

Computational Fluid Dynamics Model for a Closed Infant Incubator

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Abstract— Incubators are essential tools to provide thermal comfort for neonates. The main heat transfer processes in these systems are convection and thermal radiation. The objective of the present work is to analyze the flow structure and heat transfer processes using computational fluid dynamics (CFD). The computational domain consists of a simplified incubator and neonate where two cases are considered. In the first case, the mattress was assumed adiabatic whereas in the second one the mattress is assumed to have a constant heat flux. Case one showed an excess of heat loss from the neonate by both convection and radiation, thus the neonate may suffer from hyperthermia and cold stress. This was solved by using a heat mattress with appropriate fixed heat flux in order to provide the desired thermal comfort.

Keywords: CFD; biomedical engineering; Incubators; thermal comfort.

I. INTRODUCTION

Healthy neonates can regulate their body temperature while premature and ill infants face difficulties keeping a controlled body temperature without external assistance. Consequently, they can suffer from cold stress and hypothermia that leads to an increase in the rate of morbidity and mortality [1]. This is why there is a need to maintain an optimal thermal environment for the neonate. This can be achieved by using incubators.

Incubators are enclosed chambers with climate-controlled equipment used to keep an infant warm and safe from germs exposure. This is achieved by circulating warm air over the infant skin. The design of efficient incubators is crucial for the neonate survival. Many methods can be used to design and optimize incubators. Numerical simulations, namely CFD (computational fluid dynamics), is one of the most used tools since it does not necessitate expensive experimental work and it can assess locally the incubator environment such as the temperature and velocity [2]. Moreover, experimental studies exhibit risks on the human life especially on neonatal infants.

CFD has been significantly enhanced over the last decade due to advanced engineering technologies [2, 3]. In recent studies, computational fluid dynamics has been greatly used to analyze the heat transfer between the environment and the human body, such as in incubators, panda warmers, or intensive care units [1]. CFD simulation can be very useful in many situations, as they easily allow parametric study and

can be of great assistance in the design of more efficient, safe, and reliable medical equipment.

Continuous research is being conducted for designing neonate incubators. The main objective is to provide a controlled temperature in order to increase the neonate survival and growth. In fact, the temperature inside the incubators is correlated with the flow structure which is in its turn affected by the ventilation system. Thus, understanding the relation between these parameters could be a solution to solve many problems inside incubators.

The flow inside the incubator is complex and it is usually considered turbulent. This necessitates the use of a turbulence model to compute the governing equations. The most used turbulence models for incubators are the SST $k - \omega$ and RNG $k - \epsilon$ models [1]. Ginalski *et al.* [2] used the SST $k - \omega$ to study the heat transfer in an infant incubator with and without an overhead screen. In their study, the human body and incubator geometry were generated using CAD application CATIA. Then the CFD software ANSYS Fluent was used to analyze the heat transfer and flow structure.

Many others used the standard or RNG $k - \epsilon$ turbulence model to study the heat transfer and fluid flow in closed incubators or radiant warmers [4-6]. A fair agreement was observed between the results obtained numerically and those from experimental analysis. For example, Sedin *et al.* [7] performed both experimental studies and numerical simulations and compared the body core temperature and mean skin temperature obtained from both techniques. The maximum deviation between experimental and numerical results did not exceed 0.8°C for the worst case, i.e. a relative error of about 2.2%.

The objective of the present work is to design a new ventilation strategy in incubators using CFD simulations. Two cases are considered here. In the first case, all the incubator walls and mattress are considered adiabatic to mimic double walled incubators. The second case higher inlet air temperature is considered and the mattress was heated with constant heat flux.

The current paper is organized as follows: Section II is devoted to the computational domain and boundary conditions. Section III presents the numerical model and algorithms. The results are then discussed in Section IV. Finally, the conclusion is presented in Section V.

II. COMPUTATIONAL DOMAIN AND BOUNDARY CONDITIONS

The computational domain consists of an incubator chamber of $700 \times 500 \times 400 \text{ mm}^3$ with a simplified neonatal model as shown in Fig. 1. There are two inlets (in cyan and green) and two outlets (red and orange) similarly to the Drager Caleo incubator [2, 8]. The total surface area of the infant skin is around 0.1344 m^2 which is similar to the models used by Kim *et al.* [5] and Fic *et al.* [6]. The inlets and outlets have same cross-sectional area of 0.01 m^2 .

