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AIR CONDITIONER FOR HUMANS WITH A THERMOELECTRIC HEAT FLUX SENSOR

The paper presents the results of development of air conditioner for humans with a thermoelectric heat flux sensor. Physical, mathematical and computer models of air conditioner have been developed. Its effcieincy for different values of heat release from human body has been determined. The efficiency of using thermoelectric sensor for control of temperature and heat release from human body has been confirmed.

Key words: thermoelectric heat flux meter, computer simulation, air conditioner for humans.

Introduction

General characterization of the problem. The use of personal air conditioners arranged in garment is a promising way of ensuring comfortable conditions for humans [1]. It is particularly important for persons who fulfill their professional duties in unfavourable temperature conditions for a long time (military men, workers in hot shops, sportsmen, doctors, etc.) [2].

In [1], physical models of personal air conditioners are described that are based on different physical methods of cooling and heating, in particular, the use of heat accumulators, blasting with ambient air, substance phase transition, thermoelectric and compression energy conversion. The simplest model is the physical model of air conditioner that employs forced heat removal from human body by ambient air.

Designs of such air conditioners are known [3 – 6]. To ensure heat removal by air flow, they employ low-power fans providing air flow circulation in peculiar channels created by garment. This design has disadvantages caused by low efficiency of heat exchange between human body and air flow due to the presence of additional garment layer. This, in turn, makes worse heat removal by sweating. In this paper, we propose to improve air conditioner for humans increasing considerably its efficiency by using heat exchange directly between human body and air flow. It eliminates the disdvantages of earlier variants of air conditioners (worse heat exchange due to the presence of intermediate layers of fabric on the body), and ensures additional heat exchange by intensification of natural heat exchange process of human body by evaporation of liquid (sweating).

Moreover, an important element of air-conditioner for humans is a device for control of the fans which ensures their necessary operating condition at different heat release levels from human body [7]. For the purpose of control of body temperature and its heat release it was proposed to use special bio heat flux meter [8, 9]. Its specific feature is the presence of channels through which perspiration products are transferred to the free surface of heat flux meter. The latter allows determining heat removal not only due to convective heat exchange, but also due to evaporation from human body surface.

Thus, *the purpose of this work* is to improve the efficiency of air-conditioner for humans with a thermoelectric heat flux sensor.

Physical model of a thermoelectric air-conditioner for garment

Calculations of the air-conditioner were performed with the use of a physical model represented in Fig. 1.

