A CFD QUALITATIVE STUDY OF AN INFANT'S PLETHYSMOGRAPH

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Abstract— In this paper, Computational Fluid Dynamics (CFD) is used to simulate the effects of respiration in displacement ventilated whole body plethysmograph for infants. It is found that CFD allows to simulate the effects seen in experimental results in a satisfactory manner. Grid density, especially in the exhalation zone, is paramount. The choice of flow rate is more important for the flow pattern, the thermal comfort and the air quality inside the plethysmograph.

Calculations are carried out in the case of an infant model, in sleep position inside the apparatus, during an exhalation phase with a constant flow rate. Airflow is predicted using a commercial computational fluids dynamic software called Fluent (FLUENT Inc.). Turbulent modeling is accomplished with the low-Reynolds number k-e model.

Keywords— Plethysmograph, Respiration, Ventilation, Modeling, Simulation, CFD.

I. INTRODUCTION

Whole-body plethysmography has proven very useful in the study of breathing and metabolism in sleeping rodents. It has also been used occasionally to study larger species, and is well suited to studies of sleeping human subjects but has been under-utilized in this regard [1]. The main advantage of the technique is that it is non-invasive and therefore enables long-term recordings from unanaesthetised and unrestrained subjects without causing instrument-induced artifacts in breathing patterns or sleep [2].

Our main objective in the current work is to study the feasibility of using an open flow chamber - of almost the same material and size as an infant incubator - as an infant whole body plethysmograph, through studying the effects of ventilation on the air quality, thermal comfort and infant respiratory signal. Air quality within enclosure environments is essential for the health and welfare of the infant, and the integrity of the measurements being conducted. It is well known that biological responses are influenced by both genetic heritage and the environment. Information on the influence of the physical environment on the infant's biological responses is needed to improve the infant plethysmograph design and management. The infant size, metabolic rate, behavior, thermal properties of the plethysmograph walls, air temperature, air humidity and air velocity, all influence the heat exchanges between the infant and the surroundings. Consequently, it is difficult to obtain and maintain a comfort thermoneutral environment. However, ventilation air is required to maintain good indoor air quality in the space.

In this study, Computational Fluid Dynamics (CFD) is used to characterize airflow patterns, temperature field and the CO_2 mass fraction distributions within an open flow infant plethysmograph for a qualitative approach. In order to generate a CFD solution, two processes must be accomplished, namely; (1) geometry definition and grid generation; (2) numerical simulation. Both processes will be discussed, respectively, in section III and section IV of the present paper. In the following section, we will review the main physical assumptions considered in this study.

II. BASIC ASSUMPTIONS

A. Exhalation flow rate

The behavior of the exhalation jet depends on its own temperature and momentum, on the temperature conditions in the room, and of interaction with other main flows. The momentum depends on the pulmonary ventilation and the cross-sectional area of the nostrils and of course on fluid properties. The pulmonary ventilation rate is approximately 1-2 liter/minute for an infant at rest and the respiration frequency is 35-40 breaths/minute. In the present study, a constant expiratory mass flow rate of 2×10^{-5} kg/s is used, and it is obtained at a pulmonary ventilation of 1 liter/minute and a frequency of 40 breaths/minute.

B. Heat output

The infant compartment airflow velocity and distribution is of paramount importance for heat exchange rates between the infant body and the enclosed environment. The infant body discharges heat to the surrounding environment mainly by the following two methods; (1) heat loss by convection, (2) heat loss by radiation. The heat conduction is neglected [5]. The following equations are used in this study:

- *Convective heat loss from the skin*

$$C_{skin} = h_c\,(A_D - A_{frac})\,(T_s - T_a) \qquad (1)$$

where

$h_c = 4\ W.m^{-2}.C^{-1}$, is the convective heat transfer coefficient.

$A_D = 0.195\ m^2$, is the Dubois surface area of total body [4].

$A_{frac} = 0.805$, is the percentage of body surface area available for convective heat exchange [5] (all surfaces not contacting the bed).

$T_s = 33^\circ C$, is the mean skin temperature.

$T_a = 22^\circ C$, is the ambient air temperature.

- *Radiant heat loss*

$$R = \sigma \varepsilon A_D\, f_r\, f_{acl}\left(T_S^4 - T_{rad}^4\right) \qquad (2)$$

where

$\sigma = 5.673 \cdot 10^{-8}\ W\ K^{-4}\ m^{-2}$, is the Stefan-Boltzmann constant.

