NUMERICAL MODELING FOR HEAT CONDUCTION IN HUMAN TISSUE BY MEANS OF THERMOGRAPHY

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Summary: The paper presents the results of simulation of the heat transport in the human tissue by means of 1D numerical model and experimentally obtained data. The model is based on the control volume numerical method with the skin temperature and heat losses to the surrounding as the boundary conditions. The thermodynamical properties of the tissue were taken from the relevant literature. The results obtained by simulation are compared with the data given in lit. [1]. The temperature droop in upper arm tissue of the observed subject is presented graphically, while the temperature distribution on the upper arm surface is given by thermograms.
Keywords: numerical modeling, heat conduction, human body, thermography

1. INTRODUCTION

The thermal comfort of human being is defined with many parameters such as: air temperature and humidity, air velocity and quality, temperatures of the surrounding objects and physical activity. The reaction of the human body to particular situation can be divided in two categories, active and passive. Conscious active reactions are dressing and undressing and unconscious are sweating and shivering. Passive reactions of human body depend on the heat transfer with the surrounding. In the case of thermal unbalance between the body and surrounding the body temperature can increase or decrease. Both situations can be dangerous. The zone of thermal comfort for sedentary humans where mean radiant temperature equals dry bulb temperature and clothing thermal conductance is 10,8 W/(m^2K) is given on fig. 1.
The goal of the research was development of the numerical model by means of which the temperature distribution in the human tissue could be calculated. The boundary conditions for the model are data obtained by thermographic measurements.

The thermoregulatory system of human body is maintaining its temperature constant. The energy supplied to the body by food transforms in heat and mechanical work. The metabolic rate is a total energy realised by oxidation in human body per unit time. The heat dissipation from human body to the surrounding takes place through heat and mass transfer.

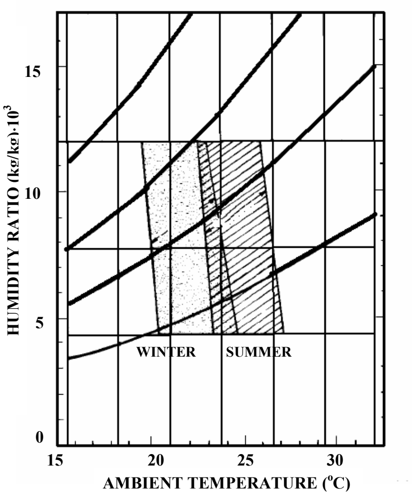

Figure 1: ASHRAE comfort zone for sedentary humans, where mean radiant temperature equals dry bulb temperature and clothing thermal conductance is 10,8 W/(m^2K)

A balance of a human body is given by Eq. (1)

$$M - W - Q_m - Q_h = 0 \qquad \textbf{(1)}$$

$$\frac{M}{A} \cdot (1-\eta) - q_m - q_h = 0 \qquad \textbf{(2)}$$

where: A = 1,77 m^2, average surface area of human body,
η - efficiency of human activity,
q_m – specific heat flow rate due to mass exchange,
q_h - specific heat flow rate due to heat transfer,
W - total physical work rate (power),
M – metabolic rate.

Table 1: The metabolic rate and work efficiency for various activities [2]

Activity	M/A W/m^2K	η
Sleeping	40	0
Sitting quietly	60	0
Driving car	60	0
Typing	70	0
Walking on level at 4,8 km/h	150	0
House cleaning	120 - 200	0 - 0,1
Handling 50 kg bags	230	0,2

Sawing wood	250	0,1 - 0,2
Playing tennis	270	0 - 0,1

The heat loss per unit area due to mass exchange effects may be subdivided into four parts:

$$q_m = q_d + q_e + q_a + q_{wa} \quad \textbf{(3)}$$

where:

q_d - the specific heat flow due to water diffusion through the skin to surroundings
q_e - the specific heat flow due to evaporation of water or sweat at the surface of the skin
q_a - the specific heat flow due to heating of air above the surrounding temperature by the respiratory system
q_{wa} - the specific heat flow due to evaporation of water in the air exchanged by the respiratory system

