re(i) = 0.04; InBuil.glas.Rew(i) = 0.04; InBuil.glas.eps(i) = 0.84**; These quantities denote the surface resistances of the glazing: interior with and without solar blinds exterior with and without. eps is the emissivity at the outside surface.

- **InBuil.oriennr = [orID]**; In the output file hourly values for solar radiation and longwave radiation on a surfaces for inputted orID(section 6) are given.(orID is a row vector at the r.h.s). This is convenient for using the output for solar systems simulation.

### 21 WAVO OUTPUT

The output contains data for:

- **Output.Tcom = 'operative'indoor temperature**;
- **Output.Tx** = resultant temperature (apparent temperature for transmission heat loss);
- **Output.RHa** = indoor relative humidity;
- **Output.Ta** = indoor air temperature;
- **Output.Tr** = mean radiant temperature;
- **Output.Qplant = hourly energy use in Wh, positive 'heating', negative 'cooling'**;
- **Output.Gplant = hourly energy use for latent cooling Wh**;
- **Output.Trans = hourly transmission heat loss in Wh**;
- **Output.Vent = hourly ventilation heat loss in Wh**;
- **Output.Zon = hourly solar energy released indoors in Wh**;
- **Output.Qint = casual gains [W]**;
- **Output.Gint = vapour production [kg/s]**;
Output.figain = hourly total heat gains: solar+casual Wh;
Output.Tw = mean wall interior surface temperature (glazings excluded);
Output.RHw = mean relative humidity at the wall surface;
Output.Tglas = mean interior surface temperature of glazing;
Output.Transglas = hourly conduction heat loss by glazing [Wh];
Output.Cx1 and Output.Cx2 = heat capacitances of room [W/sK](see Chapt2);

Output.Lnr and Output.Enr: atmospheric radiation and solar radiation [W/m²] on
surface(s) defined in InBuil.oriennr = [orID];

B.7 Extra features of HAMBASE_R

The extra features are in the m-file Xwavoextra. This file must be inserted below
Hambasefun and above Xwavox (not wavox!). Data must be typed directly into
this m-file.

SUBDIVISION OF AN HOUR
InClimate.interhour = 1
If interhour = 1 no subdivision, 2 each halve hour etc.

AIR INFILTRATION
Air leakages (cracks and openings) are characterized with two coefficients C and
N. Each different leakage has an ID (lekID).

BASE.Lek{lekID} = [C, N];
C (dm³/s) = flow coefficient and N = flow exponent

Openings between zones are defined by BASE.Lekin and openings between a
zone and outdoors are defined by BASE.Lekex. Each opening gets a number
BASE.Lekin{linID} = [zone1, zone2, distance, lekID];
Distance is the distance to a reference plane e.g. the top of the roof.
BASE.Lekex{lexID} = [zoneNo, 0, distance, lekID, Cp];
Cp wind pressure coefficient; values for 'length(Cp)' wind directions.
E.g. if length(Cp) = 4:
Cp(1:4) = [Cp(north), Cp(east), Cp(south), Cp(west)]
All openings to the exterior must have the same number of Cp values.

Mechanical ventilation
Ventilation in BASE.vvmin{proID} = [ . . . ] is considered as the supply air per zone. For the infiltration simulation the exhaust air for each proID must be known.

BASE.Qmv{proID} = net mechanical ventilation = exhaust - supply air flow (dm³/s)

Mechanical induced airflow between zones can be entered in the standard input file and is stored in InBuil.Linkv. It can be changed or inserted also here.
The leakage data are stored in the files:
InBuil.infiltration = infiltration; (no infiltration :0, else 1)
InBuil.Lekin and InBuil.Lekex;

HEATING PLANT WITH A TIME CONSTANT
If the time constant is tau hours the maximum heating power is:
Qmax(zoneNo) = CFcontrol(zoneNo, 1)*Qpmax(zoneNo) +
CFcontrol(zoneNo, 2)* Qstook*(zoneNo)
Qstook* = the heating power of the previous time step.
CFcontrol(zoneNo, 2) = exp(-1/tau) (a standard step of 1 hour is chosen).
(CFcontrol(zoneNo, 1) + CFcontrol(zoneNo, 2) = 1)
tau = 0 means CFcontrol(zoneNo, 2) = 0
The values of CF are stored in the array Control.CFcontrol.

