Heat Mass Transfer
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Experimental parametric study of servers cooling management in data centers buildings

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Abstract A parametric study of air flow and cooling management of data centers servers is experimentally conducted for different design conditions. A physical scale model of data center accommodating one rack of four servers was designed and constructed for testing purposes. Front and rear rack and server's temperatures distributions and supply/return heat indices (SHI/RHI) are used to evaluate data center thermal performance. Experiments were conducted to parametrically study the effects of perforated tiles opening ratio, servers power load variation and rack power density. The results showed that (1) perforated tile of 25% opening ratio provides the best results among the other opening ratios, (2) optimum benefit of cold air in servers cooling is obtained at uniformly power loading of servers (3) increasing power density decrease air re-circulation but increase air bypass and servers temperature. The present results are compared with previous experimental and CFD results and fair agreement was found.

List of symbols

Q	Heat gained by air in server (W)
T	Temperature (°C)
T_{ref}	Supply air reference temperature (°C)
CRAC	Computer room air conditioning
RHI	Return heat index
SHI	Supply heat index
δQ	Heat gained by air before entering the server (W)

Subscripts

in	Inlet
out	Outlet

1 Introduction

Data centers are widely used in industrial applications such as telecommunications, data storage/processing in banks, market transactions and others special/private applications that need large/speed data processing. Recent studies showed that data centers consume 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]. It is important to properly manage data center cooling process as almost 50% of data centers energy consumption is utilized in the cooling system of data centers. Consequently, a detailed understanding of air flow and temperature distributions in data centers is very important to operate the data centers within the required specifications while avoiding excessive use of cooling energy.

Layout and features of all data centers are similar where most of them use raised-floor configuration [2, 3]. Figure 1 shows a typical schematic view of open aisle data centers [2]. The racks are arranged in a hot-/cold-aisle configuration. Table 1 shows the most common IT server alignment standard [4] which gives the real dimensions of the racks arrangement. Perforated tiles are located in the cold aisle to supply cold air to the server's intakes. The hot air

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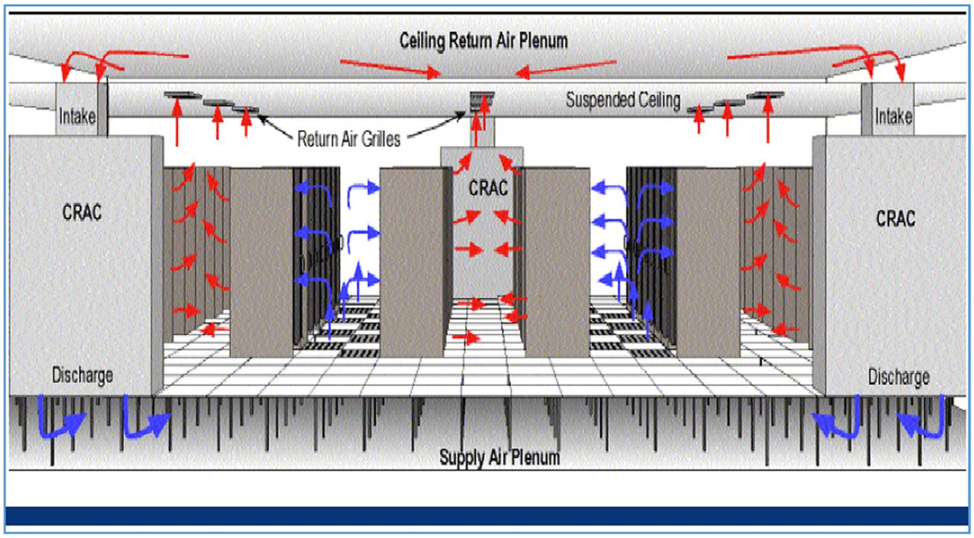
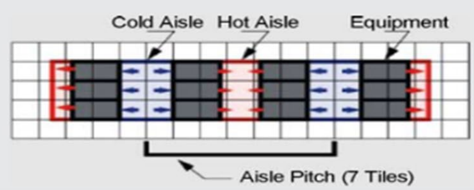


Fig. 1 Typical open aisle data center [2]

Table 1 Aisle pitch allocation and rack arrangements with separation [4]

	Tile size	Aisle pitch	Cold-aisle size	Hot-aisle size
U.S.	2 ft (610 mm)	14 ft (4267 mm)	4 ft (1220 mm)	3 ft (914 mm)
Global	600 mm (23.6 in)	4200 mm (13.78 ft)	1200 mm (3.94 ft)	914 mm (3 ft)
Seven-title aisle pitch, equipment aligned on cold aisle				

discharged by the server's fans is extracted by the computer room air conditioning (CRAC) units to re-cool and supply it to data center plenum. This concept prevents the recirculation of the hot air discharged from the servers and mixing with the supplied cold air from the perforated tiles. However, hot air re-circulation and cold air bypass must be considered in design and operation stages to avoid inefficient cooling system; especially hot air recirculation which is the main reasons of rising the servers temperatures exceeding the allowable limits.

Efficient thermal management of data centers rooms can be maintained by using proper air distribution in the rooms. So, to improve data centers cooling efficiency, it is necessary to study airflow patterns and temperature distribution inside the data centers. Data centers thermal management performance and effectiveness are normally evaluated by Supply Heat Index (SHI) and the Return Heat Index (RHI) [5, 6] 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 et al. [7] who studied air distribution inside high compute density (Internet) data centers. It was concluded that the air velocity is not an important factor for the data center designers as human thermal comfort is not a significant factor in the data center. Shrivastava et al. [8] 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. They also supported Nakao et al. [9] finding that the ceiling supply with under floor return leads to the worst air distribution and thermal managements in data centers. Similar investigations were conducted [10, 11] to evaluate and compare under floor supply and overhead supply configurations. They reported that although under floor 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. Ham et al. [12] presented a simplified server model to simulate data centers cooling energy consumption. They reported that the proposed server model should be able to solve the problems with the existing simulation method in the design stage, especially when the data center has a high ambient temperature and uses an economizer. Fulpagare et al. [13] studied the effect of plenum chamber obstructions on data center performance. They reported that the obstructions in plenum chambers may lead to a reduction in the cold air flow rates reaches to 80% elevating the racks exit air temperature by about 2.5 °C and increasing the possibilities of the occurrences of hot spots. Almoli et al. [14] presented a computational fluid dynamic investigation of liquid rack cooling in data centers. They reported that liquid rack cooling enables potential benefits of CRAC load reduction as compared with the traditional air cooling.

