MEASUREMENT AND PREDICTION OF INDOOR MICROENVIRONMENTS FOR THE CONTROL OF BIOCONTAMINANTS

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ABSTRACT

The severe impact on health associated with biocontaminants, such as dust mites, has become increasingly apparent in recent years. Consequently, a considerable effort has taken place to develop biocontaminant growth models and to assess the efficacy of possible psychrometric control measures, involving the modification of room conditions. However this approach is not always successful due to the low correlation between room conditions and those within the microenvironments inhabited by biocontaminants. Obviously, if accurate growth models are to be developed and psychrometric control measures successfully applied, it will be necessary to distinguish microclimatic conditions from the adjacent ambient conditions.
Whilst the measurement of temperature within microenvironments is feasible, the main restriction has been the lack of a suitable humidity sensor. The authors have sourced a microchip-based humidity sensor which meets a set of appropriate performance criteria for measurements within typical microenvironments. A dynamic heat and moisture transfer model, MATCH, was applied to validate the measurements from laboratory trials. Following a domestic application of the sensors, simulation results were coupled with a model to predict dust mite activity in soft furnishing.

Key words: Biocontaminants, microenvironments, relative humidity, simulation

1. INTRODUCTION

Indoor air quality can have a significant impact on health and well-being. In recent years the impact on health in buildings of biocontaminants, such as dust mites and microfungi, has been a major cause for concern in some developed countries. For example, the UK is top of the league table for asthma in 13-14 year olds [1]. Amongst other factors, Holgate [1] suggests that 'tight' centrally heated houses may increase allergen exposure due to dust mites, mould and pets. In Cleveland, USA, 'toxic' mould (*Stachybotrys*) growing in water-damaged homes has been implicated in cases of infant pulmonary haemorrhage [2, 3]. Considerable research has taken place to develop biocontaminant growth models and to assess the efficacy of a wide range of possible control measures [4]. The crucial factor for the presence of biocontaminants is the existence of suitable environmental conditions. Both dust mites and moulds are sensitive to dehydration and each species has a critical relative humidity below which it will not survive. Consequently, one of the principal non-chemical control measures for the suppression of biocontaminants to clinically acceptable levels involves the modification of room temperature and humidity. Howieson et al. [5], for example, recommend mechanical heat recovery ventilation to reduce humidity in small volume, air tight homes in temperate/maritime climatic regions.

In principle, the control of biocontaminants in this way should invariably be effective, since their activity is restricted to a relatively narrow range of relative humidity. However, this method is not always successful, necessitating more aggressive treatments, since the conditions within the microenvironments inhabited by biocontaminants, whilst influenced by the ambient room conditions, are dependant on a large number of other factors. For example, adjacent heat and moisture sources (e.g. people, underfloor heating) and sinks (e.g. hygroscopic wall linings, cold bridges) will exert an important effect. It is clear that, if accurate growth models are to be developed and psychrometric control measures successfully applied to biocontaminants, it will be necessary to distinguish microclimatic conditions from the adjacent ambient conditions.

Whilst the measurement of temperature within microenvironments does not present a problem, the measurement of humidity has proved to be the main restriction on the development of an understanding of microenvironments. However, with the recent availability of microchip based sensors, it is now feasible to measure humidity accurately with improved spatial resolution. This paper reports the results of a research project which focussed on the development of a methodology for measuring and modelling conditions in the biocontaminant microenvironments typical in housing.

The project comprised the following activities:

- The selection of suitable sensors and the validation of measurements.
- Trials of sensors in laboratory and field investigations.
- The assessment of the measurements using a dynamic heat and moisture transfer model to simulate the test environments.
- The use of the model, coupled with a simplified growth model to predict dust mite activity in domestic environments.

2. SENSOR SELECTION

Following a search of available devices, a capacitive sensor with integrated signal conditioning was chosen as meeting performance criteria considered appropriate for microenvironment measurements [6]. The sensor is a thermoset polymer-based capacitive humidity sensor with integrated signal conditioning and a linear voltage output proportional to relative humidity (RH). The manufacturer claims fast response, high linearity, low hysteresis and excellent long term stability, with resistance to dirt, dust, oil and many organic contaminants. The sensors recover rapidly from wetting or condensation. However, long term exposure to humidities over 90%RH causes a reversible shift of 3% RH. A drawback of the sensors is that they are light sensitive; therefore precautions must be taken to shield them from bright light. For increased accuracy a temperature correction may be applied. The size of the sensor is sufficiently small (9.3mm × 4.3mm × 2mm) to be unobtrusive and minimise disruption in carpets, furniture, etc. (Figure 1).

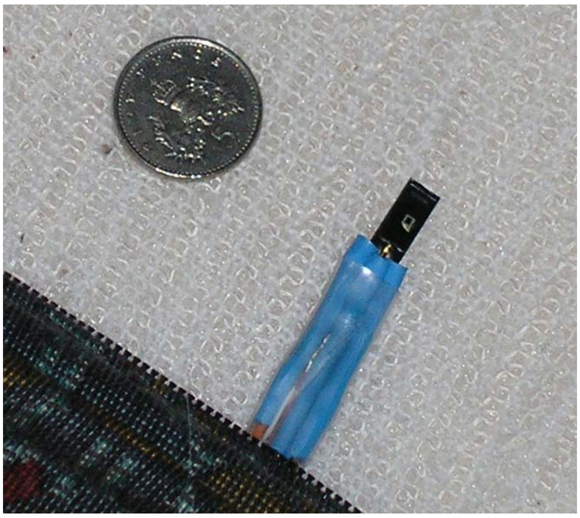

Figure 1. The relative humidity sensor.

