Ziemowit OSTROWSKI[1], Marek ROJCZYK[1], Joanna ŁASZCZYK[1], Ireneusz SZCZYGIEŁ[1], Jan KACZMARCZYK[2], Andrzej J. NOWAK[1]

Silesian University of Technology, Institute of Thermal Technology (1),
Silesian University of Technology, Department of Heating, Ventilation and Dust Removal Technology (2)

Infant care bed natural convection heat transfer coefficient – measurements and estimation

***Abstract**. The energy balance and heat exchange for newborn baby in infant care bed environment (radiant warmer) are considered. Convective and radiant heat losses from an infant in radiant warmer were studied using copper cast anthropomorphic thermal manikin and controlled climate chamber setup. The total body heat loss was measured for several mean skin and ambient temperatures, leading to total heat transfer coefficient estimation.*

***Streszczenie.** Rozważany jest bilans energii oraz mechanizmy wymiany ciepła dla noworodka w otwartym inkubatorze dla niemowląt. Wykorzystano miedziany antropomorficzny manekin termiczny noworodka do zbadania konwekcyjnej i radiacyjnej wymiany ciepła z otoczeniem w komorze klimatycznej. Zmierzono całkowity strumień traconego ciepła dla wybranych średnich temperatur skóry oraz otaczającego powietrza, a następnie wyznaczono konwekcyjny współczynnik wnikania ciepła. (**Pomiary i wyznaczanie współczynnika wnikania ciepła dla konwekcji swobodnej w otwartym inkubatorze dla niemowląt**).*

Keywords: convection, heat transfer coefficient, radiant warmer, thermal manikin.
Słowa kluczowe: konwekcja swobodna, współczynnik wnikania ciepła, otwarty inkubator dla niemowląt, manekin termiczny.

doi:10.12915/pe.2014.05.28

Introduction

The heat exchange with the environment are 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], [8].

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.

There are numerous studies on natural convection heat transfer coefficient in adults based on direct measurements and thermal manikins [9], [10], as well as based on numerical simulations [11]. Review and comparison of convective heat transfer coefficients of the adult human body in several studies is presented in [12].

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 [13], were based on simplified geometry manikins, while recent studies of dry heat losses from the manikin [14], [15] account for anthropomorphic premature newborn sized manikins. No study 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 open incubator conditions.

Materials and methods

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. The model was designed to mimic newborn baby with body surface area S=0,13278m^2 (measured by means of 3D manikin scan and Oracle AutoVue software).

Fig.1. Cooper cast infant anthropomorphic thermal manikin

The cross-section dimensions of manikin are presented in the Table 1.

Table 1. Thermal manikin cross section dimensions

Body section	Diameter [mm]	Length [mm]
Head	102	–
Trunk	92	180
Arm	38	160
Tight	48	180

Initially to maintain and control the constant surface temperature of the manikin, the electrical heater and fan was installed inside the manikin. However problems were encountered with obtaining stable and uniform manikin surface temperature distribution.

Finally, the water heating system was proposed instead. Stabilized (±0.01°C) temperature water (Advanced Digital Controller 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.

An exemplary IR (ThermaCam SC2000, FLIR, USA) picture of body surface temperature is shown in Figure 3. For proposed water heating system uniform temperature distribution was achieved (as for example shown in fig. 3: 36,42±0,13°C[1]). Slightly elevated temperature was measured only in self irradiated areas of the manikin surface (and were excluded form above mentioned mean temperature).

