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► To cite this version:

Aziza Hannouch, Thierry Lemenand, Khalil Khoury, Charbel Habchi. Coupled radiative and convective heat losses from preterm infant inside an incubator with radiant heaters. VIII International Conference on Computational Methods for Coupled Problems in Science and Engineering, COUPLED PROBLEMS 2019, Jun 2019, Sitges, Spain. hal-02568379

HAL Id: hal-02568379

<https://univ-angers.hal.science/hal-02568379>

Submitted on 9 May 2020

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COUPLED RADIATIVE AND CONVECTIVE HEAT LOSSES FROM PRETERM INFANT INSIDE AN INCUBATOR WITH RADIANT HEATERS

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Key words: Preterm neonate, Infant incubator, Convection heat transfer, Radiation heat transfer, Thermal comfort.

Abstract. Preterm infants face difficulties in maintaining their body temperature due to low metabolic rates of heat generation. Therefore, using incubators and radiant warmers is crucial for their comfort and health. The objective of the present work is to analyze the heat transfer processes for a preterm infant nursed in a simplified incubator under two different operating conditions: in the first one a classical simple incubator is considered and in the second case radiant heaters are used. This is achieved by using ANSYS Fluent 19.0 which is based on the finite volume method to discretize the Navier-Stokes, energy and radiation transfer equations. Conduction, convection and radiation heat transfer modes are modelled in the simulations and coupled to empirical correlations for metabolic heat generation and evaporative heat losses. The different incubator scenarios considered here are compared in terms of convection and radiation heat losses and skin temperature to assess the thermal comfort of the preterm infant.

1 INTRODUCTION

In 2010, 11.1% of babies were born premature [1]. These babies face difficulties keeping a controlled body temperature without external assistance. Consequently, they can suffer from cold stress and hypothermia. Therefore, it is crucial to maintain an optimal thermal and humidity environment of the neonate by using incubators.

Infant incubators are essential tools to provide thermal comfort for neonates especially

premature and sick infants. The complex heat transfer process in these systems combines convection, conduction, thermal radiation and evaporation. Incubators are used since 1860 in order to maintain an optimal thermal environment for the neonate [2].

Several studies were conducted in the open literature to evaluate the dry and latent heat losses from neonates nursed inside incubators. These studies are classified in three main categories, theoretical bioheat modeling, numerical and experimental.

Bioheat modeling and thermoregulation are based on mathematical models in order to analyze the bioheat transfer in the neonate body and to determine its thermal responses to ambient conditions [3–5].

Numerical simulations of heat losses from neonate use the computational fluid dynamics (CFD) method. The aim of this method is to optimize existing devices and to design new techniques aiming to enhance the thermal comfort of neonates inside the incubators [6–8].

Experimental study are performed on cohort of human neonates or thermal manikins in order to evaluate convection, radiation and evaporation heat transfer coefficients and thermal balance in preterm neonates [9–12]

The aim of the present paper is to perform numerical simulations of the coupled convective and radiative heat transfer in infant incubators under two different conditions. The first case the incubator walls are at mean radiant temperature while in the second case, the incubator walls are assumed to radiate heat at a given heat flux so that to reduce radiation heat losses from the infant skin.

2 COMPUTATIONAL DOMAIN AND BOUNDARY CONDITIONS

An anthropomorphic 3D model representing a preterm neonate is used in the present study. Its dimensions correspond to a preterm with 35 week of gestational age in 50th percentile having a mass of 2.3 kg [13,14]. The neonate is shown in Figure 1 and it has a surface area of 0.133 m² and a body length of 45 cm. The neonate 3D model was built using the SolidWorks CAD software and imported to ANSYS Space Claim in which further modifications are performed. The infant is then inserted in a simplified incubator 25 cm in width, 20 cm in height and 60 cm in length. The incubator has one inlet and one outlet both located at the mattress level as shown in the figure below. The air stream entering the incubator has a speed of 0.2 m/s and a temperature of 38°C. The outlet is assumed at atmospheric pressure. No slip boundary conditions are imposed on all solid surfaces.

