

Dry heat loses of newborn baby in infant care bed: use of a thermal manikin

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Abstract. The energy balance and heat exchange for newborn baby in infant care bed environment (radiant warmer) are considered. The present study was performed to assess the body dry heat loss from an infant in radiant warmer, using copper cast anthropomorphic thermal manikin and controlled climate chamber laboratory setup. The total body dry heat losses were measured for varying manikin surface temperatures (nine levels between 32.5°C and 40.1°C) and ambient air temperatures (five levels between 23.5°C and 29.7°C). Radiant heat losses were estimated based on measured climate chamber wall temperatures. After subtracting radiant part, resulting convective heat losses are compared with computed ones, based on Nu correlations for common geometries. Simplified geometry of newborn baby was represented as: (a) single cylinder and (b) weighted sum of 5 cylinders and sphere. The computed values are significantly overestimated relative to measured ones by: 28.8% (23.5%) for (a) and 40.9% (25.2%) for (b). This shows that use of adopted general purpose correlations for approximation of convective heat losses of newborn baby can lead to substantial errors, hence approximation formula is proposed. The thermal manikin appears to provide a precise method for the noninvasive assessment of thermal conditions in neonatal care.

1. Introduction

The heat exchange with the environment is of greater importance in the infant than in the adult, explaining the increased risk of body hypo- or hyperthermia [1]. As result, maintaining fluid and heat balance is of vital importance to the newborn infant [2]. The infants are exposed to a cold and dry environment, and are then at risk of dehydration and hypothermia. These conditions may have serious consequences and significantly influence mortality and morbidity.

Moreover in recent years there is a growing interest in therapeutic use of hypothermia for treatment of neonatal encephalopathy [3–6]. To assist both therapy design and control, attempts are made to use mathematical models of human thermal physiology (i.e. heat transfer and active thermoregulation) [7–11].

To take advantage of all above mentioned the hypothermic therapy and its modelling it is important to understand and quantify the heat transfer processes between the baby and his environment whilst he is in the radiant warmer.

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Figure 1. Cooper cast infant anthropomorphic thermal manikin.



Figure 2. Stabilized temperature water delivery system.

Table 1. Thermal manikin dimensions.

	Diameter, cm	Length, cm
Head	10.2	-
Trunk	9.2	18
Arm	3.8	16
Tight	4.8	18

There are numerous studies on natural convection heat transfer coefficient in adults based on direct measurements and thermal manikins [12, 13], as well as based on numerical simulations [14]. Review and comparison of convective heat transfer coefficients of the adult human body in several studies is presented in [15].

However, for a case of newborn babies, the available literature sources are very limited. The only available data are obtained for newborn thermal manikins in a single-walled, air-heated closed incubators. Early reports, like [16], were based on simplified geometry manikins, while recent studies of dry heat losses from the manikin [17, 18] account for anthropomorphic premature newborn sized manikins. Yet, except of initial measurements reported in [19], no detailed reports have been found for infant care bed (radiant warmer) that are widely used in pediatric centers.

Due to ethical reasons, experiments cannot be performed on living infants, while they are at risk of body cooling and cannot tolerate the experimental procedures. In such situation, the idea of thermal manikins usage for heat exchange identification arises in natural way. As result, within current research, the heated thermal manikin and controlled climate chamber setup is being proposed, designed and used to study dry heat loses in stagnant air for the infant laying in infant care bed conditions.

2. Materials and methods

2.1. Thermal manikin

The anthropomorphic thermal manikin is used in the present study to represent newborn baby. The manikin, shown in Figure 1, was cast in copper and painted matt black (see Fig. 6). The model was designed to mimic newborn baby with body surface area $S = 0,13278\text{m}^2$ (measured by means of 3D manikin scan). The cross-section dimensions of manikin characteristic parts are presented in the Table 1.

To maintain and control the constant surface temperature of the manikin, the water heating system was proposed. Stabilized ($\pm 0.01^\circ\text{C}$) temperature water (Advanced Digital Controller

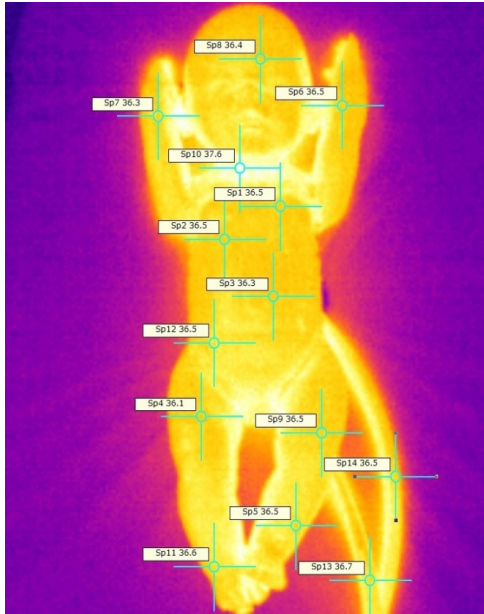


Figure 3. exemplary IR picture of manikin surface temperature.

