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Local Optimization of Bonnet Thickness in Global Heat Balance of Neonate

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Abstract
Global heat transport for an neonate body is determined by means of heat balance with the term describing evaporation. The heat storage rate is the unbalanced difference between the metabolic heat production and various heat loss mechanisms within all body parts. The most sensitive portion is the head, which forces local optimization of the bonnet thickness. The local problem is described by differential heat and mass transport equations and the set of conditions. The changeable covering area of the bonnet can equalise the global heat balance and prevent hyperthermia or hypothermia.

Key words: *local optimisation, heat and mass transport, neonate.*

Nomenclature

A postnatal age of newborn baby, days
$\mathbf{A}$ matrix of heat conduction coefficients, $Wm^{-1}K^{-1}$
A_{body} total surface of newborn body, m^2
A_{co} proportional area of head covered by bonnet, –
B_T conversion factor of units for experimental temperature rise equation, $1°C\ kg^2\ s^{-1}$
B_t conversion factor of units for characteristic times equations, $1\ W\ kg^{-2}\ s$
C heat loss by convection on external surfaces, $W\ kg^{-1}$
c thermal heat capacity, $J\ kg^{-1}K^{-1}$
c_v volumetric heat capacity of textile material, $J\ m^{-3}K^{-1}$
C_{resp} heat loss by convection from muscosa in respiratory tract, $W\ kg^{-1}$
C_p heat capacity of air in normal conditions; $C_p = 1,044\ kJ\ kg^{-1}K^{-1}$
C_b heat capacity of soft tissues; $C_b = 9,78 \cdot 10^{-4}\ kJ\ s^{-1}$
$\mathbf{D}$ matrix of water vapour diffusion coefficients within fibers, m^2s^{-1}
E heat loss by evaporation, $W\ kg^{-1}$
E_{resp} heat loss by evaporation from muscosa in respiratory tract, $W\ kg^{-1}$
F objective functional, –
F_{cl} reduction factor of thermal radiation and convection by clothing, –
F_{pcl} reduction factor of mass transport by clothing, –
$g_p = \frac{Dg}{Db_p}$ global (material) derivative of g in respect of design parameter b_p, –
$g^p = \frac{\partial g}{\partial b_p}$ partial (local) derivative of g in respect of design parameter b_p, –
H mean curvature of external boundary Γ, m^{-1}
h surface film conductance, $Wm^{-2}K^{-1}$
h_{ci} convectional heat transfer coefficient; $W\ m^{-2}K^{-4}$
h_{ei} evaporative heat transfer coefficient, $h_{ei} = 0,46\ h_{ci}\ W\ hPa^{-1}m^{-2}$
h_k conductive heat transfer coefficient; $h_k = 0,23\ Wm^{-2}$
h_w mass transport coefficient of water vapour in air, $m\ s^{-1}$
I_{cl} thermal insulation of bonnet, $m^2K\ W^{-1}$
K heat loss by conduction, $W\ kg^{-1}$
$\dot{M}$ metabolic heat production, $W\ kg^{-1}$
M_E absolute humidity of exhaled air, kg H_20/kg of dry air
M_I absolute humidity of inhaled air, kg H_20/kg of dry air
$\mathbf{n}$ unit vector normal to the external boundary Γ, directed outwards to the domain Ω bounded by this boundary, –
$p_{s,H20}$ water vapuor partial pressure on skin, hPa
$p_{a,H20}$ water vapour partial pressure in atmosphere, $p_{a,H20} = 1 \cdot 10^5$ hPa
p_E partial pressure of water vapour in exhaled air, kPa
$\mathbf{q}$ vector of heat flux density, Wm^{-1}
$\mathbf{q_w}$ vector of mass flux density, $kg\ m^{-2}s^{-1}$
$q_n = \mathbf{n} \cdot \mathbf{q}$ heat flux density normal to external boundary, Wm^{-1}
$q_w = \mathbf{n} \cdot \mathbf{q_w}$ mass flux density normal to external boundary, $kg\ m^{-2}s^{-1}$
R heat loss by radiation on external surfaces, $W\ kg^{-1}$
R_{dyn} dynamic total evaporative resistance of clothing and boundary layer of air, $m^2\ kPa\ W^{-1}$
S heat stored in body, $W\ kg^{-1}$
$t_{38°C}$ time required to reach warning body temperature 38°C, 3600 s
$t_{40°C}$ time required to reach heat stroke in 40°C, 3600s
$t_{43°C}$ time required to reach extreme value of temperature 43°C, 3600 s
T temperature, °C
T_a temperature of surrounding air, °C
T_E temperature of exhaled air according to Hanson, °C
Th material thickness of bonnet, m
T_I temperature of inhaled air equal to surrounding temperature, $T_I = T_a$ °C
T_m temperature of mattress, °C
T_r mean temperature of radiation measured by infrared thermometer, °C
t real time in primary and additional structures, s
u unit cost of the structure, –
$\dot{V}_E$ pulmonary ventilation rate; 0,00028 $kg\ s^{-1}$
$\mathbf{v^p}(\mathbf{x}, \mathbf{b}, t)$ transformation velocity field associated with design parameter b_p, –
$v_n^p = \mathbf{n} \cdot \mathbf{v^p}$ transformation velocity normal to the external boundary Γ, –
w relative humidity of skin segment, –
w_a water vapor concentration in air filling the interfiber void space, $kg\ m^{-3}$
w_f water vapor concentration within fibers, $kg\ m^{-3}$
$W_C = \frac{w_f}{\rho}$ fractional water content on fiber surface, –
W_t body mass of neonate, kg
Γ external boundary of the structure, –
β approximation coefficient of sorption / desorption on boundary of fibers, –
γ boundary integrand of the objective functional, –
δ latent heat of vaporisation; $\delta = 243 \cdot 10^{-3}$ kJ/kg H_20
ε effective porosity of textile material, –
ε_{sk} skin emissivity; $\varepsilon_{sk} = 0,97$
ξ_c area coefficient of body portion subjected to convection A_c/A_{body}, –
ξ_e area coefficient of body portion subjected to evaporation A_e/A_{body}, –
ξ_k area coefficient of body portion contacting mattress during conduction A_k/A_{body}, –
ξ_r area coefficient of body portion subjected to radiation A_r/A_{body}, –
σ Stefan-Boltzmann constant; $\sigma = 5,67 \cdot 10^{-8}\ W\ m^{-2}K^{-4}$
η absorption coefficient, –
λ_w cross coefficient, described as the heat sorption of water vapor by fibers, $J\ kg^{-1}$
ξ slack variable of Lagrange functional for inequality problems, –
Σ discontinuity line between adjacent parts of piecewise smooth boundary Γ, –
ρ density of fibers, $kg\ m^{-3}$
χ Lagrange multiplier, –
Ω domain of the structure, m^2
∇ gradient operator, –