To mimic metabolic heat generation, a constant heat flow is imposed on the outer surface of the model according to the empirical equation obtained by Bruck [15] which depends on the infant mass m_{inf} and age in days t_{inf} (Eq. (1)). Therefore, for the present simulations the surface heat flow is fixed to 4.23 W.

$$q_m = m_{inf}(0.0522t_{inf} + 1.64) \quad (1)$$

The thermal emissivity of the neonate surface is assumed 0.95 [10] and the mean radiant temperature of surrounding surfaces is obtained from empirical correlation obtained by Decima *et al.* [16] and depending on the air temperature T_a as given below:

$$T_r = 0.724(T_a - 31.93) + 29 \quad (2)$$

Moreover, evaporative heat loss from the skin are obtained from Lyon and Oxley [17] and it depends on the surface area of the neonate and humidity inside the incubator which was

assumed equal 70%. Thus the resulting evaporative cooling is 1.25 W.

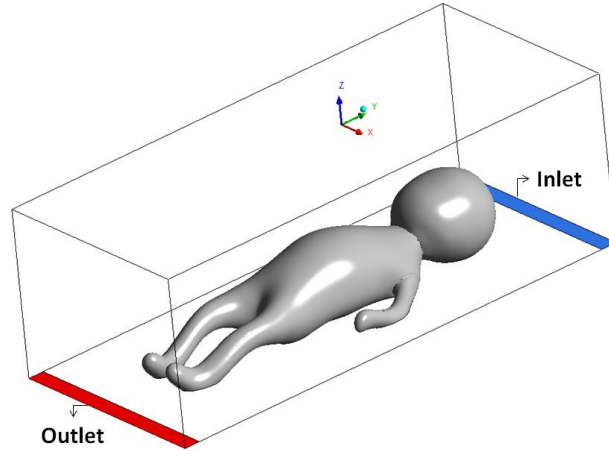


Figure 1: Isometric view of the 3D model representing the preterm neonate nursed inside a simplified incubator

Two different cases are studied in this paper. In the first one all surfaces surrounding the baby (mattress and incubator walls) are assumed at standard radiant temperature obtained from Eq. (2). In the second case, radiant heating elements are used and thus the incubator walls are now assumed to radiate heat at an average heat flux of 0.55 W/m^2 .

3 NUMERICAL METHOD

A non-uniform polyhedral mesh is used in the present study with 4 prism layers refined near the neonate skin surface. The total number of elements is around 840,000 cells. A mesh sensitivity analysis was conducted prior to choosing this mesh density in order to verify mesh convergence. The criteria for the mesh convergence are the surface temperature and total surface heat flux. Navier-Stoke and energy equations for laminar flow are using ANSYS Fluent 19.0 which based on the cell centered finite volume method. Second order double precision numerical schemes are used for diffusive and convective terms and Coupled model is adopted for velocity-pressure coupling. The buoyancy effects are included by using the Boussinesq approximation for air density. Radiation heat transfer is computed using the Discrete Ordinates Method which solves the radiative transfer equation for a finite number of discrete solid angles.

The energy equation for heat losses from preterm infants is given below:

$$q_m - q_{\text{evaporation}} = q_{\text{convection}} + q_{\text{radiation}} + q_{\text{conduction}} \quad (2)$$

The two terms on the left hand side are obtained from empirical equations as discussed previously while the terms on the right hand side are computed. For both cases studied in this paper, conduction heat transfer was very small relative to the other modes of heat losses. Thus we will focus on convective and radiative heat losses and their effects on the neonate skin temperature in the next section.

4 RESULTS

Figure 1 shows the heat rates from the infant nursed inside the incubator for both studied

cases. The metabolic heat generation is lost through latent heat by evaporation which is the same for both cases since it was obtained using empirical correlation.

Meanwhile, radiation heat losses from the neonate are reduced due to the addition of radiant heaters. These radiant heaters will lead also to a slight decrease in conduction heat losses since the mattress temperature will increase. However, convective heat losses have increased since as will be seen next, the skin temperature exceeds the surrounding air leading to higher convective heat loss. However, the overall impact is beneficial since the thermal comfort is enhanced from skin temperature point of view.

