KSME International Journal, Vol. 15, No. 7, pp. 1051~1060, 2001

Flow Visualizations and Hot-Wire Measurements on Air Flow in Two Different Neonate Incubators

Seoung-Chool Yoo
Department of Mechanical Engineering, Halla University, Kangwon 220-710, Korea
Young-Ho Kim*, Chi-Ho Kwon
Department of Biomedical Engineering, College of Health Science, Institute of Medical Instrumentation and Rehabilitation Engineering, Yonsei University, Seoul 120-749, Korea

Flow visualizations and hot-wire measurements on the inside flows of two different incubators are presented in this paper. An anatomically-correct neonate model was fabricated using the rapid prototyping machine, based on the 3-D scanned data. The result showed that air flow in the incubator was affected not only by the air circulation system but also by the design of incubator chamber. Large rotating motions were located around the corners of free space. A number of small eddies were found in regions of high shear flow, in areas such as that between the air inlet and the neonate. But, these small eddies were found to be stationary at that locations. Those small eddies might interfere with convective and evaporative heat transfers from the neonate. This study has led to a better understanding of flow mechanism in an incubator chamber and provided the guidance needed for the advancement of improved computational fluid dynamic models.

Key Words : Neonate Incubator, Flow Visualizations, Hot-wire Anemometry, Rotating Vortices, Turbulence

1. Introduction

Competition in the incubator industry has increased the need to develop technologies for the superior air circulation system. Electronic monitoring and control systems provide a level of sophistication and performance that has not previously been available in neonate incubators. An accurate design of these control systems has become an important priority. Of particular relevance is the precise control of the air flow-temperature. Convective air flow systems have nearly become a standard on today's modern incubator. These systems have achieved a very high degree of reliability and an accurate heat supply control, and thus the design of incubator chamber becomes equally important.

An increased attention has been given to devise more satisfactory methods for analyzing the inside flows of incubators. The design of a more efficient incubator requires the knowledge of the associated flow structure. In particular, the incubator control system has a great impact on the air flow near the neonate.

The relationship between the flow field and the incubator environment continues to be the subject of extensive research effort. The inside flow characteristics of an incubator are dependent on the air circulation system and the design of an incubator. The inside flow of the incubator is three-dimensional and very complicated. Because of its highly turbulent nature, it has not been easily quantified even with the most modern techniques. A good discussion of the computational method for the inside flow characteristics of an incubator

---

* Corresponding Author,
E-mail : yhkim@dragon.yonsei.ac.kr
TEL : +82-33-760-2492 ; **FAX** : +82-33-760-2197
Department of Biomedical Engineering, College of Health Science, Yonsei University, 234 Maeji, Heungup, Wonju, Kangwon 220-710, Korea.

is given by Hasegawa et al. (1993).

Visual studies with high-speed motion cameras provide the physical insight into the fundamental and applied engineering aspects of the fluid motion. However, it is generally recognized that the experiment has not previously been performed to visualize inside flow structures of commercial incubator models. To characterize the various flow fields, such as large eddies and small vortexes, it is useful to employ a reliable flow visualization technique in various planes of the incubator, and to perform hot-wire measurement for quantifying the flow field of interest.

A flow visualization study of air flow in two models of incubators (Model 1: air flow perpendicular to the axis of an neonate's body, Model 2: air flow parallel to the axis of an neonate's body) showed that conventional thinking should be reevaluated. Air flow in an incubator chamber is highly complicated and varies greatly among different air circulation system. The air circulation system influences the heat exchange between the neonate and the surroundings, and, consequently, modifies the obtention of thermo-neutrality. Moreover, studies of the major flow patterns by which the neonate regulates body heat storage suggest that turbulence characteristics should also be taken into account. A better understanding of flow field characteristics in incubators is very important for improvement of flow characteristics, which can lead to a stable and uniform air temperature. A nonuniform characteristic of the air flow might significantly affect the neonate's body heat loss. Homogeneity of the air flow in the incubator chamber might also be crucial to the maintenance of uniform concentrations of oxygen and other gases (Hasegawa et al., 1993).

