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TOWARDS WHOLE BUILDING MOISTURE MODELLING OF THE IMPACTS OF SHORT DURATION MOISTURE RELEASE

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ABSTRACT

Considerable progress has been made in the field of building simulation for combined heat, air and mass transfer processes occurring in the indoor environment, yet concerns persist over the reliability and suitability of moisture property data integrated into available tools and the approaches taken in modelling physical phenomena. Particular interest lies in predicting the impact of indoor moisture production schemes and sources observed in housing, linked to occupant activity. To this end, the work included in this paper includes studies to verify and develop the capabilities of the building simulation tool ESP-r in modelling indoor environmental conditions resulting from occupant-related moisture production. The activities include modelling a realistic scenario taken from IEA Annex 41, a laboratory based experiment focused on short-duration, high moisture loading pulses and the development of a moisture release model associated with the passive drying of clothes.

INTRODUCTION

Relationships have been identified between perceived building indoor air quality (IAQ) and the presence of moisture (Heinrich 2011). IAQ is the result of occupant activity and the product of other biological and toxicological emissions. It is intrinsically linked to the air being supplied to the indoor environment as part of mechanical integrated air management systems and/or passive movement of air between the indoor and outdoor environment, driven by pressure gradients (Sherman and Walker, 2011). Recent improvements, focused on improving building energy efficiency and indoor thermal comfort have tended to neglect the issue of IAQ. Indeed, as reducing infiltration rates and increasing the level of insulation are some of the main energy efficiency actions being taken, IAQ could deteriorate through increasing concentrations of airborne contaminants including moisture (Jones 1999).

The presence of moisture in the indoor environment, commonly measured as relative humidity (RH), is influential on the overall perception of thermal comfort and IAQ. Elevated levels of RH have been linked to enhanced transfer of certain types of biological contaminants, such as moulds (Hersoug 2005), which have been associated with adverse effects on occupant respiratory symptoms (Haverinen et al 2003) and even the durability and integrity of building materials (Cerolini et al 2009). Subsequently, developing methods for managing and analysing indoor air humidity conditions has become a major concern in building design.

The work presented in this paper focuses on the modelling of the moisture performance of the indoor environment. The coupled nature of the heat, air and moisture (HAM) related events that are commonly observed in the indoor environment have been investigated and modelled through a series of modelling exercises and assessed by looking at the level of agreement achieved between measured and predicted data. This work was carried out using the whole building integrated simulation system, ESP-r (Clarke 2001).

After a brief summary of the importance of material moisture properties, surface parameters and sources of moisture generation considered in HAM modelling, the paper focuses on tests to check on ESP-r's HAM modelling capabilities, with a view to modelling the factors affecting the indoor environmental conditions associated with short duration occupant-related moisture release. The main application is on the impact of passive drying within dwellings (Porteous et al 2012).

An initial exercise was conducted with the aim of assessing the whole building integrated moisture modelling approach adopted in ESP-r. Following this, a second exercise was designed with the aim of comparing ESP-r model predictions with results taken from a controlled laboratory experiment, when considering surface moisture exchange between building materials and the indoor air. The emphasis was on the reliability of material property data and the influence of this data on numerical predictions when modelling moisture buffering effects inherent in hydrophilic porous building material. Detailed modelling of several strongly-coupled phenomena including air flow rates, surface boundary conditions, moisture release rates and hygrothermal material properties is required to determine the effectiveness of moisture buffering materials subject to dynamic indoor environmental conditions. The suitability and accuracy of experimental procedures used to determine these properties has been questioned

(Kumaran 2006) and are highly dependent on the manner in which the procedures are conducted and the process used to interpret the resultant data i.e. different specimens of the same material display inconsistency in material properties (Pedersen 1992). For this reason it is necessary to conduct sensitivity studies to estimate the degree of uncertainty on modelling predictions, some of which are reported in this paper. The final exercise focuses on modelling the short-duration moisture release rate from passive indoor drying of clothes, which is common practice in UK social housing and is a common cause of poor IAQ.