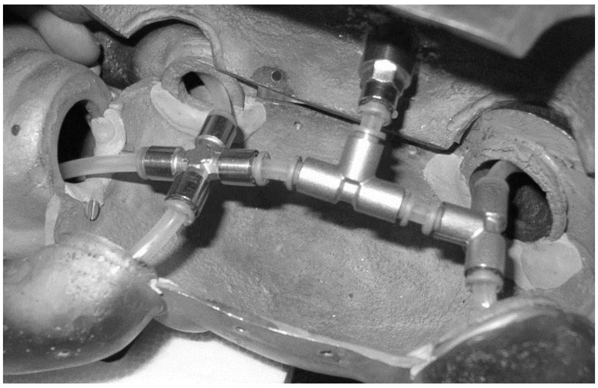

Fig.2. Stabilized temperature water delivery system

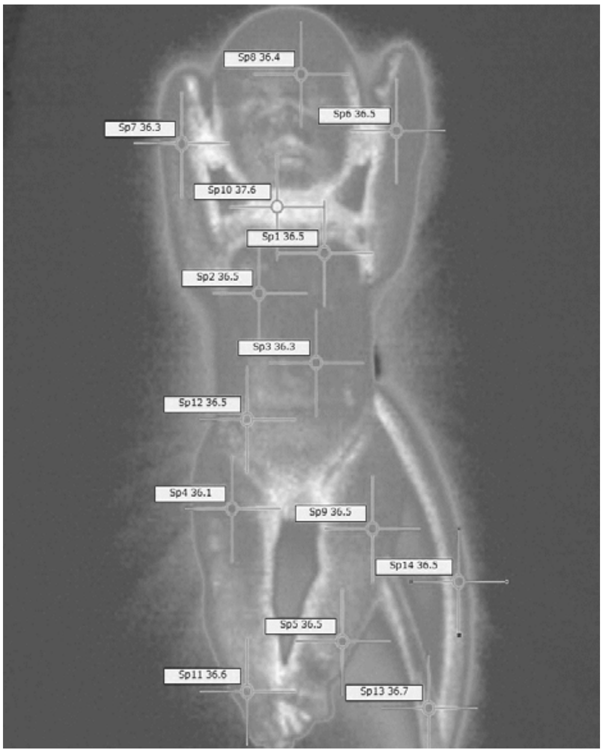

Fig.3. Exemplary IR picture of body surface temperature

Personal computer (LabView Signal Express software and 24-Bit Universal Analog Input card, type NI9219, National Instruments, USA) was used to record the surface temperatures and water supply of the manikin using thermocouples (Type K, diameter 0.5mm, CZAH-Pomiar, Poland).

Manikin surface temperature was recorded by two contact thermocouples 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) tight.

The heating power delivered to the manikin (i.e. dry heat loses) 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 loses) are:

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

where: P – heating power (dry heat losses) [W], m – water mass flow rate [kg·s^{-1}], c_p – water heat capacity [J·kg^{-1}·K^{-1}], $T_{w,in}$, $T_{w,out}$ – thermal manikin inlet and outlet water temperatures, respectively [K].

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 3340mm, width 2320mm and height 2200mm. The 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 inside and outside zone of the camber. 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 on the 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.

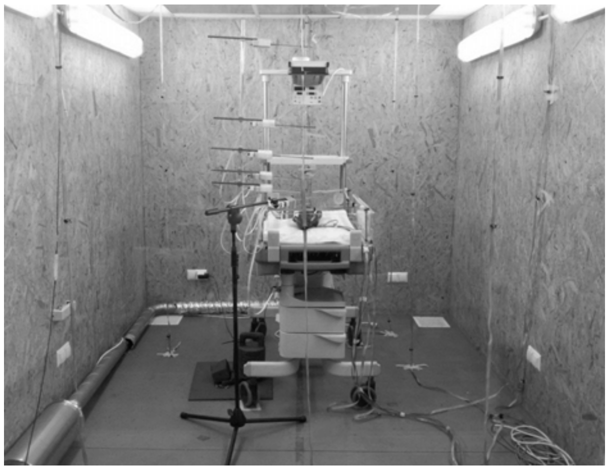

Fig.4. Laboratory setup and equipment – thermal manikin (central) lying on the mattress of radiant warmer bed inside the climate chamber

[1] mean ± SD

Air velocity inside the climate chamber was monitored as well 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.

Open incubator.

The manikin was lying in a spread-supine (with hands heading up) position on a mattress in an open incubator (Babytherm 8000, Dräger Medical, Germany). Radiant warmer of the incubator 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, active body surface area was measured to be S'=0.107m^2.

Sensor calibration

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.

Measurements

The measurements were carried out under steady state conditions. The manikin was exposed to two different air temperatures (~23°C for test cases #1 and ~28°C for test cases #2), and three manikin surface temperatures (ranging between 34°C and 37°C for test cases A,B and C).

During each experimental session, steady state was strictly required and obtained. First, for given air/manikin surface temperature pairs 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 approx. 15 minutes) the chamber air, wall temperatures, manikin surface temperature & heat loses were recorded in steady state conditions.

Continuous temperature measurements were recorded with 2Hz frequency for approx. 20 minutes of steady state operation (for each test case). Mean values of recorded manikin surface temperatures, air & wall temperatures as well and dry heat losses, calculated according to eq. (1), are presented in Table 2. Low levels of standard deviations (SD) of recorded temperatures for all test cases confirm that the data were recorded when in the steady state conditions.

