Environmental Assessment of Domestic Laundering

Final Modelling Report

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March 2012
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Note
There was a serious fire in early February 2012, towards the end of the project, in the James Weir building at the University of Strathclyde. This interrupted some of the final research and report writing with some computers used in the project not recovered until the end of March. This report has two missing sections: section 3.2, which will describe the comparison of predictions with additional cyclic tests undertaken near the end of the project, and section 6 which will report on a simulation with a detailed realistic user behaviour profile. These sections will be added in the near future with a report update.
1. **Overview of the modelling study and integration with other project modules**

The main aim of this EPSRC project was to evaluate the energy consumption and associated indoor environmental conditions which affect health and comfort as a result of the use of wet appliances and associated clothes drying, and to suggest practical solutions to problems identified.

The modelling study was undertaken to quantify the energy and environmental effects of a range of scenarios associated with laundry, in particular the influence of ventilation, insulation, moisture buffering and moisture loads. The study had two major inputs from the other work packages within the project.

- Firstly, the housing survey and associated analysis of representative dwellings undertaken by the Glasgow School of Art enabled typical patterns of wet appliance use, drying and ironing to be identified. These patterns led to the development of a number of scenarios that were tested in the modelling work.
- Secondly, a barrier to modelling the hygrothermal response of buildings is the paucity of data on hygrothermal properties of materials. Therefore, an experimental programme was conducted by Glasgow Caledonian University to obtain the necessary fundamental material properties for common building internal finishes and possible moisture control materials. Experiments on moisture release rates for passive drying of washing loads were also undertaken.

The modelling of heat flow, air flow and moisture flow requires a detailed integrated modelling approach. The following steps were undertaken to ensure the modelling work could produce reliable results.

- A review of the moisture flow modelling capability in the Open Source simulation program ESP-r (2012), which was used for the modelling work in this study, was undertaken. The thermal and airflow integration capabilities were well established; integrated moisture flow modelling was less well developed.
- Additional capabilities were added to the functionality of the simulation program to deal with the material hygrothermal properties (vapour permeability and moisture absorption/desorption) which may have a variety of functions describing the variation with temperature and humidity.
- Moisture release models were added based on the experimental data.
- A number of validation exercises were undertaken based on tests published in IEA Annex 41 (IEA 2005) to ensure model predictions were acceptable.
These steps are described in Sections 2 and 3 of this report.

The scenario modelling required a large number of parametric variations. This was undertaken in a systematic way by developing a structured set of scripts. Details are included in Section 2.

For the scenario modelling, a 3-step procedure was followed.

- The first step was to undertake an initial series of parametric simulations focusing on lower and upper limits of the main parameters influencing indoor moisture conditions. The aim of this step was to identify those parameters having the greatest influence on moisture levels and to establish key areas for further investigation.
- The second step involved more specific investigations e.g. comparing ventilation strategies when moisture control materials are incorporated into the structure.
- Lastly, a detailed occupancy and house usage patterns was modelled as an example of a “realistic” case.
2. Modelling capabilities and enhancements

2.1 Integrated moisture flow modelling

Heat, air and moisture simulation requires an integrated modelling approach involving the simultaneous solution of equation-sets representing the processes occurring in each technical domain (building-side heat flow, inter-space air flow and constructional moisture flow). Within ESP-r this is achieved by invoking solvers that are tailored to individual domain equation-sets, and placing the solvers under global iteration control to ensure that appropriate interface variables are exchanged at the required frequency (Clarke 2001).

Figure 1 shows the domains that can be included in an ESP-r analysis, illustrating those used in the current study together with the main performance metrics that were analysed.

Figure 2.1: Integrated modelling of heat, air and moisture
A finite volume approach is used for the building thermal analysis (Clarke and Tang 2004) which includes the conductive, convective, advective and radiative exchanges within the various thermal zones representing the building. The approach is based on a semi-implicit scheme, which is second-order time accurate, unconditionally stable for all space and time steps and allows time dependent and/or state variable dependent boundary conditions and coefficients. An optimised numerical technique is employed to solve the system equations simultaneously, while keeping the required computation to a minimum.

For the inter-zone air flow, ESP-r employs a ‘node-arc’ representation of infiltration and mechanical ventilation (Clarke and Hensen 1991). A set of non-linear equations represents the conservation of mass at nodes as a function of the pressure difference across flow restrictions (arcs). The flow rates through the flow restrictions are calculated from empirical relationships that express mass flow as a function of pressure difference. At each timestep of the simulation, the network is solved based on the known boundary pressure conditions at that timestep. An iterative solution is required because of the non-linear flow-pressure relationships. The converged solution gives the air flow rates throughout the network established to represent a building’s infiltration and ventilation, natural and/or mechanical. The flow of moisture in the air is tracked knowing the moisture concentrations in the various zones represented by the air flow nodes, together with any specified moisture source.

Intra-construction moisture flow was described by Nakhi (1995). Building constructions are subjected to four wetting phenomena – absorption, vapour transport, capillary condensation (vapour and liquid transport) and liquid transport – with the driving potentials for moisture transfer being density gradient (molecular diffusion) and temperature/pressure gradient (filtration motion).

ESP-r’s modelling approach is based on mass and energy conservation considerations applied to homogeneous, isotropic, constructional control volumes and is based on three principal assumptions: 1) that vapour and liquid flows are slow enough to allow thermodynamic equilibrium between phases, 2) the filtration flow due to total pressure difference between inside and outside is negligible and 3) while liquid flow and capillary condensation is considered in the moisture equations, the associated enthalpies are combined and estimated from the vapour specific enthalpy alone, with the heat absorption/dissipation due to phase change assumed to occur at saturation.

For moisture flow the governing mass conservation equation is
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\[
\rho_o \xi \frac{\partial \left( \frac{P}{P_s} \right)}{\partial t} + \frac{\partial \rho_l}{\partial t} = \frac{\partial}{\partial x} \left( \delta_x \frac{\partial P}{\partial x} + D_x \frac{\partial T}{\partial x} \right) + s
\]

where \(\rho\) is density (kg/m\(^3\)), \(o\) and \(l\) denote porous media and liquid respectively, \(\xi\) is moisture storage capacity (kg/kg), \(P\) is partial water vapour pressure (Pa), \(P_s\) is saturated vapour pressure (Pa), \(\delta\) is water vapour permeability (kg/Pa.m.s), \(D\) is thermal diffusion coefficient (kg/m\(^2\).K.s) and \(s\) is a moisture source term (kg/m\(^3\).s). \(X\) and \(Y\) denote temperature and pressure driving potentials respectively, with the principal potential given as the subscript.

For energy, the governing equation is

\[
\left[ \rho_o (c_o + c_v u_v) + c_l \rho_l \right] \frac{\partial T}{\partial t} + h_v \frac{\partial \rho_v}{\partial t} + h_l \frac{\partial \rho_l}{\partial t} = \frac{\partial}{\partial x} \left( \lambda \frac{\partial T}{\partial x} \right) - \frac{\partial h_s J_v}{\partial x} + g
\]

(equation 2.1)

where \(c\) is specific heat (J/kg.K), \(u\) is moisture content (kg/kg), \(T\) is temperature (K), \(\lambda\) is heat conductivity (W/m.K), \(J_v\) is vapour mass flux (kg/m\(^2\).s), \(g\) is a source of heat (W/m\(^3\)) and \(h_v\), \(h_l\) and \(h_s\) are enthalpies of vapour, liquid and moisture flux sources respectively (J/kg).

For condensation and evaporation processes, a control equation is implemented as a one-way liquid valve connected to the control volume. When the relative humidity reaches its maximum value, the valve opens to deliver the condensate to an imaginary tank. Conversely, when the relative humidity falls below its maximum value, liquid is returned to the control volume where it re-evaporates. At the present time this process is implemented as a function of the saturation pressure only with no account of capillary condensation.

Application of these coupled equations allows for the solution of the three dependent variables, \(P\), \(T\) and \(\rho_l\), for each control volume within a construction when evolving under the influence of boundary heat and mass transfers being simultaneously resolved within the connected domain models as described above. To achieve this solution, a finite difference approximation is applied to the foregoing equations.

For moisture:
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\[
a_i^{n+1} P_i^{n+1} + \sum_{j=1}^{2} a_j^{n+1} P_j^{n+1} + (m_i)^{n+1} - \gamma \Delta t S_i^{n+1}
\]

\[
= a_i^n P_i^n + \sum_{j=1}^{2} a_j^n P_j^n + (m_i)^n - (1 - \gamma) \Delta t S_i^n
\]

\[
+ \sum_{j=1}^{2} b_j^n (T_j^n - T_i^n) + \sum_{j=1}^{2} b_j^{n+1} (T_j^{n+1} - T_i^{n+1})
\]

(equation 2.2)

where \( \gamma \) is the degree of implicitness, \( n \) and \( n+1 \) refer to the present and future time-rows of some arbitrary simulation time step, \( \Delta t \) (s), \( m \) the specific mass (kg/m\(^3\)), and

\[
a_j^{n+1} = -\gamma (\delta x_j)^{n+1} A \Delta t / \Delta x_{j-i}
\]

\[
a_j^n = (1 - \gamma) (\delta x_j)^n A \Delta t / \Delta x_{j-i}
\]

\[
a_i^k = \rho \xi_i V / (P_s)_i^k - a_i^k - a_i^{k+1}
\]

\[
b_j^{n+1} = -\gamma (\delta D_j)^{n+1} A \Delta t / \Delta x_{j-i}
\]

\[
b_j^n = (1 - \gamma) (D_j)^n A \Delta t / \Delta x_{j-i}
\]

\[
m_i^k = V \rho_i^k \text{ (kg moisture)}
\]

\[
S_i^k = V S_i^k \left( kG_{moisture}/S \right)
\]

(equation 2.3)

where \( A \) is area (m\(^2\)), \( \Delta X \) is flow-path length (m) and \( V \) is volume (m\(^3\)).

For energy:
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\[ a_i^{n+1}T_i^{n+1} + \sum_{j=1}^{2} a_j^{n+1} T_j^{n+1} - \gamma G_i^{n+1}\Delta t = a_i^n T_i^n + \sum_{j=1}^{2} a_j^n T_j^n + (1 - \gamma)G_i^n\Delta t + (1 - \gamma)(h_{is}\hat{m}_{pv})^{n+1}\Delta t - (h_i)_i^{n+1}[(m_i)_i^{n+1} - (m_i)_i^n] - (h_{pi})_i^{n+1}[(m_{pv})_i^{n+1} - (m_{pv})_i^n] \]

(equation 2.4)

where

\[ a_j^{n+1} = -\gamma A\lambda_{j-i}^{n+1}\Delta t / \Delta X_{j-i} \]

\[ a_j^n = (1 - \gamma)A\lambda_{j-i}^n\Delta t / \Delta X_{j-i} \]

\[ a_i^k = \rho_o V(c_o + c_v u_v) + c_i m_i - \sum_{j=1}^{2} a_j^k. \]

The moisture storage capacity, \( \xi \), in equation 2.3 is found from an expression by Hansen (1986):

\[ \xi = \frac{U_n}{n} A \phi \left( 1.0 - \frac{ln \phi}{A} \right) \frac{n+1}{n}; 0 \leq \phi \leq 1 \]

(equation 2.5)

where \( \phi \) is relative humidity and a mass-weighted value of \( \xi \) is used where the control volume material is heterogeneous. The calculation of the vapour permeability \( \delta \) is described in section 2.2.

The coupled moisture/energy equations for a given system are then given by

\[ \begin{bmatrix} \mathbf{E} \\ \mathbf{M} \end{bmatrix} \mathbf{x} = \begin{bmatrix} \mathbf{T} \\ \mathbf{P} \end{bmatrix} = \begin{bmatrix} \mathbf{B}_e \\ \mathbf{B}_m \end{bmatrix} \]

where \( \mathbf{E} \) and \( \mathbf{M} \) are the energy and moisture coefficient matrices respectively, \( \mathbf{T} \) and \( \mathbf{P} \) are the temperature and vapour pressure vectors, and \( \mathbf{B}_e \) and \( \mathbf{B}_m \) are the energy and moisture boundary conditions.
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With temperature and partial vapour pressure used as the transport potentials for moisture, the model gives rise to a coupled heat and moisture transport model.

2.2 Hygrothermal Properties

In order to model the behaviour of moisture in hygroscopic material, ESP-r requires the implementation of specific hygrothermal property data. This data is provided in the form of moisture diffusion coefficients. These values relate to the vapour permeability and the sorption isotherm function of a particular material in the model construction, necessary for ESP-r to calculate the rate of moisture transfer. The equations used by ESP-r to calculate these two material properties are explained below in further detail.

2.2.1 Vapour Permeability:

The vapour permeability (symbol $\delta$: units $kg/m.s.Pa$) at a point is defined as the ratio between the density of vapour flow rate at that point and the magnitude of the vapour pressure gradient in the direction of the moisture flow. In ESP-r, three vapour diffusion coefficients are required denoted a, b and c below.

