Chapter 2
Inputs for Hygrothermal Simulation Tools

The hygrothermal performance of a construction material can be assessed by analysing energy, moisture, and air balances. The hygrothermal balances consider the normal flows of heat by conduction, convection, and radiation; moisture flows by vapour diffusion, convection, and liquid transport; and airflows driven by natural, external, or mechanical forces.

The prediction of the hygrothermal performance of the building enclosure typically requires some knowledge of geometry of the enclosure, boundary conditions and material properties.

2.1 Geometry of the Enclosure

The enclosure geometry must be modelled before any hygrothermal analysis can begin. In simple methods the geometry is reduced to a series of one-dimensional layers. The enclosure geometry includes all macro building details, enclosure assembly details and micro-details.

2.2 Boundary Conditions

The boundary conditions imposed on a mathematical model are often as critical to its accuracy as the proper modelling of the moisture physics. In general, the following environment needs to be known: Interior environment, exterior environment and boundary conditions between elements.

The correct treatment of the interfacial flows at boundaries between control volumes of different type is an important point in successful modelling.

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2.2.1 Exterior Environment

HAM models normally provide hourly evolution of temperature and moisture distributions on the building component under study, considering not only the processes inside the component but also the interaction with the surroundings that, for building physics, is the ambient air (outdoor and indoor). The outdoor ambient air or the exterior environment is described, for most HAM models, in terms of hourly meteorological parameters. The climate data, on hourly bases, that is required for most hygrothermal software tools are:

- Temperature of the exterior air in °C.
- Relative humidity of the exterior air in %.
- Barometric pressure in hPa. This parameter has a small effect on the calculations performed by HAM models, so a mean value over the calculation period may be acceptable.
- Solar radiation incident on the surface in W/m^2. This parameter must include direct and diffuse solar radiation (often reflected solar radiation is neglected). To calculate the total amount of solar radiation incident on the surface, the inclination and the orientation of the surface must be considered. If the HAM models perform these calculations, the climatic data that shall be used is solar radiation (direct and diffuse) on a horizontal surface, which are common meteorological parameters. Otherwise, calculations have to be performed manually or direct measurements must be carried out and then introduced as input data.
- Rain load vertically incident on the exterior surface in l/m^2 h. This parameter, as solar radiation, is not a conventional weather measurement. The determination of this load can be made manually or by the hygrothermal tool. For the calculation it must be considered orientation and inclination of the component and the normal rain in mm, the wind velocity in m/s and the wind direction in °, counted clockwise from north (0°) over east (90°).
- Long-wave atmospheric radiation incident on the surface in W/m^2, if the radiative balance on the surface is to be performed explicitly in the calculation. This parameter may be measured or calculated based on the air temperature, barometric pressure and cloud index. The inclination of the component must be known so the appropriate fraction of the radiation incident on the surface can be calculated from the long-wave atmospheric radiation incident on a horizontal surface.

Common climatic data that is necessary to hygrothermal simulations is: (a) wind velocity [m/s]; (b) wind direction [°] counted clockwise from north (0°) over east (90°); (c) normal rain [mm]; (d) ambient air pressure [hPa]; (e) air temperature [°C]; (f) air relative humidity [%]; (g) direct or global solar radiation incident on a horizontal surface [W/m^2]; (h) diffuse solar radiation incident on a horizontal surface [W/m^2]; (i) thermal radiation of the atmosphere incident on a horizontal surface [W/m^2]; (j) cloud index [–]. This data can be measured by a weather station, can be calculated using weather software tools that create synthetic values or can result from a statistical treatment of meteorological datasets of individuals months selected from different years over an available data period, containing characteristic weather data of a representative year (Test Reference Years, Design Reference Years, Typical Meteorological Years, etc.).

2.2.2 Interior Environment

The indoor ambient air or the interior environment is characterized by hourly values of temperature, in °C, and relative humidity, in %. These climatic parameters can be provided to the HAM model by a climatic file, containing measured values on the site using temperature and relative humidity probes, or generated values derived from exterior climate. There are a few standards that rule the simulation of indoor climate like EN ISO 13788 (2002), EN 15026 (2007) or ASRAE 160P (2009).

