Simulation of temperature and humidity in mattresses to evaluate risks on house dust mite allergy

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Abstract

Faeces of house dust mites constitute a major source of allergens. In modern, thermally well-insulated houses mattresses and carpets in bedrooms are the most important habitats of house dust mites. There, the human skin provides nutrition, water vapour and heat to create conditions that are conducive to mite growth. The temperature and the time span during which the relative humidity exceeds the critical equilibrium humidity (CEH) mainly determine growth of house dust mites.
This paper presents a simulation model that describes transient and spatial distributions of temperature and humidity levels in a mattress influenced by the human body and ambient conditions. The aim of this model is to formulate strategies to reduce risks on house dust mite allergy from mattresses and carpets.

Preliminary results of the computations showed that the transmission of water vapour occurred much faster than transmission of heat. This was due to the fact that the diffusion coefficient of water vapour is lager than the thermal diffusivity (on average: $D_{vap} = 6x10^{-6}$ and $a = 7x10^{-8}$ m^2s^{-1}).
As soon as the human body occupied the mattress, the temperature of the surface of the mattress increased up to 30 to 36 °C. At some depth in the mattress the absolute humidity in the air containing voids increased faster than the temperature. This resulted in an (temporary) increase of relative humidity, often to levels above the CEH.

Conclusions

1. The model presented in this paper gives a reasonable prediction of the spatial and temporal distribution of the temperature in a mattress occupied by a human body.
2. The agreement between model predictions of the relative humidity and experimental data is poor;
3. There is some evidence that a spring mattress with a thin layer of foam has a lower risk on growth of house dust mites than a foam mattress.

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Introduction

Faeces of house dust mites constitute a major source of allergens (Platts-Mills and Chapman., 1987). House dust mites feed on human skin scales (Korsgaard, 1998) and satisfy their demands for water by extraction of vapour from the air by hygroscopic secretion (Arlian and Veselica, 1981). Mites simultaneously lose water by physiological processes and evaporation. The critical equilibrium humidity (CEH) is the relative humidity at which the rate of water loss is equal to the rate of water uptake. Since human skin scales are generally available in the human habitat, the humidity level determines the growth of mites. Therefore, house dust mites live in the human habitat where the relative humidity exceeds the CEH.

In modern, thermally well-insulated houses mattresses and carpets in bedrooms are the most important habitats of house dust mites (Sidenius et al., 2002). During winters in temperate climatic regions, levels of indoor relative humidity are low. Here, the mattress provides a refuge for house dust mites (De Boer and Kuller, 1997) as a result of the heat and water vapour emanating from the human body (Crowther et al., 2001, Van Bronswijk, 1981). De Boer and Kuller (1994) found live mites deep inside the foam core of mattresses. Mattresses and carpets are therefore of considerable importance when interventions of the houses of allergic patients are planned.

Replacing carpets by smooth floor coverings can reduce allergen exposure. However, avoidance of allergen exposure from mattresses is more difficult to achieve. Use of allergen impermeable mattress covers seems clinical ineffective in adults with asthma (Woodcock et al., 2003) and allergic rhinitis (Terreehorst et al., 2003). Also vacuuming of mattresses appeared ineffective (Wickman et al, 1997, Burr et al., 1989). Schei, Hessen and Lund (2002) reported significant lower mite allergens concentrations in spring mattresses than in mattresses consisting of foam.

Since the growth of house dust mites is mainly determined by temperature and relative humidity (RH), control of these parameters is often mentioned as a means to reduce house dust mite allergy (De Boer and Kuller, 1997). However, clear control strategies to avoid growth of house dust mites in mattresses and carpets are not known thus far. This study therefore aims to develop a tool to formulate these strategies. This tool consists of a simulation model that predicts the spatial en temporal distributions of temperature and RH in a mattress occupied by a human body.

Pretlove et al. (2001) developed a transient hygrothermal model of a mattress. In spite of the complexity of their model, the agreement between computed en experimental RH levels was weak. To avoid that the simulation model becomes too complex to handle, this study started with the formulation of a simple model that can be expanded with more relevant processes if necessary.

