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NEONATAL INTENSIVE CARE COMPLEX BASED ON THERMOELECTRIC POWER CONVERTERS

This paper is concerned with a calculation of temperature mode of thermoelectric neonatal complex. The fundamental design ratios based on differential equations describing convective heat exchange in the system are given. The results of a numerical experiment in the form of temperature variation at different complex points and with time as a function of cooling capacity and heat productivity of thermopiles are presented.

Key words: thermoelectric complex, neonatology, thermopile, thermal conductivity, heat exchange.

Introduction

For treatment of premature newborns of great significance are optimal temperature conditions, since a baby with a low birth weight has an ill-defined subcutaneous tissue with respect to large skin area and minimal energy reserves. This factor is primary not only for survival, but also for further adequate development of newborns with pathology.

Maintenance of optimal temperature ambient conditions during the first days of baby’s life is one of the primary factors not only for survival, but also for further adequate development of newborns with pathology, owing to which the immature baby’s organism can resist the aggressive effect of other environmental factors. Such a newborn has a limited potential of thermoregulation. This is due to a relatively larger surface of skin cover as compared to body mass, which results in considerable loss of heat by a premature newborn. Insufficient development of a subcutaneous layer, combined with a marked vascular bed, contributes to intense heat exchange. Such children are easily cooled, and excessive external heating quickly leads to overheating, which creates difficulties for medical staff in nursing process.

For the efficient restoration of vital functions of newborns, special neonatal resuscitation complexes are used nowadays, providing for the opportunity of accurate maintenance and control of microclimate, namely temperature, humidity, pressure, etc. [1].

For the initial control of ambient air temperature in the incubator depending on the body weight and age, it is necessary to meet the accepted medical requirements given in Table 1 [2].

Among the developers and producers of such complexes one can single out companies DRAEGERMEDICAL (Germany), TAXAT (Belarus), AIR-SHIELDS (USA), FANFM (Brazil), Axion-Holding (Russia), Closed JSC SPE Medintekh-M (Russia), et al. [3, 4, 5]. In Russia, investigations in this field are pursued in D. O. Ott Research Institute of Obstetrics and Gynecology (Saint-Petersburg), Ivanovo Research Institute of Maternity and Childhood, Research Institute of

Pediatrics and Human Reproduction (Irkutsk), I. M. Sechenov Moscow Medical Academy, Moscow Regional Research Institute of Obstetrics and Gynecology, et al. The main emphasis in the development and research in this field is made on the use as thermoregulation systems of units based on vapor compression, absorption, air and liquid methods. The use of thermoelectric power converters as a means of microclimate control in resuscitation chamber is impractical because of low reliability characteristics of low-current thermopiles. However, if the above disadvantage is removed, the use of thermoelectric power converters for temperature control inside a resuscitation incubator will be efficient in view of their absolute ecological safety, ease of transition from cooling to heating mode, and vice versa, fire safety, noise-free operation, and long service life.

Table 1

Age and body weight	**Temperature**	**Age and body weight**	**Temperature**
C – 6 *hours*		24 – 36 *hours*	
less than 1200 g	34.0 – 35.4	less than 1200 g	34.0 – 35.0
1200 – 1500 g	33.9 – 34.4	1200-1500 g	33.1 – 34.2
1501 – 2500 g	32.8 – 33.8	1501-2500 g	31.6 – 33.6
2500 (36 weeks)	32.0-33.8	2500 (36 weeks)	30.7 – 30.5
6 – 12 *hours*		36 – 48 *hours*	
less than 1200 g	34.0 – 35.4	less than 1200 g	34.0 – 35.0
1200 – 1500 g	33.5 – 34.4	1200 – 1500 g	33.0 – 34.1
1501 – 2500 g	32.2 – 33.8	1501 – 2500 g	31.4 – 33.5
2500 (36 weeks)	31.4 – 33.8	2500 (36 weeks)	30.5 – 33.3
12 – 24 *hours*		48 – 72 *hours*	
less than 1200 g	34.0 – 35.4	less than 1200 g	34.0 – 35.0
1200 – 1500 g	33.3 – 34.2	1200 – 1500 g	33.0 – 34.0
1501 – 2500 g	31.8 – 33.8	1501 – 2500 g	31.2 – 33.4
2500 (< 36 weeks)	31.0 – 33.7	2500 (36 weeks)	30.1 – 33.2

The purpose of this work is design study of neonatal resuscitation system based on thermopiles characterized by rather high supply currents [6].

