Heat Transfer Simulation Modelling for Unclothed Human Infants

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Received 26 November 2014, in revised form 24 February 2015 and accepted 17 March 2015

The thermal regulation response of a neonate has to maintain temperature homeostasis, thereby resisting the changes to core temperature caused by heat loss to the unstable external environment. In this paper a theoretical heat transfer simulation model for a human infant subject to a well-defined environment is presented. This model will aid in understanding the influences of environmental effects, such as temperature, relative humidity and air velocity, on core and skin temperature. The influence of subject-specific properties, such as metabolic heat production capability, weight and surface area subject to heat loss is also evaluated. A clinical trial was conducted to facilitate a better understanding of thermal stability in neonates. The data acquired during the clinical trial was used to validate the theoretical simulation model. From the results gleaned it can be concluded that this theoretical simulation model can be used with reasonable confidence and accuracy to predict the outer skin layer temperature of the neonate.

Additional keywords: Temperature response, neonate, heat transfer, numerical modelling, thermal environments

Nomenclature

Roman

A	area [m^2]
c	specific heat constant [J/kgK]
D	diameter [m]
D_{AB}	diffusion coefficient
E	energy [J]
$\dot{E}$	energy [W]
F	form factor
g	gravitational acceleration [m/s^2]
h	latent heat of vaporization or heat convection coefficient [J/kg]
k	thermal conductivity [W/mK]
KE	kinetic energy [J]
L	length [m]
m	mass [kg]
$\dot{m}$	mass flow rate [kg/s]
n	decimal percentage value
Nu	Nusselt number
P	pressure [Pa]
PE	potential energy [J]
Pr	prantl number
$\dot{Q}$	heat transfer rate [W]
R	thermal resistance [°C/W]
Ra	Rayleigh number, $Ra = g\beta\, Pr(T_1 - T_2)\, L^3/(\mu/\rho)^2$
Re	Reynolds number, $Re = V_a L/(\mu/\rho)$
Sc	Schmidt number, $Sc = (\mu/\rho)/D_{AB}$
St	Stanton number, $St_{mass} = St_{heat} Pr^{0.67}/Sc_a^{0.67}$, $St_{heat} = Nu_a/Re_a Pr$
t	time [s]
T	temperature [°C/K]
U	internal energy [J]
V	velocity [m/s]
W	weight [kg]
$\dot{W}$	work energy [W]
x	thickness [m]

Greek

β	volume expansivity [1/K]
Δ	change
δ	thickness [mm]
ε	emissivity
μ	dynamic viscosity [kg/ms]
ρ	density [m^3/kg]
σ	Stefan-Boltzmann's constant
ϕ	relative humidity
ω	specific humidity [kg H_2O/kg dry air]

Subscripts

a	air
act	actual
art	artery
atm	atmosphere
b	body
bl	blood
c	convection, clothing
d	diffusion
e	evaporation, enclosure
f	fluid, fat layer, forced
g	gas, vapour
gen	generate
h	heat, head
in	direction of flow
isl	inner skin layer
l	lung
mt	mass transfer
n	natural
osl	outer skin layer
out	direction of flow
r	room, radiation
s	skin surface
sl	skin lung

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1 Introduction

The actual human thermal regulation system is very complex; however, a simple engineering based model can be derived as shown in figure 1. The thermal regulation system essentially consists of complex physiological systems such as the respiratory system, the blood circulation system and the largest organ of the human body, the skin. The thermal regulation system further includes the control mechanism located in the hypothalamus.

Figure 1 shows the heat transfer $\dot{Q}$ from the "body" to the air, at a temperature T_a, relative humidity ϕ_a and atmospheric pressure P_a in an enclosure at temperature T_e. The respiratory system consists of a reciprocating diaphragm air pump and a valve to allow air to pass through the nose or mouth. The respiratory system further includes a diffusion barrier of thickness δ_{sl} through which mass (water vapour, oxygen, carbon dioxide, etc.) and heat may be transferred between the air in the lung and the blood. Heat and mass (water vapour) is transferred from the blood through the skin to the air and surroundings.

In this paper only the heat transfer by conduction, convection, radiation and evaporation, from the blood through the skin to the surrounding air and surfaces will be considered. A transient heat transfer simulation model for an unclothed infant to its isolated surroundings is developed, assuming a given constant blood temperature T_{bl}. The simulation model is developed from first principles by applying the conservation of energy and heat transfer theory to clearly identified control volumes representing various layers of skin tissue. The set of difference equations so obtained are solved numerically using an explicit transient numerical solution method. Before developing the simulation model a literature review will be given as well as some background physiology relating to blood and skin. The validity of the results provided by the theoretical simulation model will be discussed and conclusions will be provided.

2 Literature Review

In physiological terms homeostasis can be defined as "*the dynamic consistency of the internal environment and refers to the physiological control processes that must fight the changes, caused by external factors, in order to maintain relatively constant conditions within our body*"[1]. Normal body temperature represents the optimal thermal conditions needed to support internal functions, such as the digestive system, respiratory system, blood circulation system etc. Thermoregulatory responses are generated in the hypothalamus and balance heat production through metabolism to maintain normal core body temperature. Body heat is mainly produced by metabolism and non-shivering thermogenesis, although heat generation by shivering is possible after 3 months. Metabolism reflects the overall energy needs which support maintenance, repair and growth[3] of the infant, which is counterbalanced by heat loss via convection, conduction, radiation and evaporation heat transfer. Core body temperature is the variable that is precisely controlled by means of thermal regulation and is the most important parameter for maintaining temperature homeostasis within the body. The principal external factors that influence changes in skin and consequently core