More recently, Van Gilder et al. [15] 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. They reported a recommendation for plenum depth clear airflow space to be 0.61 m or more. Kumar et al. [16] 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. Baptiste et al. [17] studied the simulation of a temperature adaptive control strategy for an IWSE economizer in a data center. They reported that the increase in blown air temperature allows the system to raise the evaporator loop temperature. As a results, the number of WSE or IWSE operations increase and reduce the load on the heat pump. They also reported that energy costs in data center can provide up to 17% of electric energy savings on the cooling plant requirement. Khalaj et al. [18] studied the multi-objective efficiency enhancement using workload spreading in an operational data center. They reported that the optimal workload distribution can be achieved by applying a MOPSO algorithm. Ham et al. [19] studied the energy saving potential of various air-side economizers in a modular data center. They reported that the indirect air-side economizers equipped with a heat wheel achieved significant annual energy savings of 63.6–67.2% compared to the conventional CRAH system.

Karlsson and Moshfegh [20] 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. Alkharabsheh et al. [21] experimentally studied pressure drop characterization in a server rack. In this study, the effect of the server's internal resistance, rack doors and cable management arm on the airflow are investigated. The result for the rack door, showed that the reduction in air flow rate is 3.5 and 0.3% for the 64 and 81% perforation ratios, respectively. Cho et al. [22] studied the air management system and thermal performance in high density data center for different air distribution configurations. Results showed that cooling efficiency can be improved by installing a simple partition wall on the rack server.

Arghode et al. [23] studied the thermal characteristics of open and contained data center cold aisle and they reported that Containment of the cold aisle tended to equalize the tile and rack air flow rates. Gondipalli et al. [24] conducted a computational study of the effect of using cold aisles compartments. The results showed that a 15–40% reduction in rack inlet temperature can be obtained by using cold aisle compartments for the same room layout and cold air supply. Fulpagare et al. [25] studied the advances in data center thermal management. They reported that the research carried out on thermal management of data centers has helped in improve performance in many instances (such as rear door water cooled heat exchanger type rack), and in establishing some physics-based criteria for data center designers. More recently, Nada et al. [26–31] presented comprehensive CFD studies and experimental studies using a scaled physical model to investigate the effects of the different geometric and operating parameters such as percentage of opening area of floor tiles, racks power density, power loading conditions, CRACs locations and distributions and using aisles containments and partitions on the air flow and temperature distribution in data centers, and the thermal managements of the data centers measured by the four performance indices parameters (RTI, SHI, RHI and RCI).

Actually, most of these investigations 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. [32] and later Nada et al. [30], 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 showed accurate thermal similarity while the airflow similarity cannot be obtained with reasonable accuracy.

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 scaled model data centers and its effectiveness and accuracy of its applicability on real data centers. In the present study, a physical scaled room model is designed and constructed to simulate a real data center and using it to conduct the present experimental parametric study at a wide range of operating parameters and geometric conditions. The main objective of the current work is using the scaled model data center to experimentally study the effects of opening ratio of perforated tiles, server load variation and data center power density on air flow and temperature distributions, thermal performance and energy efficiency. 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 set up

The experimental facility of the present work is constructed using a scaled model of a full size standard dimension data center (see Table 1 where the real standard dimensions are given) based on a length-scale ratio of 1/6. Scale modeling techniques, selection of scaled dimensions for racks, servers and data center room compared to real systems used for the present work can be found in our previous recent paper [30]. A physical model room was constructed to carry out the experimental parametric study to avoid the exhaustive effort and cost of using real data center. The experimental set up consists of a room model, a rack of servers and cooling air supplying apparatus circuit. Instrumentation and measuring devices are installed in the set up to measure the required different parameters needed for the analysis such as air flow rates, temperatures ad servers powers. The schematic diagram of the experimental set up and measuring devices is shown in Fig. 2. The model room dimensions is 400 × 329.5 × 500 mm and is made from Plexiglas wall having a thickness 1 cm. The room side walls were air tight assembled using silicon. The depth of the raised floor is 100 mm. The cold ails and hot ails tiles dimensions are 101.6 and 75 mm respectively. A full details of the data center room is given in Fig. 3.

A blower is used to supply the cooling air into the plenum of the data center model room. This air is then flow into the data center room via the perforated tiles to passes through the servers rack to cool it. The exhaust hot air discharged from the rack at the rack rear face of the rack and is discharged outside from the top of the room using exhaust fan. Four different perforated tiles with different opening ratios of 25, 50, 75% and fully opened as shown in Fig. 4 are used to supply the cooling air to the room. A code for tile designation code [33, 34] is used to identify the tiles characteristics and dimensions such as orifice diameter, tiles opening ratio, pitch between adjacent orifices.

The data center room accommodate one rack of dimensions 101.6 × 152.6 × 334 mm (height) located in the center of the room. This rack simulate a real rack of a