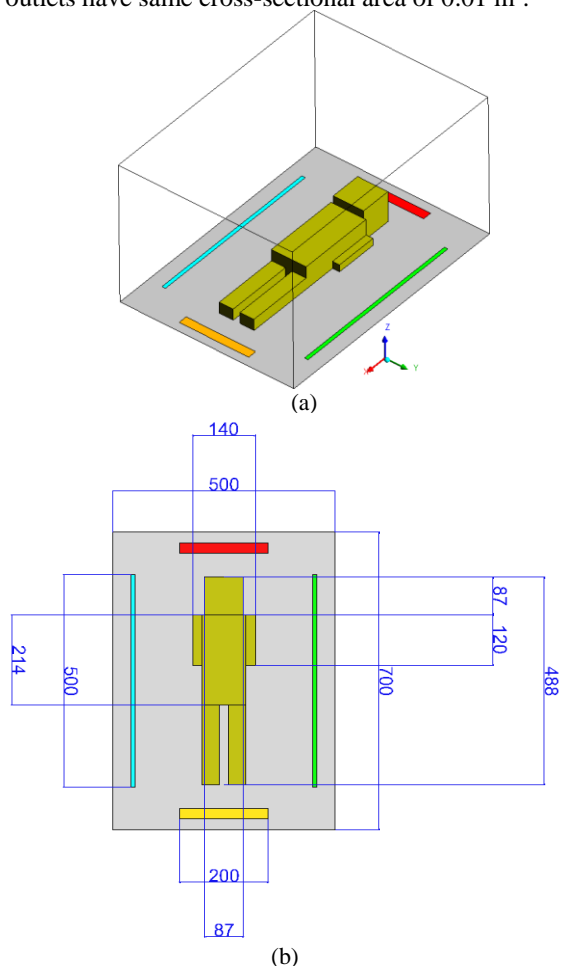


Figure 1. (a) 3D view of the computational domain and (b) top view with main dimensions

TABLE 1. BOUNDARY CONDITIONS FOR THE TWO CASES

	Case 1	Case 2
Newborn	$T = 36^\circ\text{C}$	$T = 36^\circ\text{C}$
Inlet air	$T = 34^\circ\text{C}$ $u = 0.1 \text{ m/s}$	$T = 34^\circ\text{C}$ $u = 0.1 \text{ m/s}$
Mattress	Adiabatic	$q'' = 5 \text{ W/m}^2$
Walls	Adiabatic	Adiabatic

The airflow velocity at the inlets is assumed 0.1 m/s as proposed by Amezzane *et al.* [9] basing on ISO7730 [10]. The pressure at the outlets is considered constant equal to atmospheric pressure. No slip-boundary condition is

assumed at all solid boundaries. The incubator walls are assumed adiabatic. Two cases are considered in the present study, as presented in Table 1. For both cases, the baby skin temperature is set to normal temperature of 36°C [11]. The two cases are summarized in TABLE 1. In the first case, the mattress is adiabatic, while in second case, the mattress is heated with a uniform heat flux. A hexahedral mesh is used in the present study consisting of 522,290 cells. The mesh was refined near the wall boundaries to insure y^+ values less than 4 in order to better compute the near wall regions. In the present studies a maximum y^+ of 2.8 was obtained.

III. NUMERICAL METHOD

ANSYS Fluent [12] is used to compute the Navier-Stokes and energy equations using a second order accuracy. This code is based on cell-centered finite volume discretization. The flow equations are solved sequentially with double precision and a second-order upwind scheme for spatial discretization of the convective terms. The diffusion terms are central differenced and second-order accurate. Pressure-velocity coupling is achieved by the COUPLED algorithm. The $k-\omega$ SST turbulence model is used with a correction for flows characterized by a low Reynolds number. The Boussinesq approximation was adopted to include the buoyancy effects. The radiation process was computed using the Discrete Ordinates (DO) model with 10 iterations. The emissivity of all solid boundaries is assumed equal to 0.9 while the newborn emissivity is set to 0.95 [2]. The residual value 10^{-6} is set as the convergence criterion for the solutions of the flow and energy equations. Beyond this value no significant changes were observed in the velocity and temperature fields and turbulence quantities.

IV. RESULTS AND DISCUSSIONS

The energy rate balance on the neonate body can be written as follows [2]:

$$\Delta q = q_M - q_E - q_C - q_R \tag{1}$$

where q_M is the metabolic heat generated by the infant, q_E is the heat lost by evaporation, q_C the convective heat loss and q_R the radiative heat loss.