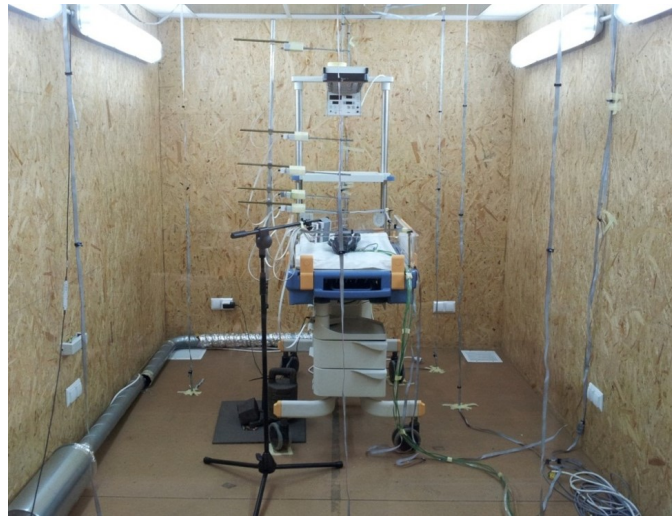


Figure 4. Laboratory setup and equipment - thermal manikin (central) lying on the mattress of radiant warmer bed inside the climate chamber.

Refrigerated/Heated Circulating Baths, model AD07R-20, VWR International, USA) was supplied into the thermal manikin by means of rubber hoses. To obtain uniform temperature distribution over body surface, the water inlet was divided into 5 separate outflow ports located in limbs (four) and head (one). The outlet port was located on the back of the manikin (see Figure 2). The mass flow rate of heating water was kept on elevated level, to ensure uniform manikin surface temperature distribution. Uniform temperature distribution was achieved, an exemplary IR thermogram (ThermaCam SC2000, FLIR, USA) of body surface temperature is shown in Figure 3, mean value of surface temperature with one standard deviation (SD) is $36.42(0.13)^{\circ}\text{C}$. Slightly elevated temperature was measured only in self irradiated areas of the manikin surface (and were excluded from above mentioned mean temperature computation). Personal computer (LabView Signal Express software and 24-Bit Universal Analog Input card, type NI9219, National Instruments, USA) was used to record the manikin surface temperatures and in/out water supply (thermocouples type K, diameter 0.5mm, CZAH-Pomiar, Poland). Manikin surface temperature was recorded by two contact thermocouples (same type) attached to the manikin surface by adhesive tape and protected by aluminium foil coating to prevent its direct irradiation. First was located in anterior (front) trunk, the latter one on posterior (back) thigh. The heating power delivered to the manikin (i.e. dry heat losses) was measured by means of water mass flow rate measurement (rotameter type KM, Z.A. Rotametr sp. z o.o., Poland) and the two thermocouples installed in inlet and outlet water ports of manikin. Therefore the heating power (i.e. dry heat losses) can be calculated as:

$$P = mc(T_{w,in} - T_{w,out}) \quad (1)$$

where: P heating power (dry heat losses), W; m water mass flow rate, $\text{kg}\cdot\text{s}^{-1}$; c water heat capacity, $\text{J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$; $T_{w,in}$, $T_{w,out}$ thermal manikin inlet and outlet water temperatures, respectively, $^{\circ}\text{C}$.



Figure 5. Thermal manikin covered with graphite (high emissivity) spray coating.



Figure 6. Thermal manikin lying on the mattress of radiant warmer bed. Visible water ports and thermocouples measuring surface temperature protected with aluminium foil.

2.2. Climate chamber

The measurements were performed in the double wall climate chamber located in the Laboratory Hall of Department of Heating, Ventilation and Dust Removal Technology (Silesian University of Technology, Gliwice, Poland). The climate chamber was made of wooden oriented strand boards (OSB), having inside dimensions: length 334cm, width 232cm and height 220cm. The internal wooden chamber is located in slightly larger room, with thermal insulated walls.