Equation 2.5 is the general form used for calculating the vapour permeability:

$$\delta = \frac{\delta_a}{\mu}$$

(equation 2.6)

$\delta$ is the vapour permeability of the material, $\delta_a$ is the vapour permeability of stagnant air (a standard value of $1.89923 \times 10^{-10}$ kg/m.s.Pa is used in ESP-r) and $\mu$ is the vapour diffusion resistance factor of the material and is dimensionless. The vapour diffusion resistance factor is defined as the ratio between the vapour permeability of stagnant air and that of the material, under identical thermodynamic conditions (same temperature and vapour pressure). Stagnant air, for example, has a vapour resistance factor equal to 1. From experimental measurement, the vapour diffusion resistance factor is represented using equation 2.7.

$$\mu = \frac{1}{a + b.exp^{c.\phi}}$$

(equation 2.7)

By substituting equation (2.7) into equation (2.6), the final form of the vapour permeability equation used in ESP-r is found:
\[ \delta = \delta_o \times \left( a + b \cdot e^{c\theta} \right) \]  
(equation 2.8)

2.2.2 Standard Diffusion Thickness

The vapour diffusion thickness (symbol \( s_d \); units m) is a function of the air layer thickness analogous to the vapour transfer distance in the material. This variable can be used instead of the vapour diffusion resistance factor for the following reasons:

- Material layers which are difficult to measure or have a non-uniform thickness
- Composite thin layers (such as vapour barriers)
- Composite layers such as masonry work
- Defining the vapour transfer potential through poor building construction e.g. cracks, leaks, etc. In this scenario, the property is called the ‘equivalent diffusion thickness’; however, the diffusion process assumes each building to be dry at the start of its service life

The formula used to calculate the standard diffusion thickness is as follows:

\[ s_d = \mu \times d \]  
(equation 2.9)

\( \mu \) = Vapour diffusion resistance factor (-)  
\( d \) = layer thickness (m)

Equation 2.9 can be rearranged to determine the vapour diffusion resistance factor and then substituted into equation 2.5.

2.2.3 Vapour Resistivity

The inverse of the vapour permeability is known as the vapour resistivity (symbol \( \rho_v \); units MN.s/g.m) of a material. This property is found in the ESP-r materials database and can be used as part of an alternative method for calculating the vapour permeability of the construction material, if empirically sourced moisture diffusion coefficient data is unavailable. To incorporate the vapour resistivity into the existing vapour permeability calculation, the following equation is used:

\[ \mu = \rho_v \times 0.189923 \]  
(equation 2.10)

Equation (2.10) converts the vapour resistivity value into a vapour diffusion resistance factor. The inverse of the vapour diffusion resistance factor can then be incorporated into
equation (2.8) to represent the coefficient labelled ‘a’, so that the vapour permeability can be calculated.

2.2.4 Vapour Permeance

The vapour permeance (symbol \( d_i \): units kg/Pa.m².s) of a material is defined as the ratio between the density of vapour flow rate and the magnitude of the vapour pressure difference across two flat parallel bounding surfaces under steady state conditions. The vapour permeance is equal to the vapour permeability divided by the thickness of the relevant material, shown in equation (2.6).

\[
d_i = \frac{\delta}{L}
\]  
(equation 2.11)

\( L = \text{Distance between two bounding surfaces (m)} \)

This equation can be modified to determine the vapour permeability and then substituted into equation (2.6) to calculate the vapour diffusion resistance factor of the material. Again, the inverse of the vapour diffusion resistance factor can replace the variable \( a \) in equation (2.8) and the remaining variables, \( b \) and \( c \), can be disregarded.

2.2.5 Convective surface resistance to vapour diffusion

Equation (2.12) displays the relationship between vapour permeance and the convective surface resistance to vapour diffusion (symbol \( Z_v \): units MN.s/kg) of a material.

\[
Z_v = \frac{1}{d_i}
\]  
(equation 2.12)

The inverse of the convective surface resistance variable is also equal to the convective mass transfer coefficient (symbol \( \beta \): units s/m). This variable is calculated in ESP-r using a heat and mass transfer analogy that incorporates a Lewis relationship. Equation (2.13) shows the relation between these two variables.

\[
\beta = \frac{h_c \times M_{H_2O} \times \left( \frac{Sc}{Pr} \right)^{n-1}}{C_p \times R \times T}
\]  
(equation 2.13)
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\( h_c = \text{Convective heat transfer coefficient (W/m}^2\cdot\text{K)} \)
\( M_{H_2O} = \text{Molecular mass of water (kg/kmole)} \)
\( \frac{Sc}{Pr} = \text{Ratio between the Schmidt number and the Prandtl number equivalent to the Lewis (Le) number. This ratio is given a value of 0.85 in ESP-r} \)
\( C_p = \text{Specific heat capacity of air (J/kg.K)} \)
\( R = \text{Universal gas constant (J/kmole.K)} \)
\( T = \text{Air temperature (K)} \)

In some of the IEA Annex 41 common exercises that were modelled as part of the validation of ESP-r’s moisture modelling capabilities (section 3 of this report), a mass transfer coefficient was provided. Equation (2.13) could then be rearranged to determine the convective heat transfer coefficient. This value could then be entered as a surface heat transfer coefficient within ESP-r.

2.2.6 Sorption Isotherm Function

Moisture transport within a porous material is a process involving both the absorption and desorption of moisture to and from the material, driven by pressure and temperature differences. When moisture in the internal zone air comes into contact with the building envelope surfaces, a fraction of this moisture will penetrate the surface of the material pore structure. The amount will depend on the permeability of the surface material which varies according to the type of surface finish that may be applied e.g. paint, wallpaper. The absorptive nature of some of the porous materials installed in a building construction is represented in ESP-r using the updated Hansen formula, found in the IEA Annex 14 (1991) catalogue of material properties. This function calculates the moisture content in the material based on the relationship between relative humidity and equilibrium moisture content (equation 2.14).

\[ u = u_h \times \left[ 1 - \left( \frac{\ln \phi}{A} \right) \right]^{-\frac{1}{n}} \quad 0 \leq \phi \leq 1 \]

(equation 2.14)

\( u = \text{Moisture content (kg/m}^3) \)
\( u_h = \text{Maximum hygroscopic capacity (kg/m}^3) \)
\( \phi = \text{Relative Humidity} \)
\( A = \text{Coefficient found from curve fitting} \)
\( n = \text{Coefficient found from curve fitting} \)

The terms \( u \) and \( u_h \) can be expressed as either the volumetric moisture content (kg/m\(^3\)) or the mass by weight moisture content (kg/kg). To derive the volumetric moisture content, \( u_h \) should be multiplied by the dry density of the material to convert from kg/kg to kg/m\(^3\).
The absorption and desorption isotherm functions are both described using Equation 2.14. ESP-r uses the absorption isotherm function as the default function in the current modelling work.

Alternative functions were added to ESP-r in order to accommodate more of the available data provided in the validation exercises and in the sources mentioned in the following section. These were as follows:

\[ u = 0.0661 \times \phi \]  
\[ (equation 2.15) \]

\[ u = a \phi^2 + b \phi + c \]  
\[ (equation 2.16) \]

Equation 2.15 was taken from an IEA Annex 41 validation exercise and referred to the mean of the absorption and desorption curves for Aerated Concrete. It was adapted in the simulation software so as to output the moisture content as a volumetric value.

The quadratic form of equation 2.16 was produced from curve fitting using measured moisture content data for the absorption and desorption phases that was available in material property source books. An average moisture content could be calculated from sorption and desorption data if experimental measurements were available for both. The resulting moisture content value was multiplied by the dry density of the material in order to produce a volumetric result.

### 2.2.7 Sources for Hygrothermal Material Property Data

Hygrothermal material properties were taken from the IEA Annex 24 Final Report Volume 3 Task 3: Material Properties (1996) and the IEA Annex 14 Material Properties (1991) data. Additional experimental work, carried out at Glasgow Caledonian University as part of the EPSRC project, provided sorption data for a selection of materials commonly found in Scottish housing construction. This sorption data was translated into the form of the Hansen equation (equation 2.14), so that it would be compatible with ESP-r.

The relevant material property data can be found in Table 2.1 for the vapour permeability and Table 2.2 for the sorption isotherm function.

Vapour permeability data were provided in these sources either in the form shown in equation (2.7), where 3 coefficient values are required, or as a single vapour diffusion resistance factor (VDRF) value which is presented in the form of a dry cup or wet cup value. These values represent the vapour resistance of the material in specific RH ranges. The dry
cup value is measured in the range of 0-50% relative humidity and the wet cup value is found at relative humidity levels greater than 50%.

To simulate the moisture transfer between materials in multi-layer constructions and at the boundary layer (thin layer of air adjacent to the internal surface of the building envelope) sorption diffusion coefficients are required.

<table>
<thead>
<tr>
<th>Material</th>
<th>Diffusion Coefficients</th>
<th>VDRF (μ)</th>
<th>Zv</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>a</td>
<td>b</td>
<td>c</td>
</tr>
<tr>
<td>Concrete</td>
<td>6.80E-03</td>
<td>8.21E-05</td>
<td>5.66</td>
</tr>
<tr>
<td>Woodwool (board)</td>
<td>3.48E-03</td>
<td>0.107</td>
<td>0.25</td>
</tr>
<tr>
<td>Cellular Concrete</td>
<td>0.116</td>
<td>6.28E-03</td>
<td>4.19</td>
</tr>
<tr>
<td>Linoleum</td>
<td>1.1E-04</td>
<td>4.14E-06</td>
<td>6.35</td>
</tr>
<tr>
<td>Mortar</td>
<td>0.0769</td>
<td>2.43E-03</td>
<td>3.61</td>
</tr>
<tr>
<td>Bricks</td>
<td>0.0536</td>
<td>4.67E-03</td>
<td>2.79</td>
</tr>
<tr>
<td>Gypsum Plasterboard</td>
<td>0.0712</td>
<td>2.81E-03</td>
<td>4.1</td>
</tr>
<tr>
<td>Claytec</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Vinyl Wallpaper</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Laminate Flooring</td>
<td>2.0E-04</td>
<td>1.62E-05</td>
<td>5.47</td>
</tr>
<tr>
<td>Carpet Underlay UL</td>
<td>0.019</td>
<td>5.1E-05</td>
<td>5.07</td>
</tr>
<tr>
<td>Carpet Underlay ULHD</td>
<td>0.118</td>
<td>1.1E-04</td>
<td>5.07</td>
</tr>
<tr>
<td>Carpet Underlay ULFELT</td>
<td>0.147</td>
<td>2.72E-04</td>
<td>5.07</td>
</tr>
<tr>
<td>Carpet</td>
<td>0.07</td>
<td>8.24E-05</td>
<td>5.07</td>
</tr>
</tbody>
</table>

Table 2.1: Moisture Transport Coefficients required in vapour permeability function.
Data sourced from IEA Annex 14 and IEA Annex 24.

<table>
<thead>
<tr>
<th>Material</th>
<th>Diffusion Coefficients</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Uh (kg/m3)</td>
</tr>
<tr>
<td>Concrete</td>
<td>147.5</td>
</tr>
<tr>
<td>Wood wool (board)</td>
<td>-</td>
</tr>
<tr>
<td>Cellular Concrete</td>
<td>300</td>
</tr>
<tr>
<td>Linoleum</td>
<td>212.5</td>
</tr>
</tbody>
</table>
2.3 Modelling enhancements

2.3.1 Summary of source code changes

An important aspect of this project was to assess the impact of different surface materials on the peak and mean relative humidity in rooms following moisture release events. The moisture buffering performance of various hygroscopic materials can be represented by transport functions that determine the rate of moisture transfer, as described in Section 2.2.
The established transport functions included in the moisture modelling module of ESP-r are the sorption isotherm function and the vapour permeability. The source code was modified to enhance the range of functions that can be used to model the behaviour of moisture in existing housing construction materials.

In addition to the new moisture transport functions entered, experimental data was used to develop a moisture source model. This model was used to represent wet clothing releasing moisture into the indoor air, resulting in an increase in relative humidity. This is reported in Section 2.4

### 2.3.2 Moisture Transport Functions

#### Moisture Content

For ESP-r to calculate the moisture content of a material found in the building envelope construction, three moisture transport coefficients are required. These coefficients are determined from curve fitting, using empirical data obtained from the wet and dry cup tests. Equation 2.13 is used in ESP-r to calculate the moisture content.

Values for the three transport coefficients specified in the original moisture content calculation in ESP-r were taken from IEA Annex 14 and 24 and also supplied by Glasgow Caledonian University (GCU). Experimental results collected by GCU for a range of materials were manipulated to provide the data format required by ESP-r.

The new moisture transport functions added to ESP-r to calculate the material moisture content are as follows:

\[ u = (0.0661 \times \phi) \times \rho \]  
(equation 2.17)

\[ u = (a \phi^2 + b \phi + c) \times \rho \]  
(equation 2.18)

Equation 2.17 was incorporated into the code in order to model the hygrothermal behaviour of aerated concrete. The equation represents the mean of the absorption and desorption curves. Equation 2.18 is a polynomial function obtained from curve fitting and regression analysis using empirical data sourced from IEA Annex 14 and 24. Each equation is multiplied by the density \( \rho \) of the relevant material (cf equations 2.15 and 2.16). This density value is included in the construction file associated with the building model.
An index variable was used to indicate which equation should be used with the data for the particular material.