HEATING WITH A MAXIMUM TEMPERATURE INCREASE PER HOUR
For each zone a maximum temperature increase by the heating plant can be given.
\[ \text{delTstook(zoneNo)} = \text{maximum temperature increase} \]
If this is not used a large number has to be given e.g.:
\[ \text{delTstook(1)} = 100; \] (heating in zone 1 with max. 100 Kelvin/hour). If a hygrostatic control is used (see below) this option is bypassed.

The values are stored in the array: Control.delTstook

HYGROSTATIC CONTROL
The relative humidity indoors can be controlled by (de)humidification, (the usual solution) but also by changing the temperature (hygrostatic control) i.e. the temperature is increased in order to decrease the relative humidity. Of course there is a limit to this increase: Tsetmaxhygrostat. For increasing the humidity the temperature can be decreased. Also here is a limit: Tsetminhygrostat.

In the program cooling is disabled when hygrosatic control is used (the combination is not logical). Also (de)humidification is disabled. It might be necessary not to use free cooling as the ventilation might be contra-effective for the humidity control.

For each zone the data needed are:

\[ \text{hygrostat(zoneNo, :) = [1, Tsetminhygrostat, Tsetmaxhygrostat]}; \]
If the first number at the r.h.s is 0 instead of 1 there is no hygrostatic control.
This input is stored in Control.hygrostat

WALL/FLOOR HEATING OR COOLING
The input for wall/floor heating or cooling is stored in Flheat.
In each zone but one construction component (wall, floor or ceiling) (or part of it) can be used for heating or cooling. If the component is situated between two zones (wallin) the control of the heating is in the zone that is found in the first
column of wallin. If no system is present then Flheat should not be defined. If there are several zones with wall heating Flheat.property will be an array. The fluid in the system can be either water or air.

Flheat.br(1) = distance between the tubes in the construction.

Flheat.Rvw-s(1) = one dimensional heat resistance (m²K/W) between the surface of the wall at the side of the temperature control and the parallel surface through the centre of the tubes.

Flheat.Tmax(1) = maximum inlet temperature of the system e.g. 50°C, for cooling the minimum temperature. If the system is not controlled (base heating system) Tmax = a constant not controlled inlet temperature.

Flheat.Rflow(1) = 1/(massflow x heat capacity).

One way to estimate this is from design conditions: very rough \((Tmax - Tout)/Fiflhmax\) (Tout = outlet temperature, Fiflhmax = max heating power e.g. surface area x 100 W). For a better determination of Fiflhmax the thermal resistance between the whole tube register and the surface has to be calculated (with wavorespf9): \(R11 \text{ (K/W)}\). Then Fiflhmax = \((Tmax+Tout-2*Ti)/(R11*2)\), Ti design temperature of the zone.

Flheat.Ri(1) = total surface heat transfer coefficient in the controlled zone when the system is on (design condition) e.g. 1/13W/m²K (Ri>0.2!)

Flheat.Re(1) = total surface heat transfer coefficient in the not controlled zone when the system is on (design condition).

Flheat.wandtyp(1) = ..; Here a number for the construction component has to be inserted: -1:wallex, 0:walli0, -2:wallia, >=1:wallin. Note that if the heating/cooling is in wallin and if one of the zones is not defined, there is no wallin and also no heating.

Flheat.wandnr(1) = wall ID (exID, i0ID, iaID or inID)

Flheat.oppervlakte(1) = surface area of the system. This can be less than the area of the wall.

Flheat.qmax(1) = maximum heat flow density at the surface e.g \(13*(Tsurface - Tset)\)W/m² = 100W/m². If there is cooling the value is negative.

Flheat.fig(1) = 1 then a figure of the transfer (response) factors is made (calculated 2D) (with pause so press button to continue). If 0 no figure.
Flheat.basis(1) = 0. If this is 1 the system is not controlled and has a constant inlet temperature. Another heating system can be defined and controlled.