Calibration of a batch of sensors confirmed the manufacturer’s specification that over the range of relative humidities the accuracy of the sensors is within ±2% RH. The sensors show a good linear response to changes in humidity, however at higher relative humidities (>~80% RH) there is some hysteresis.

3. VALIDATION OF MEASUREMENTS IN MICROENVIRONMENTS

Once a sensor has been deployed, for example between carpet and underlay, within furniture, etc., the key question arises to what extent are the measurements representative of the actual physical phenomena occurring? Obviously, there are limitations to any measurement protocol. Generally, the sensors can only be placed at the interfaces between two materials or at the boundary of a material with the air. Humidity sensors at an interface effectively measure the humidity of an air pocket surrounding the sensor. The properties of the body of the sensor may also influence the measurement. Hygrothermal modelling provides a possible means of validation, by comparing the measured results with predictions from an accurate computational model and offers the possibility to extrapolate to other scenarios.

Preliminary tests were carried out with the sensors sandwiched between the layers within a sample of flooring with carpet and underlay, in order to assess whether measurements were affected by the orientation of the sensors between constituent layers and also to examine sensor response by imposing dynamic conditions. The measurements indicated that there were no significant directional effects from sensors facing up or down between layers within a sample exposed to a humidity gradient. A step change in the boundary conditions was imposed by exposing the sample to high humidity followed by a period of drying at lower humidity (Figure 2).

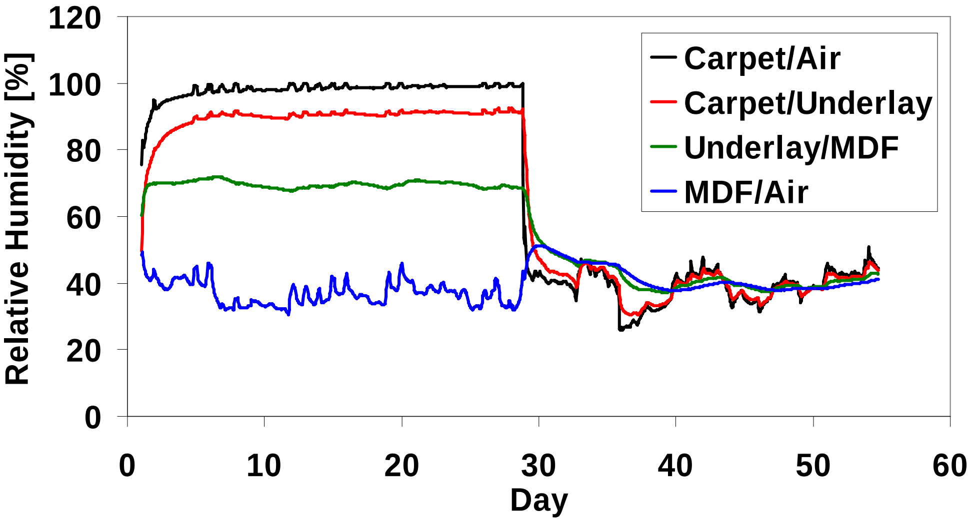

Figure 2. Measured RH in sample assembly comprising medium density fibre board (MDF), underlay and carpet.

The sample assembly was modelled using the 1-D heat and moisture transfer model MATCH [7]. The measurements of relative humidity and temperature at the external surfaces were taken as the boundary conditions, in order to predict the relative humidities at the carpet/underlay and underlay/MDF interfaces for comparison with the measured data. Where the properties of the materials used in the study were unavailable in the MATCH database, the moisture properties (i.e. water vapour permeabilities and moisture sorption isotherms) were measured and values for thermal conductivity and specific heat capacity were assumed from EN12524:2002 [8].

The results are shown in Figures 3 and 4. The measured and predicted results are within ±5% RH, showing good agreement, which gives confidence in both the measurements and model.

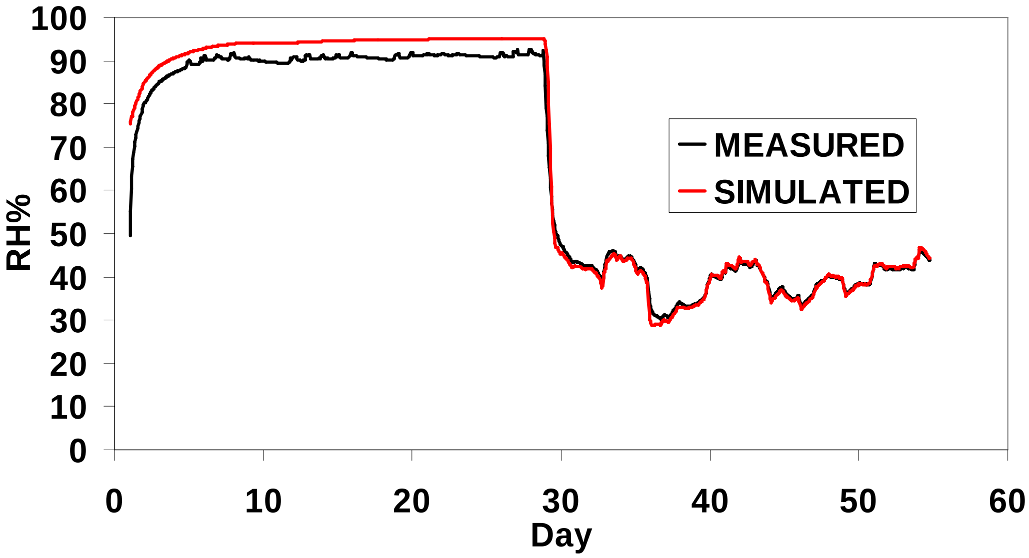

Figure 3. Comparison of measured at predicted RH at carpet/underlay interface.

