INFLUENCE OF EMISSIVITY CHANGES ON THE BLOOD FLOW RATE DETERMINED ON THE BASIS OF HEAT BALANCE EQUATION

Marek Jasiński

Department of Strength of Materials and Computational Machanics
Silesian University of Technology, Gliwice, Poland, marek.jasinski@polsl.pl

Abstract. The changes of human skin emissivity with regard to the skin and ambient temperature are discussed. The concept of body heat balance equation is used to evaluate of blood flow rate. In order to determine the influence of variations of emissivity on radiative heat transfer and blood flow rate value the direct approach of sensitivity analysis is applied.

Introduction

The body heat balance equation (HBE) [1, 2] describes the equilibrium between various factors influencing on the thermal state of human body. It contains the parts associated with the phenomena of radiation, evaporation, air convection, perfusion, metabolism and body conduction. One of the most important applications of the HBE is determination of thermophysical parameters of the human body [1].

In the last decade the concept of HBE is often used in biometrics, especially in combination with the IR thermography in order to develop the facial recognition system [1]. On account of that humans are homoiotherm most of those systems bases on determination of blood perfusion (or blood vessels) distribution [1] - it is well-know that the thermal pattern of face is determined by its vascular structure, which is unique. Moreover IR images are almost invariant with make up or facial expression.

The blood perfusion data on the basis of the IR thermography are usually obtained under the following assumption [1]:

1. The temperature of body core is constant and the thermal regulation of body (e.g. sweating) is not considered.
2. The ambient temperature is lower than the skin temperature.
3. Pathological and psychological conditions as: fever, headache, inflammation, anger, blush are not considered.

The estimation of blood perfusion (or another parameter) requires to assume the exact values of several parameters, from which some are dependent on environmental conditions (e.g. temperature, humidity).

In this paper the changes of human skin emissivity due to skin and ambient temperature and their influence on the evaluation of blood flow rate are considered.

1. Emissivity of human skin

The emissivity of human skin ε is usually assumed as a near unity [1-3]. The most frequent reported values are 0.99 or 0.98. Those values correspond to the skin in "normal conditions", that means without any injuries or dirtiness. Moreover, in the visible spectrum of light the emissivity is independent of pigmentation of skin.

In the case when there are sweat, grease or wounds on the skin (that is in so called "hospital conditions") the skin emissivity could change its value. Denoting skin temperature as T_s [K] and reading/ambient temperature as T_{amb} [K] the evaluation of emissivity basis on relation [3]

$$\Delta T = T_s - T_{amb} = T_{amb}\left(\sqrt[4]{\frac{1}{\varepsilon}} - 1\right) \tag{1}$$

and then

$$\varepsilon = \left(\frac{T_{amb}}{\Delta T + T_{amb}}\right)^4 = \left(\frac{T_{amb}}{T_s}\right)^4 \tag{2}$$

According to the assumption 2 the equation (2) is true only when $T_{amb} < T_s$.

Table 1

Emissivity of human skin

T_s [°C]	T_{amb} [°C]						
	24	23	22	21	20	19	18
25	0.987	0.973	0.960	0.947	0.935	0.922	0.909
26	0.974	0.960	0.948	0.935	0.922	0.910	0.897
27	0.961	0.948	0.935	0.922	0.910	0.898	0.885
28	0.948	0.935	0.923	0.910	0.898	0.886	0.874
29	0.935	0.923	0.911	0.898	0.886	0.874	0.862
30	0.923	0.911	0.899	0.886	0.874	0.863	0.851
31	0.911	0.899	0.887	0.875	0.863	0.851	0.840
32	0.899	0.887	0.875	0.863	0.852	0.840	0.829
33	0.887	0.876	0.864	0.852	0.841	0.829	0.818
34	0.876	0.864	0.853	0.841	0.830	0.819	0.807
35	0.865	0.853	0.842	0.830	0.819	0.808	0.797
36	0.854	0.842	0.831	0.820	0.809	0.798	0.787
37	0.843	0.831	0.820	0.809	0.798	0.787	0.777

In Table 1 the results of human skin emissivity for different values of ambient and skin temperatures obtained on the basis of (2) are shown.