The heat flow by convection and radiation from the surface to the surroundings at temperature ϑ_s can be expressed as:

$$q_h = q_c + q_r = -(h_c + h_r)\cdot(t_s - t_{sk}) \quad \textbf{(4)}$$

or from the surface of the clothes to the surroundings:

$$q_h = q_c + q_r = -(h_c + h_r)\cdot f_{cl} \cdot (t_s - t_{cl}) \quad \textbf{(5)}$$

q_c – specific heat flow by convection, W/m^2
q_r – specific heat flow by radiation, W/m^2
h_c – heat transfer coefficient (convection), W/m^{2}K
h_r – heat transfer coefficient (radiation), W/m^{2}K
$f_{cl} = \frac{A_c}{A}$ – the area factor for the clothes
t_s – the surroundings temperature, ^{o}C
t_{sk} – the mean skin temperature, ^{o}C
t_{cl} – the temperature at the outer surface of the clothing, ^{o}C

2. EXPERIMENT

The experimental part of the work was done on the subject at rest in the conditioned room. The period of accommodation on the certain air temperature and humidity was at least one hour. The thermograms of the subject upper arm were taken from the distance of 1m with IR camera ***FLIR ThermaCAM SC2000*** at the ambient temperatures of: 18, 22, 25, 28 ^{o}C and relative humidity of 40 %. The results of thermographic measurements are presented in Table 1. They were obtained from the thermograms by means of ***ThermaCAM Researcher 2002*** software. The thermograms for one set temperature are presented on fig. 2. The emissivity of the human skin was taken as ε = 0,97 according to lit. [1].

The goal of the experiment was to find out the temperature of the skin surface as a factor of ambient temperature.

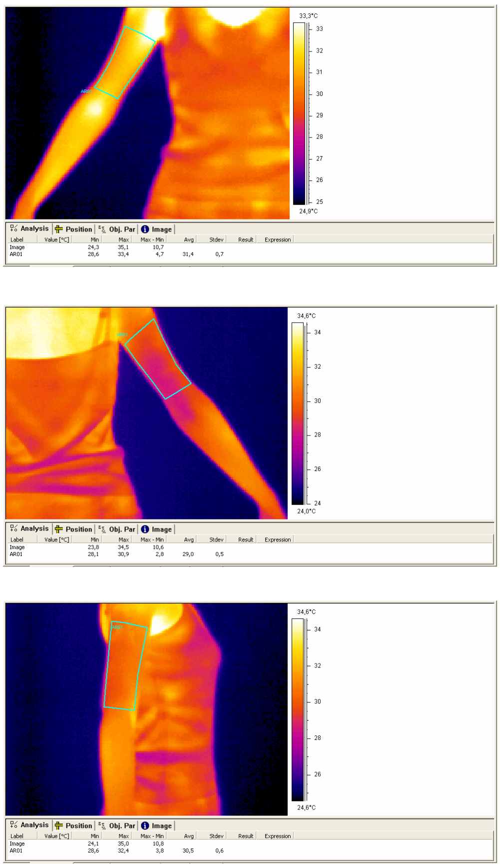

Figure 2: The thermograms of the upper arm

3. NUMERICAL MODEL

The numerical model is based on the control volume method and is expressed in cylindrical coordinates. The upper arm was assumed to be a cylinder having outer diameter of 100 mm. The model has four layers with outer radius: core 28 mm, muscle 44 mm, fat 48 mm and skin 50 mm. The thermal conductivity was taken according to lit. [1] as: λ = 0,418 W/mK for core and muscle, and λ = 0,334 W/mK for fat and skin. The 1D stationary heat conduction numerical model has 18 control volumes having thickness of Δr = 2 mm. The source term of equal intensity is added to each control volume of single layer. It reperesents a heat transported by blood and metabolic rate. The observed segment is shown on fig. 3 and control volume net on fig. 4.