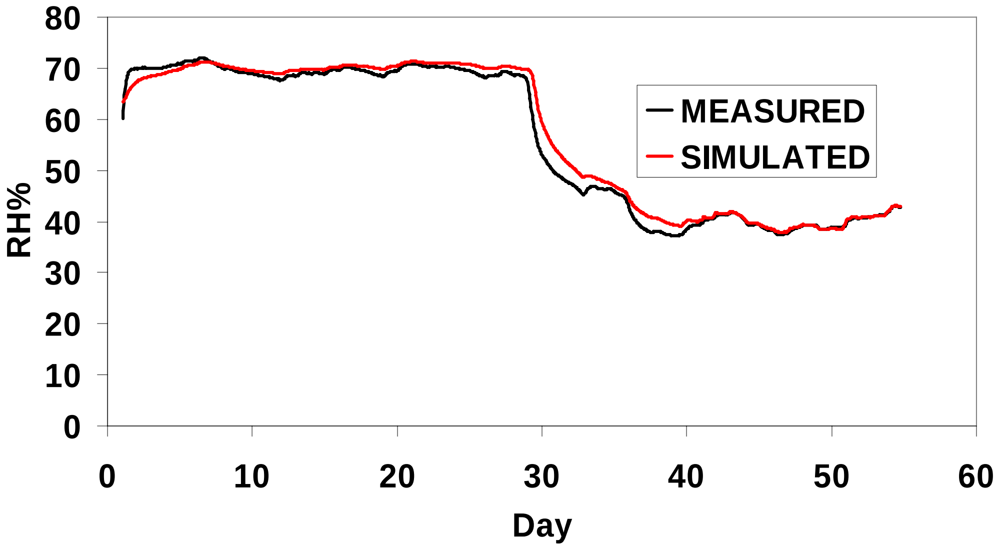

Figure 4. Comparison of measured at predicted RH at underlay/MDF interface.

4. TRIALS OF SENSORS IN LABORATORY AND FIELD INVESTIGATIONS

4.1 Laboratory trials with flooring constructions

Tests were performed with two typical flooring constructions, each approximately 1m^2 in area, built into the environmental chamber at Glasgow Caledonian University, to provide controlled temperature and humidity above and below the flooring. The floors comprised (1) traditional timber floorboards and (2) an insulated floor constructed from extruded polystyrene and chipboard. Each floor construction was covered with four different combinations of underlay and carpet, with temperature and humidity sensors located between the layers. The tests were carried out with varying environmental conditions above and below the floors (Figures 5 and 6).

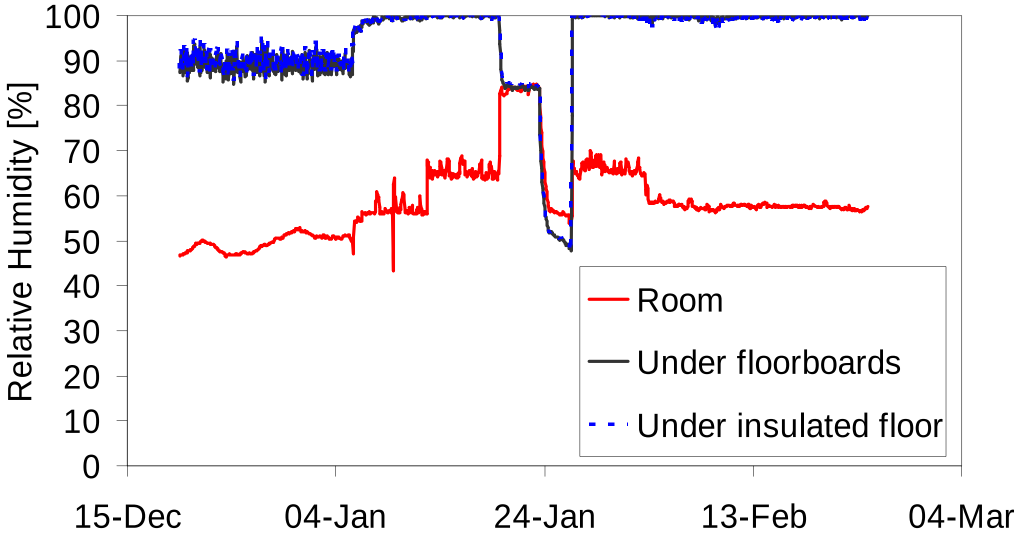

Figure 5. Boundary conditions for flooring tests: relative humidity above and below floors.

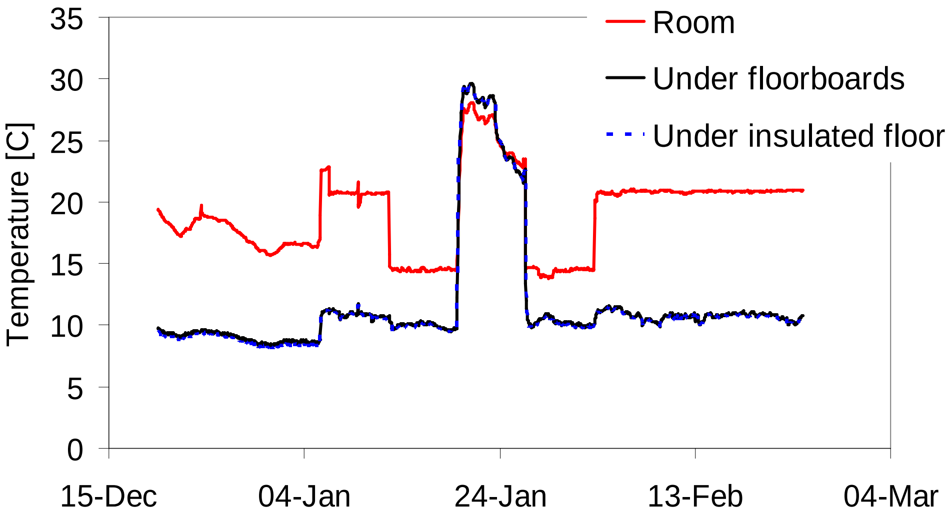

Figure 6. Boundary conditions for flooring tests: temperatures above and below floors.