FACTORS INFLUENCING MODELLING OF INDOOR AIR HUMIDITY

Material moisture response characteristics

Indoor air humidity undergoes diurnal fluctuations as a result of the influence of several physical and time dependent environmental parameters. One such example is the response of hygroscopic building material to the indoor air conditions. When accounting for the interaction between indoor air and the building envelope in a combined heat, air and moisture model, knowledge of material thermal and moisture related storage and transport properties is required. For moisture modelling, this involves introducing measured material property data obtained from experimentation. A range of experimental techniques are used to determine properties such as the open porosity, bulk density, matrix density and moisture related properties. The integrated coupled heat and moisture flow model used in ESP-r uses the moisture permeability and sorption isotherm material moisture properties for a homogeneous, isotropic material when solving the moisture flow model in one dimension. Equation (1) is applied to the moisture domain:

$$\rho_o \zeta \frac{\partial (P/P_s)}{\partial t} + \frac{\partial \rho_l}{\partial t} = \frac{\partial}{\partial x}\left[\delta_P^\theta \frac{\partial P}{\partial x} + D_\theta^P \frac{\partial \theta}{\partial x}\right] + s \qquad (1)$$

where θ and P denote the temperature and pressure driving potentials, with the principal potential given as the subscript; and ρ_o and ρ_l represent the density (kg/m^3) of porous medium and liquid respectively. A detailed description of ESP-r's approach to modelling moisture transport and storage in building materials and the method used to discretise the building model spatially and temporally is given in Nakhi (1995). To populate and solve this HAM equation, material property databases are available, although the reliability of their data sets is questioned due to the difficulty linked with attaining uniformity in the measurement techniques, hence raising concern over uncertainty in building simulation predictions (Defraeye et al 2013).

In addition to the necessary material property data, a detailed understanding of the parameters (some of which exist at the microscopic scale) that influence boundary moisture transfer in and out of the material (i.e. at the air/solid interfacial region) is required. Several time varying surface parameters such as the air flow velocity, the reference temperature of the air, and the surface relative humidity need to be taken into account. Macroscopic continuum models have been developed to model these features by adopting convective heat and mass transfer coefficients as a means of simplifying the complex surface boundary conditions of this coupled heat and mass exchange. This is the approach taken in ESP-r where a heat and mass transfer analogy is applied to determine the convective mass transfer coefficient. The impact of using this method on the modelling accuracy of convective exchange processes is an important area to consider (Defraeye et al 2012) and will be explored later in this paper.

Sources of indoor moisture generation

In order to develop a viable building integrated moisture flow model, indoor moisture generation is another key component. Few attempts have been made to model occupant-related moisture release and questions have been raised over the adequacy of moisture generation models (Emmerich 2002). The variability of moisture production activities is high, depending on occupant behaviour and the type of activity taking place (Pallin et al 2011). The methods available for evaluating indoor moisture generation rates of occupant related activities are generally lacking in HAM analysis. Often trial and error is used to determine moisture generation rates during the combined heat and moisture transfer analysis (Lu 2003). An aim of this study is to improve ESP-r's capabilities in modelling the moisture release rate of passive drying of domestic laundry. Modelling of the mass transfer rate associated with evaporative processes usually involves the use of a mass transfer coefficient and multiplying this by a driving force and the area of the surface considered. This is the case in ESP-r (shown in Equation 2) where the humidity ratio is the driving force in the process and a simplified Lewis relation is used to determine the mass transfer coefficient.

$$ev = h_c \cdot A_s(\omega_{surf-}\omega_{air})/C_p \qquad (2)$$

Determining the accuracy of this modelling approach will involve making comparison between predicted results and measured data.

VERIFICATION OF ESP-r's EXISTING MODELLING CAPABILITY

Approach

A number of tests were undertaken to assess the integrated approach to building physics modelling within ESP-r, with particular focus on the relevant hygrothermal processes taking place in a building subject to short duration moisture injections (in the order of a few hours).

- Firstly, several of the validation tests developed in IEA Annex 41 (2008) were undertaken, one of which is presented here.
- Secondly, a comparison between experiments and modelling was carried out using measured data obtained from laboratory experiments.
- Finally, a simulation study was carried out to assess the application of the modelling approach to a clothes drying process, with particular focus on surface parameters influencing mass flow rates.