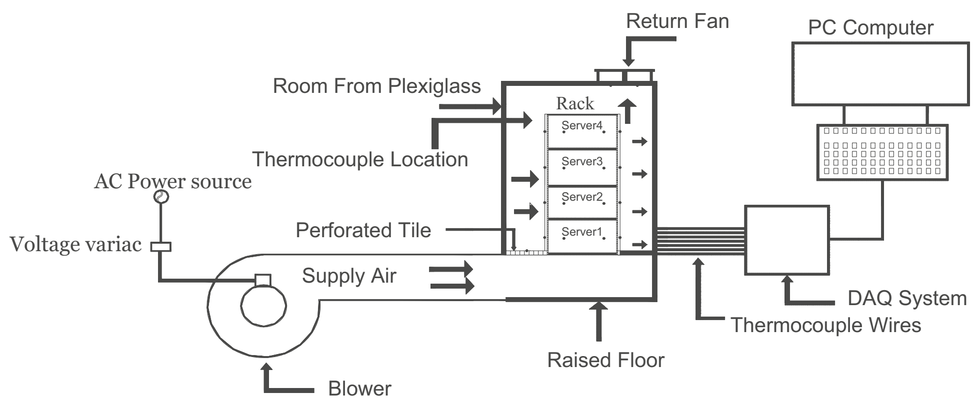


Fig. 2 Schematic diagram of the experimental setup

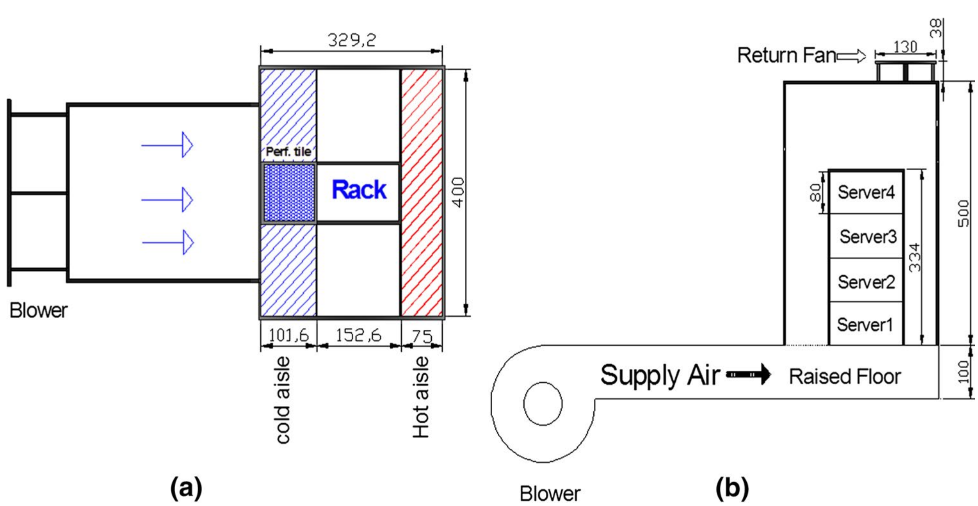


Fig. 3 Model room **a** top view, **b** side view (dimensions in millimeters)

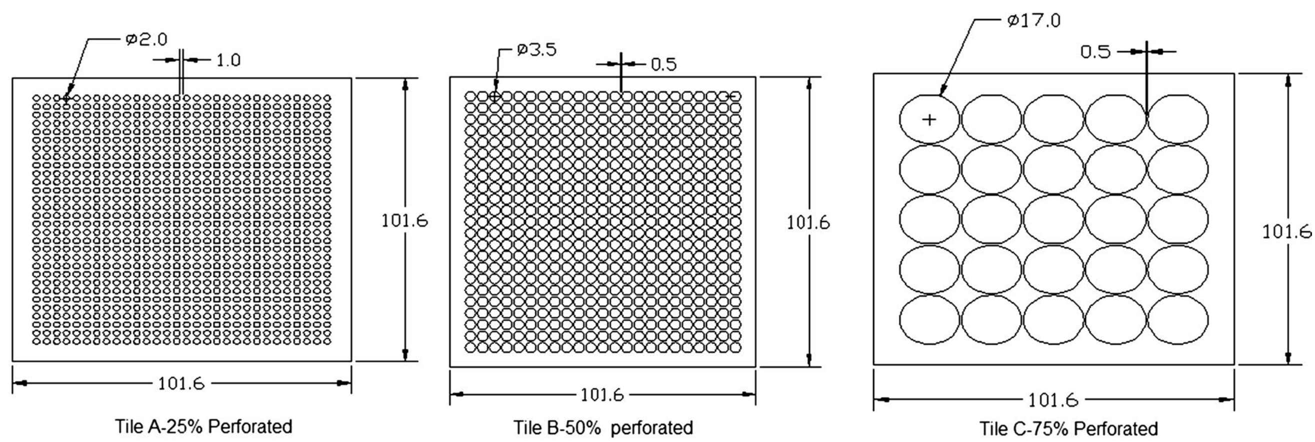


Fig. 4 Tested perforated floor tiles (dimensions in millimeters)

data center in racks surrounded by hot and cold aisles. The rack houses four servers cabinets [4, 32], each cabinet includes a server simulator. The dimensions of the server cabinet simulator is 101.6 × 80 × 152.6 mm. The rack front and rear doors are made of screen mesh of 65% opening ratio to simulate actual servers [32]. A variable speed fan (0.45 m^3 min^{-1}) and electric heater (150 W) are used in each server cabinet to simulate the fan and heat generation of actual servers. The server fan flow rate is controlled by controlling the input power supplied to the fan using a variac. Hot wire anemometer is used to measure the fans flow. A nickel–chromium wire wrapped around mica plate and covered by a 0.5 mm in thick stainless steel plate is used to generate heat in each server as shown in Fig. 5. A variac is used to control the input power to the server..

For measuring temperature profile inside the room a group of twenty eight thermocouples (T-type) distributed in room were used. The thermocouples were fixed on a Plastic frames in front and behind rack to measure the front and back temperature distribution along the rack height. Eight thermocouples are installed in each frame at different heights of the rack. To measure the temperature of the supply and exhaust air to and from the room, two sets of two thermocouples are fixed underneath the perforated tile and on the exhaust fan intake. Two other thermocouples mounted on the heater surface of each server (see Fig. 5) are used to measure the servers surface temperatures. All thermocouples readings are recorded via Data Acquisition connected with PC. Reading of all thermocouples received by DAQ has been corrected against calibrated thermometer.

2.2 Experimental conditions

For the parametric study, the experiments were conducted tiles opening ratio, servers power density and server power

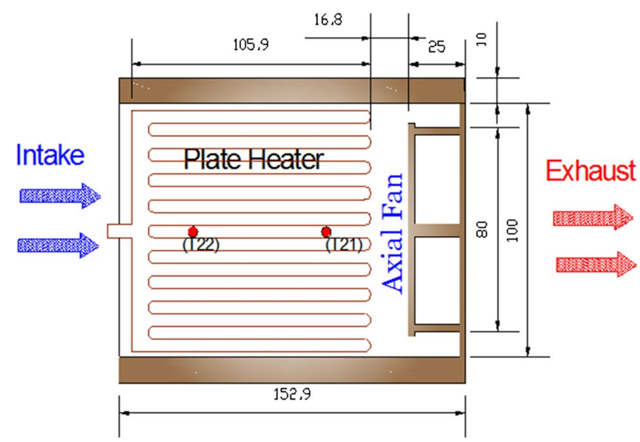


Fig. 5 Server plate heater (dimensions in millimeters)

variation condition to study the effects of these parameters on the cooling performance of the servers of the data centers. The studied parameters and ranges are given below:

Opening ration of perforated tiles	25, 50, 75 and 100% (fully open)
Room power density (W m^{-2})	379, 759, 1139, 1518 and 1898
Blower air discharge temperature	22 °C
Servers power modes	Uniform, discrete, segmented and clustered (cases A, B, C and D in Fig. 6)

