A Hygrothermal Model of House Dust Mite Response to Environmental Conditions in Dwellings

Summary Report

of a two year research project funded by the
Engineering and Physical Sciences Research Council

September 2002

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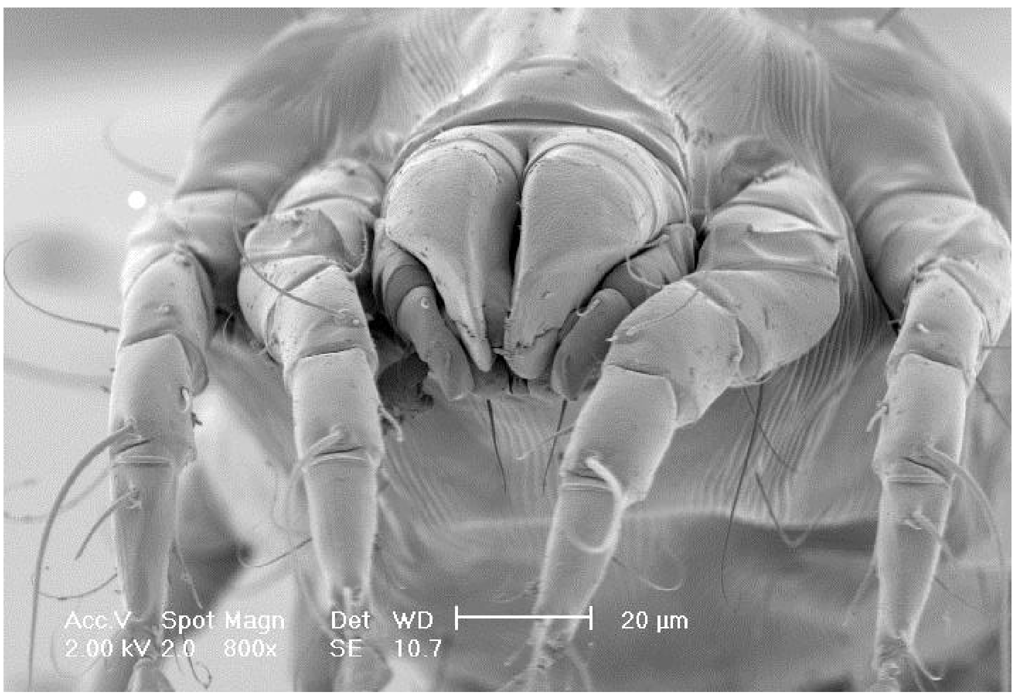

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1 Background

Inhaled allergens derived from house dust mite (HDM) faeces play a major role in allergic disease, especially in asthma. The number of people affected is rising throughout Europe (and indeed worldwide), now impairing the health and quality of life of a substantial proportion of children, as well as many adults, and placing a significant burden on health services. Less than a millimetre in size, house dust mites feed off human skin scale and live where a) skin scale is plentiful and b) hygrothermal conditions (ie. temperature and relative humidity) are suitable. In the UK and Europe they are found mostly in bedding, but carpets and upholstery can also be favourable locations.

Various methods are used to reduce mite populations in the home, such as microporous barrier covers for bedding, acaricide sprays, steam treatments and draconian cleaning regimes. However, even when effective, these methods are costly and/or inconvenient and tend only to be adopted once symptoms have occurred. While useful as curative measures, they are unlikely to be adopted by more than a small proportion of householders.

Mites require a particular combination of temperature and relative humidity to flourish and another approach is to control mite populations by environmental means, ie. by manipulating hygrothermal conditions in the home. In fact it is often suggested that the rise is asthma is partly as a result of reduced ventilation in dwellings. At the macro scale, regional differences in mite numbers can be related to overall external climatic conditions, but at the micro scale there can be wide variations within a geographical region and even from one house to the next. This reflects the fact that hygrothermal conditions can vary greatly according to factors such as different construction, heating and ventilation regimes, and occupant behaviour. Several studies have shown that allergen levels are significantly affected by indoor climate, thereby demonstrating the scope for controlling mites by environmental means.