The hot-wire anemometer has been used as a research tool in fluid mechanics for many years. Recently, the application of anemometry has expanded greatly due to better equipment and more interest in details of fluid flow. The hot-wire anemometry will refer to the use of a small, electrically heated element exposed to a fluid medium for the purpose of measuring a property of that medium. Normally, the velocity and turbulent intensity are the properties being measured. Since these elements are sensitive to heat transfer between the element and its environment, temperature can also be sensed. Typical dimensions of the wire sensor are 0.0038 to 0.005 mm in diameter and 1.0 to 2.0 mm long. The change in resistance induced by the cooling effect of air currents is measured with a potentiometer or a galvanometer. The time lag of the response is very low. Using a hot-wire anemometer with the probe parallel to the long axis of the incubator compartment, Bell (1983) reported that air velocity was low in all tested incubators (about of 0.05m/s) and was below the sensitivity of the anemometer.

The objective of the current study was to develop and to demonstrate experimental measurement techniques to allow direct observation of the salient flow features in the incubator. This study will lead to a better physical understanding of inside flows of the incubator. The longer-term goal is to develop quantitative methods which correlate inside flows of the incubator with the performance of the incubator. Effects of the air circulation system and the incubator chamber design were examined in this study. As a non-corrosive, high light-scattering seed was desired, it was decided to use smoke to visualize the inside flows of the incubator. The advantage to use smoke is that, with properly controlled seeding, one would preserve the regions of scattered light. Thus, sufficient light-scattering gradients would exist to enable discrimination of large-scale structures.

2. Methods

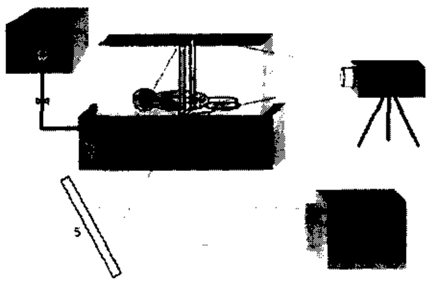
2.1 Incubators and the neonate model

Model 1 had a long inlet at the right side of the neonate and an exit of similar shape at the left side of the neonate so that the major flow in the incubator chamber would be transverse directional. On the other hand, Model 2 had the flow inlet distant from the neonate's head and two exits in the direction of the feet. A manikin was digitized and scanned with roughness of 5mm using the three-dimensional laser scanning system (Conveyeor DS-2016, LaserDesign, U. S. A.), and then, the scanned data was converted into

STL file. The scanned model was enlarged to the actual dimension of the neonate, and then the data was transmitted to the rapid prototype machine (Z-402, Z-corporation, U. S. A.). The neonate model was made by the three-dimensional printing technique with microstone in a short time.

2.2 Flow visualization system

The flow visualization system used in this study is shown in Fig 1. It consisted of a flood light, a digital video camera, a light slit system and a smoke generator. For qualitative flow visualization experiments, the region of interest was illuminated by a sheet of light, and a video system was used to record the images of the inside flow in the incubator. A flood lighting was supplied by a 2kW projection lamp with a reflector. The lighting of the smoke provided the illumination of air movements in the incubator. The density of the smoke played an important role in the amount of light required for proper exposure. The projection lamp would heat the surface of the plexiglass in a relatively short time. The projection lamp was turned on only during actual experiments in order to eliminate this heating that could cause buoyancy effects in the flows. The light source was directed toward the incubator chamber by a set of light slit system. This system provided an angular control with coplanar-orthogonal adjustments. A Sony DSR-2000A digital video camera is used to film flow images on a PDV-124ME tape.



1. Incubator
2. Smoke Generator
3. Digital Video Camera
4. Light Source with Slit System
5. Mirror

Fig. 1 Schematic of the flow visualization system

2.3 Seeding procedure

In an early stage of this investigation, a series of experiments was conducted using different types of seeding particles. In the first attempt, phenolic micro-balloon particles (5~40 μm in diameter) were tested. Micro-balloons are discrete tracers and provide information about local velocities and the general features of large-scale flow structures. However, our visual observations implied that an alternative seeding process was required to improve the clarity of the flow patterns owing to the complex nature of the flow field in the incubator. Therefore, in the present study a solid particle generator was modified so that both the particles' concentration and the flow rate can be changed in order to provide the appropriate seeding conditions.