Typical results are shown in Figure 7 for the relative humidities at the carpet/underlay interface for both floor types. There is a considerable variation in the humidity at the interface for different combinations of floor type and underlay material; for example there is an average 10%RH difference between the floorboard/carpet/sponge underlay assembly and the insulated floor with felt underlay and carpet.

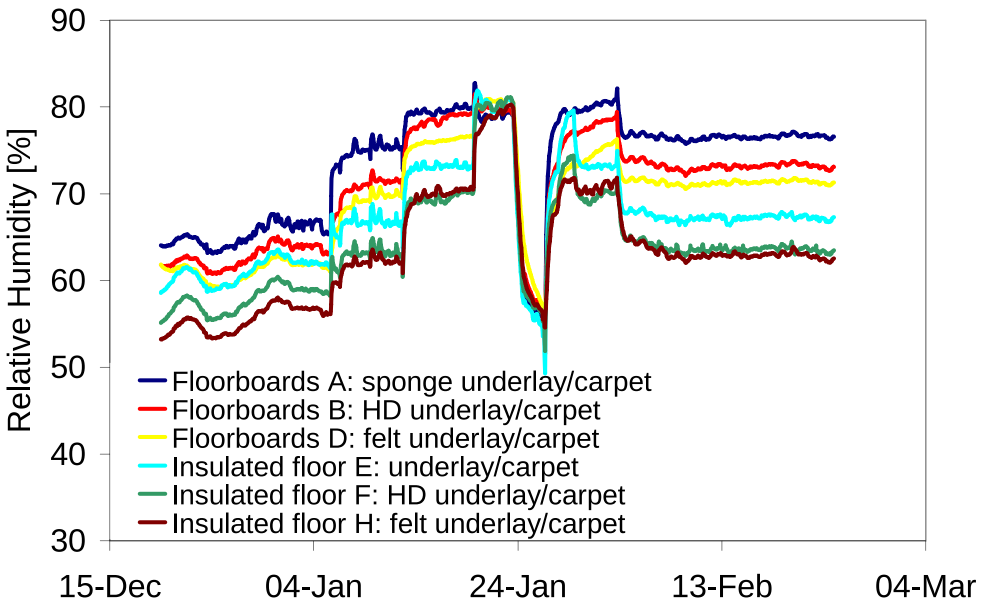

Figure 7. Comparison of relative humidities measured at carpet/underlay interface.

Whilst the materials clearly exhibit a wide range of moisture properties (Table 1), in the absence of a straightforward empirical method of analysis, the analytical approach, using the MATCH program offers a viable means of predicting performance.

Table 1. Vapour resistivity and sorption properties at 50%RH & 70%RH of the underlays and carpets.

	Vapour Resistivity MN.s/g.m		Sorption at 20°C			
	Dry Cup	Wet Cup	50%RH		70%RH	
			absorption	desorption	absorption	desorption
sponge underlay	277	206	0.3%	0.5%	0.5%	1.1%
heavy duty underlay	44	40	0.5%	0.7%	0.7%	1.0%
felt underlay	36	29	9.5%	12.8%	11.7%	15.0%
wool carpet	32	32	5.3%	6.9%	6.6%	8.5%
contract carpet (rubber backed)	72	63	0.2%	0.3%	0.2%	0.4%

The eight different flooring combinations were modelled using the ambient room and under floor temperatures and humidities as boundary conditions. A sensitivity study was also carried out, perturbing each boundary condition by its possible error (e.g. the error of room temperature measurement is ±1K) to give an estimate of the confidence limits of the simulation. Figures 8 and 9 show examples of the results for floor B (carpet + heavy duty underlay on floorboards). Generally, there is good agreement between measured and simulated behaviour.

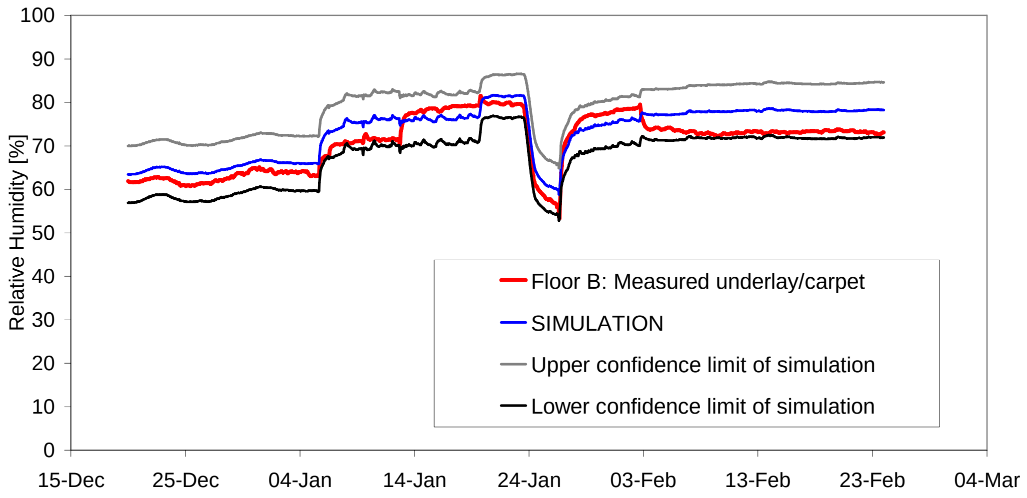

Figure 8. Floor B: comparison of measured and predicted RH.

