Thermal Management of Electronic Servers under Different Power Conditions

S.A. Nada, K. E. Elfeky*, Ali M.A. Attia, W.G. Alshaer,
Department of Mechanical Engineering, Benha Faculty of Engineering, Benha University, Benha, 13511, Egypt.
****Corresponding author (Karem Elfeky). Email: samehnadar@yahoo.com***

Abstract

An experimental study of thermal management of rack of servers of a data centers is presented for different schemes of server's power loadings. Four scheme of server's power loading (uniform, discrete, segmented and clustered) are considered. A total of eleven cases of servers loading conditions are investigated. Temperature distributions and dimensionless measuring indices (SHI/RHI) are used to measure and evaluate the thermal management of the data center. The results showed that (i) uniform power loadingprovides the best results for (SHI/RHI) among the other schemesconsidered where the optimum benefit of cold air in server cooling is obtained at uniformly power loading of servers, (ii) clustering of active servers lead to better air flow management compared to discretely individual active servers and segmented distributions of active servers, and (iii) servers located at the bottom rack cabinet always has better thermal performance compared to servers at higher levels.

Keywords
Data center, physical modeling, air flow management, temperature management, parametric study.

1. Introduction

Data center is a facility used for large/speed data processing in a wide range of applications, such as banks, telecommunications, market transactions and others special and private applications.Recent studies showed that data center consumes a huge amount of the total power consumption of modern cities. For example, EPA (Environmental Protection Agency) reported that data centers consumed 61 billion kWh (about 1.5 % of U.S. total electricity consumption) in 2006 [1]. Since data centers heat loads continue to increase very rapidly to meet the requirements of high efficient and compact servers, cooling of servers to maintain their temperature within the allowable limits becomes a challenge [2].Layout and features of all data centers are similar; most of them use raised-floor configuration. Fig. 1 shows a typical schematic view of open aisle data centers. The racks are arranged in a hot-/cold-aisle configuration]. Perforated tiles are located in the cold aisle to supply cold air to the server'sintakes. The hot air discharged by the server's fans is extracted by the Computer Room Air Conditioning unit (CRAC) to re-cool and supplies it to the data center plenum.

Data center thermal management performance and effectiveness is normally evaluated by Supply Heat Index (SHI) and the Return Heat Index (RHI) [3, 4] dimensionless parameters. Using these indices, heat transfer and thermal management inside the data centers can be understood and evaluated.

One of the relevance work in this area is the work of Cho J., Lim T., and Kim B. S[5] who studied air distribution inside high compute density (Internet) data centers. It was concluded thatthe air velocity is not animportant factor for the data center designers as human thermal comfort is not a significant factor in the data center.Shrivastava S., Sammakia B., Schmidt R., andIyengar M. [6] studied different data center configurations. They reported that supply cold air from raised floor and extract return air from the ceiling is the most efficient air distribution system. Similar investigations were conducted [7-8] toevaluate and compare underfloor supply and overhead supply configurations. They reported that although underfloor supply is recommended for proper air distribution and thermal managements it can result in hot spots at the servers located at the rack top due to hot air recirculation.

More recently, VanGilder and Schmidt [9] studied the uniformity of air flow through the raised floor perforated tile and they reported that perforated tiles of 25% opening ratio gives the best flow uniformity. Kumar et al. [10] studied air flow distribution and thermal management in a data centers for different servers load schemes. The results showed that best air flow management is obtained in case of uniformly loading of rack servers. Karlsson and Moshfegh [11] experimentally studied the temperature distribution at racks inlet using infrared cameras. They reported that a temperature gradient exists along racks height, where the rack top has higher inlet temperatures .Actually, most of theseinvestigations were conducted on a real data center. Conducting research on a real data center is not an easy task as it costs a lot and difficult to be controlled.Fernando et al. [12], studied the viability of design and construct a scaled model for the purpose of testing an actual data center using the theory of scale modeling for airflow experiments. Results showedaccurate thermal similarity while the airflow similarity cannot be obtained with reasonable accuracy.

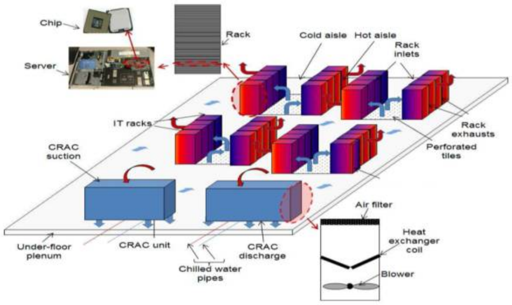


Fig. 1.Schematic representation of a raised-floor data center layout.

