A Numerical Study on the Heat Loss from Clothed Humans
—Effects of Air Space and Clothing Properties

Qingrong Bo and Tsuyoshi Nakajima

Department of Mechanical Engineering, Kobe University,
Rokkodai, Nada-ku, Kobe 657–8501, Japan

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Abstract

This paper presents a numerical model of heat transfer and fluid flow in the air space formed between
the human body (modeled as a horizontal cylinder) and clothing (modeled as porous media). Factors that af-
ect heat transfer and fluid flow in the air space are the thickness of the space between the body and clothing,
and properties of the clothing, such as porosity or air flow resistance. Several clothing parameters are used to
approximate various types of fabric. A critical air-space thickness at which the clothing retains the most heat
was identified and found to be a function of the environmental temperature. The simulation results showed
that the porosity of the clothing had little effect on the heat transfer. As the air flow resistance of the clothing
decreased, the heat flux from the body increased. An approximate formula for the mean Nusselt number of a
clothed human body was determined. The results showed that a circulating flow was present in the air space.

Key words: clothed human, microclimate, heat loss, porosity, air flow resistance

1. Introduction

The thermal comfort of a clothed human is becoming
more important with recent developments in sci-
ence and technology, both in everyday life and under
special environmental conditions, such as working in
the deep sea or living in a spaceship (Fu, 1995). In
the heating, ventilating, and air conditioning (HVAC)
design industry, thermal comfort during transient con-
ditions is of interest; thus, steady state information
predicted by numerical solution is of importance
(Gagge, et al., 1971; Nunson and Hayter, 1978; Bore-
gowda, et al., 1997).

Thermal comfort is determined by factors internal
and external to the human body. The internal factors
consist of thermoregulatory and physiological vari-
ables. The thermoregulatory system is the psycho-
physiological system responsible for maintaining the
core temperature at a normal level by enhancing or
inhibiting heat production and heat loss. Physiologi-
cal responses relate the thermal comfort of the
human body to the surroundings. External factors in-
clude the temperature and humidity of the environ-
ment, and properties of the clothing. It is well known
that clothing plays an important role in separating the
human body from the environment and aiding in the
maintenance of thermal comfort. When a person
wears clothing, a small air space is formed between
the skin and the textile layer. Temperature, humidity
and fluid flow contribute to the characteristics of a
“microclimate” within this airspace. The microcli-
mate directly affects the comfort of the wearer. A mi-
icroclimate with an air speed of 25±15 cm/sec, tem-
perature of 32±1°C, and humidity of 50±10% RH
provides the most comfort to Japanese people (Japan

Many mathematical thermal models have been pre-
sented over the past five decades of human ther-
moregulation studies. Some well-known thermal
models developed during this period are the Pennes
(1948), Gagge (1971), and Wissler (1964) models.
These models have their own limitations in terms of
computational efficiency, and in their control equa-
tions that represent the integration processes of the
human thermoregulatory system. More recently, com-
prehensive three-dimensional thermal models for an
unclothed body were constructed by Smith (1991).
To observe the effects of clothing, Jones et al. (1992)
developed another unsteady-state thermal model for
the whole clothing system. Takemori (1995) added an
arteriovenous anastomosed (AVA) model and a dual
vascular network to Smith's model to simulate vaso-
motor control of the capillaries. Fu (1995) incorpo-
rated a clothing model into Smith's model (1991) to
develop a transient three-dimensional thermal model
for a clothed human. However, in these models, the fluid flow around the human body was not accommodated, even though it is one of the most essential factors influencing the comfort of humans.

This paper presents research into the influential factors that affect the thermal comfort of a clothed human body from the viewpoint of fluid dynamics, and aims to provide comfort indices in a uniform static environment. The paper concentrates on the influence on heat loss and fluid flow of the air-to-skin temperature, and the environmental temperature. The body was modeled as a cylinder enclosed by clothing, and the clothing was considered to be a porous medium.