Validation tests: test building with two parallel rooms

The results from this exercise typify ESP-r's performance in modelling the moisture response of a space. This exercise is one of a range of tests developed in IEA Annex 41.Two adjacent test rooms were used as an initial case study for a simulation based investigation into hygrothermal whole building behaviour. The interior walls were lined with a selection of finishing materials in three separate modelling steps, so that the impact of the wall lining materials on internal relative humidity could be compared between the two rooms. One of the rooms had a standard gypsum plaster with a latex coating (CGP) and is used as a benchmark case. The walls of the adjacent test room were lined with aluminium foil initially; the second step introduced uncoated gypsum plasterboard (UGP) to the walls before finally applying the plasterboard to the ceiling in the final step. Both rooms had a constant air temperature of 21°C with infiltration rates of 0.63 and 0.66 ac/h in the Reference and Test room, respectively. A total moisture load of 2.4kg/day was introduced to both rooms. A basic moisture production of 25g/h was applied to the rooms to represent plants and pets. Between 6 and 8am the production level increased to a peak of 400g/h, simulating human activity before dropping back to the basic level. Moisture production increased again between 4 and 10pm to 200g/h, accounting for activities such as cooking. To model these rooms, the convective surface heat transfer coefficients were set to fixed values at each building façade as follows (as specified in the exercise):

Table 1 Surface Convective Heat Transfer Coefficient data for building model

Surface Heat Transfer Coefficients W/m^2.K		
	$h_{c,i}$	$h_{c,e}$
Internal wall	8	8
External wall	8	18
Ceiling	8	8
Floor	8	100

The convective mass transfer coefficient β (s/m) is then calculated in ESP-r using the following analogy with the heat transfer coefficient (Equation 3):

$$\beta = \frac{h_c \cdot M_{H_2O} \cdot (0.85)}{\rho \cdot C_p \cdot R \cdot T} \qquad (3)$$

The value 0.85 is representative of the Lewis number at standard atmospheric pressure. The moisture permeability is determined by using Equation (4), substituting in the vapour diffusion resistance function and the relevant transfer coefficients:

$$\delta = \frac{\delta_a}{\mu} = \frac{\delta_a}{\left(\dfrac{1}{a + be^{c\phi}}\right)} \qquad (4)$$

$$\therefore \quad \delta = \delta_a \times (a + be^{c\phi})$$

Equation (5) is used in ESP-r to calculate the moisture content of a building material:

$$u = u_h \left(1.0 - \frac{\ln \phi}{A}\right)^{-\frac{1}{n}} \qquad (5)$$

The moisture transport coefficients applied in equations 4 and 5 describing the hygroscopic performance of the internal wall lining materials are listed in Tables 2 and 3.

Table 2 Moisture Permeability data for Coated Gypsum Plaster (CGP) and Uncoated Gypsum Plasterboard (UGP)

	Moisture Permeability data		
	a	b	c
CGP	4.9e-05	(-)	(-)
UGP	0.0712	2.81e-03	4.1

Table 3 Sorption Isotherm data for Coated Gypsum Plaster (CGP) and Uncoated Gypsum Plasterboard (UGP)

	Sorption Isotherm data		
	Uh	A	n
CGP	0.012	0.007	0.015
UGP	150.0	2.99e-04	4.81

Measured boundary conditions were used within the model: the external climate, the internal climate, fixed conditions on adjacent walls and a fixed ground temperature of 2°C. The simulation time step resolution was 15 minutes and 6 moisture nodes were applied to each layer in the building envelope construction. Using the gypsum plasterboard as an example, the spatial discretisation used translates to a moisture node applied every 2mm in a 12mm thick sample of gypsum plasterboard.

The modelling involved three distinct steps. Step 1, which compares coated material wall surfaces of the Reference room with impermeable surfaces in the Test room, was run from 17.01.2005 to 02.02.2005.

Step 2, which replaced the wall materials in the Test room with uncoated gypsum plasterboard, ran between 14.02.2005 and 20.03.2005. Step 3, which added uncoated gypsum plasterboard to the ceiling of the Test room, was run from 27.03.2005 to 22.04.2005. The RH profiles for selected parts of the simulation periods for steps 1-3 are presented in Figures 1, 2 and 3.

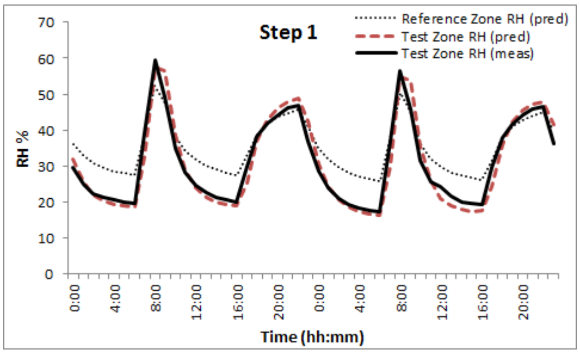

Figure 1 Measured vs. Predicted RH in Test Room (25.1.2005-26.1.2005)

