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Comparison between k- ε RANS Model and SST k-ω SAS Model in Data Centre Simulations

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Abstract

Thermal management of data centres does not depend only on the air conditioning sizing or facility arrangement Bash, et. al. [1]. A precise estimation of airflow and thermal distribution is necessary to predict the server rack inlet temperature. In previous studies of data centres, numerical simulations using the k-ε RANS model have been extensively used to explore the airflow and thermal distribution within the data centre room. These types of simulations can give reasonably accurate results for the average velocity, pressure and temperature in many industrial applications especially for fully turbulent flows. RANS models have the benefit of being less computationally intensive compared to DES (Detached Eddy Simulation) models; however, they behave poorly in cases of high stream line curvature, severe pressure gradients and flow separation. All these features may be present in the data centre due to the complex interactions between different air streams. In this paper the SST k-ω SAS turbulence model will be used to generate the DES simulation results. The SST k-ω SAS model is a hybrid model, using a RANS model near the wall and a LES model away from the wall. Although, this model is much more computationally intensive than the k-ε model, it allows large transient turbulent structures to be captured. Additionally, comparisons with the results using the k-ε model will be carried out. This will enable to understand any limitations in using the k-ε model for data centre numerical simulations to be identified.

Introduction

Recent advancements in computing hardware have resulted in rapid growth of computing; as a result, data centres have become indispensable facilities in the world. According to Cho and Kim [2] data centres are defined as "facilities that house IT servers and data storage systems".

Data centre cooling system must guarantee a reliable and continuous operation. However, there are many sources that may cause cooling inefficiencies that should be avoided. For instance, hot air recirculation, which is the process of the hot air infiltration into the cold aisle, as well as short-circuiting, which is the returning of the cold air directly into the computer room air conditioning units (CRAC) without entering the server racks. As a result, significant effort has been made to explore the airflow and thermal distribution in data centres which are affected by many factors such as the air distribution system, pressure distribution in the data centre room and the placement of CRAC units.

One of the most important issues concerning data centres is the energy consumption where one large data centre may consume around 10-20 MW of electricity. Also, it has been found that the energy consumption of a data centre has doubled every four years in the last decade Cho, et. al. [3]. Therefore, the consequences of very high usage of electricity and the methods of the heat dissipation are the main concerns for data centres designers. In fact, this gives rise to the importance of the cooling process efficiency in data centres as the cooling system for a data centre consumes around 40% of the total energy Cho, et. al. [3]. The cooling process is not only important to save energy but also to guarantee continuous and reliable operation as any interruption may cause serious implications in computing operations at all levels.

Most of related work has been concentrated on developing performance parameters based on CFD modelling of different data centre configurations in order to optimize cooling efficiency. Computational Fluid Dynamics CFD simulations are used to visualize the air and thermal distribution throughout the data centre's rooms. It has the ability to give a detailed insight and accurate values for the rack and CRAC inlet and outlet temperatures. However, to figure out the cooling efficiency from the CFD simulations, it may be challenging as CFD simulations give qualitative description for the thermal distribution which could not be used to construct numerical data regarding the data centre thermal performance. Hence, there is a necessity for proposing dimensionless indices to give a quantitative analysis to construct numerical data as yardsticks to interpret those measured temperatures Herrlin [4]. Typically, thermal indices interpret the CFD simulation and can give various solutions to enhance the cooling efficiency.

In previous studies of data centres, numerical simulations using the k-ε RANS model have been extensively used; therefore, in this paper results using the k-ε model will be carried out and compared with the more robust turbulence model SST k-ω SAS to identify the limitations of the k-ε RANS model.

Data Centre Cooling Infrastructure

A common standard data centre is a raised floor with room return layout. Figure 1 shows the modelled data centre in this study which represents a typical raised floor data centre with room return. The server racks convert the electrical power into heat which is removed by recirculating cold air out of the CRAC units. The CRAC units should be sized to remove the heating load of the server racks. Typically, CRAC units cool air by chilled water or refrigerant $10^{\circ}C$ to $17^{\circ}C$. Data centres are frequently designed in cold/hot aisle arrangement approach. The cold aisle receives the cold air provided by the CRACs through the vent tiles, then the server racks draw this cold air to remove the heat dissipated by the servers. After that, the hot aisle receives the hot air exhausted by the sever fans before ducting it to the CRAC units' inlets.