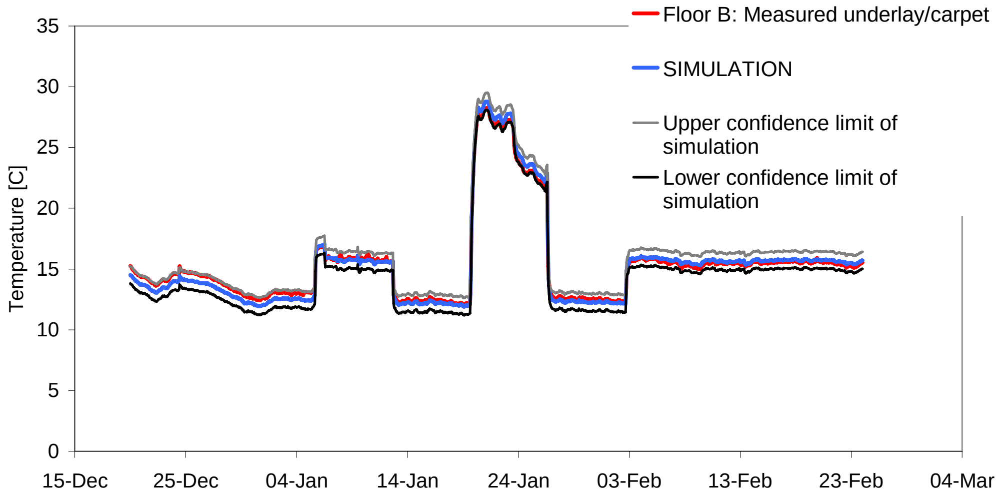

Figure 9. Floor B: comparison of measured and predicted Temperatures.

4.2 Field study

The field study was carried out in the Glasgow home of one of the authors in early 2004. Room environmental conditions and temperatures and humidities within three cushions of a sofa were monitored over a three month period.

The measurements indicate that the temperature and humidities in the unoccupied sofa follow the ambient conditions within the room. However, when the sofa is occupied the temperatures at the surface of the sofa rise to near skin temperature (~34^{o}C) and the humidity falls, although there is a sharp rise in vapour pressure (Figure 10) indicating an increase in moisture loading. After occupancy, the sofa conditions return to ambient rapidly near the top of the cushions, and within a few hours at the base.

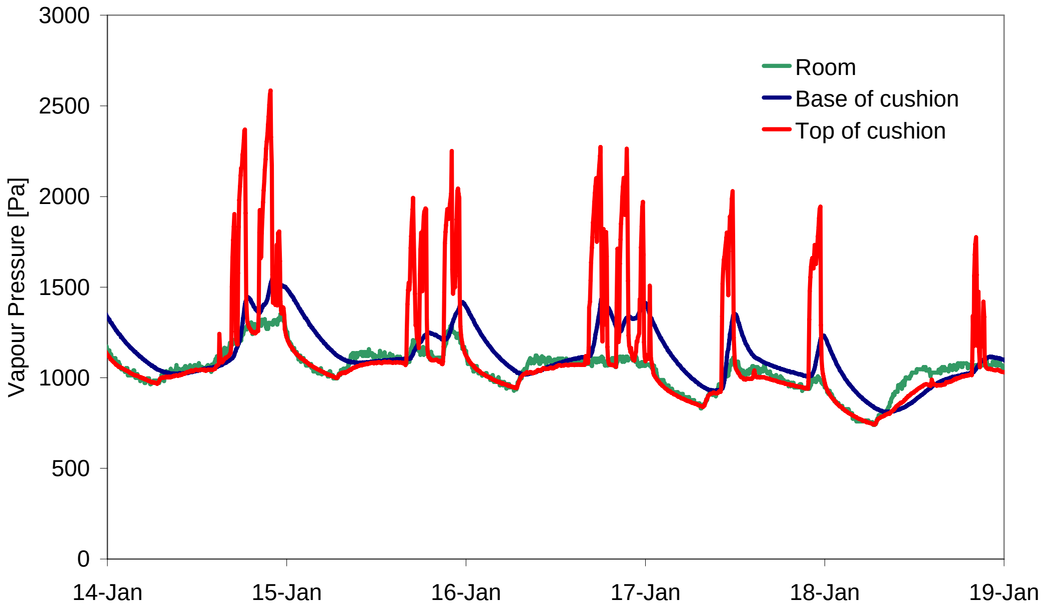

Figure 10. The response of vapour pressure of the sofa to occupation over a five day period.

In order to generalise the behaviour of the sofa, the simulation approach was again used. Some assumptions were made about the hygrothermal properties of the sofa by using the most similar materials available in the MATCH database. It was assumed that the boundary conditions for modelling around the sofa were the measured ambient conditions. However, during occupancy the room air temperature was replaced by the human skin temperature of 34°C and, initially, the relative humidity was recalculated for this temperature from the room vapour pressure (i.e. no additional moisture load from the occupant(s) was assumed). Further simulations were carried out for different over-pressures to simulate an increased moisture load when the sofa is occupied. Examples of the results are shown in Figures 11-13 for an over-pressure of 500Pa during occupancy of the sofa, which is equivalent to the average measured vapour pressure difference between the room and the sofa. The comparison between the measured and predicted results is satisfactory, provided the over-pressure is considered.