2. Heat balance equation (HBE)

The thermal physiology states that skin temperature is the resultant balance of the heat transport within the tissue and its transport to environment. The state of heat equilibrium is described by the heat balance equation (HBE) in the following form [1, 2]

$$q_{in} = q_{out} \tag{3}$$

where

$$q_{out} = q_r + q_e + q_f \tag{4}$$

while

$$q_{in} = q_c + q_m + q_b \tag{5}$$

where q [Wm^{-2}] represents the heat fluxes resulting from radiation (q_r), evaporation (q_e), air convection (q_f), body conduction (q_c), metabolism (q_m) and blood perfusion (q_b), respectively.

The radiative heat flux q_r is described by the Stefan-Boltzmann law in the form [1]

$$q_r = \varepsilon\sigma\left(T_s^4 - T_{amb}^4\right) \tag{6}$$

where σ [Wm^{-2}K^{-4}] is the Stefan-Boltzmann constant.

Introducing (2) into equation (6) one has

$$q_r = \sigma T_{amb}^4 \left(1 - \frac{T_{amb}}{T_s^4}\right) \tag{7}$$

According to the assumption 1 - no sweating is considered - the evaporation heat flux q_e is neglected.

The definition of heat flux resulting from air convection q_f basis on the Newton's law of cooling [1, 4]

$$q_f = \alpha\left(T_s - T_{amb}\right) \tag{8}$$

where α [Wm^{-2}K] denotes the convection coefficient, or in more complex form [1]

$$q_f = A\lambda_{air} d^{3M-1}\left(\frac{P_r g\beta}{\nu^2}\right)^M \left(T_s - T_{amb}\right)^{M+1} \tag{9}$$

where λ_{air} [$Wm^{-1}K^{-1}$] is the thermal conductivity of air, P_r is the Prandtl number, g [ms^{-2}] is the local gravitation acceleration, β [K^{-1}] is the air thermal expansion coefficient, ν [m^2s] is the kinematic viscosity of air, d [m] is the characteristic length of the object while A and M are constants determined experimentally.

The body conduction heat flux q_c is described by Fourier law [1, 5]

$$q_c = \frac{\lambda_s\left(T_c - T_s\right)}{D} \tag{10}$$

where λ_s [$Wm^{-1}K^{-1}$] is the thermal conductivity of skin tissue, T_c [K] is the body core temperature and D [m] denotes the distance from the body core to the skin surface.

The metabolic heat flux q_m is assumed to be a constant one (c.f. assumption 1) and equal 4.186 Wm^{-2}.

The definition of heat flux resulting from blood perfusion q_b is determined using the Keller and Seiler model [5-7]

$$q_b = \psi c_b \omega\left(T_a - T_s\right) \tag{11}$$

where ψ is the countercurrent exchange radio, c_b [J kg^{-1} K^{-1}] is the blood specific heat, ω [kg m^{-2} s^{-1}] is the blood flow rate per unit cross-section area and T_a [K] is the artery blood temperature.

Taking into account equations (6-11) one can write the blood flow rate as follows

$$\omega = \frac{q_r + q_f - q_c - q_m}{\psi c_b (T_a - T_s)} \tag{12}$$

To determine the influence of emissivity value on the radiative heat flux and the blood flow rate in skin tissue domain, the direct approach of sensitivity analysis has been applied [4, 8].

According to the rules of direct method the equations (6) and (12) are differentiated with respect to the emissivity

$$\frac{\partial q_r}{\partial \varepsilon} = \sigma\left(T_s^4 - T_{amb}^4\right) \tag{13}$$

and

$$\frac{\partial \omega}{\partial \varepsilon} = \frac{1}{\psi c_b (T_a - T_s)} \frac{\partial q_r}{\partial \varepsilon} \tag{14}$$

3. Results of computations

The values of parameters assumed at the stage of computations are collected in Table 2. Most of them are taken from [1] and the geometrical parameters *d* and *D* correspond to the dimensions of human head. Calculations have been made for the scope of skin temperature T_s: 29÷37°C, and for various values of emissivity and ambient temperature. It should be pointed out that the value of arterial blood temperature T_a has been assumed as equal to 37.1°C only from the mathematical purpose (denominator must be different from zero - c.f. equations (12) and (14)).