Table 2. Mean values (±SD) of measured: manikin surface, air & wall temperatures and dry heat losses

Test case #	Air t_a [°C]	Manikin surface t_s [°C]	Chamber walls t_w [°C]	Dry heat losses P [W]
1A	22,93±0,17	34,11±0,02	22,77±0,08	11,07±0,28
1B		35,73±0,03		13,09±0,28
1C		36,57 ±0,04		13,53±0,27
2A	27,97±0,14	34,08±0,02	27,84±0,04	6,14,±0,24
2B		35,73±0,02		7,65±0,20
2C		36,55±0,02		8,28±0,22

During data recording sessions there were almost no vertical temperature gradients inside the chamber (within ±0.1°C). Air velocity was kept far below 0.1m/s.

To account for radiative heat loses, 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. 5), with known emissivity of 0,99. Remaining surfaces data has obtained from manufacturers' datasheets, and are all listed in Table 3.

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

Table 3. Emissivities of the surfaces

Surface name	Emissivity, ε
Wooden oriented strand boards (OSB)	0,92
Manikin surface (graphite spray coating)	0,99
Stainless Steel (air inflow panels)	0,20

Results

In order estimate pure convective heat transfer coefficient, the radiation part of the manikin heat loses should be estimated first. As first step the radiative part of dissipated heat flux is computed as:

(2) $$P_{rad} = S'\sigma\varepsilon_{s-w}\left(T_s^{\,4} - T_w^{\,4}\right)$$

where: P_{rad} – radiative heat losses [W], S' – active body surface area [m^2], σ = 5.670373×10^{-8} [W·m^{-2}·K^{-4}] - Stefan-Boltzmann constant, ε_{s-w} – corrected emissivity coefficient (for radiative heat exchange between manikin and surrounding walls), T_s – manikin surface temperature [K], T_w – chamber wall temperature [K].

Corrected emissivity coefficient ε_{s-w} (for radiative heat exchange between manikin and surrounding walls) has been computed assuming that manikin is exchanging heat with upper hemisphere of the climate chamber (on and above the mattress level). Next mean (surface area weighted) emissivity was computed for ceiling, walls, mattress and virtual surface closing the computational domain from below (in mattress level plane).

Then, the radiative heat losses heat flux is subtracted from total heat losses:

(3) $$P_{conv} = P - P_{rad}$$

where: P_{conv} – convective heat losses [W], P – dry heat losses [W], P_{rad} – radiative heat losses [W].

Finally convective heat transfer coefficient can be estimated using Newton law of cooling:

(4) $$h_{conv} = P_{conv} / \left(T_s - T_a\right)$$

where: h_{conv}– convective heat transfer coefficient [W·m^{-2}·K^{-1}], T_s, T_a – manikin surface and air temperature respectively [K].

Estimated convective heat transfer coefficients together with convective and radiative heat losses are presented in Table 4.

Table 4. Estimated convective and radiative heat loses and convective heat transfer coefficients

Test case #	Radiative heat loses P_{rad} [W]	Convective heat loses P_{conv} [W]	Convective heat transfer coefficient h_{conv} [W·m^{-2}·K^{-1}]
1A	7,47	3,60	3,01
1B	8,61	4,48	3,27
1C	9,20	4,33	2,96
2A	4,21	1,93	2,95
2B	5,37	2,28	2,74
2C	5,95	2,33	2,53

Summary

The anthropomorphic newborn baby thermal manikin was used to carry out measurements of the whole body heat transfer coefficients under natural convection in the infant care bed.

The experimental setup and proposed methodology proved to be effective way of estimating convective heat transfer coefficients for non-standard geometrical cases. Obtained convective heat transfer coefficients can be used to estimate dry heat loses of newborn baby in real hospital conditions.

Further measurements sessions are planned in near future to cover wide range of air, wall and skin temperature configurations. New empirical formula for convective heat transfer coefficients is anticipated.

The work of ZO, MR, IS, JK and AJN was supported by Ministry of Science and Higher Education within statutory research funding scheme. The work of JŁ was supported by the National Science Centre within project No N519 657840. This help is gratefully acknowledged herewith.