Comfortable and maximum surface temperatures:
Example:
Flheat.br(1) = 0.3;
Flheat.Rvw_s(1) = 0.015/0.8+0.1/1.7;
Flheat.oppervlakte(1) = 2*(5.1*9-5);
Flheat.Tmax (1)= 15;
Flheat.Rflow (1)= (30-20)/100;
Flheat.qmax(1) = 100;
Flheat.Ri (1)= 0.1;
Flheat.Re(1) = 1;
Flheat.wandtyp(1) = 0;
Flheat.wandnr(1) = 1;
Flheat.fig(1) = 0;

CONденSATION
In order to calculate possible condensation at night on glazing with ventilated blinds, the heat resistance from the glazing to the interior must be known.
InBuil.glas.Riwa(glaID) = resistance at the interior side. If there are no blinds this is InBuil.glas.Ri(glaID)
InBuil.glas.Rewa(glaID) = resistance at the exterior side. If there are no blinds this is InBuil.glas.Re(glaID)

B.8 Extra output in HAMBASE_R

Extra output of HAMBASE_R
Row of Output file: 1 till (number of hours) x interhour
Output.Twflh1 = surface temperature of heated (cooled) floor;
Output.RHwflh1 = surface relative humidity of heated (cooled) floor;
Output.Tset = set temperature (changes when there is hygrostatic control);

Surface temperature and relative humidity of walls: 1 and 2 surfaces. Column: 1 through number of walls
Output.Twall1(nninter, :) = Twall1; Output.RHwall1(nninter, :) = rvwall1;
Output.Twall2(nninter, :) = Twall2; Output.RHwall2(nninter, :) = rvwall2;

Surface temperature and relative humidity of windows: i en e interior and exterior surface, Column: 1 till number of windows
Output.Twindowi(nninter, :) = Twdowi;
Output.RHwindowi(nninter, :) = rvwindowi;
Output.Twindowe(nninter, :) = Twdowe;
Output.RHwindowe(nninter, :) = rvwindowe;
Output.U = Building.U. The different U-values of the constructions
Appendix C  IEA-annex41 common exercise

C.1 ASRHAE BESTEST

In IEA-annex41 four Bestest cases were proposed:
- Case 600FF: lightweight structure, base case, free floating temperature,
- Case 900FF: heavyweight structure, base case, free floating temperature,
- Case 600: lightweight structure, base case, heating and cooling system,
- Case 900: heavyweight structure, base case, heating and cooling system,

The building is depicted in figure 3-4 (windows are facing south)

GENERAL INFORMATION
- altitude : 1609 m, latitude : 39.8° north, longitude : 104.9° west
- ground temperature : 10°C
- weather file is provided by annex41, a good description of the used climate data can be found at : http://rredc.nrel.gov/solar/pubs/tmy2/
- Radiative properties:
  Internal / external opaque surfaces: emissivity = 0.9 and short wave absorption = 0.6
- Internal gains = 200 W (100% sensible : 60% radiative, 40% convective; 0% latent)
- Ventilation 0.5 ach, altitude adjustment factor: 0.822 (if the program doesn’t perform the automatic altitude adjustment)
- Windows : U = 3.0 W/m2K (double pane)
- double pane shading coefficient (at normal incidence) : 0.916
- double pane solar heat gain coefficient (at normal incidence) : 0.787

Detailed characteristics of the windows can be found in the BESTEST report (table 1-7 and 1-8 page 1-8)
SPECIFIC CONDITIONS FOR CASES 600 AND 900:
- 100% convective air system
- no latent load
- heating if air temperature < 20°C (infinite heating capacity)
- cooling if air temperature > 27°C (infinite cooling capacity – sensible only)