A simple hygrothermal model of a mattress

The model presented here describes the flow of heat and water vapour in a mattress of thickness L when occupied by a human body. It is a one-dimensional model, which means that penetration of heat and vapour is assumed to occur in vertical direction only. It is further assumed that the temperature and absolute humidity at the surfaces of the mattress are constant. The human body determines the conditions at the top surface (x=L), whereas ambient conditions prevail at the bottom surface (x=0) of the mattress.

The risk on mite growth depends on the period in which the relative humidity is above the CEH. De Boer et al. (1998) found house dust mites that gained weight when moist air was given for only 1.5 hours daily and mites producing eggs when the daily humid spells last for at least 3 hours. Therefore, the model presented in this paper focuses on the calculation of the time span during which relative humidity's are above the CEH.

The critical equilibrium humidity depends on the temperature. From data given by Arlian and Veselica (1981) it was deduced that CEH = 0.97*T+34.8 (with T [°C]).

A mattress can be characterized as a porous medium consisting of a system of interconnected air filled pores in a polyurethane mass. It consists of a solid and a gaseous phase with volume fraction subjected to the constraint:

$$\Theta_g + \Theta_s = 1, \qquad (1)$$

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where Θ_g and Θ_s are the volume fractions occupied by the gaseous and solid phase, respectively. The true density γ_i [kg m^{-3}] of phase i is equal to the mass of phase i divided by the volume occupied by phase i, whereas the bulk density ρ_i [kg m^{-3}] of phase i is equal to the mass of i divided by the volume occupied by all the phases. Thus,

$$\rho_i = \Theta_i \gamma_i \tag{2}$$

In general, the contribution of the gaseous phase to the total bulk density is negligible and therefore ρ is approximately equal to ρ_s.

The gaseous phase is considered to consist of stagnant air (a mixture of nitrogen and oxygen) and water vapour. For the mass balance of water vapour it is assumed that:

- Air filled porosity of the mattress does not change, thus Θ_g is constant;
- Vapour transfer takes place by diffusion only;
- Vapour transfer is only driven by the concentration difference between the human skin and ambient air of the mattress;
- Sorption of water vapour on the solid matrix is negligible;
- The vapour density (absolute humidity) does not change with temperature, thus disregarding expansion.

Using these assumptions the mass balance equation of water vapour is given by (Bird et al., 1960):

$$\frac{\partial(\gamma_{H2O})}{\partial t} = \frac{D}{\Theta_g} \frac{\partial^2(\gamma_{H20})}{\partial(x^2)} \tag{3}$$

where t is the time [s] and D [m^2 s^{-1}] is the coefficient of diffusion of water vapour in the air mixture.

The heat balance of the mattress is given by:

$$\frac{\partial(T)}{\partial t} = \frac{\lambda}{\rho c_p} \frac{\partial^2(T)}{\partial(x^2)}, \tag{4}$$

where T is the temperature [K], λ the thermal conductivity coefficient [W m^{-1} K^{-1}], and c_p specific heat capacity of the mattress [J $kg^{-1}K^{-1}$]. The term $\lambda/\rho c_p$ is designated as the thermal diffusivity a, which has the same dimensions as D in Equation 3.

To find an analytical solution for Equation 4, T is replaced by T^* which is equal to T minus the ambient temperature T_a. With the initial and boundary conditions:

for: $t = 0$ and $0 < x < L$: $T^* = 0$;
$t > 0$ and $x = 0$: $T^* = 0$;
$t > 0$ and $x = L$: $T^* = T^*_1$,

the analytical solution of Equation 4 is given by (Carslaw and Jaeger, 1986) :

$$T^* = T^*_1 \sum_{n=0}^{\infty} \{ \operatorname{erfc} \frac{(2n+1)L-x}{2\sqrt{(at)}} - \operatorname{erfc} \frac{(2n+1)L+x}{2\sqrt{(at)}} \}. \tag{5}$$

Values of erfc are given by Carslaw and Jaeger (1986).