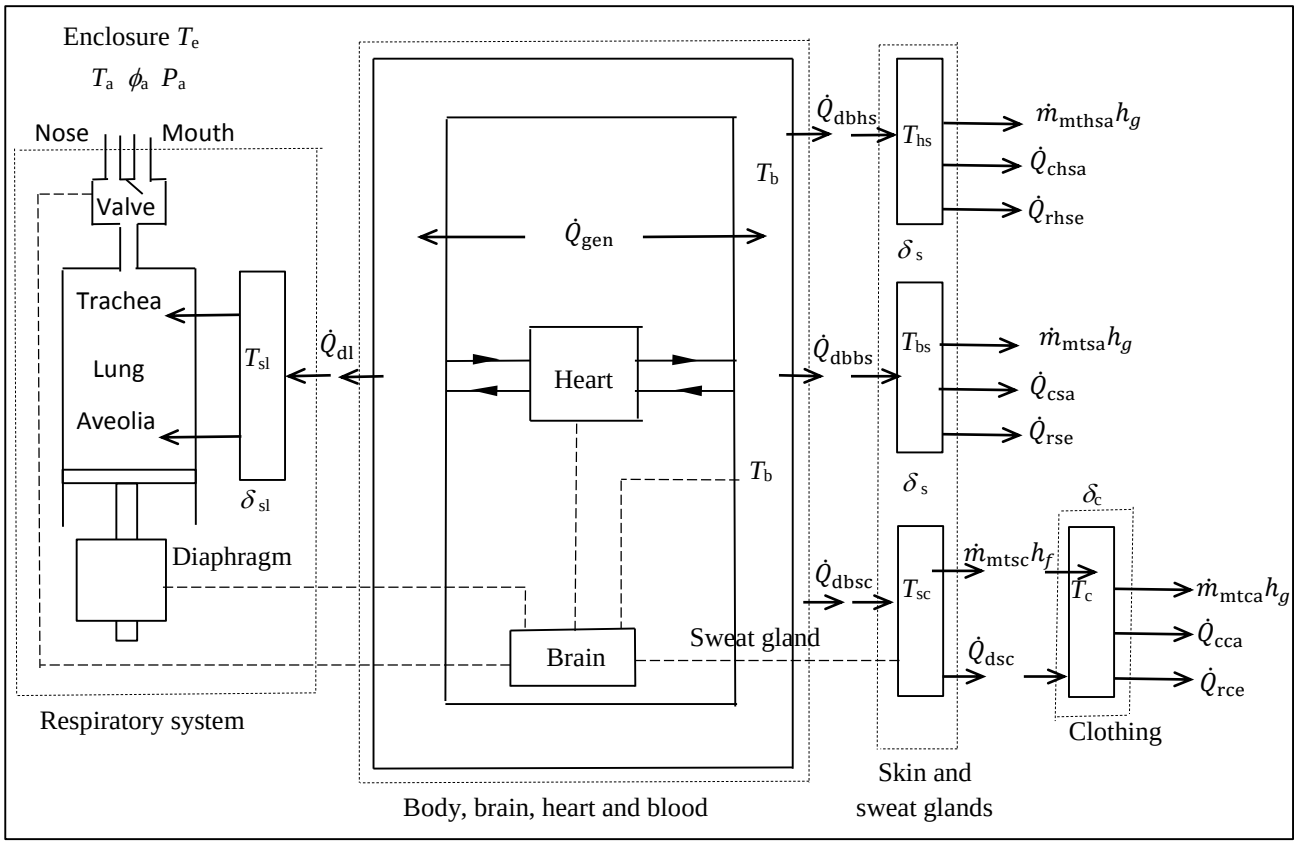

Figure 1: Simple model of the thermal regulation system of the human body in an enclosure

temperature, include temperature, relative humidity and air velocity. Thermal stability is that property of a system which opposes variations in heat content under conditions allowing net thermal exchange between the object and its environment. Thermal stability is a function of body size, surface area, thermal insulation and the degree by which heat output can be altered[3]. An understanding of these avenues for heat exchange provides the basis for modification of the enclosed/immediate environment.

Heat is lost from the skin surface as well as the conditioning surface area in the respiratory tract. Surface area is directly related to the amount of heat exchange between the body and environment. The greater the ration of surface area to mass, the greater the imbalance between heat producing ability and heat loss. Infants have a large body surface area to mass ratio of between 2.5:1 to 3:1, which results in increased heat loss[4].

Heat loss via conduction occurs directly through body tissue from the internal heat producing organs to the skin surface area and diffuses heat to contacting surface areas such as a mattress[5]. The temperature gradient between the skin and contacting surface has the largest influence on the rate of conduction heat loss.

There are three principal ways in which convection heat loss takes place[5]: convection heat loss from the blood stream to the skin. Convection heat loss also occurs when cold air moves across the skin surface. The third method of convection entails transfer of warmed inspired air to the environment during an exhalation phase; this is also called respiratory convective heat loss.

Heat loss via radiation occurs from the infant's skin to surrounding surfaces and is influenced by the emissivity of the radiating surfaces, temperature gradient between radiating surfaces, the surface areas and the distance between the radiating surfaces.

Heat loss via evaporation can also be accounted for by three methods[5]: insensible heat loss from the skin surface, evaporation of sweat from the skin surface during heat exhaustion; and evaporation heat loss during the respiratory process with evaporation from the mucous of the respiratory tract into expired air. Premature infants have increased evaporative heat losses as water diffuses across the permeable skin barrier and evaporates. Factors that influence the rate of evaporation are the air velocity, surface area and the vapour pressure (which is related to the temperature and water vapour gradients of the air).

3 Physiology

Physiology regarding the blood circulation system and skin tissue is presented to serve as a background for the development of the theoretical heat transfer simulation model that is presented later in this paper.

3.1 Blood

Blood is the fluid that delivers substances such as oxygen, nutrients and hormones to cells and transports metabolic wastes away from those same cells[1]. Bioheat transfer is the process in which living tissues are influenced by the local temperature distribution as well as the blood perfusion rate through the vascular network[6]. When there is a significant temperature difference between the blood and the tissue through which it flows, convective heat transfer will occur, altering the temperature of both the blood and the tissue. Perfusion based convective heat transfer is critical to thermal regulation where the rate of perfusion of blood through different tissues depend on physical activity, physiological stimulus and environmental conditions[6].

3.2 Skin

The skin is a vital organ of the human body; it is self-maintaining, self-repairing and it has a sensory and protective function. The skin plays an important role in thermal regulation, water excretion, fat storage and insulation[7]. Skin acts as a chemical barrier in limiting penetration by foreign substances and also provides mechanical protection against physical penetration. The three layers of the skin considered in this paper are the viable epidermis layer, dermis layer and the hypodermis layer as indicated by figure 2.

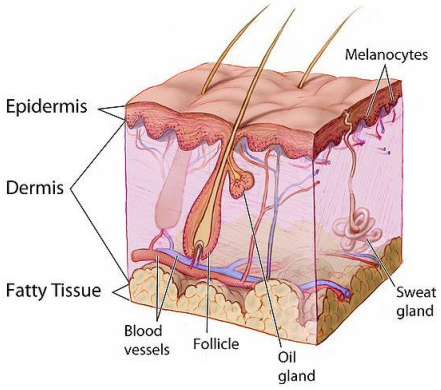

Figure 1: Skin physiology[8]

The total thickness of the epidermis varies between 30 to 100 μm [9] and is influenced by environmental conditions such as relative humidity and temperature. The basal layer of the epidermis is attached to the next considered layer in the skin physiology, the dermis. The dermis thickness ranges from 1 to 4 mm [9] and cushions the body from stress and strain.