2. Analysis

The geometrical system under study consists of a horizontal cylinder of radius \( r \) enclosed by porous media, as shown and labeled clothing in Fig. 1(a). The cylinder is assumed to be at a constant temperature \( T_{\text{skin}} \). Because of the symmetry of the velocity and temperature profiles with respect to the central perpendicular line of the cylinder, only the region between \( 0 \leq x \leq x_1 \) and \( -x_1 \leq y \leq x_1 \) is considered.

2.1. Mathematical formulation

The air flow is assumed to be steady, laminar, incompressible, and two-dimensional. The thermophysical properties of fluid and the effective properties of the porous media are assumed constant, except for the density in the buoyancy term of the momentum equations that is obtained from the Boussinesq approximation (Arakawa, 1994). Moreover, the porous media are considered to be homogeneous and isotropic, with constant thermodynamic properties. The viscosity and density of the porous media are the same as those of a fluid. An effective thermal conductivity is used for the porous media heat transfer calculations. With the foregoing assumptions, the governing equations for the fluid are as follows.

Continuity equation:
\[
\nabla \cdot U = 0
\]

(1)

Momentum equation:
\[
\rho(U \cdot \nabla)U = -\nabla P + \nabla \cdot (\mu \nabla U) + \rho \beta \nabla (T - T_0)
\]

(2)

Energy equation:
\[
\rho c_p (U \cdot \nabla T) = \nabla \cdot (\kappa \nabla T)
\]

(3)

where \( \rho \) = density of the fluid, \( c_p \) = specific heat of the fluid, \( \kappa \) = thermal conductivity of the fluid and \( \beta \) = thermal expansion coefficient of the fluid. In the above equations, \( U = (u, v) \), \( T \), and \( P \) are the velocity vector, temperature and pressure in the fluid.

The conservation equations for the porous layer are based on Darcy’s law (Johnson, 1998). The governing equations for the porous media are:
\[
\nabla \cdot (K \cdot U) = 0
\]

(4)

\[
U = -R_e^{-1} \cdot \nabla P
\]

(5)

\[
\rho c_p \nabla \cdot (K \cdot U T) - \nabla \cdot (\Gamma_e K \cdot \nabla T) = \gamma Q
\]

(6)

where \( K \) = permeability, \( R_e \) = resistance constant to flow in the porous medium, \( \gamma \) = porosity of porous media, \( \Gamma_e \) = effective thermal conductivity and \( Q \) = heat source to or from the porous media. The effective thermal conductivity was calculated from the empirical relationship (Combarnous and Bories, 1975)
\[
\Gamma_e = k_{e} f (\gamma^{(1-\gamma)})
\]

(7)

where \( k_{e} \) is the thermal conductivity of solid matrix and \( \gamma \) is the porosity of porous media.

2.2. Numerical procedure

The conservation equations (1)-(6) were solved numerically using the iterative SIMPLER algorithm (Patankar, 1980) with an open boundary condition (Leone, 1990). This algorithm is based on a control-volume formulation (Patankar, 1980), which ensures the continuity of mass, momentum and heat fluxes across the control surfaces. In order to accelerate the convergence of the solver, the false time step method was used as an under-relaxation factor.

The computational domain, shown in Fig. 1(a), was divided into three regions according to the three outer sides of the boundary. A radial-type mesh was used for each region. The angular grid lines were spaced every 1.73°. The radial mesh number was 88 between \( -0.05 \leq y \leq -0.094 \) for region 1, the grading factor was 80 (i.e., the ratio of the first element width to the last element width on a radial line segment was 80). The radial meshes for the other two regions were the same as in region 1. The computational meshes are shown in Fig. 1(b). Grids of \( 26 \times 185 \), \( 52 \times 185 \), and \( 26 \times 185 \) nodal points were used to cover a 0.5 m × 1 m domain in each region.