This approach has two major advantages. First, as our results confirm, effective control can in many cases be achieved by relatively minor adjustments to heating, ventilation, or occupant behaviour. Significant reductions in the prevalence of disease are thus achievable at a cost far below that of drug therapies. Moreover, where capital expenditure is required, this tends to be desirable for other reasons, eg. raising insulation standards also improves energy conservation and lowers Excess Winter Deaths. The second advantage is that environmental means of control have potential as preventive measures, that is to say before symptoms have occurred. With adequate support from public health initiatives and the building industry, they could be adopted by a high proportion of households.

The possibility of environmental control of mites has been recognised for some time by the international community of acarologists, but it has only recently been taken up by building scientists, notably Cunningham in New Zealand. Because of the complexity of the many interacting factors, it has until now been difficult to model hygrothermal conditions within dwellings and mite habitats in sufficient detail for determining the most effective, energy efficient and socially acceptable ways of achieving control. The advent of reliable models of hygrothermal conditions and of small cheap monitoring sensors has revolutionised the situation, reawakening interest in this area. However, there are as yet few successful collaborations between acarologists and building scientists of the kind required to develop and exploit the enormous potential worldwide for a combined hygrothermal population model.

Objectives

Our overall aim has been to develop the first model to predict house dust mite populations in dwellings accurate enough to determine the impact of modifications to building fabric, services and occupant behaviour. In this way it is possible to establish the most effective means of controlling mite populations for any specific climate, house type and occupant behaviour. By achieving this aim, we have become international leaders in a field of growing relevance, although further research is required if we are to maintain this position.

2 Research undertaken

The two-year multidisciplinary project has involved both laboratory and field measurements as well as model development. Two models have been developed, a simple easy to use model, **BED3**, which has a steady state hygrothermal model linked to an empirical population model, and a more complex model, **Lectus**, which is a transient, three dimensional model that simulates all stages of mite development.

Measurement of hygrothermal conditions in beds

A series of experiments were undertaken to examine the conditions to which HDM are exposed in bedding, this data being used to develop, test and validate a hygrothermal model of the bed environment. An instrumented test bed was set up to investigate transient and spatial variations in hygrothermal conditions, when both empty and occupied. The relationship between bed and room conditions, and variations caused by occupants were also examined. Seventy-five relative humidity (RH) and temperature sensors were placed on the surface of the mattress, in the duvet and deep within the mattress itself. Volunteers of different gender, age, and body weight were asked to sleep in the test bed on two nights and on two different types of mattress, polyurethane foam and open coil sprung.

The results demonstrate that hygrothermal conditions in different zones of the bed are very different and that RH in some parts of the bed can *reduce* when occupied, eg. directly beneath the occupant where the surface temperature rises to 34 °C. Due to occupant moisture production, there is a vapour pressure excess compared to room conditions, tending to increase RH in other parts of the bed, although the edges of the bed remain in equilibrium with the room.

When the occupant leaves the bed conditions return to equilibrium with the room in approximately 4 hours with the covers left on. An empirical model to predict conditions on the surface of the mattress, using the room conditions, mattress type and occupant characteristics, was developed from the experimental results. Measurements were also carried out in three test houses for one year, with loggers placed in the bedroom, bed, under the bed and external to the house. This data was used to test the validity of BED3 and Lectus models.