$\varepsilon = 0.99$, is the emissivity for human skin.

$f_r = 0.530$, is the radiating fraction of surface area [5].

$f_{acl} = 1$ for the nude state, is the factor by which clothing changes the radiating fraction of the surface area [5].

T_{rad} is the mean temperature of the plethysmograph walls, converted to Kelvin. We considered $T_{rad} = T_a$ in the present study for a simplification reason.

C. Density of expired air

The temperature of the expired air is assumed to be 34°C, and the supply air temperature is assumed to be 22°C. Density variation with temperature, which cannot be neglected in free convection, are accounted for in the body force in the momentum equations using the Boussinesq approximation.

D. Thermal comfort

Several works were conducted in order to quantify and qualify the variables that affect thermal comfort (Fanger [6], ISO Standard 7730 and ASHRAE Standard 55). They showed that comfort could be evaluated from three different classes of variables: ambient variables (mean radiant temperature, humidity, air temperature and velocity), physical activity and clothing. Fanger correlated the body thermal load to an index, PMV (Predicted Mean Vote). We have used this index to estimate, theoretically, some thermal comfort parameters which needed to be defined before starting simulations, like ambient air temperature, mean radiant temperature, relative humidity, metabolic rate, clothing coefficient and air velocity. We chose a combination that allows a thermal comfort nearly neutral regarding PMV index.

III. GEOMETRY DEFINITION AND GRID GENERATION

The physical geometry is modeled relatively simple, as represented in Fig.1, since the geometry is well defined and composed mainly of geometrical primitives. Gambit (Fluent Inc) is the software used for the construction of the geometrical model as well as for grid generation. The size of the plethysmograph considered for this study is the same as for an infant incubator. The infant is modeled as a rectangular box.

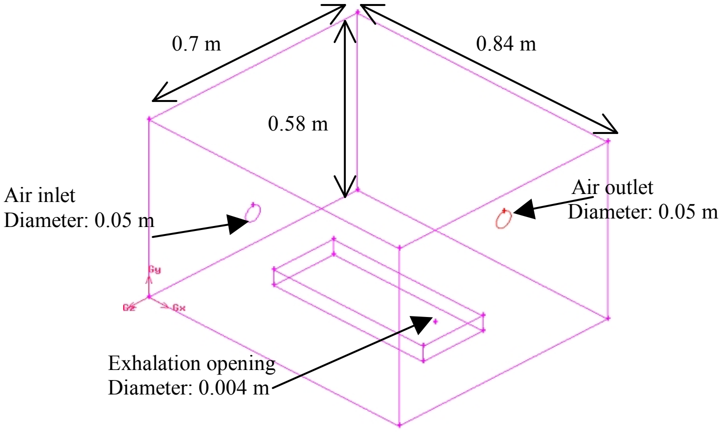

Fig.1: The plethysmograph geometrical model.
Note: the rectangular infant box is not part of the computational domain.

Infants are known to breath mainly from the nose, thus the infant model has an opening, which is used, as an inlet to simulate exclusively the exhalation, in the present work.

An unstructured grid with tetrahedral elements was used. Initially, a grid of approximately 350.000 cells for the three-dimensional model was created with high concentration of cells close to the infant model, especially at the "nose", and also close to the air inlet and outlet. Furthermore, after the initial analysis had been run, the mesh was refined to increase its density in areas where the flow was poorly resolved and, more importantly, to achieve grid independence.

For a first complete qualitative approach and in order to save memory and CPU time, the symmetry longitudinal plane Z1, that cuts through the middle of both the infant body and the plethysmograph, is considered as a two-dimensional model. A grid of 9819 triangle elements is used.

IV. NUMERICAL SIMULATION

Turbulent convection inside the plethysmograph can be described mathematically by assuming that the fluid is Newtonian, that compressibility effects and viscous dissipation can be neglected, and that fluid properties can be taken as constant except in the buoyancy term. The differential equations describing the conservation of energy, momentum, concentration and mass can be written in the following generic form:

$$\frac{\partial}{\partial t}(\rho\varphi) + div\left(\rho\nabla\varphi - \Gamma_\varphi\, grad\,\varphi\right) = S_\varphi \qquad (3)$$

The variable phi (φ) represents any of the predicted quantities such as air velocity, temperature, or concentration at any grid point in the three dimensional model. This equation is descretized on a small, or finite, volume of fluid. The left- hand side of the equation refers to the change in time of a variable within this volume added to that advected into it, minus the amount diffused out. This is in turn equal to the amount of the variable flux (i.e., momentum, mass, thermal energy) that is added or subtracted within the finite volume.