The heat transfer from the newborn to the surrounding environment, especially the radiation and convection rates, is directly related to the temperature and air velocity within the incubator. The convective and radiative heat fluxes are determined from CFD simulations. The first two terms are calculated using the Caleo Drager web application [13]. The baby in the present study has a surface area of 0.134 m^2 . The corresponding weight is 1374 g [14]. Thus with this weight and assuming a neonate age of 1 day, this gives $q_M - q_E = 2.24 \text{ W}$.

For thermal balance the energy difference must be close to zero. In fact, if Δq is negative this means that the baby needs additional heating, and vice versa.

TABLE 2 recapitulates the results for the radiative and convective rates of heat transfer obtained from CFD simulations for case 1 and 2. It is shown than for the case

with adiabatic mattress, the heat balance is negative which means that the neonate is losing heat to the environment. This necessitates the addition of an additional heat source to decrease the heat loss.

TABLE 2. ENERGY BALANCE RESULTS FOR CASE 1 AND CASE 2

Heat rate (W)	q_M	q_E	q_C	q_R	Δq
Case 1	3.26	1.02	2.15	5.23	-5.14
Case 2	3.26	1.02	1.10	1.27	-0.13

Fig. 2 to 4 (a) show calculation results for case 1 without heated mattress, while Fig. 2 to 4 (b) show calculation results for case 2 with heated mattress. It can be observed from the streamlines shown in Fig. 2 (a) and (b), that the flow structure for both cases is similar since forced convection is dominant. The flow leaving the inlets is directed upward then the interaction with the upper surface of the incubator redirects the flow downward towards the neonate. Thus a convective heat exchange occurs between the neonate skin and the flowing warm air. Moreover, the temperature of the airflow in case 2 is slightly greater than that in case 1. This explains the reduction in the convective heat loss from the neonate from 2.15 W to 1.1 W. In fact, the average air temperature inside the incubator in case 1 is around 34.8°C while it reaches around 35.3°C in case 2 due to the addition of the heated mattress.

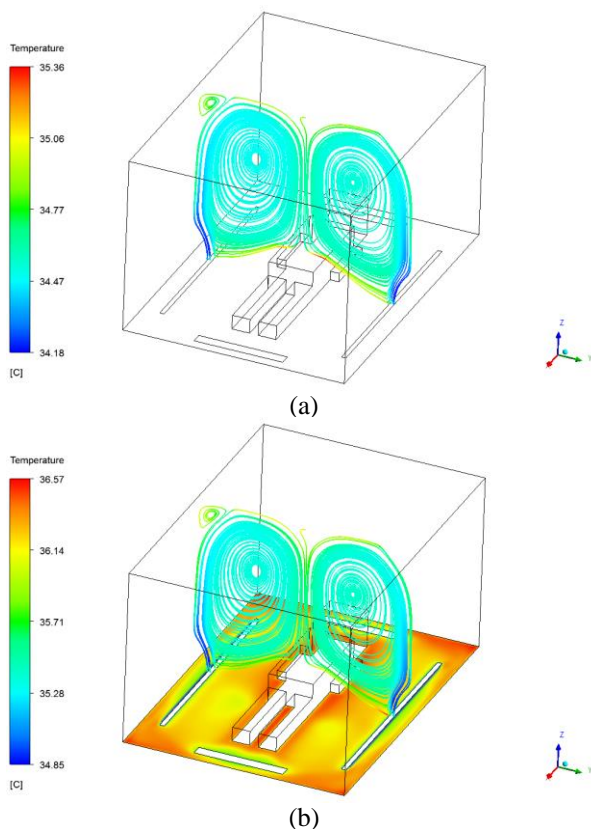


Figure 2. Streamlines colored by temperature for (a) case 1 and (b) case 2.

The convective heat loss from the neonate for case 1 is shown in Fig. 3 (a) where the values range from -0.31 W/m² to 8.12 W/m². Positive value means the heat is lost from the neonate while negative value means heat is gained by the neonate skin. Comparing with Fig. 3 (b) for case 2, it is shown that the neonate loses less heat by convection but more heat is added since the air flow temperature is slightly higher in case 2. The convective heat loss is greater at the neonate chest and face due to the impinging flow caused by the two vortices.

