INFLUENCE OF VENTILATION IN THE AIR LAYER OF CLOTHING ON HEAT AND MOISTURE TRANSFER AROUND THE HUMAN BODY

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Introduction

In the air layer between the human body and clothing, ventilation with the ambient air occurs through the apertures of clothing such as the collar, sleeve, hem, and pores of the clothing. Measurements of ventilation rate in the air layer have been attempted [1]. However, it is difficult to measure the whole characteristics of the ventilation because the air velocity is generally low and is distributed. From the viewpoint of simulating the thermal comfort of indoor occupants, it is important to quantify the ventilation rate in the air layer of clothing and to evaluate the influence on the thermophysiological responses of the human body. In this study, the transient heat and moisture balance equations for the clothing and human body system [2] were solved coupled with calculation of ventilation rate in the air layer of clothing, and the influence of the ventilation on human body was clarified.

Methods

The target of the calculation was the heat and moisture transfer in and around a Japanese male in his twenties with an average body shape and wearing only a T-shirt. Figure 1 shows a conceptual diagram of the movement of heat and moisture in and around the human body, and the human thermal model used in this study (Stolwijk model) [3]. Here the trunk segment was treated as the covered skin. The calculation was conducted for a given condition with a stepwise change in air temperature and humidity (Figure 2).

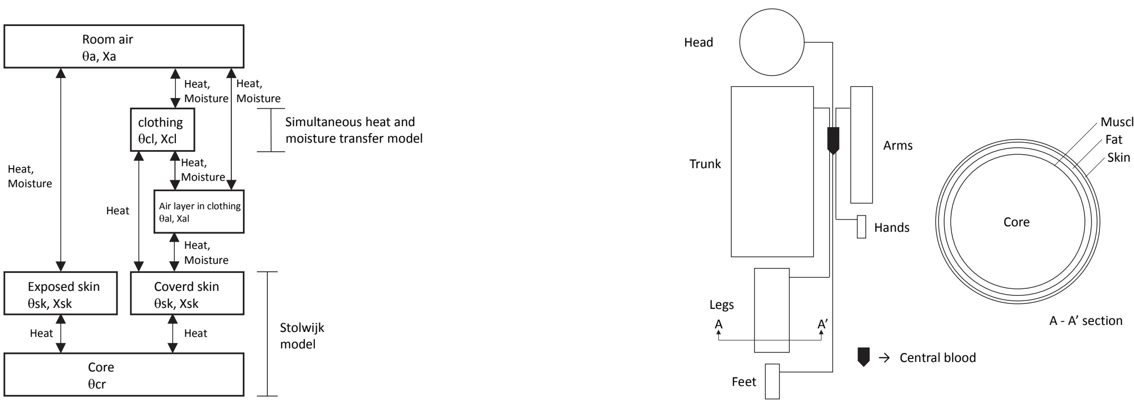


Fig. 1 Conceptual diagram of the heat and moisture transfer models
(left: human body and clothing model, right: Stolwijk model)

Ventilation in the air layer of clothing was expressed by equations (1)-(3). Heat and moisture balance equations for the air layer and the clothing with their boundary conditions were given by equations (4)-(12). A correction coefficient k was introduced to equation (2) to match the ventilation rate calculated by computational fluid dynamics for the target case considering the real shape of the human body [4]. Temperature differences and wind pressure were taken as the forces driving the ventilation. The areas of the apertures at the sleeves, hem, and neck were based on a three-dimensional scan of a real human body and clothing [5]. Permeation of air through pores in the clothing was also considered. The wind pressure coefficient and discharge coefficient of the apertures were determined using computational fluid dynamics to simulate the target conditions [4]. Each aperture was divided into front and back of the human body. The conditions were given in Tables 1-4. Cases of no air flow in the room and those considering air flow from the front wall of the human were calculated.

$$\Delta p_{j,l}(z) = -p_0 - \Delta\rho g z + \frac{1}{2} C \rho_{out} V^2 \tag{1}$$

$$0 = \sum_j k \cdot \mathrm{sign}(\Delta p_j) \cdot \alpha A_j \sqrt{\frac{2|\Delta p_j(z)|}{\rho_{ave}}} + \sum_l k \cdot \mathrm{sign}(\Delta p_l) \cdot \int_0^{Z_h} \frac{|\Delta p_l(z)|}{R} B dZ \tag{2}$$

$$\text{and,} \quad \mathrm{sign}(\Delta p_{j,l}(z)) \equiv \begin{cases} +1, & \Delta p_{j,l}(z) \geq 0 \\ -1, & \Delta p_{j,l}(z) < 0 \end{cases} \tag{3}$$

