Development of a Simulation Tool for Mould Growth Prediction in Buildings

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ABSTRACT

Epidemiological evidence suggests that mould infestation in buildings can have serious health implications for the occupants. On the basis of an analysis of published data, growth limit curves for six generic mould categories have been generated in terms of the minimum combination of temperature and relative humidity required to sustain growth on indoor building surfaces. These limits have been incorporated within the ESP-r system for use in conjunction within combined heat and moisture flow simulations. The result is a design tool which can predict the likelihood and extent of mould growth. This paper describes the mould growth model, the approach taken to moisture flow simulation within multi-layered constructions and the results from comparisons with monitored data and mycological samples taken from a mould-infested house.

Keywords: air quality, mould growth, moisture flow simulation.

INTRODUCTION

A significant proportion of houses world-wide are affected by mould growth on internal surfaces (Scottish Homes 1991, Clarke et al 1996, Dales et al 1991). Apart from possible degradation of the building fabric, there is growing epidemiological evidence to suggest that mould infestation can present a distinct health risk to the people who live in such environments (Dales et al 1991, Platt et al 1989). Respiratory and/or allergenic disorders, particularly in children, have been diagnosed and a range of other symptoms, including nausea and vomiting, have been reported (Burr et al 1988, Martin et al 1989). While the precise mechanisms for these symptoms are not fully understood, toxic fungal metabolites, particularly mycotoxins produced by fungal spores and absorbed through the mucous membrane of the respiratory tract, are increasingly being implicated (Lewis et al 1989, 1994).

In the light of these health implications, it is clear that the provision of mould-free housing should be a priority: the key questions are how can the problem be prevented from occurring in new designs and how can it be alleviated in existing dwellings. As the use of biocidal compounds on affected surfaces is only acceptable in special circumstances, there is a general consensus that the preferred strategy is the elimination of the conditions which can lead to mould initiation and proliferation (Hens and Sneave 1991). A key element in such an approach would be the ability to predict where, when and under what conditions mould growth will occur.

Now with the Building Research Establishment, Garston, England.

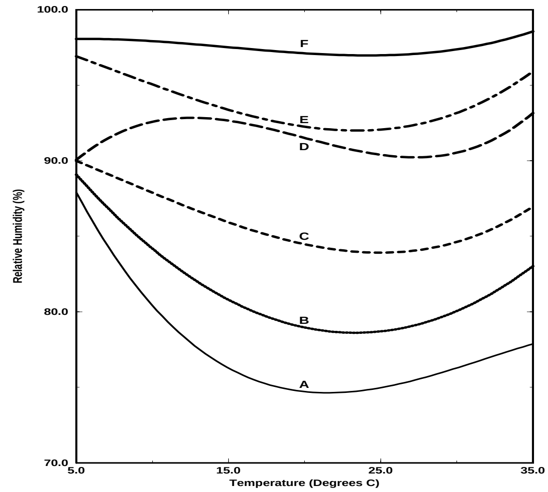
As a result of an inter-disciplinary engineering and bioscience research project, such a prediction is now possible (Clarke et al 1996). The project had two components. The first was to categorise the mould types which are problematic in housing and to develop a model of the limiting growth conditions for each category. The second was to incorporate this model within the ESP-r building energy and environmental simulation program in order to produce a facility which can predict the likelihood of mould growth for any combination of environment, construction and climate.

MOULD GROWTH MODEL

The moulds encountered in the built environment are members of the Deuteromycetes sub-group of fungi. Mould growth is essentially a surface phenomenon and will occur if fungal propagules are present on a surface and the physiological requirements for growth are met (Adan 1994). The most important factors known to control growth are the relative humidity (microbiologists use the term 'water activity') and the temperature. The widely held belief that physical condensation, with the deposition of liquid water on a surface, has to occur before mould growth will appear is invalid.