**Moisture Capacity**

The moisture capacity of a material is calculated using Equation 2.19 (repeated from Equation 2.5 for clarity) in the moisture domain of ESP-\(r\):

\[
\xi = \frac{\partial u}{\partial \phi} = \frac{u_h}{n.A.\phi} \times \left[ 1.0 - \frac{A \log \phi}{A} \right] \left( \frac{n+1.0}{n} \right)
\]

(equation 2.19)

This equation is the derivative of the sorption isotherm function used to calculate the moisture content of a material. The new sorption isotherm functions were differentiated with respect to relative humidity and incorporated into the corresponding subroutine of the source code. The resulting equations are 2.20 and 2.21.

\[
\xi = \frac{\partial u}{\partial \phi} = u_h \times \rho
\]

(equation 2.20)

\[
\xi = \frac{\partial u}{\partial \phi} = (2a\phi + b) \times \rho
\]

(equation 2.21)

As was the case with the moisture content equation, an index variable was used to identify the appropriate equation for the supplied data.

**Vapour Permeability**

ESP-\(r\) calculates the vapour permeability using the equation 2.8.

The source code was also modified to incorporate a new vapour permeability function to represent gypsum plasterboard. The relationship between the relative humidity and vapour permeability was developed by Galbraith et al (1998) and was referenced by one of the IEA Annex 41 Common Exercises and is given as equation 2.22.
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\[ \delta = (a + (b \times \phi)) \times 10^{-11} \]

equation 2.22

Once again, an index was used to indicate the appropriate function for the data.

**Air Node Moisture Balance**

ESP-r is able to perform an air node moisture balance, taking into account all sources of moisture in the modelled zone and exfiltration. Mass flow into the zone is quantified in terms of the amount of air infiltration and mechanical ventilation (if being modelled) taking place in the selected zone. This moisture is then added to the moisture that is generated inside the zone, such as surface evaporation and/or the latent gains injected into the space (the latent gains being representative of occupant activity, for example). Improvements and checks were made to the code to ensure that the moisture exchanges at surfaces and moisture injections into the zones were both included correctly in the moisture balance.

**2.4 Moisture Source Model**

**2.4.1 Evaporative models**

An existing ESP-r facility was able to simulate evaporation from an open water surface and a wetted material surface. This method was used as the basis for the modelling of wet clothes drying inside a building. Code modifications were made to update the model and enable the user to specify certain variables relevant to their own laundry drying practice. These are:

- Clothes drying frequency (daily or single event)
- Initial mass of moisture contained within the clothing fabric
- Start time of clothes drying (expressed as an hour fraction)
- Start day of clothes drying (expressed as an integer)

Equation 2.23 is used to calculate the rate of evaporation \( e_v \) (kg/s) from a wetted surface (e.g. the surface of a material undergoing drying).

\[ e_v = \frac{h_c \times A_x \times (\omega_{surf} - \omega_{air})}{C_p} \]

(equation 2.23)

\( h_c \) = Convective heat transfer coefficient (W/m\(^2\)K)
Aₕ = Surface area of material (m²)
ωₙₕₕ = Mass of moisture per mass of dry air at the surface of the material (kg_moisture/kg_dry_air)
ωₙₕₐᵢᵦ = Mass of moisture per mass of dry air in the zone air (kg_moisture/kg_dry_air)
Cₚ = Specific heat capacity (J/kg.K)

A simple form of the Lewis relationship (Steeman et al 2009) is used in equation 2.23 to determine the mass transfer coefficient at the surface of the material.

\[ hₘ = \frac{h}{Cₚ} \]  
(equation 2.24)

hₘ = Convective mass transfer coefficient (kg/m².s)

Three alternative evaporation rate equations were added to the ESP-r special materials facility. These are shown in equations 2.20, 2.21 and 2.22.

\[ e_v = \sigma \times h \times Aₕ \times \left( \omegaₙₕₕ - \omegaₙₕₐᵢᵦ \right) \bigg/ Cₚ \]  
(equation 2.25)

\[ e_v = hₘ \times Aₕ \times \left( Pₙₕₕ₋ₙₕₚₜₕ₋ₙₕₚₜₕ \right)^n \]  
(equation 2.26)

\[ e_v = hₘ \times \sigma \times Aₕ \times \left( Pₙₕₕ₋ₙₕₚₜₕ₋ₙₕₚₜₕ \right)^n \]  
(equation 2.27)

Pₙₕₕ = Saturated vapour pressure at the material surface (N/m²)
Pₙₕₚₜₕ = Saturated vapour pressure in zone air (N/m²)
ϕ = Relative humidity
σ = Evaporation coefficient

Equation (2.26) represents a standard form of the relationship between the evaporation rate and the ambient air conditions (Tang et al 2004).

An evaporation coefficient σ was added to the code to represent the total amount of moisture evaporated from the surface of the material as a fraction of the initial mass over each time increment of the simulation. The initial value is set to 1.0 as no moisture would
have evaporated prior to the starting time and day specified by the ESP-r user. Once the drying process has started, the ratio between total evaporated and initial mass of moisture is subtracted from the initial value 1.0 to obtain an evaporation coefficient. At the next time step, the resulting evaporation rate will therefore be taking into account the total amount of moisture that was lost in the previous time step. Without this variable, the rate of evaporation is solely relying on the vapour pressure difference at the surface of the material, which produces an unrealistic linear rate of moisture loss from a wetted material surface and does not account for the surface of the material drying out.

\[ \sigma = 1.0 - \left( \frac{m_{ev}}{m_{init}} \right) \]  

(2.28)

\( m_{ev} \) = Total mass of moisture that has been evaporated (kg)

\( m_{init} \) = Initial mass of moisture at the surface of material (kg)

The process of drying is viewed as taking place over two or three stages (Mujumdar 1980). The first stage is a constant rate of drying, driven primarily by a vapour pressure gradient across the interfacial region of the material i.e. the thin boundary layer just above the surface of the material. A combination of pressure and temperature differences become the driving forces during the second stage of drying until finally a more complex mixture of physical factors influence the rate of moisture transfer through the material e.g. capillary pressure and pore structure. Some materials take longer to dry than others due to the physical complexity of the material composition and for this reason a more simplistic approach was taken in the ESP-r model.

2.4.2 Experimental data

Six items of laundry (a towel, two t-shirt’s, a shirt, jeans and a facecloth) were passively air dried inside a dwelling. Drying times can extend over a period of hours and so the mass of each item was recorded every 1 to 2 hours. Tables 2.3 and 2.4 compare the data produced from both experimental measurements and through computer simulations using ESP-r, for Jeans and a Towel item.

The computer simulation results are produced over a 6-day simulation period. Conditions were kept isothermal, where external and internal temperatures were maintained at 23°C. The internal relative humidity was kept at 67% RH, the average calculated condition based on in-situ measurements recorded at the time of laundry drying, and the infiltration rate was fixed at 0.5ac/hr. The internal temperature is the mean value calculated from the experimental results recorded over the whole drying period.
2.4.3 Results of comparison of measurements with model predictions

Example results, for jeans and a towel, are given in Tables 2.3 and 2.4 and Figures 2.2 and 2.3. The exponent values used for equations 2.26 and 2.27 are $n=1.18$ and $n=1.2$. Similar tables and graphs were produced for other clothing items.

<table>
<thead>
<tr>
<th>Time</th>
<th>Mass of item kg</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Towel (Measured data)</td>
</tr>
<tr>
<td>13:33</td>
<td>0.620</td>
</tr>
<tr>
<td>14:17</td>
<td>0.580</td>
</tr>
<tr>
<td>15:17</td>
<td>0.528</td>
</tr>
<tr>
<td>16:17</td>
<td>0.482</td>
</tr>
<tr>
<td>18:17</td>
<td>0.420</td>
</tr>
<tr>
<td>20:17</td>
<td>0.402</td>
</tr>
<tr>
<td>00:15</td>
<td>0.402</td>
</tr>
<tr>
<td>07:15</td>
<td>0.400</td>
</tr>
</tbody>
</table>

Table 2.3: Results for drying of towel

<table>
<thead>
<tr>
<th>Time</th>
<th>Mass of item kg</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Jeans (Measured data)</td>
</tr>
<tr>
<td>13:33</td>
<td>1.004</td>
</tr>
<tr>
<td>14:17</td>
<td>0.980</td>
</tr>
<tr>
<td>15:17</td>
<td>0.942</td>
</tr>
<tr>
<td>16:17</td>
<td>0.906</td>
</tr>
<tr>
<td>18:17</td>
<td>0.836</td>
</tr>
<tr>
<td>20:17</td>
<td>0.780</td>
</tr>
<tr>
<td>00:15</td>
<td>0.732</td>
</tr>
<tr>
<td>07:15</td>
<td>0.708</td>
</tr>
</tbody>
</table>

Table 2.4: Results for drying of jeans
A two phase drying process is apparent from these results. The linear nature of the drying process during the first 2-4 hours of the drying period is visible in the experimental data.
Predicted results from ESP-r’s evaporation rate calculations show reasonable correlation with experimental data in most clothing items during this initial drying period. The non-linear rate of decay is observed after this initial period until the clothing items have reached their dry weight.

The agreement is poorer for equations 2.25 and 2.27. The predicted drying curves showed a much longer time needed for the items to reach their dry weight in comparison to the measured results - this was the case for most items. The most prominent differences are seen when modelling the towel and jeans. This is possibly due to the more complex material structure of these items that creates greater resistance to mass transfer and the combined effect of vapour and liquid transfer processes occurring in this type of material.

Although more experimental data is needed to improve the models for moisture release, it was considered that the models developed were adequate to represent the moisture release within this project.

### 2.5 Parametric test structure

In order to assess the influence of various environmental and building parameters on indoor humidity, an automated, parametric test tool was developed for ESP-r. This enabled large numbers of simulations to be run, testing the impact of a specific parameter, such as ventilation level or moisture loading, on humidity over a range of user defined values or states for that parameter. Figure 2.4 illustrates the operation of the structure; this was used in the simulations documented in Section 4.
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Figure 2.4 Parametric Testing Structure
3. Validation

The ability of ESP-r to model moisture transfer was tested using a number of validation tests developed within IEA Annex 41 Subtask 1 (Woloszyn and Rode 2007). Also, a number of cyclic tests were conducted by Glasgow Caledonian University within the scope of this project.

3.1 IEA 41 validation tests

Over the last few decades, there has been continuing development and increased use of heat, air and moisture (HAM) modelling software tools in the building services and design industries. A vast majority of these tools are able to simulate the behaviour of heat, air and moisture at the air point in a building. However, the need to develop reliable and accurate modelling of the hygrothermal interactions at the surface of the material and within the envelope construction is growing rapidly.

To this end, IEA Annex 41 test exercises 1-3 have been used to validate the moisture modelling domain within ESP-r. The focus of these exercises, with the scope of the EPSRC project in mind, is to assess the software’s ability to accurately predict the relative humidity within the indoor air, whilst taking into account fluctuating boundary conditions and the moisture buffering impact of the materials found in the construction. This was done by comparing the predicted outcomes of ESP-r’s simulations with measured and analytical data but also with results provided from other simulation tools. A brief overview of each exercise is provided below:

- **Common Exercise 1**: This exercise involved five individual cases. Two types of building were being modelled, a lightweight, wood based interior wall and a heavyweight construction made up of inorganic materials (concrete, foam insulation). A set ventilation rate and scheduled moisture injection was modelled. Two of the cases were analytical studies that maintained isothermal boundary conditions and investigated the impact of vapour tight and vapour permeable surface linings at the interior surface. The final three cases involved simulating the same lightweight and heavyweight models but this time with addition of hygric material data sourced from IEA Annex 24 and the addition of a paint and a vapour retarder to one of the models. A Denver climate was also included for the final three cases, providing the external boundary conditions.
• **Common Exercise 1A**: Two analytical cases were modelled in this exercise. The construction in both cases was made of a monolithic aerated concrete and the boundary conditions were isothermal. A scheduled moisture injection was included and a constant ventilation rate was set. The first case (Case 0A) involved modelling the internal surfaces of the construction as vapour tight, which would help to assess the accuracy of the moisture balance calculation carried out at the air point by ESP-r. Case 0B modelled the interior surfaces as vapour permeable, incorporating the buffering potential of the material. Under the simplified climatic conditions being used, this exercise helps to analyse the hygrothermal modelling capability of ESP-r at the point where air is in contact with the building envelope and when moisture transfer takes place within the material structure.

• **Common Exercise 1B**: Exercise 1B was divided into three cases. The construction was made of monolithic aerated concrete and the climate for Copenhagen was used. Internal temperatures were either kept constant at 20°C or fluctuated between upper and lower limits of 20°C and 27°C respectively. The first two cases did not take solar radiation into account whereas the third case did. Constant indoor temperature would better reveal the deviations in the moisture modelling calculations and by adding fluctuating internal temperatures and solar radiation in the later cases, a more dynamic and realistic scenario was developed.