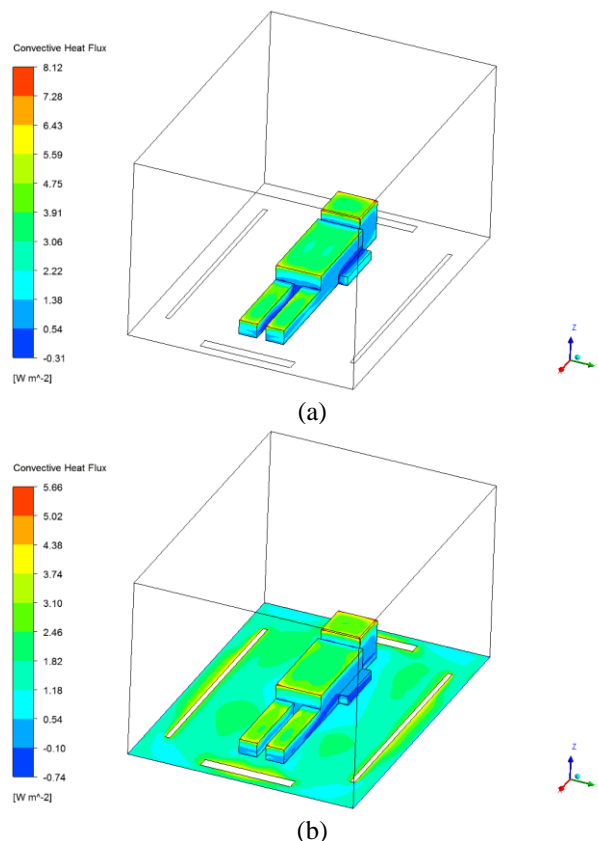


Figure 3. Convective heat flux on the neonate skin for (a) case 1 and (b) case 2.

The radiative heat flux distribution is presented in Fig. 4, where in case 1 the heat loss by thermal radiation from the neonate is greater than that in case 2. The lowest radiative heat loss is from the inside legs while the maximum is from the baby’s face and chest. After the addition of the heated mattress, the radiative heat loss is decreased by almost a factor of 3. Another important issue is that the heated mattress temperature should be almost equal to the neonate skin temperature to avoid conductive heat transfer. This is well obtained here since the heat flux between baby’s sides near the mattress tends to zero, avoiding thus overheating issues.

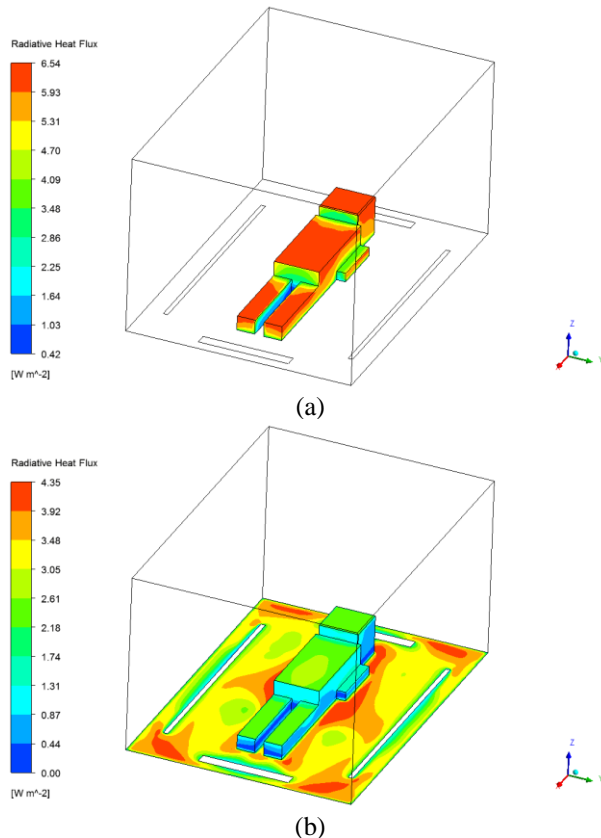


Figure 4. Radiative heat flux on the neonate skin for (a) case 1 and (b) case 2.

V. CONCLUSION

Computational fluid dynamics study was performed to analyze the flow structure and heat transfer in a neonate incubator. Two cases were considered: one with an adiabatic mattress and one with a heated mattress. The first case shows that the heat loss from the neonate is high especially for the radiation heat transfer which reaches around 5.23 W. This problem was solved by providing additional heat to the mattress. This could be done for instance by putting an electric resistor underneath the mattress. The heat loss from the neonate with heated mattress where decreased from around 5 W to around 0.1 W. Moreover, the temperature of the mattress did not exceed 36.6°C to avoid burn in the neonate skin.

In future work, the CFD study will account for the humidity comfort and new solutions will be proposed based on the corresponding results.

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