MATERIAL SPECIFICATIONS

<table>
<thead>
<tr>
<th>Lightweight case (600FF)</th>
<th>$\lambda$ (W/mK)</th>
<th>Thickness (m)</th>
<th>R $(m^2K/W)$</th>
<th>Density $(kg/m^3)$</th>
<th>$c_p$ (J/kgK)</th>
<th>Area $(m^2)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exterior wall (inside to outside)</td>
<td>63.60</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Int surf coeff</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plasterboard</td>
<td>0.16</td>
<td>0.012</td>
<td>0.075</td>
<td>950</td>
<td>840</td>
<td></td>
</tr>
<tr>
<td>Fiberglass quilt</td>
<td>0.04</td>
<td>0.066</td>
<td>1.650</td>
<td>12</td>
<td>840</td>
<td></td>
</tr>
<tr>
<td>Wood siding</td>
<td>0.14</td>
<td>0.009</td>
<td>0.064</td>
<td>530</td>
<td>900</td>
<td></td>
</tr>
<tr>
<td>Ext surf coeff</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.034</td>
</tr>
<tr>
<td>Floor (inside to outside)</td>
<td>48.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Int surf coeff</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.121</td>
</tr>
<tr>
<td>Timber flooring</td>
<td>0.14</td>
<td>0.025</td>
<td>0.179</td>
<td>650</td>
<td>1200</td>
<td></td>
</tr>
<tr>
<td>Insulation</td>
<td>0.04</td>
<td>1.003</td>
<td>25.075</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Roof (inside to outside)</td>
<td>48.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Int surf coeff</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.121</td>
</tr>
<tr>
<td>Plasterboard</td>
<td>0.16</td>
<td>0.010</td>
<td>0.063</td>
<td>950</td>
<td>840</td>
<td></td>
</tr>
<tr>
<td>Fiberglass quilt</td>
<td>0.04</td>
<td>0.1118</td>
<td>2.794</td>
<td>12</td>
<td>840</td>
<td></td>
</tr>
<tr>
<td>Wood siding</td>
<td>0.14</td>
<td>0.019</td>
<td>0.136</td>
<td>530</td>
<td>900</td>
<td></td>
</tr>
<tr>
<td>Ext surf coeff</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.034</td>
</tr>
<tr>
<td>Heavyweight case (900FF)</td>
<td>λ (W/mK)</td>
<td>Thickness (m)</td>
<td>R (m²K/W)</td>
<td>Density (kg/m³)</td>
<td>cp (J/kgK)</td>
<td>Area (m²)</td>
</tr>
<tr>
<td>--------------------------</td>
<td>----------</td>
<td>---------------</td>
<td>-----------</td>
<td>-----------------</td>
<td>------------</td>
<td>-----------</td>
</tr>
<tr>
<td><strong>Exterior wall</strong> (inside to outside)</td>
<td>63.60</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Int surf coeff</td>
<td>0.121</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Concrete block</td>
<td>0.51</td>
<td>0.100</td>
<td>0.196</td>
<td>1400</td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>Foam insulation</td>
<td>0.04</td>
<td>0.0615</td>
<td>1.537</td>
<td>10</td>
<td>1400</td>
<td></td>
</tr>
<tr>
<td>Wood siding</td>
<td>0.14</td>
<td>0.009</td>
<td>0.064</td>
<td>530</td>
<td>900</td>
<td></td>
</tr>
<tr>
<td>Ext surf coeff</td>
<td>0.034</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Floor</strong> (inside to outside)</td>
<td>48.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Int surf coeff</td>
<td>0.121</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Concrete slab</td>
<td>1.13</td>
<td>0.080</td>
<td>0.071</td>
<td>1400</td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>Insulation</td>
<td>0.04</td>
<td>1.007</td>
<td>25.175</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Roof</strong> (inside to outside)</td>
<td>48.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Int surf coeff</td>
<td>0.121</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plasterboard</td>
<td>0.16</td>
<td>0.010</td>
<td>0.063</td>
<td>950</td>
<td>840</td>
<td></td>
</tr>
<tr>
<td>Fiberglass quilt</td>
<td>0.04</td>
<td>0.1118</td>
<td>2.794</td>
<td>12</td>
<td>840</td>
<td></td>
</tr>
<tr>
<td>Roofdeck</td>
<td>0.14</td>
<td>0.019</td>
<td>0.136</td>
<td>530</td>
<td>900</td>
<td></td>
</tr>
<tr>
<td>Ext surf coeff</td>
<td>0.034</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### C.2 0A0B `MOISTURE BESTEST`

In annex 41 two cases were proposed for analytical solution
- Case 0A: Analytical test. Isothermal exposure. Construction surfaces are tight.
- Case 0B: Analytical test. Isothermal exposure. Construction surfaces are open.