• **Common Exercise 2**: An investigation into the effect of the ventilation rate and the quantity and location of moisture buffering internal wall cladding formed the basis of common exercise 2. The exercise involved modelling air conditioned at 20°C and 50% RH being drawn into a test chamber. An evaporating source was installed in the test chamber to provide a set period of humidification, which additionally provided both sensible and latent heat gains over the simulation period. The initial study focused on the effect of varying the ventilation rate, ranging from no ventilation to 5 air changes per hour. The second study involved the modelling of vapour permeable surfaces in conjunction with a constant ventilation rate. A comparison could then be made against measured data from the climate chamber experiment.

• **Common Exercise 3**: This exercise was designed to assess the influence of the moisture buffering potential found in common building materials that are located at internal surfaces of the building construction on the internal humidity levels. A comparison was drawn between the ESP-r simulation results and measured data obtained from the outdoor investigation area in Holzkirchen (Germany) where the initial test was carried out empirically. A model connecting a series of zones with individually specified internal climates and boundary conditions was constructed in ESP-r. Focus was placed on two of the constructed zones (identical in geometry), where several material finishes were applied, varied in position and in total applied surface area. The results would provide insight into the accuracy of the modelling
process in determining internal relative humidity levels using dynamic external boundary conditions.

The results included in this report are for Common Exercise 1A, Common Exercise 1B and Exercise 3. The complete set of results for the exercises described can be found in Markopoulos (2012).

3.1.1 Common Exercise 1A

Objective
This exercise is a variation of Common Exercise 1 and incorporates more simplified conditions in terms of the boundary conditions but also introduces new material properties, which can be used to solve the exercise analytically.

Model Outline

General Information

Two cases are proposed, using both numerical and analytical solutions. The conditions for these two cases are as follows:

1. Case_0A – Isothermal exposure where both internal and external temperatures are set at 20°C. The internal surfaces of the building are kept vapour tight.
2. Case_0B – Similar isothermal conditions applies as in Case_0A. Internal construction surfaces are now assumed open to moisture transfer.

In comparison to previous versions of Common Exercise 1 and the BESTEST cases, the following edits have been made to the model used in this exercise:

- The altitude is 0m.
- Building envelope construction is made of monolithic aerated concrete with constant/linear properties.
- Vapour tight membranes are applied on the exterior surface of the construction (and the interior in Case_0A), preventing loss of moisture through the building walls from the internal environment.
- The exposure is completely isothermal.
- The building has no windows.
- The outside and initial conditions are stated as 20°C and 30% RH (relative humidity). These are also the initial conditions of the materials in the building envelope construction.
- The building is assumed to be floating (i.e. no ground).
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Material Specification
All surfaces including Exterior Wall, Roof and Floor (inside to outside)

<table>
<thead>
<tr>
<th></th>
<th>λ (W/mK)</th>
<th>Thickness (m)</th>
<th>Dry Density kg/m³</th>
<th>Dry Cp J/kg.K</th>
<th>U W/m².K</th>
<th>U W/m².K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aerated Concrete</td>
<td>0.18</td>
<td>0.15</td>
<td>650</td>
<td>840</td>
<td>8.29</td>
<td>29.30</td>
</tr>
</tbody>
</table>

Table 3.1: Thermal Property data for Aerated Concrete

Hygric Material Properties for Aerated Concrete
1. Water Vapour Permeability $\delta_p = 3.0 \times 10^{-11}$ kg.m.s.Pa
2. Porosity 76%
3. Mean sorption curve $u = 0.0661\phi$
   - $u$ is moisture content (kg/kg)
   - $\phi$ is the relative humidity

Heating and Ventilation
A moisture injection strategy is employed in this exercise, similar to that used in the original Common Exercise 1. Between 09:00 and 17:00 every day, moisture is injected at a rate of 0.5kg/h. This rate was converted into a latent gain that could be incorporated into the operational details specified in the simulation package ESP-r. Outside these hours there are no additional moisture gains; and there are no heat gains whatsoever in this exercise.

Methodology

Specific Conditions
As previously mentioned, the internal surfaces of the model in Case_0A are clad with a vapour tight material. In addition, there are no solar gains. Aside from the vapour tight internal surfaces, the conditions in Case_0B are identical to Case_0A. The potential for moisture transfer in Case_0B is only in the form of diffusion through the construction material. The convective surface resistance specified in the exercise, for all the constructions, is $5.0 \times 10^7$ Pa.m²/s/kg.

Results
Figure 3.1: Common Exercise 1A_0A - Hourly RH results obtained
Figure 3.2: Common Exercise 1A_0B - Inter simulation model comparison. Included are hourly RH results obtained using ESP-r (default convection coefficient calculation ESP-r#1) and analytical result
Figure 3.3: Common Exercise 1A_0B - Hourly RH results obtained. Varied convective heat transfer coefficients used for surface of building envelope materials. Default ESP-r setting (buoyancy driven convection labelled ESP-r#1) and fixed coefficients specified in exercise were tested (labelled ESP-r#2).

**Discussion**

Under isothermal conditions and using a vapour tight interior lining on the building envelope, it is apparent in Figure 3.1 that the ESP-r model is capable of predicting internal humidity conditions with reasonable agreement to the analytical results. However, this correlation is not as strong when a hygroscopic material is introduced to the model.

The spread in results provided from other modelling tools, as can be seen in Figure 3.2, suggests that results from ESP-r are within the predicted range even when incorporating the default heat transfer convection coefficient calculation.

Figure 3.3 emphasises the influence of the convective surface resistance on the moisture transfer. The line labelled ESP-r#2 represents a fixed convective heat transfer coefficient (8 W/m².K) that has been applied to the model. There is agreement between the predicted and analytical values of peak relative humidity during the period of moisture injection in the space but the level of humidity either side of this period does not decrease sufficiently,
possibly due to the release of moisture back into the space from the material during the desorption phase, which will be driven by the vapour pressure gradient created at the surface when the moisture in the air is removed by the ventilation.

The default setting for calculating the convective heat transfer coefficient in ESP-r is buoyancy controlled, which considers the variations in temperature at a point to calculate this value. The line labelled ESP-r#1 in Figure 3.3 displays the results produced when using this assumption. Peak relative humidity during the moisture injection period is slightly overestimated, indicating that a reduced value for the surface heat transfer coefficient has been calculated resulting in a decrease in the potential moisture transfer occurring at the surface. The reasonable correlation between the predicted and calculated analytical values is more likely due to the effect of ventilation in the space.

Conclusion

This exercise introduced more simplified environmental conditions and new material properties into ESP-r. The initial part of the exercise did not consider the buffering impact of the envelope material on the internal relative humidity. The focus was simply on modelling the internal relative humidity correctly. Simulation results produced when using a vapour tight internal surface material showed good agreement when compared to analytical results, emphasising the accuracy of the internal air moisture balance being carried out by ESP-r under isothermal conditions. The second study looked at the impact of modelling the moisture buffering effect of the concrete construction. Reasonable agreement was achieved again between the ESP-r output and analytical results.

3.1.2 Common Exercise 1B

Objective

This exercise further develops the original BESTEST model, which was initially revised in Common Exercise 0 and 1. Analysis of the indoor and building envelope moisture conditions are carried out focusing on indoor relative humidity. The construction of the model was simplified after initial uncertainties were observed in Common Exercise 1. The climate of Copenhagen was used for these simulations. There are 3 cases designed for the purposes of testing the transient moisture behaviour.

Methodology

Specific Cases looked at were as follows.
1. Case ‘20°C, no external radiation’, where the influence of the solar radiation is neglected and where constant indoor temperature better reveals the deviations in moisture calculations.

2. Case ‘20 to 27°C, no external radiation’, which is a more realistic case but still without solar and long wave radiation.

3. Case ‘20 to 27°C’, now with solar and long wave radiation through the windows and on the external opaque surfaces.

**Model Specification**

The location is Copenhagen (altitude: 5m, latitude: 55°37’ north, longitude: 12°40’ east). The building is constructed entirely out of monolithic aerated concrete and every surface is subject to the same outdoor boundary conditions, including the floor. No coatings or membranes are applied to any face.

**Material Specification**

<table>
<thead>
<tr>
<th>Thickness (m)</th>
<th>0.15</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inside surface area of walls (m²)</td>
<td>75.6</td>
</tr>
<tr>
<td>Inside surface area of roof (m²)</td>
<td>48.0</td>
</tr>
<tr>
<td>Inside surface area of floor (m²)</td>
<td>48.0</td>
</tr>
<tr>
<td>Internal surface resistance for heat transfer (m².K/W)</td>
<td>0.121</td>
</tr>
<tr>
<td>External surface resistance for heat transfer (m².K/W)</td>
<td>0.034</td>
</tr>
<tr>
<td>Dry density (kg/m³)</td>
<td>600</td>
</tr>
<tr>
<td>Dry heat capacity (J/kg.K)</td>
<td>840</td>
</tr>
<tr>
<td>Dry thermal conductivity (W/m.K)</td>
<td>0.18</td>
</tr>
<tr>
<td>Initial temperature of construction and indoor air (°C)</td>
<td>20</td>
</tr>
<tr>
<td>Initial relative humidity of constructions and indoor air (RH%)</td>
<td>80</td>
</tr>
</tbody>
</table>

Table 3.2: Thermal properties for monolithic aerated concrete and construction dimensions (IEA Annex 41, Subtask 1, Common Exercise 1 “Realistic” Case)

| Internal convective surface resistance for vapour transfer (Pa·m²·s/kg) | 5.0x10⁷ |
| External convective surface resistance for vapour transfer (Pa·m²·s/kg) | 1.6x10⁷ |
Table 3.3: Hygric properties used for monolithic aerated concrete (IEA Annex 41, Subtask 1, Common Exercise 1 “Realistic” Case)

**Water Vapour Permeability (kg/m.s.Pa):**

\[
\delta = 0.176 \times 10^{-9} \left(0.116 + 0.00628 \exp(4.19\phi)\right)
\]

(equation 3.1)

**Moisture Content (kg/m³):**

\[
\omega = 300 \left(1.0 - \frac{\ln \phi}{0.0011}\right)^{-1.99}
\]

(equation 3.2)

**Moisture Content (kg/kg):**

\[
u = 0.5 \left(1.0 - \frac{\ln \phi}{0.0011}\right)^{-1.99}
\]

(equation 3.3)

**Results**
Figure 3.4: Case 1 - Indoor temperature is kept constant at 20°C and no external radiation is included.

Figure 3.5: Case 2 - Indoor temperature fluctuates between 20 and 27°C and again no external radiation was considered in predicted results.
Figure 3.6: Case 3 - More realistic case where indoor temperature fluctuates between 20 and 27°C and now solar and long wave radiation is considered.

**Conclusion**

This exercise involved the simulation of a vapour permeable construction under varied environmental conditions both inside and outside the construction. An isothermal case and two cases with set temperature control were modelled, with the exclusion of solar gains in the first case and a constant ventilation rate in all cases. A sensible heat gain was also modelled in all three cases. Results from ESP-r and the solutions provided by other hygrothermal modelling software show that there is a large degree of variation in outcomes. The complexity surrounding moisture transfer even under isothermal conditions, as was the situation in Case 1, shows that it is not only the influence of temperature that creates difficulty in accurately predicting internal relative humidity. The use of a real climate highlights the need for further investigation into improving the analysis involved in calculating the indoor air moisture balance.
3.1.3 Common Exercise 3

Objective

This exercise was designed to observe if the moisture buffering effect of common building materials, positioned at the internal face of the building envelope, influence the internal humidity levels and to what extent, using performance predictions produced by simulation tools. A comparison is then drawn between the simulation results and measured data obtained from the outdoor investigation area in Holzkirchen (Germany) where the same test was carried out empirically. A model connecting a series of zones with individually specified internal climates and boundary conditions was constructed using the building simulation tool called ESP-r. Focus was placed on two of the constructed zones (identical in geometry), where several material finishes were applied, varied in position and the total applied surface area. The results provide insight into the accuracy of the modelling process in determining internal climate conditions and energy consumption under real conditions.

Methodology

The two rooms shown in Figure 3.7 are identical in geometry; however, they differ in terms of the materials that are applied to the internal wall surfaces. In the first step, the zone labelled Test Room is lined with an Aluminium foil layer to prevent moisture transfer through the envelope surfaces. Steps 2 and 3 specified a standard type of Gypsum Board to be installed in the Test room, firstly on the walls and then the walls and ceiling. The floor material is also considered impermeable to vapour transfer with a layer of PVC installed; this was the case in both the Reference and Test zone. In the Reference room, a standard type of Gypsum Plaster with a latex paint coating was used for all three simulation steps. This coating had a measured equivalent diffusion layer thickness of 0.15m.

The two zones are part of a series of single zones connected by a passageway. However, for the purposes of this exercise only these two zones were modelled and the adjacent zones were considered as exterior elements when assigning boundary conditions.
The temperature in both Reference and Test zone was maintained at 20°C using a basic heating controller system existing in ESP-r. The maximum power output from this heating method was kept at 1kW as was specified in the exercise.

One modelling parameter differing between the two zones was the infiltration rate. Due to surface defects and natural leakage through joints in the buildings construction, masking tape was used to seal these sources of uncontrolled airflow. A ventilation system was applied to the Reference and Test zones after tracer gas tests were carried out to calculate the air change rate during operational hours. The results showed an air change rate of 0.63 for the Reference room and 0.66 ac/h for the Test room.