From an extensive literature review covering over 250 publications, the principal mould species affecting dwellings were identified and their minimum growth requirements in terms of temperature and relative humidity (RH) established. The moulds were then assigned to one of six categories, A-F, ranging from highly xerophilic (dry loving) to highly hydrophilic (wet loving). Each category constitutes a family of mould species possessing similar growth requirements. On the basis of a representative mould from each category, growth limit curves were developed as shown in Figure 1.

These curves define the minimum combination of local surface temperature and humidity for which growth will occur on building surfaces; below any given curve, growth will not occur for moulds in that category. Examples of moulds in each category include *Aspergillus repens* (A), *Aspergillus versicolor* (B), *Penicillium chysogenum* (C), *Cladosporium sphaerospermum* (D), *Ulocladium consortiale* (E) and *Stachybotrys atra* (F). In all cases, it was found that the best fit to the experimental data was given by third-order polynomial functions. An example, based on *Aspergillus versicolor* is given in Figure 2.



A - highly xerophilic
B - xerophilic
C - moderately xerophilic
D - moderately hydrophilic
E - hydrophilic
F - highly hydrophilic

Figure 1: Mould limiting growth curves.

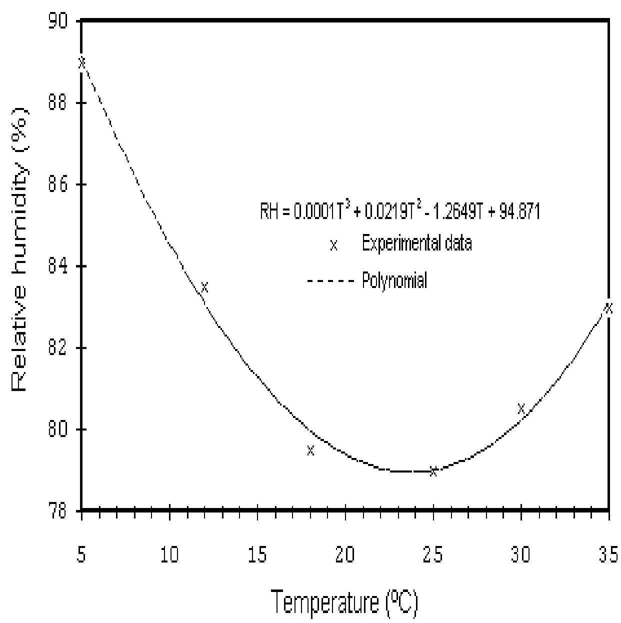


Figure 2: 3rd order polynomial derived from experimental data for *Aspergillus versicolor*.

GROWTH LIMIT VALIDATION

In order to apply a test to the growth limit curves of Figure 1 at a selected temperature,

Table 1: Mould growth data.

Isolated mould	Growth category	Lowest RH (%) permitting growth	Time (days) for growth
Yeasts	F	94.5	85
Cladosporium sphaerospermum	D	88.5	78
Penicillium spp.	C	85.5	97
Alternaria alternata	D	88.5	90
Aureobasidium pullulans	D	88.5	103
Aspergillus versicolor	B	81.0	97
Eurotium herbariorum	A	78.5	97
No mould growth was observed at 74.5% RH after 120 days.			

mould samples were collected from a mould infested house. This was done by pressing RH adjusted agar contact plates against an area of prolific mould growth. The cultures were then laboratory incubated at 25°C under a range of RH conditions, namely 98.7, 94.5, 88.5, 81, 78.5, 74.5, 71.2 and 67.8% for a period of 120 days. The plates were examined for the presence of fungal growth on a daily basis using conventional microbiological techniques (Samson and van Reenen-Hoekstra 1989). The mould species identified, their growth categories and the lowest RH value at which growth was detected are given in Table 1.

At the selected test temperature, the results of the mycological study show a good agreement with the mould growth curves. The minimum RH values supporting growth for category A, B and C moulds, and the lack of growth at 74.5%, are consistent with the predictions of the model. Although the minimum RH values for the category D and F moulds are one RH step below that predicted by the model, this difference can be explained, in part, by the fact that the moulds were cultivated on laboratory media which are nutritionally richer than building materials.