The form and boundary conditions of Equation 3 and 4 are similar. Therefore, the analytical solutions of these equations are similar and the solution of Equation 3 can be formulated by replacing T^*_1 by $\gamma^*_{H2O,1}$ and a by D/Θ_g in Equation 5.

The temperature of the human skin is approximately 34 °C (Adams et al., 1998, Havenith et al., 2002). The actual vapour density at the skin surface $\gamma_{H2O,1}$ is calculated from the skin wetness w, which is defined by the ratio between the actual sweat evaporation and the maximum evaporation possible in the present climate. Thus, w is given by:

$$w = \frac{p_{skin} - p_a}{p_{sat} - p_a} \qquad (6)$$

where p_{skin} is the actual vapour pressure at the skin surface, p_{sat} the saturated vapour pressure at skin temperature and p_a is the actual vapour pressure at ambient conditions. The value of w varies between 0.06 and the upper comfort limit of 0,2 to 0.3 (Adams et al., 1998). The saturated vapour pressure at skin temperature (34 °C) was calculated by the formula given by Goff and Gratch (1946). Subsequently, the actual vapour density at the skin surface $\gamma_{H2O,1}$ followed from p_{skin} using the perfect gas law. Then, $\gamma^*_{H2O,1}$ was computed by subtracting the ambient vapour density from $\gamma_{H2O,1}$.

Table 1. Parameter values used in the simulations

Parameter	Value	Reference
λ [W m^{-1} K^{-1}]	0.003	VDI Wärmeatlas 1977
ρ_s [kg m^{-3}]	30	VDI Wärmeatlas 1977
γ_s [kg m^{-3}]	1350	VDI Wärmeatlas 1977
D [m^2 s^{-1}]	6x10 $^{-6}$	Marshall (1959), Mason and Monchick (1962)
c_p [J $kg^{-1}K^{-1}$]	1470	VDI Wärmeatlas 1977
w [-]	0.3	see text

Table 1 gives parameter values used in the simulations. From this table it can be calculated that the thermal diffusivity a is equal to $7x10^{-8}$ [m^2 s^{-1}]. Thus, a is approximately 100 times smaller than the diffusion coefficient D of water vapour.

Comparison between simulated and experimental data

In this study I compared numerical results from the simple transient model with experimental results from De Boer and Kuller (1997) and Pretlove et al. (2001). They described detailed experiments in which the temperature and the relative humidity in mattresses were measured.

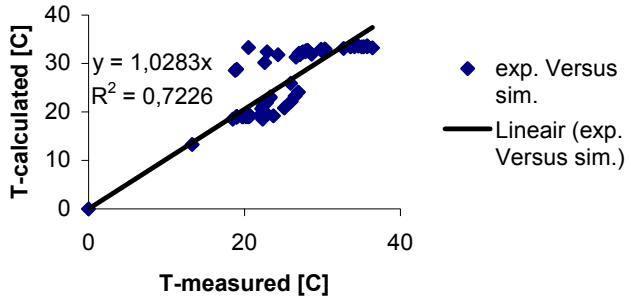
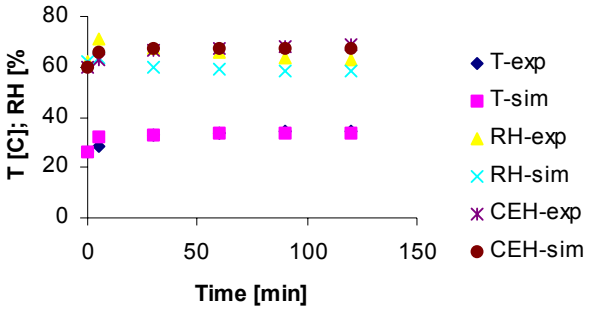