The moisture production schedule shown in Figure 3.8 is representative of a three person household. This has been converted for the test rooms and the diurnal pattern is as follows:

1. Between midnight and 6am, a basic production rate of 0.025 kg/h is assumed analogous to pets and general items such as plants.
2. Between 6am and 8am, the rate increases to 0.4 kg/h to account for human activities such as showering and washing.
3. The basic rate of 0.025 kg/h is subsequently assumed again after human activity ceases.
4. A longer moisture production period of 6hrs becomes active between 4pm and 10pm, which represents activities such cooking or drying laundry.
Figure 3.8: Moisture Production schedule

Boundary Conditions

The boundary conditions varied depending on the location of the building. At the South face of the building an external climate for Holzkirchen, provided in the exercise literature, was used. A second climate labelled ‘Internal Climate’ was specifically applied to the North face of the building and in the region above the ceilings of the two zones. The ground temperature was specified as 2°C on average. This was assigned to the model using a ground temperature profile facility available in ESP-r. Figure 3.9 is a diagram of the model built in ESP-r and points out the different climate regions.

The literature in the exercise outline described the radiative surface properties and also provided the total surface resistance coefficients for the ceiling, floor and both inside and outside walls. This caused confusion with respect to which values to model. Thus the surface heat transfer coefficients used in the model were values calculated by ESP-r in its default setting.

Table 3.4 gives an overview of the simulations to be carried out. Step 1 was used to highlight the total impact of moisture absorptive surfaces included within the Reference zone on room humidity in comparison to a zone (Test zone) with impermeable wall surfaces. The simulation setup progresses in Step 2 where the inclusion of some vapour permeable materials in the building envelope allows a comparison to be drawn between the relative humidity achieved in the two zones, accounted for by the difference in the number of surfaces open to moisture transfer and their position.

Finally, Step 3 defines all surfaces to be vapour permeable, the only difference between the two zones in this case being the paint finish applied to all of the internal surfaces in the Reference room. The paint finish is present in the Reference room for all three steps; however, Step 3 enables us to compare the effect of the paint on the absorption rate and moisture capacity of the gypsum plaster layer.
Figure 3.9: ESP-r Model

Table 3.4: Summary of simulations undertaken
Results

Step 1

Figure 3.10: Step 1 - Simulation results for Reference Room versus measured data (simulation period 25.1.2005 – 26.1.2005)

Figure 3.10 shows the relative humidity obtained from measured data and from the results obtained using ESP-r simulations over a selected period of two days. There is reasonable agreement between the peak humidity measured in both sets of results. On average, the peak humidity at 08:00 is 3.6% less than the measured value. There is also reasonable agreement between the measured and simulated results during the second period of moisture injection. The agreement between measured and simulated data is not as strong during the period after which the moisture injection has finished. The rate of decay observed in the simulated results produces a higher base value when the decay period stops and the next moisture injection period commences. An average absolute difference of 4% in relative humidity is seen at the end of the decay period.

Figure 3.11 displays the RH profile for the Test room obtained from simulation compared with the measured data. There is good agreement between these two sets of data. This confirms the accuracy of the modelling of vapour tight surfaces in ESP-r.
Figure 3.11 Comparison between simulated results and measured data for the Test room (simulation period 25.01.2005 – 26.01.2005)

**Step 2**

Figure 3.12 shows the relative humidity performance inside the Reference room over a selected two-day period. Again a similar relative humidity pattern emerges at peak periods as in Step 1. A slow rate of decay is visible here as well, where the simulation results produce mean base humidity values 8.6% higher than the measured data. During the entire simulation period (35 days), the average RH obtained from simulation is 8.3% greater.
Figure 3.12: Step 2 – Simulation results for Reference Room versus measured data (simulation period 17.2.2005 – 18.2.2005)

Figure 3.13: Comparison between simulated results and measured data for the Test room (simulation period 17.02.2005 – 18.02.2005)
Figure 3.13 displays the RH performance in the Test room which changes significantly when Gypsum Board is applied to the internal wall surfaces. The peak humidity is on average 10% less than the peak conditions achieved in the Reference room. The buffering potential of the uncoated Gypsum Board is clearly more effective than the coated plaster. The higher infiltration rate in the Test room, however, does not remove the emitted moisture sufficiently to match the base RH value that is achieved in the Reference room.

Step 3

![Graph](image)

Figure 3.14: Step 3 - Simulation results for Reference room versus measured data (simulation period 4.4.2005 – 5.4.2005)

Average humidity differences at peak times show reasonable agreement (Figure 3.14) after the first moisture injection period and an overestimation in the peak difference of 2% on average after the second moisture load period. Simulation predictions show a reduced decay rate resulting in overestimations of the base relative humidity values, with an average difference of 8.2%. Over the course of the whole simulation period (26 days) the average difference achieved in RH is 5.7% greater in predicted results in comparison to actual data.

Figure 3.15 presents the results of introducing more hygroscopic material into the simulation model. The level of agreement between the measured and simulated results in the Test room is considerably reduced over the entire simulation period. Peak humidities
are overestimated by approximately 3% in absolute humidity terms, which could be considered negligible. However, over the entire simulation period, there is an average difference of 10% between simulated and measured values. The main difference is seen during the period after peak humidity has been reached. A much higher relative humidity is seen in the simulated results over this period, which could be due to higher levels of moisture desorption from the hygroscopic material.

Figure 3.15: Comparison between results and measured data for the Test room (simulation period 04.04.2005 – 05.04.2005)

Discussion of Steps 1 to 3

The moisture buffering capability of vapour permeable materials is clearly seen in the Step 1 when comparing peak humidities. The addition of gypsum board walls to the Test room in Step 2 reveals the benefit of not applying surface coatings, such as latex paint, to the internal cladding. By comparing the peak humidity results in the Reference room with the Test room, in Figures 3.12 and 3.13, differences of approximately 5% are achieved. Results show that the moisture buffering potential of moisture absorbent materials is reduced when surface coatings are applied. The experiments show that by applying the paint, the vapour resistance of the surface material is increased resulting in reduced moisture absorption during periods of moisture injection.
From Step 3, it can be seen that the uncoated Gypsum Board at the internal surfaces is more effective than Gypsum Plaster coated with latex paint at helping to reduce relative humidity peaks. Reduced fluctuations in the relative humidity are also achieved by applying the uncoated Gypsum Board. Smaller RH fluctuations in the air will ultimately be beneficial for the long-term integrity and durability of the construction material. By repeatedly exposing the material to long periods of high moisture loads, 70% and above, the possibility of surface degradation through biological corrosion increases and in addition the onset of health related problems for occupants begins as a result of mould growth.

3.2 Cyclic tests

See note at the end of the report contents.
4. Modelling - General Parametric Study

An initial parametric study was undertaken to assess the impact of a range of parameters on indoor relative humidity and energy consumption. These included moisture production levels, ventilation rates, surface finishes, insulation levels, levels and climate. The parametric values chosen were to cover the likely maximum realistic range for the investigated parameters.

The different parameters analysed are shown in Table 4.1 – all possible combinations were simulated.

<table>
<thead>
<tr>
<th>Building Type (insulation)</th>
<th>Moisture generation</th>
<th>Infiltration (ac/h)</th>
<th>Materials and finishes</th>
<th>Occupancy and heating</th>
<th>Climate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poor insulation</td>
<td>Light</td>
<td>Poor (1.5)</td>
<td>Vinyl Uncoated Gypsum Plasterboard Clay Board</td>
<td>Light and intermittent High and continuous</td>
<td>Dundee London</td>
</tr>
<tr>
<td>Well insulated (current regs)</td>
<td>Heavy</td>
<td>Good (0.6)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Passive house insulation levels.</td>
<td>MHVR (Passive house only)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4.1. Parameter combinations considered in the study

The following metrics were used to compare the different changes to the model: change in peak RH; change in average RH; and (where appropriate) total energy used for space heating ($kWh/m^2$) – note this does not include any system inefficiencies.

4.1 Model Type

A simple semi-detached dwelling model was used for this study, with the internal spaces divided into a ‘living space’ and ‘sleeping space’, the objective being to develop a model that was thermodynamically faithful to a typical building rather than architecturally faithful. The daytime occupancy and drying was situated in the living space.
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**ESP-r models and Passive House Insulation Levels**

The thermal characteristics of the constructions used with the typical and passive house model variants are summarised in Table 4.2.

Note that the passive house construction insulation values (representative of the future housing stock) were determined by an iterative process, whereby the insulation levels were altered until the building met the Passive House standard for heating energy consumption of 15 kWh/m².year [2]. The average air infiltration for the Passive House cases is 0.03 air changes per hour, augmented with a mechanical ventilation heat recovery system (MVHR) with an effectiveness of 80% supplying 0.4 air changes per hour (this is the actual ventilation rate).

The constructions of Table 4.2 were varied with different surface finishes: impermeable vinyl wallpaper, uncoated gypsum plasterboard (commonly found in generic social housing) and moisture control, clay plasterboards. The clay plasterboards are a combination of clay, reed and hessian, which are thicker and heavier than gypsum plasterboards.

<table>
<thead>
<tr>
<th>Construction</th>
<th>Passive house standard U-Values (W/m²K)</th>
<th>Impermeable construction Poor Insulation U-Values (W/m²K)</th>
<th>Impermeable construction Good Insulation U-Values (W/m²K)</th>
<th>Permeable construction Poor Insulation U-Values (W/m²K)</th>
<th>Permeable construction Good Insulation U-Values (W/m²K)</th>
<th>Clay Board Poor Insulation U-Values (W/m²K)</th>
<th>Clay Board Good Insulation U-Values (W/m²K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wall</td>
<td>0.14</td>
<td>1.568</td>
<td>0.305</td>
<td>1.568</td>
<td>0.307</td>
<td>1.281</td>
<td>0.294</td>
</tr>
<tr>
<td>Windows</td>
<td>0.70</td>
<td>5.621</td>
<td>2.059</td>
<td>5.621</td>
<td>2.059</td>
<td>5.621</td>
<td>2.059</td>
</tr>
<tr>
<td>Floor</td>
<td>0.14</td>
<td>0.850</td>
<td>0.252</td>
<td>0.850</td>
<td>0.252</td>
<td>0.850</td>
<td>0.252</td>
</tr>
<tr>
<td>Ceiling</td>
<td>0.14</td>
<td>0.992</td>
<td>0.161</td>
<td>0.992</td>
<td>0.161</td>
<td>0.992</td>
<td>0.157</td>
</tr>
<tr>
<td>Mean infiltration rate (air changes/hour)</td>
<td>0.03 [0.4 from MVHR]</td>
<td>1.5. or 0.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4.2. ‘U-values’ for external constructions for the typical and passive house levels of insulation and infiltration rates
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*Occupancy and Associated Heating Schedule*

The dwelling models were set up to include heat gains consistent with continuous occupancy from a family of four, continuous occupancy by an elderly couple, and intermittent occupancy from a working couple. The heating strategies implemented in the model were designed to reflect the occupancy patterns (Table 4.3). Outside of the set heating periods, the heating system was switched off.

<table>
<thead>
<tr>
<th>Occupancy pattern</th>
<th>Heating schedule (hours in use)</th>
<th>Heating schedule (temperature setting)</th>
</tr>
</thead>
<tbody>
<tr>
<td>High occupancy (family)</td>
<td>0700-0000</td>
<td>21°C</td>
</tr>
<tr>
<td>Low occupancy constant use (elderly)</td>
<td>0700-0000</td>
<td>21°C</td>
</tr>
<tr>
<td>Intermittent occupancy (working couple)</td>
<td>0700-0900; 1600-0000</td>
<td>21°C</td>
</tr>
</tbody>
</table>

Table 4.3. Heating schedules

The process of laundry drying in the living space was modelled based on the aggregated sum of various items of clothing being hung up to dry. The moisture load was represented as a latent gain in the space. Based on clothes-drying experiments carried out at home, moisture weight loss from these items was measured hourly, over a period of 7-8 hours, until the mass of the item remained constant. Two types of drying process were modelled, the first representing a heavy wash load hung up to dry (10 items); and the second a lighter washing load, with fewer items hung up (6 items). The scheduling of these two drying processes is shown in Table 4.4:

<table>
<thead>
<tr>
<th>Moisture load</th>
<th>Moisture injection period</th>
<th>Days applied</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light</td>
<td>1000-1700;</td>
<td>Weekdays; Saturday</td>
</tr>
<tr>
<td>Frequent Washing</td>
<td>1000-1700; 1900-0200</td>
<td>Weekdays; Saturday; Sunday</td>
</tr>
</tbody>
</table>

Table 4.4: Moisture load schedule
Infiltration Rates

A range of air change rates were investigated. For these simulations, an air change rate of 0.6 was used for a ‘tight’ construction and a rate of 1.5 was used to represent a more leaky construction characteristic of older dwellings.

4.2 Parametric Study Results

Figures 4.1 and 4.2 are indicative of the results emerging from the parametric study and show the extreme ranges of mean RH, maximum RH and energy from the different simulations for specific parametric changes to the models as outlined in Table 4.1. The maximum values on these graphs show the maximum potential impact of the tested parameters on the living room RH. For example, the greatest difference in mean RH (in summer and winter) due to changing the surface materials was about 15% between all parametric variations tested. The figures illustrate the relative importance of material finishes on the RH, indicating that (particularly in summer) changing internal material finishes can result in changes to RH of a comparable magnitude as changes caused by variations in both moisture load and infiltration. However both moisture loading and ventilation levels had a more significant effect on the mean RH.