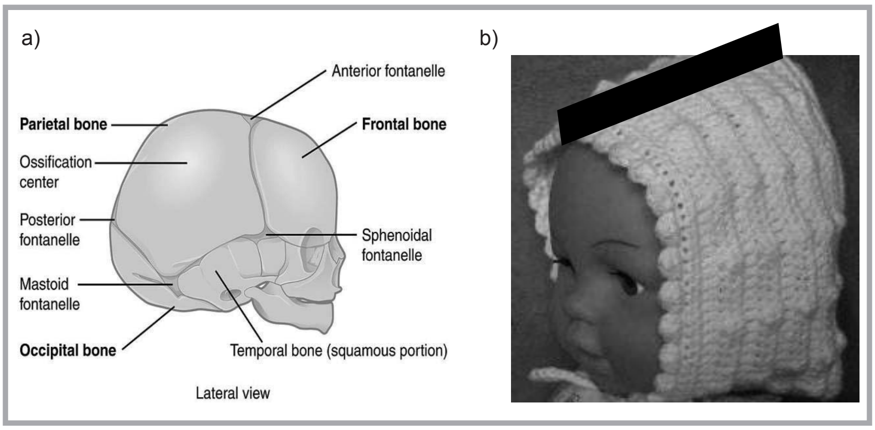

Figure 1. *a) newborn skull (https://commons.wikimedia.org/wiki/File:905_The_Newborn_Skull.jpg); b) bonnet on the newborn head and its cross-section along the symmetry plane (http://maikabezmetki.blogspot.com/2015/11/czapka-noworodkowa-w-dawnym-stylu.html).*

Introduction

Newborns after epicutateneous cava catherisation (which is a surgical operation) require special medical care in a closed incubator of a regulated microclimate inside. The neonate is located on a commercially available medical mattress covered by a textile. The controlled parameters secure that clothing is superfluous. An open incubator needs a completely different strategy in respect of hyperthermia. An effective method for reducing body cooling consists of wrapping the neonate in special clothing made of PVC-foil and textiles as well as using a bonnet which reduces heat loss from the surface of the head [1]. Thus it is necessary to ensure an adequate microclimate of the skin, that is the temperature and humidity. Irrespective of the protection applied, the risk of hyperthermia can be determined by characteristic times $t_{38^{\circ}C}$, $t_{40^{\circ}C}$, $t_{43^{\circ}C}$ that involve calculating metabolic heat protection and various local body heat losses.

Newborn skin is covered by amniotic fluid, water of amniotic fluid and vernix cascosa, showing a tendency to evaporation [2]. Thus it can generate hypothermia, and the main idea is always to optimise the coupled transport from the skin. A special structure made of PVC-foil provides almost the complete absence of moisture transport to the surroundings. Alternative clothing can be made of a textile structure (knitted fabric) and optional additional PVC-foil. The textile component provides both thermal protection and a pleasant feel, whereas the foil serves as a membrane blocking moisture transfer [3].

The survival chances of newborn babies depend on the thermal balance [4], which can be secured, for example, by a supplemental heating blanket in an incubator of two warming devices. A neonatal thermal environment is defined by a set of technological parameters influencing the psychology and current methodology of thermoregulation in clinical care [5]. Hyperthermia has been used successfully to treat isolated neoplastic lesions and regional tumors, and is under investigation as either an adjunct to, or therapy for, locally disseminated and systemic disease, cf. Vertrees et al [6]. Researchers have used multiple techniques to assess thermoregulation in infants and adults, including the technique of infrared thermography, which measures and visualises skin surface thermal patterns, see Knobel, Guenther and Rice [7]. Investigators have used this novel methodology to study cancer, peripheral vascular disease, trauma, and wound management. Gurgel et al [8] showed that the application of semipermeable membranes to the skin of premature newborns can aid in protecting the skin, reduce disturbances in fluid and electrolyte levels, and decrease neonatal mortality. They verify the effect of using semipermeable membranes on low-birth-weight preterm newborns. Sedin [2] analysed water loss from the skin and different mechanisms of heat exchange, proving that the heat balance does not depend on surrounding conditions. Exposure to cold may increase thermogenic responses and metabolic heat production, whereas the skin reflex decreases heat loss. Sahni & Schulze [9] observed the basic responses to cold: increased heat production and decreased heat loss, the timing of these events and their development pattern.

Local optimization is determined for coupled heat and mass transport. The problem needs differential transport equations and a set of boundary and initial conditions [10-12]. Thus necessary optimisation criteria of clear physical interpretation should be applied because we introduce the varied approach of the finite element method. Crucial is also the modelling of the temperature field in different materials [13,14].

The main goal of the paper is to introduce local optimization of the bonnet thickness into the global heat balance of the neonate. Physically speaking, both models introduce the coupled transport, that is the global balance, by the term of evaporative mass exchange, whereas the local one – by coupled transport equations. The global model is next solved, which helps to evaluate the risk of hyperthermia using characteristic times and temperature changes. The input data were determined by other Authors [1] using an extensive program of statistical measurements and critical evaluations. The paper is an extension of previous analysis concerning the heat balance for neonates [3]. The novelty elements are the application of a local optimization procedure into the global heat balance as well as calculations for both stages of sorption in fiber materials (which is equivalent to long moistening time). Additionally the impact of different materials was determined in respect of their fractional water content on the fiber surface. The heat storage rate, rise in temperature, and characteristic times should be described to evaluate the risk of hyperthermia.

The newborn skull has a different shape than that of an adult, see the lateral view in ***Figure 1a***. The bonnet should cover the entire head without there being a craniofacial space problem, ***Figure 1b***. To reduce the calculation time and computational effort, local optimisation of the bonnet is reduced to the cross-section along the symmetry plane, that is the plane problem.

Global coupled heat balance model

The theoretical model: newborn skin – clothing – different environmental conditions is always approximate because of a number of individual neonate organisms in various environmental conditions. The main goal is to prevent the hyperthermia and hypothermia of the neonate i.e. secure a constant body temperature by means of balanced heat production and exchange with the environment [2,3]. Heat, including evaporation, is transported directly from the skin through the clothing and bonnet to the interior of the incubator. Although the transport is a coupled one, the balance is characterised by the only state variable, that is the temperature. Moisture on the skin is regulated by the evaporative component. The boundary conditions are determined by the prescribed temperature and moisture concentration on the skin as well as within the incubator open to the surroundings.