Accordingly, a series of experiments were conducted with different sizes of particles (0.5-3 μm in diameter). Results from the motion pictures demonstrated a relative improvement in the level of contrast, however both the particles' concentration and the flow rate were not sufficient to reflect the details of the flow features. This was due to the fact that the concentration of particles in the entrained air was not sufficient. In accordance with the previous result, it was evident that larger concentration of particles would be required in order to observe the flow characteristics of interest. The motion pictures using a smoke generator with special mineral oil showed significant improvement and consistency in visual contrast. The smoke generated by this method was clean, dense, and pure white in color. A gas pressure control valve was externally mounted at the front of the smoke generator so that the gas pressure could be adjusted quickly to suit the particular requirement for which the smoke was used. The particle size of the smoke varied, from 0.5 μm to about 4.5 μm in diameter according to the pressure setting.

2.4 Air flow rig assembly

Parts of the incubator were removed and modified to make an optical access through the incubator chamber and the air inlet for the flow visualization study. Because of the seams, inspection doors and rubber connector with clamps on the clear plastic doors, flow visualization would be very limited. In order to avoid this problem, the incubator chamber was modified using the clear transparency film. The transparency film was glued with a clear adhesive to attach on the chamber around doors, creating an identical image of the inside of the chamber. The neonate model fabricated by the rapid prototyping machine was placed on top of the mattress in the incubator in the supine position. The amount of air flow through the test assembly was fixed by the manufacturer.

The seeding materials were introduced at the surface of the filter element. A small slit was cut into the filter to mount 3.8cm long sections of 0.95cm thin wall copper tubing. The tubing was pressed to form a thin oval shape (1.27cm long by 0.5cm wide) that was inserted between the filter and pushed through the slit until the tubing edge was flush with the filter surface. The tube was glued and sealed to the filter to prevent air from bypassing the filter, and tested at various locations on the filter surface until the seed was feeding the area of interest.

A hole of 0.87cm in diameter was drilled in the housing of the incubator to insert a tube through the housing connected to the copper tubes in the filter. On the outside of the assembly, a manifold from the smoke generator fed the plastic tube. The usefulness of these flow visualizations depends on the degree to which the seed can be introduced without affecting the actual flow. This is referred to as isokinetic seeding. In order to avoid flow disturbances while seeding the flow, the smoke velocity was matched to the local flow velocity. Therefore, the smoke velocity from the tubes was approximately the same velocity as the air passing through the filter. Observation of changes in flow pattern when the seeding system was over-pressurized or under-pressurized led us to believe that this seed was introduced in an isokinetic manner. A preliminary testing with a stagnation pressure probe inserted through the cover of the incubator showed very small pressure variations between the measurements made at outlets of the seeding tube outlets and nearby filter surfaces.

2.5 Hot-wire anemometer

A thermoelectric hot-wire anemometer, ThermoAir3 (Schiltknecht, Germany) was used to measure low air velocities (0.01-5m/s) and the degree of turbulence in incubators. Automatic temperature compensation, barometric pressure correction for local altitude and simple zero-adjustment guarantee a high-precision measurement and a simple handling.

3. Experimental Work

3.1 Flow visualizations

Before each test, the rig was disassembled and washed with soap water to remove any oil film. The film concentrates around the neonate model, the surface of mattress, and in the air circulation system including the inner side of the chamber. After the parts were cleaned and inspected for any anomalous damage, the rig would be reassembled.

The flood light was used as a light source for the flow visualization process. Once the flood light beam was on, the slit system was adjusted to form a sheet of light through the area of interest. The film was then loaded and the digital video camera positioned and focused on the sheet of light in the incubator, which was filled with incense smoke to scatter light for focusing. The smoke generator was connected to the intake system of incubator. The air circulation fan was turned on while the laboratory lights were turned off to reduce unwanted light intensity to the camera. Smoke was introduced into the incubator through the intake system. It was necessary to take the images at high speed to obtain a satisfactory level of the unstable flow features.

Flow visualizations were conducted in four vertical planes, as shown in Fig. 2. Plane 1 passed through the neonate's body axis. Plane 2 was perpendicular to the Plane 1 and passed through the neonate's head. Plane 3 was parallel to the Plane 2, and passed through the midline of the neonate. Plane 4 was parallel to the Plane 2, and passed through the foot of the neonate.