Figure 2 shows the air distribution of the room return infrastructure. The figure shows the main air distribution problems, which have been identified in a typical data centre, hot air recirculation and cold air bypass. The hot air recirculation will result in a significant difference in the inlet temperature between the upper and the lower part of the server racks. Whereas, the cold air bypass affects the cooling process efficiency by reducing the cold air received by the servers. Another important inefficiency due to the cold air bypass is the possibility of mixing the cold air and hot air streams in the upper part of the data centre room which may not be avoidable especially with longer path of exhaust air Ratnesh, et. al. [5] .The focus in this paper will be on the raised floor with room return layout only as shown in Figure 1.

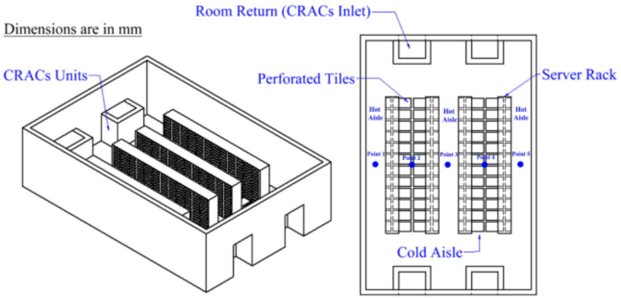


Figure 1: The modelled data centre schematic diagram with room return.

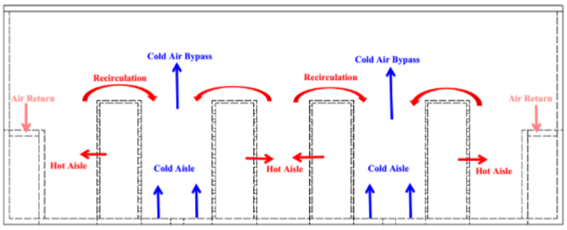


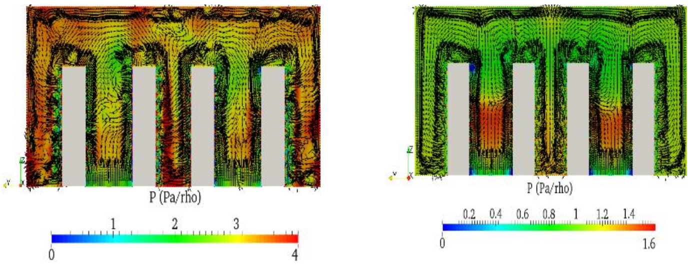
Figure 2: Typical data centre air distribution with room return.

Results and Discussion

The findings of this research shows that there is a strong indication that the k-ε RANS model behaves unsatisfactory in the case of data centre simulations. Whereas, in the case of the SST k-ω SAS turbulence model, the pressure distribution and hence the air distribution was successfully estimated. The results of both models were compared with experiment conducted by Sundaralingam, et. al. [6] and from comparing the simulation results with the experiment, the SST k-ω SAS turbulence model gives a strong indication that it is much more robust and to be used in the data centre simulations. The simulations have been conducted by using the open source software tool OpenFOAM. The solver of the k-ε RANS model is the buoyantBoussinesqPimpleFoam; whereas, for the SST k-ω SAS model a modified version of this solver was used to be able to perform a LES solution.

