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On the numerical accuracy of particle dispersion simulation in operating theatres

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SUMMARY

In this investigation it is explored in what manner CFD calculations of operating rooms have to be conducted in order to provide usable information in a design process. CFD simulations of an operating room are compared to measurements of the same situation. In the different CFD simulations variations are made in the method used in calculating the turbulence in the room. A Reynolds averaged approach was used in the form of a K-ω model in a steady state simulation. The LES turbulence model required a transient simulation.

The LES model was able to predict the particle concentrations in the clean area much more accurately than the K-ω model.

IMPLICATIONS

The steady state RANS approach is not able to predict the particle concentrations accurately. The results are too optimistic and will lead to wrong conclusions in a design process. The LES simulations are too optimistic as well, but show the right tendencies. Further simulations are necessary to see if these are able to distinguish the performance of different designs.

KEYWORDS

Operating room ventilation, CFD, turbulence modelling

INTRODUCTION

Ventilation of operating rooms serves several purposes, but the most important one is to keep airborne bacteria from entering an operating wound. To accomplish this, various different ventilation systems can be used. The design depends on the type of operations that are going to be performed in that room, especially the equipment used and the risks involved. New operating rooms are usually equipped with a laminar downflow system.

During the design phase of the ventilation system in a room decisions need to be made that may affect the performance of the ventilation system. To make informed decisions on these choices airflow simulations can be made using CFD (Computational Fluid Dynamics) software to predict the amount of protection these systems can bring.

A fair comparison between different ventilation systems in a somewhat standardized situation can be made using the VDI 2167 [1]. This setup however describes measurements to be taken after a room is built, to validate whether the ventilation system works properly.

In this paper the method described in the VDI 2167 is used in CFD simulations. To see what works well, simulations using a Reynolds averaged (RANS) and a large eddy (LES) approach to model turbulence are compared to measurements of the same situation to evaluate which methods lead to acceptable results.

METHODS

In the reference case measurements of the performance of the ventilation system were made according to the VDI2167 method, using fixed smoke sources on the floor and multiple measurement points, including the instrument tables as extra measurement positions (see Figure 1).

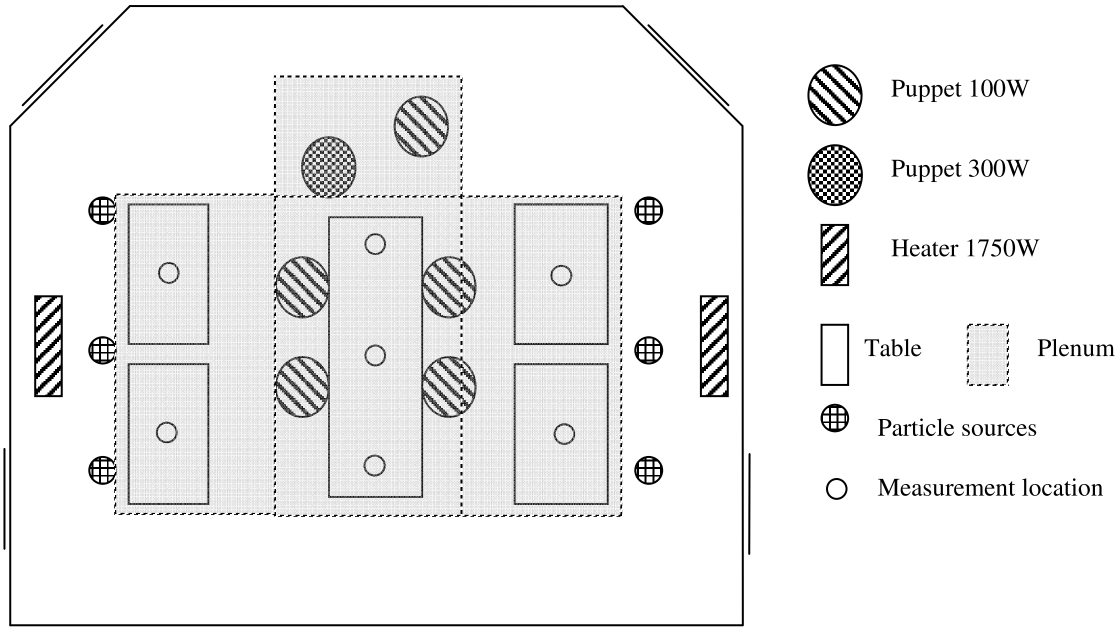

Figure 1. Floor plan of the experimental setup.