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

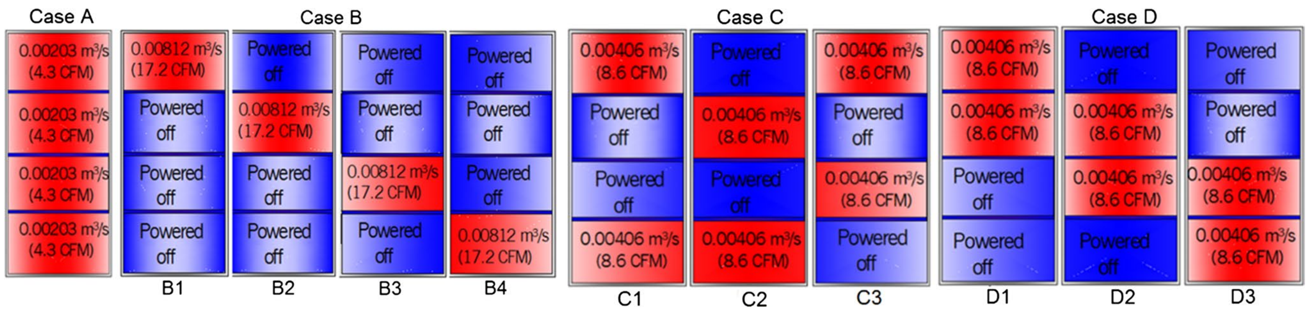


Fig. 6 Details of the various cases active power loaded servers

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 are identically set to discharge a sum of uniform air flow rate of 0.00812 m^3 s^{-1} across the 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^{-1}. 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^{-1}. 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.

2.3 Experimental procedure and program

The procedure and experimental program were as follows:

1. Make sure the room is clean and accessible before starting the experiment.
2. Make sure that blower is operational and adjust the blower fan speed according to the experimental program.
3. Supply and adjust power to each server in the rack according to the program.
4. Turn on the server fans and adjust the fan speed according to the experiment objective.
5. Turn on the data acquisition system.
6. Wait until steady state condition is achieved.
7. Measure the tile flow rates as well as all temperature values.
8. Record the readings of all instruments (voltage, current, flow rate and temperatures).
9. Repeat steps 3–8 at different opening ratio of the perforated tile (25, 50, 75% and fully open) and the different power densities.
10. Repeat steps 3–8 at the same power density for the different sever loading schemes.

Each experiment is repeated twice to ensure the consistency in measurements. 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.

2.4 Data reduction and thermal metrics for data centers

Thermal performance indices are used to measure the airflow and thermal management of the data center. In real data centers hot air recirculation and cold air bypass or infiltration around the racks occur and badly affect the thermal performance and cooling efficiency of data centers. Accordingly, air passes through the rack is a mixture of supplied cold air and rearticulated hot airflow. The uncontrolled hot air recirculation elevate the server intake air temperature and may lead to unsafe servers operating temperatures. Cold air bypass is another uncontrolled phenomena in which part of the supply cold air bypasses the rack and moves around the rack to mix with the hot exhaust air at the rack back. Figure 7 shows the hot air recirculation and cold air bypass phenomenon.

Sharma et al. [6] proposed dimensionless thermal indices parameters SHI and RHI (supply heat index ad return heat index) for the evaluation of the hot air recirculation and cold air bypass phenomena for the sake of thermal management of data centers. The supply heat index is defined as the ratio between the heat gained by the air in

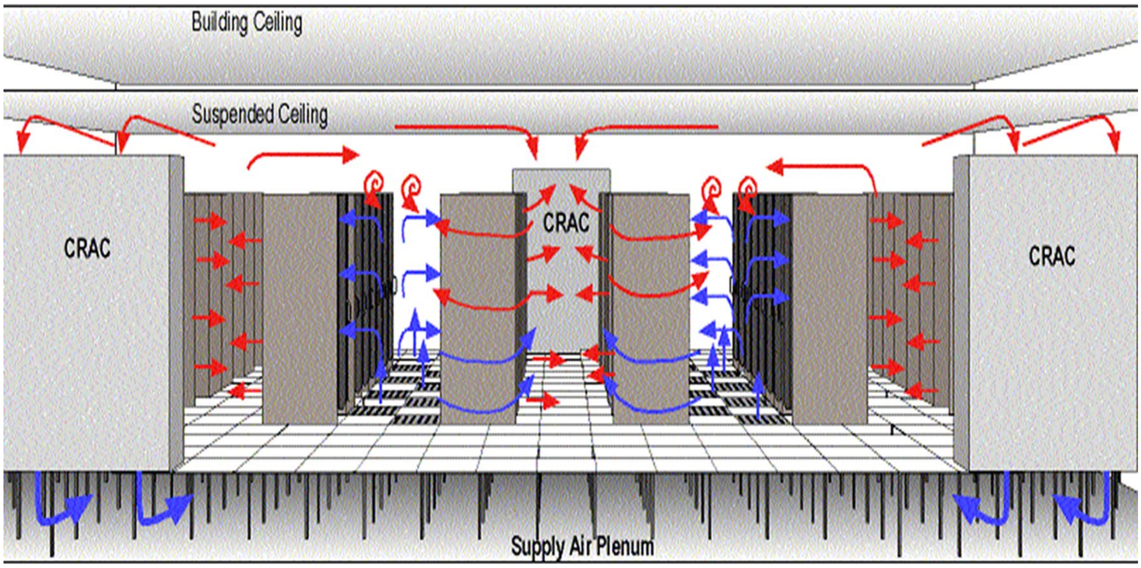


Fig. 7 Hot air re-circulation and cold air by-pass phenomena

the cold aisle (due to hot air recirculation) before it enters the racks to the total heat gained by the air after leaving the racks, i.e.:

$$\mathrm{SHI} = \left(\frac{\delta Q}{Q + \delta Q}\right) = \frac{\text{Enthalpy rise in cold aisle before entring the server}}{\text{Total enthalpy rise of the cold air}} \quad (1)$$

The return heat index is the ratio between the heat gained by the cold air during it passes the servers to the total heat gained by the cold air, i.e.

$$\mathrm{RHI} = \left(\frac{Q}{Q + \delta Q}\right) = \frac{\text{Total heat extraction by the CRAC units}}{\text{Total Enthalpy rise of the cold air}} \quad (2)$$

It is clear that

$$\mathrm{SHI} + \mathrm{RHI} = 1 \quad (3)$$

where Q is the heat gained by the cold air during it passes on the servers of the rack due to servers heat dissipation and δQ is the heat gained by the cold air before entering the racks. SHI can be rewritten in terms of the of inlet air and exit air temperatures of the rack and the cold air supply temperature as follows:

$$\mathrm{SHI} = \left(\frac{\sum \left(\mathrm{T}^{\mathrm{r}}_{\mathrm{in}} - T_{ref}\right)}{\sum \left(\mathrm{T}^{\mathrm{r}}_{\mathrm{out}} - T_{ref}\right)}\right) \quad (4)$$

where $\mathrm{T}^{\mathrm{r}}_{\mathrm{in}}$, $\mathrm{T}^{\mathrm{r}}_{\mathrm{out}}$, and $\mathrm{T}_{\mathrm{ref}}$ are the rack air inlet temperature, rack air exit temperature and the supply tile inlet air temperature, respectively.