$$c_a \rho_a V \frac{d\theta_{al}}{dt} = \alpha_{csk}(\theta_{sk} - \theta_{al})S + \alpha_{ci}(\theta_{cl,i} - \theta_{al})S + c_a \rho_a Q_t (\theta_a - \theta_{al}) \tag{4}$$

$$\rho_a V \frac{dX_{al}}{dt} = \alpha'_{sk} (X_{sk} - X_{al})S + \alpha'_i (X_{cl,i} - X_{al})S + \rho_a Q_t (X_a - X_{al}) \tag{5}$$

$$c_{cl} \rho_{cl} \frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}\left(\lambda \frac{\partial \theta}{\partial x}\right) + L \frac{\partial}{\partial x}\left(\lambda' \frac{\partial X}{\partial x}\right) \tag{6}$$

$$\rho_w \frac{\partial w}{\partial t} = \frac{\partial}{\partial x}\left(\lambda' \frac{\partial X}{\partial x}\right) \tag{7}$$

$$w = f(X, \theta) \tag{8}$$

$$-\lambda \left.\frac{\partial \theta}{\partial x}\right|_{s,\ in} = \alpha_{ci}(\theta_{al} - \theta_{cl,i}) + \alpha_{ri}(\theta_{sk} - \theta_{cl,i}) + L\alpha'_i (X_{al} - X_{cl,i}) \tag{9}$$

$$-\lambda' \left.\frac{\partial X}{\partial x}\right|_{s,\ in} = \alpha'_i (X_{al} - X_{cl,i}) \tag{10}$$

$$-\lambda \left.\frac{\partial \theta}{\partial x}\right|_{s,\ out} = (\alpha_{co} + \alpha_{ro})(\theta_{cl,o} - \theta_a) + L\alpha'_o (X_{cl,o} - X_a) \tag{11}$$

$$-\lambda' \left.\frac{\partial X}{\partial x}\right|_{s,\ out} = \alpha'_o (X_{cl,o} - X_a) \tag{12}$$

Symbols Δp: Pressure difference [Pa], p_0: Static pressure at standard level [Pa], $\Delta\rho$: Difference in density between inner and outer air volumes [kg/m³], g: Gravity acceleration [m/s²], z: Vertical coordinate [m], C: Wind pressure coefficient [-], ρ_{ave}: Average density of air in and out of the air layer [kg/m³], V: Wind velocity [m/s], Q_t: Ventilation rate [m³/s], k: Correction coefficient [-], α: Discharge coefficient [-], A_j: Area of aperture [m²], Z_h: Height of shirt [m], R: Air resistance [Pa・s/m], B: Width of aperture [m], H: Height of aperture [m], c: Specific heat [J/kg/K], V: Volume of air layer in clothing [m³], θ: Temperature [°C], t: Time [s], S: Surface area [m²], X: Absolute humidity [kg/kg'], α_c: Convective heat transfer coefficient [W/m²/K], α_r: Radiative heat transfer coefficient [W/m²/K], α': Moisture transfer coefficient [kg/m²/s/(kg/kg')], λ: Thermal conductivity [W/m/K], L: Latent heat [J/kg], λ': Moisture conductivity [kg/m/s/(kg/kg')], w: Volumetric moisture content [m³/m³]

Subscripts j: Number of apertures with infinitesimal height , l: Number of apertures as porous media , in: Inner side of clothing, out: Outer side of clothing, a: Room air, al: Air layer in clothing, sk: Skin, cl: Clothing, w: Water

Table 1. Cases of calculation

	Wind velocity (m/s)	Correction coefficient	Ventilation
Case 1 (no wind)	0	0.08	Considered
Case 2 (no wind)			Not considered
Case 3 (wind from front)	0.5	0.28	Considered
Case 4 (wind from front)			Not considered