Figure 4.1: absolute change in RH (%) for winter simulations
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Figure 4.2: absolute change in RH (%) for summer simulation

4.3 Impact of Surface Material Finish
Focusing on the impact of surface finishes, an example of the peak and mean RH differences between vapour permeable materials lining the internal surface of the building envelope and impermeable surface finish materials for is illustrated in Figures 4.3 and 4.4.

Figure 4.3 Dundee climate, winter week, low infiltration levels
Figure 4.4: Dundee climate, summer week, low infiltration levels

The two figures show the variation in mean and peak RH over a simulated winter and summer week for a Dundee climate. The house simulated has a low air change rate and heavy internal moisture loading. In both cases, the peak RH encountered over the simulated week drops significantly from near 100% to approx. 70% with unfinished gypsum plasterboard and to around 65% with clay plaster. Mean RH is also reduced, with the greatest reduction (12%) occurring with the Dundee climate under heavy moisture conditions and low natural ventilation (0.6 ac/h).

These results indicate that large permeable surface areas have a significant impact on internal RH, particularly where higher RH conditions prevail. However, the difference in performance between typical permeable materials such as plasterboard and dedicated moisture control materials is less distinct. Table 4.5 highlights the greatest absolute differences in maximum relative humidity achieved between the two vapour permeable materials modelled (Gypsum Plasterboard and Clay Plasterboard), again accounting for location and season. The plasterboard was taken as the reference.

<table>
<thead>
<tr>
<th>Climate</th>
<th>Winter</th>
<th>Spring</th>
<th>Summer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dundee</td>
<td>-5.6</td>
<td>-8.4</td>
<td>-7.0</td>
</tr>
<tr>
<td>London</td>
<td>-4.0</td>
<td>-5.9</td>
<td>-9.6</td>
</tr>
</tbody>
</table>

Table 4.5: Differences in maximum RH with different permeable finishes
Typically, the clay plaster performed best in the simulations with low air change rates (0.6 air changes per hour), reducing peak RH levels by 4-5% in comparison to plasterboard and 2-6% for mean RH levels.

### 4.4 Impact of Building Fabric Quality

A key factor examined in the parametric study was the impact of building fabric quality – this included both airtightness and insulation levels (shown in Table 4.2). Figure 4.5 shows the combined effect of these two elements extracted from the simulations, showing results from a building insulated to average UK levels (with infiltration levels of 0.6 and 1.5 ac/h) along with a passive house version of the same building (insulation levels shown in Table 4.2) featuring mechanical ventilation heat recovery (MVHR).

![Image of RH obtained with different fabric and infiltration regimes](image)

**Figure 4.5:** Example of RH obtained with different fabric and infiltration regimes (Winter simulation, London climate)

With the standard insulation levels, the higher the infiltration rate the lower the RH levels inside the building (with a clear energy penalty as shown in Figure 4.6). The RH levels obtained in the passive house simulations, where the ventilation supplied by the MVHR system is a fixed 0.4 air changes per hour, are a result of the higher average internal air temperatures rather than greater dilution of internally generated moisture with outside air.

Figure 4.6 shows the resulting energy requirements from the same three simulations, clearly showing the significant reduction in energy consumption associated with the higher insulation levels in the passive house construction.
The resulting impact on CO₂ emissions is shown in Figure 4.7, assuming heating with natural gas, a carbon coefficient of 0.18kgCO₂/kWh and an overall heating system efficiency of 70%.
Figure 4.7: Resulting CO₂ emissions from space heating (Winter simulation, London climate)
5 Modelling – Specific studies

5.1 Heating Load Study

A set of simulations were initiated to assess the impact of clothes drying on energy consumption as experienced in field studies of social housing – with windows in the living room left open most of the day in the drying room and the heating set point increased. To quantify the impact of such a drying regime on space heating, the detached house model from the parametric study was employed and two annual simulations were undertaken using a Dundee climate set. In the first, the house air change rate was fixed at 0.6 ac/h and the heating was scheduled to maintain a set point of 21°C during the period when the house is actively occupied (0700-2400). The model was then adapted to include passive drying, in which the ventilation was increased to 4 ac/h 1000-1700 in the living room, representing windows being opened during the drying period. Additionally, the heating system set point was boosted to 24°C during the drying to mirror behaviour seen in the field trials. The energy figures for an annual simulation were compared and are shown in Figure 5.1.

![Figure 5.1: The impact of clothes drying on living room space heating energy consumption over the year (Dundee climate)](image)

Both Table 5.1 and Figure 5.1 highlight that there is a significant energy penalty associated with the passive drying behaviour modelled (i.e. opening windows and increasing the
heating set point). An extra 3595 kWh of space heating input to maintain space temperatures is required under the modelled scenario.

It is useful to compare this drying approach to the alternative – drying the load in a tumble dryer. Assuming that typical tumble dryer energy consumption is approximately 3 kWh per cycle tumble drying results in 1404 kWh being expended over the course of the year. Hence, the passive drying behaviour in the case modelled here uses more than twice the energy associated with tumble drying.

<table>
<thead>
<tr>
<th>Drying method</th>
<th>Heating System</th>
<th>Fuel</th>
<th>kgCO₂/kWh (delivered)</th>
<th>Additional energy due to drying (kWh/yr)</th>
<th>kg CO₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open windows and increased heating set point</td>
<td>Gas</td>
<td>Natural gas</td>
<td>0.26*</td>
<td>3,595</td>
<td>935</td>
</tr>
<tr>
<td>Open windows and increased heating set point</td>
<td>Electrical resistance</td>
<td>Electricity</td>
<td>0.54</td>
<td>3,595</td>
<td>1941</td>
</tr>
<tr>
<td>Tumble dryer</td>
<td>-</td>
<td>Electricity</td>
<td>0.54</td>
<td>1,404</td>
<td>758</td>
</tr>
</tbody>
</table>

Table 5.1: energy use and carbon emissions associated with passive and tumble drying.

*assuming overall heating system efficiency of 0.7

The resulting carbon emissions associated with passive drying are approximately 23% higher than those associated with tumble drying. However, if (as is the case in many older social housing properties) the space heating uses direct electric resistance heating, then the carbon emissions associated with the passive drying modelled here would be 156% higher than where tumble drying is used.

5.2 Drying Laundry in a Purpose-Built Space

The previous simulations clearly indicated the energy penalty associated with providing adequate ventilation to dry clothes and mitigate high humidity levels by opening windows throughout a dwelling. An alternative approach is the provision of a designated drying space within a dwelling, which is ventilated to prevent moisture permeating throughout the building. To this end, the impact of a specific space for clothes drying in a dwelling was investigated using a model of an existing council dwelling in which a cupboard 3.45m³ was
converted to an indoor drying space. The house is assumed to have a background infiltration rate of 0.6 air changes per hour.

Two simulations were run, one in which clothes drying took place within the occupied space of the dwelling, with a background infiltration level of 0.6 air changes per hour and another where the drying is isolated from the rest of the dwelling within the drying space, which was heated and ventilated continuously with approximately 15 l/s. The simulations were undertaken using a Dundee climate for a spring week.

Figure 5.2 shows the resulting impact of the change in drying strategy on living room relative humidity levels. By excluding laundry drying taking place in the occupied space of the building model, the peak and mean relative humidities differ greatly compared to where the drying was done in the occupied space, showing the dramatic impact of removing drying from the living space. The same reductions in RH would result if tumble drying or communal drying solutions were implemented.

The energy penalty associated with the provision of a separate, ventilated and heated drying space is approximately 1025 kWh over the course of simulated year, compared to the base case with no passive drying, which is significantly less than associated with opening windows and increasing the heating set point, but still more than that associated with a tumble dryer.
Figure 5.2: living room relative humidities with laundry drying within the house against laundry drying in a separate ventilated space.

5.2.1 Drying Space Ventilation and Operating Strategies

A further set of simulations were undertaken focusing on the operation of a purpose built drying space, analysing the conditions within the drying space, and the energy required for drying (particularly the means to reduce the energy penalty associated with drying). The drying space modelled was 1.75m³, as set out in the design guide (Menon and Porteous 2012) and comprises the drying space and associated ventilation equipment. Several different cases were examined, these were as follows:

- Drying space supplied with 15 l/s from an extract only system, with continuous fan operation and with fan subject to humidistat control ON/OFF control with deadband;
- Drying space supplied with 15 l/s from an MVHR system (80% heat exchanger effectiveness), with continuous fan operation and with fan subject to humidistat control ON/OFF control around 50% RH.
The above simulations were also undertaken with plasterboard and Claytech liner material. Note that the initial simulations did not model surface moisture absorption and so can be assumed to be of an impermeable surface finish.

For the extract-only simulations, the fan drawing 15 l/s has a rated power consumption of 12W. In the MVHR case, a supply and extract fan are used consuming 24W.

In all cases, the drying room temperature was controlled to 21°C using a heating coil. The heating requirement accounts for ventilation losses and the energy required for evaporation. The assumption is that there is heavy use of the drying room, with 1 small wash per day dried and 2 washes at weekends. The simulations were conducted for characteristic winter spring and summer weeks using a Dundee climate set. As the indoor drying space is being heated to a fixed temperature in all seasons, the external moisture content of the air will be one of the main determining factors on indoor moisture conditions. The moisture characteristics of the outdoor air are shown in Figure 5.3.

For the climate data set used, the summer external air moisture content is significantly higher than that seen in either spring or autumn; this is to be expected as the moisture capacity of air is higher in warmer summer conditions than where cooler conditions prevail.
**CASE 1 – Impermeable Finish, Extract Only (no heat recovery)**

Figure 5.4 shows the typical time-series output from one of the spring simulations with the fan supplying the drying space operating continuously at 15 l/s. Points to note are that the drying activity raises the RH by approximately 25% and drops the space temperature by around 3°C before they recover due to the action of space heating control, which tries to maintain the temperature at 21°C. Also notice that whilst external RH is high, when this air is brought into the drying space and heated, the internal RH is maintained around 30% outwith the drying period.

![Figure 5.4. Typical results a simulation – spring, continuous fan operation, extract only.](image)

Figure 5.5 and Table 5.2 summarise the time-series results from 6 simulations for the case with the fan running continuously at 15 l/s and where the fan runs only to limit humidity levels, using an on/off controller with a dead band of 50-70% RH, for winter spring and summer weeks. The results comprise the mean temperature, mean RH, peak RH and energy use for the fan and heater (kWh).
As expected the mean RH is lowest in winter and higher in summer, when external air moisture contents are at their lowest and highest respectively (Figure 5.5). In all cases, continuous operation of the fan results in lower mean RH. However, the peak RH is consistently high, and summer mean RH are over 50% indicating that a higher ventilation rate may be required than the stipulated 15 l/s in the design guide. Humidistat-based fan control brings significant energy use reductions (e.g. 57kWh/week to 22 kWh per week in winter); however, this is at the expense of higher mean RH.
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Figure 5.5: Impermeable surface finish, air extraction only.

**CASE 2 – Impermeable Finish, MVHR**

Figure 5.6 and Table 5.3 show the results from the simulations for the case with the fan running continuously at 15 l/s and where the fan runs only to limit humidity levels, using an on/off controller with a dead band of 50-70% RH. However, in this case the ventilation system operates with ventilation heat recovery (requiring a heat exchanger and a supply and extract fan).

![Dryingspace Winter Base](image1)

**Table 5.3: Impermeable surface finish, mechanical ventilation heat recovery (MVHR).**

<table>
<thead>
<tr>
<th>Temp (°C)</th>
<th>Ave RH</th>
<th>Peak RH</th>
<th>Energy (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>dryingspace winter base</td>
<td>21.01</td>
<td>39.09</td>
<td>19.28</td>
</tr>
<tr>
<td>dryingspace winter hstat</td>
<td>21.57</td>
<td>46.67</td>
<td>12.08</td>
</tr>
<tr>
<td>dryingspace spring base</td>
<td>21.01</td>
<td>41.79</td>
<td>18.88</td>
</tr>
<tr>
<td>dryingspace spring hstat</td>
<td>21.54</td>
<td>47.74</td>
<td>12.03</td>
</tr>
<tr>
<td>dryingspace summer base</td>
<td>21.25</td>
<td>53.92</td>
<td>14.68</td>
</tr>
<tr>
<td>dryingspace summer hstat</td>
<td>21.38</td>
<td>58.56</td>
<td>10.91</td>
</tr>
</tbody>
</table>

Total energy requirements are very significantly reduced e.g. from over 57 kWh per week for the winter case with an extract only system to 19 kWh per week. Humidistat-based fan control again reduces energy use but results in an increase in the mean and RH compared to the case where the fan runs continuously. Also, mean summer RH is above 50% and the peak RH values is very high.
Figure 5.6: Impermeable surface finish, mechanical ventilation heat recovery (MVHR).