The hypodermis, also known as the subcutaneous adipose layer, is not a functional part of the skin. The purpose of the hypodermis is to attach the skin to underlying bone and muscle as well as supplying the skin with blood vessels and nerves. The thickness of the hypodermis varies with anatomical site, age, sex, race and nutritional status of an individual. The functions of the hypodermis include heat insulation as well as providing a caloric reservoir where stored fat is the predominant component.

Two types of subcutaneous adipose tissue can be defined, namely brown adipose tissue and white adipose tissue. Brown adipose tissue (brown fat) differs morphologically and metabolically from ordinary white adipose tissue (white fat) in that it contains more capillaries than white fat because of its greater need for oxygen. Brown fat is of particular relevance to this study because of the role it plays in generating heat in infants. Brown adipose tissue is located primarily in the subscapular, axillary, adrenal and mediastinal regions and can rapidly increase cellular metabolic rates and oxygen consumption, thereby generating heat[2]. Brown adipose tissue may account for as much as one third of the overall metabolic rate[10]. Brown adipose tissue does not

continue to develop after birth. The primary function is to generate body heat in infants.

4 Theoretical heat transfer simulation model

A heat transfer simulation model for the human body thermal response can be considered as a possible valuable tool which can be used to understand the human body thermal behaviour under different environmental conditions and activity levels. The simulation model presented in this article is used to determine how the thermal regulation system of the infant, at any premature age, has to adapt and function to maintain thermal stability in a given environment (e.g. incubator or bassinette in a neonatal ward). The theoretical model includes analysis of heat loss from blood flow to the hypodermis, conduction through the skin layers and heat loss from the skin surface, via convection, radiation and evaporation.

4.1 Derivation of heat transfer equations based on energy conservation

From the conservation of energy it follows that the total energy expended for a control volume is equal to the difference between the sum of the input energy and the sum of the output energy[11] as shown in equation 1.

$$\Delta E/\Delta t = \sum \dot{E}_{in} - \sum \dot{E}_{out} \quad (1)$$

The energy that a system possesses ($\Delta E/\Delta t$) is calculated by taking the internal- (U), kinetic- (KE) and potential (PE) energy into account, as shown in equation 2, and multiplying the energies with the rate of mass flow ($\dot{m}$).

$$\Delta E/\Delta t = \Delta \sum \dot{m}(U + KE + PE) \quad (2)$$

The case studies in this theory are considered as stationary systems, thus it follows that the potential and kinetic energy can be neglected in equation 2. Further, the input and output energy can also be calculated by taking into account the heat ($\dot{Q}$), work ($\dot{W}$) and mass transferred ($\dot{E}_{mass}$) within the specified control volume, as described by equation 3.

$$\Delta E/\Delta t = \Delta \sum \dot{Q} + \Delta \sum \dot{W} + \Delta \sum \dot{E}_m \quad (3)$$

The major focus in this theory is the internal energy as well as the heat and mass transferred. Equations 2 and 3 are used to develop equation 4, which relates the total internal energy of a system to the difference in total heat and mass transfer crossing the system boundaries.

$$\Delta U/\Delta t = \sum \dot{Q}_{in} - \sum \dot{Q}_{out} + \sum \dot{E}_{m,in} - \sum \dot{E}_{m,out} \quad (4)$$

The internal energy can be simplified as $U = mc\Delta T$ so that equation 4 is a function of mass (m), specific heat (c) and temperature (T).

$$\Delta(mcT)/\Delta t = \sum \dot{Q}_{in} - \sum \dot{Q}_{out} + \sum \dot{E}_{m,in} - \sum \dot{E}_{m,out} \quad (5)$$

An approximation for the specific heat constant is made, where $c_p \sim c_v = c$. Equation 5 may then be solved using an explicit transient numerical solution method such that equation 6 is developed.

$$(mcT)^{t+\Delta t} = (mcT)^t + \Delta t\left(\sum \dot{Q}_{in} - \sum \dot{Q}_{out} - \dot{m}h_g\right)^t \quad (6)$$

Further, assume that properties such as specific heat and density are constant over small temperature variations; it then follows that equation 6 can be reduced to form equation 7. The equation developed for calculating temperature according to the explicit finite difference method, stated in equation 7, will be applied to predefined control volumes for the fat layer, inner skin layer and outer skin layer.

$$T^{t+\Delta t} = T^t + \Delta t/mc\left(\sum \dot{Q}_{in} - \sum \dot{Q}_{out} - \dot{m}h_g\right)^t \quad (7)$$

4.2 Heat transfer through fat layer

The fat layer thermal resistance diagram is presented in figure 3 and introduces blood circulation into the fat layer which results in heat conduction to the inner skin layer (dermis).

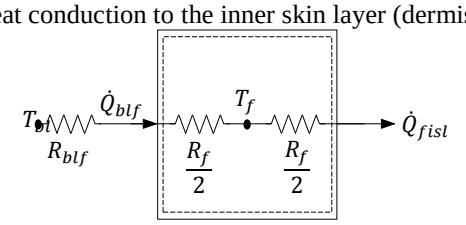

Figure 2: Thermal resistance diagram for the fat layer (hypodermis) beneath the skin

The temperature of the blood is a function of the metabolic heat produced and the heat transferred to the fat layer by means of convection. If the infant has fully functional metabolic heat production capability it is assumed that the blood temperature stays constant at core body temperature throughout the simulation.

The blood temperature $T_{bl}^{t+\Delta t}$ is expressed by equation 8 according to the explicit finite difference method as stated in section 4.1.

$$T_{bl}^{t+\Delta t} = T_{bl}^t - (\Delta t/(mc)_f)(\dot{Q}_{blf}^t) + \dot{Q}_{metabolic}^t \quad (8)$$

The heat transfer, via convection, from the blood to the fat $\dot{Q}_{blf}^t$ is given by equation 9, and the metabolic heat production capability is given by equation 10.

$$\dot{Q}_{blf}^t = (T_{bl} - T_{fat})/\left(R_{blf} + R_f/2\right) \quad (9)$$

$$\dot{Q}_{metabolic}^t = n(\Delta t/(mc)_f)(\dot{Q}_{blf}^t) \quad (10)$$

The efficacy of the metabolic heat production system is incorporated by a factor n. Efficacy is defined as the capability of producing metabolic heat to maintain constant core body temperature.