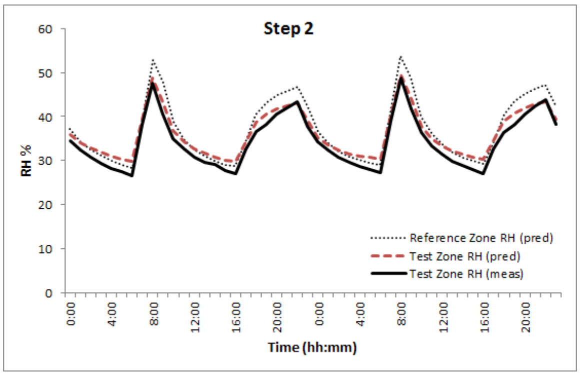

Figure 2 Measured vs. Predicted RH in Test Room (17.2.2005-18.2.2005)

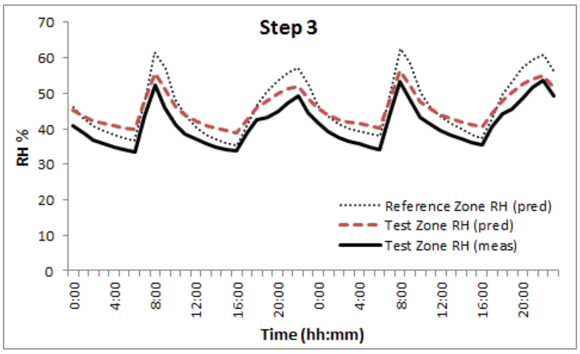

Figure 3 Measured vs. Predicted RH in Test Room (4.4.2005-5.4.2005)

Validation tests: results and discussion

In Figure 1, ESP-r is able to model the moisture balance in the Test room with close agreement to the measured data. The impact of coated material wall surfaces in the Reference room on peak internal RH is similar to that of the peak humidity levels observed in the Test room. The RH fluctuations between moisture loading periods were smaller in the Reference room due to the damping effect of the moisture buffering potential in the walls. The results shown in Figure 2 show that the introduction of the uncoated Gypsum Plasterboard in the Test room walls raised the average RH, and that the dynamics of the RH profile in both rooms were similar. The predicted results for the Test room were close to the measured data, indicating that the modelling of the buffering effect of the material was satisfactory.

The addition of Gypsum Plasterboard to the ceiling of the Test room however, did result in a decrease of peak RH levels. The RH fluctuations and peak RH levels were dampened further in Figure 3 as more hygroscopic material was introduced to the Test room. The predicted peak humidity results for the Test room were similar to the measured peaks, showing the modelling of the moisture absorption phase is able to achieve satisfactory agreement with the measured data. The average RH however, increased and was greater than that found in measured data. ESP-r models the absorption and desorption phases using the average of the two or the absorption isotherm alone. The higher RH observed in the Test room may be due to the increased release of moisture back into the zone and the omission of hysteresis effects in absorption/desorption of the material.

Comparisons with other tools

The performance of ESP-r illustrated in the tests in the previous section is similar to other integrated heat and moisture modelling tools. However, the overall reliability of moisture predictions in ESP-r and other tools requires further study. This is evidenced in other validation tests within the IEA Annex 41 programme which sometimes showed a high degree of variability of predictions between tools and with experimental data.

Modelling short duration, high moisture loading experiment

As mentioned previously, a key element of this paper is to assess ESP-r's ability to model the response of a building to short duration moisture inputs. Using an environmental test chamber with an internal volume of $0.015m^3$, two sample material specimens were exposed to a short duration period (2 hours) of high moisture loading, in the range 50-90%RH. This regime was chosen to reflect short term moisture production activities observed in buildings such as showering and cooking (Tenwolde and Pilon, 2008). Accurate measurement of the material response under realistic time and moisture conditions is vital in reliably quantifying the material response (Janssen and Roels 2008). The materials tested were painted Gypsum Plasterboard (PGP) and Clayboard (CB) – the latter has been promoted as a moisture buffering material. The air temperature inside the chamber was maintained constant at 23°C. The conditioned air supplied to the chamber had a flow velocity of 0.5m/s and measured data (automatically weighed samples) were recorded at 10min intervals. Further information on the environmental test chamber and its operation can be found at www.gintronic-instruments.com. The exact surface boundary conditions of the material specimens were not measured and the assumption was made that the air was well mixed and air flow over the samples was laminar. A convective heat transfer coefficient value of 2.3 W/m^2K was calculated using an expression for air flow through a square duct and applied to the ESP-r model as a constant.