Improvements in the specification of the material properties of the sofa are required, as well as considering the inclusion of moisture generated by the occupant. It is not straightforward to translate physiological generation of moisture, e.g. insensible perspiration, into suitable boundary conditions for the model. Factors such as the effect of the properties of the occupant’s clothing may be significant. Additionally, the mechanism of heat and moisture transfer at the surface of the sofa to the surrounding environment will be convection for the unoccupied state and conduction for the occupied state. However, the selection of the skin temperature of 34°C appears to be suitable as a boundary condition.

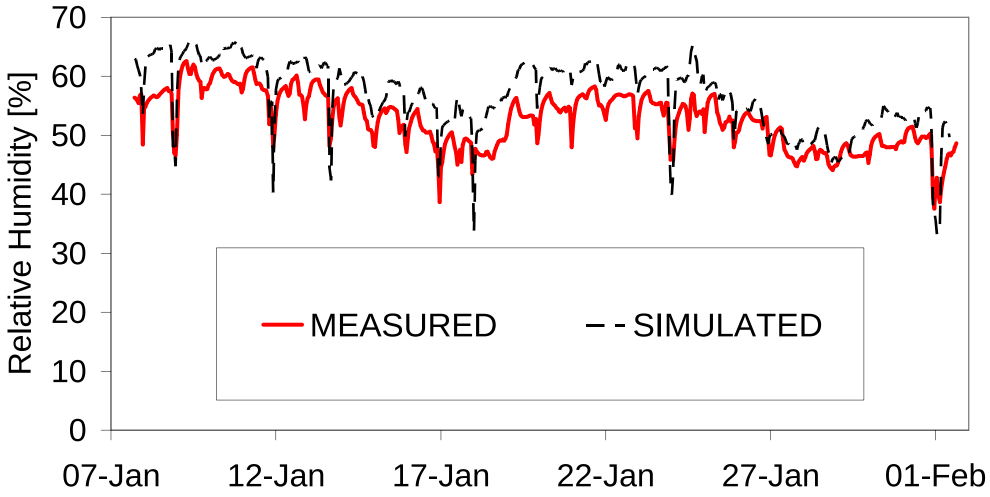

Figure 11. Measured and predicted RH near surface of cushion.

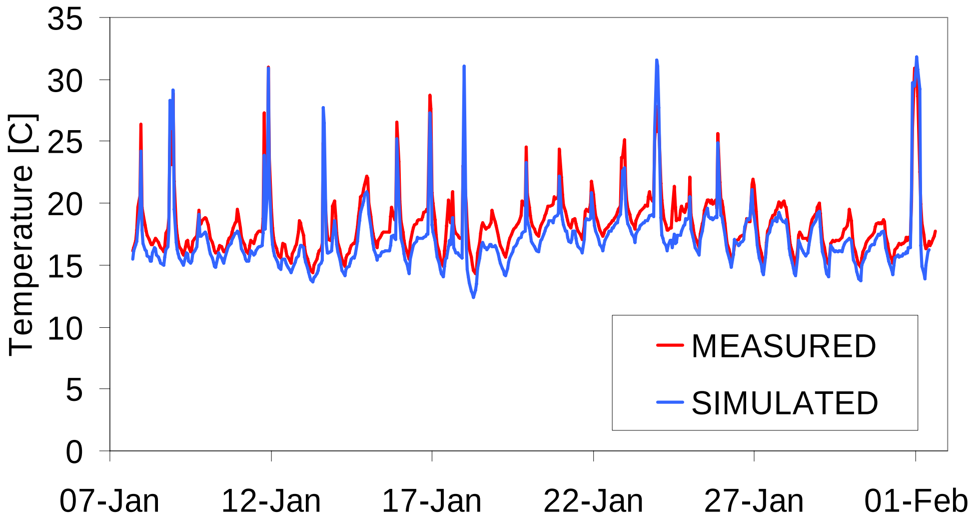

Figure 12. Measured and predicted temperature near surface of cushion.

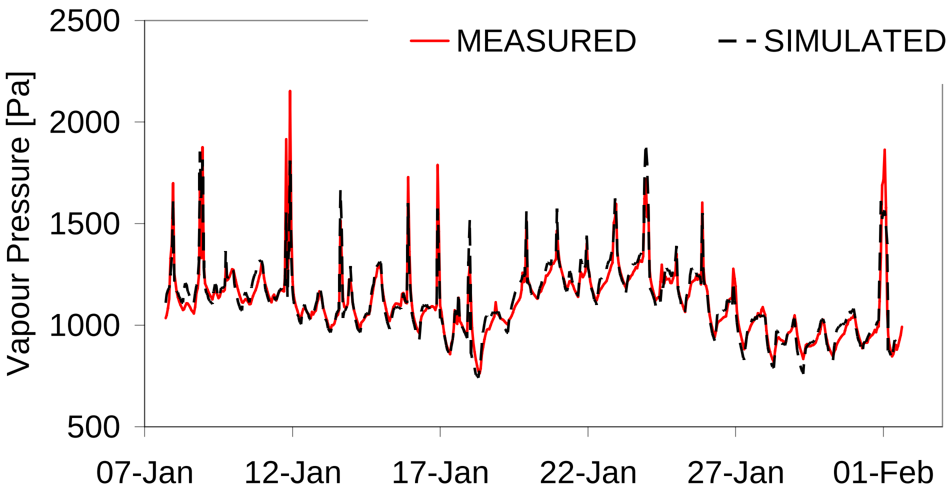

Figure 13. Measured and predicted vapour pressure near surface of cushion.

5. THE PREDICTION OF DUST MITE ACTIVITY

The most common dust mite in the UK, *Dermatophagoides pteronyssinus*, occurs in carpets, mattresses, sofas and other upholstered furniture where human skin scales can accumulate. The allergens linked to the faeces of this mite play a major role in allergic disease, particularly asthma. A possible means of predicting *Dermatophagoides pteronyssinus* activity is by using the MATCH predictions of temperature and relative humidity as input to an appropriate population growth model.