Central air conditioning system is used to deliver stabilized temperature air both to in- and outside zone of the chamber. The inside air inflow is provided by means of holes in ceiling panels made of stainless steel, while four air outflow ports are located in corners (floor level). Such setup allows to precise control of the climate chamber wall temperature (by means of circulating air on both sides of chamber wall). There were 45 temperature sensors (Programmable Resolution 1-Wire Digital Thermometer, type 18B20, Maxim Integrated, USA) installed inside the climate chamber to continuous monitor both wall and air temperatures. Sensors were located in 11 vertical locations: 10cm, 110cm, 160cm and 210cm above the floor level.

Air velocity inside the climate chamber was monitored by means of omnidirectional (spherical) air speed (magnitude of velocity vector) sensors (AirDistSys 5000, Sensor Electronic, Poland). Complete laboratory setup is shown in the Figure 4.

3. Infant care bed

The manikin was lying in a spread-supine (with hands heading up) position on a mattress in an infant care bed (Babytherm 8000, Dräger Medical, Germany). Built in radiant warmer was set off. The mattress was not heated, and in current research can be treated as thermal insulation. Under this assumption (i.e. no conductive heat losses on the manikin mattress interface), the body surface area used in further computations should be corrected. The manikin surface being in contact with mattress has been marked and measured (3D scan). Finally, effective body surface area was measured to be $S_e = 0.107\text{m}^2$.

4. Measurements

During each experimental session, steady state was strictly required and obtained. First, for given air temperature and lowest surface temperature the steady state was reached (after approximately 4 hours), then the air flow inside the climate chamber was turned off. When the heat transfer between thermal manikin and thermal environment reached equilibrium (after

Table 2. Emissivities of the surfaces.

Surface	Emissivity, ϵ
Wooden oriented strand boards (OSB)	0.92
Manikin surface (graphite spray coating)	0.99
Stainless Steel (air inflow panels in chamber)	0.20

approx. 15 minutes) the chamber air, wall temperatures, manikin surface temperature & heat losses were recorded in steady state conditions. Then the surface temperature was increased up to next test case value, and after reaching equilibrium data were recorded again.

The temperature measurements were recorded with 2Hz frequency for every test case in steady conditions (for approx. 10 minutes each, resulting in approx. 1200 samples for every test case). Mean values of recorded manikin surface temperatures, air & wall temperatures as well and dry heat losses, calculated according to (1) are presented in Table 3. Low levels of standard deviations (SD) in recorded temperatures for all test cases confirm that the data were recorded in the steady state conditions regime, as planned.

Prior to the test sessions all temperature measurement devices (ie. thermocouples and digital sensors) has been calibrated in ice water (0°C). Device specific offsets has been set and used.

During data recording sessions there were almost no vertical temperature gradients inside the chamber (within $\pm 0.1^\circ\text{C}$). Air velocity was kept far below 0.1m/s.

To account for radiative heat losses, emissivity of all surfaces exchanging heat by radiation have to be determined. The thermal manikin surface has been covered with graphite high emissivity spray coating (see Fig. 6), with known emissivity of 0.99. Remaining surfaces data has obtained from manufacturers datasheets, and are all listed in Table 2.

5. Results

The measurements were carried out under steady state conditions. The manikin was exposed to five different ambient air temperatures (between 23.5°C and 29.7°C) and nine different manikin surface temperatures (between 32.5°C and 40.1°C). Dissipated dry heat losses calculated using Eq. (1) for each test case are listed in details in Table 3.

Similar to the observations reported in [17] for single walled, air-heated closed incubator, the dissipated power in current experiment increases linearly with the increasing excess temperature of the manikin surface over ambient air: $P^{\text{fit}} = 0.9662(T_s - T_a) + 0.4531$; $r^2 = 0.9852$; $p < 0.001$ (cf. Fig. 7, full line —).

In order estimate pure convective heat losses, the radiation part of the manikin heat balance should be estimated first. The radiative part of total dissipated heat flux (P_r) is computed as:

$$P_r = S_e \sigma F_\epsilon (T_s^4 - T_w^4) \quad (2)$$

where: S_e effective body surface area, m^2 , $\sigma = 5.670373 \times 10^{-8}$, $\text{W} \cdot \text{m}^{-2} \cdot \text{K}^{-4}$ - blackbody radiation constant; F_ϵ transfer factor (to account geometrical view factors for radiative heat exchange between manikin and surrounding), -; T_s and T_w manikin surface and chamber wall temperatures, respectively, K.