MOULD PREDICTION PROGRAM

ESP-r (Clarke 1985) is a modelling system for the assessment of the environmental and energy performance of buildings. It is capable of modelling the heat, power and fluid flows within combined building and plant systems when subjected to control actions. The package comprises a number of interrelating program modules addressing project management, simulation, results analysis and client report generation. In use, the spaces comprising the building are defined in terms of geometry, construction and usage profiles. HVAC systems may then be defined in terms of their comprising components and networks added to explicitly represent air, moisture and power flow-paths. The defined system is then subjected to simulation processing against user-specified control definitions and climate. The problem definition exercise is achieved interactively and with the aid of pre-existing databases offering standard construction materials, glazing systems, event profiles and plant components. The process of problem definition, simulation and results analysis is coordinated by a central Project Manager which supports the importing/exporting of building geometry from/to CAD packages and other simulation environments, e.g. for lighting simulation or time series analysis.

ESP-r's mould growth prediction facility utilises information from two sources. Firstly, ESP-r is able to represent a building at some specified level of resolution with an enhanced resolution at some surface(s) of concern, e.g. at a point where a thermal bridge exists, where insulation levels are low or where there exists a local moisture source. Based on this enhanced resolution, an explicit simulation of constructional moisture flow and local air movement enables a prediction of the local surface temperature and relative humidity profile. Secondly, the growth limit curves are contained in a moulds' database. This allows the predicted local conditions to be superimposed on the mould growth curves. The concentration of plotted points relative to the various growth bands allows an assessment of the risk of mould growth and its probable persistence over time.

The prediction of local surface conditions requires knowledge of the adjacent psychrometric air state and the flow of moisture within the adjacent porous medium. In the former case, ESP-r is equipped with air movement models by which the local air state may be assessed (Clarke and Hensen 1991, Negrão[*] 1995). In the latter case, a combined heat and moisture flow model has been developed (Nakhi 1995) against the following considerations.

Application of mass and energy conservation considerations to a stationary, homogeneous, isotropic, constructional control volume, gives rise to the following differential equation system for combined moisture and heat transfer.

For the moisture term:

$$\rho_o \zeta \frac{\partial (P/P_{s)}}{\partial t} + \frac{d\rho_l}{dt} = \frac{\partial}{\partial x}\left(\delta_P^T \frac{\partial P}{\partial x} + D_T^P \frac{\partial T}{\partial x}\right) + s \quad (1)$$

where ρ is density (kg/m^3; o and l denote porous media and liquid respectively), ζ is the moisture storage capacity (kg/kg), P is the partial water vapour pressure (Pa), P_s is the saturated vapour pressure (Pa), δ is the water vapour permeability ($kg/Pa.m.s$), D is the thermal diffusion coefficient (kg/m^2Ks) and s is a moisture source term (kg/m^3s). T and P denote temperature and pressure driving potentials respectively, with the principal potential given as the subscript. The significance and characteristics of the thermal diffusion coefficient are the subject of current research (McLean and Galbraith 1996).

For the energy term (in one dimension):

$$[\rho_o(c_o + c_v u_v) + c_l \rho_l]\frac{\partial T}{\partial t} + h_v \frac{\partial \rho_v}{\partial t} + h_l \frac{\partial \rho_l}{\partial t} \quad (2)$$

$$= \frac{\partial}{\partial x}\left(\lambda \frac{\partial T}{\partial x}\right) - \frac{\partial h_s J_v}{\partial x} + g$$

where c is specific heat (J/kgK), u is moisture content ($kg/kg_{material}$), T is temperature (°C), λ is heat conductivity (W/mK), J_v is the vapour mass flux (kg/m^2s), g is a source of heat (W/m^3) and h_v, h_l and h_s are the enthalpies (J/kg) of vapour, liquid and moisture flux source respectively.