The balance applied is a global one because all phenomena are determined at the macro level for a neonate body, cf. [1,2]. Impacts of clothing and environmental conditions are determined using the appropriate coefficients. It is impossible to diversify the temperature within the particular body portion because the balance model does not introduce the local description of coupled transport. The stable physiology of a neonate is always determined by balanced metabolic heat production and different heat losses. The balance introduces the diversified heat loss phenomena together with heat loss through mucosa in the respiratory tract, which is significant for neonates. The problem is described using empirical relationships. Heat is supplied by metabolic heat production and described empirically [1].

$$\dot{M} = \left(0{,}00165\,A^3 - 0{,}138\,A^2 + 3{,}56\,A + 35{,}4\right)4{,}185/24 \quad (1)$$

Heat is lost by different global mechanisms through six body parts: head, trunk, two arms & two legs. The balance is formulated as follows.

$$\dot{M} - \left|\sum_{\text{i,body parts}}\left(R_i + C_i + K_i + E_i\right) + C_{resp} + E_{resp}\right| = S \quad (2)$$

The physiology of the neonate is determined by means of heat stored in body S. The most advantageous case is $S = 0$; i.e. the metabolic heat production balanced by global heat losses. Thermal instantaneous equilibrium is described by the constant skin temperature. Metabolic overproduction compared to heat lost ($S > 0$) denotes that heat is accumulated within the body and that the increased temperature causes hyperthermia. The excessive heat loss related to the metabolism causes a reduction in temperature ($S < 0$), which leads to hypothermia.

Heat is lost by all body parts using different mechanisms [1,2]. Conduction is a function of the temperature difference between the surfaces of the skin and mattress, expressed as follows:

$$K = \sum_{\text{i,body parts}} K_i = h_k A_{body} W_t^{-1} \cdot \sum_{\text{i,body parts}} \left(T_i - T_m\right)\xi_{ki} \quad (3)$$

Radiation and convection from the skin surface are jointly described as the dry heat loss. Both are temperature-dependent in the form:

$$R + C = \sum_{\text{i,body parts}}\left(R_i + C_i\right) = A_{body} F_{cl} W_t^{-1} \cdot \sum_{\text{i,body parts}}\left[\sigma\,\varepsilon_{sk}\,\xi_{ri}\left[\left(T_i + 273\right)^4 - \left(T_r + 273\right)^4\right] + h_{ci}\left(T_i - T_a\right)\xi_{ci}\right] \quad (4)$$

The reduction factor of thermal radiation and convection depends on the clothing structure. The combined medical structure made of PE-foil and fabric is defined by $F_{cl} = 0{,}86$, and the typical PE-foil for a newborn bag by $F_{cl} = 0{,}98$ [1,2].

A part of heat is transported during evaporation from the skin and described as follows:

$$E = \sum_{\text{i,body parts}} E_i = w A_{body} F_{pcl} W_t^{-1} \cdot \sum_{\text{i,body parts}} h_{ei}\left(p_{s,H_2O} - p_{a,H_2O}\right)\xi_{ei} \quad (5)$$

Two components describe the behaviour of muscosa within the respiratory tract, that is heat loss by convection C_{resp} and evaporation E_{resp} [1,2].

$$C_{resp} = \dot{V}_E C_P \left(T_E - T_l\right) W_t^{-1}; \quad E_{resp} = \dot{V}_E \delta \left(M_E - M_l\right) W_t^{-1} \quad (6)$$

Head is covered by the bonnet to reduce heat loss, and its thickness is optimised to ensure the correct balance. The basic parameter is the thermal insulation of the bonnet material $I_{cl\,head}$ [15].

$$I_{cl\,head} = 0{,}067 \cdot 10^{-2} A_{co} + 0{,}217\,Th\,A_{co} \quad (7)$$

Assuming the same convectional heat transfer coefficients $h_{c\text{-}head} = h_{r\text{-}head}$, the corresponding heat reduction factors are described according to [15].

$$F_{cl-head} = \left[\left(h_{c-head} + h_{r-head}\right) I_{cl\,head} + \left(1 + 1{,}971 I_{cl\,head}\right)^{-1}\right]^{-1}$$

$$F_{pcl-head} = \left\{\left(1 + 2{,}22 h_{c-head}\right)\left[I_{cl\,head} - \left[1 - \left(1{,}971 I_{cl\,head}\right)^{-1}\left(h_{c-head} + h_{r-head}\right)^{-1}\right]\right]\right\}^{-1} \quad (8)$$

The time to reach a temperature hazardous to health depends on the heat stored in the body and other global parameters. The empirically determined temperature rate has the form [1].

$$\Delta T_b = B_T S \left(W_t C_b\right)^{-1} \quad (9)$$

Hyperthermia is characterised by growing skin temperature. The basis are the effective times of temperature increase [1,2] from *37°C* to *38°C* ($t_{38°C}$) – the warning time, *40°C* ($t_{40°C}$), and *43°C* ($t_{43°C}$) – the mortality rate.

$$t_{38°C} = 3{,}49\,B_t W_t S^{-1}; \quad t_{40°C} = 3 t_{38°C}; \quad t_{43°C} = 6 t_{38°C} \quad (10)$$

Local model of coupled heat and mass transport

The bonnet covering the newborn head is of a complex 3D structure and its analysis requires considerable computational time and programming effort. To simplify the calculations and limit the time, let us reduce the 3D problem to a small fragment of bonnet cross-section along the symmetry plane, that is the maximal contour of the skull. The model is sufficient for a rectangular shape of the same thickness on the entire head. The temperature of the head is assumed as constant. Heat is partially transported with moisture, whereas mass transport with heat is insignificant.

A textile bonnet is a heterogeneous textile product composed from different layers. Each layer is a systematized, repeatable arrangement of fibers and void spaces between the material which is homogenised during "external" homogenisation. The single fiber is also inhomogeneous, made of monofilaments and voids between the material during spinning. Homogeneous fiber is obtained by means of "internal" homogenisation. Thus the heat and mass transfer coefficients are porosity-dependent.