3.2 Hot-wire measurements

Although flow visualizations can determine

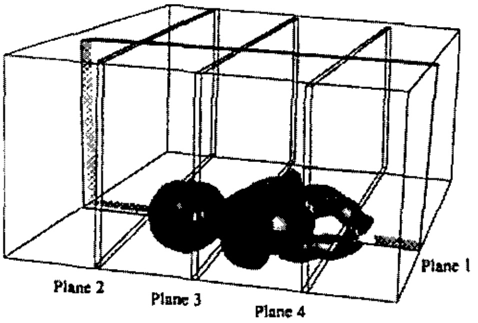


Fig. 2 Incubator chamber with view plane locations

bulk flow features, the detailed quantitative information on the flow field can not be described by the flow visualization alone. The inside flows of the neonate incubator are turbulent. Turbulence can be characterized by the local fluctuations in the flow field. For this purpose a hot-wire anemometer was employed to measure local velocity and fluctuations.

Turbulent motion is randomly time-dependent, strongly non-linear, and generated in the presence of mean velocity gradients. Its characteristics include disorder, randomness, and it generally results in enhanced mixing under fully three-dimensional flow motion. Within this random variation of quantities, statistically distinct average values can be defined. Turbulent motion can be expressed as a time-averaged part and a fluctuating part:

$$u=\bar{u}+u'$$

The time mean $\bar{u}$ of a turbulent function $u(x, y, z, t)$ is defined by

$$\bar{u}=\frac{1}{T}\int_0^T u dt$$

where T is an averaging period taken to be longer than any significant period of the fluctuations.

The turbulent intensity is calculated from the fluctuating part, and defined by:

$$\overline{u'^2}=\frac{1}{T}\int_0^T u'^2 dt$$

The degree of turbulence is defined by:

$$\frac{\overline{u'^2}}{\bar{u}}$$

4. Results

The interpretation of results from flow visualizations and hot-wire measurements for the flow in an incubator chamber was a complicated task. Flow visualization shows the total flow field on the plane where the light beam is placed and provides qualitative interpretation of the flow field. Hot-wire measurement allows one to examine averaged point data which can be used to describe the flow quantitatively. The combination of these two methods makes it possible to understand the inside flow of the incubator not only by the qualitative configuration but also by quantitative information.

4.1 Flow visualizations

Flow fields in two incubator models were examined in several planes parallel and perpendicular to the axis of the neonate's body. The motion pictures (smoke particles were used to seed the intake air) demonstrated that the flow in the planes was complicated, turbulent, unsteady and three-dimensional. In the vicinity of the inlet, the motion picture showed that the fluid was constantly varying with irregular motions. Oscillating flows near the inlet were observed in the movies. This flow became turbulent and unsteady, as illustrated in the motion pictures. The effect of the upper part of the incubator chamber on the turbulent flow led to separation at the wall near the inlet. This flow structure formation was a result of the interaction between the air stream and the vortex layers springing from the corners of the incubator chamber, especially near the restricted corners. Analysis of the films indicated that the instability convected through the wall was introduced by the disturbances from the corners of the incubator chamber, by centrifugal effects, and by the sharp entry of the incubator.

Figures 3 and 4 illustrate the overall structures of the flow fields inside Model 1 and Model 2, respectively. Only one plane along the neonate's body axis in Model 2 (Fig. 4) and perpendicular to the neonate's body axis in Model 1 (Fig. 3) is shown, because of the similarity of flow. In Model