Convective only heat losses P_c are then computed by subtracting radiative heat losses P_r from total dry heat losses P :

$$P_c = P - P_r \quad (3)$$

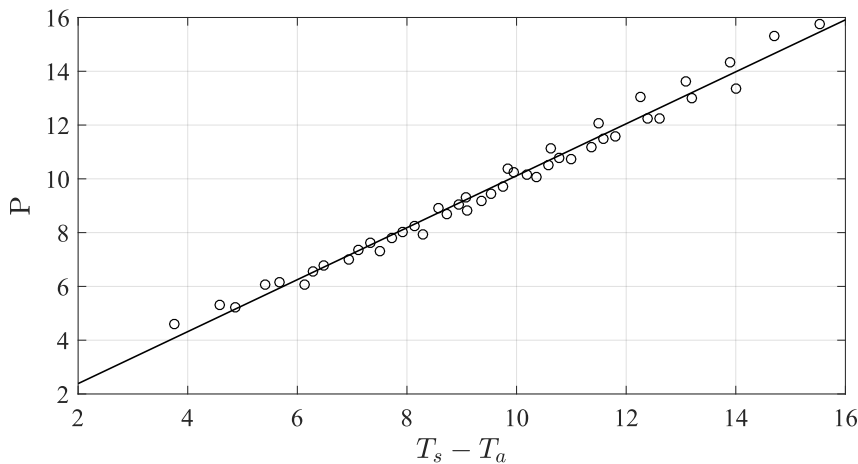


Figure 7. Dry heat losses (P , W) plotted against excess temperature of the manikin surface over ambient air ($T_s - T_a$), K.
○ : current experiment
—: linear data fit.
Detailed measurement data are presented in Table 3.

Measured convective heat losses P_c are compared with computed ones and are shown in Figure 8. Computed values are based on Nu correlations for common geometries: free convection, horizontal cylinder [20] and sphere [21]. Two cases are considered, for which convective heat transfer coefficient is estimated by simplified geometry of newborn baby represented as:

- (a) single horizontal cylinder (with diameter as for trunk),
- (b) weighted sum of 5 horizontal cylinders and sphere (*Rule of nines*⁴ with skin surface weights: 0.36 trunk (anterior and posterior), 0.09 arm (2x), 0.14 leg(2x) and 0.18 head).

Statistical analysis t-test (MatLAB, The MathWorks, Inc., USA) shows that computed values are significantly ($p < 0.001$) overestimated relative to measured values by (mean with one SD): 28.8% (23.5%) for (a) and 40.9% (25.2%) for (b).

To overcome overestimation, the dissipated power due to convection can be approximated using two-term power series function of excess temperature of the manikin surface over ambient air: $P_c^{\text{fit}} = 0.01149(T_s - T_a)^{2.092} + 1.544$; $r^2 = 0.8231$; $p < 0.001$ (cf. Fig. 8, full line —).

⁴ Rule of nines. (n.d.) 2009 Mosby's Medical Dictionary 8th edition. Retrieved March 30 2016 from <http://medical-dictionary.thefreedictionary.com/rule+of+nines>

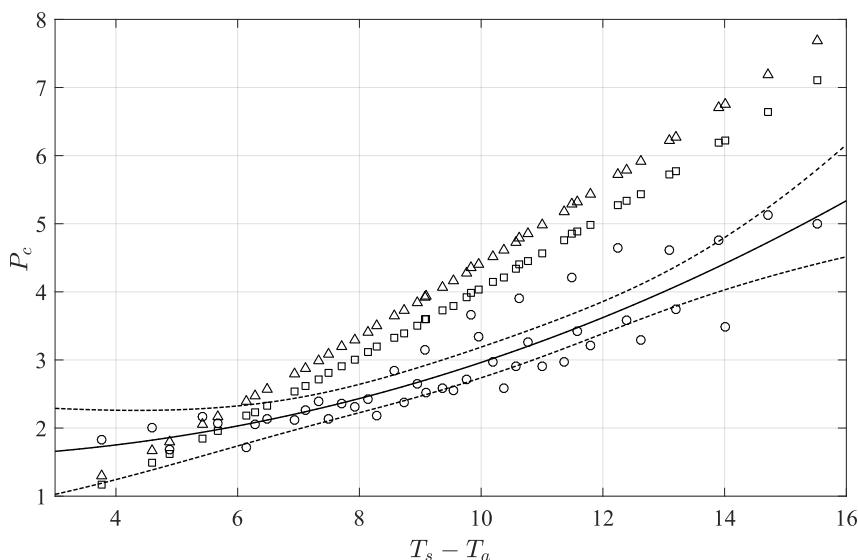


Figure 8. Total convective heat losses (P_c , W) plotted against excess temperature of the manikin surface over ambient air ($T_s - T_a$), K.
△ empirical formula case (a)
□ empirical formula case (b)
○ current experiment
— power data fit
- - - fitted curve
95% confidence bounds.