Table 2

Nomenclature

Symbol	Representation	Value	Unit
q_e	Evaporation heat flux	0	Wm^{-2}
q_m	Metabolic heat flux	4.186	Wm^{-2}
T_a	Arterial blood temperature	37.1	°C
T_c	Body core temperature	37	°C
λ_s	Thermal conductivity of skin	0.5	$Wm^{-1}K^{-1}$
λ_{air}	Thermal conductivity of air	0.024	$Wm^{-1}K^{-1}$
d	Characteristic length of object	0.2	m
D	Distance from body core to skin surface	0.1	m
c_b	Blood specific heat	3780	$J\,kg^{-1}\,K^{-1}$
β	Thermal expansion coefficient of air	3.354e–3	K^{-1}
ν	Kinematic viscosity of air	1.56e–5	$m^2\,s^{-1}$
g	Local gravitational acceleration	9.8	$m\,s^{-2}$
σ	Stefan-Boltzmann constant	5.67e–8	$Wm^{-2}K^{-4}$
ψ	Countercurrent exchange ratio of skin	0.8	
P_r	Prandtl number	0.72	
A	Constant	0.27	
M	Constant	0.25	

The values of blood flow rate ω are presented in Tables 3 and 4. It is clear visible that lower values are obtained for the lower values of emissivity (see: table 3) whereas for fixed value of emissivity, increase of ambient temperature has an effect in decrease of blood flow rate - Table 4.

In Tables 5 and 6 the values of radiative heat flux are presented. Similarly to the previous results, decrease of radiative heat flux could arise from decrease of emissivity as well as increase of ambient temperature.

Table 3

Values of blood flow rate ω [g m^{-2} s^{-1}], T_{amb} = 21°C

T_s [°C]	ε					
	0.99	0.98	0.95	0.9	0.85	0.8
29	0.67	0.65	0.59	0.49	0.39	0.30
30	1.38	1.36	1.28	1.15	1.03	0.90
31	2.33	2.30	2.20	2.04	1.87	1.71
32	3.67	3.62	3.49	3.28	3.06	2.84
33	5.66	5.60	5.42	5.13	4.83	4.53
34	8.95	8.87	8.61	8.18	7.76	7.33
35	15.00	15.00	15.00	14.00	13.00	13.00
36	34.00	33.00	32.00	31.00	30.00	28.00
37	416.00	413.00	403.00	386.00	370.00	353.00

Table 4

Values of blood flow rate ω [g m^{-2} s^{-1}]

T_s [°C]	ε = 0.99			ε = 0.8		
	T_{amb} [°C]			T_{amb} [°C]		
	18	21	24	18	21	24
29	1.62	0.67	0	1.11	0.30	0
30	2.47	1.38	0.29	1.84	0.90	0
31	3.61	2.33	1.06	2.81	1.71	0.61
32	5.20	3.67	2.13	4.17	2.84	1.52
33	7.58	5.66	3.73	6.19	4.53	2.88
34	12.00	8.95	6.39	9.53	7.33	5.12
35	19.00	15.00	12.00	16.00	13.00	9.52
36	41.00	34.00	26.00	35.00	28.00	22.00
37	496.00	416.00	335.00	422.00	353.00	283.00

Table 5

Values of radiative heat flux q_r [Wm^{-2}], T_{amb} = 21°C

T_s [°C]	ε					
	0.99	0.98	0.95	0.9	0.85	0.8
29	47.62	47.14	45.69	43.29	40.88	38.48
30	53.84	53.30	51.67	48.95	46.23	43.51
31	60.13	59.52	57.70	54.66	51.62	48.59
32	66.48	65.80	63.79	60.43	57.08	53.72
33	72.89	72.15	69.94	66.26	62.58	58.90
34	79.36	78.56	76.16	72.15	68.14	64.13
35	85.90	85.03	82.43	78.09	73.75	69.41
36	92.50	91.57	88.76	84.09	79.42	74.75
37	99.17	98.17	95.16	90.15	85.14	80.14

Table 6

Values of radiative heat flux q_r [Wm^{-2}]

T_s [°C]	ε = 0.99			ε = 0.8		
	T_{amb} [°C]			T_{amb} [°C]		
	18	21	24	18	21	24
29	64.50	47.62	30.21	52.12	38.48	24.41
30	70.72	53.84	36.43	57.15	43.51	29.44
31	77.01	60.13	42.72	62.23	48.59	34.52
32	83.36	66.48	49.07	67.36	53.72	39.65
33	89.77	72.89	55.48	72.54	58.90	44.83
34	96.24	79.36	61.95	77.77	64.13	50.06
35	102.78	85.90	68.49	83.06	69.41	55.35
36	109.39	92.50	75.09	88.39	74.75	60.68
37	116.05	99.17	81.76	93.78	80.14	66.07

Tables 7 and 8 present the sensitivity functions of radiative heat flux and blood flow rate. It should be pointed out that the greater values are obtained for the bigger differences between ambient and skin temperature. In both tables the values of sensitivity function are multiplied by $\Delta\varepsilon = 0.1$. Important thing is that according to the equations (13) and (14) the sensitivity functions (radiative heat flux and blood flow rate with respect to the emissivity) are independent of emissivity itself.