Equations (1) and (4) shows that increasing δQ cause an increase in ($\mathrm{T}^{\mathrm{r}}_{\mathrm{in}}$) and SHI. Rising ($\mathrm{T}^{\mathrm{r}}_{\mathrm{in}}$) may leads to systems failure and reliability problems. Increasing ($\mathrm{T}^{\mathrm{r}}_{\mathrm{in}}$) also causes entropy generation decreasing energy efficiency. Therefore, SHI may be used as an indication of thermal management and energy efficiency in data center.

A low RHI indicates bypass of the cold air and its mixing with the rack exhaust air without passing on the servers. Ideal values of (SHI and RHI) are (0 and 1) while typical benchmark acceptable ranges of SHI and RHI are $\mathrm{SHI} < 0.2$ and $\mathrm{RHI} > 0.8$.

3 Results

3.1 Effect of perforated tiles opening area

Figure 8 shows the temperature profiles at front and rear of the rack for the different opening ratios of the perforated tile at 379 W m^{-2} power density corresponding to air flow rate of 0.0042 $\mathrm{m}^3\ \mathrm{s}^{-1}$ for server's power loading according to Scheme A. The figure shows that a temperature profile at front of the rack is uniform and the temperature variation along the rack height is narrow in case of 25% opening ratio. At higher opening ratios the temperature at the rack top levels substantially increases. This indicates that the air flow through the perforated tiles for 25% opening ratio is more uniform compared to the other opening ratios. Figure 8 also shows the increase of the temperature at the front of the rack and consequently at the back of the rake with increasing the tile opening ratio. This can be attributed to the decrease of the air velocity with

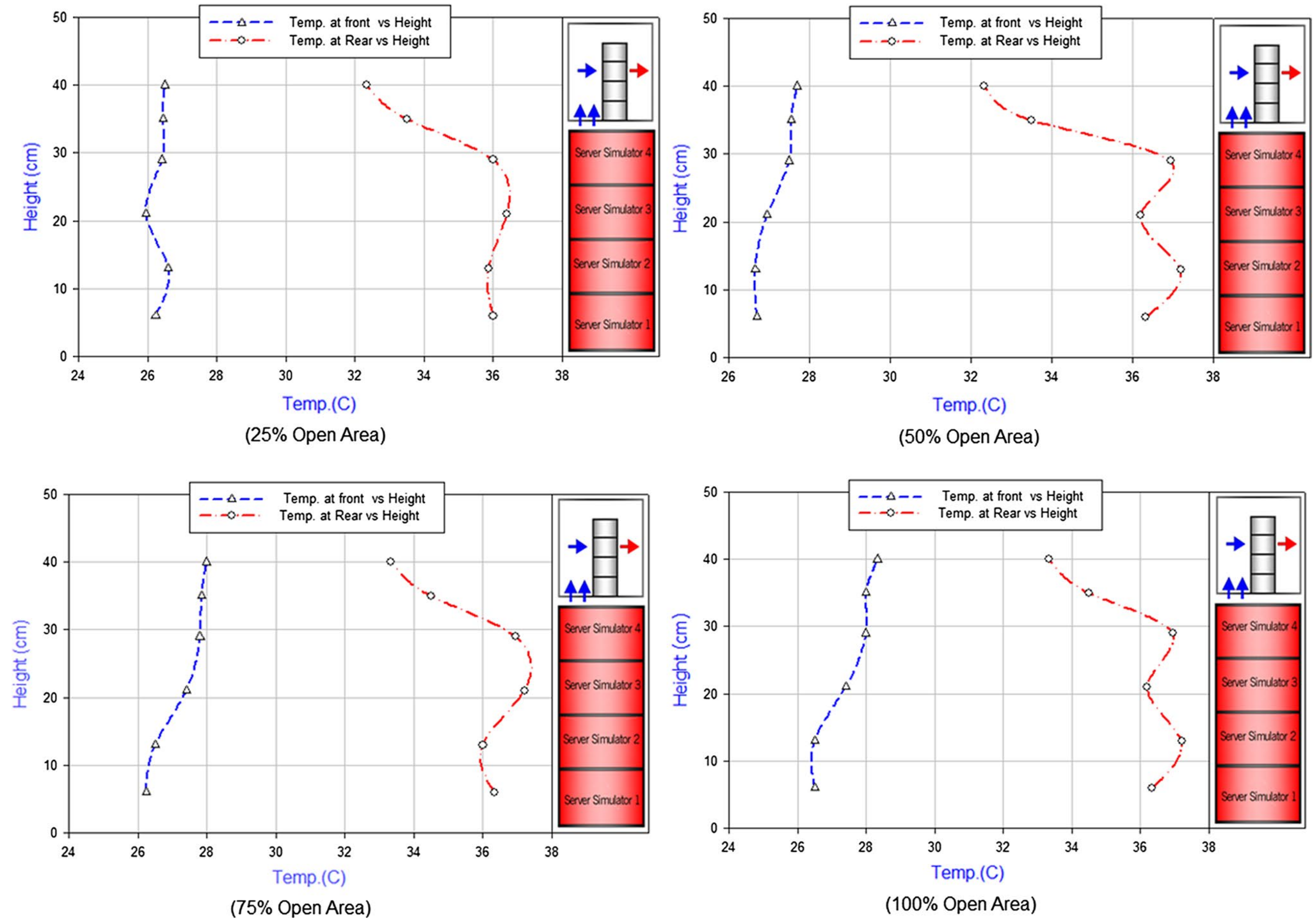


Fig. 8 Temperature profile at front and rear of rack for the different perforated tile opening ratios at 379 W m^{-2} for case A of servers loading schemes

increasing the opening ratio that leads to higher temperature along the rack height.

Figure 9 shows the variation of SHI and RHI with the perforated tile opening ratio at 379 W m^{-2} power density for uniform server's power loading. The figure shows the increase of SHI and the decrease of RHI with increasing the opening ratio. This means the decrease of the bypass and the recirculation with the decrease of the opening ratio. This can be attributed to that as the tile opening area decreases, the flow across the perforated tiles tends to become more uniform and possess higher momentum as the variations in the horizontal pressure gradients in the plenum under the perforated tile become less significant.