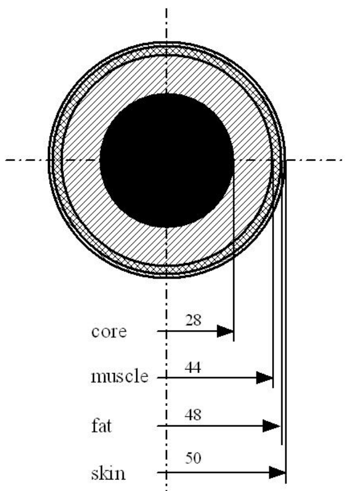

Figure 3: The cross section of upper arm

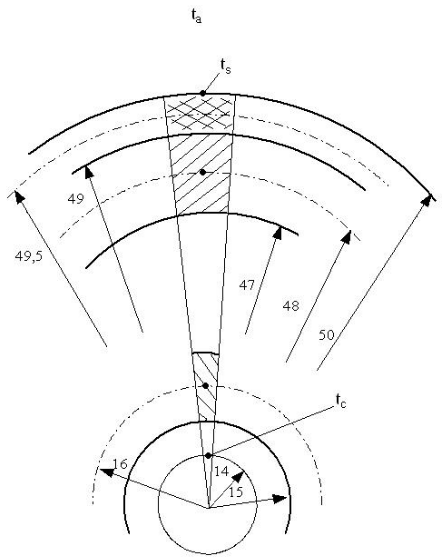

Figure 4: The control volume net

3.1. Boundary conditions

Set point temperature of core	t_c = 35,53 °C at r = 14 mm
Heat transfer coefficients	
Radiant:	h_r = 4,2 W/m^{2}K
Convective:	h_c = 2,1 W/m^{2}K
Basal evaporation loss:	q_e = 5,52 W/m^2

Basal heat production ratio related to the core heat production
$n_c = 1$
$n_m = 0,8988$
$n_f = 0,5941$
$n_s = 0,8534$

Skin temperature t_s is obtained from thermograms.

$$Q_r = h_r \cdot A_s \cdot (t_s - t_a) \tag{6}$$

$$Q_c = h_c \cdot A_s \cdot (t_s - t_a) \tag{7}$$

$$Q_e = q_e \cdot A_s \tag{8}$$

where t_a is the ambient temperature.

3.1. Heat balance

In stationary state the heat losses from the observed surface segment are equal to the total heat production in the segment volume:

$$Q_r + Q_h + Q_e = Q_c + Q_m + Q_f + Q_s \tag{9}$$

where the indexes refer to:

c - core
m - muscle
f - fat
s - skin
a - ambient

4. RESULTS OF THE NUMERICAL ANALYSIS

Table 2: The results of numerical analysis

Measurement No		1	2	3	4
t_a, °C measured		28	25	22	18
t_s, °C measured		33,47	30,3	28,47	26,77
Heat sources W/m^3	q_c	1740,4	1743,4	2145,8	2745,1
	q_m	1566,1	1566,9	1928,7	2467,3
	q_f	1029,3	1035,7	1274,8	1630,9
	q_s	1485,8	1487,8	1831,3	2342,7
Heat production, W		1,035	1,029	1,243	1,590
Δt , °C		2,28	2,79	3,4	4,29

tissue temperature droop				
Surface heat flow q, W/m^2	38,37	39,3	47,45	60,7
t_c, ^{o}C calculated	35,75	33,09	31,87	31,06

The temperature distributions in the observed segment are given on fig. 5.

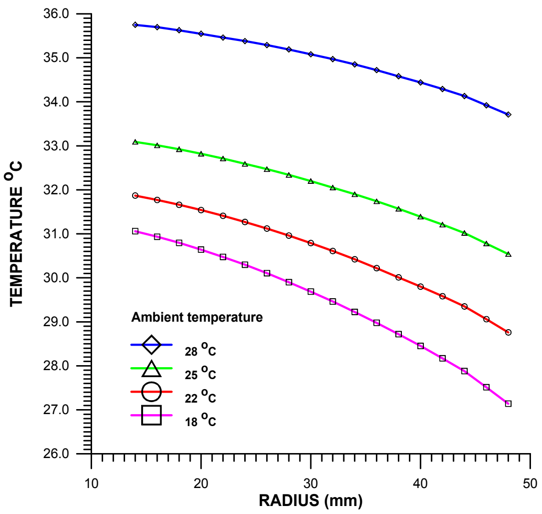

Figure 5: Temperature distribution through tissue for different ambient temperatures

5. CONCLUSION

The obtained results show that, at the ambient temperature of 28 ^{o}C, the core temperature is nearly the same as given in referent lit. [1]. For the three other ambient temperatures the core must be at lower temperature when the observed segment of upper arm is in thermal balance with the surrounding and the heat conduction coefficients remain unchanged. The obtained metabolic rate of heat production and the heat exchanged by blood flow were higher than those given in literature [1], [6]. The specific heat flow from the skin surface increases at lower ambient temperatures and is within the values given in reference literature.

It can be concluded that only a value of thermal source or sink can be obtained by developed system. More precise model which include the behavior of human tissue as a factor of temperature conditions are necessary to be known as well as relations between blood dispersion within the tissue to build more realistic model.

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