The reaction of a dust mite population to an imposed temperature and humidity regime is known to be complex. However, research studies, such as by de Boer et al. [9], have indicated that a simple understanding of the response of mites to changing environmental conditions can be related to the Critical Equilibrium Humidity (CEH). Dust mites are 70-75% water by weight. They do not ingest free water, but absorb moisture from their environment through a hyperosmotic solution that is secreted by the supra coxal glands [10]. The CEH is the relative humidity at which the water obtained using this mechanism balances that lost due to evaporation, egg laying and excretion. De Boer et al. [9] found a distinct correlation between egg production, which can be equated to population growth and allergen production, and the period of time the relative humidity exceeded the CEH.

The CEH is temperature-dependent and for *Dermatophagoides pteronyssinus* can be represented by the polynomial

$$\mathrm{CEH} = 0.2556\mathrm{T}^2 - 8.7\mathrm{T} + 130.78$$

The predicted hourly temperatures from the simulations were converted into equivalent CEH values, using the polynomial equation derived for *D. pteronyssinus*. The predicted relative humidities were then compared to the derived CEH values and categorised as being above or below the CEH.

Subsequently, for each day, the longest continuous period (P) that the predicted relative humidity exceeded the CEH was calculated. Each day was then classified as follows based on the observations of de Boer et al. [9]:

- Stress - the daily conditions put the population under stress (P less than 3 hours);
- Survival - the daily conditions enabled survival of the existing population (P is 3-5 hours); and
- Growth - the daily conditions are conducive to mite population growth and allergen production (P is 6 hours or more).

5.1 Simulation results

MATCH was used to model the sofa as described above using measured room environmental conditions from an uninterrupted monitoring period from 8th July 2004 to 17th May 2005 as boundary conditions (Figure 14). The data show that, whilst the room temperature is relatively stable over the period, the relative humidity is high over the summer of 2004. The room during this period was unheated. For the simulation it was assumed that the sofa was occupied for four hours each evening.

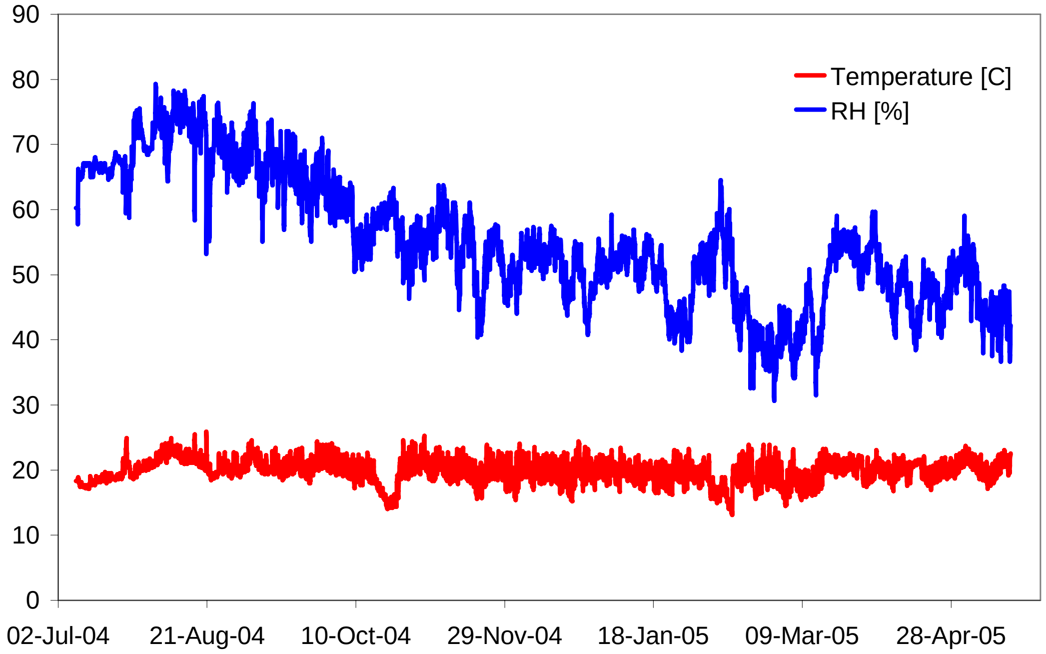

Figure 14. Measured room environmental conditions for the simulation period.

Figure 15 shows the predicted relative humidity in the upper part of the cushion compared to the CEH value: daily averages are shown for clarity. During the summer period of higher humidity, the relative humidity in the cushion tends to exceed the CEH value.