The above literature review reveals that although several researches have shown promise on a real scale data centers, very little information is available on the effect of the distribution of power loading of the servers along the data centers rack on the temperature distribution and thermal management inside the data centers. The present paper is devoted to study this effect. A physical scaled model data center rack is designed and construct to conduct the present. It is believed that the results of such studies on scaled room data center will help data center designer to understand the different operating and geometric parameters affecting the thermal performance of data centers.

2. Experimental facility and procedure

2.1. Experimental setup

A physical scale room model with a one-sixth geometrical scaled model and a time scale factor based on Archimedes number equality [13, 14]was designed and constructed to conduct the experimental investigation of the present study to avoid the required exhaustive construction, measurements costs and time-length efforts of actual data centers.Scale modeling theory was utilized to design and construct the scale room model. A test facility including a scaled data center room, a rack of servers inside the scaled room and cooling air supplying circuit was designed and constructed to simulate the conditions and arrangements of actual data centers. Measuring devices and instrumentations are connected in the test facility to measure the different parameters needed for the study such as temperatures, powers, and air flow rates. Fig. 2 shows a schematic diagram of the test facility and measuring instruments. A blower delivers air into a space that simulates the raised floor of actual data center. This air enters the data center room through perforated tiles and passes through the front face of the data center rack to cool its servers. The hot air exits from the rear face of the rack and is discharged to the atmosphere at the top of the scaled room using discharging fan. A single rack including four servers is sued to simulate the actual rack of a real data center located at the center of a rakes row with inside rakes matrix and surrounded by hot and cold aisles. Twenty eight thermocouples (T-type) distributed throughout the scaled model room were used for temperature distributions measurements inside the room. Plastic frames were used to fix the thermocouples on rack inlet and exit to measure the corresponding air temperature distribution. The thermocouples were mounted at 2 cm in the front and back of the air intake and exit rack door. Each frame contains eight thermocouples distributed on it at different heights. Two sets of two thermocouples are installed underneath the perforated tile and on the return fan intake to measure the supply and exit air temperatures. The analog signal of all thermocouples has been converted into digital values and saved in Excel data sheet for later analysis via Data Acquisition.

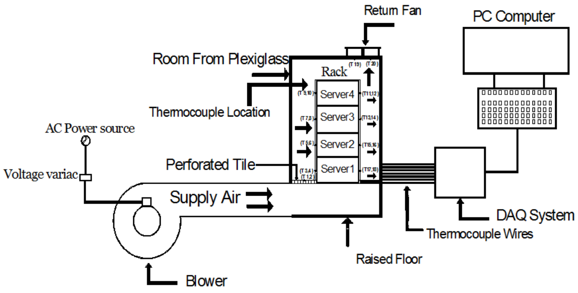


Fig. 2. Schematic diagram of the experimental setup.

2.2.Scale Model Overall Design

The data center room used in the experimental facility is a scale model of a full size standard dimension data center room with a length-scale ratio (α=1/6).Figure 3 gives full details of the scaled data center room. It is made from Plexiglas wall of thickness 1cm, air tight assembled using silicon. The room dimensions is 400 x 329.5 x 500 mm. The raised floor thickness of the room is 100 mm. The cold ails and hot ails dimensions are 101.6 and 75 mm respectively.

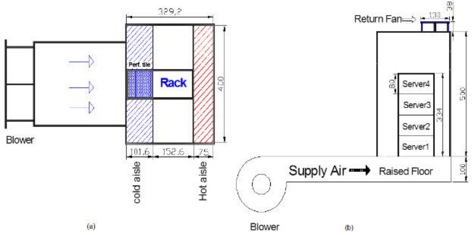


Fig. 3. Scale model data center (a) top view, (b) side view (dimensions in millimeters)