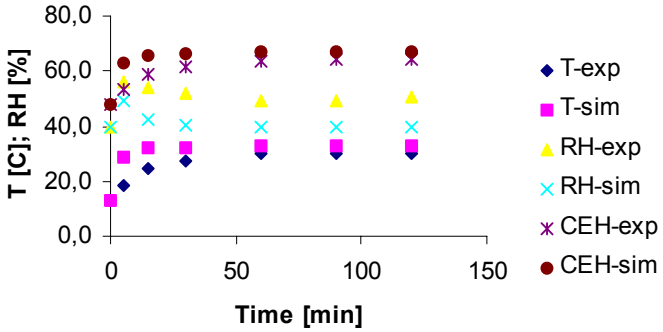
Figure 1. Agreement between experimental and calculated temperatures

The simulated temperatures agreed reasonably with experimental values (R^2 = 0.7, Figure 1). However, for the relative humidity's the agreement was, in general, very poor (R^2 = 0.1). Figures 2a to 2c show the results of simulations pertaining to the experiments of De Boer and Kuller. They measured the temperature and relative humidity directly underneath the ticking at the centre of the occupants back (2a and 2 b) and at 4.5 cm below the surface of the mattress (2c). De Boer and Kuller used a mattress of polyurethane foam with thickness of approximately 12 cm. Directly underneath the

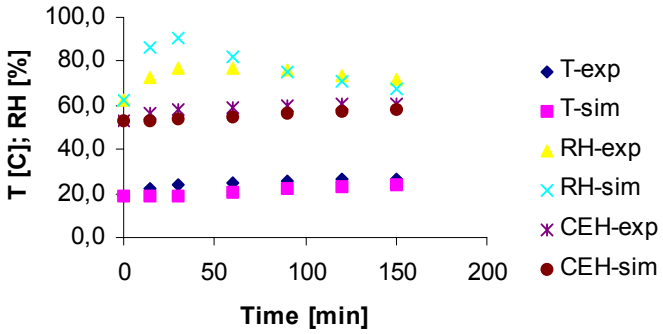
ticking the calculated values of relative humidity were lower than the experimental values. This might be due to the fact that vapour sorption was disregarded in the simple model.



(a)

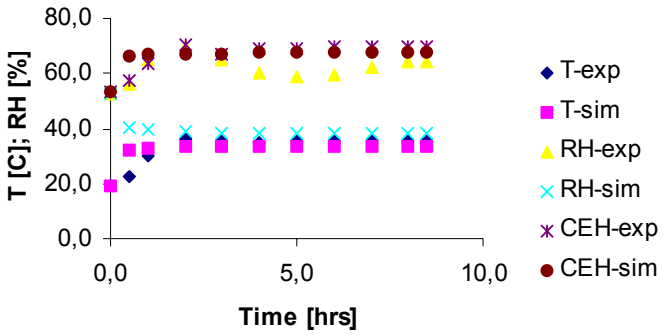


(b)

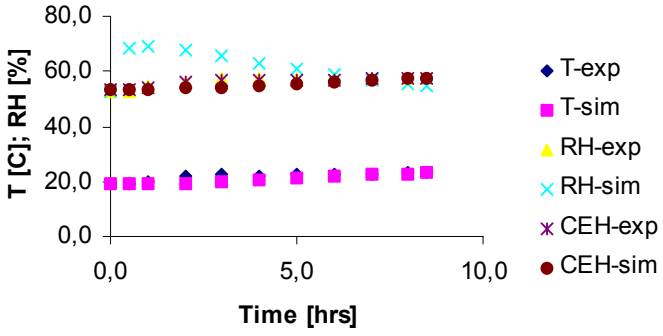


(c)

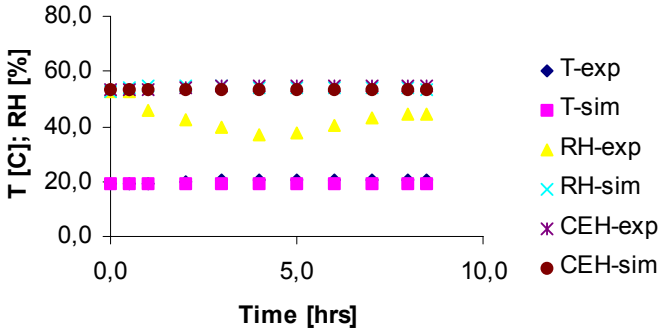
Figure 2. Comparison between measured and simulated levels of the temperature and the relative humidity in the mattress directly underneath the ticking (2a and 2b) and at 4.5 cm below the human body (2c). Experimental results were obtained from De Boer and Kuller (1997)



