

HEAT TRANSFER AND AIR-FLOW ANALYSIS OF A NON-UNIFORMLY COOLED DATA CENTRE

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ABSTRACT

The trend towards deployment of computer systems in large numbers, in dense configurations of servers in a data centre, has led to very high power densities at room level. Establishing the temperature and airflow pattern for a typical data centre is important for the thermal management and ensuring reliable operation. In the project presented here, an operational data centre is studied with the aim of clarifying some of the thermal issues. To this end, air temperature and velocity have been measured and the results will be presented. Further, a CFD analysis has been performed to provide detailed flow and thermal fields. The experimental measurements have clearly identified that the flow distribution in the data centre is very complex and exhibits non-uniformity, with critical hot spots observed in the measured temperature maps. The CFD results were in a reasonable agreement with the measurements, identifying critical regions of limited cooling.

INTRODUCTION

Due to the rapid increase in energy consumption of data processing equipment, large computing infrastructure systems are facing many thermal issues and the limit of air-cooling in high-density data centres is a matter of great concern and debate. The heat generated by the electronic systems is increasing owing to demands for higher processor speeds and miniaturisation. However, their temperature is designed not to exceed a definite maximum, during continuous operation, based on electrical performance and material usage limits. A computer room air conditioning (CRAC) unit with the associated air distribution system constitute the cooling system of the data centre. In the majority of modern data centres, the cold air supplied by the CRACs, enters the racks of IT systems, which in the optimal case are arranged in hot aisle-cold aisle configuration. The cold air enters the server racks through perforated tiles located between rows of racks. The hot exhaust

air from the rack diffuses back to the CRACs to complete this airflow loop.

Access to operating data centres is limited due to their high reliability constraints, and the large variations in data centre architectures limit the extendibility of measurements to other facilities. As a result, most previous investigations on data centre thermal characterisation have involved computational fluid dynamics to predict airflow and heat transfer characteristics. A reliable simulation methodology for data centres allows thermal designers to identify potentially dangerous local hot spots, quickly evaluate alternatives in cooling systems and investigate next generation data centre architectures [1]. Schmidt et al. studied the perforated tile flow rates and flow field in raised floor data centre [2-4], and investigated the effect of different parameters on the rack inlet air temperature [5-8]. Sharma et al. [9, 10] have proposed dimensionless groups to describe the thermal efficiency of data centres. Unified treatment of various cooling modalities to study air flow and thermal management of high-power-density data centres is presented in [11]. In recent analysis of data centre thermal management, the energy efficiency in data centre associated with different air distribution systems is examined by Jinkyun et al. [12].

The aim of this paper is to provide the CFD analysis of an actual data centre for better understanding of how global air flow patterns affect the temperature field around the racks, which can lead to more efficient design of these facilities, resulting in large savings and improvements in data centre thermal management.

CFD MODELLING

The room of the operational data centre considered is modelled as 363m²x3m enclosure located over a 30 cm deep plenum. The purpose of this project is to study the flow and temperature patterns inside the data centre environment around the server racks. Hence, the racks are modelled with cuboids in

conjunction with recirculation devices defined by characteristic heat load and flow rate, representing rack inlet and server fans respectively. The rack heat generation and flow rate are based on the IT system specification. Non-uniform heat loads are specified as heat sources in rack models, based on the servers specifications in this typical data centre, and are indicated for different rack rows in table 1. Obstructions (cable trays, piping) are modelled with cuboids located under the floor in the same positions as in the data centre. CRACs are modelled with solid cuboids characterising coils and fans and recirculation devices detailing the CRAC's supply and extract areas, as well as turning vanes in the plenum to direct the CRAC exhaust in the perpendicular direction. The flow rates in all the air conditioning units were based on typical industry design points, $5.5 \text{ m}^3/\text{s}$ with 16°C supply air temperature. Leakage airflow is not included in the CFD modelling. The floor grilles are modelled as bars run along the local z-axis (Fig. 1) of the assembly such that flow will be straightened by the grille in the x-direction only, with fully open damper. Mesh sensitivity runs were carried out at different grid sizes to obtain near grid-independent results with respect to CRAC return temperatures. For the modelling, 2.3×10^6 grid cells have been employed. FloVENT V8.2 by Mentor Graphics Mechanical Analysis [13] was used for all CFD modelling. A Cartesian grid and the standard k- ϵ turbulence model were used for all simulations.