A single rake of dimensions 101.6 x 152.6 x 334 mm (height) located in the center of the data room was designed and built to accurately simulate a rack in actual data center located in the middle of racks matrix. In order to simplify the modeling, the rack was designed to housefour servers [16] accommodating four servers simulators.To ensure that there is no internal recirculation, server intake and exhaust face is attached to the rack perforated doors. The rack front and rear doorsare made of screen mesh of 65%opening ratio simulating actual servers opening ratio. The dimensions of each server cabinet simulator is 101.6 mm wide and 80 mmhigh and 152.6 mmdeep.Each server has a variable speed fan (up to ~ (0.45 m^3/min) and electric heater of variable heating power (up to ~ 150 W) simulating the fan and heat generation of actual servers. The advantage of using these servers' simulators rather than actual servers is the ability to quantify the controlling parameters such as fan speed and heat dissipation .The flow rate for the server fan is controlled by changing the power supplied to the fans using variac. The fans flow rates are measured by using hot wire anemometer. Heat is generated in each server by using a nickel-chromium wire wrapped on a plate of mica (electrical insulation and not thermally insulated) covered by layer of stainless steel. Figure 5 shows a top view of the server heater. In order to obtain a uniform surface temperature a 0.5 mm in thick stainless steel plate was attached to the outer surface of the heater. The input power to server was controlled using a variac that regulate voltage in the range of 0 – 220 volts. Two thermocouples located on the heater surface of each server (see Fig. 5) are used to measure the temperature of the heaters.

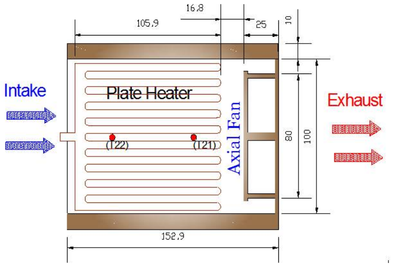


Fig.5.Shows a top view of the server (dimensions in millimeters).

2.3.Servers power schemes

The experiments were conducted at different Servers power modes to study the effects of the servers power distribution schemes on the server's temperature distribution, thermal and air flow management inside the data centers. Four servers power modes: uniform, discrete, segmented and clustered (cases A, B, C and D in Fig. 6) are investigated. The room power density is the sum of active server's power per unit area of the data center room. Four scheme of server's power loading (uniform, discrete, segmented and clustered) are considered as defined below: A total of eleven cases of servers loading conditions are investigated. Figure 6 shows the four schemes and the details of the active servers for the eleven cases investigated as described below:

-Uniform server power (case A):the four servers are power loaded and their fans speed settings are identically set to discharge a sum of uniform air flow rate of 0.00812 m^3/s across the entire rack.

- Discrete server power (case B): only one server is power loaded at a time and the fan speed of this server is adjusted to match the total perforated tile flow rate of 0.0.00812 m^3/s.This scheme includes four cases (B1-B4) where in each case the location of the active server is varied along the rack height.

Segmented server power (case C): Two servers are being simultaneously powered loaded and their fans speed setting in each server is identically adjusted to match the total perforated tile flow rate of 0.00812 m^3/s.This set includes three cases (C1-C3). In each case the powered servers are dispersed in the rack to create a segmented rack air distribution.

Clustered sever power (Case D): It is identical to set C, except that the two powered servers are grouped together and moved in the rack as a cluster resulting in three distinct cases (D1-D3) of server air distribution.

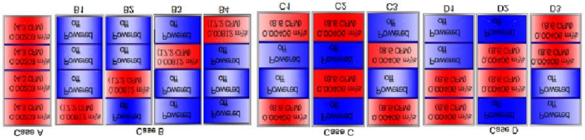


Figure 6. Details of the various cases active power loaded servers.

2.4. Experimental procedure and program.

The procedure and experimental program were as follows:

1. Supply and adjust power to each server in the rack according to the program.
2. Turn on the server fans and adjust the fan speed according to the experiment objective.
3. Turn on the data acquisition system.
4. Wait until steady state condition is achieved.
5. Measure the tile flow rates as well as all temperature values.
6. Record the readings of all instruments (voltage, current, flow rate and temperatures).
7. Repeat steps 3–8 at the same power density for the different sever loading schemes.

The quantities measured directly in each experiment include air flow rate, air temperatures, input voltage and input current. The uncertainties in measuring these quantities were evaluated to be ±2%, ±0.2 °C, ±0.25% and ±0.25%, respectively.

2.5. Data reduction and thermal metrics for data centers

Thermal metrics are used to evaluate the data center airflow performance and thermal management. In a real data centers recirculation, bypass or infiltration phenomena may occur (see fig.7). In general, thermal metrics depend on the geometric and physical parameters of the data centers. The thermal indices can be applied on entire data center, server, rack, or row of racks.