Tables 3 (i) and (ii) display the hygrothermal performance coefficients used for the materials used in the ESP-r model. The surfaces of the climate chamber were impermeable to moisture and therefore hygrothermal data for these was not required to set up the moisture model.

Table 3 Hygrothermal material property data for eqns 4 and 5, respectively.

	Vapour Permeability data		
	A	b	c
PGP	-0.13	-0.196	0.326
CB	-9	2.445	8.05

(i)

	Sorption Isotherm data		
	Uh	A	n
PGP	21.4	2.65e-2	1.54
CB	944	2.7e-3	1.54

(ii)

The thicknesses of the Gypsum Plasterboard and Clayboard samples are 12.5 and 20mm respectively.

Short duration moisture loading - results

Figure 4 presents the results produced for the two materials when using the dynamic RH dependent function shown in Equation (4) for vapour permeability for both materials. The importance of having a comprehensive set of measured data for the permeability of both materials is apparent, as there is still a significant difference in the magnitude of the predicted results when compared to the measured data. The profile of the predicted surface exchange behaviour is more in agreement with the measured.

There was uncertainty over the nature of the air flow regime inside the test chamber and the associated impact this would have on surface transfer conditions. To this end, a sensitivity analysis was conducted investigating the impact of the surface convective mass transfer coefficient by using a range of convective heat transfer coefficients, as the boundary layer conditions are known to strongly influence the interaction between indoor air and material surfaces (Mortensen et al 2006). These were calculated using Nusselt numbers derived for laminar flow in ducts of varying geometry (Incropera 2002) and over a flat plate with fixed temperature (Neale et al 2007).

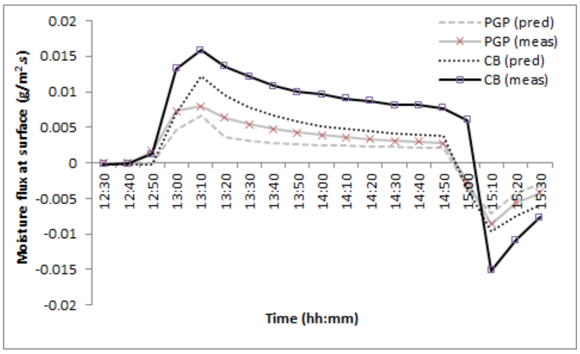

Figure 4 Comparison between measured and predicted surface moisture flux for range of materials and hygrothermal properties

Figure 5 presents results highlighting the heightened effect of the surface convective mass transfer coefficient on the surface moisture flux predictions for CB in comparison to the variation in predicted results brought about by a change in material properties. The sensitivity analysis carried out on the convective heat transfer coefficient indicated the true value would lie in the range between 1.9 and 5.0W/m^2K. A value of h_c=5.0W/m^2K resulted in overpredicting the level of surface moisture exchange during the initial stages of the moisture injection period, although agreement is seen to improve during the period when RH is constant in the chamber. Using values of 1.9 and 2.3W/m^2K are seen to underpredict the amount of surface moisture exchange.

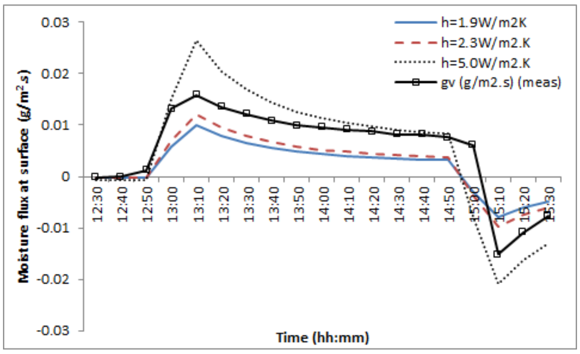

Figure 5 Impact of surface mass transfer coefficient on surface moisture flux predictions for Clayboard

Discussion

Simulations undertaken have indicated the importance and strong influence of material property data in moisture modelling. Integrating RH dependent material properties into this modelling exercise has been shown to have significant influence on predictions. It is also apparent that in addition to accurate material property data, necessary for improved predictions, a more detailed analysis of the interfacial region is needed to improve the modelling of surface parameters influencing moisture exchange. Convective heat and mass transfer from porous building material involves transfer processes taking place both in the air and in the material structure, indicating a conjugate transport problem, which requires numerical modelling to simultaneously account for both physical domains. Some of the approaches available to model these coupled processes are described in Defraeye et al (2012).