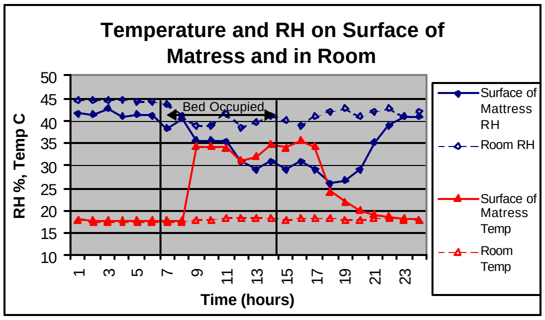

Fig. 1. Temperature and RH on surface of mattress and in bedroom

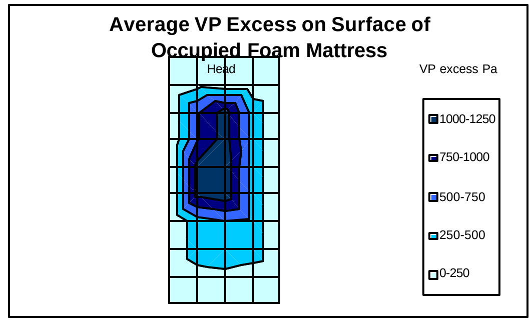

Fig. 2. Average Vapour Pressure Excess on surface of occupied foam mattress

Bed3: Simple hygrothermal model

A model has been developed to predict the average monthly temperature and RH in the bed and bedroom of a house. This model is based on *Condensation Targeter II*, a monthly steady state model developed by Oreszczyn and Pretlove. Utilising a modified version of BREDEM-8, this is ideally suited for the task. The required data inputs relate to climate, dwelling characteristics, fuel expenditure and moisture production. Condensation Targeter has been extended to include the bed environment by incorporating a simple heat transfer and moisture balance model of a human and the bed. The model requires input values for vapour resistivities and mattress thickness, and has been adapted to predict monthly average temperature and RH in the core of bed, ie. between mattress and covering. The thickness of the cover (tog) is varied so that the comfort temperature (34 ºC) is always maintained whilst the bed is occupied. Upward and downward heat and moisture movement is calculated whilst the bed is occupied. The model can thus predict the average monthly RH and temperature in both the bedroom and the bed.

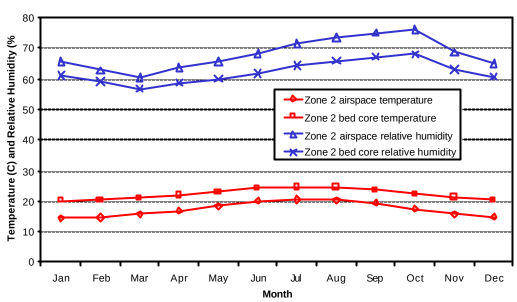

Fig. 3. Example predictions of the BED3 model

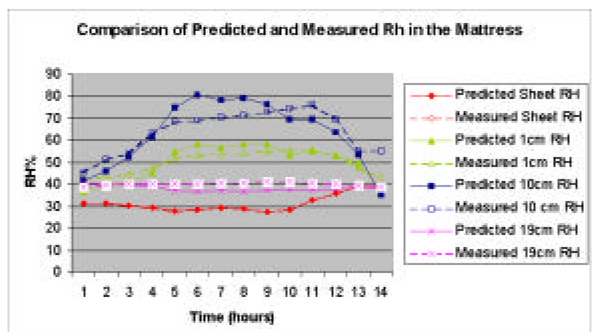

Fig. 4. Comparison of predicted and measured RH at different depths within the mattress

Lectus: Complex hygrothermal model

A transient model has been developed to predict temperature and RH on a 3D grid within the mattress on an hourly basis. The user inputs details of the building fabric, ventilation, heating and moisture production schedules, and hourly weather data. The model works in 3 steps. First, a building simulation program such as TAS or EnergyPlus is used to predict hourly values of temperature and RH in the bedroom. The surface conditions on the top surface and on the sides and bottom of the mattress, during occupation of the bed, are then predicted, using the room conditions and the empirical model based on results from the experimental test bed. These boundary conditions are then used as input to a 3D transient heat conduction and vapour diffusion model, to calculate the conditions at points within the mattress, using an explicit finite difference scheme. Only vapour diffusion is considered; for this study, liquid water is assumed not to form within the mattress. The dimensions of a bed are such that edge effects must be considered; so that a full 3D model is required. The mattress is divided into a grid of 75 finite elements in three horizontal layers. A Gauss-Seidel iterative method is used to solve the explicit finite difference scheme.

Laboratory measurements of HDM carrying capacity

Laboratory studies were undertaken to fill some of the most critical gaps in knowledge with respect to HDM behaviour. HDM population growth appears to be unusually free of the normal constraints of food supply, space and competition from predators, but for modelling purposes the maximum density that a population can reach in a mattress, or carrying capacity *K*, is a fundamental variable that needs to be determined. Mating pairs of HDM were placed in test tubes with a set amount of food (as a proxy for bedding conditions) and kept at ideal conditions of temperature and RH, their numbers being counted at regular intervals. Growth peaked at about 12,000 mites per gram of food (although there was considerable variation) before gradually declining. It appeared likely that at its peak growth was being limited by lack of space and that the decline was the result of a reduction of food quantity or quality. Further experiments were carried out to investigate this and it was concluded that K can be affected by both food quantity/quality and space according to circumstances. The effect of population density on mite migration behaviour was also examined. It was found that migration increases significantly once population reaches certain threshold levels that are of the same order of magnitude as the K values observed in the other experiments.