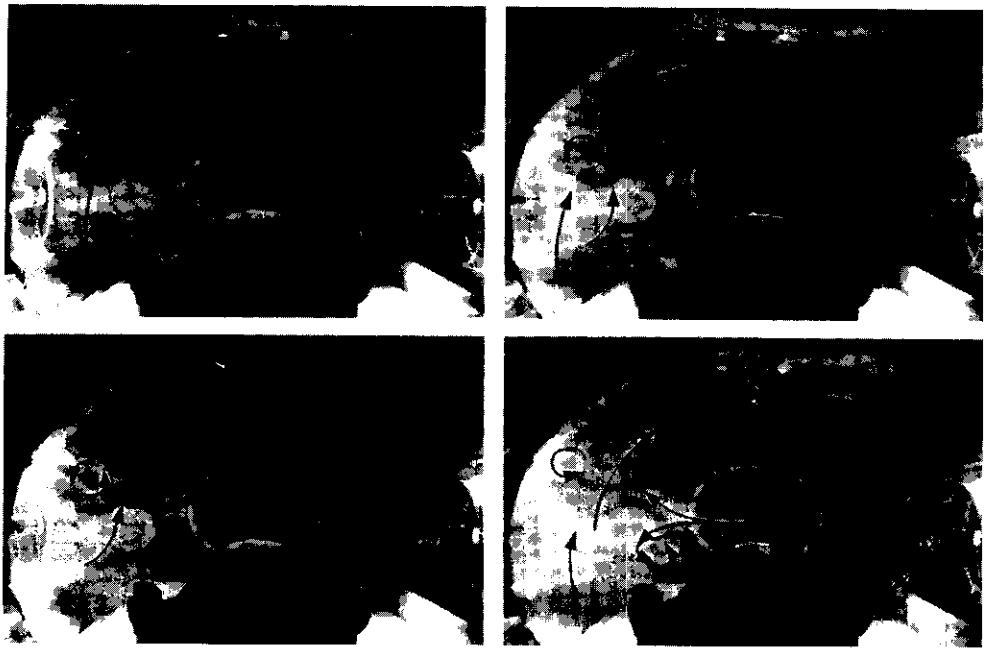


Fig. 3 Flow visualization pictures in plane 2 for Model 1

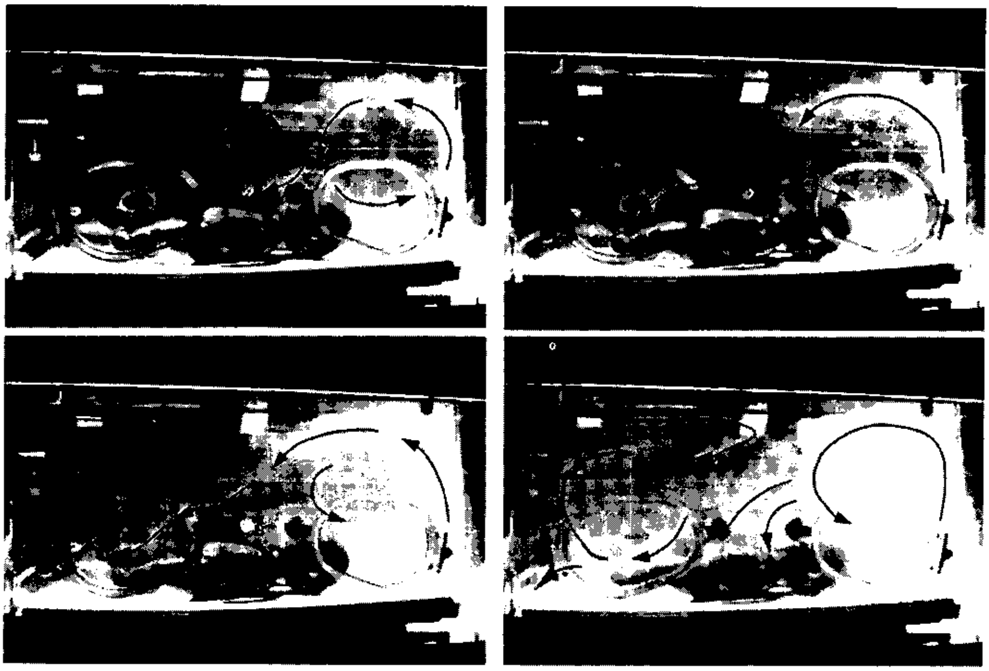
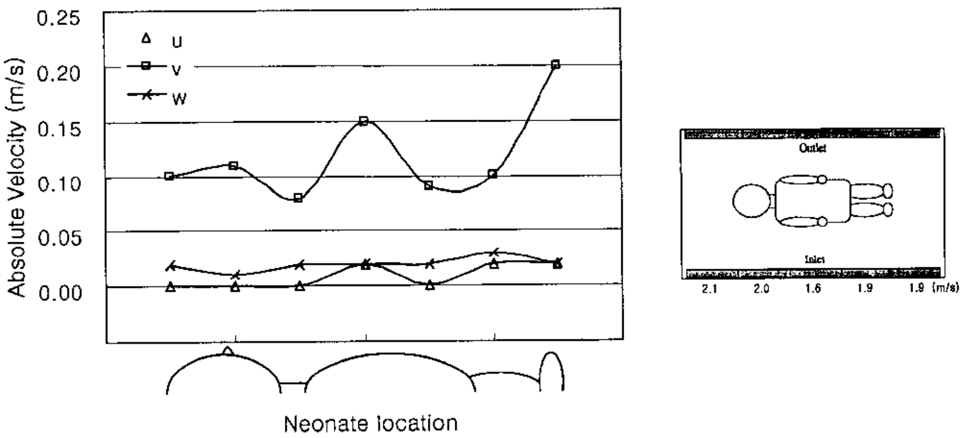