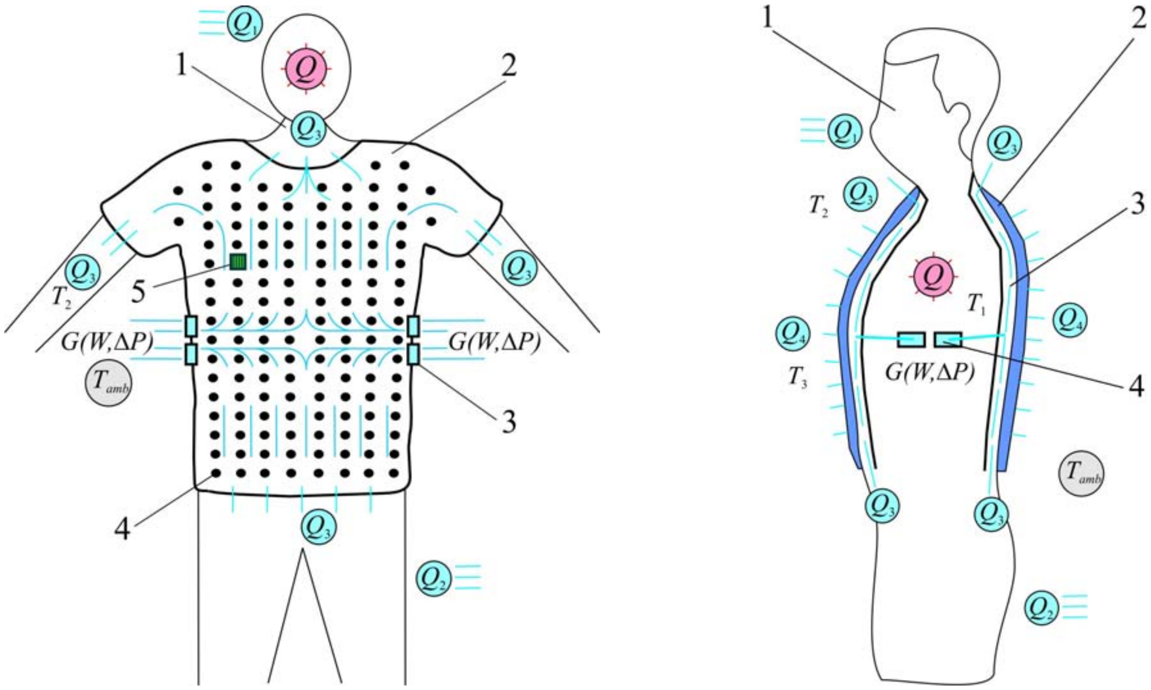

Fig. 1. Physical model of air-conditioner for humans: 1 – human body; 2 – elastic linen; 3 – fans; 4 – spacers on the internal surface of garment that form air gaps, 5 – thermoelectric temperature and heat flux sensor.

Physical model of air-conditioner for humans is comprosed of human body 1 which releases heat flux of power Q and has temperature $T_1 = 36.6$ °C. Elastic linen 2 is put directly on human body 1. On the linen 2 flat fans 3 are fixed which create air flow between the linen and the human body. Air flow created by the fans is transferred through the gaps created by spacers 4 fixed on the internal surface of the linen.

Depending on the body condition (rest, physical loads of various intensity, etc), it releases heat flux of power $Q = 100 – 800$ W [7]. Part of thermal power from human body Q_1 is removed through breathing, part by heat exchange from other body areas not covered with linen 2 with the ambient Q_2, and part through mechanisms of heat exchange from the surface of linen 2 Q_4. Created by fans 3, heat flux with consumption G which depends on power supply to fans W and pressure difference ΔP (created inside the garment by air flow) removes thermal power Q_3. Air flow which is heated in the garment to temperature T_2, is removed to the environment with temperature T_{amb} through the holes in the garment (as shown in Fig. 1).

It is clear that to ensure the necessary heat removal, of vital importance is information on the dimensions and arrangement of spacers on the garment, as well as on the supply power to electric fans.

Mathematical and computer models of air-conditioner for humans

To calculate the energy characteristics of air-conditioner for humans on the basis of a physical model shown in Fig. 1, object-oriented computer simulation in Comsol Multiphysics software was used. Mathematical description of the model is given below.

The processes of heat and mass exchange of heat carrier in the air gaps of the garment created by spacers in the steady-state case are described by Eqs. (1 – 3):

$$-\Delta p - f_D \frac{\rho}{2d_h} v\left|\vec{v}\right| + \vec{F} = 0 \tag{1}$$

$$\nabla(A\rho\vec{v}) = 0 \tag{2}$$

$$\rho \mathrm{AC_p} \vec{v}\cdot\nabla T_2 = \nabla\cdot Ak_2\nabla T_2 + f_D\frac{\rho A}{d_h}\left|\vec{v}\right|^3 + Q_2 + Q_{wall}, \tag{3}$$

where p is pressure, ρ is heat carrier density, A is effective cross-section of the channel where heat carrier is moving, $\vec{F}$ is the sum of all forces, C_p is heat carrier specific heat, T_2 is temperature, $\vec{v}$ is velocity vector, k_2 is heat carrier thermal conductivity, f_D is the Darcy coefficient, $d = 4A \div Z$ is effective diameter, Z is channel wall perimeter, Q_2 is heat released due to viscous friction [W/m] (from the unit length), Q_{wall} is heat flux coming from heat carrier to the walls [W/m].

$$Q_{wall} = h\cdot Z\cdot\left(T_1 - T_2\right), \tag{4}$$

where h is heat transfer coefficient found from the equation

$$h = \frac{Nu\cdot k_2}{d}. \tag{5}$$

To determine the Nusselt number, the Gnielinski equation is employed ($3000 < Re < 6\cdot10^6$, $0.5 < Pr < 2000$)

$$Nu = \frac{\left(\frac{f_d}{8}\right)\left(Re-1000\right)Pr}{1+12.7\left(\frac{f_d}{8}\right)^{\frac{1}{2}}\left(Pr^{\frac{2}{3}}-1\right)}, \tag{6}$$

where the Prandtl number $Pr = C_p\mu \div k_2$, μ is dynamic viscosity, $Re = \rho v d \div \mu$ is the Reynolds number.