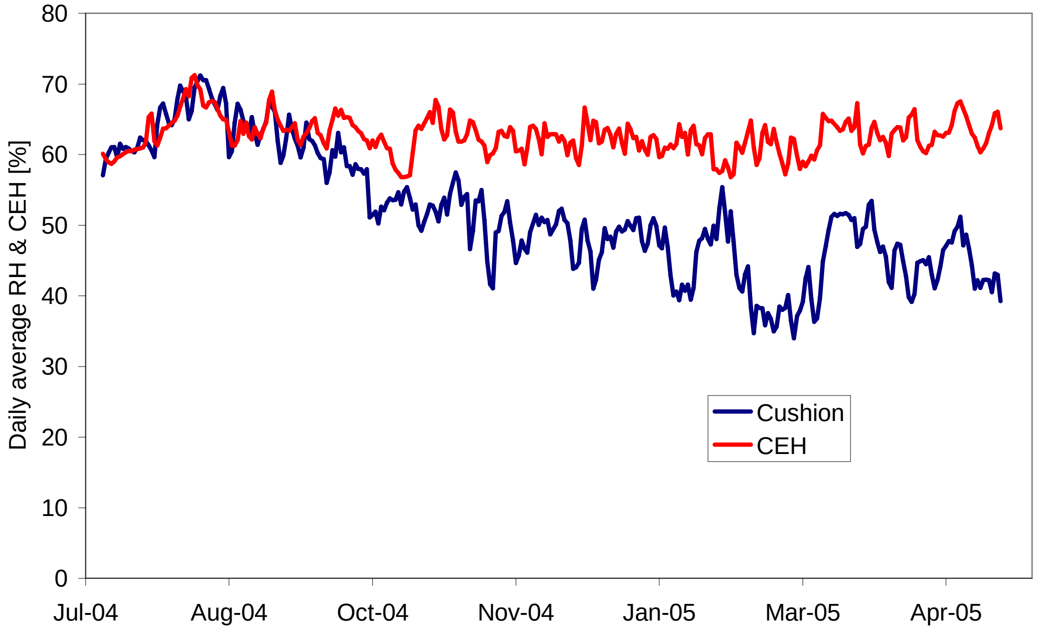

Figure 15. Predicted relative humidities in the upper part of a cushion and CEH values.

The CEH analysis results are shown in Figure 16. The analysis predicts that throughout the summer and early autumn the conditions within the sofa are conducive to mite population and growth. During this period the room relative humidity remains high due to the absence of heating, the influx of humid air and the additional moisture loading of the occupants. However, during the heating season the conditions become much less favourable as the relative humidity in the room, and consequently that in the sofa, falls below the CEH threshold. This prediction corresponds well to actual seasonal mite data obtained in UK houses by Hunter et al. [11]. These authors observed a general increase in mite numbers in the carpets of the sampled rooms during the summer months with the peak occurring during September. Subsequent to the autumnal peak, numbers declined to a relatively static "baseline" during the January to April period.

Improving the room conditions in the summer is problematic, particularly if the climate is mild and wet, since for most of the day (assuming adequate ventilation and no heating) the relative humidity in the room will tend to follow the external RH with additional load from the occupants. If there proved to be a dust mite infestation, de-humidification would be a possible solution by lowering the RH to, say, 55%.

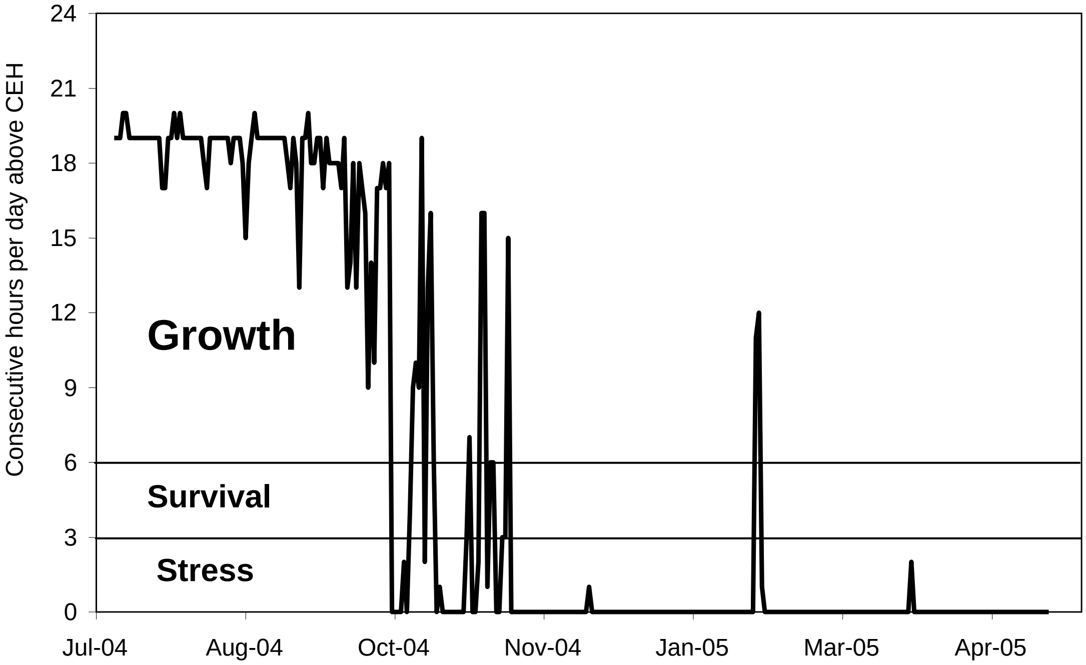

Figure 16. CEH analysis.

6. CONCLUSIONS

A commercially available relative humidity sensor, which meets appropriate performance requirements for microclimatic measurements, was selected and successfully tested in a range of environments and applied in a field study of a domestic sofa.

A dynamic heat and moisture transfer model was used to model the test environments and the monitored conditions found in the domestic study. Generally, good agreement was found between the measurements and model predictions, and modelling consequently seems to offer the best approach to the prediction of the likely conditions in microenvironments. However, the project showed that in order to perform accurate simulations it is necessary to extend the material properties data base of typical programs to include the range of materials available for domestic flooring and furniture. For simulating furniture, particular attention should be focussed on refining modelling techniques to include "casual" heat and moisture gains, e.g. physiological moisture production.

The simulation output can be used as input to biocontaminant population growth models. This feature was demonstrated by using MATCH in conjunction with a simple dust mite population model, which was based on the criterion of Critical Equilibrium Humidity.

The approach developed in the project offers a means of assessing the effectiveness of possible psychrometric control measures.

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