For the condensation and evaporation processes, a control equation is implemented as a one-way liquid value connected to the control volume. When the relative humidity reaches its maximum value, the valve opens to deliver the condensation 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: future modification of the algorithm is planned for the case of capillary condensation.

Use of the above equations allows for the solution of the three dependent variables, P, T and ρ_l, for each control volume within a multi-layered construction when evolving through time under the influence of the boundary heat and mass transfers being simultaneously resolved within ESP-r. To achieve this, a finite difference approximation is applied to eqns (1) and (2) giving, for moisture:

$$a_1^{n+1}P_i^{n+1} + \sum_{j=1}^{2} a_j^{n+1}P_j^{n+1} + (m_l)_i^{n+1} - \gamma \Delta t S_i^{n+1} \quad (3)$$

$$= a_i^n P_i^n + \sum_{j=1}^{2} a_j^n P_j^n + (m_l)_i^n + (1-\gamma)\Delta t S_i^n$$

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

where γ is the degree of implicitness, n and $n+1$ refer to the present and future time-rows respectively, Δt is the time-step (s), m is the specific mass (kg/m^3), and

$$a_j^{n+1} = -\gamma(\delta_P^T)_{j\to i}^{n+1} A\Delta t/\Delta X_{j\to i}$$

$$a_j^n = (1-\gamma)(\delta_P^T)_{j\to i}^n A\Delta t/\Delta X_{j\to i}$$

$$a_i^k = [\rho\zeta_i V/(P_s)_i^k - a_{i-1}^k - a_{i+1}^k$$

$$b_j^{n+1} = -\gamma(D_T^P)_{j\to i}^{n+1} A\Delta t/\Delta X_{j\to i}$$

$$b_j^n = (1-\gamma)(D_T^P)_{j\to i}^n A\Delta t/\Delta X_{j\to i}$$

$$m_l^k = V\rho_l^k \ (kg_{moisture})$$

$$S_i^k = Vs_i^k \ (kg_{moisture}/s)$$

where A is area (m^2), ΔX is the flowpath length (m) and V is the node volume (m^3).

For the energy term:

$$a_i^{n+1}T_i^{n+1} + \sum_{j=1}^{2} a_j^{n+1} - \gamma G_i^{n+1}\Delta t - \gamma(h_s \dot{m}_v)^{n+1}\Delta t \quad (4)$$

$$= a_i^n T_i^n + \sum_{j=1}^{2} a_j^n T_j^n + (1-\gamma)G_i^n \Delta t + (1-\gamma)(h_s \dot{m}_v)^n \Delta t$$

$$-(h_l)_i^{n+1}[(m_l)_i^{n+1} - (m_l)_i^n] - (h_v)_i^{n+1}[(m_v)_i^{n+1} - (m_v)_i^n]$$

where

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

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

$$a_i^k = \rho_o V(c_o + c_v u_v) + c_l m_l - \sum_{j=1}^{2} a_j^k.$$

For a homogeneous control volume, the moisture storage capacity, ζ, is found from an expression by Hansen (1986):

$$\zeta = \frac{u_h}{n} A\phi \left(1.0 - \frac{\ln \phi}{A}\right)^{\frac{-n+1}{n}} ; 0 \le \phi \le 1 \qquad (5)$$

where ϕ is the relative humidity and a mass weighted average value of ζ is used for the heterogeneous case. The vapour permeability, δ, is evaluated from

$$\delta = \frac{\delta_a}{\mu} = \frac{1.89923e - 10}{\mu} \quad @ \, 25^o C \qquad (6)$$

where the vapour resistance factor, μ, is given by $\mu = 1/(a + be^{c\phi})$ for $0 \le \phi \le 1$ and a, b and c are constants for a given material.