The building is shown in figure 3-4 (with windows that should be neglected).

**GENERAL INFORMATION**

Compared to the BESTEST cases the following changes were made for the new cases:
- The altitude is 0 m.
- Constructions are made of monolithic aerated concrete with constant/linear properties.
- Tight membranes on the outside, and in case 0A also on the inside, prevent loss of vapour from the building by transport all the way through the walls.
- The exposure is completely isothermal, i.e. the same temperature outside as inside the building. However, if solutions consider the latent heat of condensation/evaporation this may generate some (local) temperature changes. Outside and initial indoor conditions are: Temperature is 20°C and relative humidity is 30% RH. These are also the initial conditions of materials in the constructions.
- The environment below the building is outside air (i.e. no ground).
- The building has no windows
- Internal moisture gain = 500 g/h from 9:00 - 17:00 every day. No moisture gains outside these hours.
- No heat gains at any time.
- Constant ventilation of 0.5 ach

SPECIFIC CONDITIONS

Case 0A:
The indoor temperature is constant at 20°C, no solar gain.
The interior surfaces are clad with a vapour tight material.

Case 0B:
Same as 0A, but now the interior surfaces are open. Only vapour transfer is to be considered, and only by diffusion. All constructions have a convective surface resistance to vapour transfer of $5.0 \times 10^7$ Pa·m$^2$·s/kg.

MATERIAL SPECIFICATIONS

Additional material properties for aerated concrete:

Water vapour permeability \( \delta_p = 3.0 \times 10^{-11} \, \text{kg/(m·s·Pa)} \)

Mean sorption curve: \( u = 0.0661 \cdot \varphi \)

where: \( u \) = moisture content (kg/kg) and \( \varphi \) = relative humidity (-)
### Table

<table>
<thead>
<tr>
<th></th>
<th>Dry λ (W/mK)</th>
<th>Thickness (m)</th>
<th>R (m²K/W)</th>
<th>Dry Density (kg/m³)</th>
<th>Dry cp (J/kgK)</th>
<th>Area (m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Exterior wall</strong> (inside to outside)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>75.60</td>
</tr>
<tr>
<td>Int. surf. coeff.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.121</td>
</tr>
<tr>
<td>Aerated concrete</td>
<td>0.18</td>
<td>0.15</td>
<td>0.750</td>
<td>650</td>
<td>840</td>
<td></td>
</tr>
<tr>
<td>Ext. surf. coeff</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.034</td>
</tr>
<tr>
<td><strong>Floor</strong> (inside to outside – the outside is air)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>48.00</td>
</tr>
<tr>
<td>Int. surf. coeff</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.121</td>
</tr>
<tr>
<td>Aerated concrete</td>
<td>0.18</td>
<td>0.15</td>
<td>0.750</td>
<td>650</td>
<td>840</td>
<td></td>
</tr>
<tr>
<td>Ext. surf. coeff</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.034</td>
</tr>
<tr>
<td><strong>Roof</strong> (inside to outside)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>48.00</td>
</tr>
<tr>
<td>Int. surf coeff</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.121</td>
</tr>
<tr>
<td>Aerated concrete</td>
<td>0.18</td>
<td>0.15</td>
<td>0.750</td>
<td>650</td>
<td>840</td>
<td></td>
</tr>
<tr>
<td>Ext. surf. coeff</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.034</td>
</tr>
</tbody>
</table>

### C.3 Whole building heat and moisture analysis

Two measured cases are compared with simulations:

1. Test room only with aluminum foil
2. Reference room with a standard common used gypsum plaster

The building is shown in figure 3-7.