Convection R_{blf} and conduction R_f resistances for the blood and fat layer are defined respectively in equations 11 and 12. The fat layer conduction coefficient k_f is 0.16 W/mK [12].

$$R_{blf} = 1/h_{bl}A_f \quad (11)$$

$$R_f = \Delta x_f/k_f A_f \quad (12)$$

In order to determine the heat transfer coefficient of blood h_{bl}, it is assumed that blood flow in arteries close to the skin is laminar because of the small artery diameters[6]. Artery diameters near the skin ranges from 0.01 to 0.00001 mm. The Nusselt number for laminar flow in a tube is 3.6 [13]. The convection coefficient of the blood can now be calculated using equation 13, where the blood conduction coefficient k_{bl} is 0.492 W/mK [12].

$$h_{bl} = Nuk_{bl}/D_{artery} \quad (13)$$

The temperature for the fat layer $T_f^{t+\Delta t}$ is given by equation 14 and is developed according to the explicit finite difference method, as derived in section 4.1.

$$T_f^{t+\Delta t} = T_f^t + (\Delta t/(mc)_f)(\dot{Q}_{blf}^t - \dot{Q}_{fisl}^t) \quad (14)$$

The conduction from the fat layer to the inner skin layer $\dot{Q}^t_{fisl}$ is described by equation 15.

$$\dot{Q}^t_{fisl} = (T_f - T_{isl})/(R_f/2 + R_{isl}/2) \quad (15)$$

Equation 16 can be used to calculate the inner skin layer conduction resistance R_{isl}, where the inner skin layer conduction coefficient k_{isl} is 0.47 W/mK [12].

$$R_{isl} = \Delta x_{isl}/k_{isl}A_{isl} \quad (16)$$

4.3 Heat transfer through dermis

The inner skin layer (dermis) thermal resistance diagram is located between the fat layer and the outer skin layer (epidermis) as presented in figure 4.

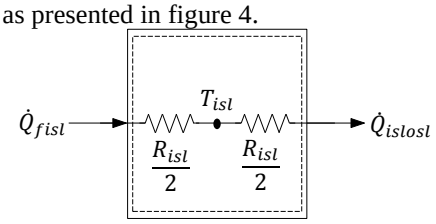

Figure 3: Thermal resistance diagram for the inner skin layer (dermis)

The equation developed for temperature of the inner skin layer $T^{t+\Delta t}_{isl}$ according to the explicit finite difference method, as derived in section 4.1, is given by equation 17.

$$T^{t+\Delta t}_{isl} = T^t_{isl} + (\Delta t/(mc)_{isl})(\dot{Q}^t_{fisl} - \dot{Q}^t_{islosl}) \quad (17)$$

Heat is transferred from the fat layer to the outer skin layer by conduction as described by equations 18 and 19 respectively.

$$\dot{Q}^t_{fisl} = (T_f - T_{isl})/(R_f/2 + R_{isl}/2) \quad (18)$$

$$\dot{Q}^t_{islosl} = (T_{isl} - T_{osl})/(R_{isl}/2 + R_{osl}/2) \quad (19)$$

The conduction coefficient for the inner skin layer is given by equation 16. The conduction resistance for the outer skin layer R_{osl} is defined by equation 20, where the outer skin layer conduction coefficient k_{osl} is 0.47 W/mK [12].

$$R_{osl} = \Delta x_{osl}/k_{osl}A_{osl} \quad (20)$$

4.4 Heat transfer through epidermis

The outer skin layer thermal resistance diagram is presented in figure 5 and indicates how the skin temperature is affected by four heat transfer mechanisms. These heat transfer mechanisms include heat conduction through the outer skin layer $\dot{Q}^t_{islosl}$ and $\dot{Q}^t_{osls}$, convection to the air $\dot{Q}^t_{c,sa}$, radiation to the surrounding walls $\dot{Q}^t_{r,sw}$, and the evaporation of moisture from the skin surface to the air $\dot{Q}_{e,sa}$.

The temperature of the unclothed outer skin layer $T^{t+\Delta t}_{osl}$ can be calculated by using equation 21, and is developed according to the explicit finite difference method as derived in section 4.1. Note that the convection from the air to the incubator wall is not included because it does not affect the skin temperature directly.

$$T^{t+\Delta t}_{osl} = T^t_{osl} + (\Delta t/(mc)_{osl})(\dot{Q}^t_{islosl} - \dot{Q}^t_{osls} - \dot{Q}^t_{c,sa} - \dot{Q}^t_{r,sw} - \dot{Q}_{e,sa}) \quad (21)$$

The conduction heat transfer into the outer skin layer $\dot{Q}^t_{islosl}$ is given by equation 22, where the conduction resistance R_{osl} is given by equation 20. Equation 23 is used to calculate the conduction out of the outer skin layer $\dot{Q}^t_{osls}$.

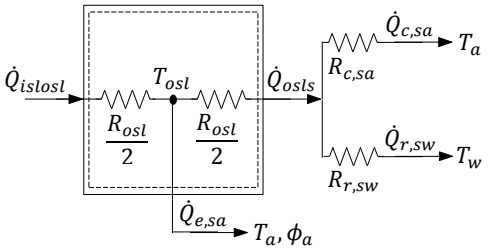

Figure 4: Thermal resistance diagram for the outer skin layer (epidermis) without clothing

$$\dot{Q}^t_{islosl} = (T_{isl} - T_{osl})/(R_{isl}/2 + R_{osl}/2) \quad (22)$$

$$\dot{Q}^t_{osls} = (T_{osl} - T_s)/(R_{osl}/2) \quad (23)$$

Radiation heat transfer $\dot{Q}^t_{r,sw}$ is calculated with equation 24, with temperature measured in Kelvin.

$$\dot{Q}^t_{r,sw} = (T^4_{osl} - T^4_w)R_{r,sw} \quad (24)$$

The convection from the outer skin layer to the surrounding air $\dot{Q}^t_{c,sa}$ is taken into account by using equation 25.

$$\dot{Q}^t_{c,sa} = (T_{osl} - T_a)/R_{c,sa} \quad (25)$$

Evaporation heat transfer $\dot{Q}^t_{e,sa}$ is given by equation 26 and will continue to take place until the surrounding air has saturated completely, reaching a relative humidity value of 100%.