**CASE 3 – Plasterboard Finish, Extract Only (no heat recovery)**  
Figure 5.7 and Table 5.4 again show the results from the simulations for the case with the fan running continuously at 15 l/s and where the fan runs only to limit humidity levels, for winter spring and summer weeks. In this case there is a permeable plasterboard finish and no MVHR.

<table>
<thead>
<tr>
<th></th>
<th>dryingspace winter base</th>
<th>dryingspace winter hstat</th>
<th>dryingspace spring base</th>
<th>dryingspace spring hstat</th>
<th>dryingspace summer base</th>
<th>dryingspace summer hstat</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean Temp (°C)</td>
<td>20.99</td>
<td>21.60</td>
<td>20.99</td>
<td>21.88</td>
<td>21.01</td>
<td>21.61</td>
</tr>
<tr>
<td>Mean RH</td>
<td>39.25</td>
<td>45.93</td>
<td>42.00</td>
<td>60.21</td>
<td>55.32</td>
<td>67.76</td>
</tr>
<tr>
<td>Peak RH</td>
<td>80.24</td>
<td>100.00</td>
<td>91.02</td>
<td>100.00</td>
<td>99.38</td>
<td>100.00</td>
</tr>
<tr>
<td>Energy (kWh)</td>
<td>57.12</td>
<td>22.17</td>
<td>54.98</td>
<td>20.99</td>
<td>32.73</td>
<td>16.45</td>
</tr>
</tbody>
</table>

Table 5.4: Plasterboard finish, extract only (no heat recovery)
The results indicate that changing the surface finish has a marginal effect on energy consumption. Mean RH increases in spring and summer when the fan is subject to humidity control in comparison to the impermeable case there is a very slight reduction in some peak RH. Humidistat-based fan control has a significant beneficial effect on energy consumption, at the expense of poorer control of RH.

**Drying Room - Extract Only**

![Graph showing Mean RH, Peak RH, and Energy (kWh) for different settings of the drying room.](image)

Figure 5.7: Plasterboard finish, extract only (no heat recovery)

**CASE 4 – Plasterboard Finish, MVHR**

Figure 5.8 and Table 5.5 show the results from the simulations for the case with the fans running continuously at 15 l/s and where the fan runs only to limit humidity levels, using an on/off controller with a dead band of 50-70% RH. In this case the ventilation system is configured for MVHR with a heat exchanger and a supply and extract fan.
Table 5.5: Plasterboard finish, extract only (no heat recovery)

<table>
<thead>
<tr>
<th></th>
<th>Temp (°C)</th>
<th>Ave RH</th>
<th>Peak RH</th>
<th>Energy (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>dryingspace winter</td>
<td>21.01</td>
<td>39.46</td>
<td>85.76</td>
<td>19.28</td>
</tr>
<tr>
<td>continuous fan</td>
<td>21.70</td>
<td>56.77</td>
<td>100.00</td>
<td>11.83</td>
</tr>
<tr>
<td>dryingspace spring</td>
<td>21.01</td>
<td>42.18</td>
<td>89.00</td>
<td>18.88</td>
</tr>
<tr>
<td>continuous fan</td>
<td>21.65</td>
<td>61.09</td>
<td>100.00</td>
<td>11.80</td>
</tr>
<tr>
<td>dryingspace summer</td>
<td>21.01</td>
<td>55.08</td>
<td>99.31</td>
<td>14.69</td>
</tr>
<tr>
<td>continuous fan</td>
<td>21.63</td>
<td>66.59</td>
<td>100.00</td>
<td>10.91</td>
</tr>
</tbody>
</table>

Figure 5.8: Plasterboard finish, MVHR

The same trends are evident as in case 3, and again MVHR results in reduced energy consumption.

**CASE 5 – Claytech Finish, Extract Only**

Figure 5.9 and Table 5.6 show the results from simulations for the case with the fan running continuously at 15 l/s. Note that the higher humidity levels encountered with the humidistat
controlled case led to numerical problems with the Claytech material model and so no results are available for this material.

<table>
<thead>
<tr>
<th></th>
<th>dryingspace winter continuous fan</th>
<th>dryingspace winter fan humidity ctrl</th>
<th>dryingspace spring continuous fan</th>
<th>dryingspace spring fan humidity ctrl</th>
<th>dryingspace summer continuous fan</th>
<th>dryingspace summer fan humidity ctrl</th>
</tr>
</thead>
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<td>55.9321</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak RH</td>
<td>82.35</td>
<td>89.53</td>
<td>99.47</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energy (kWh)</td>
<td>57.10807</td>
<td>54.97727</td>
<td>32.72247</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 5.6:** Claytech finish, extract only.

The use of Claytech lining caused a slight reduction in peak RH, with this reducing in all three simulated cases in comparison to both the simulations with plasterboard and an impermeable surface. However, mean summer RH and the peak RH are still high.

![Drying Room - Extract Only](image)

**Figure 5.9:** Claytech finish, extract only
CASE 6 – Claytech Finish, MVHR

Similar trends are evident as in the other cases, with marginal reduction in peak RH in comparison to similar those plasterboard and an impermeable finish (Figure 5.10 and Table 5.7). Again MVHR has a minimal effect on the space humidity characteristics but a significant effect on the energy consumption.

<table>
<thead>
<tr>
<th></th>
<th>Claytech Finish</th>
<th>Claytech Finish</th>
<th>Claytech Finish</th>
<th>Claytech Finish</th>
<th>Claytech Finish</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Winter Fan CT</td>
<td>Winter Fan CT</td>
<td>Spring Fan CT</td>
<td>Summer Fan CT</td>
<td>Summer Fan CT</td>
</tr>
<tr>
<td>Dryingspace Temp (oC)</td>
<td>21.01</td>
<td>21.01</td>
<td>21.01</td>
<td>21.01</td>
<td>21.01</td>
</tr>
<tr>
<td>Ave RH</td>
<td>39.76</td>
<td>42.52</td>
<td>55.68</td>
<td>99.22</td>
<td>99.22</td>
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<tr>
<td>Peak RH</td>
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<td>99.22</td>
<td>99.22</td>
<td>99.22</td>
</tr>
<tr>
<td>Energy (kWh)</td>
<td>19.27</td>
<td>18.88</td>
<td>14.68</td>
<td>14.68</td>
<td>14.68</td>
</tr>
</tbody>
</table>

Table 5.7: Claytech finish with mechanical ventilation heat recovery (MVHR).

Figure 5.10: Claytech finish with mechanical ventilation heat recovery (MVHR).
All of the simulations undertaken here indicate that there are potential problems with high RH in the drying space during the drying period. Further, moisture control surface finishes had a limited effect on RH; this is likely to be due to the fact that the available surface area for absorption is small. In summer both mean and peak RH are high; this indicates that the 15 l/s recommended in the draft drying specifications (Menon and Porteous, 2012) may be inadequate with regards to maintaining acceptable RH levels in the drying cupboard. Additionally, whilst the humidistat-based control is effective in reducing the fan energy consumption, it has a detrimental effect on the RH. Consequently, a further set of simulations were undertaken in order to 1) analyse the effect of increasing the fan flow rate to 30 l/s and 2) change the dead band of the fan humidistat-based controller to 40-60% in order to reduce the detrimental effect on RH.

5.2.2 Enhanced Drying Space Ventilation

The following cases were examined.

- Drying space supplied with 15 l/s from an MVHR system (80% heat exchanger effectiveness), with continuous fan operation and with fan subject to humidistatic ON/OFF dead band control between 40-60% RH;
- Drying space supplied with 15 l/s from an extract only system, with continuous fan operation and with fan subject to humidistatic ON/OFF dead band control between 40-60% RH;
- Drying space supplied with 30 l/s from an MVHR system (80% heat exchanger effectiveness), with continuous fan operation and with fan subject to humidistatic ON/OFF dead band control between 40-60% RH;
- Drying space supplied with 30 l/s from an extract only system, with continuous fan operation and with fan to humidistatic ON/OFF dead band control between 40-60% RH.

For all cases above, moisture absorbing surfaces were not modelled due to their limited effect on overall RH, as evidenced in Section 5.2.1. This is due to the limited surface area available in the drying space for absorption of moisture.

The drying room temperature was controlled to 21°C using a heating coil with a 1kW capacity. The heating requirement accounts for ventilation losses and the energy required for evaporation. The assumption is that there is heavy use of the drying room, with 1 small wash per day dried and 2 washes at weekends.
The 15 l/s fan power consumptions are as stated previously, for the extract-only simulations the fan drawing 30 l/s has a rated power consumption of 26W. In the MVHR case, a supply and extract fan are used consuming 52W.

**CASE 7 – 15L/s Extract Only (no heat recovery)**

Figure 5.11 and Table 5.8 show the results of the simulations for the case of the fan running continuously at 15 l/s and where the fan runs with ON/OFF control with dead band limits of 40 and 60% RH, for winter spring and summer weeks.

<table>
<thead>
<tr>
<th></th>
<th>dryingspace winter base</th>
<th>dryingspace winter hstat</th>
<th>dryingspace spring base</th>
<th>dryingspace spring hstat</th>
<th>dryingspace summer base</th>
<th>dryingspace summer hstat</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean Temp (°C)</td>
<td>20.98</td>
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<td>20.99</td>
<td>21.64</td>
<td>21.01</td>
<td>21.32</td>
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<tr>
<td>Mean RH</td>
<td>39.14</td>
<td>43.14</td>
<td>41.88</td>
<td>43.92</td>
<td>55.01</td>
<td>55.77</td>
</tr>
<tr>
<td>Peak RH</td>
<td>84.22</td>
<td>100.00</td>
<td>94.31</td>
<td>100.00</td>
<td>100.00</td>
<td>100.00</td>
</tr>
<tr>
<td>Energy (kWh)</td>
<td>56.13</td>
<td>24.75</td>
<td>54.04</td>
<td>24.78</td>
<td>31.85</td>
<td>18.07</td>
</tr>
</tbody>
</table>

Table 5.8: 15 l/s Extract only

The results for the continuous case are identical to case 1, whilst the effects of changing the ON/OFF dead band limits are reflected in the results for the humidistatic control cases. Changing the dead band limits from 57-70%RH to 40-60%RH has the effect of slightly reducing the mean RH by approximately 2% and slightly increasing the overall energy consumption by approx. 10-12% compared to the humidistat-based fan control in Case 1. The peak RH is unchanged.

Whilst the revised humidistatic control still achieves a significant energy saving in comparison to the continuous fan operation, the continuous fan operation still results in lowest mean RH overall. However, in both cases, the peak RH is consistently high with the summer mean RH over 50%.
To further investigate the humidity levels prevalent in the drying space, frequency histograms of RH were extracted from the simulation data. Figure 5.12 shows the frequency histogram for each of the simulations given in Table 5.8; there are clear bi-modal distributions of RH in spring and winter with the peak occurrence of RH around 35% and a lesser peak around 60% RH (a result of the drying process). However in summer the distribution has a single peak occurrence of RH around 45%. Note that although the peak RH values in Figure 5.12 are often 100%, the frequency of occurrence of RH above 70% is relatively low.
Case 7 was also repeated with an MVHR system rather than extract-only. The humidity results were almost identical. However as has been noted previously, the overall energy consumption associated with drying in significantly reduced.

**CASE 8 – 30 l/s Extract only (no heat recovery)**

In the previous cases, it was noted that a 15 l/s flow rate resulted in high average RH, particularly in summer. In an attempt to alleviate this potential problem, the ventilation rate in the drying cupboards was boosted to 30 l/s. Figure 5.13 and Table 5.9 show the results from the simulations for the case of the fan running continuously at 30 l/s and where the fan was controlled with a humidistat with no heat recovery in both cases.

The results indicate that there is a marginal effect on the mean RH and a pronounced effect on both the mean and the peak RH. However, this is at the expense of an increase in energy consumption. For example, compared to the equivalent case with 15 l/s extract-only ventilation in winter, mean RH falls from 39 to 35% and peak RH drops from 81 to 63%, whilst energy use increases from 56 to 104 kWh. Again, humidistat-based fan control has a significant beneficial effect on energy consumption, but the reduction in RH levels is reduced in comparison to the case with continuous fan operation. Also note, that the mean summer RH remains above 50% for both continuous and humidistatic control of the fan.
Comparison of time series data from the 15 l/s and 30 l/s cases (Figure 5.14) shows the impact of increasing the fan flow rate, with a significant reduction in periods of higher RH seen in the drying room (particularly with continuous operation). Using humidistatic control still results in improvement in higher RH values, but the benefit is reduced. Note particularly
the final two days in winter, when very low RH is experienced in the drying room if the fan is on continuously. The RH with humidistat-based control is higher as the fan will rarely switch on as RH sits within the 40-60% RH dead band. Narrowing the dead band would reduce this effect, but will increase the energy consumption for both fan power and drying room heating.

Figure 5.14: Time series plot, showing the difference between prevailing humidity in the drying room for 30 l/s and 15 l/s fan flow rates for the winter week simulation.

Figure 5.15 shows the results for the summer simulation. Again, peak RH values are reduced in comparison to the case with a flow rate of 15 l/s
Figure 5.15: Time series plot, showing the difference between prevailing humidity in the drying room for 30 l/s and 15 l/s fan flow rates for the summer week.