### GENERAL INFORMATION

- altitude: 680 m NN; latitude: 47.88°, north; longitude: 11.73°, east
- weather files are supplied in annex41 as TRY (external climate). Only the south side is exposed to the external climate
- On the north side (passage way) and over the ceiling there is an internal climate, but the space is unheated. On the left and right side of the rooms the climate conditions are 20 °C and 50 % RH. For the calculations the climate in the next rooms is not very important because the indoor walls are thermal decoupled.

- The boundary conditions for the ground are on the average 2°C.

- Radiative properties: internal and external opaque surfaces: emissivity and absorption: long wave: 0.9, short wave: 0.4

The temperatures in the rooms are controlled to 20±2°C. It is regulated through a small electric radiator. The radiator has a power of circa 1000 W.

The required energy was recorded. The moisture production in both test rooms corresponds to a normal four person household and is converted to the test rooms. In the rooms the moisture production is 2.4 kg/d. There is a permanently present basic humidity production of 25 g/h due to e.g. plants or pets. In the early morning hours between 6 am and 8 am, this value is increased to a peak level of 400 g/h in order to simulate human activities, like having a shower and washing. Subsequently, the moisture production will drop back to the basic rate of production 25 g/h. In the late afternoon the moisture production will increase again to a moderate level (200 g/h) until the evening hours (4 pm until 10 pm) which represents certain activities like cooking, cleaning or doing the laundry.

The air-tightness of the rooms was measured with blower-door method. The measurement results are n₆₀ = 1.3 h⁻¹ for the reference room and n₃₀ = 1.01 h⁻¹ for the test room. After conversion to the air change by infiltration under normal pressure conditions, ach = 0.09 h⁻¹ for the reference room and ach = 0.07 h⁻¹ for the test room (multiplication of the value determined for Δp = 50 Pa with the factor 0.07). The additional air change rate of the ventilation system is ach = 0.5 h⁻¹ which means a constant air flow of about 25 m³/h. (Volume of the rooms: 48.49 m³ + volume of reveals 0.86 m³).
The window is included in the southern wall. It is a double-glazed window with a U-value of 1.1 Wm²K and a dimension of 1.41 x 1.94 m². During the tests a wool blanket was situated in front of the window on the outside in order to exclude any solar radiation into the rooms. Therefore for the calculations only the U-value is important. The doors from the passage way to the rooms have 5 cm polystyrene on the inside and the size of it is 1.94 x 0.82 m².

Measured data were supplied by the Fraunhofer-Institut of Building Physics in Holzkirchen. The measurements run from 2005-01-17 to 2005-02-02.

**MATERIAL SPECIFICATIONS**
In the table below is the data for the different walls, ceiling and floor types. In the table is a mistake; the right $s_d$-value of the aluminum foil is $s_d = 10000$ m.
The gypsum plaster is painted : $s_d = 0.15$ m

The retention curve can be calculated from:

\[ w(\phi) = w_f(b-1)\phi/(b- \phi) \rightarrow w_{80} = w_f(b-1)0.8/(b- 0.8) \]