$$\dot{Q}^t_{e,sa} = \dot{m}_{e,sa}h_{g@Tosl} \quad (26)$$

The calculated radiation resistance $R_{r,sw}$ must take into account the emissivity of both the skin surface ε_{osl} and the surrounding wall surface ε_w and is calculated with equation 27. A form factor must be incorporated to compensate for the amount of radiation leaving the skin and transmitting to the incubator wall surface. For the case under consideration the form factor $F_{osl,w}$ is 1, because all the radiation leaving the infant's skin is assumed to transmit to the surrounding walls.

$$R_{r,sw} = \sigma/\left[\left(\frac{1-\varepsilon_{osl}}{\varepsilon_{osl}A_{osl}}\right) + \left(\frac{1}{F_{osl,w}A_{osl}}\right) + \left(\frac{1-\varepsilon_w}{\varepsilon_w A_w}\right)\right] \quad (27)$$

Further calculations discussed in this section revolve around the parallel development of the heat h_h and mass h_m convection coefficients for convection and evaporation heat transfer. The convection resistance, given by equation 28, is dependent on the heat transfer coefficient.

$$R_{c,sa} = 1/h_h A_{osl} \quad (28)$$

The heat transfer coefficient is calculated by using the Nusselt number as given by equation 29. The Nusselt number incorporates the geometry and orientation of the infant. The body of the infant is approximated as a horizontal cylinder for the heat and mass transfer convection calculations in this section.

$$h_h = Nu_a k/L \quad (29)$$

The Nusselt number Nu_a used for convection consists of a combination of natural and forced convection as indicated by equation 30.

$$Nu_a = (Nu_f^{1/3} + Nu_n^{1/3})^3 \quad (30)$$

Forced convection Nu_f is caused by air velocity in the vicinity of the infant's surroundings. An increase in the forced Nusselt number will cause an increase in the

convection heat transfer. The forced convection Nusselt number for flow over a horizontal cylinder is given by equation 31.

$$Nu_f = 0.3 + \left[\frac{\left(0.62Re^{\frac{1}{2}}Pr^{\frac{1}{3}}\right)}{\left(1+(0.4/Pr)^{\frac{2}{3}}\right)^{\frac{1}{4}}}\right]\left[1+\left(\frac{Re_a}{282000}\right)^{\frac{5}{8}}\right]^{\frac{4}{5}} \quad (31)$$

The Reynolds number Re, given by equation 32, integrates the velocity, as well as the dynamic viscosity and density of the surrounding air.

$$Re = V_a L/(\mu/\rho) \quad (32)$$

Natural convection takes place due to a temperature difference between the infant's skin and the surrounding air. The natural convection Nusselt number Nu_n is described by equation 33 for a horizontal cylinder.

$$Nu_n = \left(0.6 + \left[0.387Ra_a^{\frac{1}{6}}\right] / \left[1+\left(\frac{0.559}{Pr}\right)^{\frac{9}{16}}\right]^{\frac{8}{27}}\right)^2 \quad (33)$$

The Rayleigh number Ra_a, calculated with equation 34, is used to incorporate the temperature difference between the infant's skin and the surrounding air.

$$Ra_a = g\beta\, Pr(T_{osl} - T_a)\, L^3/(\mu/\rho)^2 \quad (34)$$

The last heat transfer mechanism taken into account is evaporation, where the amount of water diffused from the exposed skin surface must be calculated to determine the evaporative heat loss. When the infant is born, the whole body is covered by a layer of amniotic fluid, which implicates large evaporative heat losses. When the infant is dried off and placed in an incubator or bassinette, water diffuses through the sweat glands only. The area used in equation 35 depends on the particular situation under consideration. Mass evaporation $\dot{m}_{e,sa}$ will continue until the air is sufficiently humidified (100 % relative humidity).

$$\dot{m}_{e,sa} = h_m A_{infant} \rho(\omega_{osl} - \omega_a) \quad (35)$$

The mass convection coefficient h_m is calculated with equation 36. For a larger surrounding air velocity the mass convection coefficient will increase causing larger evaporative heat loss.

$$h_m = St_m V_a \quad (36)$$

For the approximations used in the development of the theoretical simulation model the dimensionless Stanton numbers, equation 37 for mass St_m and equation 38 for heat St_h, are used to relate the heat and mass convection.

$$St_m = St_h(Pr^{0.67}/Sc_a^{0.67}) \quad (37)$$

The heat Stanton number is calculated by using the Reynolds and Nusselt numbers from equations 32 and 30.

$$St_h = Nu_a/Re_a Pr \quad (38)$$

The Schmidt number Sc_a, given by equation 39, is used to characterise the mass evaporation process and is dependent on the diffusion coefficient D_{AB}. The diffusion coefficient for evaporation from water vapour to air is $2.5x10^{-5}$ [13].

$$Sc_a = (\mu/\rho)/D_{AB} \quad (39)$$

Evaporative heat transfer is dependent on the relative humidity of the surrounding air. The relative humidity is used to determine the amount of water vapour in the air using equations 40 and 41, where atmospheric pressure is defined as 101325 Pa.

$$P_{act,a} = \phi_a P_{sat@T_a} \quad (40)$$

$$\omega_a = 0.662P_{act,a}/(P_{atm} - P_{act,a}) \quad (41)$$

Sections 4.2 to 4.4 constitute the theoretical model developed for the infant skin without clothing. This model is used in section 4.5 where the infant is subjected to different thermal environments.

4.5 Environment

"*Thermal stability is that property of a system which opposes variations in heat content under conditions allowing net thermal exchange between object and environment*"[3]. Thermal stability is primarily a function of body size and surface area and is dependent on the degree to which heat output can be altered. The simulation model for the thermal environment discussed in this section will be used to analyse thermal stability of the infant in various thermal environments. The thermal resistance diagram for heat loss from the skin is depicted by figure 6.

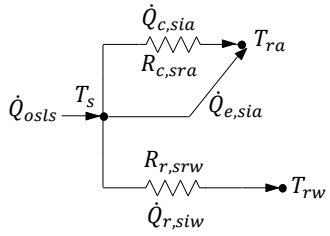

Figure 5: Thermal resistance diagram for heat loss from the skin

Equation 42 is used to calculate the temperature drop accordingly.

$$T_s^{t+\Delta t} = T_s^t + (\Delta t/(mc)_{osl})(\dot{Q}_{osls}^t - \dot{Q}_{c,sra}^t - \dot{Q}_{r,srw}^t - \dot{Q}_{e,sra}) \quad (42)$$

The theoretical simulation model for this section can be used to indicate the influence of environmental factors as well as to compare conventional drying after birth to placing the infant in the incubator before drying.