A physical model of coupled heat and mass transport is determined by some assumptions [16]. (i) Heat is transported by conduction within fibers as well as by convection and radiation from fiber surfaces to interfiber voids. Moisture is transferred by diffusion in fibers and in-

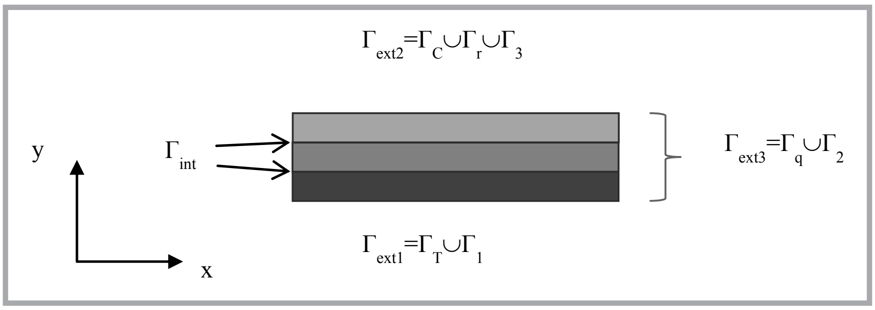

Figure 2. *Boundary conditions of multilayer bonnet structure.*

terfiber spaces. (ii) Volume changes of wet textiles can be neglected. (iii) Instantaneous thermodynamic equilibrium exists between the textile material and air in void spaces irrespective of time characteristics. Textiles have small diameters and a large surface/volume ratio.

The bonnet does not include heat and mass sources ($f = f_w = 0$) nor the initial heat and mass flux densities $\boldsymbol{q}^* = \boldsymbol{q}_w^* = 0$.

$$\begin{cases} \eta^{(i)}\left(1-\varepsilon^{(i)}+\dfrac{\varepsilon^{(i)}}{\beta^{(i)}}\right)\dfrac{dw_f}{dt} = -\mathrm{div}\,\mathbf{q}_w^{(i)}; \quad \mathbf{q}_w^{(i)} = \mathbf{D}^{(i)}\cdot\nabla w_f^{(i)}; \\ \rho^{(i)}c^{(i)}\dfrac{dT^{(i)}}{dt} + \lambda_w^{(i)}\left(1-\varepsilon^{(i)}\right)\dfrac{dw_f^{(i)}}{dt} = -\mathrm{div}\,\mathbf{q}^{(i)}; \quad \mathbf{q}^{(i)} = \mathbf{A}^{(i)}\cdot\nabla T^{(i)}. \end{cases} \tag{11}$$

$$\begin{aligned} &\Gamma_{ext1}:\ T(\mathbf{x},t) = T^0(\mathbf{x},t)\ \ \mathbf{x}\in\Gamma_T; \quad w_f(\mathbf{x},t) = w_f^0(\mathbf{x},t)\ \ x\in\Gamma_1; \\ &\Gamma_{ext2}:\ q_n(\mathbf{x},t) = h\left[T(\mathbf{x},t) - T_\infty(\mathbf{x},t)\right]\ \mathbf{x}\in\Gamma_c; \\ &\qquad q_w(\mathbf{x},t) = h_w\left[w_f(\mathbf{x},t) - w_{f\infty}(\mathbf{x},t)\right]\ \mathbf{x}\in\Gamma_3; \qquad \mathbf{n}\cdot\mathbf{q}^r(\mathbf{x},t) = q_n^r(\mathbf{x},t)\quad \mathbf{x}\in\Gamma_r; \\ &\Gamma_{ext3}:\ q_n(\mathbf{x},t) = 0\quad \mathbf{x}\in\Gamma_q; \qquad q_w(\mathbf{x},t) = 0\quad \mathbf{x}\in\Gamma_2; \\ &\Gamma_{\mathrm{int}}:\ T^{(i)}(\mathbf{x},t) = T^{(i+1)}(\mathbf{x},t)\ \ \mathbf{x}\in\Gamma_4; \quad w_f^{(i)}(\mathbf{x},t) = w_f^{(i+1)}(\mathbf{x},t)\ \ \mathbf{x}\in\Gamma_4; \\ &T(\mathbf{x},0) = T_0(\mathbf{x},0)\quad \mathbf{x}\in(\Omega\cup\Gamma); \quad w_f(\mathbf{x},0) = w_{f0}(\mathbf{x},0)\quad \mathbf{x}\in(\Omega\cup\Gamma). \end{aligned} \tag{12}$$

$$F = \int_0^{t_f}\left[\int_{\Gamma(\mathbf{b})}\gamma(w_f, w_{f\infty}, q_w)\,d\Gamma\right]dt; \tag{13}$$

$$\begin{cases} \eta^{(i)}\left(1-\varepsilon^{(i)}+\dfrac{\varepsilon^{(i)}}{\beta^{(i)}}\right)\dfrac{dw_f^p}{dt} = -\mathrm{div}\,\mathbf{q}_w^{(i)p}; \quad \mathbf{q}_w^{(i)p} = \mathbf{D}^{(i)}\cdot\nabla w_f^{(i)p}; \\ \rho^{(i)}c^{(i)}\dfrac{dT^{(i)}}{dt} + \lambda_w^{(i)}\left(1-\varepsilon^{(i)}\right)\dfrac{dw_f^{(i)p}}{dt} = -\mathrm{div}\,\mathbf{q}^{(i)p}; \quad \mathbf{q}^{(i)p} = \mathbf{A}^{(i)}\cdot\nabla T^{(i)p}. \end{cases} \tag{14}$$

$$\begin{aligned} &\Gamma_{ext1}:\ T^p(\mathbf{x},t) = -\nabla T^0\cdot\mathbf{v}^p\quad \mathbf{x}\in\Gamma_T; \quad w_f^p(\mathbf{x},t) = -\nabla w_f^0\cdot\mathbf{v}^p\quad \mathbf{x}\in\Gamma_1; \\ &\Gamma_{ext2}:\ q_n^p(\mathbf{x},t) = h\left(T^p - T_\infty^p\right) + \mathbf{q}_\Gamma\cdot\nabla_\Gamma v_n^p\quad \mathbf{x}\in\Gamma_c; \\ &q_w^p(\mathbf{x},t) = h_w\left(w_f^p - w_{f\infty}^p\right) + q_{w\Gamma}\cdot\nabla_\Gamma v_n^p\quad \mathbf{x}\in\Gamma_3; \qquad q_n^{rp} = 4\sigma T^3 T^p\quad \mathbf{x}\in\Gamma_r; \\ &\Gamma_{ext3}:\ q_n^p(\mathbf{x},t) = 0\quad \mathbf{x}\in\Gamma_q; \qquad q_w^p(\mathbf{x},t) = 0\quad \mathbf{x}\in\Gamma_2; \\ &\Gamma_{\mathrm{int}}:\ T^{p(i)}(\mathbf{x},t) = T^{p(i)}(\mathbf{x},t)\quad \mathbf{x}\in\Gamma_4; \quad w_f^{p(i)}(\mathbf{x},t) = w_f^{p(i)}(\mathbf{x},t)\quad \mathbf{x}\in\Gamma_4; \\ &T_0^p(\mathbf{x},0) = -\nabla T_0\cdot v^p\quad \mathbf{x}\in(\Omega\cup\Gamma); \quad w_{f0}^p(\mathbf{x},0) = -\nabla w_{f0}\cdot v^p\quad \mathbf{x}\in(\Omega\cup\Gamma). \end{aligned} \tag{15}$$

Equation (11), (12), (13), (14) and (***15).***

State variables are the temperature T and water vapour concentrations in fibers and voids w_a; w_f. The heat and mass transport equations are derived in the *(i)-th* material layer in the form of ***Equation (11)***, cf. [10-12].