Pressure and Air Distribution

Figure 3 shows velocity vectors and pressure distribution in the cold and hot aisles for the k-ε RANS and SST k-ω SAS turbulence models. The figure clearly clarifies the difference between the pressure distribution calculated by each model. Pressure was measured at three different vertical planes (X=5m) across the data centre. In the k-ε RANS approach the highest pressure is located in the cold aisle which should prevent the hot air from being infiltrated into the cold aisle. Also, in the rest of the data centre room space the pressure is evenly distributed. Whereas, in the SST k-ω SAS turbulence model, the highest pressure is located in the hot aisle. Also, this model shows that the pressure in the upper part of the cold aisle is lower than the rest of the data centre room space; however, in the middle and lower part of the cold aisle the pressure is comparable to the data centre room space. In fact, these two distinct pressure distributions can give different air distribution patterns which in turn will affect the thermal distribution. In the k-ε RANS, the hot air will infiltrate into the servers located in the upper part of the rack, while the middle and lower servers of the cold aisle will not have been subjected to any hot air streams due to the restriction caused by high pressure in the middle of the aisle. Nevertheless, the SST k-ω SAS indicates that the pressure in the upper part of the cold aisle is less than the data centre room space pressure, that will cause strong air streams entering the cold aisles from the room and the hot aisles. Due to the fact that the cold aisles are opened to the data centre room space and its middle pressure is comparable to the upper part of the room, the hot recirculated air will infiltrate to the middle part of the cold aisle causing starvation for some servers located in middle part of the cold aisles.



X =5 m (SST k-ω SAS).

X =5 m (k-ε RANS).

Figure 3:Velocity vectors and pressure distribution in the cold and hot aisles.

Utility sample is used to know how the pressure changes within the cold and the aisles. Figure 1 shows, points 1-5, the locations of the vertical lines where 50 points have been sampled over each line in each aisle. Figure 4 displays the pressure variations within the cold and hot aisles for the SST k-ω SAS and clearly shows that the highest pressure is within the hot aisle located in the middle of the data centre; whereas, the pressure in the rest of the aisles is comparable to the cold aisle pressure except for the upper part of the cold aisles where the pressure drops significantly compared to the same location in the hot aisles. In general, the pressure of the hot aisles is higher than the pressure in the cold aisle due to the high jet velocity of the vent tiles causing lower static pressure. On the other hand, the velocity within the hot aisles is lower than the velocity in the cold aisle causing higher static pressure. This pressure distribution should affect the airflow pattern considerably where more pressure gradient between the hot aisles and the cold aisles forces more air to infiltrate into the cold aisle. The high static pressure in the hot aisle also may cause other issues especially in such air distribution system, it will cause more mixing in the room as the room return plenum is not located in the direction of the hot air jets. In addition, there is a remarkable difference in the pressure variations between SST k-ω SAS model and the k-ε RANS model. Figure 5 shows the pressure variations within the cold aisles and the hot aisles for the k-ε RANS model. In k-ε RANS model the pressure in the middle of the cold aisles is considerably higher than the pressure in the hot aisle; however, in the upper part of the cold aisles the pressure is comparable with pressure in the upper part of the hot aisles. This pressure distribution will result in different airflow pattern as the hot air will infiltrate into the cold aisle in a slower pace than that in the SST k-ω SAS model. Moreover, from the figures of the pressure variations, the SST k-ω SAS can detect the static pressure drop in front of each server in the hot aisles in the expense of dynamic pressure because of the air jet of the server; whereas, the k-ε RANS does not detect this pressure exchange.

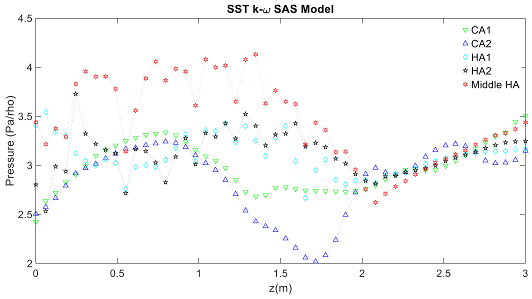


Figure 4: Pressure variation within the cold and hot aisle for SST k-ω SAS.

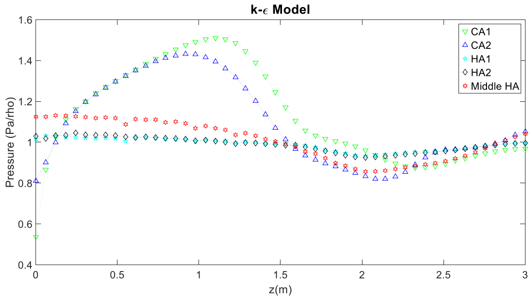


Figure 5: Pressure variation within the cold and hot aisle for k-ε RANS.