Table 7

Sensitivity of radiative heat flux [Wm^{-2}] ($\partial q_r/\partial\varepsilon\cdot\Delta\varepsilon$, $\Delta\varepsilon = 0.1$)

T_s [°C]	T_{amb} [°C]						
	24	23	22	21	20	19	18
29	3.05	3.64	4.23	4.81	5.38	5.95	6.52
30	3.68	4.27	4.86	5.44	6.01	6.58	7.14
31	4.32	4.91	5.49	6.07	6.65	7.22	7.78
32	4.96	5.55	6.13	6.71	7.29	7.86	8.42
33	5.60	6.20	6.78	7.36	7.94	8.51	9.07
34	6.26	6.85	7.44	8.02	8.59	9.16	9.72
35	6.92	7.51	8.10	8.68	9.25	9.82	10.38
36	7.59	8.18	8.76	9.34	9.92	10.49	11.05
37	8.26	8.85	9.44	10.02	10.59	11.16	11.72

Table 8

Sensitivity of blood flow rate [g m^{-2} s^{-1}] ($\partial\omega/\partial\varepsilon\cdot\Delta\varepsilon$, $\Delta\varepsilon = 0.1$)

T_s [°C]	T_{amb} [°C]						
	24	23	22	21	20	19	18
29	0.12	0.15	0.17	0.20	0.22	0.24	0.27
30	0.17	0.20	0.23	0.25	0.28	0.31	0.33
31	0.23	0.27	0.30	0.33	0.36	0.39	0.42
32	0.32	0.36	0.40	0.44	0.47	0.51	0.55
33	0.45	0.50	0.55	0.59	0.64	0.69	0.73
34	0.67	0.73	0.79	0.86	0.92	0.98	1.04
35	1.09	1.18	1.27	1.37	1.46	1.55	1.63
36	2.28	2.46	2.63	2.81	2.98	3.15	3.32
37	27.31	29.27	31.21	33.12	35.02	36.90	38.76

Final remarks

The emissivity has a visible influence both on the blood flow rate and the radiative heat flux, so its evaluation for "hospital conditions" could play an important role in the estimation of thermophysical tissue parameters.

Findings of sensitivity study indicate that skin temperature has a dominant influence on the value of sensitivity parameters (c.f. tables 7, 8) in comparison to the ambient temperature, so the sensitivity analysis with respect to those both temperatures should be also considered.

Acknowledgement

This paper is part of project No N N501 3667 34.

References

[1] Wu S., Lin W., Xie S., Skin heat transfer model of facial thermograms and its application in face recognition, Pattern Recognition 2008, 41, 2718-2729.
[2] Herman I.P., Physics of the Human Body, Springer-Verlag, Berlin, Heidelberg 2007.
[3] Dziuban E., Human body measurement - class program, Joint IMEKO TC-1 & XXXIV MKM Conference 2002, Wrocław, Poland 2002.
[4] Jasiński M., Modelling of tissue heating process, Ph.D. Thesis, Silesian University of Technology, Gliwice 2001 (in Polish).
[5] Nakayama A., Kuwahara F., A general bioheat transfer model based on the theory of porous media, International Journal of Heat and Mass Transfer 2008, 51, 3190-3199.
[6] Keller K.H., Seiler Jr. L., An analysis of peripheral heat transfer in man, Journal of Applied Physiology 1971, 30, 5, 779-786.
[7] Charny C.K., Mathematical models of bioheat transfer, [in:] Y.I. Cho (ed.), Advances in Heat Transfer, 22, Academic Press, San Diego 1992, 19-155.
[8] Kleiber M., Parameter sensitivity in nonlinear mechanics, J. Willey & Sons Ltd, Chicester 1997.