Fig. 4 Flow visualization pictures in plane 1 for Model 2

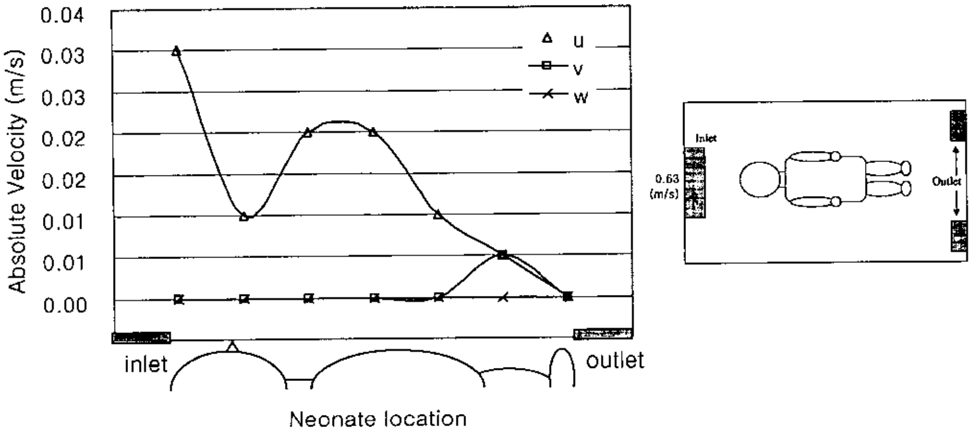
1 and 2, the disturbances near the wall are caused by the vortices originated near the corners of the chamber and along the wall of the incubator. This flow pattern dominates the boundary of the upper part of the incubator chamber and finally leads to a separation from the wall. Deceleration of the fluid around the upper wall appears to reduce disturbances at this location. As observed in the experiment, the vortices originating in the corners curl up in concentrated spiral motions. In Model

2, a pair of counter rotating large scale motions, whose scale is one half order of the longest scale of the chamber, were clearly formed. One of the counter rotating flows originated near the neonate's head was moved faster than that observed near the neonate's leg. This flow pattern may interfere with convective heat transfers in the free space of incubator chamber, and provides a basic understanding of the flow process and the effects of the design parameters relevant on air circulation system performance. In Model 1, there was also a large scale rotating motion like that observed in Model 2. Several vortex can be clearly seen in Fig. 3 in the vicinity of the air inlet, along and near walls, in particular at corners, and around the model of neonate. When the structure of the flow fields in Figs. 3 and 4 was closely observed, a number of small-scale eddies were found to be consecutively produced where local shear velocity was high, in areas such as that between the air inlet and the model of neonate. But, these small eddies were found to be stationary at that locations. Those small eddies may interfere with convective and evaporative heat transfers from the neonate.

To conclude this description of the flow field from flow visualizations, it can be stated that the formation of the large rotating flow structure was generated by the disturbed flow before arriving the body of neonate. This finding indicated that



(a) Model 1



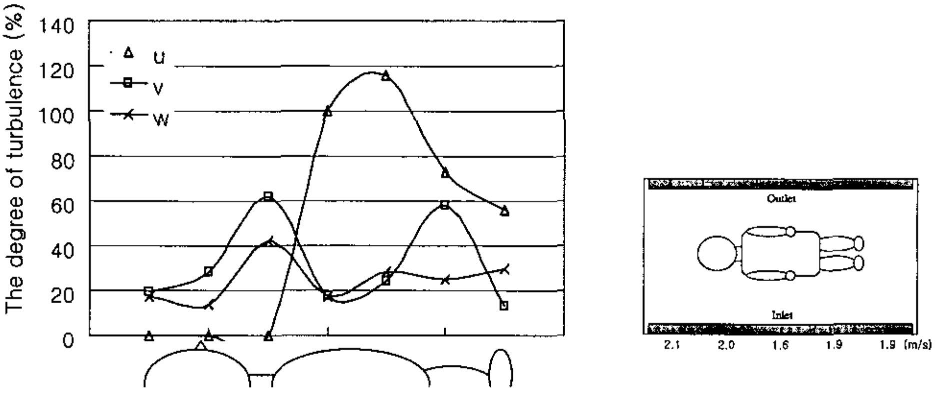
(b) Model 2

Fig. 5 Velocity information along the contour of neonate 0.2cm from the body (the air inlet, neonate and the outlet on the floor are shown) the design of an incubator should incorporate aerodynamic factors. Consequently, detailed analytical and experimental data are needed to permit one to achieve a better understanding of the physical mechanism involved in the air circulation of the incubator.