5 Results

Results obtained from the developed theoretical simulation model with regards to the thermal response of the neonate will be presented in this paper with reference to the influence of environmental factors as well as subject-specific properties. The properties of an average healthy neonate, born at 39 weeks gestation, will be used where the average weight is 3.3 kg. According to the Fetal-Infant Growth chart[14] the length and head circumference of the neonate is used as 0.50 m and 0.345 m, respectively. The core temperature is assumed as constant at 37 °C.

The environmental elements that influence the thermal response of the neonate include the room temperature and relative humidity as well as air velocity. These environmental factors will be evaluated by considering the skin temperature response of the neonate whilst looking at the time it takes for the neonate's skin temperature to reach equilibrium.

The subject-specific properties that will be investigated include the functioning metabolic heat production ability, weight of the infant in comparison to the exposed skin surface

area, as well as the surface area subject to evaporation. The latter will indicate the importance of drying the infant immediately after birth. The effects of these properties will be discussed with respect to the skin temperature response of the neonate. The results are evaluated for the first 300 seconds (5 minutes) of the infant's life.

5.1 Skin temperature distribution

Figure 6 presents the neonate's skin temperature distribution for the fat, inner skin and outer skin layer with a constant blood temperature of 37 °C. The room and wall temperatures were simulated at a constant temperature of 20 °C. The average relative humidity in Cape Town of 60% [15] was used with low air velocity simulated as 0.1 m/s.

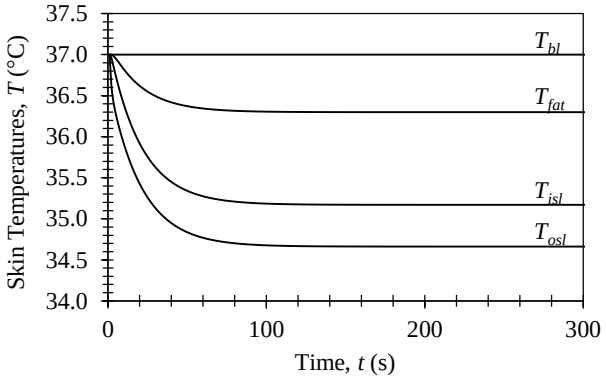

Figure 6: Skin layer temperature distribution

The results presented in figure 7 were simulated for a dried neonate (the ideal case) and indicates that it takes 113 seconds (approximately 2 minutes) to reach skin temperature equilibrium with temperature accuracy of 2 decimal places. The resulting difference between core body temperature (37.00 °C) and outer skin layer temperature (34.66 °C) is 2.34 °C. In healthy adults there is a ± 4.00 °C temperature difference between core body temperature and outer skin layer temperature.

5.2 Environmental elements

Figure 7 presents the neonate's outer skin layer temperature at various room temperatures, while the relative humidity and air velocity were simulated as constant. It can be seen from figure 8Figure 7 that a warmer environment results in a higher outer skin layer temperature. For a room temperature of 18 °C, the outer skin layer temperature decreases to 34.43 °C compared to the outer skin layer temperature of 35.38 °C, for a room temperature of 26 °C. These results implicate that lower metabolic heat production is needed for thermal regulation of the neonate at higher room temperatures.

The relative humidity is rarely adjusted or controlled, because of the assumed limited influence it has on thermal regulation. Figure 8 presents the neonate's outer skin layer temperature response at various delivery room relative humidity values, with a constant room temperature of 20 °C. For a relative humidity value of 30%, the outer skin layer temperature decreases to 34.58 °C compared to the outer skin layer temperature of 34.69 °C, for a relative humidity value of 70%. It is clear that the relative humidity does not have a big influence on the resulting skin temperature and thus the thermoregulation of the infant. It only assists in limiting the evaporative heat losses of the infant, as discussed in a later subsection.

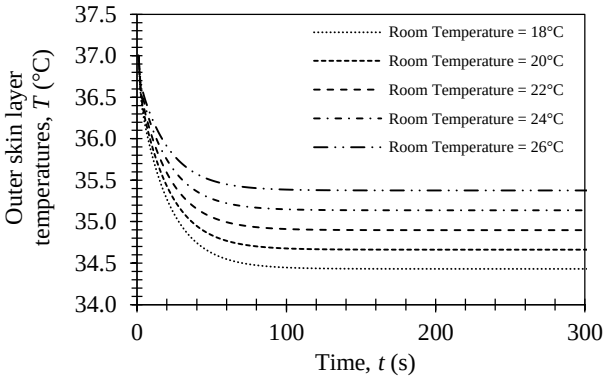

Figure 7: Outer skin layer temperature at different room temperatures and 60% relative humidity and 0.1 m/s air velocity

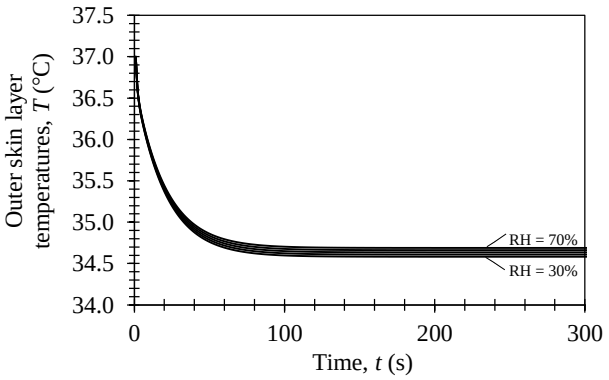

Figure 8: Outer skin layer temperature as a result of various relative humidity values with a room temperature of 20 °C and 0.1 m/s air velocity

The influence of air velocity on the skin temperature response of the neonate is presented in figure 10. These results were obtained for a constant room temperature and relative humidity of 20 °C and 60%, respectively.

From figure 10 it can be seen that low air velocities do not significantly affect the temperature response of the outer skin layer. Standard maximum air velocities for indoor rooms are specified as 2.4 m/s [16]. For a room air velocity of 0.5 m/s, the outer skin layer temperature is 34.29 °C compared to the outer skin layer temperature of 32.51 °C, for an air velocity of 2.4 m/s. It can be noted that the air velocity has a significant effect on the skin temperature response and thus the thermoregulation of the neonate. These results imply that more metabolic heat production is needed by the thermoregulation system of the neonate, at higher room air velocities.

5.3 Subject-specific properties

Metabolic rate has an influence on the time it takes for the infant's skin temperature to reach equilibrium. It takes less than 150 seconds for an infant outer skin layer temperature to reach equilibrium of 34.66 °C in a 20 °C room temperature with 60% relative humidity and low air velocity (that is < 0.1 m/s).