Description of system design

The system design is shown in Fig. 1, and its external view – in Fig. 2.

Neonatal intensive care complex comprises a mobile table 1 with incubator 2 with double walls, upper flap lid 3 and lateral sliding lid 4. On the bottom of the incubator 2 there is a gel mattress for preventing pressure sores 5 of high thermal conductivity materials whose cells 6 are filled with gel 7 with high thermal conductivity coefficient. Each of the cells 6 of the gel mattress 5 is in thermal contact with the hot junctions 8 of thermopile 9, whose second junctions 10 are connected with a single air heat exchanger 11. The thermopile is divided into sections that can be connected in series according to signals from temperature sensors located at different points of the mattress. Inside the incubator there is a head hypothermic device 12 shaped as a cylinder glass 13 with a spherical inner cavity 14 and gel layer 15, which is in contact with the hot junctions 16 of thermoelectric module 17, the second junctions of which are in contact with liquid heat exchanger 18. Thermoregulation of a newborn body is done by means of temperature sensors 19 connected to control unit 20 and located on the surface of mattress 5 and in gel layer 15 of head hypothermic device 12.

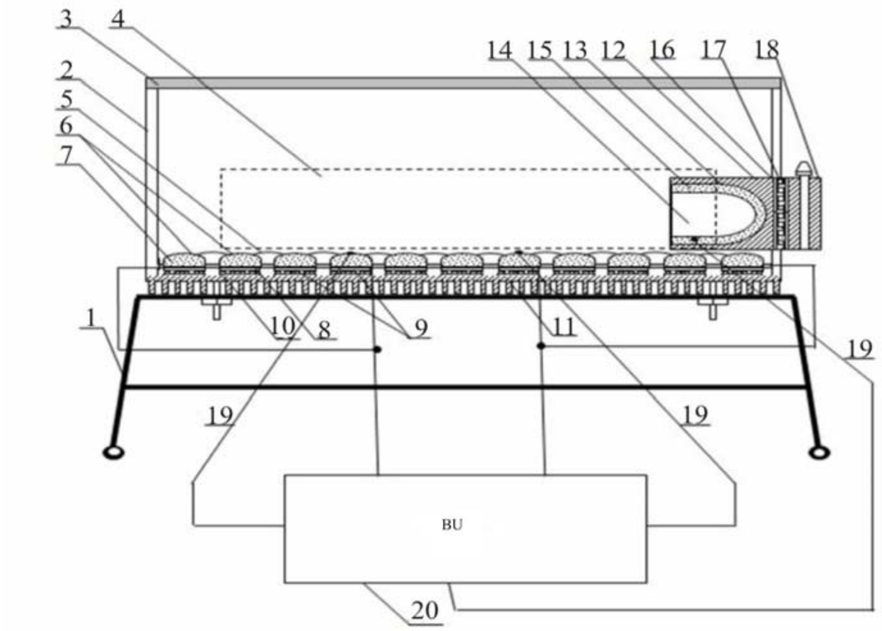

Fig. 1. Structural schematic of a system for the intensive therapy of newborns.

The operating principle of proposed device is as follows. A newborn patient is placed in the incubator 2, and his head in case of need is placed into a spherical inner cavity 14 of head hypothermic device 12. Special sensors are mounted for temperature control of newborn body, following which power supply to thermopile 9 and thermoelectric module 17 is switched.

Fig. 2. External view of neonatal intensive care complex.

Depending on the selected method, the necessary level of thermal effect is set on control unit 20. A change in supply current of thermopile 9 and thermoelectric module 17, as well as a series connection of sections of thermopile 9 will allow a smooth temperature control of a gel mattress for preventing pressure sores 5, and supply current reversal will permit to pass from cooling to heating mode. Simultaneously, heat pickup is done from the second junctions of thermopile 9 and thermoelectric module 7 by means of heat exchangers 11 and 18.

Simulation results

A generalized thermal scheme of neonatal complex comprises a chamber filled with air and a special bed for the newborn. A thermopile with cooling capacity q_{TEB} is brought into a good thermal contact with the lateral surface. Heat pickup from the hot thermopile junctions can be done by means of fan-blown air heat exchangers, as well as by means of liquid cooling. The lower surface of the neonatal resuscitation complex chamber exchanges heat with the environment with heat exchange coefficient α_{amb}.