Our numerical simulation is based on the control-volume finite-element technique as implemented in Fluent release 6.1 (Fluent Inc).

The low-Reynolds-number k-ε model is often used in the analysis of turbulence fields surrounding the human body, thus, the airflow is modeled using the k-ε/RNG turbulence model of Fluent, with inclusion of first-order discretisation scheme.

With the assumption of a non-participating media, radiation heat transfer is coupled only to the convection heat transfer through the boundary conditions. Each surface is considered grey and diffuse. The walls of the plethysmograph are considered adiabatic and having a material emissivity of a Plexiglas, ε = 0.9.

The boundary conditions used are velocity inlet for both air inlet and "nose" opening, pressure outlet for air exhaust, and wall functions at all surfaces. The exhalation is forced to leave the "nose" opening with a 30º upward inclination.

The introduction of CO_2 into the room space is modeled by the Species Transport model of Fluent.

The model development proceeded as follows. First, the basic room airflow field was simulated. Once a solution is converged and the conservation laws verified, the energy equations were added and solved. Once a solution is converged and conserved again, the species equation for CO_2 is added and a solution is calculated until convergence.

One of the major advantages of using CFD for such research is the confidence to simulate different configurations knowing that all conditions, except those being varied, remain constant. This makes comparison of CFD simulations much more reliable than comparison of experimental studies, where there is always uncertainty that all conditions are kept the same. However, it is important that all conditions are understood and correctly specified in the CFD model so the results it produces are as accurate as possible. In this study, turbulence quantities k and ε at boundary conditions; needed to be defined. As these data were not available from previous experiments, we considered the worst case.

V. SIMULATION RESULTS

Initially, this section will look at the flow patterns and the qualitative results generated, as this will give a basic understanding of the infant room airflow. The vectors are plotted so that the tail of the arrow is at the point where the value was calculated and points in the direction of air movement, while the color indicates the overall magnitude of air speed at the tail. Fig.2 (a) shows velocity field in the longitudinal symmetry plane Z1. The plane Z1 velocity vectors are dominated by a large clockwise air re-circulation, which occupies almost the entire plethysmograph. Air discharged from the air inlets, moves upward towards the upper air outlet by turning and sweeping along the inside of the plethysmograph ceiling. Air turns again and moves downward. The airflow journey, starts from the inlets (supply and exhalation air inlets) and ends at the outlet, forms a large clockwise re-circulation fluid zone, which forces most of the air to move as a back-flow. Air trapped in the re-circulation zone will rapidly loose its freshness characteristics; for example CO_2 content will rise. A better sight of this re-circulation zone is shown in Fig.2 (b).