VALIDATION OF THE CFD MODEL

The IT environment of an operational data centre located in Sydney is measured to validate the model for investigating flow and temperature fields. Figure 1 shows a schematic layout of the position of the server racks, CRACs and perforated tiles in the data centre. The data centre is populated with 102 such racks with non-uniform heat load distribution, with some empty racks demonstrated by blue solid boxes. Seven CRACs are positioned on the outer boundary of the data centre. Server racks are placed in the middle of the data centre in a hot and cold aisle arrangement. 59 perforated tiles are identified by the solid gray boxes in the schematic. The total heat generation in this data centre is 270 kW. Table 1 shows the heat loads for individual rack rows. The gridlines in figure 1 correspond to standard 0.61m (2 ft) x 0.61m (2 ft) floor tiles.

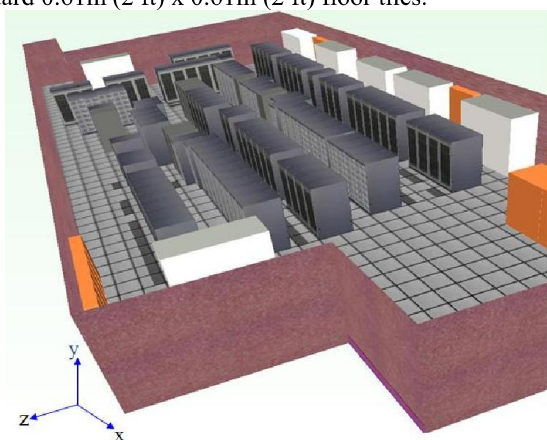


Figure 1 Overall view of the data centre

Experimental Apparatus

In order to collect experimental temperature data in the operational data centre, an apparatus is designed, as shown in figure 2. A frame stand is constructed with 8 K-Type thermocouples attached on it, linked up to a data acquisition device, capable of reading K-Type thermocouples.

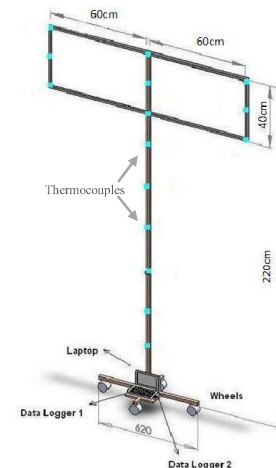


Figure 2 Experimental apparatus

However, for mapping the more detailed data at heights 180-220 cm, a large horizontal frame is attached to the top of the stand, with 8 additional K-Type thermocouples to provide a thorough study on the region near the top of the racks. As shown in figure 3, approximately 1400 measurement points (597 measurement points from 0-160 cm and 768 measurement points between 180-220 cm), at 10 different heights between 0-220 cm, were recorded by data logger. Measurements were performed after installing blanking panels onto the vertical blank spaces in rack enclosures for preventing hot air from recirculation, and cold air from bypassing the server racks.



Figure 3 Data centre layout- measurement apparatus locations

Measurement Results

Based on the measurements, the largest hotspots are near the rack rows "a" and "b" at coordinates 36-44 in aisles F and G. The highest temperature measured is at 38°C , and the average