2.2.3 Indoor and Outdoor Surface Transfer

Heat exchanges between the surface and the adjacent air occur by convection. The convective flow is expressed as a function of the convective heat transfer coefficient, h_c (Hagentoft 2001).

$$q_c = h_c \cdot (T_a - T_s) \tag{2.1}$$

The methodology to calculate accurately the convective heat transfer coefficient is not consensual. Different nominal values or functions are available on the literature. The reason for this diversity is the complexity of the convective heat transfer that is dependent on temperature differences between the air and the surface, the magnitude and direction of the air flow and the nature of the surface (geometry and roughness). Table 2.1 presents some examples of functions/values found in the literature for the convective heat transfer coefficient, considering the two types of convection: natural convection, caused by temperature differences, and forced convection, caused by wind, fans, etc.

The radiative heat transfer coefficient, h_r, specifies the long-wave radiation exchange between the building surface and other terrestrial surfaces (sky included), that is governed by the Stefan-Boltzmann Law (σ is the Stefan-Boltzmann constant). As all surrounding surfaces of the building have similar temperatures, the heat flux, q_r, dependent on the fourth power of the temperature, can be linearized with good approximation. Since normally the temperatures of the terrestrial surfaces are not known, they are assumed, by approximation, to be identical to the air temperature.

Table 2.1 Convective heat transfer coefficient

Natural convection		
$h_c = 2 \cdot \lvert T_a - T_s \rvert^{1/4}$	At interior surfaces	Hagentoft (2001)
$0.3 \leq h_c \leq 0.8$	Stable air layers horizontal surface	
$h_c = a \cdot \left(\frac{\Delta\theta}{L}\right)^b$	At ambient temperatures	Hens (2007)
3.5	Inside vertical surfaces	
5.5	Inside horizontal surfaces (heat upwards)	
1.2	Inside horizontal surfaces (heat downwards)	
2.5	Inside vertical surfaces	EN 15026 (2007)
5	Inside horizontal surfaces (heat upwards)	
0.7	Inside horizontal surfaces (heat downwards)	
$3 \leq h_c \leq 10$	–	Kuenzel (1995)
Forced convection		
$h_c = 5 + 4.5 \cdot v_v - 0.14 \cdot v_v^2$	Windward side	Hagentoft (2001)
$h_c = 5 + 1.5 \cdot v_v$	$v_v \leq 10$ m/s	
	Leeward side	
	$v_v \leq 8$ m/s	
$h_c = 5.6 + 3.9 \cdot v_v$	$v_v \leq 5$ m/s	Hens (2007)
$h_c = 7.2 \cdot v_v^{0.78}$	$v_v > 5$ m/s	
19.0	Outside surfaces	
$h_c = 4 + 4 \cdot v_v$	–	EN 15026 (2007)
$h_c = 4.5 + 1.6 \cdot v_v$	Windward side	Kuenzel (1995)
$h_c = 4.5 + 0.33 \cdot v_v$	Leeward side	
$10 \leq h_c \leq 100$	–	

Furthermore, is also assumed that all objects have similar long-wave emissivities, ε, as long as they are non-metallic, which is usually the case in the context of building physics. Three of the four powers of the temperature are lumped together with the radiative heat transfer coefficient and a simple linear relationship analogous to the convective heat transfer is obtained (Hagentoft 2001).

$$q_r = \varepsilon_t \cdot \sigma \cdot T_a^4 - \varepsilon_s \cdot \sigma \cdot T_s^4 \approx h_r \cdot (T_a - T_s) \tag{2.2}$$

$$h_r = 4 \cdot \varepsilon \cdot \sigma \cdot T_0^3 \tag{2.3}$$

where T_0 is an average temperature depending on the surface, the surrounding surfaces and the sky.

Although these temperatures change in time, in most formulations they are assumed as constant. Providing that outside surfaces have similar emissivity, a constant value for the radiative heat transfer coefficient may be adopted. For two close, extended, parallel, plane, non-metallic surfaces more or less at ambient temperature the radiative heat transfer coefficient lies between 3 and 6 W/m^2 K.