Mathematical formulation of the problem of temperature field calculation for such system is given by [7]:

at $x, y, z \in D_1$

$$\rho_1 C_1 \frac{\partial T_1}{\partial t} = \lambda_1 \left(\frac{\partial^2 T_1}{\partial x^2} + \frac{\partial^2 T_2}{\partial y^2} + \frac{\partial^2 T_3}{\partial z^2} \right) + Q_{ext}, \tag{1}$$

at $x, y, z \in D_2$

$$\rho_2 C_2 \frac{\partial T_2}{\partial z} = \lambda_2 \left(\frac{\partial^2 T_2}{\partial x^2} + \frac{\partial^2 T_2}{\partial y^2} + \frac{\partial^2 T_3}{\partial z^2} \right),$$

at $x, y, z \in D_3$

$$C_3 \rho_3 \left(\frac{\partial T_3}{\partial t} + \omega_x \frac{\partial T_3}{\partial x} + \omega_y \frac{\partial T_3}{\partial y} + \omega_z \frac{\partial T_3}{\partial z} \right) = \lambda_3 \left(\frac{\partial^2 T_3}{\partial x^2} + \frac{\partial^2 T_3}{\partial y^2} + \frac{\partial^2 T_3}{\partial z^2} \right),$$

$$\frac{\partial \omega_x}{\partial x} + \frac{\partial \omega_y}{\partial y} + \frac{\partial \omega_z}{\partial z} = 0,$$

$$\rho_3 \left(\frac{\partial}{\partial \tau} + \omega_x \frac{\partial}{\partial} + \omega_y \frac{\partial}{\partial} + \omega_z \frac{\partial}{\partial} \right) \omega_y =$$

$$= -\frac{\partial P}{\partial y} + \frac{\partial}{\partial x} \left[\mu_3 \left(\frac{\partial \omega_y}{x} + \frac{\partial \omega_x}{y} \right) \right] + 2 \frac{\partial}{\partial y} \left(\mu_3 \frac{\partial \omega_y}{\partial y} \right) + \frac{\partial}{\partial z} \left[\mu_3 \left(\frac{\partial \omega_y}{\partial z} + \frac{\partial \omega_z}{\partial y} \right) \right] - \frac{2}{3} \times$$

$$\times \frac{\partial}{\partial y \left(\mu_3 div \varpi \right)} - g_y \times \rho_3$$

$$\rho_3 \left(\frac{\partial}{\partial \tau} + \omega_x \frac{\partial}{\partial} + \omega_y \frac{\partial}{\partial} + \omega_z \frac{\partial}{\partial} \right) \omega_y =$$

$$= -\frac{\partial P}{\partial z} + \frac{\partial}{\partial x} \left[\mu_3 \left(\frac{\partial \omega_z}{\partial x} + \frac{\partial \omega_x}{\partial z} \right) \right] + \frac{\partial}{\partial y} \left[\mu_3 \left(\frac{\partial \omega_z}{\partial y} + \frac{\partial \omega_y}{\partial z} \right) \right] + 2 \frac{\partial}{\partial_z} \left(\mu_3 \frac{\partial \omega_z}{\partial z} \right) - \frac{2}{3} \times$$

$$\times \frac{\partial}{\partial y \left(\mu_3 div \varpi \right)} - g_y \times \rho_3$$

$$\rho_3 \left(\frac{\partial}{\partial t} + \omega_x \frac{\partial}{\partial x} + \omega_y \frac{\partial}{\partial y} + \omega_z \frac{\partial}{\partial z} \right) \omega_z =$$

$$= -\frac{\partial P}{\partial z} + \frac{\partial}{\partial x} \left[\mu_3 \left(\frac{\partial \omega_z}{\partial x} + \frac{\partial \omega_x}{\partial z} \right) \right] + \frac{\partial}{\partial y} \left[\mu_3 \left(\frac{\partial \omega_z}{\partial y} + \frac{\partial \omega_y}{\partial z} \right) \right] + 2 \frac{\partial}{\partial_z} \left(\mu_3 \frac{\partial \omega_z}{\partial z} \right) - \frac{2}{3} \times$$

$$\times \frac{\partial}{\partial z} \left(\mu_3 div \varpi \right) + g_z \times \rho_3$$

$$\beta = -\frac{1}{\rho_3} \frac{\partial \rho_3}{\partial \rho T_3},$$

where T is temperature; indexes 1, 2, 3 correspond to newborn, bed and air medium in the volume of neonatal complex; ρ_1, ρ_2, ρ_3 is the density of D_1, D_2, D_3 domains; C_1, C_2, C_3 is the heat capacity of D_1, D_2, D_3 domains; λ_1, λ_2, λ_3 is the thermal conductivity of D_1, D_2, D_3 domains; t is time, Q_{ext} is specific amount of heat released by a newborn per unit time; ω_x, ω_y, ω_z are components of air motion velocity vector; P is air pressure; μ_3 is air dynamic viscosity; g_x, g_y, g_z are components of free fall acceleration vector; β is air thermal expansion coefficient.