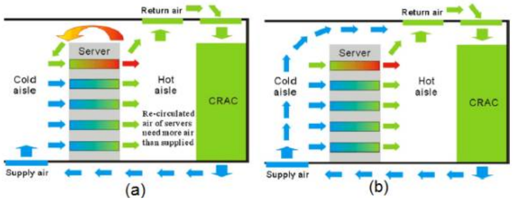


Fig. 7Typical data center airflows. (a) Re-circulation airflow and (b) by-pass airflow.

Sharma et al. [4] proposed dimensionless parameters for thermal indices evaluation for the sake of study thermal design and data centersperformance. The utilization of dimensionless parameters allowsthese formulas to be scalable for any size system. These indices are defined as:

$$SHI = \left(\frac{\delta Q}{Q + \delta Q}\right) = \frac{\text{Enthalpy rise due to infiltration in cold aisle}}{\text{Total Enthalpy rise at the rack exhaust}} \quad (1)$$

$$RHI = \left(\frac{Q}{Q + \delta Q}\right) = \frac{\text{Total heat extraction by the CRAC units}}{\text{Total Enthalpy rise at the rack exhaust}} \quad (2)$$

$$Q = \sum_j \sum_i m^r{}_{i,j} Cp((T^r{}_{out})_{i,j} - ((T^r{}_{in})_{i,j}) \quad (3)$$

$$\delta Q = \sum_j \sum_i m^r{}_{i,j} Cp((T^r{}_{in})_{i,j} - ((T_{ref})_{i,j}) \quad (4)$$

$$SHI + RHI = 1 \quad (5)$$

Where Q is the total heat dissipation from all the racks in the data center, δQ is the enthalpy rise of the cold air before entering the racks, $m^{r}_{i,j}$ is the mass flow of air through the i^{th} rack in the j^{th} row of racks, $(T^{r}in)_{i,j}$and $(T^{r}out)_{i,j}$ are the average inlet and outlet temperature from the i^{th} rack in the j^{th} row of racks and $T_{ref}$is the vent tile inlet air temperature (assumed to be identical for all rows). For a single rack data center, this gives:

$$SHI = \left(\frac{\sum\left(T^{r}{}_{in} - T_{ref}\right)}{\sum\left(T^{r}{}_{out} - T_{ref}\right)}\right) \tag{6}$$

Equations 1 and 2reveals that higher δQ leads to higher $(T^{r}in)$ and hence a higher SHI. When the inlet temperature $(T^{r}in)$ to the rack rises, systems failure is expected and reliability problemsexist. Increasing $(T^{r}in)$ increases entropy generation due to mixing and this reduces energy efficiency for the data center. Therefore, SHI can be an indicator of thermal management and energy efficiency in data center. Target values of (SHI and RHI) are (0 and 1) and typical benchmark of recommended acceptable ranges of SHI and RHI are SHI<0.2 and RHI>0.8.

3. Results

Experiments are performed for a perforated tile air flow rate of 0.00812 m3/s with tile opening area of 25% for a bitter flow uniformity, at different server’s power loading schemes that are shown in Fig. 6. The Blower speeds are adjusted to achieve the desired tile air flow rate. In all power loading schemes, the total air flow rates from the rack is matched to the perforated tile flow rateby adjusting the servers fans speed settings.

Fig.11, shows temperature profiles along the rack height at the rack front and back for uniform power scheme. The figure shows uniform temperature profiles at the rack front and rack back where the variation of the temperature along the rack height is limited. This can be attributed to the uniformdistribution of the rack load along the rack servers and height (Height <30). However, Fig. 11 shows that at levels higher than the rack height (H > 30) the back rack temperatures starts to decrease due to mixing of the hot air of the hot ails with the cold air of the cold ails that occurs above the rack. The variation of the rack servers temperatures along the rack heights is shown in Fig. 12 that shows the increase of the server temperature with increasing its height in the rack where the temperature of server 4 (located at height 28 cm) is higher than the temperature of server 3 (located at height 20 cm) and so on. The increase of the server temperature with the increase of its location height can be attributed to the buoyancy force effect that makes the environment of the server at higher levels in the rack hotter than those at lower levels of the rack.

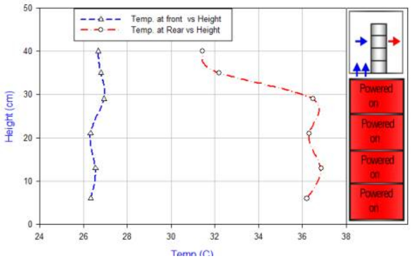


Fig.11. Temperature profile at front and rear of the rack for uniform power scheme.