Temperature Distribution

The main goal of the cooling system in data centres is to supply adequate cold air to the servers to be cooled to avoid any failure. Therefore, the inlet temperature of the servers should be within the manufacturers recommendations. To evaluate how effectively each turbulence model predicts both the servers' inlet temperatures, the temperature contour at the inlet of the same rack is shown below. Figure 6 shows the temperature distribution at the inlet of the servers' rack for SST k-ω SAS model. As it is clearly shown that the hot air not only infiltrated form the upper part of the cold aisle but also from the both sides. This means that the servers at the top and the sides of the cold aisle will be subjected to excessive heat which may lead to serious damage in these servers. It is also clearly shown in the figure that the hot air infiltration affect the servers located at both sides of the rack from up to the bottom of the rack. In addition, Figure 7 shows the temperature distribution at the inlet of the same server rack for k-ε RANS model. The figure displays how k-ε RANS model predicts the temperature at the inlet of the servers' rack. The model shows that the hot air infiltration affects the middle upper part of the servers' rack. It also fails to predict the problematic racks in the sides of the rack indicating that it behaves poorly to be relied on its results once it is used to build a reliable data centre. Another important issue with k-ε RANS model is that it does not give any indications about the cold air bypass. In the previous studies, the cold air bypass was estimated by using some thermal indices without knowing its exact pattern.

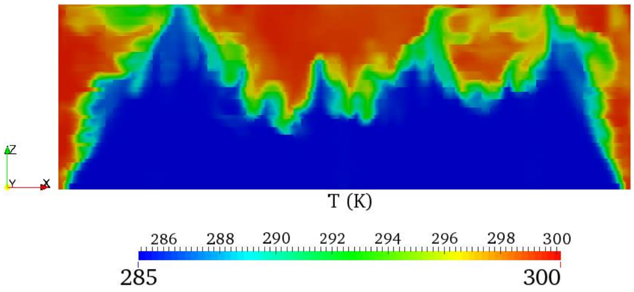


Figure 6: Temperature contour for SST k-ω SAS model.

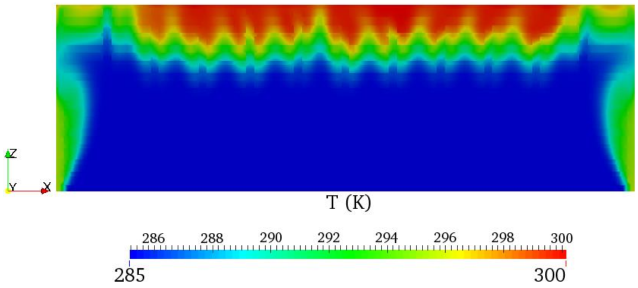


Figure 7: Temperature contour for k-ε RANS model.

In this paper and due to the research limitations only the supply heat index, SHI, will used among the thermal indices to quantify the servers' inlet and outlet temperatures since they are the most important data computed by the CFD simulations. SHI could be evaluated by using:

$$SHI = \frac{T_{in\,rack} - T_{ref}}{T_{out\,rack} - T_{ref}} \qquad (1)$$

T_{ref} is the vent-tile air temperature. To achieve optimum cooling, SHI should tend to zero. However, its value is acceptable in the range from zero to 20%, where its maximum value is 100%. The pressure and airflow patterns, computed by the turbulence models, affect the temperature distribution and hence will affect the performance heat index SHI significantly as Figure 8 illustrates. The SHI was computed by using sampling utility where the temperature was sampled over line on the servers' inlets. The lines of sampling are horizontal at the inlets of each row of servers; 200 points were sampled on each line, then the average of each line was calculated to find the SHI for each row of the cold aisle servers. The figure shows that the hot air infiltration, in the case of SST k-ω SAS, affect the servers located in the upper and lower parts of the cold aisle, at a height of around 0.9 m above the vent tiles the SHI > 0.2 which is considered not good. Though, the k-ε RANS model does not depict the problematic servers in this area, instead it shows that the problematic servers located at height around of 1.5 m. The servers below 1.5 m do not have any excessive temperature giving misleading result to the data centres builders. Above 1.5 m both turbulence models can detect the problematic servers which may be subjected to excessive heat due to the hot air infiltration. In the upper part of the cold aisle the SHI computed from k-ε RANS model is higher than the SHI of SST k-ω SAS model and this can be attributed to that the SST k-ω SAS model predicts the cold bypass air which means not all the upper servers will draw hot air. Nonetheless, the k-ε RANS model does not have the ability to show how the cold air bypass escapes from the cold aisles. The figure also shows that the mean values of the SST k-ω SAS are not following the k-ε RANS model indicating that the k-ε RANS model is not giving accurate results even for the mean values of the temperature.

