CONVECTIVE HEAT TRANSFER FROM HEAD AND ARMS

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Introduction

The convective heat exchange between head and arms and their environment has aroused interest amongst engineers, see Cena (1981) and Clary (1975). When people stay indoors, their heads and arms are often bare, sometimes even when they were outside. Although the surface areas of the head and arms are not too large, the total heat losses from these segments can be quite significant when they are bare.

Because the air velocity is relatively low in air conditioned rooms, the affect of free and forced convective heat transfer should be considered together. Unfortunately, there are few formulae describing this common affect. Usually, formulae describe free convective and forced convective heat transfer separately, the convective heat transfer coefficient is not continuous for the whole range of air velocity, see Rapp (1973). This does not confirm to reality for the low air velocity. However some empirical correlations have been made, see Nishi (1970), of the interaction between free and forced convective heat transfer.

This paper reports on a series of experiments which have been carried out to obtain the convective heat transfer coefficients at various air velocities and with varying temperature differences between the skin and air. A new type of interpolation equation of the interaction mentioned above has been used for the head and arms.

Measusements

A nude full-scale manikin was used, see Fig.1 from Johansson et al (1987) and Wang (1990).

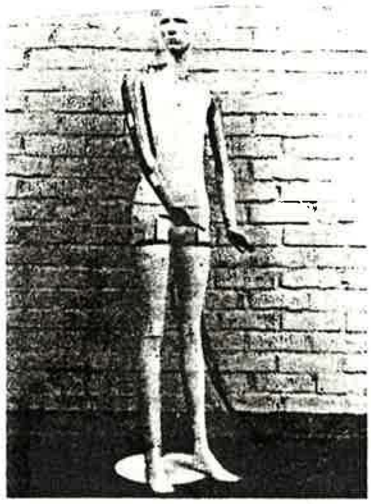

Fig. 1. Thermal manikin.

The manikin was divided into seven segments, e.g. head, trunk, arms, hands, thighs, legs and feet. Every segment had an individual electric heating circuit. Seven electric transformers were used to create different skin temperatures. During the measurement, the manikin was placed in the wind tunnel, and it was illustrated in Fig. 2.

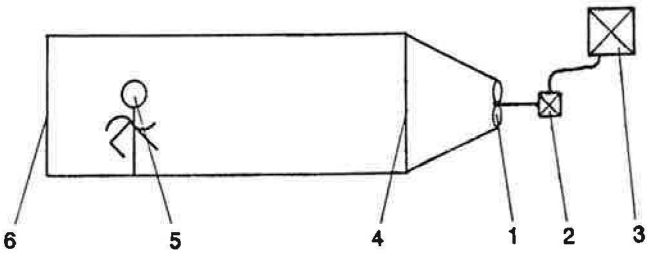

Fig. 2. Wind tunnel.

1. axial fan	2. electric motor
3. frequency converter	4. preforated plate
5. thermal manikin	6. clothing curtain.

The cross-section of wind tunnel was 2 × 1,2 m. The distribution of the air velocity was not uniform through the cross-section, see Yu (1984). The velocities near every segment of the manikin were measured in 5 to 7 points. An average velocity was taken for every segment. And a frequency converter was used to vary the air velocity. In order to simplify the calculation, a clothing curtain was used to form an enclosed space in the wind tunnel. For more details on the method of measurement, see Wang (1990).

Calculations and results

For every segment, the heat production, Q, is equal to the heat losses, i.e. to the heat losses by convection and radiation.

$$Q = \alpha_c \cdot (\theta_s - \theta_a) \cdot A + \sigma \cdot \varepsilon \cdot \phi \cdot A \cdot (T_s^4 - T_r^4) \quad (1)$$

where

Q	is the heat production which is equal to electric power, W
α_c	is the convective heat transfer coefficient , $W/m^2 \cdot °C$
θ_s	is the mean segment surface temperature, °C
θ_a	is the air temperature, °C
T_s	is the mean segment tempearture, K
T_r	is the mean radiant temperature, K
σ	is the Stefan-Boltzmann constant $=5,67 \times 10^{-8}$ $W/m^2 \cdot K^4$
A	is the surface area, m^2
ε	is the emissivity of the surface
ϕ	is the effective radiation area factor.