The test chamber measured 6 x 6 x 3 m. The ventilation system present in the room is a laminar downflow system with air supplied through a plenum divided into 4 separate zones. Air velocity is kept as uniform as possible across these zones at 0.24 m/s. Inlet temperatures are 18.7°C from the central plenum, 20.6°C from the side plenums, and 21.9°C from the anaesthesia plenum.

As some portion of the air is recirculated and a large amount of particles is generated in the room, the installed filters were not able to clean the air completely. Therefore the inlet air was sampled as well, and inlet concentrations are known.

The simulation configuration and conditions agree exactly with the measurement situation. This means that the particle concentrations at the inlet were also included in the simulations. The simulations are made to determine minimum CFD simulation requirements for accurate and useful results.

First a k-ω and a LES simulation have been compared. Both simulations use the ideal gas law to simulate the effects of temperature differences. Boussinesq approximation is avoided because temperatures inside the heaters become too high to provide acceptable results. Radiant heat transfer is modelled using a surface-to-surface radiation model.

Particles are simulated using the Eulerian method. The measured particles are in the range of 0.5 to 1.0µm. According to Zhang and Chen (2007) using the eulerian method is acceptable in a steady state situation. Additionally, the low particle concentrations measured would require an unfeasibly large number of particles to be tracked.

The grid is generated using an automated tetrahedral mesh generator that generated a finer grid on the surfaces of heat and smoke sources, expanding to a maximum cell size of 0.08m in the rest of the room. Both the steady state and transient simulations were performed with a base grid of 2.1M cells.

The VDI 2167 prescribes a measurement period of "at least 15 to 20 minutes in case of cyclic behaviour". Therefore the measurements were performed over a 16 minutes period with reporting intervals of 4 minutes to identify this cyclic behaviour. The transient simulations followed this same pattern. The time step in the transient simulations was initially chosen to be 0.25 seconds

The transient simulation was subjected to a grid sensitivity analysis and a time step sensitivity analysis. For the grid sensitivity the grid size was reduced everywhere by a factor 1.26 as to double the total number of cells. For the time step sensitivity analysis the time step was reduced to 0.05s in order to get the cell courant number of 80% of the cells below 1.

RESULTS

The investigated configuration produced higher particle concentrations at both the foot and head of the operating table compared to the concentrations from the plenum itself. The middle of the operating table was as clean as the air from the plenum. Particle concentrations on the instrument tables were much higher. Figure 2 summarizes all measurement and simulation results.