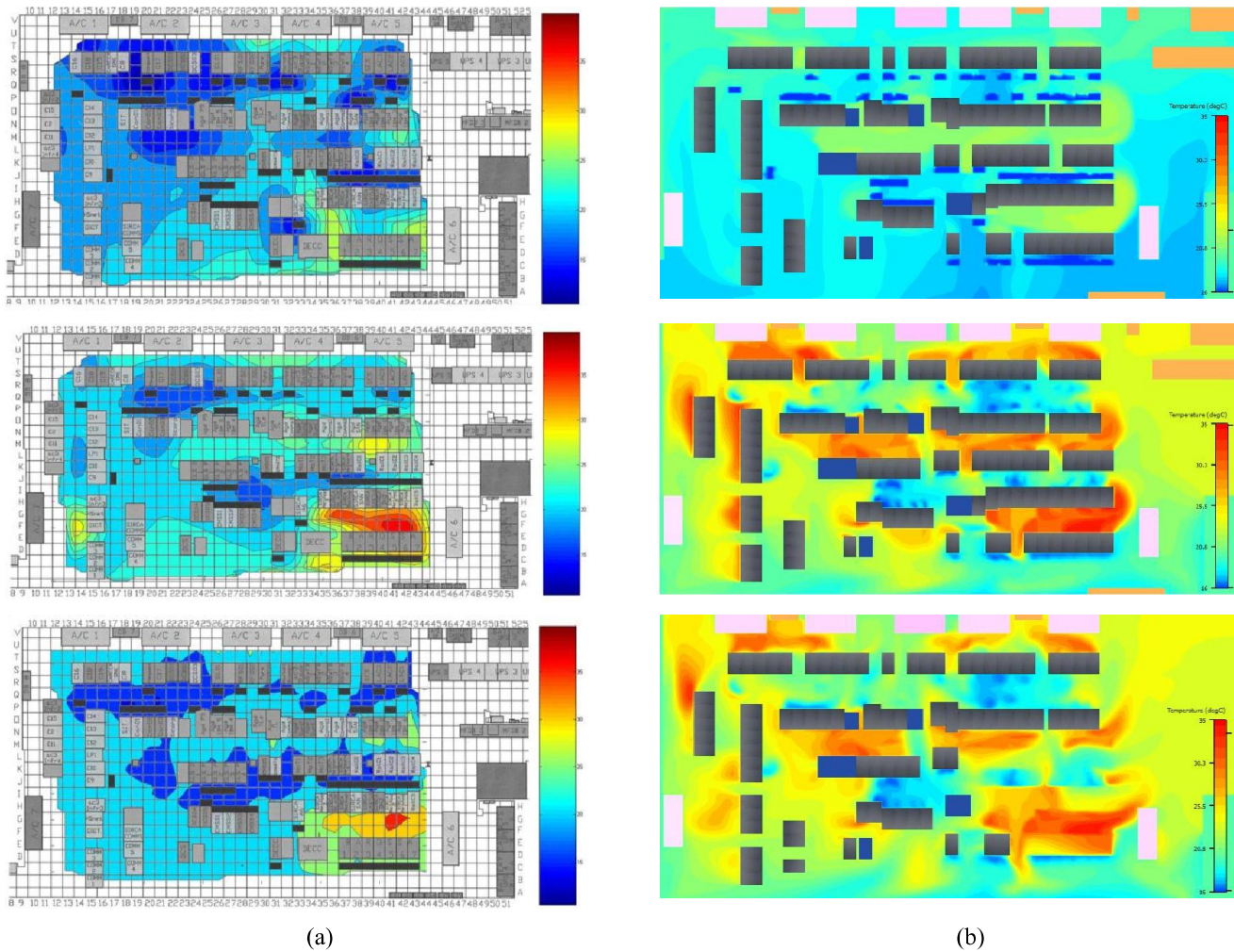


Figure 5 Field measurements (a) and simulation results (b) at 3 different heights, 0, 140 and 200 cm respectively in the data centre

temperature over the rest of the data centre is approximately 20°C. The highest average temperature was noted at height 140 cm, where the hotspots are distributed over a large area. At heights 180–220 cm the hotspots are concentrated in a smaller region. The hotspot between G36–G43 appears to be dominant over all height ranges from 0–220 cm. From the measurements, there is an obvious hotspot in the aisles F33–F44. Even though this aisle is a designated hot aisle, the temperatures are significantly high compared to the overall data centre temperature. This hot spot region is intuitively due to a few different factors including:

Insufficient CRACs in that area; insufficient cold air supplied by perforated tiles; high amounts of servers in the racks; lack of exhaust ventilation for the hot air to return to CRAC; mixing of the hot and cold air; lack of suitable direction of the CRACs with respect to the aisles [8]; disorganized aisle widths; insufficient number of the perforated tiles; blank spaces inside rows; airflow non-uniformity through the vent tiles; and data centre perturbed architecture.

Figure 4 shows the maximum, minimum and mean temperature variations in aisles F and G between the rack rows “a” and “b”. The measurements in hot aisles F–G, indicates that there are intense hotspots around the 200–220 cm region with temperatures of 36.8°C and 35.8°C. The lowest average temperature of 21.4°C exists at 0 cm. The average temperature sharply increases to 28.3°C between 0–80 cm. From height 80 cm onward, the mean temperature increases at a lower rate and gradually flattens to 31°C.