Table 2. Parameters used in calculation

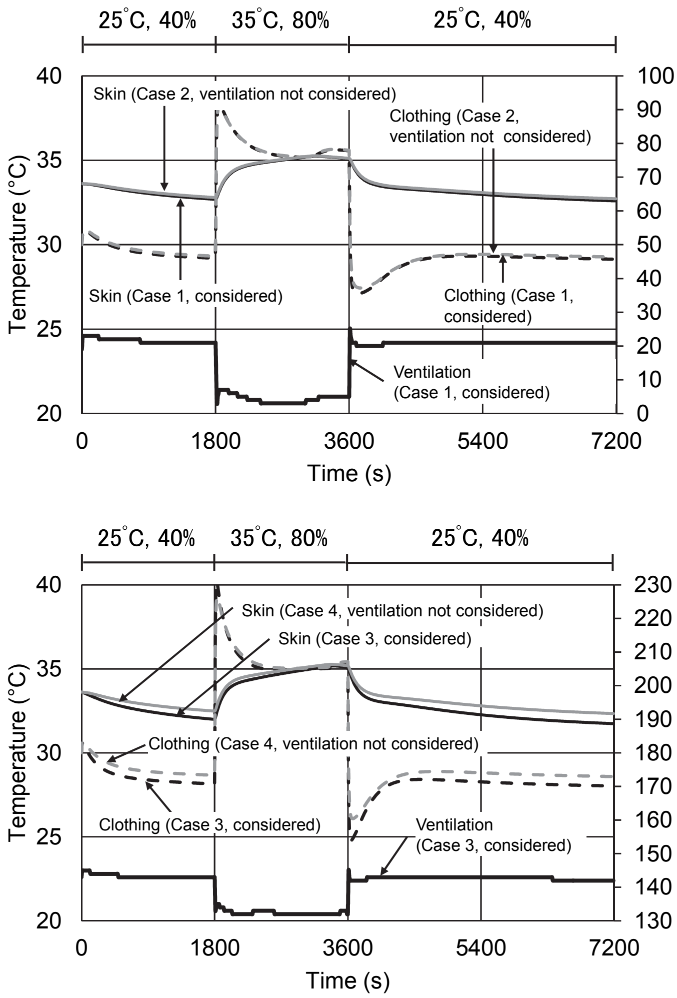
λ (clothing) [W/m/K]	5.6×10^{-2}	ρ (clothing) [kg/m³]	3.5×10^{2}	c (air) [J/kg/K]	1.0×10^{3}
λ' (clothing) [kg/m/s/(kg/kg')]	6.5×10^{-7}	d (clothing) [m]	5.0×10^{-4}	L [J/kg]	2.5×10^{6}
c (clothing) [J/kg/K]	1.4×10^{3}	S (clothing) [m²]	7.0×10^{-1}	V [m³]	8.0×10^{-3}

Table. 3 Parameters related to calculation of ventilation rate

Aperture	Hem		Sleeve		Collar		Pores of clothing	
Position	Front	Back	Front	Back	Front	Back	Front	Back
k	(Wind velocity 0.0m/s) 0.08 , (Wind velocity 0.5m/s) 0.28							
α	0.6							
R [Pa･s/m]							249	
H [m]	0		0.4		0.6		0 - 0.6	
S [m^2]	1.5×10^{-2}	1.2×10^{-2}	6.8×10^{-4}	8.1×10^{-3}	1.3×10^{-3}	6.3×10^{-4}	2.8×10^{-1}	4.4×10^{-1}
C	0.63	-1.08	0.64	-0.33	0.62	-0.60	0.71	-0.74

Table. 4 Heat and moisture transfer coefficient

	Covered skin, Clothing inner side	Exposed skin, Clothing outer side
α_c [W/m^2/K]	10.0	(Wind velocity 0.0 m/s) 3.1 (Wind velocity 0.5 m/s) 5.5
α_r [W/m^2/K]	4.65	4.65
α' [kg/m^2/s/(kg/kg')]	0.01	(Wind velocity 0.0 m/s) 0.0031 (Wind velocity 0.5 m/s) 0.0055



(a) Cases of no wind

(b) Cases of wind from the front

Fig 2. Calculated skin and clothing temperatures and ventilation rate

Results

The ventilation rate was lower in the high temperature condition than in the low temperature condition because the difference between the room air and skin temperatures was small (Fig. 2). The clothing temperature rise at 1800 seconds was due to the absorption of moisture, and that at 3000 seconds was due to the onset of sweating. At 3000 seconds, the skin temperature was decreased by sweat evaporation. The ventilation rate in the case with wind (Case 3) was larger than that in the case without wind (Case1), and the skin and the clothing temperature was lower. In the cases without wind, the difference between Case 1 (with ventilation) and Case 2 (without ventilation) was small. In contrast, in the cases with wind the difference between Case 3 (with ventilation) and Case 4 (without ventilation) was as high as 0.6°C. The variation in the ventilation rate due to the temperature difference between the air layer in the clothing and in the room had no significant influence on the skin temperature.

Conclusions

The influence of the ventilation rate in the air layer on skin temperature was negligible under natural convection, whereas when there was a wind of 0.5 m/s from the front of the human subject, a 0.6 °C difference in skin temperature was observed. The variation in the ventilation rate caused by stepwise changes in the temperature difference between the air layer and the ambient air had no significant influence on skin temperature.

Acknowledgements

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