The single-valuedness conditions are as follows.

The initial conditions:

$$T_{2,3}\left(x,\ y,\ z,\ t\right)=T_{amb},\ T_1\left(x,\ y,\ z,\ t\right)=309.6\text{ K at } t=0, \tag{2}$$

$$\omega_x=0;\ \omega_y=0;\ \omega_z=0 \text{ at } t=0,\quad P=100\text{ kPa at } t=0;$$

The boundary conditions:

$$\lambda_3\frac{\partial T_3}{\partial n}=q_{TEB}\quad\text{for } S_{3\text{-}0},\ \lambda_2\frac{\partial T_2}{\partial n}=q_{OP}\quad\text{for } S''_{3\text{-}0},$$

$$\lambda_2\frac{\partial T_2}{\partial n}=\alpha_{amb}T_{amb}-T_2\quad\text{for } S_{2\text{-}0},\ \lambda_2\frac{\partial T_2}{\partial n}=\lambda_x\frac{\partial T_1}{\partial n}\quad\text{for } S_{2\text{-}1},$$

$$\omega_x=\omega_y=\omega_z=0\ \text{ for } S_{3\text{-}0} \text{ in the general case,}$$

$$\omega_x=\omega_y=\omega_z=0\ \text{ for } S'_{3\text{-}0},\ S''_{3\text{-}0},\ S_{3\text{-}1},\ S_{3\text{-}2},\ S_{2\text{-}1},\ S_{2\text{-}0},$$

where $S_{3\text{-}0}$ is D_3 domain-environment contact area along the lateral surface; $S_{3\text{-}2}$ is D_3 domain-D_2 domain contact area; $S_{3\text{-}1}$ is D_3 domain-D_1 domain contact area; $S_{2\text{-}0}$ is D_2 domain-environment contact area; $S_{2\text{-}1}$ is D_2 domain-D_1 domain contact area; $S'_{3\text{-}0}$ is D_3 domain-environment contact area along the upper surface; $S''_{3\text{-}0}$ is D_3 domain-environment contact area along the lower surface; α_{amb} is coefficient of heat exchange with the environment; $\alpha_к$ coefficient of heat exchange with the chamber air; T_{amb} is ambient temperature.

Solution of this set of differential equations (1) with single-valuedness conditions (2) will make it possible to determine temperature variation at each point of the system at any time instant, as well as to follow its variation depending on cooling capacity and heat productivity values of thermopile and ambient conditions. Calculation of the above problem was done by finite-element numerical method offering high efficiency and accuracy in the calculation of heat exchange in the inhomogeneous systems of complicated configuration.

The results are represented in Figs. 3 – 5 as the plots of temperature variation at different system points as well as with time at different values of thermopile cooling capacity and thermal conductivity.

According to the plots, the temperature in the volume of neonatal resuscitation complex strongly depends on the refrigerating capacity of thermopile. According to estimated data, at q_{TEB} = 700 W/m^2 the minimum value of temperature near the wall is 293 K, and in the centre – 309 K. With increase of q_{TEB} to 800 and 900 W/m^2, the respective temperature values are reduced to 290 K and 308 K and 289 K and 307 K. Thus, adjusting the refrigerating capacity of thermopile, one can control baby temperature. In case of newborn hyperthermia, the thermopile power should be increased, and at hypothermia it should be reduced, thus creating optimal conditions for developmental care.

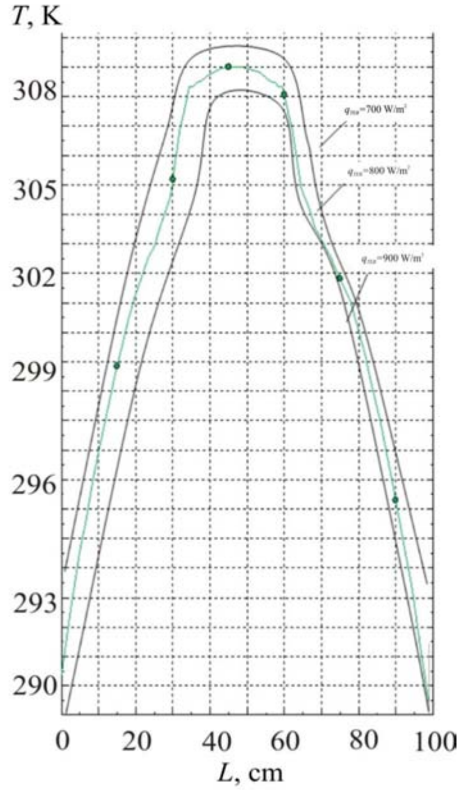

Fig. 3. Temperature distribution along central axial line in cross direction at different q_{TEB}.