<table>
<thead>
<tr>
<th>Material</th>
<th>$\lambda$ (W/mK)</th>
<th>Thickness (m)</th>
<th>Density (kg/m³)</th>
<th>$c_p$ (J/kgK)</th>
<th>$w_{80}$ kg/m³</th>
<th>$w_f$ kg/m³</th>
<th>$\mu$ (-)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Exterior wall</strong> (inside to outside)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$A = 24.75$ m²</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aluminium foil*</td>
<td>5e-6</td>
<td></td>
<td></td>
<td>0</td>
<td>0</td>
<td>2e+8</td>
<td></td>
</tr>
<tr>
<td>Gypsum plaster</td>
<td>0.2</td>
<td>0.01</td>
<td>850</td>
<td>850</td>
<td>6.3</td>
<td>400</td>
<td>8.3</td>
</tr>
<tr>
<td>Old inside plaster</td>
<td>0.2</td>
<td>0.02</td>
<td>1721</td>
<td>850</td>
<td>1.8</td>
<td>264</td>
<td>13</td>
</tr>
<tr>
<td>Brick</td>
<td>0.6</td>
<td>0.24</td>
<td>1650</td>
<td>850</td>
<td>9</td>
<td>370</td>
<td>9.5</td>
</tr>
<tr>
<td>Mineral plaster</td>
<td>0.8</td>
<td>0.015</td>
<td>1900</td>
<td>850</td>
<td>45</td>
<td>210</td>
<td>25</td>
</tr>
<tr>
<td>Polystyrene</td>
<td>0.04</td>
<td>0.07</td>
<td>30</td>
<td>1500</td>
<td>0</td>
<td>0</td>
<td>50</td>
</tr>
<tr>
<td>Mineral plaster</td>
<td>0.8</td>
<td>0.005</td>
<td>1900</td>
<td>850</td>
<td>45</td>
<td>210</td>
<td>25</td>
</tr>
<tr>
<td><strong>Wall between test room and reference room, $A = 9.7$ m²</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Int surf coeff = 1/8
Ext surf coeff = 1/18
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminium foil</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gypsum plaster</td>
<td>0.2</td>
<td>0.01</td>
<td>850</td>
<td>850</td>
<td>6</td>
<td>400</td>
<td>9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solid Brick</td>
<td>0.6</td>
<td>0.115</td>
<td>1650</td>
<td>850</td>
<td>9</td>
<td>370</td>
<td>9.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mineral wool</td>
<td>0.04</td>
<td>0.10</td>
<td>60</td>
<td>850</td>
<td>0</td>
<td>0</td>
<td>1.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solid Brick</td>
<td>0.6</td>
<td>0.115</td>
<td>1650</td>
<td>850</td>
<td>9</td>
<td>370</td>
<td>9.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gypsum plaster</td>
<td>0.2</td>
<td>0.01</td>
<td>850</td>
<td>850</td>
<td>6</td>
<td>400</td>
<td>9</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Wall between rooms and passage**

**A = 13.26m²**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminium foil</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gypsum plaster</td>
<td>0.2</td>
<td>0.015</td>
<td>850</td>
<td>850</td>
<td>6</td>
<td>400</td>
<td>9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lime silica brick</td>
<td>1</td>
<td>0.175</td>
<td>1900</td>
<td>850</td>
<td>25</td>
<td>250</td>
<td>28</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polystyrene</td>
<td>0.04</td>
<td>0.05</td>
<td>30</td>
<td>1500</td>
<td>0</td>
<td>0</td>
<td>50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gypsum plaster</td>
<td>0.16</td>
<td>0.0125</td>
<td>850</td>
<td>870</td>
<td>35</td>
<td>400</td>
<td>6</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Ceiling**

**A = 19.34m²**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminium foil</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gypsum plaster</td>
<td>0.2</td>
<td>0.015</td>
<td>850</td>
<td>850</td>
<td>6</td>
<td>400</td>
<td>9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Concrete</td>
<td>1.6</td>
<td>0.175</td>
<td>2300</td>
<td>850</td>
<td>85</td>
<td>150</td>
<td>180</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polystyrene</td>
<td>0.04</td>
<td>0.2</td>
<td>30</td>
<td>1500</td>
<td>0</td>
<td>0</td>
<td>50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Concrete screed</td>
<td>1.6</td>
<td>0.05</td>
<td>1950</td>
<td>850</td>
<td>38</td>
<td>155</td>
<td>75</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wood</td>
<td>0.09</td>
<td>0.025</td>
<td>400</td>
<td>1500</td>
<td>60</td>
<td>575</td>
<td>200</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Floor (inside to outside)**

**A = 19.34m²**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>PVC linoleum</td>
<td>0.16</td>
<td>0.003</td>
<td>1000</td>
<td>1500</td>
<td>0</td>
<td>0</td>
<td>15e3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Concrete screed</td>
<td>1.6</td>
<td>0.05</td>
<td>1950</td>
<td>850</td>
<td>38</td>
<td>155</td>
<td>75</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polystyrene</td>
<td>0.04</td>
<td>0.2</td>
<td>30</td>
<td>1500</td>
<td>0</td>
<td>0</td>
<td>50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Concrete</td>
<td>1.6</td>
<td>0.25</td>
<td>2300</td>
<td>850</td>
<td>85</td>
<td>150</td>
<td>180</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*only in the right test room.*