The trends of Figs. 8 and 9 are the same for the different power densities where and as shown in Fig. 10, the 25% opening ratio gives the lower supply heat index and the large return heat index at any power density. The lower SHI means the better the performance of the data centers. The results presented in Figs. 8, 9 and 10 are in a good agreement with that obtained by Van Gilder and Schmidt [15]. This generalizes that the 25% perforated tile opening ratio is the recommended opening ratio for any data centers power densities and layouts.

3.2 Effects of servers power loading schemes

Experiments are performed for a perforated tile air flow rate of 0.00812 m^3 s^{-1} 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 rate by adjusting the servers fans speed settings.

Figure 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 uniform distribution 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

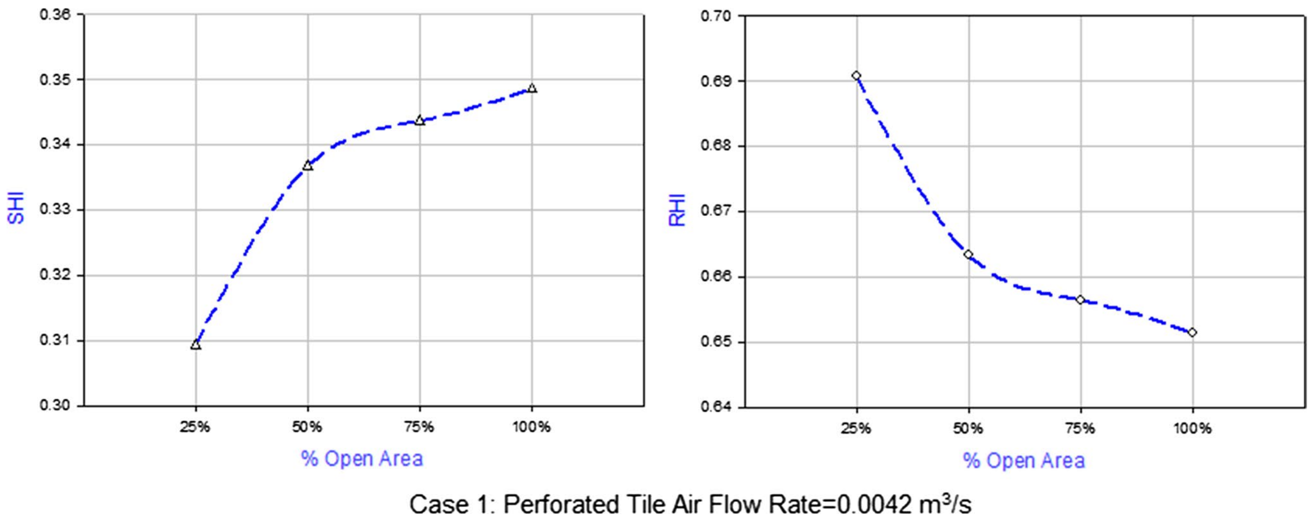


Fig. 9 Variation of SHI and RHI with perforated tile opening ratio for uniform servers power schemes

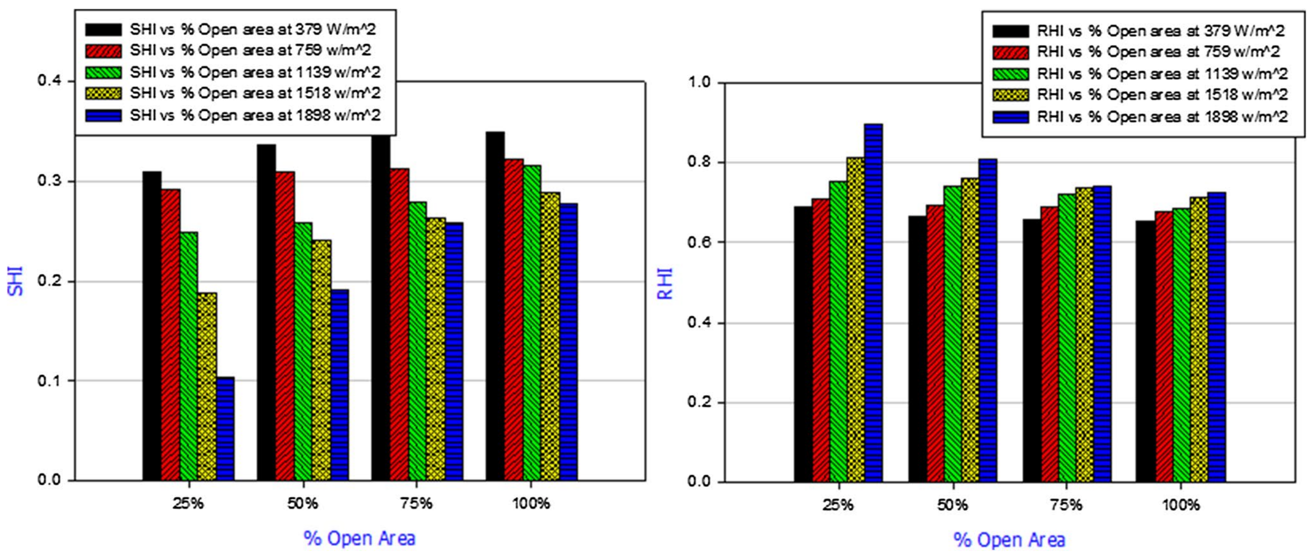


Fig. 10 Variation of SHI and RHI of data center with perforated tile opening ratio at different power densities

back rack temperatures starts to decrease due to mixing of the hot air of the hot ails with the cold air of the cold aisles that occurs above the rack.

The servers temperatures are the most important parameters to avoid failures of servers due to the presence of hot spots by exceeding its temperature above the allowable limit of operation. 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 25 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.

Figure 13 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 = 22 cm in B3 and H = 14 cm in B2 and H = 10 cm in B1). This non-uniform trend in the average temperatures arises from the non-uniform server heat loads. Figure 14 shows that for the four cases (B1–B4), the surface temperature of the active servers is always

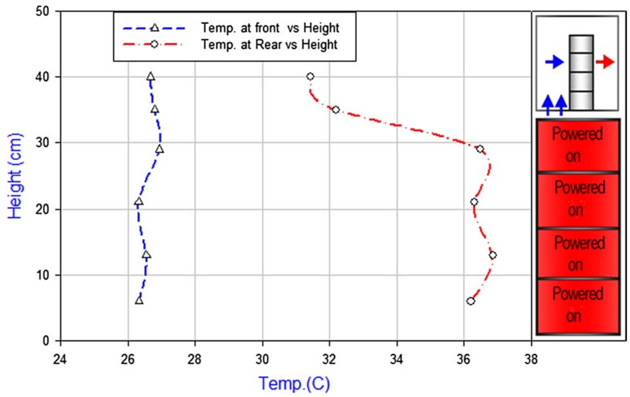


Fig. 11 Temperature profile at front and rear of the rack for uniform power scheme