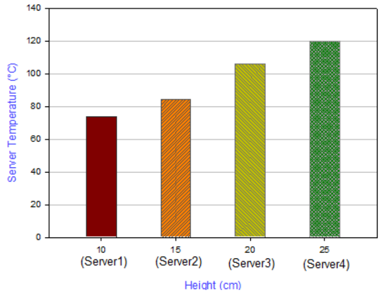
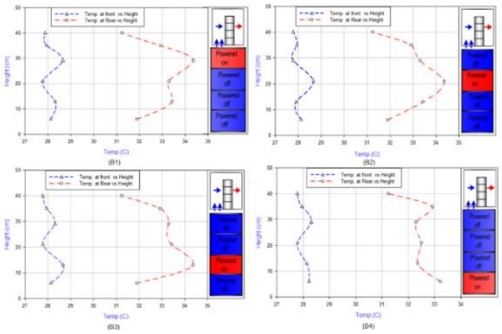


Fig.12. Servers temperature distributionfor uniform powerscheme (Case A).

Error! Reference source not found. shows the temperature profiles at the front and back of the rack for cases of discrete power scheme (B1-B4). As shown, there is a highly variation in temperature profiles at the front and back of the rack and the highest temperature occurs just above the location of the powered server (H=28 cm in B4, H=20 cm in B3 and H=12 cm in B2 and H=4 cm in B1). This non-uniform trend in the average temperatures arises from the non-uniform server heat loads. **Error! Reference source not found.** shows that for the four cases, the surface temperature of the active servers is always higher than that of the nonactive servers, but with different degree according to the active server location. Locating the active server at lower levels of the rack reduces the server temperature owing to the fact that, the cooling of the server becomes more effective when the server is located at lower levels in the rack. This effect is resulted from the buoyancy effect that accelerates the motion of hot air without recirculate around the server location. This contribution can be translated as a design guidelines to put the active servers or the server of high power density at lower cabinets of the rack.



(B1)
(B2)
(B3)
(B4)

Fig.13. Temperature profile at front and rear of the rack fordiscrete powerscheme (Case B).

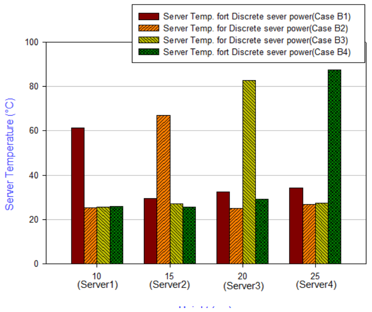


Fig.14. Servers temperature distribution for discrete power scheme (Case B).

Fig. 15 shows the temperature profiles at the front and back of the rack for three cases (C1-C3) of the segment power scheme. Fig. 15 shows that the temperatures distributionsat the front and back of the rack of the three cases (C1-C3) are non-uniform where the temperatures just above the active servers are higher than the upstream and downstream temperatures.This non uniformity of the temperature distribution is supported by the non-uniformity nature of the server's powers of the three cases (C1-C3). Fig. shows the variation of the server'ssurface temperature for the three cases (C1-C3). The figure shows that for the three cases, there are highly variation in the server's temperature where the temperature of the active servers is always higher than the temperature of the nonactive servers. Fig. 16 also shows that for each case of C1-C3 the temperature of the active server locating at lower levels of the rack is always lower than the temperature of the active server locating above it. This reveals that and as shown in Fig. 16 for lower servers temperatures it is recommended to put one of the active powered servers at the lower cabinet and put the other one in cabinet No 3, i.e. case C2.

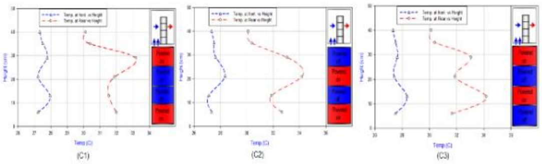


Fig.15. Temperature profile at front and rear of the rack for segmented power scheme (Case C).