Where $w_f = \rho\beta w_a$; $\beta = \rho$ for the first and $\beta = \eta$ for the second stage of the sorption process.

Let us introduce the set of conditions depicted in ***Figure 2***. The internal boundary of the bonnet contacts a head of prescribed temperature and moisture distribution, which determine the first-kind conditions $\Gamma_{ext1} = \Gamma_T \cup \Gamma_1$. The external boundary is subjected to heat and mass convection to the surrounding (that is third-kind conditions) as well as heat radiation $\Gamma_{ext2} = \Gamma_C \cup \Gamma_r \cup \Gamma_3$. Side boundaries have insignificant dimensions, i.e. heat and mass flux densities are negligible according to the second-kind conditions $\Gamma_{ext3} = \Gamma_q \cup \Gamma_2$. Internal boundaries Γ_4 ensure the same temperature and moisture concentration. The initial conditions describe the distribution of temperature and moisture at the beginning of the transport. The set of conditions has the form of ***Equation (12).***

The optimisation problem is solved using the material derivative concept, that is the first-order sensitivity $\frac{DF}{Db_p} = F_p$ is the material derivative of an objective functional in respect of the parameters. The general objective functional is a function of some independent variables, see ***Equation (13)***.

Where γ is a continuous and differentiable function of the variables listed. The first-order sensitivity of the objective functional is analysed using the direct approach [12], which is beneficial for the shapes defined by several design variables, for example material thickness. State variables are the temperature T^p and moisture concentrations w_f^p, w_a^p. It is necessary to solve a set of additional transfer problems associated with each design parameter. Introducing design parameters P, we solve primary *1* and additional problems P. Transport equations and boundary conditions are similar in all problems. The transport equations have the form [10-12] of ***Equation (14)***.

Let us derive ***Equations (12)*** for the state parameters defined in advance for an adequate part of the external boundary. Denoting $\dfrac{DT^0}{Db_p} = 0; \mathbf{x}\in\Gamma_T;\ \dfrac{Dw_f^0}{Db_p} = 0; \mathbf{x}\in\Gamma_1;$

$\frac{Dq_n^0}{Db_p} = 0; \mathbf{x} \in \Gamma_q; \qquad \frac{Dq_w^0}{Db_p} = 0; \mathbf{x} \in \Gamma_2;$

$\frac{DT_0}{Db_p} = 0; \; \frac{Dw_{f0}}{Db_p} = 0; \mathbf{x} \in (\Omega \cup \Gamma)$, the set of conditions has the final form of ***Equation (15)***.

The first-order sensitivity expression can be simplified to the form [10,12] of ***Equation (16)***.

Optimal design of bonnet thickness

Thickness optimization in respect of the particular criterion is a search for the minimum of the objective functional F with the inequality constraint of the structural cost C. The structure of each material layer is homogeneous, hence the structural cost is proportional to the domain Ω. The optimality conditions are formulated using (i) the Lagrangian functional in the form $F' = F + \chi\left(C - C_0 + \xi^2\right)$ and (ii) its stationarity conditions.

$$\begin{cases} \dfrac{DF}{Db_p} = -\chi \displaystyle\int_{\Omega} u \, v_n^p \, d\Gamma \\ \displaystyle\int_{\Omega} u \, d\Omega - C_0 + \xi^2 = 0. \end{cases} \tag{17}$$

Variational formulation of the finite element method is applied. Thus the particular objective functional describes the real problem of clear physical interpretation, with optimisation concerning its differential description. It is advantageous to minimise the moisture flux density on the external boundary of the bonnet because the neonate skin should always be moisturised. The objective functional has the form:

$$F = \int_0^{t_f} \left| \int_{\Gamma_{ext}} q_w d\Gamma_{ext} \right| dt \rightarrow \min \tag{18}$$

The other criterion is equalised moisture distribution on the external boundary. The objective functional is the global measure of local moisture concentration in fibers w_f applied at assumed level w_{f0}. The minimal global measure obtained assures that the state variables reach the local maxima. ***Equation 19***.

A solution algorithm of the global thermal balance including the local thickness optimisation of material layers within the bonnet is shown in ***Figure 3***.

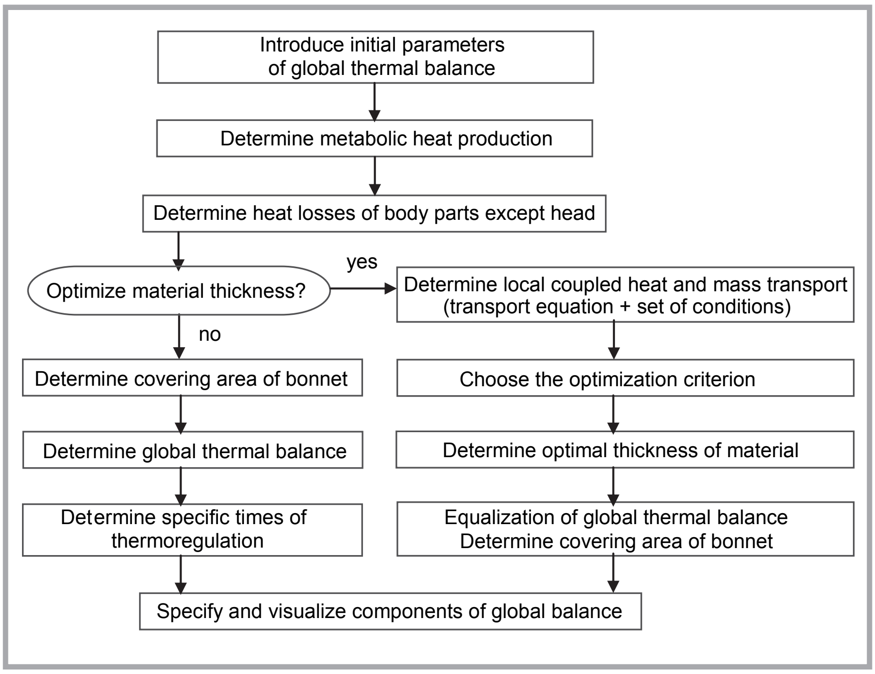

Figure 3. *Algorithm of thickness optimization of material layers within bonnet.*

