Conceptual analysis of Intensive Care Room with Computational Fluid Dynamics

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SUMMARY

Since 2005, the Leiden University Medical Center started the building of the new department of children Intensive Care (IC). Several types of geometry have been planned in the department. In order to minimize the cost and get the most applicable result, an IC room with two beds in serial has been chosen for the detailed aerodynamic study. The CFD model of the IC room with two beds in serial is studied. The CFD model will split the whole room as many small mesh elements to fulfill the conservations of mass, momentum and energy. The IC room has a high internal heat load from the devices (approx. 60W/m²) and the hospital owner has a strong expectation on the indoor comfort of the air speed and temperature. Therefore, several difference ventilation concepts have been modeled and the best choice has been made for the final design.

INTRODUCTION

Intensive Care (IC) Medicine is a branch of medicine concerned with the provision of life support or organ support systems in patients who are critically ill who usually also require intensive monitoring.

Patients requiring intensive care usually require support for hemodynamic instability, airway or respiratory compromise (such as ventilator support), acute renal failure, potentially lethal cardiac dysrhythmias, and frequently the cumulative affects of multiple organ system failure. Patients admitted to the intensive care unit not requiring support for the above are usually admitted for intensive/invasive monitoring, such as the crucial hours after major surgery when deemed too unstable to transfer to a less intensively monitored unit.

Medical studies suggest a relation between intensive care unit (ICU) volume and quality of care for mechanically ventilated patients. [1] After adjustment for severity of illness, demographic variables, and characteristics of the ICUs, higher ICU volume was significantly associated with lower ICU and hospital mortality rates. For example, adjusted ICU mortality (for a patient at average predicted risk for ICU death) was 21.2% in hospitals with 87 to 150 mechanically ventilated patients annually, and 14.5% in hospitals with 401 to 617 mechanically ventilated patients annually. Hospitals with intermediate numbers of patients had outcomes between these extremes.
It is generally the most expensive, high technology and resource intensive area of medical care.

Since 2005, the Leiden University Medical Centrum started the building of the new department of Children Intensive Care. The new department will have 40 IC rooms and the gross floor area is about $3250 \text{ m}^2$.

Figure 1 shows an example floor plan of the IC department. Several types of geometry have been planned in the department, for example, one bed room; two bed room; two beds in parallel in one room or two beds in serial in one room, etc.

In order to minimize the cost and get the most general result, an IC room with two beds in serial has been chosen for the detailed aerodynamic study which is indicated with a blue dot line in Figure 1.

**APPROACH**

In order to study and evaluate the performance of the new concept, Computer Fluid Dynamics (CFD) analysis has been carried out.

Computational Fluid Dynamics (CFD) has grown with the progress of computer technology and numerical analysis [2]. It comes from a mathematical curiosity to become an essential tool in almost every branch of fluid dynamics, from aerospace propulsion to indoor climate analysis. CFD is commonly accepted as referring to the broad topic encompassing the numerical solution, by computational methods, of the governing equations which describe...
fluid flow, the set of the Navier-Stokes equations, continuity and any additional conservation equations, for example energy or species concentrations.

As a developing science, Computational Fluid Dynamics has received extensive attention throughout the international community since the advent of the digital computer. The attraction of the subject is twofold. Firstly, the desire to be able to model physical fluid phenomena that cannot be easily simulated or measured with a physical experiment, for example fire and smoke development. Secondly, the desire to be able to investigate physical fluid systems more cost effectively and more rapidly than with experimental procedures.

There has been considerable growth in the development and application of Computational Fluid Dynamics to all aspects of fluid dynamics. In design and development, CFD programs are now considered to be standard numerical tools, widely utilised within industry [3].

The CFD model of the IC room with two beds in serial is shown in Figure 2. The size of the room is 7.875x5.055x2.7m (LxBxH).