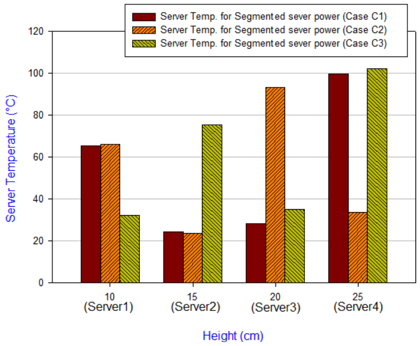


Fig.16. Servers temperature distribution for segmented power scheme(Case C).

For clustered power scheme, there is a slight uniform of the temperature distribution due to clustering of the two active servers as shown in **Error! Reference source not found.**. **Error! Reference source not found.** also shows that Case D1 where the clustered servers located at the bottom of the rack has lower and better temperature distributions comparing to the other cases of D1 and D2. The corresponding surface temperatures of servers for the mentioned scheme are shownin **Error! Reference source not found.** where the surface temperature of the active servers is always higher than that of the non-active servers. It is noticed that for each case of D1-D3 the surface temperature of the active server locating at lower levels of the rack is always lower than the surface temperature of the active server locating above it. The figure also reveals that the order of surface temperature is that case D1 is lower than case of D2 and lower than case of D3. This contributes that for lower server's temperatures it is recommended to put the active clustered powered servers at the lower cabinets of the rack where buoyancy effect proceeds the server cooling with lower tendency for recirculation.

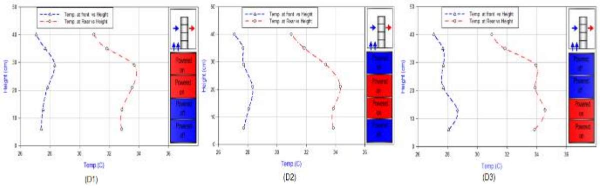


Fig.17. Temperature profile at front and rear of the rack for the clustered power scheme(case D).

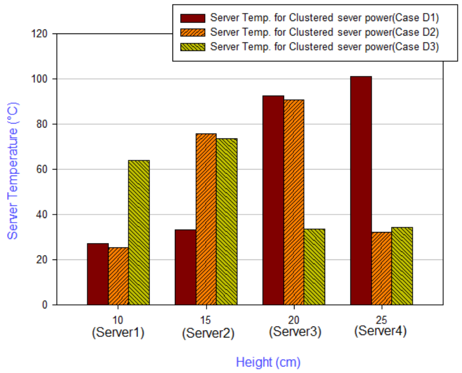


Fig.18. Servers temperature distribution for clustered power scheme (case D).

To distinguish and evaluate the overall performance of the entire rack for the different cases of power schemes, the variations in SHI/RHI for the various cases are plotted as shown in **Error! Reference source not found.**. It is observed for general power scheme the best thermal management efficiency is received for the uniform power scheme (case A), then that of the clustered power scheme (case D), followed by that of the segmented power scheme (case C) and finally that of the discerned power scheme (case B).Fig. 19 also shows that case B4, which was has the lowest server temperature compared to the other cases B1, B2 and B3 (see Fig. 14), has the lowest SHI value compared to the other cases of the discrete power schemes.

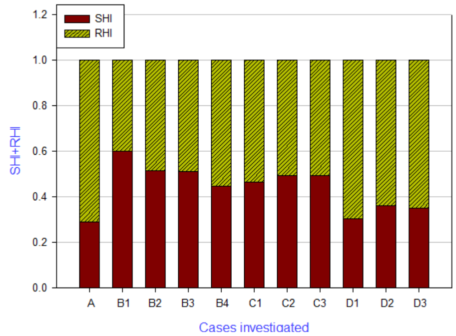


Fig. 19 variations in SHI/RHI for the various cases of servers powers schemes

Fig.19 can be considered as an efficient guidelines for the servers distributions along the rack according to the power density, server's power distribution natures and the on/off operation schedules of the rack servers. The distribution that gives minimum values of SHI is normally chosen for better thermal management and energy saving of the data center.

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4. Conclusions

Thermal management of a scaled data center are experimentally investigated under different power conditions of the servers rack. A scaled data center of one rack accommodating four servers was designed and constructed based on a scale ratio of 1/6. Front and rear rack temperatures distributions, server's temperatures and supply and return heat indices are measured and used to study and evaluate the thermal management and the performance of the data center. The results show that

- Rack of uniformly power loaded servers has better thermal performance and heat indices than other studied cases.
- Clustering of active servers lead to better air flow management compared to discretely individual active servers and segmented distributions of active servers.
- Servers located at the bottom rack cabinet always has better thermal performance compared to servers at higher levels.

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