Equation (1) can be rewritten to give the convective heat transfer coefficient as:

$$\alpha_c = (Q - \sigma \cdot \varepsilon \cdot \phi \cdot A \cdot (T_s^4 - T_r^4)) / (\alpha_c \cdot \Delta\theta_{s-a} \cdot A) \quad (2)$$

For more details on the calculations, see Wang (1990). From the experimental data, the α_c value can be easily computed. The results are given in Tables 1 and 2.

Table 1. Air velocity, m/s, temperature difference, °C, and convective heat transfer coefficients for head, $W/m^2 \cdot °C$.

v = 0,75	$\Delta\theta_{s-a}$	10,2	13,2	16,8	13,6	18,8			
(m/s)	α_c	8,5	8,7	8,7	8,6	8,8			
v = 0,55	$\Delta\theta_{s-a}$	12,4	15,7	18,8	14,1	17,5			
	α_c	9,1	9,1	9,3	9,2	9,1			
v = 0,20	$\Delta\theta_{s-a}$	24,4	9,9	14,1	17,9	7,1	20,4	22,6	25,3
	α_c	5,1	5,0	5,3	5,2	4,9	5,2	5,1	5,2
v = 0,31	$\Delta\theta_{s-a}$	12,9	14,5	16,3	18,1	20,1			
	α_c	5,8	6,0	5,9	6,2	6,1			
v = 0,08	$\Delta\theta_{s-a}$	12,6	13,4	22,7	27,3	30,8	20,4		
	α_c	2,8	2,4	2,6	2,7	2,6	1,9		
v = 0,44	$\Delta\theta_{s-a}$	8,9	10,9	13,7	17,6	22,0			
	α_c	7,3	7,6	7,9	7,6	7,7			

Table 2. Air velocity, m/s, temperature difference, °C, and convective heat transfer coefficients for arms, $W/m^2 \cdot °C$.

v = 1,07	$\Delta\theta_{s-a}$	3,9	5,3	6,6	8,5	2,5	3,7	6,8	9,5
	α_c	14,9	16,1	16,4	16,2	16,6	16,0	16,3	16,3
v = 0,80	$\Delta\theta_{s-a}$	2,6	4,0	5,1	6,9	8,4	10,6	7,5	9,5
	α_c	15,1	14,0	15,6	14,9	14,8	14,7	15,7	15,5
v = 0,40	$\Delta\theta_{s-a}$	13,7	5,3	7,4	9,8	3,8	11,0	12,3	8,4
	α_c	9,4	9,5	9,8	9,7	9,8	9,7	9,4	9,5
v = 0,47	$\Delta\theta_{s-a}$	12,1	5,4	6,9	8,0	9,2	9,7	11,3	
	α_c	10,7	10,2	10,1	10,4	10,4	11,4	10,4	
v = 0,14	$\Delta\theta_{s-a}$	4,6	6,7	9,0	12,0	13,9	15,7	17,3	
	α_c	6,7	6,5	7,2	6,9	7,1	7,1	7,2	
v = 0,68	$\Delta\theta_{s-a}$	3,6	4,6	6,0	7,9	9,9	12,2		
	α_c	10,9	12,1	12,8	13,0	12,7	12,8		

When the air velocity is equal to zero or very small, i.e. $v < 0,15$ m/s, the convective heat loss only depands on free convection. Conversely, when the air velocity is very large, a forced convection situation exists. Between these two velocities, there is an interaction between free and forced convection. Considering this situation, the following type of interpolation equation is used

$$\alpha_c = (\alpha_{cfree}{}^n + \alpha_{cforced}{}^n)^{1/n} \qquad (3)$$

where

α_{cfree} is the pure free convective heat transfer coefficient, W/m2·°C

$\alpha_{cforced}$ is the pure forced convective heat transfer coefficient, W/m2·°C.