From figure 11, for an infant with 75% metabolic capability, temperature drops below 20 °C within 1227

seconds (20 minutes and 27 seconds) where 100% functioning metabolic capability allows the skin temperature to stabilise at 34.66 °C within the first 113 seconds (1 minute and 53 seconds). For lower metabolic heat producing capability percentiles, the time it takes for the skin to reach room temperature decreases rapidly from 868 seconds for 50% functioning metabolic heat production, to 691 seconds for a non-responsive metabolic heat production system. These results emphasise the importance of monitoring the core temperature of the neonate. These results can also be used to determine whether the influence of environment elements are too great, and whether the infant is capable of increasing its metabolic heat production rate in order to maintain a stable core body temperature.

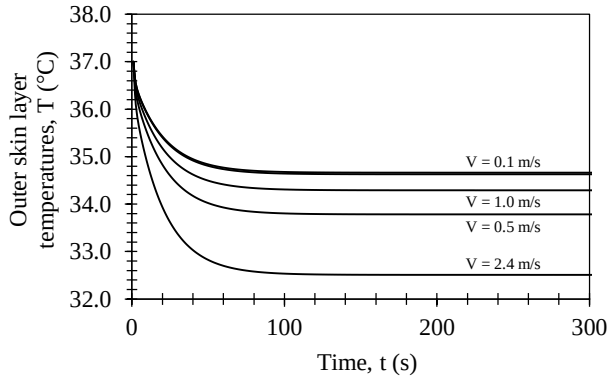

Figure 9: Outer skin layer temperature for various air velocities at a constant room temperature of 20 °C and 60% relative humidity

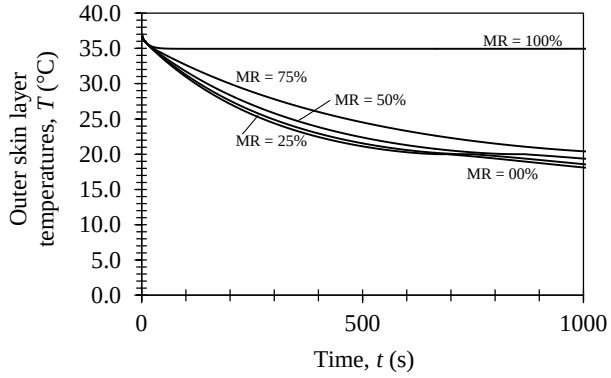

Figure 10: Outer skin layer temperature response with various metabolic heat producing capabilities at a constant room temperature of 20 °C and 60% relative humidity with 0.1 m/s air velocity

The weight and exposed surface area are important neonate-specific properties to consider in evaluating the thermal regulation capability of the neonate. Table 1 contains the Fetal-Infant growth chart[14] values used for the weight and surface area evaluations.

Table 1: Fetal-Infant growth chart values used for subject-specific properties (Fenton, 2003)

	3%	10%	50%	90%	97%
Weight (kg)	2.4	2.7	3.3	4.0	4.3
Length (mm)	0.460	0.470	0.500	0.525	0.540
Head Circumference (mm)	0.315	0.325	0.345	0.360	0.370

For evaluation of the influence of weight, the average length (0.5 m) and average head circumference (0.345 m) of an infant was used. The results gained by various input weights are presented in figure 12. The weight varied from 2.4 kg (3rd percentile) to 4.3 kg (97th percentile), which resulted in an overall temperature difference of 0.0003 °C. It is thus clear that weight does not play a big role in heat loss to the environment and a subsequent lowering in skin and core temperature.

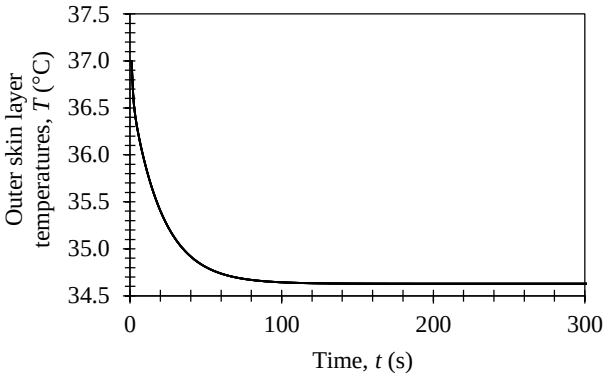

Figure 11: Outer skin layer temperature as a result of various infant weights at constant length of 0.5 m and head circumference of 0.345 m

For the evaluation of the influence of skin surface area, the weight was taken as constant at 3.3 kg, and the length and head circumference was adjusted accordingly. The results for increased surface area and constant weight are given in figure 13. From the figure it can be seen that the surface area also does not have a significant influence on the skin temperature. Increasing the surface area resulted in an overall outer skin layer temperature difference of 0.0238 °C. Increased surface area has a larger effect on outer layer skin temperature than increased weight; but is also not a crucial property in evaluating the role of heat loss and subsequent temperature changes.

In considering the initial cool down period of an infant, it is important whether the infant is dried immediately after delivery, or left as wet. This property was evaluated by changing the area subjected to evaporation. For the dried infant, evaporation only takes place from the sweat glands in the outer skin layer, whereas for the wet infant, evaporation takes place over the complete skin surface area. These results are indicated by figure 14. It can be noted that the time it takes for the skin to reach temperature equilibrium is equal for both scenarios, but it can further be noted that the wet infant will have a lower skin temperature of 31.36 °C in comparison to the dried infant with a skin temperature of 34.66 °C.

6 Verification of Simulation Model

For verification of the theoretical simulation model a clinical trial was conducted where information of 10 neonates was acquired including the weight, length and head circumference as well as the breathing rate. This information is presented in table 2. Information acquired during the clinical trial also included the room temperature, relative humidity and the air velocity as is provided in table 3. The information presented in tables 2 and 3 was used as input values to validate the heat transfer simulation model. The outer skin layer temperatures

was then predicted with the use of the heat transfer simulation model and are presented in figure 15.