To determine the Darcy coefficient f_D, we will use Churchill's equation for the entire spectrum of the Reynolds number and all the values of $e \div d$ (e is surface roughness)

$$f_D = 8\left[\frac{8}{Re}^{12} + \left(A+B\right)^{-1.5}\right]^{1/12}, \tag{7}$$

where $A = \left[-2.457\cdot\ln\left(\left(\frac{7}{Re}\right)^{0.9} + 0.27\left(e/d\right)\right)\right]^{16}$, $B = \left(\frac{37530}{Re}\right)^{16}$.

Solving Eqs (1) – (3), we obtain the distribution of velocities and pressure for heat carrier.

To determine the electric power of the fans, their real characteristics [11] in the form of polynomials were used.

Thermoelectric temperature and heat flux sensor

Fig. 2 represents a physical model of thermoelectric temperature and heat flux sensor which is composed of human body 1 which releases heat flux Q, thermoelectric sensor comprising chains of thermoelectric materials legs 2 and air gaps 3.

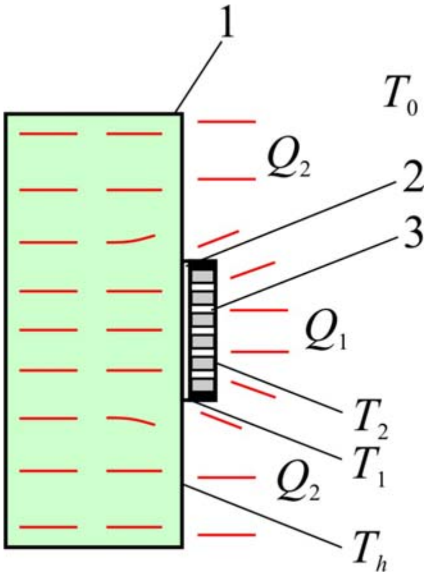

Fig. 2. Physical model of a thermoelectric temperature and heat flux sensor:
1 – human body; 2 – sensor material; 3 – air gaps.

The thermoelectric sensor used in this paper is composed of 50 couples of legs of *n*- and *p*-type material legs interconnected by solder into a series chain, in rows 10 couples each, with air gaps arranged in between. Its appearance is shown in Fig. 3.

Fig. 3. Appearance of a thermoelectric temperature and heat flux sensor.

The use of such temperature sensor allows precise control of heat release from human body and its temperature with a minimum effect of the sensor itself on the body heat exchange.

Determination of the effect of such sensor on the heat release from human body and its optimization to achieve the highest precision of temperature and heat flux measurement is the subject of a separate study and was performed in [10].

Simulation results

Thus, the input parameters of the model include: thermal power which is to be removed from the human body via thermoelectric modules and which is a function of ambient temperature and physiological condition of the body; ambient temperature T_1 = 20, 25, 30 °C; the area of the external surface of the vest from which heat exchanbge takes place $S = 0.5$ m^2; dimensions and arrangement of spacers on the internal surface of the linen – spacer radius $r = 5$ mm, its height $h = 5$ mm, the number of spacers $n = 136$; air fans are located as shown in Fig. 1.

As a result of simulation, heat carrier consumption necessary to ensure constant temperature of human body ($T = 36.6$ °C) was calculated as a function of ambient temperature and heat release from the body (Fig. 4).