REFERENCES

[1] Delanaud S., Tourneux P., Ghyselen L. , Le A., and Bach V., Heat exchanges and thermoregulation in the neonate, *Arch. Pediatr.*, 16 (2009), 1057–1062

[2] Sedin G. and Agren J., Water and heat - the priority for the newborn infant., *Ups. J. Med. Sci.*, 111 (2006), 45–59

[3] Edwards A.D., The discovery of hypothermic neural rescue therapy for perinatal hypoxic-ischemic encephalopathy, *Semin. Pediatr. Neurol.*, 16 (2009), no. 4, 200–206

[4] Shankaran S., Neonatal encephalopathy: treatment with hypothermia, *J. Neurotrauma*, 26 (2009), no. 3, 437–443

[5] Rutherford M., Ramenghi L., Edwards D, Brocklehurst P., Halliday H., Levene M., Strohm B., Thoresen M., Whitelaw A., and Azzopardi D., Assessment of brain tissue injury after moderate hypothermia in neonates with hypoxic-ischaemic encephalopathy: a nested substudy of a randomised controlled trial, *Lancet Neurol.*, 9 (2010), no. 1, 39–45

[6] Schulzke S. M., Rao S., and Patole S. K., A systematic review of cooling for neuroprotection in neonates with hypoxic ischemic encephalopathy - are we there yet?, *BMC Pediatr.*, 7 (2007), 30

[7] Van Leeuwen G. M., Hand J. W., Lagendijk J. J., Azzopardi D. V., and Edwards D., Numerical modeling of temperature distributions within the neonatal head., *Pediatr. Res.*, 48 (2000), no. 3, 351–356

[8] Wrobel L.C., Ginalski M. K., Nowak A. J., Ingham D. B., and Fic A. M., An overview of recent applications of computational modelling in neonatology, *Philos. Trans. A. Math. Phys. Eng. Sci.*, 368 (2010), 2817–2834

[9] Mitchel D., Wyndham C. H., Vermeulen A. J., Hodgson T., Atkins A. R., and Hofmeyer H. S., Radiant and convective of nude men in dry air heat transfer, *J. Appl. Physiol.*, 26 (1969), no. 1, 111–118

[10] Clark R. P. and Toy N., Natural convection around the human head, *J. Physiol.*, 244 (1975), 283–294

[11] Najjaran A., Determining natural convection heat transfer coeffcientof human body, *Trans. Control Mech. Syst.*, 1 (2012), no. 8, 362–369

[12] Kurazumi Y., Tsuchikawa T., Ishii J., Fukagawa K., Yamato Y., and Matsubara N., Radiative and convective heat transfer coefficients of the human body in natural convection, *Build. Environ.*, 43 (2008), no. 12, 2142–2153

[13] Wheldon A. E., Energy balance in the newborn baby: use of a manikin to estimate radiant and convective heat loss, *Phys. Med. Biol.*, 27 (1982), no. 2, 285–296

[14] Elabbassi E. B., Belghazi K., Delanaud S., and Libert J.-P., Dry heat loss in incubator: comparison of two premature newborn sized manikins., *Eur. J. Appl. Physiol.*, 92 (2004), no. 6, 679–682

[15] Sarman I., Bolin D., Holmér I., and Tunell R., Assessment of thermal conditions in neonatal care: use of a manikin of premature baby size, *Am. J. Perinatol.*, 9 (1992), 239–246

***Authors**: dr inż. Ziemowit Ostrowski, Politechnika Śląska, Instytut Techniki Cieplnej, ul. Konarskiego 22, 44-100 Gliwice, E-mail: Ziemowit.Ostrowski@polsl.pl; dr inż. Marek Rojczyk, Politechnika Śląska, Instytut Techniki Cieplnej, ul. Konarskiego 22, 44-100 Gliwice, E-mail: Marek.Rojczyk@polsl.pl; mgr inż. Joanna Łaszczyk, Politechnika Śląska, Instytut Techniki Cieplnej, ul. Konarskiego 22, 44-100 Gliwice, E-mail: Joanna.Laszczyk@polsl.pl; dr hab. inż. Ireneusz Szczygieł, Prof. nzw. w Pol. Śl., Politechnika Śląska, Instytut Techniki Cieplnej, ul. Konarskiego 22, 44-100 Gliwice, E-mail: Ireneusz.Szczygiel@polsl.pl; dr inż. Jan Kaczmarczyk, Politechnika Śląska, Katedra Ogrzewnictwa, Wentylacji i Technik Odpylania, ul. Konarskiego 20, 44-100 Gliwice, E-mail: Jan.Kaczmarczyk@polsl.pl; prof. dr hab. inż. Andrzej J. Nowak, Politechnika Śląska, Instytut Techniki Cieplnej, ul. Konarskiego 22, 44-100 Gliwice, E-mail: Andrzej.J.Nowak@polsl.pl.*