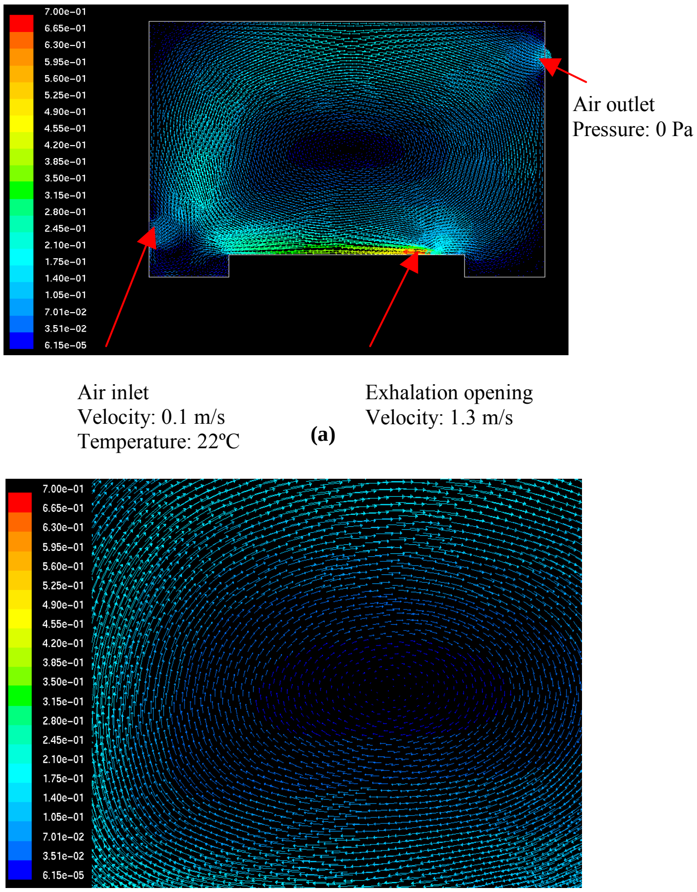

Fig.2: Velocity vectors plot predictions on longitudinal plane Z1: **(a)** The entire velocity field, **(b)** An increased sight of the velocity airflow re-circulation zone.
Note: Velocities > 0.7 m/s (close to the exhalation opening) are omitted.

The temperature distribution predictions show signs of stratification with significantly higher temperatures than 22°C. This is illustrated in Fig.3 with a plot of the temperature contours in the model, which shows the temperature stratification, the boundary layer, and exhalation flow close to the infant.

As seen in Fig.2, the flow inside the plethysmograph is at low velocity except in the local areas around inlets, as would be expected. Air velocity in the corners and in the middle of the re-circulation zone is typically below 0.1 m/s. Thus, there is a time lag in the convective transport of CO_2 within the chamber. The determination of this "time constant", in a future work, for the plethysmograph is important information to accurately evaluate the air quality.

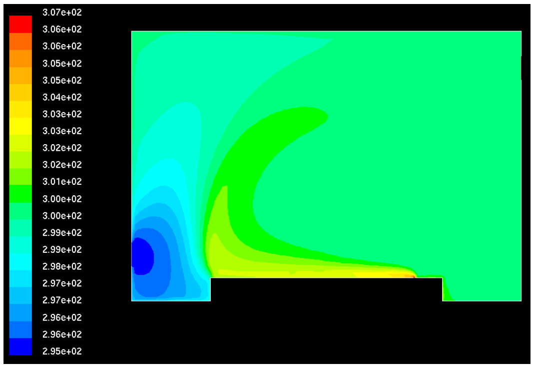

Fig.3: Predicted temperature contours in the symmetry plane Z1. (Air temperature in K)

As shown in Fig.4, the intent of the CFD model was also to help determine the steady state mass fraction of CO_2 reached assuming steady supply airflow and steady occupancy. The flow rate introduced to represent the introduction of CO_2 via respiration of the infant is 5% of the total exhaled flow. It is known from the literature [7] that infants should breathe air with CO_2 under 500 ppm.

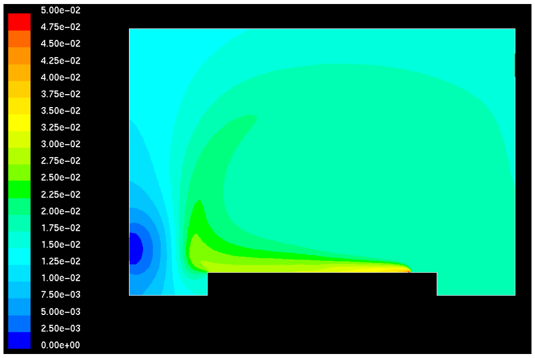

Fig.4: Steady state predicted contours of mass fraction of CO_2 in the symmetry plane-Z1.

It is attempted here to simulate an inherently unsteady flow-the respiration - with a constant flow rate. This is of course not likely to produce entirely accurate results. However, we find that it is possible to reproduce typical features of the flow by such a simplified approach [7].

VI. CONCLUSION

In this paper, CFD is used to characterize airflow patterns, temperature distribution and air quality within a two dimensional model of an infant's plethysmograph as a first qualitative approach.

In general, the simulations were carried out with steady state conditions, but to identify time dependency in the simulation results of CO_2 concentration, transient simulations are currently being made. The simulation will be run until a steady-state point is reached. These unsteady simulations will allow the determination of the time required to achieve a constant CO_2 concentration inside the plethysmograph. Comparisons will be done, at the end of this project, between the simulation results of both two and three-dimensional models for a validation approach.

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