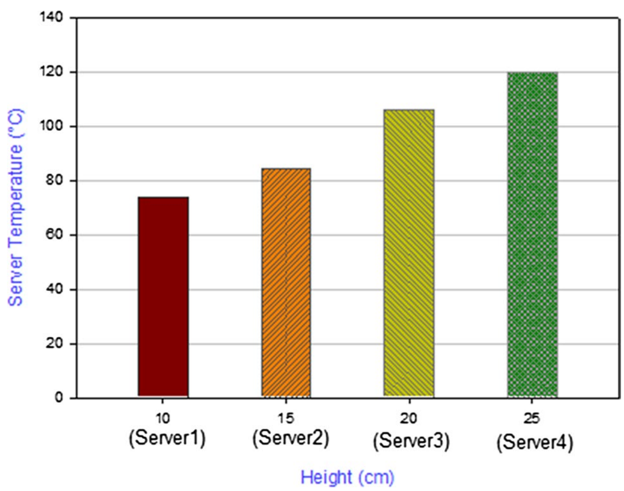


Fig. 12 Servers temperature distribution for uniform power scheme (case A)

higher than that of the non-active 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.

Figure 15 shows the temperature profiles at the front and back of the rack for three cases (C1–C3) of the segment power scheme. Figure 15 shows that the temperatures distributions at 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). Figure 16 shows the variation of the server's surface 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 non-active servers. Figure 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.

For clustered power scheme, there is a slight uniform of the temperature distribution due to clustering of the two active servers as shown in Fig. 17. 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 shown in Fig. 18 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.

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 Fig. 19. 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). Figure 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.

Figure 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

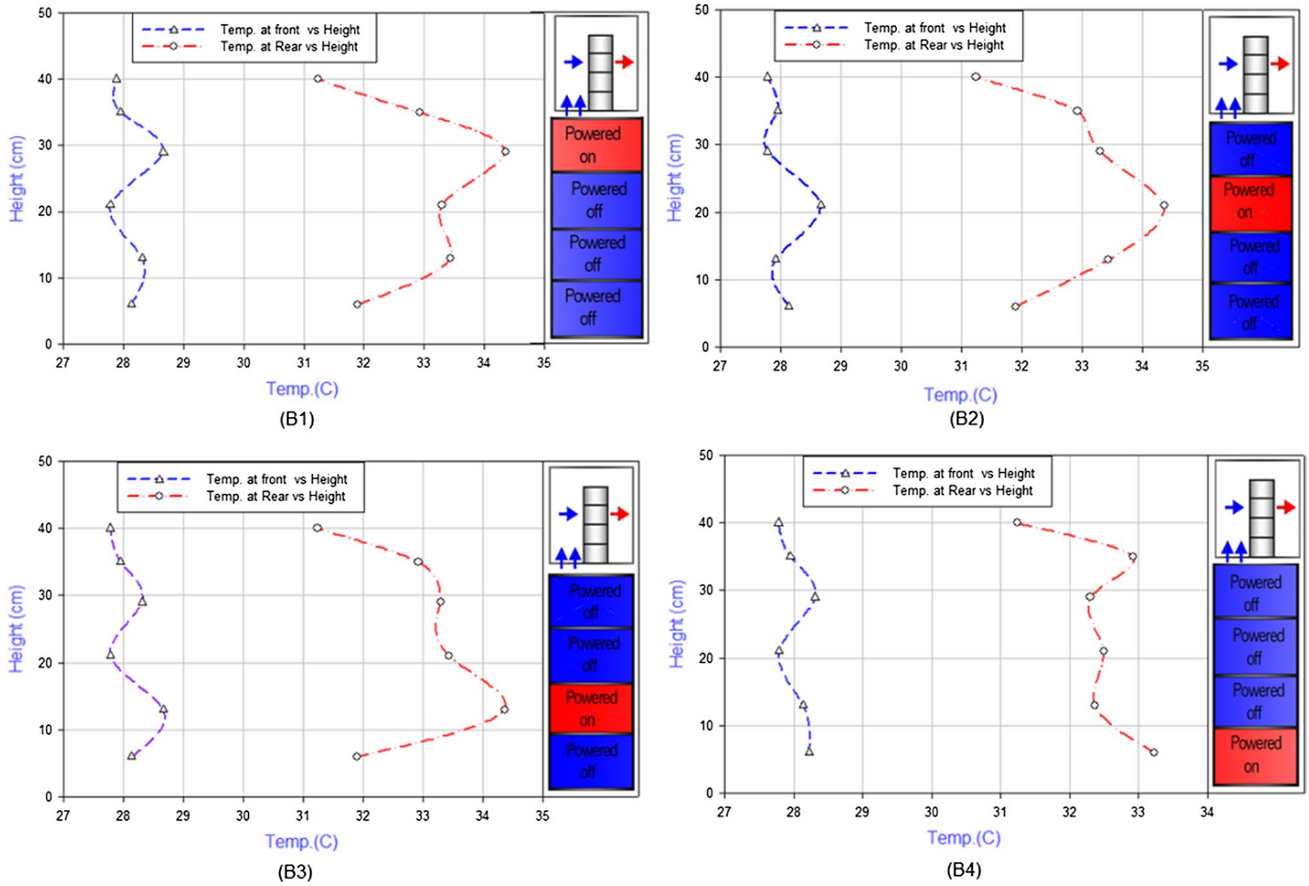


Fig. 13 Temperature profile at front and rear of the rack for discrete power scheme (case B)

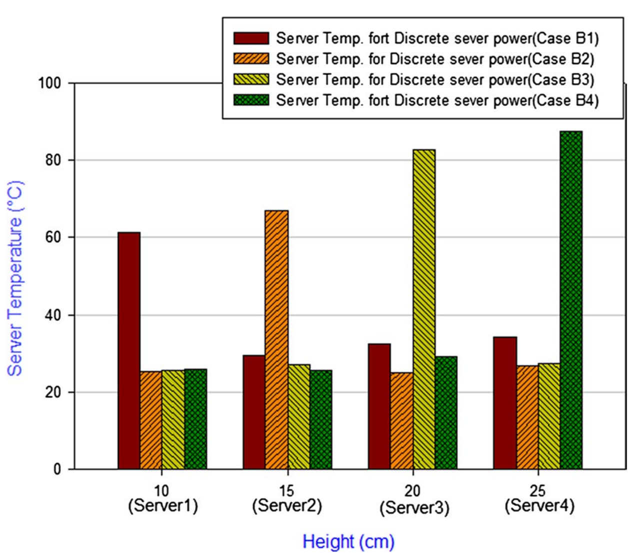


Fig. 14 Servers temperature distribution for discrete power scheme (case B)

distribution that gives minimum values of SHI is normally chosen for better thermal management and energy saving of the data center.