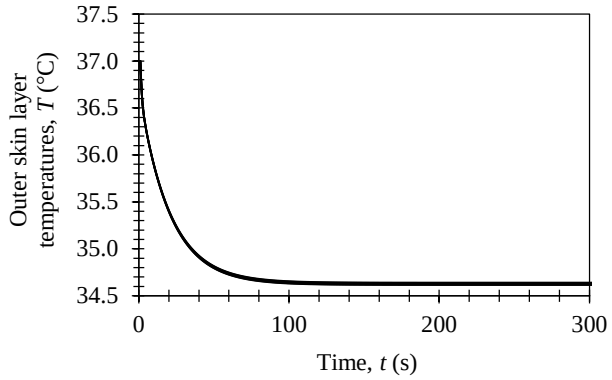

Figure 12: Outer skin layer temperature at various lengths and head circumference with a constant weight of 3.3 kg

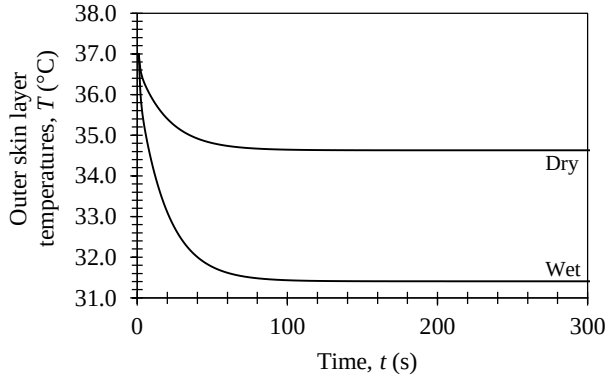

Figure 13: Outer skin layer temperature as a result of evaporation surface area

Table 2: Subject specific information acquired during the clinical trial for 10 infants

	Weight (kg)	Length (cm)	Head Circumference (cm)	Breathing Rate (breaths/min)
1	2.60	40.0	36.5	56
2	2.19	45.5	31.0	56
3	3.07	48.0	35.0	56
4	3.28	44.0	35.7	56
5	2.57	50.0	35.0	56
6	3.67	49.0	39.0	56
7	1.76	38.0	36.8	56
8	2.56	40.0	36.7	60
9	2.265	40.0	36.6	60
10	1.98	49.0	36.0	54

The outer skin layer temperatures for each of the neonates presented in table 3 were obtained by measuring the skin temperature at 10 minute intervals over a period of 60 minutes. The average outer skin layer temperature measurements, indicated in figure 15, was used in validating the simulation model to accommodate the varying outer skin layer temperatures. The results obtained from the theoretical simulation model are also indicated in figure 15.

The results obtained from the simulation program included the effects of subject specific properties and surrounding environmental factors. From figure 15 it can be seen that the predicted outer skin layer temperatures compared well with the average measured outer skin layer temperatures. The largest prediction temperature difference was 0.46 °C for infant 7, and the smallest temperature difference with respect to the measured temperature was -0.001 °C for infant 3. The standard deviation of simulated temperatures to the measured temperature was calculated as 0.22 °C. From these results it was concluded that the developed theoretical mathematical simulation model was successful in predicting the outer skin layer temperature.

Table 3: Calculated average value obtained from the measured room temperature, relative humidity and air velocity as well as core temperature acquired during the clinical trial () indicates the standard deviation

	Room Temperature (°C)	Room Relative Humidity (%)	Air Velocity (m/s)	Core Temperature (°C)
1	26.46 (0.74)	44.4 (0.55)	0.25	37.12 (0.34)
2	24.94 (0.09)	44.8 (0.84)	0.10	37.14 (0.36)
3	24.80 (0.48)	48.2 (3.49)	0.50	36.08 (1.05)
4	23.76 (0.99)	45.2 (2.39)	0.10	37.04 (0.63)
5	24.90 (0.41)	38.4 (3.97)	0.10	37.00 (0.66)
6	24.86 (0.34)	37.9 (2.66)	0.10	37.64 (0.66)
7	35.42 (0.18)	36.7 (0.91)	0.10	37.40 (0.25)
8	25.04 (0.36)	50.2 (1.16)	0.30	37.72 (0.49)
9	25.48 (0.13)	48.8 (0.61)	0.10	37.38 (0.37)
10	25.46 (0.17)	48.4 (0.70)	0.50	34.86 (0.19)

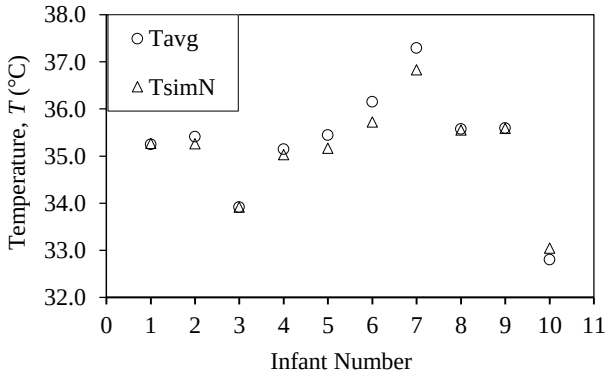

Figure 14: Results obtained for the outer skin layer temperature, based on the information gained during the clinical trial and data acquisition

7 Conclusions

The heat transfer simulation model presented in this paper was developed by using heat transfer equations together with energy conservation and solved according to the explicit finite difference method. The development of the theoretical simulation model allowed evaluating different environmental factors and subject-specific properties influencing the outer skin layer temperature of a neonate.

Indicated by the results gleaned from the theoretical simulation model it became clear that environmental effects have a large influence on thermal regulation and skin temperature response of the neonate. Not all environmental effects play as big a role when compared to each other. From the results it was concluded that variation of air temperature had the most significant influence on the resulting skin temperature, where air temperature higher than 22 °C was

considered comfortable. A difference of 40% relative humidity caused a small temperature change of 0.11 °C in skin temperature and can be neglected when evaluating the thermal environment, except in cases where water loss is of great concern. Air velocity presented no significant effects at low velocities, but caused a large decrease in skin temperature at the maximal accepted indoor air velocity of 2.4 m/s [16].

From the information gathered on thermal response in the literature study it became apparent that a neonate has sufficient metabolic heat production capability if the skin or core temperature stays constant. This fact was validated by the simulation model, where an infant's temperature drops below 20 °C within 1227 seconds if the infant had only 75% metabolic heat producing capability. Further it was found that the weight to surface area ratio of infants do not have a great influence on the resulting heat loss. Results indicated no significant variance when the weight was kept constant while the surface area exposed to heat loss was increased. The same results were obtained when the surface area was kept constant with an increase in weight of the infant. Evaluation of the surface area subject to evaporation indicated that lower skin temperatures are induced if the infant is covered in amniotic fluid as shown in figure 14.

It can be concluded that this theoretical simulation model can be used with reasonable confidence and accuracy to predict the outer skin layer temperature of the neonate.

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