Most models consider explicitly the effect of solar radiation as it has an enormous impact on exterior surface temperatures that cannot be included in the radiative heat transfer coefficient. Solar radiation, considered as a source of heat that increases the surface temperature during the day, depends on short-wave radiation absorptivity, α_s, and on the solar radiation normal to component surface, I_s (Hagentoft 2001)

$$q_s = \alpha_s \cdot I_s \tag{2.4}$$

The solar radiation normal to a surface can be calculated depending on the inclination and orientation of the component, from direct (or global) and diffuse solar radiation incident on a horizontal surface. Short-wave radiation absorptivity depends on the colour and brightness of the material.

Water vapour transfer from air to a surface, or vice versa, is affected by a resistance due to the existence of a boundary air layer. It may be described, in analogy to the heat transfer, by the water vapour transfer coefficient, β_v, and the difference between the vapour pressures of the air, p_v, and of the surface, p_s.

$$g_v = \beta_v \cdot (p_v - p_s) \tag{2.5}$$

The water vapour transfer coefficient depends on the air velocity close to the surface and it can be derived from the convective heat transfer coefficient through some simplifications to the Lewis formula.

$$\beta_v = 7 \cdot 10^{-9} \cdot h_c \tag{2.6}$$

Some numerical HAM models allow simulating the effect of wind-driven rain (WDR) on the water content of a component by introducing a load of moisture on the exterior surface calculated by a semi-empirical model. The semi-empirical models refer to models with a theoretical basis and with coefficients that are determined from measurements. Practically all semi-empirical methods available nowadays are based on the WDR relationship (Eq. 2.7) that estimate the amount of rain that reaches a surface based on the weather data for normal rain, wind velocity and wind direction. One of the biggest problems of these methods is to obtain a reliable WDR coefficient. This value is what distinguishes the models and it can vary between 0.02 and 0.26 s/m (Blocken 2004).

$$R_{WDR} = k \cdot R_h \cdot v \cdot \cos\,\theta \tag{2.7}$$

where R_{WDR} is the wind-driven rain intensity [l/(m^2 h)], k is the WDR coefficient [s/m], R_h is the horizontal rainfall amount [mm/h], v is the wind speed which is admitted to be at 10 m height [m/s], and θ is the angle between the wind direction and the normal to the façade [°].

If the rain load in known and if the surface is not completely wetted the moisture sate of the surface, g_w, can be calculated by Eq. 2.8 (similar to Eq. 2.4 for solar radiation).

$$g_w = \alpha_{WDR} \cdot R_{WDR} \tag{2.8}$$

The concept of precipitation absorptivity, α_{WDR}, allows take into account that a part of the rain water impacting the surface splashes off again. The value of precipitation absorptivity depends on several factors such as roughness, orientation and nature of precipitation (Kuenzel 1995).

2.3 Material Properties

Hygrothermal simulation is highly demanding on the number of material properties required. Those properties can also present variation with temperature, moisture content and age, as well as present chemical interaction with other materials. Typical material properties needed in hygrothermal simulation include: bulk density, porosity, specific heat capacity, thermal conductivity, vapour permeability, water absorption coefficient, sorption isotherm and moisture retention curve. On the following sections, experimental processes for determination of material properties are described.

2.3.1 Bulk Density (ρ)

Several standards can be applied for the experimental determination of this property, as EN ISO 10545-3 (1995) for ceramic tiles, EN 12390-7 (2000) for concrete, EN 772-13 (2000) for masonry units. The samples must be dried until constant mass is reached. The samples volume is calculated based on the average of three measurements of each dimension.

2.3.2 Porosity (ε)

The standards EN ISO 10545-3 (1995) for ceramic tiles and ASTM C 20 (2000) for fired white ware products, could be used to measure the bulk porosity of building materials. The samples are dried until constant mass is reached (m_1). After a period of stabilization, the samples are kept immersed under constant pressure. Weigh of the immersed sample (m_2) and the emerged sample (m_3) the bulk porosity is given by: $\varepsilon = (m_3 - m_1)/(m_3 - m_2)$.

2.3.3 Specific Heat Capacity (c_p)

This test method employs the classical method of mixtures to cover the determination of mean specific heat of thermal insulating materials. The materials must be essentially homogeneous and composed of matter in the solid state (see ASTM C 351-92b (1999)).