Table 3. Measurement data for all test cases (mean with one SD).

Test case #	Ambient air temperature, °C	Chamber wall temperature, °C	Manikin temperature, °C	Dry heat loses, W
1 A	23.48 (0.19)	23.11 (0.21)	32.55 (0.02)	9.32 (0.23)
1 B			33.32 (0.02)	10.37 (0.21)
1 C			34.12 (0.02)	11.15 (0.24)
1 D			34.98 (0.02)	12.06 (0.26)
1 E			35.74 (0.03)	13.06 (0.22)
1 F			36.58 (0.04)	13.61 (0.24)
1 G			37.39 (0.03)	14.35 (0.27)
1 H			38.20 (0.03)	15.29 (0.28)
1 I			39.00 (0.02)	15.76 (0.28)
2 A	25.25 (0.17)	24.87 (0.22)	32.75 (0.02)	7.33 (0.22)
2 B			33.54 (0.02)	7.93 (0.31)
2 C			34.35 (0.02)	8.84 (0.29)
2 D			35.20 (0.03)	10.26 (0.22)
2 E			36.03 (0.02)	10.76 (0.25)
2 F			36.83 (0.02)	11.49 (0.26)
2 G			37.65 (0.02)	12.25 (0.22)
2 H			38.45 (0.02)	12.99 (0.25)
2 I			39.26 (0.02)	13.36 (0.34)
3 A	26.90 (0.16)	26.51 (0.21)	33.03 (0.02)	6.08 (0.25)
3 B			33.84 (0.02)	7.02 (0.20)
3 C			34.62 (0.02)	7.80 (0.24)
3 D			35.47 (0.02)	8.90 (0.26)
3 E			36.27 (0.02)	9.19 (0.20)
3 F			37.09 (0.02)	10.17 (0.21)
3 G			37.90 (0.03)	10.73 (0.27)
3 H			38.69 (0.02)	11.59 (0.25)
3 I			39.52 (0.02)	12.27 (0.22)
4 A	28.41 (0.14)	28.04 (0.19)	33.28 (0.02)	5.21 (0.21)
4 B			34.08 (0.02)	6.15 (0.23)
4 C			34.90 (0.02)	6.77 (0.24)
4 D			35.74 (0.02)	7.62 (0.19)
4 E			36.55 (0.02)	8.25 (0.21)
4 F			37.36 (0.03)	9.05 (0.25)
4 G			38.17 (0.02)	9.71 (0.16)
4 H			38.98 (0.03)	10.50 (0.28)
4 I			39.78 (0.03)	11.16 (0.22)
5 A	29.74 (0.14)	29.44 (0.15)	33.50 (0.01)	4.59 (0.18)
5 B			34.32 (0.02)	5.32 (0.18)
5 C			35.16 (0.01)	6.07 (0.20)
5 D			36.03 (0.01)	6.56 (0.22)
5 E			36.84 (0.02)	7.37 (0.20)
5 F			37.66 (0.03)	8.01 (0.25)
5 G			38.48 (0.03)	8.67 (0.19)
5 H			39.28 (0.03)	9.42 (0.25)
5 I			40.10 (0.03)	10.08 (0.24)

6. Summary

The anthropomorphic newborn baby thermal manikin was used to carry out measurements of the whole body dry heat loses under free convection regime in the infant care bed. The experimental

setup and proposed methodology proved to be effective way of estimating dry and convective heat losses for non-standard geometrical cases. Presented results show that using general purpose Nu correlations leads to significant overestimation. This is due to the fact that general purpose formulas are valid for long cylinders surrounded by air (no obstructions to air flow), while in analyzed geometry – newborn baby in infant care bed – part of the body surface is insulated and air flow is obstructed by mattress and infant care bed itself. Proposed formula can be used to model dry and convective heat losses of newborn baby in real hospital conditions.

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