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

$$\begin{bmatrix} \mathbf{E} \\ \mathbf{M} \end{bmatrix} \times \begin{bmatrix} \mathbf{T} \\ \mathbf{P} \end{bmatrix} = \begin{bmatrix} \mathbf{B}_e \\ \mathbf{B}_m \end{bmatrix} \qquad (7)$$

where **E** and **M** are the energy and moisture coefficient matrices respectively, **T** and **P** are the temperature and vapour pressure vectors, and $\mathbf{B}_e$ and $\mathbf{B}_m$ are the energy and moisture boundary conditions.

Within ESP-r the solution of eqn (7) proceeds as follows.

□ Because the energy equations can often be linearised, while the moisture equations typically cannot, the two equation systems are processed separately but under global iteration control to handle the coupling effects. This allows each equation-set to be integrated at different frequencies depending on the characteristics of the system they represent.

□ For the energy equations, a matrix partitioning technique is employed as reported elsewhere (Clarke 1985). The method allows variable time-stepping and incorporates iteration for non-linear cases, i.e. where the equation coefficients are a function of the state variables.

□ Because of their highly non-linear nature, the moisture flow equations are solved by a Gauss-Seidel method, with linear under-relaxation used to prevent convergence instabilities in the case of strong non-linearity or where discontinuities occur in the moisture transfer rate at the maximum relative humidity due to condensation. A false time step relaxation factor is used. This acts to magnify the vapour storage term at the future time-row and so lessen the difference between the present and future values of the dependent variable. Because some of the terms within the moisture equations are dependent on temperature, the moisture solution is constrained to proceed at a frequency matched to or less than that imposed on the energy equations.

□ The global iteration control is invoked whenever the liquid mass variations exceed some specified limit. When this occurs, the energy matrix is resolved on the basis of the recently computed moisture-side variables but with no recalculation of the energy-side parameters.

□ For highly coupled cases, both equation systems are solved at matched and small time-steps.

Based on the foregoing theory, with temperature and partial vapour pressure used as the transport potentials for moisture, a one dimensional, coupled heat and moisture transport model has been implemented within ESP-r and subjected to validity testing (Nakhi 1995).

MODEL APPLICABILITY

An evaluation of the ESP-r mould prediction model was carried out using data collected from a house with a severe mould growth problem. Firstly, monitored temperature and relative humidity data for a selected location were compared to the corresponding data as predicted by ESP-r. Secondly, an extended simulation run was conducted in order to establish if ESP-r would have predicted the extent and type of mould growth as observed in the mycological study.

5.1 The Test House

This is a 1940's prefabricated, three bedroom semi-detached house located on an estate in Edinburgh. The house is of a steel frame construction, with poor insulation levels, and is prone to thermal bridging. The lower floor of the house consists of a living room, hall, kitchen, bathroom and a store room, while the upper floor consists of three bedrooms and a hall. The building is heated by a 3kW electric fire situated in the living room and a 1kW electric slim-line heater located in the upstairs hallway. During the time of the monitoring exercise the house had two occupants.

5.2 Monitored Data

The main problems with mould growth occurred in the bedroom areas: the north bedroom was chosen for the monitoring exercise. The monitoring equipment, comprising a thermocouple and humidity sensor attached to a data logger, was positioned approximately 2mm from the junction of the north wall and ceiling where mould growth was prolific. This was also the location used to obtain the mould samples for the mycological study. The accuracy of the humidity sensor was ±2% and the accuracy of the thermocouple was ±0.5°C. The monitored data were recorded at 0.5 hour intervals over a 6 day period in March 1996.

5.3. ESP-r Model

A model of the test house was created to enable ESP-r to quantify the energy, air and moisture flows throughout the house. The north bedroom was modelled in the greatest detail by employing a moisture flow network centred on the test location as shown in Figure 3. Simulations were performed using climate data collected at the site during the monitoring programme. Notwithstanding significant uncertainties with regard to the constructional materials, occupant behaviour and micro-climate influences, comparisons between predicted and monitored temperature/humidity profiles indicated reasonable agreement over time.