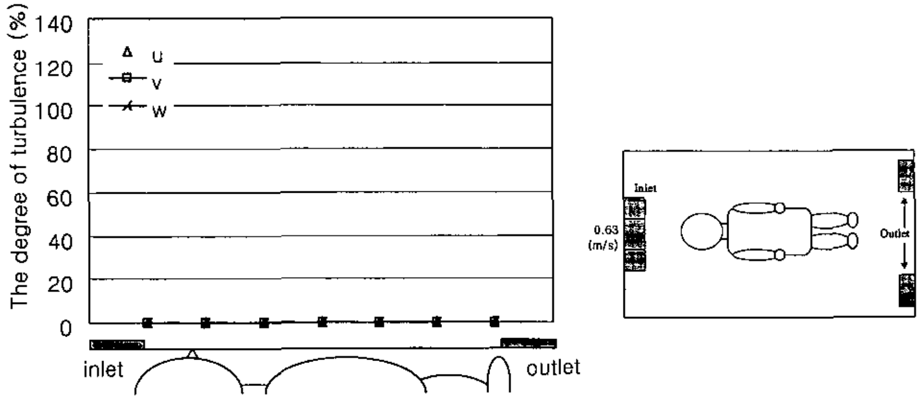
4.2 Hot-wire measurements

To allow close examination of the flow field characteristics in the models, hot wire measurements along the contour of neonate 0.2cm from the body and around the air intake and outlet sections were employed to measure local velocities and fluctuations. Three velocity components were measured in this study, one component parallel to the axis of neonate's body (u-component), one component perpendicular to the axis of neonate's body and parallel to the mattress (v-component), and one component in the measurement plane perpendicular to the mattress (w-component). When single hot-wire probe is used, it is impossible to distinguish the flow direction. Therefore, the absolute velocities were presented in this paper.

Figure 5 shows the absolute velocities in three different components along the contour of the neonate 0. 2cm distant from the neonate"s body. The purpose of this comparison was to determine the effect of the air circulation system on the averaged flow field and to compare the result with the flow visualization results. For reference, both the inlet and the outlet locations with respect to the neonate position are shown. In Fig. 5, positive u-component is towards the right of the page,



(a) Model 1



(b) Model 2

Fig. 6 The degree of turbulence along the contour of neonate 0.2cm from the body (the air inlet, neonate and the outlet on the floor are shown) positive v-component is into the plane of the paper and positive w-component is towards the top of the page. From the locations studied, the flow organization resulting from Model 1 produced a relatively uniform level of turbulence than for the same locations with Model 2. Figure 6 shows the degree of turbulence calculated from the velocity component in the incubator. The degree of turbulence was measured at 7 different locations along the contour of neonate 0.2cm from the body. The degree of turbulence in Model 1 (Fig. 6(a)) was higher than that in Model 2 (Fig. 6(b)). The air circulation system has a very significant effect on the flow field around the neonate. Fluid particles moved in very irregular paths, causing an exchange of momentum from one portion of the fluid to another. This might be an efficient way to improve the performance of the incubator.

Flow field characteristics influence convective and evaporative heat losses from the neonate to the environment. A lack of the air velocity control can mask an increase in body heat losses that imbalances the body heat storage, imposing a thermal stress and can exaggerate the problem of fluid balance encountered in pre-term neonates (Libert et al., 1997). From these observations, one may conclude that the flow field characteristics around the neonate can be controlled also by the air circulation system.

5. Discussion

Neonates exchange heat with the surroundings via four channels: conduction, radiation, convection, and evaporation. Hey (1969) proposed a well-known empirical expression of the heat loss from neonates, but the expression did not take into account convective and conductive heat transfers between the neonate and the surroundings. Conduction has long been considered to play a minor role in body heat exchanges (Swyer, 1978; Stothers and Warner, 1984). This seems to be small enough to be neglected. But, forced convection in term infants have been shown to increase the dry heat losses by some 15% (Stother, 1980). Therefore, convective heat transfer should be considered. (Forced convective heat exchange mainly depends on air velocity.)