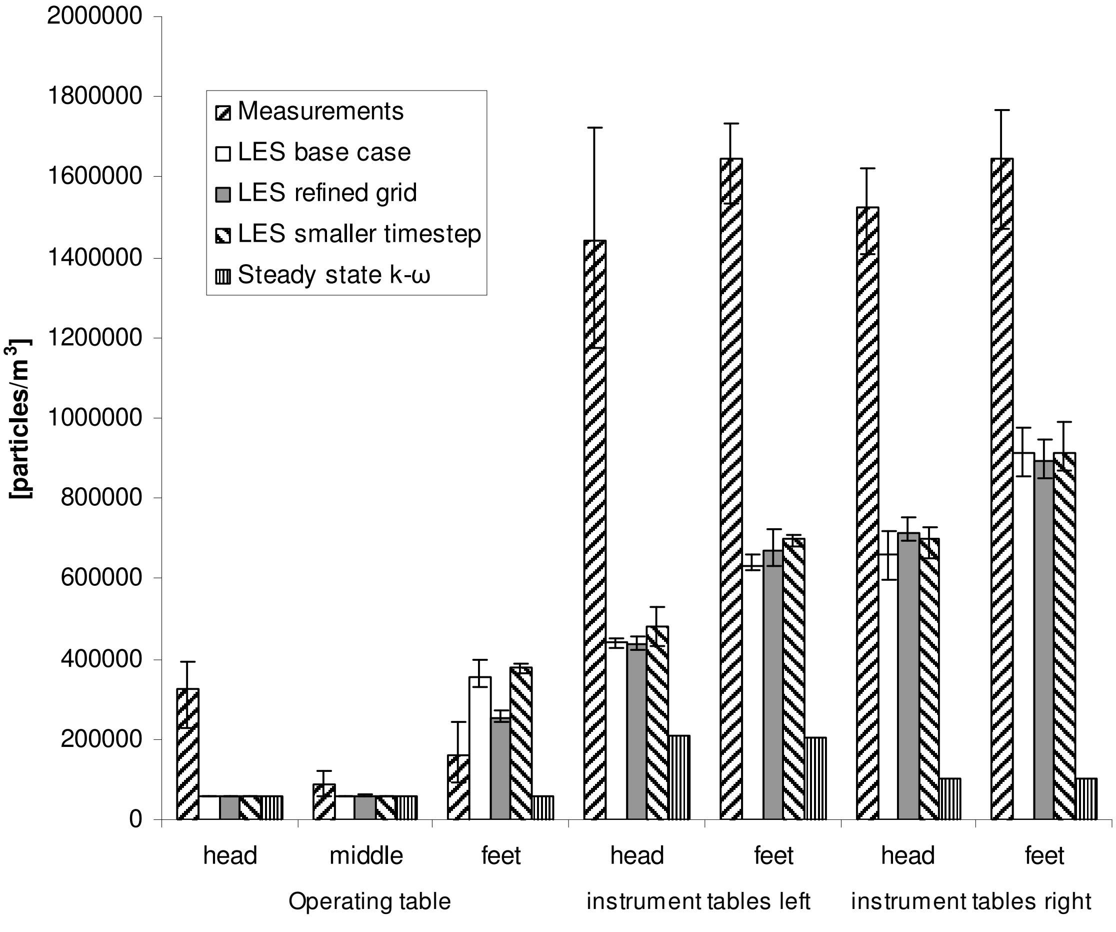

Figure 2. Particle concentrations from measurements and simulations. Values indicate the average from four measured values; error bars indicate the minimum and maximum values in these.

The particle concentrations predicted at the identified measurement locations by the steady state simulations are exactly the same as the concentration released from the plenum, thus in this simulation no particle transport into the clean area was modelled at all.

Although the particle concentrations produced by the transient simulations are lower than the measurements, they show the same tendency of higher concentrations on the instrument tables and lower concentrations on the operating table. Figure 3 presents an example of the complex flow field present in the room.