$$F_P = \int_0^{t_f} \left\{ \int_{\Gamma_1} \left[-\gamma,_{w_f} \left(\nabla_\Gamma w_f^0 \cdot \mathbf{v}_\Gamma^p + w_{f},_n^0 v_n^p \right) + \gamma,_{q_w} \left(q_w^p - \mathbf{q}_{w\Gamma} \cdot \nabla_\Gamma v_n^p \right) \right] d\Gamma_1 + \int_{\Gamma_2} \left\{ \gamma,_{w_f} w_f^p - \gamma,_{q_w} \left(\nabla_\Gamma q_w^0 \cdot \mathbf{v}_\Gamma^p + q_{w},_n^0 \cdot v_n^p \right) \right\} d\Gamma_2 + \int_{\Gamma_3} \left[\gamma,_{w_f} w_f^p + \gamma,_{q_w} h_w \left(w_f^p - w_{f\infty}^p \right) \right] d\Gamma_3 + \int_{\Gamma} \left(\gamma,_n - 2H\gamma \right) v_n^p \, d\Gamma + \int_{\Gamma} \left(\gamma,_{w_{f\infty}} w_{f\infty}^p \right) d\Gamma + \int_{\Sigma} \left] \gamma \mathbf{v}^p \cdot \boldsymbol{\upsilon} \right[\right\} dt \qquad p = 1, 2...P. \tag{16}$$

$$F = \int_0^{t_f} \left(F_w \right)^{\frac{1}{n}} dt = \int_0^{t_f} \left\{ \left[\int_{\Gamma_{ext}} \left(\frac{w_f}{w_{f0}} \right)^n d\Gamma_{ext} \right]^{\frac{1}{n}} \right\} dt \rightarrow \min \; ; \; n \rightarrow \infty. \tag{19}$$

Equation (16) and (***19***).

General solution of thermal balance

The initial parameters are introduced by means of separate thermographic experiments on an appropriate sample size of 30 low-birth-weight neonates after epicutateneous cava catherisation (that is surgical operation) [1]. The front and upper part of the incubator are open to the surroundings (nursery) of temperature $T_a = (23,2 \pm 0,2)°C$, mean radiation temperature $T_r = (19,9 \pm 0,2)°C$, and relative humidity $w = (44 \pm 1,9)\%$. The air temperature in the incubator decreases from $T_{a0} = 33,2°C$ to $T_{ak} = 31,8°C$ in a time $t = 30\ min$. The mean temperature of the mixed air in the incubator and surroundings is equal to $T_a = (23,2 \pm 0,2)°C$; air speed within incubator $v = 0,06\ ms^{-1}$, and relative air humidity in the incubator $w = (35 \pm 4)\%$. The neonate has a body mass $W_t = (1,060 \pm 0,026)kg$, postnatal age $A = (4,5 \pm 0,4) days$, body surface $(0,100 \pm 0,010)m^2$, mean radiation temperature $T_r = 30,6°C$ and relative skin humidity $w = 0,94$. The temperature of the

Table 1. *Heat losses by convection (C) and evaporation (E) through all body portions, W kg^{-1}.*

Body portion	Heat losses
Head	C: 0.0047
Trunk	C: 0.0105 + E: 0.009
Arm (one)	C: 0.0002 + E: 0.035
Leg (one)	C: 0.0021 + E: 0.075
Whole body	C: 0.0182 + E: 0.337

mattress surface is $T_m = (31,4 \pm 0,1)°C$. The neonate clothing is a bag made of thin, impermeable plastic (PE) of average thickness $50\ \mu m$ and total mass $5 \cdot 10^{-3} kg$. The material is characterised by the heat reduction factor $F_{cl} = 0,98$. The alternative can be combined clothing made of PE and textile material of $F_{cl} = 0,86$.

Table 2. *Radiational (R) and convectional (C) heat losses for other body parts, W kg^{-1}.*

Body portion	Heat losses	
	F_cl = 0,98	F_cl = 0,86
Trunk	R: 0.588 + C: 0.061	R: 0.516 + C: 0.053
Arm (one)	R: 0.293 + C: 0.177	R: 0.257 + C: 0.157
Leg (one)	R: 0.800 + C: 0.475	R: 0.702 + C: 0.417
Whole body	R: 4.380 + C: 2.128	R: 3.843 + C: 1.867

Table 3. *Minimization of moisture content on the external boundary of bonnet.*

Case	Initial thickness [m]	Optimal thickness [m]	Reduction of obj. functional [%]	Nr of iterations
1 layer	0.004	0.0048	10.2	13
3 layers	0.003	0.0036	8.6	21
	0.0005	0.0005		
	0.001	0.0006		

$$\mathbf{D}^{(i)} = \begin{vmatrix} D_{xx}^{(i)} & 0 \\ 0 & D_{yy}^{(i)} \end{vmatrix}; \quad \begin{aligned} &\text{cotton: } D_{xx}^{(1)} = \left(0,8481 + 50,6W_C - 1100W_C^2\right) \cdot 10^{-14}; \\ &D_{yy}^{(1)} = \left(0,8100 + 50,6W_C - 1050W_C^2\right) \cdot 10^{-14}; \qquad t < 540s; \end{aligned}$$

$$\begin{aligned} &\text{cotton: } D_{xx}^{(1)} = 2,5\{1 - \exp[-3,5385(-45W_C)]\} \cdot 10^{-14}; \\ &D_{yy}^{(1)} = 2,5\{1 - \exp[-3,3000(-45W_C)]\} \cdot 10^{-14}; \qquad t \geq 540s. \end{aligned}$$

$$\text{membrane: } D_{xx}^{(2)} = 1,05 \cdot 10^{-14}; \quad t < 540s; \quad D_{yy}^{(2)} = 1,35 \cdot 10^{-13}; \quad t \geq 540s.$$