Moisture release model

With indoor moisture generation rates being reported as high as 20 kg/day in some climates (Tariku et al 2010), developing the modelling of this process in the context of coupled heat and moisture transfer analysis was a specific interest in this investigation with particular focus on the passive drying of domestic laundry. This process was investigated by modelling the moisture release from an item of clothing being dried passively on a clothes airer in a real home environment. Indoor climate variables measured at 1-minute intervals were the RH at three different points on the airer and the ambient air RH. The indoor air temperature was also measured and found to be reasonably steady. The indoor RH was measured to be approximately constant at 67%. An infiltration rate of 0.5ac/h was applied. Particular focus was on the moisture evaporation taking place at the surface of the clothing and being able to predict this behaviour within reasonable agreement to measured data. A more detailed investigation of the drying process would require more accurate knowledge of the material moisture properties and surface boundary conditions in order to replicate the different stages of this dynamic process. However, material homogeneity was assumed and emphasis was on ensuring the dynamic characteristics of the moisture released by evaporation alone at the surface of the material could be adequately modelled. The heat transfer coefficients were calculated based on buoyancy forces at the surface thus taking into account changes in surface temperature, which is the default approach used in ESP-r. Again, a more detailed investigation would include a more accurate representation of the boundary conditions based on direct measurements being applied to the model.

The drying period of a range of clothing items was measured and the mass of each item was recorded every 1 to 2 hours. The clothes were assumed initially saturated, discounting the effects of the different drying stages and hence the different modes of moisture transfer taking place through the pore network of the clothing.

Four variants of the equation were tested to calculate the evaporation.

$$ev = e_h \cdot h_c \cdot A_s \cdot (\omega_{surf} - \omega_{air}) / C_p \qquad (6)$$

$$ev = h_c \cdot A_s \cdot (\omega_{surf} - \omega_{air}) / C_p \qquad (7)$$

$$ev = h_m \cdot A_s \cdot (p_{sat,surf} - (\phi \cdot p_{sat,air}))^{\exp t} \qquad (8)$$

$$ev = e_h \cdot h_m \cdot A_s \cdot (p_{sat,surf} - (\phi \cdot p_{sat,air}))^{\exp t} \qquad (9)$$

The term e_h has been formed to represent the ratio between the moisture evaporated and the initial moisture at the material surface. This is calculated using the following expression:

$$e_h = 1.0 - \frac{m_e}{m_i} \qquad (10)$$

Results and discussion - drying

Using one of the clothing items as an example, Figure 6 presents the predicted results versus the measured data for the drying of a T-shirt. From the numerous simulations conducted, it was realised that the results predicted using equations (8) and (9) were sensitive to the exponent. Fixed values of 1.18 and 1.2 were applied respectively, which were obtained from a process of model calibration.

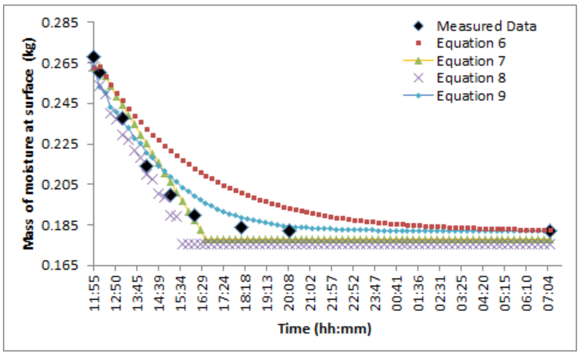

Figure 6 Comparison between measured data and predicted results for drying T-shirt

Predictions made using Equation (7) showed good agreement at the initial stages of the drying period. However, the correlation with measured data deteriorated after this initial stage. Equation (6) was adapted from the original version of the evaporation rate equation by introducing the evaporative history coefficient. This allowed for the model to take into account what moisture had already evaporated in addition to the difference calculated between surface and air humidity ratios at each time step. The level of agreement between predicted and measured data was poor although the profile of the moisture release rate was more in line with that of the measured data. Equation (8), based on the original equation found in Tang and Etzion (2004), introduces the heat and mass transfer analogy used in ESP-r to determine the convective mass transfer coefficient. Reasonable agreement at the initial stage of drying was observed for most of the clothes items. For items with a higher hygroscopicity such as jeans, the correlation between predicted and measured was worse. Finally, Equation (9) was a case of adding the evaporative history coefficient to Equation (8). An exponent of 1.2 was found to give the best agreement to the measured data.