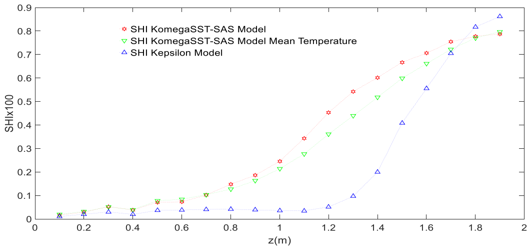


Figure 8: SHI within the cold aisle for SST k-ω SAS vs k-ε RANS.

Results Validation

To identify which of these turbulence models are correct, the results of the pressure distribution in the cold aisle as well as the temperature contour calculated by the turbulence models in this study were compared with experiment conducted by Sundaralingam, et. al. [6]. The experiment was conducted in the Data Centre Laboratory (DCL) at the Georgia Institute of Technology. In this experiment as Figure 9 shows, for all except the fully contained cold aisle, the measured cold aisle pressures differed at small magnitudes from the, reference pressure, the data centre room space pressure. In fact, this result matches the result of the SST k-ω SAS where the pressure distribution in the middle of the cold aisle is comparable to the data centre room space pressure. However, in the case of the k-ε RANS the pressure distribution in the middle of the cold aisle is significantly higher than the data centre room space pressure. In addition, the temperature contour plots of the experiment are matching the pattern of the SST k-ω SAS as well. Where, the hot air is not uniformly infiltrated into the cold aisle from the upper part of the cold aisle, instead there are some regions in the upper part where the cold air escapes into the room space. Also, the temperature plot contour shows clearly that a significant hot infiltration happening from both sides of the cold aisle matching the SST k-ω SAS. Unlike the k-ε RANS which failed to depict the hot air infiltration from the rack sides, and also it failed to depict how the cold air being escaped from the cold aisle.

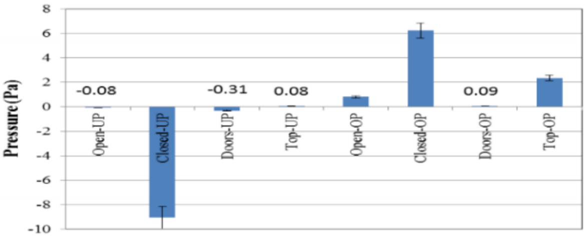


Figure 9: Measured cold aisle pressure referenced to the data centre room space pressure [6].

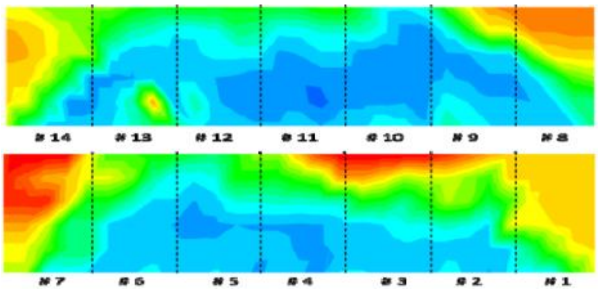


Figure 10: Temperature contour plot for non-contained data centre [6].

Conclusion

The cooling system of a common standard raised floor data centre with room return infrastructure was simulated by two different turbulence models. The first one is, widely used in the data centre numerical simulations, the k-ε RANS. The second was the SST k-ω SAS turbulence model which gives results similar to DES. By comparing the results of these two models with an experiment conducted in the Data Centre Laboratory (DCL) at the Georgia Institute of Technology Sundaralingam, et. al. [6], there is a strong indication that the SST k-ω SAS turbulence model is much more robust and to be used in the data centre simulations instead of the k-ε RANS.

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