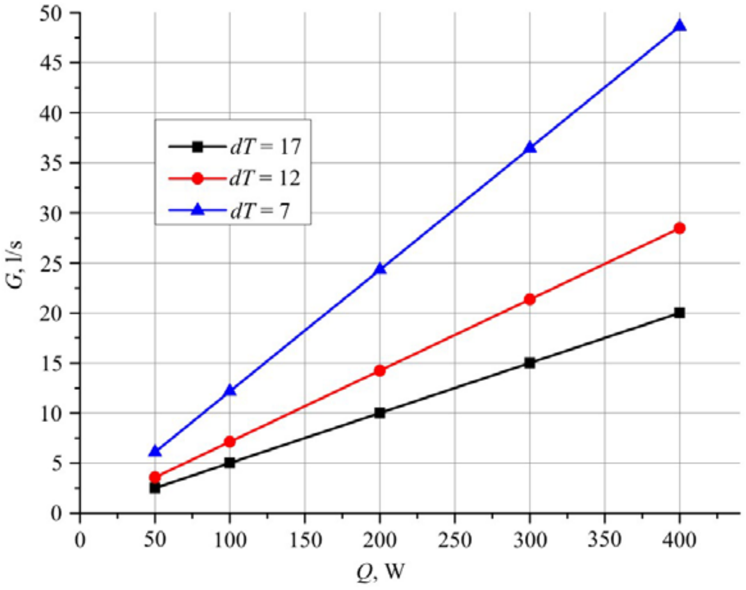

Fig. 4. Heat carrier consumption necessary to ensure constant temperature of human body (T = 36.6 °C) versus temperature difference between the body and the environment and heat release from the body.

Moreover, to determine electric power supply to the fans that ensured the necessary heat removal from the body at its constant temperature, pressure difference created by air flow from the fans was calculated as a function of air consumption (Fig. 5). Comparison of these results to real characteristics of the fans [11] made it possible to establish the real electric power supply to such air conditioner for humans.

Thus, to ensure heat removal from human body by means of a fan with characteristics described in [11], the required electric power is 5 W (for heat release in a calm state (100 W) and temperature difference between human body and the environment $\Delta T = 7$ K), which corresponds to 4 fans of power $W = 1.25$ W. For heat release from human body corresponding to strong physical load (800 W), the required electric power grows to 35 W (at temperature difference $\Delta T = 7$ K). Increase in temperature difference between human body and the environment to $\Delta T = 12$ K results in the reduction of electric power necessary for heat removal by a factor of ≈ 1.7, to $\Delta T = 17$ K – by a factor of ≈ 3.

Thus, the above described design of air conditioner for human body with a thermoelectric heat flux sensor has proved its efficiency at temperatures lower than human body temperature.

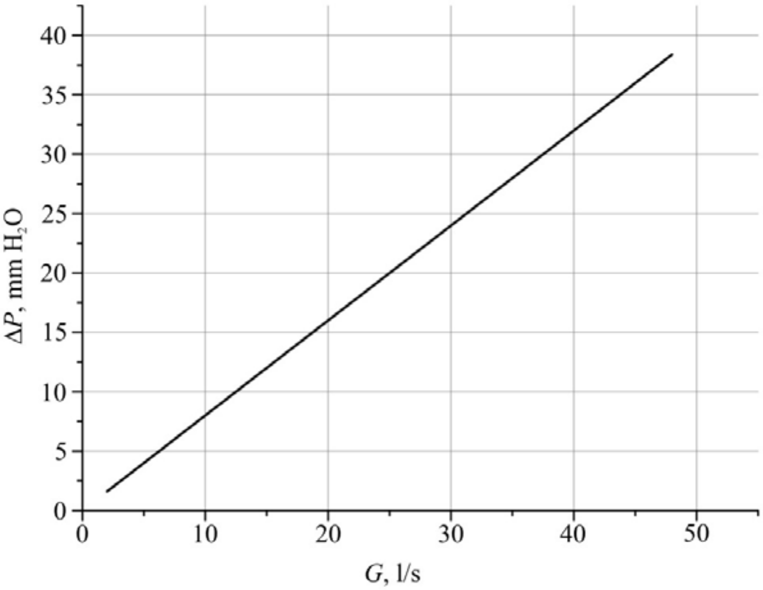

Fig. 5. Pressure difference created by air flow from the fans versus air consumption.

Conclusions

1. The possibility of creating air-conditioner for humans with a thermoelectric heat flux sensor has been confirmed.
2. It has been calculated that to ensure heat removal from human body by means of fans, the required electric power should be 5 W (for heat release in a calm state (100 W) and temperature difference between human body and the environment ($\Delta T = 7$ K).
3. For heat release from human body corresponding to strong physical load (800 W), the required electric power to ensure heat removal increases to 35 W (at temperature difference $\Delta T = 7$ K).
4. Increase in temperature difference between human body and the environment to to $\Delta T = 12$ K results in the reduction of electric power necessary for heat removal by a factor of ≈ 1.7, to $\Delta T = 17$ K – by a factor of ≈ 3.

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