Laboratory measurements of HDM movement

In view of the varied and transient nature of conditions observed in bedding, it is important for modelling purposes to know to what extent and at what speed mites are able to move from one location to another in response to changing conditions. To investigate this, a specially designed mite box has been constructed, milled out of aluminium alloy with two identical elongated chambers, one instrumented, the other not. The box is surrounded by insulation and has a double-glazed lid sealed with a rubber gasket so that vapour pressure is held constant. A temperature gradient is established by passing warm water through one end and cool water through the other resulting in a matching RH gradient along the long axes. Live adult mites are placed in the un-instrumented chamber, conditions in the two chambers being assumed to be the same. Two methods of recording mite movement have been used, one involving a digital camera, the other involving placing the mites in a sample of wadding similar to that found in mattresses. After a given time this is removed and the position of the mites in the wadding determined by heat extraction onto sticky tape. Results show that mites do move, albeit slowly, in response to RH gradients. Typically, after a 24-hour period, 65% of the mites have moved to the more humid end of the chamber.

Population growth under steady state conditions

Using incubators with controllable environmental conditions, populations of HDM were kept at different combinations of steady RH and temperature, covering the range of conditions found in UK dwellings. The starting population of mites was 1106, the final number being counted after 3 weeks' exposure to the steady state conditions to determine the rate of population growth or decline in each case. As well as being used for the BED3 population model below, this data set enabled us to determine the combinations of RH and temperature at which population growth is in equilibrium, neither growing nor declining, ie. *Population Equilibrium Conditions*.

The BED3 steady state population model

Using the above results, a 3D curve fit was performed on the data to produce a relationship that gave population growth as a function of RH and temperature. This equation forms the basis of the BED3 population model, which predicts the population of HDM in a bed on a monthly basis, using average monthly hygrothermal conditions.

RH	Temperature degC				
	15	20	25	30	35
32-46%	-84%	-84%	-100%	-100%	-100%
46-53%	-85%	-67%	-100%	-100%	-100%
66-69%	-17%	450%	698%	970%	-100%
68-82%	-5%	526%	624%	970%	-8%
85-88%	-20%	544%	1153%	1802%	290%
84-87%	-3%	663%	1236%	1766%	44%
95-95%					-63%

Fig. 5. Results of steady state growth experiments

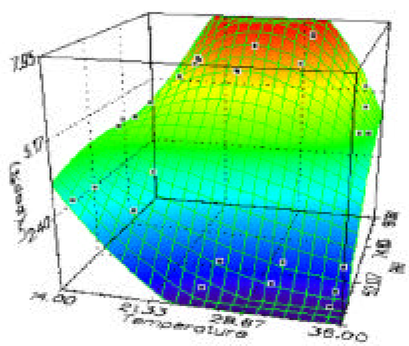

Fig. 6. 3D curve fit of steady state growth data used in steady state population model

The Lectus population model

A transient HDM population model has been developed to predict the numbers of eggs, juveniles and adult mites in each cell of a 3D grid of the bed environment as a function of hygrothermal conditions (input from the Lectus hygrothermal model). It is based on published data for *Dermatophagoides pteronyssinus* (the most common UK species) for rates of egg production, development (egg-to-larva and larva-to-adult)and mortality (eggs, juveniles and adults). In each case, a matrix of values was required for all relevant combinations of RH and temperature. Unfortunately, the existing published data sets are far from complete - a fact we hope the acarological community will help us put right. But there was sufficient data, making simplifying assumptions, to derive curve-fitted equations. The structure of the model is such that these can easily be modified as improved data becomes available.

The population model has been implemented in Visual Basic, with user-friendly input and output screens. The user sets the initial starting population and its distribution, and the model then calculates the effect of the hygrothermal conditions in each cell on an hourly basis, for each life cycle stage. Thus new eggs are laid, previously laid eggs hatch, juveniles mature and adults age and die. Juveniles and adults travel to an adjacent zone if conditions are more favourable. The model runs for a specified time and the output is the number of eggs, juveniles and adults in each cell and for the bed as a whole. Unfortunately we could find no existing mite survey data, where simultaneous hygrothermal conditions were also known, for testing the model. However, it was tested against the steady state data above, the results being in reasonable agreement.