The empirical approach used for this particular study allowed a reasonable model of the moisture release process to be developed with satisfactory agreement between measured and predicted surface moisture concentrations.

A detailed model of the moisture transfer and storage processes experienced by the clothing materials would be a further improvement. However, this is beyond the scope of this paper.

CONCLUSION

This paper presents the application of the moisture modelling facility in the integrated whole building simulation tool ESP-r for analysing a range of short-duration moisture related scenarios commonly observed in the building environment. These included modelling a realistic case taken from the IEA Annex 41 with focus on the moisture buffering performance of different materials. Reasonable agreement was observed between predicted and measured data when (a) assessing the impact of impermeable internal wall linings materials; and (b) simulating the absorption phase of permeable internal wall lining materials. The agreement was poorer during the desorption phase raising concern over the omission of hysteresis phenomena and surface transfer parameters, such as the effects of surface air flow velocity, in the model. The level of uncertainty however, between simulation tools modelling another IEA Annex 41 case study, was highlighted. A second exercise involved the numerical modelling of the hygrothermal effect of a short duration, high intensity moisture loading cycle on a Clayboard and Painted Gypsum Plasterboard sample. Satisfactory agreement was observed between predictions of the material surface moisture flux and measured data for painted gypsum plasterboard. The predictions for the Clayboard followed the profile and dynamics of the measured data although a difference in magnitude was observed. A number of issues arose from this exercise with relation to material moisture property data, signifying the importance of integrating dynamic material property functions. The sensitivity of predictions to the surface mass transfer coefficient was also presented, prompting the need for more detailed study of air flow conditions in the experimental procedure. Following on from this, a final exercise was conducted to assess the modelling of moisture release rates from a single item of drying laundry by testing different evaporation rate equations and comparing the predicted results against empirical data. Model predictions improved compared to measured data as each evaporation equation was applied. In order to develop the model further, additional properties should be investigated. Air flow conditions at the surface of the clothes were not known, hence ignoring the intrinsic effect on heat and mass transfer. Sorption properties of the clothes items would also need to be measured, thus recognising the moisture behaviour and associated phases in the pore structure. This includes the liquid and vapour diffusion that may occur and the different driving forces associated with the different drying stages.

However, the overall modelling capability was considered sufficient to investigate options for assessing the impact of passive drying of clothes. A series of parametric simulation tests are described in Porteous et al (2012).

NOMENCLATURE

a = experimentally determined coefficient [-]
A = experimentally determined coefficient [-]
A_s = exposed surface area of sample [m^2]
b = experimentally determined coefficient [-]
c = experimentally determined coefficient [-]
C_p = specific heat capacity of air [J/kg.K]
D = thermal diffusion coefficient [$kg/m^2.K.s$]
ev = evaporation rate [kg/s]
e_h = evaporative history coefficient [-]
$expt$ = exponent
h_c = convective heat transfer coefficient [$W/m^2.K$]
$h_{c,i}$ = *internal surface* convective heat transfer coefficient [$W/m^2.K$]
$h_{c,e}$ = *external surface* convective heat transfer coefficient [$W/m^2.K$]
h_m = convective mass transfer coefficient [s/m]
M_{H2O} = molecular weight of vapour [kg/kmole]
m_e = mass of evaporated moisture [kg]
m_i = initial mass of moisture at surface [kg]
n = empirically fixed component [-]
p_s = saturation vapour pressure [Pa]
R = universal gas constant [J/kmole.K]
s = moisture source term [$kg/m^3.s$]
t = time [s]
T = air temperature [K]
u = moisture content [kg/m^3]
u_h = maximum hygroscopically bound water [kg/m^3]
β = convective mass transfer coefficient [s/m]
δ = moisture permeability [kg/m.s.Pa]
δ_a = moisture permeability of stagnant air [kg/m.s.Pa]
μ = vapour resistance factor [-]
ρ = density of air [kg/m^3]
ϕ = relative humidity [-]
ω_{air} = humidity ratio of air [kg/kg dry air]
ω_{surf} = humidity ratio at surface [kg/kg dry air]
ζ = moisture storage capacity [kg/m^3]
x = spatial coordinate [m]

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