The test procedure provides for a mean temperature of approximately 60 °C (100 to 20 °C; temperature range), using water as the calorimetric fluid. By substituting other calorimetric fluids the temperature range may be changed as desired. All the samples shall be dried to constant mass in an oven at a temperature of 102–120 °C and the method is to add a measured material mass, at high temperature, to a measured water mass at low temperature in order to determine the resulting equilibrium temperature. The heat absorbed by water and container is so calculated and this value equalised to the amount of heat released expression in order to calculate the specific heat desired.

2.3.4 Thermal Conductivity (λ)

The transfer of moisture through common building materials, such as wood, concrete and brick, depends on the complex morphotopological characteristics of the pores in these materials. The thermal conductivity (λ) is a function of temperature and moisture content and is calculated as:

$$\lambda = \lambda_d + C_T\left(T - T_{ref}\right) + C_w w \tag{2.9}$$

where λ_d is the thermal conductivity of the building material under dry conditions and C_{T} and C_{w} are temperature and moisture modification coefficients, respectively. The effect of moisture on porous building material properties is quite large (Mendes et al. 2003) and neglecting it can lead to large errors in conduction heat transfer.

The standards ISO 8302 (1991), EN 12664 (2001), EN 12667 (2001) and EN 12939 (2001) can be applied to determine the thermal conductivity of building materials using the Guarded Hot Plate method (Figs. 2.1 and 2.2). The method uses two identical samples of parallel faces that must be dried, prior to the test. After the system stabilization, a constant flux is obtained, perpendicular to the

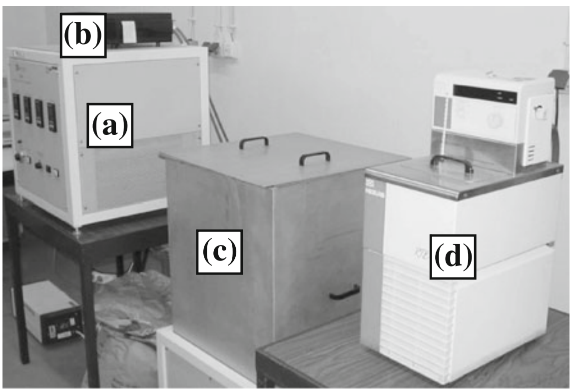

Fig. 2.1 Guarded hot plate device: **a** temperature control, **b** data logger, **c** test vessel, **d** refrigeration equipment

Fig. 2.2 Test vessel containing samples for thermal conductivity measurement

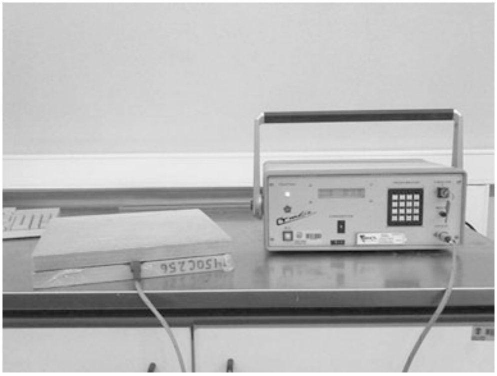

Fig. 2.3 Thermal shock method for determination of thermal conductivity of moist materials

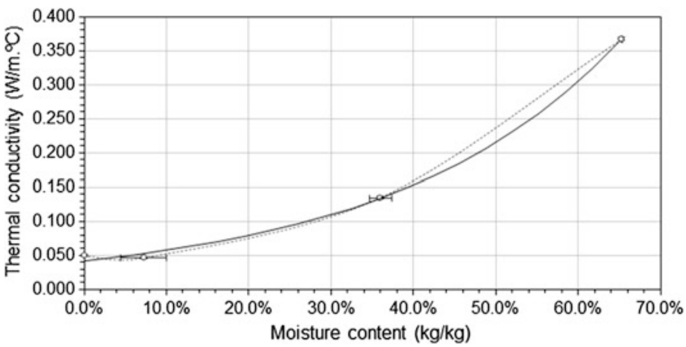

Fig. 2.4 Thermal conductivity variation with moisture content for polyurethane foam

samples dominant faces. Knowing the temperature in opposite faces and the power supply to the hot plate allows determining the thermal conductivity of the samples.