3. Results and Discussion

3.1. Comparison with empirical formula

Buoyancy-induced natural convection around a horizontal cylinder was analyzed and the results were compared with empirical formula published in JSME (1993) to verify the accuracy of the computations. The empirical formula was expressed by the following formulas.
\[ \frac{2}{\text{Nu}_d} = \ln \left( 1 + \frac{2.475}{C_i \text{Ra}_d^n} \right) \quad (10^{-3} \leq \text{Ra}_d \leq 5 \times 10^6) \quad (8) \]

\[ \text{Nu}_d = 1.03 C_i \text{Ra}_d^{1/4} \quad (5 \times 10^6 < \text{Ra}_d < 10^9) \quad (9) \]

where

\[ n = \frac{1}{4} + \frac{1}{10 + 5 \text{Ra}_d^{0.175}} \quad \text{and} \]

\[ C_i = 3 \left( \frac{\text{Pr}}{2.4 + 4.9 \sqrt{\text{Pr} + 5 \text{Pr}}} \right)^{0.25} \]

Here, \( \text{Nu}_d \) = Nusselt number, \( \text{Ra}_d \) = Rayleigh number, and \( \text{Pr} \) = Prandtl number.

The numerical simulation results were obtained based on a cylinder diameter of 0.1 m and a temperature of 32°C. Figure 2 shows that the numerical mean Nusselt number agreed well with the published empirical formula for ambient temperatures ranging from 2°C to 25°C, especially for higher ambient temperatures. This fact indicates that the mesh size, computational domain size, and solution method are appropriate for further simulations and analyses.

### 3.2. Effect of the air-space thickness

In the following simulations, the temperature and diameter of the cylinder were set to 32.5°C and 0.1 m, respectively, while the thickness of clothing was maintained at 1 mm.

Figure 3 illustrates the variation of the mean heat flux released from the body at an ambient temperature of 22°C for different air-space thicknesses. The air-space thickness was incremented at 5 mm intervals from 5 to 30 mm. The porosity and air flow resistance of the clothing remained constant at 0.85 and 0.2 kPa s m\(^{-1}\), respectively. As the air-space thickness (denoted by \( L \)) increased, the mean heat flux decreased until \( L = 15 \) mm. Further increases in the air-space thickness caused the mean heat flux to also increase. This is because increasing the thickness of the air space beyond a critical thickness (15 mm in this case) reduces thermal resistance by increasing losses.
due to convection (Cain and Farnworth, 1986; Wilson, 1999). Physically, the air-space thickness refers to the air layer between the body and the clothing. Since the thermal conductivity of air is low, the heat flux released from the body decreases with increasing air-layer thickness. However, when the thickness increases beyond a critical value, natural convection occurs and the heat flux from the body increases. Therefore, clothing has the best heat preservation characteristics when the air-space thickness is at the critical value. Cain and Farnworth (1986) reported that the onset of convection occurred with an air-space thickness of 13 mm, similar to the numerical result reported here. According to the Simulation results in this study, a circulating flow is formed in the air space, as shown in Fig. 4.

3.3. Effects of porosity and air flow resistance of clothing

The porosity and air flow resistance of the modeled clothing was altered to approximate different clothing types, while the environmental temperature was maintained at 22°C to investigate the influences of clothing properties on human comfort. The porosity of clothing ranged from 0.8 to 0.95 (Yoshida et al., 1993) and the air flow resistance ranged from 0.01 to 1.0 kPa s m$^{-1}$ (Nakanishi and Niwa, 1989). The effects of the porosity and air flow resistance for different air-space thicknesses are shown in Figs. 5–7.

Figure 5 illustrates the effect of the porosity for air-space thicknesses of 5, 15, and 25 mm. The air flow resistance was maintained at 0.2 kPa s m$^{-1}$ for each simulation. The mean heat flux is independent of the porosity of the clothing when the air-space thickness is constant. However, no matter which porosity value is used, the mean heat flux is at a minimum when the air-space thickness is 15 mm. Figures 6 and 7 show that the heat flux decreases with increased air flow resistance of clothing. This means that the greater the air flow resistance of clothing, the less heat is lost from the body.