The frequency distribution plot of Figure 5.16 shows that increasing the ventilation rate has a pronounced effect on the frequency distribution of RH, with the winter/spring bimodal distribution effectively disappearing and the occurrence of RH in the 50% to 70% band significantly reduced. The single winter and spring peak occurs around 35% RH, whilst the summer peak occurrence is around 45% RH. Occurrences of RH above 70% are generally reduced.

(Note: to enable the time series drying process to be plotted in Excel, Figure 5.15 shows 10-minute averages of all quantities (~10,000 data points per series) and masks the true magnitude of peak values.)
Figure 5.16 Frequency distribution plots for drying room RH with 30L/s and 15L/s fan flow rates.

As was reported in the previous cases, controlling the fan with a humidistat has a detrimental effect on RH levels, in comparison to the case where the fan is on continuously; however, energy performance is improved (see Table 5.9).

Figures 5.17 and 5.18 focus on the impact of humidistat control of the fan over a winter and summer week respectively. Whilst performance with respect to RH deteriorates, it is still an improvement on the case where the fan flow rate is 15 l/s.
Figure 5.17: The effect of humidistatic control of the drying room ventilation system at 30L/s, winter simulation.

Figure 5.18: The effect of humidistatic control of the drying room ventilation system at 30L/s, summer simulation.

In this case there is less effect, as the higher external air moisture contact lessens the difference in run time between the controlled and uncontrolled fan.
CASE 9 – 30 l/s MVHR

Figure 5.19 and Table 5.10 show the results from 6 simulations for the case of the fan running at 30 l/s with and without humidity control and with a mechanical ventilation heat recovery system. The humidity levels are almost identical as Case 8, however energy performance is radically improved as has been illustrated in all previous cases with MVHR.

<table>
<thead>
<tr>
<th></th>
<th>dryingspace winter base</th>
<th>dryingspace winter hstat</th>
<th>dryingspace spring base</th>
<th>dryingspace spring hstat</th>
<th>dryingspace summer base</th>
<th>dryingspace summer hstat</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temp (°C)</td>
<td>21.05</td>
<td>22.09</td>
<td>21.05</td>
<td>22.04</td>
<td>21.18</td>
<td>21.72</td>
</tr>
<tr>
<td>Ave RH</td>
<td>35.25</td>
<td>38.15</td>
<td>37.95</td>
<td>39.52</td>
<td>50.48</td>
<td>51.19</td>
</tr>
<tr>
<td>Peak RH</td>
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<td>92.16</td>
<td>62.98</td>
<td>89.19</td>
<td>100.00</td>
<td>100.00</td>
</tr>
<tr>
<td>Energy (kWh)</td>
<td>26.79</td>
<td>15.43</td>
<td>26.00</td>
<td>15.38</td>
<td>17.83</td>
<td>14.16</td>
</tr>
</tbody>
</table>

Table 5.10: 30 l/s with MVHR.
Environmental Assessment of Domestic Laundering: Modelling Report

5.3 Communal Residential Laundry Washing and Drying
A study was undertaken on the potential benefits of communal residential laundry washing and drying to see what effects it may have on the electric demand load profile. A hypothetical housing block was modelled and the effect of moving from washing and drying in individual households to communal facilities was analysed. The study included the effects of appliance energy-efficiency improvements and increased ownership rates.

Domestic washing and drying of laundry constitutes a highly energy intensive and possibly flexible demand. The drying process alone accounts for approximately 4.3% of the total UK domestic energy consumption (DEFRA\textsuperscript{b} 2008). In terms of appliance ownership within UK households, washing machines are fast approaching saturation at 94% ownership; however tumble dryers only have a market penetration of 42% ownership (DEFRA\textsuperscript{c} 2008) and so have a potential to increase in number, especially in flats and high rise buildings in cities where both access and propensity for drying in open areas are limited.

On a European level, this issue has been partly addressed through the European Energy Labelling Directive (1992). This scheme has proved successful in terms of market adoption of ‘A-rated’ type washing machines (DEFRA\textsuperscript{a} 2008), which are now the dominant type. There

Figure 5.19: 30 l/s MVHR

<table>
<thead>
<tr>
<th>Drying Room + MVHR 30L/s</th>
<th>Ave RH</th>
<th>Peak RH</th>
<th>Energy (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>dryingspace winter base</td>
<td></td>
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<tr>
<td>dryingspace winter hstat</td>
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<tr>
<td>dryingspace spring base</td>
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<tr>
<td>dryingspace spring hstat</td>
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<tr>
<td>dryingspace summer base</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>dryingspace summer hstat</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
has been less success with tumble dryers (DEFRA\textsuperscript{b} 2008), with the market being predominantly made up of ‘C-Rated’ machines.

Due to the potential health effects arising from reduced indoor air quality and high internal humidity levels resulting from indoor drying of laundry, it could be beneficial to shift laundry washing and drying from individual household owned units to communal washing and drying appliances within dedicated areas in individual housing blocks. Communal washing and drying was a common practice in the UK during the 19\textsuperscript{th} century, and today could possibly prove beneficial in terms of electrical energy demand reductions as well as changing the temporal nature of electrical demands.

An analysis was undertaken of the effect on the electrical demand profile of a residential block of flats in a scenario where domestic washing and drying is shifted from the traditional individual household-based appliances to a regulated staggered use of communal washing and drying facilities. The analysis considers the potential of a communal laundry to improve the electrical demand characteristics of the building through time-shifting demand and reducing peak electrical loading, both of which could provide more favourable operating conditions for low carbon and localised energy supplies.

The methodology used 1-minute resolution electrical demand profiles for the housing block under different scenarios for three specific days; a characteristic winter day, a characteristic summer day and one day representative of the transition months. The three days selected helped to identify the main trends from shifting to communal laundry facilities at different times of the year. The use of a 1-minute resolution for the profiles ensured that certain key characteristics such as the maximum peak demand and load duration could be clearly identified. Apart from understanding the difference between the use of individual washing and drying units and the use of communal facilities this research also aims to analyse other related aspects, such as the effect of increased demands for drying and the use of more energy-efficient technologies. In order to compare the use of individual washing machines and tumble dryer appliances \textit{versus} the use of communal units, three scenarios were considered, namely:

- individual use of washing machines and tumble dryers at current ownership rates;
- individual use of washing machines and tumble dryers at saturated ownership rates;
- regulated staggered use of communal washing machines and tumble dryers.

Figure 5.20 shows an example of the high frequency analysis.
Figure 5.20: Laundry and total demand load profile for the ‘individual use of washing machines and tumble dryers at current ownership rates with current technology’ scenario for a winter day

Details of the models and results are given in Borg et al (2011).
6. Modelling – realistic case

See note at the end of the report contents.
7. Conclusions

Software Modifications

Before commencing with the modelling of drying processes in dwellings, a series of modifications to the ESP-r simulation tool were undertaken with a view to enhancing its existing moisture modelling capabilities.

- ESP-r’s database of material moisture transport data was improved, using data from both IEA research and tests undertaken by projects partners Glasgow Caledonian University.
- Two new moisture transport functions (sorption isotherm functions) were added to ESP-r to enable the calculation of the material moisture content. One of these was specifically developed to model the moisture absorption of aerated concrete.
- The source code was modified to incorporate a new vapour permeability function for gypsum plasterboard.
- An existing ESP-r wetted surface moisture source equation was improved to better represent the characteristics of clothes drying. The equation predictions were compared to empirical data.
- Finally, parametric test software was developed to enable the ESP-r tool to be used in sensitivity analyses involving many hundreds of simulation runs.

Validation Study

To develop confidence in ESP-r’s predictions of indoor moisture levels and also in its abilites to model the effect of moisture control materials a series of validation tests were undertaken. These indicated the following.

- Simulation results produced when using a vapour tight internal surface material showed good agreement when compared to analytical results, emphasising the accuracy of the internal air moisture balance being carried out by ESP-r under isothermal conditions.
- A second study looked at the impact of modelling the moisture buffering effect of the concrete construction. Reasonable agreement was achieved again between the ESP-r output and analytical results.
- Inter-model comparison of a vapour permeable construction under dynamic conditions proved inconclusive as the results from ESP-r and the solutions provided by other hygrothermal modelling software showed large degree of variation in outcomes. However the ESP-r results tended to be in the middle of the range of results.
• Comparison of ESP-r results to empirical test data and the output from other modelling tools accounting for the effects of ventilation and moisture buffering material showed reasonable agreement with the measured data and ESP-r’s results were consistent with the spread of simulated results from other simulation software.

• Finally, modelling of moisture conditions in a realistic dwelling indicated that there was satisfactory correlation between predicted and actual measured values of peak humidity. However, differences between the rates of desorption predicted and measured were apparent. ESP-r uses an average sorption-desorption isotherm, whereas in practice the processes are not symmetrical. Although the required hygrothermal material data is not always available, it is suggested that future model developments should include the possibility to use explicit sorption-desorption isotherms.

Modelling Studies
Several distinct modelling studies were undertaken. These focused on two areas: the energy impacts of laundry drying and mechanisms to alleviate poor environmental conditions due to drying. The conclusions from these activities are as follows.

Communal Laundry Study

• This study focused on the potential energy benefits of communal laundering in high density housing in comparison to the use of separate household appliances. Both washing and tumble drying are important loads within the total electric load profile of a household unit or a housing block with an annual average energy intensity of 27% of the total electrical energy consumption of a housing block calculated at current appliance ownership rates and technologies.

• The use of a regulated, staggered system of communal washing/drying rather than the current practice of using appliances based in each individual household should lead to a flattening of the electrical load with lower peak demands. This could improve the matching with local micro-generation electricity supplies. However, communal laundering is ineffective in reducing overall electricity consumption.

• The increased use of tumble dryers (whether individual or communal) would lead to a considerable increase in terms of total daily load, average load and load intensity. To get maximum benefits, the communal use of laundry washing and drying appliances should be accompanied by a changeover to more energy-efficient appliances. Such future reductions in energy intensity of commercial type washing machines and dryers could add to the benefits of communal facilities.
**Parametric Analysis**

A parametric study was undertaken to assess the effect of key parameters on indoor relative humidity. These included climate, season, moisture load, occupancy, airtightness and insulation levels. This indicated the following.

- Introducing significant areas of moisture absorbing surfaces finish within the building could have a pronounced effect on peak RH, with absolute peak values dropping by up to 40%. However, the effect of a dedicated moisture absorbing surface finishes (e.g. clayboard) did not differ greatly from standard hygroscopic materials such as plasterboard.
- Further, both moisture load and ventilation levels had a more profound effect on the mean RH.
- Significantly, improving the quality of the building fabric also had a beneficial effect on RH, due to increased indoor temperatures.

**Energy and Humidity Impact of Indoor Clothes Drying**

Using the same model, simulations were undertaken to assess the energy impact of indoor clothes drying techniques identified in the project field trials, where clothing was dried by opening the windows and the heating systems left on. The outcomes were as follows.

- Drying under these circumstances used more than double the energy of a tumble dryer and resulted in over 20% more carbon emissions (if the space heating is provided by gas central heating).
- Simulations also indicated that the drying of clothes in the living space of a dwelling would result in high mean RH levels above 60% for significant periods of time.

**Dedicated Drying Space**

Drying clothing in a dedicated drying space was also investigated in two sets of simulations. The first looked at the impact of drying clothes in a dedicated space on conditions within the rest of a simulated house and showed that this dropped the mean RH level to approximately 40%.

Further simulations were undertaken to assess the performance of a dedicated drying space (volume of 1.75m³) for clothing as set out in the design guide (Menon and Porteous, 2012). Specifically, measures to reduce the energy penalty associated with drying were analysed along with the conditions prevailing within the drying space. Consequently, the drying space
model was modelled with extract only ventilation and mechanical ventilation heat recovery. The effect of different surface finishes were also examined.

- With a fan flow rate of 15 l/s, high mean and peak humidity levels were evident in both spring and summer simulations, with mean humidities of over 50% evident. Changing surface finishes from impermeable to permeable materials had a limited effect on peak and mean RH, probably due to the very limited internal surface area in the drying space.
- The use of humidistat control of the fan (where the fan operated with on-off control between deadband limits of 50 and 70% RH) reduced the overall energy consumption of the drying space significantly, but had a detrimental impact on humidity control.
- The use of mechanical ventilation heat recovery had a beneficial impact on energy consumption and had little impact on the RH levels in the drying space, reducing energy consumption by over 60% without MVHR.
- Increasing ventilation levels to 30 l/s was successful in reducing occurrences of high RH in the drying space, though summer RH levels were still high (due to high external air moisture content) and energy consumption almost doubled in comparison to the 15 l/s case.
- Again, humidistat control of the ventilation (this time where the fan operated with on-off control between deadband limits of 40 and 60% RH) improved energy performance at the expense of reduced effectiveness in controlling RH.
- A fan flow rate of 30 l/s MVHR reduced overall energy consumption by over 70% compared to the no-MVHR case, with no detrimental impact on RH conditions.
8 References


ESP-r (2012), http://www.esru.strath.ac.uk/Programs/ESP-r.htm


Menon R and Porteous C (2012), Design Guide: Healthy Low Energy Home Laundering, MEARU (Mackintosh Environmental Architecture Research Unit), The Glasgow School of Art (output from this EPSRC project).