$$\begin{aligned} &\text{PES}: D_{xx}^{(3)} = \left(1,20 - 400\,W_C - 8200\,W_C^2\right) \cdot 10^{-13}; D_{yy}^{(3)} = \left(1,12 - 430\,W_C - 8100\,W_C^2\right) \cdot 10^{-13}; \ t < 540\,s; \\ &\text{PES}: D_{xx}^{(3)} = 6,23 \cdot 10^{-13}; D_{yy}^{(3)} = 6,33 \cdot 10^{-13}; \ t \geq 540\,s. \end{aligned} \tag{20}$$

$$\begin{aligned} &\text{cotton knitted fabric}: \ \varepsilon^{(1)} = 0,230; \quad \eta^{(1)} = 0,320; \ \text{membrane}: \varepsilon^{(2)} = 0,050; \quad \eta^{(2)} = 0,050; \\ &\text{PES knitted fabric}: \ \varepsilon^{(3)} = 0,250; \quad \eta^{(3)} = 0,220. \end{aligned} \tag{21}$$

$$\mathbf{A}^{(i)} = \begin{vmatrix} \lambda_{xx}^{(i)} & 0 \\ 0 & \lambda_{yy}^{(i)} \end{vmatrix}; \ \begin{aligned} &\text{cotton}: \lambda_{xx}^{(1)} = \left(44,1 + 63,0W_C\right) \cdot 10^{-3}; \quad \lambda_{yy}^{(1)} = \left(46,1 + 60,0W_C\right) \cdot 10^{-3}; \\ &\text{membrane}: \lambda_{xx}^{(2)} = 66,0 \cdot 10^{-3}; \quad \lambda_{yy}^{(2)} = 75,0 \cdot 10^{-3}; \\ &\text{PES}: \lambda_{11}^{(3)} = 28,0 \cdot 10^{-3}; \qquad \lambda_{22}^{(3)} = 32,0 \cdot 10^{-3}. \end{aligned} \tag{22}$$

$$\begin{aligned} &\text{cotton}: \lambda_w^{(1)} = 2522,0 + 1030,9\exp\left(-22,39W_C\right) \quad c^{(1)} = \frac{1663.0 + 4184.0W_C}{\left(1 + W_C\right)1610.9} \\ &\text{membrane}: \lambda_w^{(2)} = 2800,0 \quad c^{(2)} = 1820,0 \qquad \text{PES}: \lambda_w^{(4)} = 2340,0 \quad c^{(4)} = 1590,0 \end{aligned} \tag{23}$$

$$F_P = \int_0^{t_f} \left\{ \int_{\Gamma_{ext}} \left[h_w \left(w_f^p - w_{f\infty}^p \right) + q_{w,n} v_n^p \right] d\Gamma_3 + \int_{\Sigma} \left] q_w \mathbf{v}^p \cdot \boldsymbol{\upsilon} \right[\right\} dt; \qquad p = 1,2 \tag{24}$$

$$\frac{DF}{Db_p} = F_p = \int_0^{t_f} \left(\frac{1}{n} \left(F_w\right)^{\frac{1-n}{n}} \frac{D\left(F_w\right)}{Db_p} \right) dt \qquad p = 1,\ 2 \ldots P.$$

$$\left(F_w\right)_p = \int_0^{t_f} \left\{ \int_{\Gamma_{ext}} \left[\frac{n}{w_{f0}} \left(\frac{w_f}{w_{f0}} \right)^{n-1} w_f^p + \left(\frac{w_f}{w_{f0}} \right)^n {}_{,n} v_n^p \right] d\Gamma_{ext} + \int_{\Sigma} \left] \left(\frac{w_f}{w_{f0}} \right)^n \mathbf{v}^p \cdot \boldsymbol{\upsilon} \right[d\Sigma \right\} dt; \quad p = 1..4 \tag{25}$$

Equation 20, 21, 22, 23, 24 and ***25.***

The total heat loss by conduction and evaporation is listed in ***Table 1*** (see page 85); the head is characterized by convectional heat loss only. Heat losses by radiation and convection are determined for different heat reduction factors (that is $F_{cl} = 0,98$ and $F_{cl} = 0,86$) for all body portions, excluding the head, cf. ***Table 2***. The global heat loss by convection is equal to $C_{resp} = 0,082\ W\,kg^{-1}$, whereas by evaporation – $E_{resp} = 0,046\ W\,kg^{-1}$.

The thickness of the bonnet material should be optimized to reduce the risk of hyperthermia or hypothermia. The material parameters of the fabric are a function of the fractional water content on the fiber surface described by the water vapour concentration in fibers and material density, whereas for the membrane they are moisture independent [17]. The particular layers are made of the materials: $i = 1$ cotton (internal knitted fabric), $i = 2$ membrane & $i=3$ PES (external knitted fabric). The directions of axes are shown in ***Figure 2***. The first stage of sorption is determined by the time $t < 540\ s$, whereas the second stage – by $t \geq 540\ s$. The orthotropic matrix of diffusion coefficients in fibers has the following form [17], see ***Equation (20)***.

(20)

The layers are homogenized by means of *the rule of mixture*. The diffusion coefficient of water vapour in air is equal to $D_a = 2,5e^{-5}$. The material porosity and sorption coefficient of water vapour in the material are introduced as a constant in the form of ***Equation (21)***.

Heat conduction coefficients in orthotropic material are defined as follows [17], see ***Equation (22)***.

The cross-transport coefficient λ_w and heat capacity c are determined in [17] see ***Equation (23)***.

Let us define the primary problem by the transport equations ***Equation (11)*** accompanied by the conditions ***Equation (12)***. The main objective is to minimise the moisture content on the external boundary of the bonnet by means of ***Equation (18)***. The direct problem is solved using ***Equation (14)*** and Eqs. (15) for the initial time $t_0 = 0$, final time $t_k = 900s$ and increment $\Delta t = 60s$. Thus both phases of sorption are analysed. The surface film conductance is equal to $h = 8W/(m^2K)$. The external boundary is a straight line of mean curvature $H = 0$. The sensitivity expression is defined in respect of ***Equation (16)*** and ***Equation (18) Equation (24).***

Optimisation is an iterative process and consists of an analysis and synthesis stage. The multilayer structure at the analysis stage is approximated during the heat and moisture transport by the same finite element net. Let us introduce the plane rectangular 4-nodal elements of the nodes in corners. The total structure has 982 elements of 2920 nodes. The set of state variables is determined using a primary and additional approach by solving the finite element equation. The directional minimum at the synthesis stage is determined by means of the second-order Newton procedure or alternatively the first-order method of steepest descent. Thus it is necessary to introduce additionally the limitation of material thickness, which can be not greater than $\pm 20\%$ in relation to the initial one. Let us analyse two cases: (i) a one-layer bonnet made of cotton knitted fabric ($i = 1$), and (ii) three-layer material made of cotton, membrane and PES ($i = 1,2,3$). The initial and optimal thicknesses, the reduction in the objective functional and the number of iterations necessary for optimisation are listed in ***Table 3***. The optimal thicknesses of layers are equal to the limit imposed.