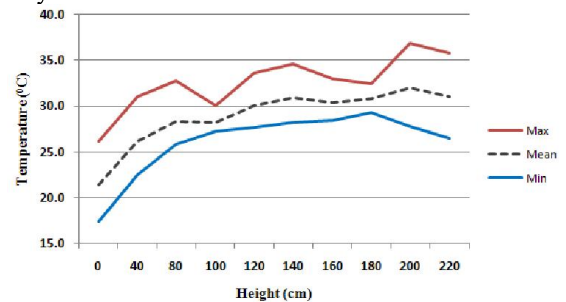


Figure 4 temperature versions in hot aisle F–G

Table 1 Calculated Rack Rows Specifications

Rack rows	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r
Heat loads (KW)	45	42.6	87.6	11	17.7	28.7	14.8	16.3	31.1	19.1	8.1	13.6	13.5	8	10.2	5.3	2.5	2.1
Mean inlet temperature (°C)	16.6	19.3	20.4	17.9	19.2	19.3	19.4	19.2	21	18.2	20.6	22.6	23.3	23.4	21.6	21.5	19.6	21
Mean outlet temperature (°C)	32	29.2	28.5	27.2	28.5	28.3	28.4	28.5	30.4	27.5	27.6	29.6	30	32.7	31	31	29	27.8
Max Inlet temperature (°C)	27.9	29.9	29	24.8	25	29.4	25.8	23.5	23.5	22.5	25.6	30	24.2	25.5	24.6	23.3	21	23
SHI	0.04	0.25	0.37	0.17	0.25	0.26	0.15	0.254	0.35	0.19	0.39	0.48	0.52	0.44	0.186	0.37	0.28	0.4

Verification of the CFD Model

Figure 5 contains the CFD simulation results and field measurements at 3 different heights in the data centre. The maximum and mean temperatures across the data centre are compared in table 2. It can be seen that there is a good agreement between the field measurements and simulation results. Both the results indicate that the hot spots can be mostly located in the aisles F-G. However the CFD results provide much more detail on the temperature and velocity fields, due to limitations of the experimental apparatus.

Table 2 Temperature distribution of CFD simulation and experimental measurements, at heights 0-220 cm

Height (cm)	0	40	80	100	120	140	160	180	200	220
Measurements										
Max(°C)	27.9	34.7	37.5	35.0	35.7	37.9	35.1	37.4	37.2	36.6
Mean(°C)	19.6	21.1	21.7	21.9	22.6	22.8	22.9	22.2	21.8	21.5
Simulation										
Max(°C)	25.7	34.8	34.8	34.8	34.8	35	34.8	35	33.5	33.5
Mean(°C)	21.1	21.5	21.7	21.8	21.8	21.9	22	22	22.1	22.1

CFD SIMULATION RESULTS

Data Centre Performance

To assess the performance of the data centre, some dimensionless metrics can be used. The supply heat index (SHI), defined as the ratio (enthalpy rise due to the infiltration)/ (total enthalpy rise at the rack exhaust) can be applied for thermal performance [9]. By lowering the SHI, the performance of the data centre is increased. SHI predicted for the whole of the data centre is 0.3 which is not showing a proper performance in this infrastructure. The predicted mean inlets and outlet air temperature as well as the maximum inlet

temperature with calculated SHI values for different rack rows are given in table 1. Considering row “a”, the perforated tiles near the racks have high cold air velocity in upward direction preventing hot air from flowing into the cold aisle C, thus reducing the heat infiltration. Consequently, the rack row “a” has the lowest inlet air temperatures, thus results in lower SHI. The high outlet temperature from this rack row is due to the high heat load produced inside the servers and weak air intake procedure through the fans. The highest SHI is recognised in rack row “m” which does not have perforated tiles nearby to supply cool air, and is located in ho region.

From CFD results, it is observed that in some locations in the data centre the rack inlet temperature reaches values above 25°C, which is not recommended according to ASHRAE’s thermal guidelines [14]. The value of the temperature at the inlet of the rack is significantly a function of the geometrical layout of the data centre. Ideally, the temperature at the inlet of the racks should be equivalent to the vent tile inlet temperature or CRAC outlet temperature. Due to perturbation of the rack layout in the data centre, which is not exactly in a hot aisle-cold aisle configuration, the airflow pattern is disturbed by changing pressure drop in the aisles and positive pressure gradients at end of aisles. This causes the warm air to recirculate in the room, creating hot spots. In addition, driving the hot air from the hot aisle back to the rack intakes will compound the thermal issues. For this reason, the highest inlet air temperatures obtained from simulation are observed at the end of the rack rows.