Because incubators do not have a directional air stream, accurate measurements of air velocities are difficult, particularly at low velocities because the flow in incubator is turbulent. Another problem refers to the fact that air velocity is often below the sensitivity limit of the measuring apparatus. Therefore, earlier investigators could not estimate convective heat transfer on a quantitative basis.

Turbulence is widely considered as one of the most difficult problems in fluid dynamics. Except in special cases, theoretical advancements are hampered by an inability to find exact solutions to the Navier-Stokes equations; approximations to these equations using closure models has met with only limited success. The range of scales involved in a turbulent flow means that only flows with relatively low Reynolds numbers are accessible numerically to the present generation of computers. As a result, the experimental work continues to play a major role in developments, the scope being limited by our ability to measure and to understand what is happening, rather than the use of the approximate fluid dynamics. The usual experimental probes, such as the Pitot tube, the hot wire but also the more advanced laser Doppler equipment, can be characterized as point measurements, i. e. they only give us information in a single spatial point in the flow field. Although useful, such information is quite limited at the same time, especially when flow phenomena are dominated by spatial structures. With the advent of flow visualization techniques, new and promising experimental methods in fluid flows have been available and make it possible to obtain spatial information. To characterize the flow fields, it is useful to employ a reliable flow visualization technique in various planes of the incubator. A hot-wire measurement is then applied to quantify the velocity field of interest. Using both the flow visualization and hot-wire measurements we were able to analyze the efficiency in the flow fields of incubator. It is generally recognized that any experimental work has not previously been performed to visualize the inside flow structures of the neonate incubator models with realistic three-dimensional shapes.

The flow visualization technique, developed in the present study, offered an efficient method to examine the influence of incubator chamber design on the internal flow. The fluid entrained into the chamber on the inlet side appeared to control the flow structures throughout the incubator chamber. The flow separation that occurred on the corner of wall created a secondary vortex. It has been shown that incubator chamber design significantly affects on the flow structure. These motions could have a serious impact on major parameters controlling the performance of the neonate incubator. Previous study (Hasegawa et al., 1993) showed that the smaller eddies were not stationary and were produced continuously, being convected along the largest eddies. But, our results showed that the small vortices produced between the neonate and the mattress were stationary which might interfere with convective and evaporative heat transfers on the surface of the neonate. Therefore, it is important to eliminate the formation of small vortices around the neonate.

Acknowledgements

This work was partly supported by 2000 RRC program (Research Institute for the Medical Instrumentation and Rehabilitation Engineering) of MOST and KOSEF. We are also thankful to Joong-Wae Medical Co., Ltd. for providing incubators for the present study.

References

Bell, E. F., 1983, "Infant Incubators and Radiant Warmers," *Early Hum. Dev.*, Vol, 8, No. 3-4, pp. 351～375.

Hasegawa, T., Horio, H., Okino, H., Taylor, T. W. and Yamaguchi, T., 1993, "Three-Dimensional Visualization of Air Flow in Infant Incubators Using Computational Fluid Mechanics," *Biomedical Instrumentation & Technology*, Vol, 27, No. 4, pp. 311～317.

Hey, E. N., 1969, "The Relation Between Environmental Temperature and Oxygen Consumption in the Newborn Baby," *J. Physiol*, Vol, 200, No. 3, pp. 589～603.

Libert, J. P., Bach, V. and Farges, G, 1997, "Neutral Temperature Range in Incubators: Performance of Equipment in Current Use and New Developments," *Critical Reviews in Biomedical Engineering*, Vol, 25, No. 4-5, pp. 287～370.

Stothers, J. K., 1980, "The Effect of Forced Convection on Neonatal Heat Loss," *J Physiol.*

Stothers, J. K. and Warner, R. M., 1984, "Thermal Balance and Sleep State in the Newborn," *Early Hum. Dev.*, Vol, 9, No. 4, pp. 313～322.

Swyer, P. R., 1978, *Heat Loss After Birth, in Temperature Regulation and Energy Metabolism in the Newborn*, Sinclair, J. C., Ed., Grune and Stratton, New York.