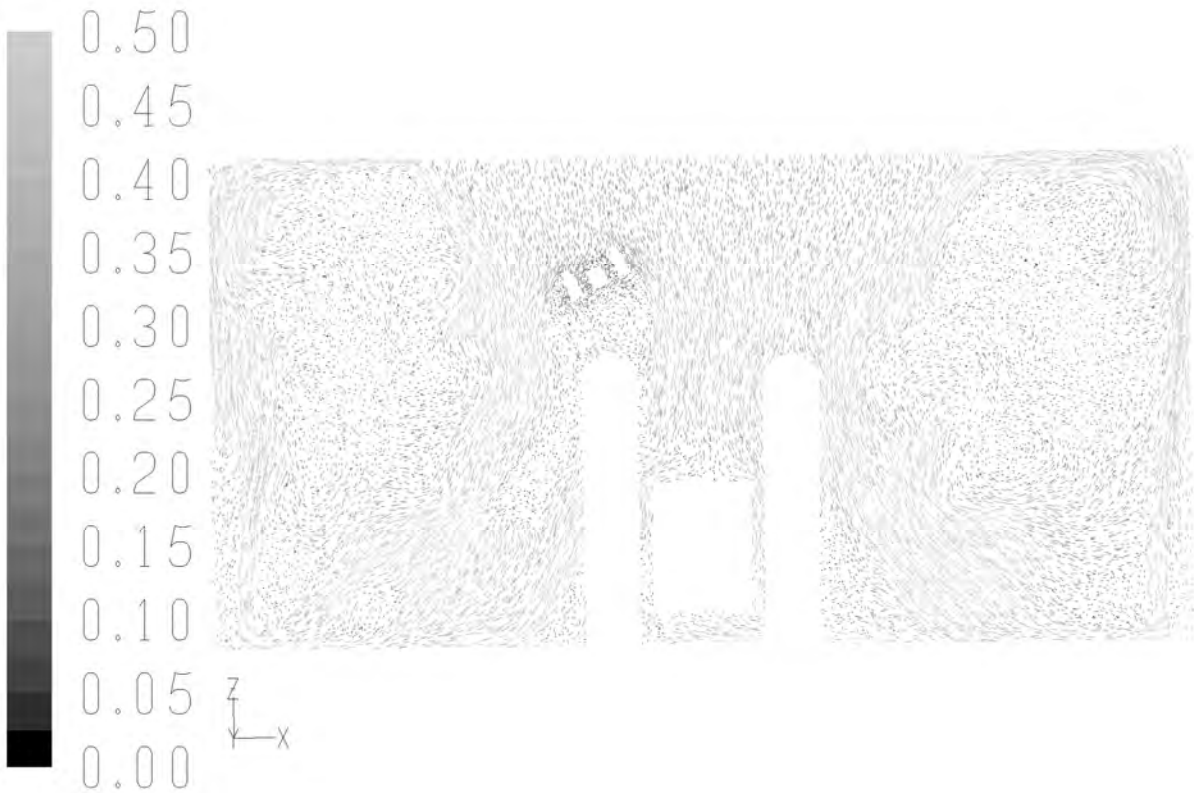

Figure 3. Example of an instantaneous flow field over a cross section of the operating theatre in the large eddy simulation.

DISCUSSION

Although the concentrations were lower than the measured values, the large eddy simulation predicted the transport of particles into the clean area. The difference in concentration can at least partially be explained by measurement errors.

A smooth flowfield resulted from the steady state k-ω simulation that underpredicted the mixture of particles into the clean area compared to the LES simulation. This is caused by the fact that the particle transport into the clean area was mainly caused by large rotating structures. Reynolds averaged turbulence models, such as the k-ε or k-ω depart from the premise that the largest eddies in the flow pattern are smaller than the cells in the simulation. The LES turbulence model is based on the premise that larger eddies are simulated and the turbulence model is used to simulate eddies smaller than the cell size.

The finer grid only improved the prediction near the feet of the patient. The boundary of the clean area is quite thin and close to the measurement point here, which would explain why this point is affected the most by grid refinement. The situation near the head of the patient is quite complicated. Therefore it is not unreasonable to expect a larger deviation from the measurements at this position.

In a design process the prediction of the absolute value of the performance is of interest, but what is more interesting is whether from two comparable simulations one can decide on the best design option. Another objective for simulations for design is whether serious design flaws can be recognised. These simulations show that a LES simulation is able to distinguish design flaws. More cases need to be simulated to see whether it can be used to differentiate between designs.

CONCLUSIONS

A steady state simulation using a k-ω turbulence model as described in this paper is not able to predict the performance of operating room ventilation. A Large Eddy simulation predicts particle concentrations that are closer to measured values. The results are not dependent on grid or time step size. Whether the transient simulations are accurate enough for making design decisions should follow from simulations of other cases to see if measured improvements are also predicted as improvements.

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