The CFD model will split the whole room as many small mesh elements to fulfil the conservations of mass, momentum and energy. For this IC room, the amount of mesh elements is ca. 500,000 (Figure 3).
SIMULATION CONDITIONS & REQUIREMENTS

The simulation condition is based on the GTR (General Technical Requirement, M/E) [4] of LUMC. Several conditions related to CFD simulation are:

- The IC room is 7.875x5.055x2.7m (LxBxH). This is 39.8m$^2$ and 1007.48m$^3$;
- Climate ceiling will be applied; condensation must be avoided;
- In order to avoid condensation problem on the surface of climate ceiling, the surface temperature is set as 18°C;
- Air speed keeps lower than 0.12m/s in the patient zone;
- Air temperature approximately 22°C when $T_{out} \leq 26°C$;
- Internal heat load approximately 112W/m$^2$ for thorax situation.

BASIC CASE STUDIES

In this research, four concepts of ventilation supply are analyzed:

a) air supply diffusers from the side walls of the middle block (Figure 4a)
b) downflow air supply diffusers from middle ceiling (laminar flow) (Figure 4b)
c) downflow air supply diffusers from ceiling of sides of bed (laminar flow) (Figure 4c)
d) ceiling diffusers (one side supply) (Figure 4d)

Models of four concepts
Figure 4. CFD model with a) air supply diffusers from the side walls of the middle block; b) downflow air supply diffusers from middle ceiling (laminar flow); c) downflow air supply diffusers from ceiling of sides of bed (laminar flow); d) ceiling diffusers (one side supply)

**Temperature comparison of four concepts**

Figure 5. Temperature distribution with air supply diffusers for case a) to d)
Air speed comparison of four concepts

Figure 6. Air speed distribution with air supply diffusers from case a) to case d)

Air stream comparison of four concepts

Figure 7. Air stream distribution with air supply diffusers from case a) to d)
SPECIAL CASE STUDY: ASYMMETRIC SITUATION

The purpose of the analysis on this asymmetric situation is to check what will be indoor climate condition in case one bed is fully occupied for the IC and another bed is only with one patient laying on the bed (the most asymmetric condition).

The following figures (8a ~ 8c) is made in such a way that the unoccupied side will only have the TV screen on and all the other apparatus will be switched off. Several control strategies have been tried. And the following figure is with the conditions of:

1. The ceiling of the room is split into two parts. Each takes care of one bed. The unoccupied side will have surface temperature as 22°C and the occupied side as 18°C.
2. The air supply temperature will be kept as the same as 19°C.

By these, the air temperature (at 1.5 meter above the floor) will be ca. 22°C. The air speed in the patient zone is lower than 0.12m/s.

With a smart control strategy, a good indoor climate will be approached.

Figure 8. Ceiling diffusers (one side supply) at asymmetric internal heat load a)Temperature distribution; b) Air speed distribution; c) Air stream distribution
CONCLUSIONS

By the CFD simulation, some conclusions can be made:

The air speed in the patient zone is limited and lower than 0.12 m/s for all concepts. However, if looking at the temperature distribution in the room, the fourth concept (ceiling diffuser to one side) has the most homogenous temperature distribution. Therefore, it will give the least temperature variation for the nurses who will walk around in the IC room.

Above results are all based on the thorax situation, i.e. the highest internal heat load condition. Under this condition, the average room temperatures are ca. 23.5 ~ 24°C. This means, the room temperature could not approach the requirement of 22°C. This will only occur with high internal heat load. In the reality, two big apparatus, dialysis apparatus and balloon pump/heart & lung device, which are 850 W, will not be used for the most situation. And this will lead to a condition under the requirement and has been studied in another report.

The general conclusions in this study are:

- The highest internal heat load condition (ca. 112 W/m^2) can not lead to a required indoor environment, i.e. the room temperature will be approximate 23.5°C instead of 22°C;
- Different concept has different advantage and disadvantage. The relatively best concept has been chosen with the ceiling diffusers of one direction supply (Waterloo DE/DF 111). This is the case (d).
- The asymmetric situation will not lead to any problem if a smart control strategy is applied.

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