$$\alpha_{cfree} = A \cdot \Delta\theta_{s\text{-}a}{}^{m_1} \qquad (4)$$

The coefficient A and exponent m_1 are taken from Wang (1990)

for head $A = 1,26$ $m_1 = 0,275$
for arms $A = 2,70$ $m_1 = 0,278$

For the pure forced convective heat transfer coefficient

$$\alpha_{cforced} = B \cdot v^{m_2} \qquad (5)$$

Equations (3) to (5) can be re-arranged to give

$$\alpha_c{}^n = (A \cdot \Delta\theta_{s\text{-}a}{}^{m_1})^n + (B \cdot v^{m_2})^n \qquad (6)$$

For a certain air velocity v, this gives

$$(B \cdot v^{m_2})^n = \text{Const} \qquad (7)$$

Hence equation (6) becomes

$$\alpha_c{}^n = (A \cdot \Delta\theta_{s\text{-}a}{}^{m_1})^n + C \qquad (8)$$

Introducing

$$Y = \alpha_c{}^n \qquad (9)$$

$$X = \Delta\theta_{s\text{-}a}{}^{m_1 n} \qquad (10)$$

$$D = A^n \qquad (11)$$

and combining equations (8) to (11) give

$$Y = D \cdot X + C \qquad (12)$$

In order to get coefficients C and D, the multiply linear regression analysis is employed. Equation (9) gives

$$f(X) = \sum_{i=1}^{k} (Y_i - D \cdot X_i - C)^2 \qquad (13)$$

where

k is the number of experiments for a certain velocity
X_i, Y_i are the experimental values.

For a certain exponent n, if $\frac{\partial f}{\partial C} = 0$, a better correlation equation can be obtained. And the most suitable exponent n is the one which gives the minimum mean square errors, see Table 3.

Table 3. Mean square relative errors for different exponents.

Body segment	Exponent, n				
	1	1,5	2,0	2,5	3,0
Head	0,028	0,023	0,022	0,022	0,023
Arms	0,028	0,021	0,020	0,021	0,022

From Table 3, it can be seen that when the exponent n is equal to 2, the mean square relative errors are at minimum. This value was chosen for following calculation.

In order to get better values for B and m_2 equation (7) can be rewritten as

$$\ln C = n \cdot \ln B + m_2 \cdot n \cdot \ln v \qquad (14)$$

For a certain air velocity, the calculated C values are shown in Tables 4 and 5 for the case when the exponent n is equal to 2.

Table 4. C values for different air velocities for the head, n =2.

v, m/s	0,75	0,55	0,20	0,31	0,44
C	69,17	77,33	19,22	29,09	51,71

Table 5. C values for different air velocities for the arms, n = 2.

v, m/s	1,07	0,80	0,40	0,47	0,14	0,68
C	243,8	209,7	66,1	83,9	21,6	138,9

Introducing

$$Z = \ln C \qquad (15)$$

$$W = n \cdot \ln v \qquad (16)$$

$$E = n \cdot \ln B \qquad (17)$$

and combining equation (14) to (17) give

$$Z = m_2 \cdot W + E \qquad (18)$$

Using multiply-linear regression analysis, it is possible to calculate m_2 and E. The results are given as

for the head

$$\alpha_{cforced} = 10{,}815 v^{0{,}55} \qquad (19a)$$

for the arms

$$\alpha_{cforced} = 15{,}23 v^{0{,}619} \qquad (19b)$$

The correlation equations of the convective heat transfer coefficient are

for the head

$$\alpha_c = \sqrt{1{,}59 \Delta\theta_{s\text{-}a}^{0{,}45} + 116{,}96 v^{1{,}10}} \qquad (20a)$$

for the arms

$$\alpha_c = \sqrt{7{,}29 \Delta\theta_{s\text{-}a}^{0{,}556} + 233{,}95 v^{1{,}238}} \qquad (20b)$$

Discussion

Free convective heat transfer coefficients have been disscussed in Wang (1990). A head and an arm can be approximated to a sphere and a cyclinder. An review of the convective heat transfer literature shows that the coefficients B and m_2 usually fall in the following ranges

$$10 < B < 20 \text{ and } 0{,}4 < m_2 < 0{,}7$$