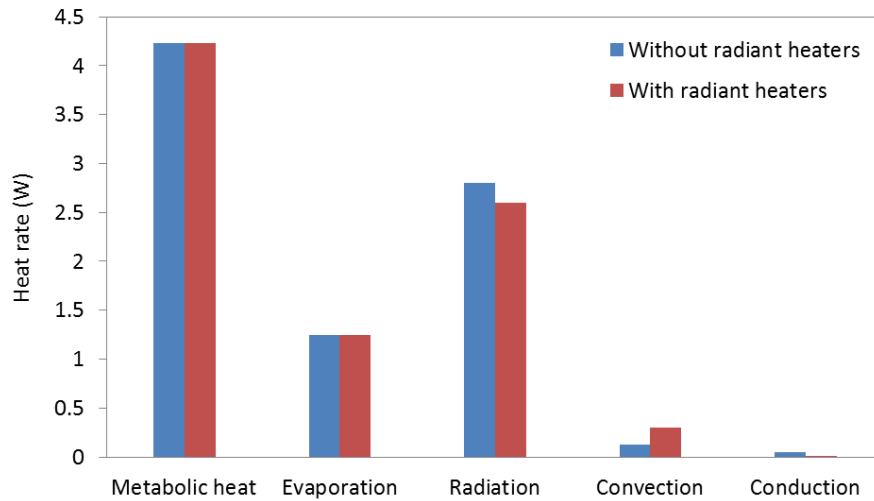


Figure 2: Heat losses from the infant skin for both studied cases

The skin temperature distribution is shown in Figure 3 for both cases. For the case without radiant heaters, the average skin temperature is around 35°C which is smaller than the comfort temperature at 37°C. The temperature is increased by addition of radiant heaters and its average value reaches around 37°C leading to better thermal comfort when compared to the reference case without radiant heaters.

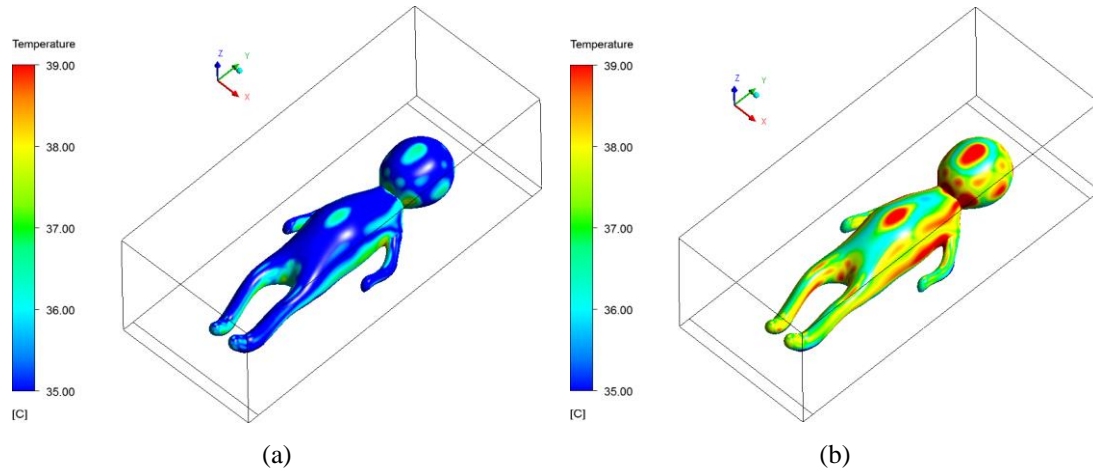


Figure 3: Skin surface temperature (a) without radiant heaters and (b) with radiant heaters

5 CONCLUSION

In this study, convective and radiative heat losses from preterm infant nursed inside an incubator are studied under two different conditions. In the first case, a simplified classical incubator is used, while, in the second case radiant heaters are added. The incubator walls are modeled thus as radiant heaters with imposed heat flux.

The flow and heat transfer are computed using ANSYS Fluent 19.0 which is based on the finite volume method. A polyhedral mesh and second order numerical schemes are adopted for the simulations.

The results show a decrease of radiation heat loss when adding radiant elements whit a slight increase in convective heat loss. Moreover, the average skin temperature of the neonate was increased from 35°C to 37°C proving the benefits of these radiant heaters.

In future studies we will use experimental method for a preterm thermal manikin nursed inside a CALEO incubator to validate our numerical simulations.

ACKNOWLEDGMENT

This research was supported by the AUF CNRSL research grant. The authors are also grateful to Dräger and PrimeMedical for donating a Caleo infant incubator.

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