From Figs. 5 to 7, it is evident that, irrespective of porosity and air flow resistance levels, when the environmental temperature is 22°C, the mean heat flux from the body is lowest when the air-space thickness is 15 mm. Thus, the clothing retains the most heat with a 15-mm-thick air layer, since then conduction alone acts in the air space. Both conduction and natural convection processes are present in air-space thicknesses exceeding 15 mm.

3.4. Effect of environmental temperature

The environmental temperature was varied between 22°C and 31°C in increments of 3°C while the skin temperature was kept constant at 32.5°C, to investigate the effect of the environmental temperature on heat loss. Figure 8 gives profiles of the mean heat flux for different ambient temperatures. The air-space thickness at which the mean heat flux is at a minimum increases with the environmental temperature. When the environmental temperature is 22°C, a minimum heat flux is obtained for a 15-mm-thick air space; for an environmental temperature of 25°C or 28°C, the minimum mean heat flux is for a 20-mm-
thick air space. This further increases to 25 mm for an environmental temperature of 31°C. Thus, the air-space thickness at which the clothing has the best heat preservation characteristics increases with increasing environmental temperature. However, the higher the environmental temperature, the lower the mean heat flux from the body.

4. Mean Nusselt Number Formula

A correlating relation was formulated for the mean Nusselt number in terms of the cylinder diameter, temperature difference between the cylinder and the environment, air flow resistance of the clothing and air-space thickness:

$$\text{Nu}_m = (10.0 \cdot d)^{1.07} \cdot (\Delta T/10.5)^{0.27} \cdot [a + (13.36 - a)^{-8.0} \cdot R]$$  (10)

where

$$a = 7.5 \cdot (d/0.01)^{0.6} \cdot \exp(-0.1032 \cdot L) \cdot \sin(L/10.27 + 0.4589 \cdot \ln(\Delta T)/-17.63) + 6.002$$

Here, $d$ is the diameter of the cylinder, ranging between 0.1 and 0.2 m, $\Delta T$ is the temperature difference between the cylinder and environment, ranging from 3.5 to 10.5°C, $L$ is air-space thickness between 5 and 30 mm, and $R$ is the air flow resistance of clothing, ranging from 0.01 to 1.0 kPa s m$^{-1}$. The air flow resistance is expressed as

$$R = R_c \cdot \Delta c$$  (11)

where $R_c$ is a air flow resistance constant with units of kg m$^{-3}$ s$^{-1}$, and $\Delta c$ is the thickness of the clothing.
with units of m.

The deviation between the formula (10) and the numerical results of the simulations is shown in Fig. 9. For these numerical simulations, the cylinder and environmental temperatures were 32.5°C and 22°C, the diameter of the cylinder was 0.1 m, and the clothing porosity and air flow resistance were 0.85 and 0.2 kPa s m$^{-1}$. In this case, the maximum relative deviation was 2.72%. The maximum deviation between the approximate formula and the numerical calculation results was less than 11% for all of the investigated cases.

5. Conclusions

A numerical study of the heat transfer and fluid flow around a human body was performed. A horizontal cylinder surrounded by a porous medium was used to approximate a part of the body surrounded by a layer of clothing. In this paper, the influence of the air-space thickness and clothing factors such as porosity and air flow resistance on the heat loss from the body were investigated. The results show that 1) the heat flux was at a minimum at a critical value of air-space thickness for a given environmental temperature, no matter which clothing porosity or air flow resistance values were used; 2) the value of the air-space thickness that gives the minimum heat flux increases with the environmental temperature between 22 and 31°C; 3) the porosity of the clothing had little effect on the heat transfer; 4) the heat flux increased as the air flow resistance of the clothing decreased; and 5) the mean heat flux decreased with increasing environmental temperature. In addition, a relation was formulated to estimate the mean Nusselt number as a function of the cylinder diameter, temperature difference between the body and the environment, air flow resistance of the clothing and air-space thickness.

References