The determination of the thermal conductivity values for moist samples cannot be performed with the guarded hot plate method. The thermal shock method (Fig. 2.3), although less precise, can be used in the characterization of moist materials. The standards EN 993-14 and EN 993-15 describe the method. Figure 2.4 presents a typical variation with moisture content of the thermal conductivity of a thermal insulation product.

2.3.5 Water Vapour Permeability (δ_p)

Vapour permeability is usually determined using the cup test method. The standard EN ISO 12572 (2001) can be used as a reference. The sample is sealed in a cup (Fig. 2.5) containing either a desiccant (dry cup) or a saturated salt solution (wet cup). The set is put inside a climatic chamber (Fig. 2.6) where the relative humidity value is regulated to be different from the one inside the cup. The vapour pressure gradient originates a vapour flux through the sample. The periodic weighing of the cup allows for the calculation of the vapour transmission rate. The method can only be applied if steady-state conditions are achieved through the thickness of the sample. This can be a difficulty for highly permeable materials as the cups will see their initial conditions change very quickly. The test characteristics also imply that it must be performed under isothermal conditions. This can be a difficulty if one intends to reflect the actual behaviour of a material in the envelope. The literature, however, considers that the influence of temperature on the vapour transfer coefficients is negligible.

Figure 2.7 presents an example of vapour permeability test results, using three different materials and three different test conditions. If several values are

Fig. 2.5 Mass determination of a sample sealed in a cup

Fig. 2.6 Cups inside a climatic chamber

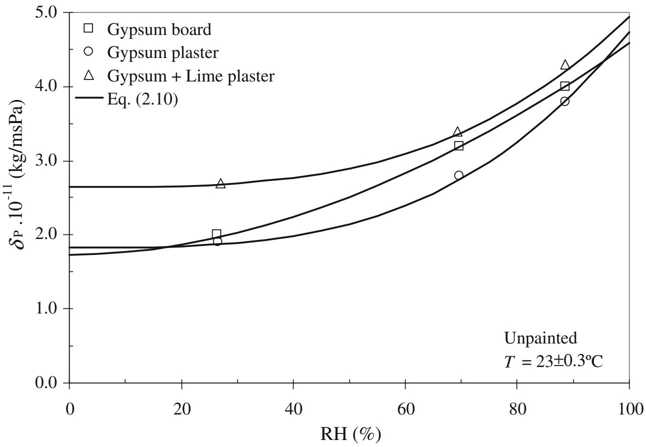

Fig. 2.7 Water vapour permeability for different specimens tested, at 23 °C, and curve fit

available, the points determined in the test a function can be fitted to the results. The literature (see Burch et al. (1992) and Galbraith et al. (1998)) suggests possible functions that typically fit these results. In the example, the following equation was selected:

$$\delta_{\mathrm{p}}(\phi) = A_1 + A_2 \cdot \phi^{A_3} \tag{2.10}$$

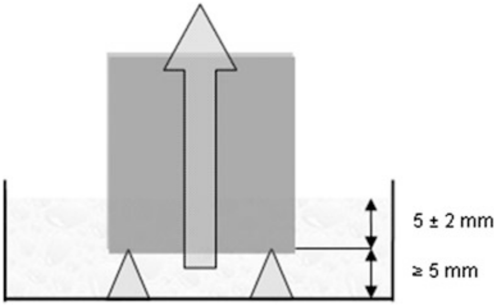

Fig. 2.8 Principle of the water absorption test

2.3.6 Water Absorption Coefficient (A)

The standard EN ISO 15148 (2002) can be applied in the determination of the water absorption coefficient by partial immersion (see Fig. 2.8). The side faces of the samples are made impermeable to obtain a directional flux. After stabilization with the room air, the samples bottom faces are immersed (5 ± 2 mm) and weighed at time intervals defined according to a log scale during the first 24 h period and after that every 24 h. This property is derived from the linear relation between mass variation and the square root of time. When that relation is not verified, only the values registered at 24 h are used.

Liquid transport coefficients can be derived from the water absorption coefficient. As an example, the Eq. (2.11) is used in the WUFI software for estimating liquid diffusivity.

$$D_{ws}(w) = 3.8\left(\frac{A}{w}\right)^2 1000^{(w-w_f)-1} \quad (2.11)$$

where D_{ws} (m^2/s) is the liquid transport coefficient for suction, A (kg/m^2 s$^{0.5}$) is the water absorption coefficient, w (kg/m^3) is the moisture content and w_f (kg/m^3) is the free water saturation.