(a)



(b)



(c)

Figure 3. Measured and simulated levels of the temperatures and the relative humidity in the mattress directly underneath the ticking (3a), in the middle of the mattress, i.e. at 10 cm below the human body (3b) and at 1 cm above the bottom of the mattress (3c). Experimental results were obtained from Pretlove et al. (2001)

At 4.5 cm below the upper surface of the mattress the simulated and experimental RH values followed a similar pattern and the agreement between both values was slightly better. At locations deeper in the mattress the temperature increase was smaller compared to the upper surface. Therefore it can be expected that the effect of vapour sorption was smaller. Experiments and simulations showed that at 4.5 cm below the upper surface the time span with relative humidity above CEH was greater than 2 hours. This indicated an elevated risk on growth of house dust mites. Simulated and experimental values of relative humidity pertaining to the experiments of Pretlove et al. (2001) showed a similar tendency but were more pronounced (Figure 3). In these experiments a mattress with thickness of 20 cm was used.
In general, the simulated temperatures increased more sharply than the experimental values. This might be due to an additional thermal resistance resulting from a reduced contact area between the human body and the surface of the mattress. The contact area between an infant body and a mattress was only 20% of the total infant surface area (Adams et al., 1998). This reduced contact area was not accounted for in the model.

Discussion

Experimental and computational results revealed that humid conditions preferentially occur in the core of the mattress. Since water vapour diffuses much faster than heat, increase of the vapour density in the mattress core will occur prior to the increase of the temperature. As a result, the relative humidity will rise. It is therefore expected that reduction of the thickness of the foam layer will reduce the volume of the mattress with elevated relative humidity and thus reduce the risk on mite growth. This can explain the results of Schei, Hessen and Lund (2002) who reported that spring mattresses had lower mite allergen concentrations than foam mattresses. Spring mattresses are ventilated. A 4 to 6 cm thin layer of foam generally covers the springs. This thin foam layer can dry more easily than the 12 to 20 cm thick foam mattress.

Although there was a reasonable agreement between temperatures calculated by the model and measured temperatures, the model can be further improved. Temperatures measured during the experiments underneath the ticking of the mattress varied between 30 and 36 °C, whereas the skin temperature was approximately 34 °C. Factors that might influence the surface temperature are:

- Individual differences between persons;
- Movement of the human body during sleep;
- Reduced contact area between the body and the mattress.

In the model, however, it is assumed that the occupant does not move at all, lies on his back and covers the mattress completely. In future versions of the model the effect of reduced contact area can be accounted for by introducing an additional thermal resistance between the body and the mattress.

The model performance with respect to prediction of relative humidity levels was poor. Improvement of the model with respect to this parameter has the highest priority. Factors that might influence the vapour balance which were not accounted for in the present model are:

- Variation of the wetness of the human skin. This value varied between 0.06 and 0.3. For average ambient conditions variation between these two limits will result in differences of the vapour density at the skin surface of more than 50%;
- Sorption of water vapour by the ticking and the solid matrix of the mattress may have considerable influence on the results (Ghenaim et al. (2002);
- Mass flow due to pressure differences;
- Diffusion of water vapour driven by temperature differences.

It is expected that incorporation of sorption processes in the model will give an important improvement of the predicted humidity levels.

Conclusions

4. The model presented in this paper gives a reasonable prediction of the spatial and temporal distribution of the temperature in a mattress occupied by a human body.
5. The agreement between model predictions of the relative humidity and experimental data is poor;
6. There is some evidence that a spring mattress with a thin layer of foam has a lower risk on growth of house dust mites than a mattress of foam.

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