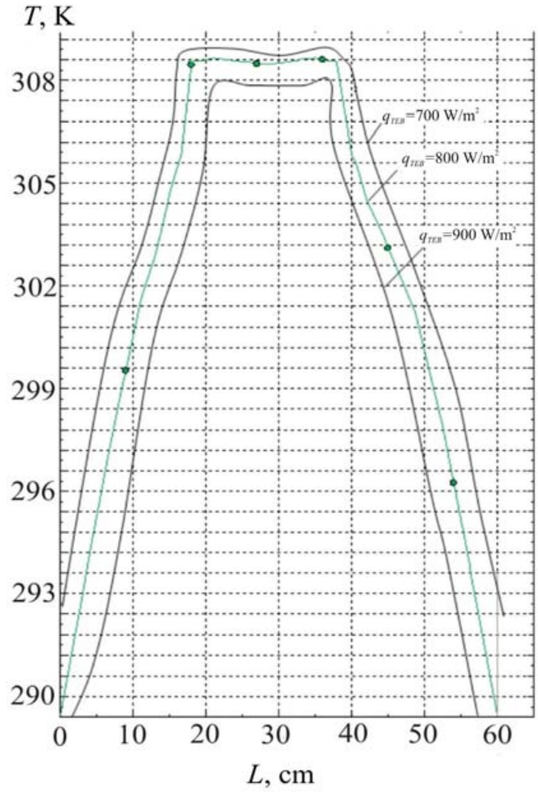

Fig. 4. Temperature distribution along central axial line in longitudinal direction at different q_{TEB}.

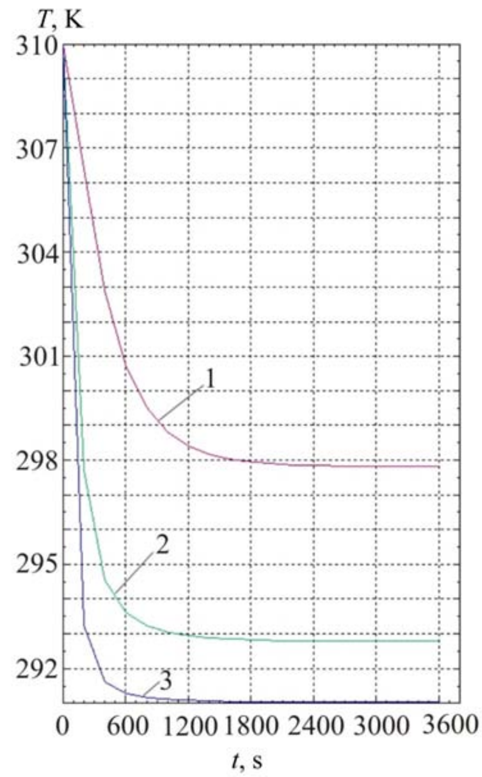

Fig. 5. Temperature variation of different parts of neonatal resuscitation complex with time.

To estimate time dependence of temperature at different points of chamber volume, the plots of temperature variation with time of different parts of neonatal resuscitation complex have been obtained. Fig. 3 shows temperature variation with time in the centre of the chamber (plot 1), at the distance of 30 cm from the centre of the chamber (plot 2) and from the lateral surface (plot 3). According to calculated data, time of reaching the steady state is about 35 min. This value is quite acceptable, since accelerated time of reaching the operating mode can cause newborn heatstroke.

Conclusions

1. A neonatal resuscitation complex based on high-current thermopiles has been developed, which allows improvement of its power and reliability characteristics.
2. A model of the complex has been created which includes a set of equations describing convective heat exchange in its chamber with regard to using of thermopiles as the source of heat (cold).
3. Based on the elaborated model, dependences of temperature variation at different complex points and with time for different cooling capacity and heat productivity values of thermopile have been obtained which show utilization efficiency of the latter.

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