The other objective functional ensures equalised moisture distribution, cf. ***Equation (19)*** for the exponent $n = 25$. The corresponding sensitivity expression has the form, cf. ***Equation (16)***: ***Equation (25).***

The structure is approximated using the same finite elements and is minimised under the same assumptions. The results are shown in ***Table 4***. The dry heat loss and evaporative heat loss in respect of the three most typical covering areas are listed in ***Tables 5*** & ***Table 6***.

Let us analyse special medical clothing made of PE-foil of $F_{cl} = 0{,}98$, and combined clothing of $F_{cl} = 0{,}86$. Introducing $A = 4{,}5$ *days*, the metabolic heat production ***Equation (1)*** and the heat storage rate ***Equation (2)*** are determined. Next we calculate the increase in temperature ***Equation (9)*** and characteristic times ***Equation (10)***. The results are shown in ***Table 7*** and ***Table 8***, except for the times of heat stroke $t_{40°C}$ and lethal threshold $t_{43°C}$, which are the simple multiplication of the warning time $t_{38°C}$. Heat storage rates and increases in temperature are

Table 4. *Minimization of moisture content on the external boundary of bonnet.*

Case	Initial thickness, m	Optimal thickness, m	Reduction of obj. functional, %	Nr of iterations
1 layer	0.004	0.0036	8.9	19
3 layers	0.003	0.0037	11.5	17
	0.0005	0.0005		
	0.001	0.0009		

Table 5. *Dry (radiational and convectional) heat loss through head, W kg*$^{-1}$.

Material thickness, m	Covering area of bonnet, %		
	20	50	80
0.0048	2.401	1.927	1.597
0.0047	2.406	1.936	1.607
0.0036	2.461	2.031	1.718
0.0051	2.386	1.903	1.570

Table 6. *Evaporative heat loss through head, W kg*$^{-1}$.

Material thickness, m	Covering area of bonnet, %		
	20	60	100
0.0048	1.536	1.233	1.022
0.0047	1.539	1.238	1.028
0.0036	1.574	1.299	1.099
0.0051	1.527	1.217	1.004

Table 7*. Characteristic parameters for combined clothing* $F_{cl} = 0{,}86$.

Increase in temperature °C/h

Material thickness, m	Covering area of bonnet, %		
	20	60	100
0.0048	0.246	0.456	0.602
0.0047	0.234	0.453	0.598
0.0036	0.233	0.411	2.033
0.0051	0.253	1.730	0.615

Time $t_{38°C}$ *h*

Material thickness, m	Covering area of bonnet, %		
	20	60	100
0.0048	4.053	2.189	1.659
0.0047	4.260	2.206	1.670
0.0036	4.280	2.433	1.820
0.0051	3.950	2.138	1.625

Table 8. *Characteristic parameters for medical clothing made of PE-foil* $F_{cl} = 0{,}98$.

Increase in temperature °C/h

Material thickness, m	Covering area of bonnet, %		
	20	60	100
0.0048	0.109	0.319	0.465
0.0047	0.107	0.316	0.461
0.0036	0.083	0.274	0.412
0.0051	0.116	0.330	0.478

Time $t_{38°C}$ *h*

Material thickness, m	Covering area of bonnet, %		
	20	60	100
0.0048	9.122	3.127	2.147
0.0047	9.306	3.163	2.166
0.0036	12.020	3.651	2.425
0.0051	8.617	3.025	2.091

always positive, which indicates a moderate risk of hyperthermia. Thus metabolic heat production is greater than the heat lost by the body, although the differences are relatively small. The warning and mortality times are also positive, but relatively long to minimise the risk of hyperthermia.

Conclusion

To ensure heat balance, the difference between metabolic heat production and different heat loss mechanisms within all body parts should approach zero. The most sensitive portion is the head, which forces local optimization of the bonnet thickness. An additional factor is the covering area of the bonnet, which balances the heat and consistently minimises the risk of hyperthermia or hypothermia. The crucial point is the interaction between the thickness and covering level. The most beneficial strategy should introduce the minimisation of both the material thickness and covering area; but there are some difficulties during modelling and calculations. Moreover the heat balance and minimisation of the material thickness are determined by means of the same physical phenomena.

The risk of hyperthermia can be estimated by empirical correlations of characteristic times. The most important is the safe temperature limit $t_{38^\circ C}$, that is the risk limit of balance self-regulation; nevertheless, the times of the heat stroke and lethal threshold $t_{40^\circ C}$; $t_{43^\circ C}$ are also important.

The balance between metabolic heat production and different heat losses is determined globally. The problem is defined for various mechanisms of heat transport and additionally by evaporation. Thus a part of heat is transported by moisture, which in fact defines the coupled heat and mass transport. These phenomena are defined mathematically by typical equations, but the input data are determined statistically.

The material thickness is determined locally by the heat and mass transport equations accompanied by the set of conditions. State variables can be determined on a local scale within the complex structure of clothing with membrane. The additional effects and various structures can be analysed, for example phase change materials, membranes, the influence of materials within textile composites etc. The state fields can also be visualised to introduce some new ideas of analysis and interpretation.

Irrespective of the different mathematical forms, the equations define the same physical model. Of course, the models presented contain some simplifications, which are, for example, the constant skin temperature in a variable metabolism, a simplified description of some components, considerable tolerances of input parameters etc. The reason is the personal physiology of heat losses within the organism.

According to calculations, the most critical body portion is the head, subjected to the greatest heat loss. Local optimisation gives the exact results of optimal thicknesses for material layers in the bonnet. However, the optimal thickness of the structure is evidently approximate because the knitted fabric can change dimensions under various loads. Practically speaking, the covering area of the bonnet is the only control parameter in respect of the balanced heat transport. Additionally the precise covering area is difficult to determine and monitor, which warrants permanent medical care of the newborn baby. Irrespective of the conditions and changes in dimensions, the results obtained show that there is no risk of hypothermia for typical thicknesses of textile bonnets. The emperature-rise limit and warning time $t_{38^\circ C}$ are relatively safe for a neonate under medical care in the incubator inspected.

Of course, theoretical analysis needs practical verification, which has already been discussed partially in literature [1]. However, the problem is complicated, time-consuming and costly-, needing statistically-oriented applied research in medical clinics, which is beyond the scope of this theoretical paper.

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