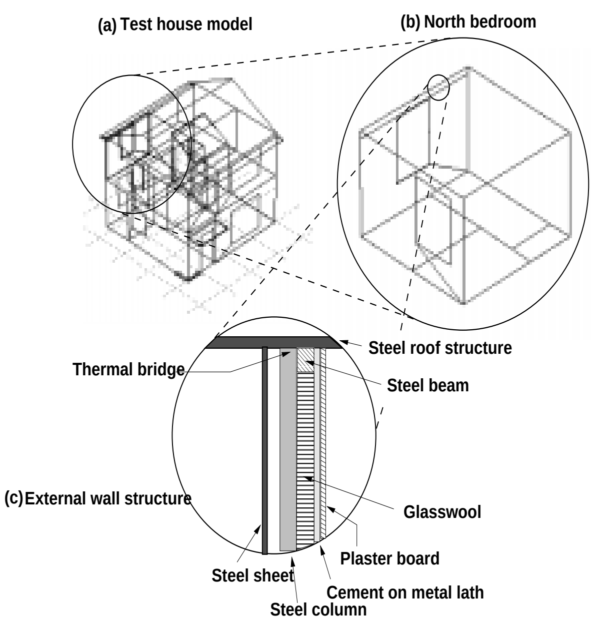


Figure 3: ESP-r model of test house.

5.4. Mould Prediction

An extended simulation was performed to obtain predictions of surface temperature and relative humidity for a period of one week under representative winter conditions. Figure 4 shows the result superimposed on the generic mould growth curves. As can be seen, the distribution of data points encompasses all growth curves. On this basis it would have been concluded that mould infestation would have spanned all the growth categories. This is in agreement with the mycological samples collected from the test house.

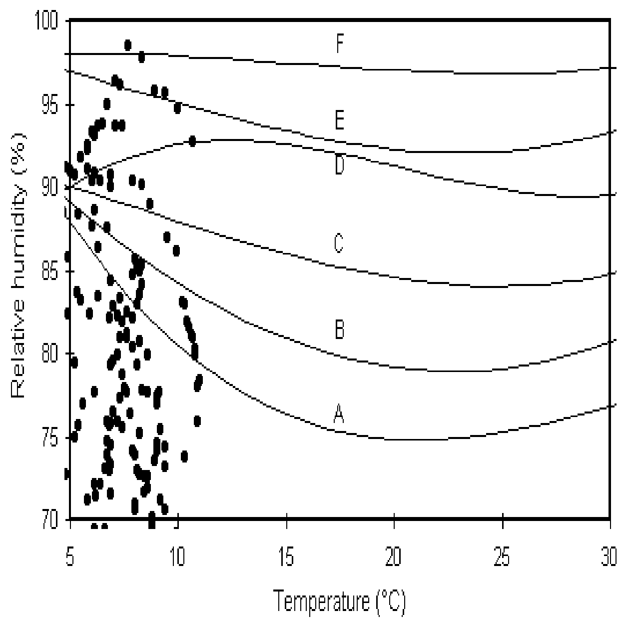


Figure 4: Predicted surface conditions, winter condition.

CONCLUSIONS

A mould growth model based on six generic mould categories has been formulated and incorporated within the ESP-r system for building energy and environmental simulation. The result is a prototype design tool for the prediction of the likelihood and extent of mould growth for a given combination of climate conditions, building construction and usage pattern. Such a tool can be applied to proposed designs, in order to correct any inherent defects prior to construction, or to existing buildings with mould problems in order to appraise the effectiveness of potential engineering solutions.

Because the mould growth curves are based on experiments in which the principal determinants of growth were maintained at fixed values, the model is essentially steady state. It is therefore unable to indicate the growth retarding effect of temperature and/or humidity fluctuations which result in non-optimum conditions over prolonged periods of time. A future mycological study will address this issue of mould growth under transient conditions and will seek to extend the current model to cover this case.

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