2.3.7 Moisture Storage Functions

The sorption isotherm, describing the moisture storage of a material in the hygroscopic range, can be determined using different methods. Gravimetric type methods are usually preferred for building materials following, for instance, the standard EN ISO 12571 (2000). According to this document, the sorption isotherms are determined by stabilizing material samples in different conditions of relative humidity and constant temperature. The obtained values allow knowing the moisture content of the material at hygroscopic equilibrium with the surrounding air. An apparatus for that test, using salt solutions, can be observed in

Fig. 2.9 Sorption isotherm determination

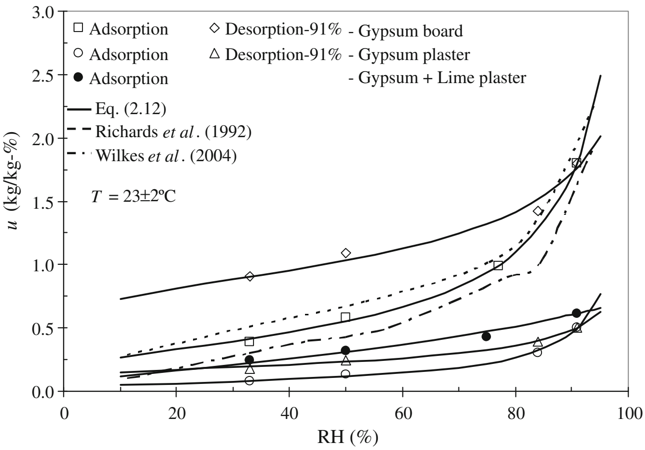

Fig. 2.10 Sorption isotherms for three types of plaster tested and comparison with other results, presented in literature, for the case of gypsum board

Fig. 2.9. In Fig. 2.10 examples of sorption isotherms for gypsum based materials are presented. The difference between adsorption and desorption, hysteresis, is highlighted, as well as the differences that can be found in different sources in literature for what was assumed to be the same material. Equation (2.12) presents an example of a function that is frequently used for fitting sorption test data:

$$u = u_{\mathrm{h}} \cdot (1 - \ln \phi / A_1)^{-1/n} \tag{2.12}$$

Table 2.2 Building material properties

Material	ρ (kg/m^3)	ε (%)	c_p (J/kg K)	λ (W/mK)	A (kg/m^2 s$^{0.5}$)
Stone	1600–2800	0.5–20	1000	0.5–3.5	0.01–0.025
Lime plaster	1600	26	1000	0.8–1.5	0.01–0.25
Concrete	2200	0.18	850	1.6	92
Brick	1000–2400	28	920	0.34–1.04	0.05
Water-repellent final stucco coat	1380	0.36	850	0.87	8
Exterior stucco undercoat	1200	0.3	850	0.25	11
Mineral-bound wood–wool panel	320	0.40	2000	0.09	1.9
Compressed surface of mineral bound wood–wool panel	750	0.15	2000	0.11	10
Medium-density fiberboard (MDF)	255	0.98	2000	0.051	5.0
Mineral wool	60	0.95	850	0.04	1.3
Oriented strand board (OSB)	555	0.6	1880	0.101	287
Liquid vapor retarder coating	1140	0.001	2300	2.3	50000
Gypsum board	1153	0.52	1200	0.32	16
Internal stucco	850	0.65	850	0.20	8.3
Resin finishing coat (acrylic stucco)	2000	0.12	850	0.70	1000
EPS (Expanded polystyrene)	15	0.95	1500	0.04	30
Cement plaster–stucco	2000	0.30	850	1.20	25

The moisture content in the over-hygroscopic region is usually defined using suction curves that can be determined using pressure plate measurements. Since these tests are time consuming, a function is often derived for the moisture storage curve based on a few points determined in sorption tests.

2.3.8 Reference Values

The standards EN ISO 10456 (2007) and EN 12524 (2000) present tabulated design values of hygrothermal properties for a wide range of building materials (see Table 2.2).

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