Modelling current and future scenarios

The complete BED3 and Lectus models, each being a combination of a hygrothermal and a population model, were both used to examine a range of scenarios covering the types of dwellings, climates and occupant behaviour found in the UK. In addition, the impact of future climate change on mite populations was investigated and the outputs of the two models using the same input data were also compared.

3 Key advances and conclusions

This project has developed a sophisticated combined hygrothermal and population model of house dust mites in beds. It is the first model in the world that is capable of modelling a) the 3D environment within any bed, in any climate, in any dwelling and with any occupant use pattern, and b) the impact that this environment has on every stage of mite development, taking account of mite movement within the bed. Although more work is required to validate the model and extend its applicability, it can already be used to investigate which feasible modifications to home environments have most impact on mite populations.

Specific key advances in knowledge resulting from the project are as follows:

1. Hygrothermal conditions in a bed are critically dependent on bedroom conditions. This is in part because beds are unoccupied and in equilibrium with room conditions for most of the time and also because, even when occupied, conditions in large areas of a bed remain similar to the room. Modelling sensitivity tests show that the levels of building insulation, ventilation and heating typically found in UK housing are *significantly more* important in determining environmental conditions in the bed than is the type of bed or bedding.
2. Counter to common belief, the RH directly underneath the occupant can, typically *decreases* when a bed is occupied, although it rises in other parts of the bed. There are thus considerable spatial variations in hygrothermal conditions within the bed, as well as variations over time. Since both temperature and relative humidity affect mite development, this highlights the importance of examining both variables.
3. Sprung mattresses result in *less* moisture in the bed compared to polyurethane foam mattresses. This is contrary to much current advertisement literature.
4. There are significant differences between people in terms of the moisture they generate in a bed; these differences do not appear to correlate with age, sex, or size.
5. Laboratory carrying capacity experiments indicate a maximum capacity of 12,000 mites per gram of dust. Simple calculations indicate that a mattress may theoretically be able to sustain up to 1.5 million mites if both food supply and hygrothermal conditions are continuously favourable.
6. Mites do move to find more favourable environmental conditions. This is important since the most favourable environmental locations within a bed shift over time, which needs to be taken into account.
7. For the first time, *Population Equilibrium Conditions* have been determined, in distinction to *Critical Equilibrium Humidity*, the humidity (for a given temperature) below which individual mites lose more water than they can gain. The difference between the two will be of great interest both to acarologists and modellers.
8. Small reductions in ventilation rate below 0.5 air changes per hour can have a dramatic impact. Modelling suggests that reducing from 0.5 to 0.4 ach will increase the mite population by 100 times. However, an increase to above 0.7 ach can lead to an increase in the mite population in a fuel poor dwelling (one where the occupants cannot heat it properly), compared with a decrease in a fuel rich dwelling (one that is heated properly).
9. Raising bedroom temperatures from 16ºC to 18ºC, ie. without reducing ventilation, results in a significant (factor of ten) reduction in mite numbers. The increase in bedroom temperatures over the last 50 years, partly as a result of increased central heating and improved insulation, is therefore likely to have had beneficial effects. This supports the case for continuing to improve the nation's housing stock
10. Modelling suggests that building occupant density is a key parameter in determining house dust mite populations. Increasing the number of occupants in a dwelling from 4 to 6 can increase the mite population by 10,000 due to the increased moisture production in the property.
11. Model predictions indicate that the highest mite populations should occur in the South West of England, followed by Northern Ireland, with London having the lowest. An identical property and occupant is predicted to have 400 times the mite population in SW England compared to London. Such regional differences in mite populations may in part explain regional differences in asthma.
12. Modelling suggests that climate change (using the 1998 UK Climate Impact Programme climate predictions) will result in a significant increase in house dust mite populations. For example a typical bed in London is predicted to have 80 times the population of mites in 2050.

More information is available on the project website at www.arct.cam.ac.uk/research/mite. Contacts: Prof Tadj Oreszczyn [t.oreszczyn@ucl.ac.uk] 020 7504 5906 or Dr David Crowther [drgc2@cam.ac.uk] 01223 331700