Figures 6 and 7 illustrate the velocity vector fields as well as the temperature fields around the server racks on the right hand side of the room, at height 100 cm, near the high temperature locations. It can be seen that due to the high recirculation of hot air, there would be a hot area near the racks at the end of the aisle. Moreover there are some blank spaces inside the rows “f” and “c” in which the hot air recirculation occurs, which results in higher inlet temperatures in nearby racks.

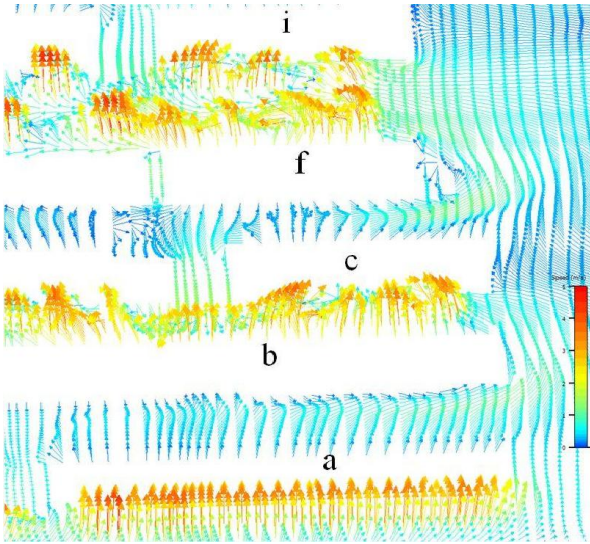


Figure 6 Velocity field around the server racks at height of 1m

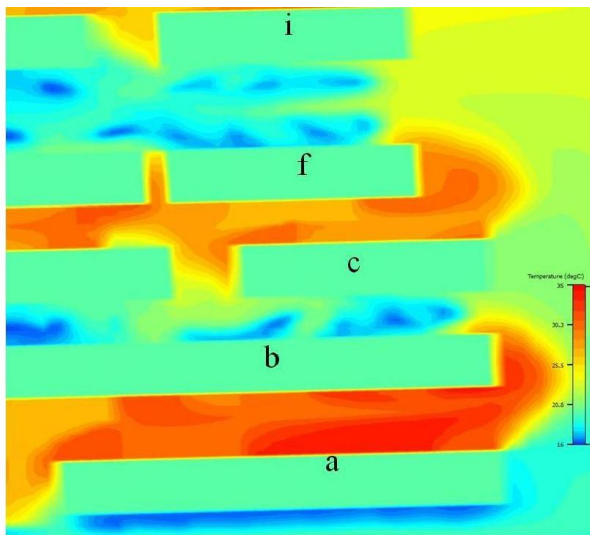


Figure 7 Temperature counter plot around the server racks at height of 1 m

The Issue of CRAC Mal-provisioning

Deviation of the CRAC's sensible cooling load from the mean load on each unit (δ) can be applied for the CRAC provisioning assessment. The CRAC inlet air temperatures obtained from the CFD analysis are used to calculate the sensible cooling load on each unit [10].

Table 3 Cooling percentage deviation of the CRACs

CRAC	1	2	3	4	5	6	7
Mean return temperature (°C)	25.3	21.9	21	20.5	23.9	24.5	22.2
Cooling percentage deviation δ (%)	+37.9	-12.5	-28.3	-32.6	+16.95	+25.89	-7.2

Table 3 indicates the cooling percentage deviation (δ) for individual CRACs in the infrastructure. The cooling loads on CRAC 1 have gone up by a third of the sized capacity; CRAC 4 is operating close to a third its capacity. CRACs 2, 3, 4 and 7 are well provisioned to meet the data centre cooling loads. By investigating visualization planes for the relative temperature distributions near the CRACs, this cooling malprovisioning is revealed. Figure 8 illustrates three thermal planes near the CRACs in the data centre. It shows that the CRACs 1 and 6 close to the high temperature areas are operating at cooling loads more than their sized capacity.

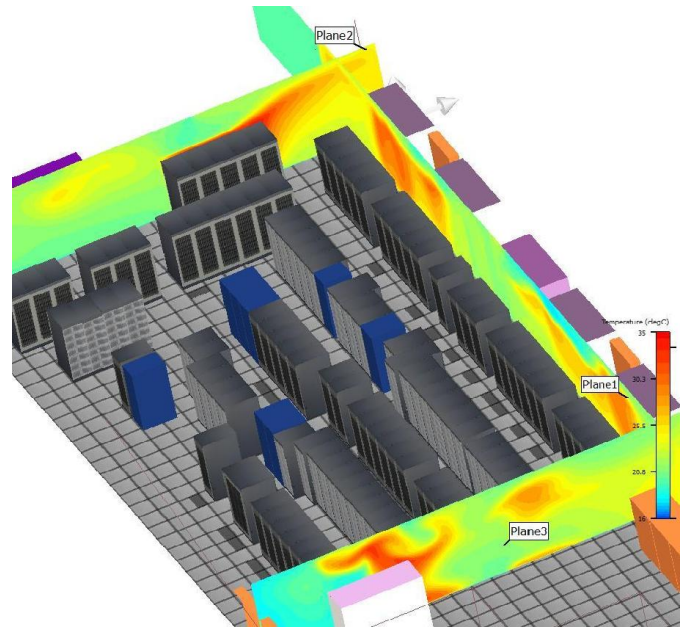


Figure 8 Visualisation planes for the relative temperature distributions near the CRACs

Air Flow Non-uniformity

Uniformity is assessed based on percentage variation from the mean perforated tile flow. The airflow delivered through any particular perforated tile may vary substantially from the mean resulting in local cooling capacity which is excessive or insufficient for cooling [15]. Equipment will draw air as needed and if sufficient cooling air is unavailable, warm exhaust air will be recirculated over the racks or around the row ends. It is therefore essential that perforated tiles located near the equipment provide sufficient cooling air.

The mean net volume flow rate exiting the perforated tiles for the present data centre evaluation is $0.65\text{m}^3/\text{s}$ with a standard deviation of $0.075\text{m}^3/\text{s}$. Figure 9 illustrates the normal distribution of the perforated tiles net volume flow rate. It reveals that some of the perforated tiles will be significantly lower/higher than average. Investigating the velocity vectors in the plenum indicates that the swirling flow pattern underneath the cold aisles accounts for the large non-uniformity in the perforated tile flow rates. Perforated tiles in aisle rows C, P and Q somehow form the reversed flow consistent with the

estimates of [16], due to the close location to the CRACs. Considering the aisle row C, the perforated tile at location C43 seems to have lower volumetric airflow and higher reversed flow than the other tiles in this row. This is because of the close distance from exhaust jet production and recirculation zone and the resultant reduced pressure distribution in the plenum caused by the CRAC 6. Similarly, the perforated tiles in aisle Q are lower than those of aisle P and also other aisles. The supply mass flow rate near the centre of the cold aisle is larger than vent tile at the end of the row. This flow rate will be too large to be completely consumed by the racks in the middle of the row, and a portion of the cold supply air will flow unused and escape into the upper portion of the data centre facility, as illustrated in figure 6. Thus, the racks near the end of the row have reduced supply flow rate and as a result, receive air from the top and sides of the cold aisle.

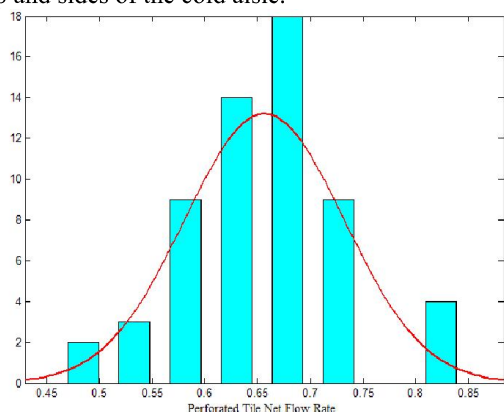


Figure 9 Normal distribution of the perforated tile flows (m^3/s)

CONCLUSION

An operational data centre is studied with the aim of highlighting some of the thermal issues. To evaluate this problem, air temperature and velocity have been measured. In addition, a CFD analysis has been performed to provide detailed flow and thermal fields. The experimental measurements have clearly identified that the flow distribution in the data centre is very complex and exhibits non-uniformity. Hence, critical hot spots were observed in the measured temperature maps. Data centre performance, perforated tile non-uniformity, CRAC provisioning and creation of the hot spots have been investigated, and these factors play an important role in data centre thermal management. The CFD results were in a good agreement with the measurements, identifying critical regions of limited cooling. For the next step of this project, the cooling effectiveness improvement of this operational data centre is going to be evaluated to overcome the thermal issues investigated.

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