3.3 Effects of power density

To study the effect of overall power density on temperature distribution and on SHI and RHI, the power level in the room was uniformly increased from 319 to 1898 W m^{-2} by step 380 W m^{-2} for the typical under-floor air cooling system of 25% perforated tile opening ratio and uniform servers power schemes configuration. Figures 20 and 21 shows the temperature profiles at the front and rear of the rack and the server's temperatures at the different power densities, respectively. Figure 20 shows that the temperature profile at the front of the rack is uniform and the temperature variation along the rack height is narrow especially at low power densities. At higher power densities the temperature at the rack top levels substantially increases. Figures 20 also shows the decrease of the temperature at the rack front with the increase of the power density and this can be attributed to the increase of the supplied air flow rate with increasing the power which leads to a lower air temperature at the rack front. However, Figs. 20 and 21 show the increase of the server's temperatures and the temperature at the rack back with the increase of the power density. This can be attributed to that increasing the power density increases the air

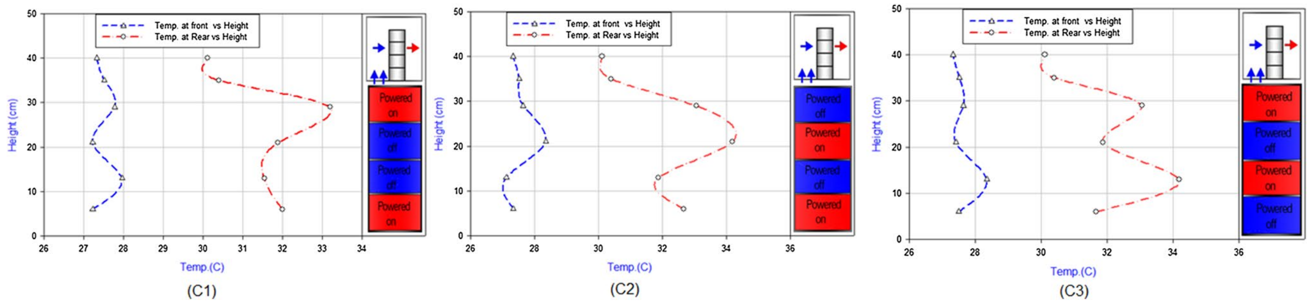


Fig. 15 Temperature profile at front and rear of the rack for segmented power scheme (case C)

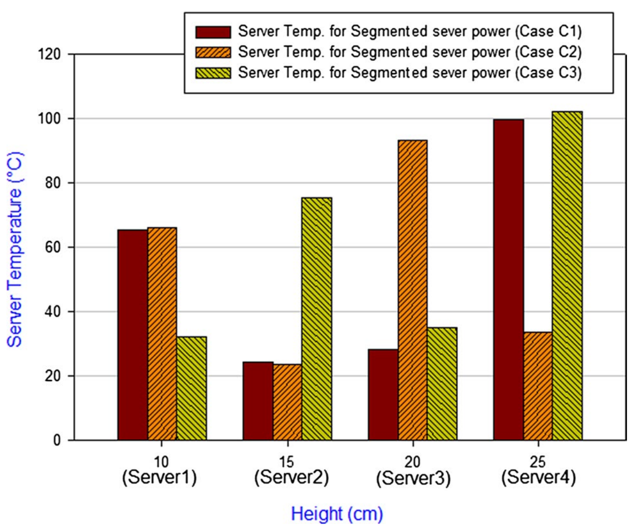


Fig. 16 Servers temperature distribution for segmented power scheme (case C)

flow rate supplied from the tile and this increases the cold air velocity discharged from the tiles which leads to lower static pressure at the cold ails. Decreasing the cold ails static pressure decreases the air flow rates of the server fans and consequently increases the by-pass and decreases re-circulation air and this increases the server's temperatures and the exit fans temperature (Temperature at rack back). Figure 21 also shows that whatever the power density, the server located at the rack bottom cabinet always has lower temperatures.

The effect of the power density on SHI is shown in Fig. 22 where a steady reduction in SHI is noticed with increasing the rack power density, for example the SHI decreases from a maximum value of 0.309 to a minimum value of 0.103 when the power density increases from 319 W m^{-2} (50 W/rack) to 1898 W m^{-2} (250 W/rack). This can be attributed to that the increase in the power density in the data center has a positive effect on the recirculation leading to a decrease in $\delta Q/Q$ (see Eq. 1).

4 Comparison with pervious experimental and CFD data of real data centers

To validate the idea of using scale physical model to simulate real data centers, the results of the present work are compared the results of the previous CFD works [35] and experimental [36] that were conducted on real data centers. Figures 23 and 24 show the comparisons for the front and rear racks temperatures and for the SHI and RHI, respectively. The figures reveals that conducting investigations and studies on data centers scale physical model can fairly simulate the results of real data centers.

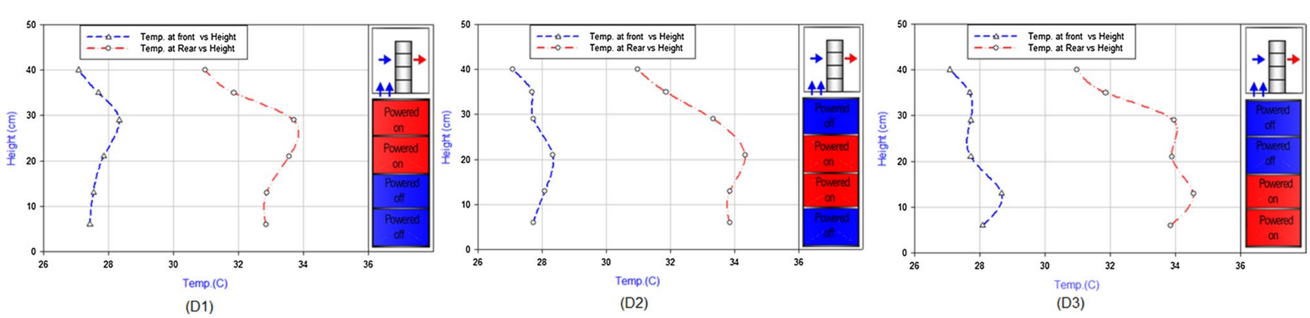


Fig. 17 Temperature profile at front and rear of the rack for the clustered power scheme (case D)

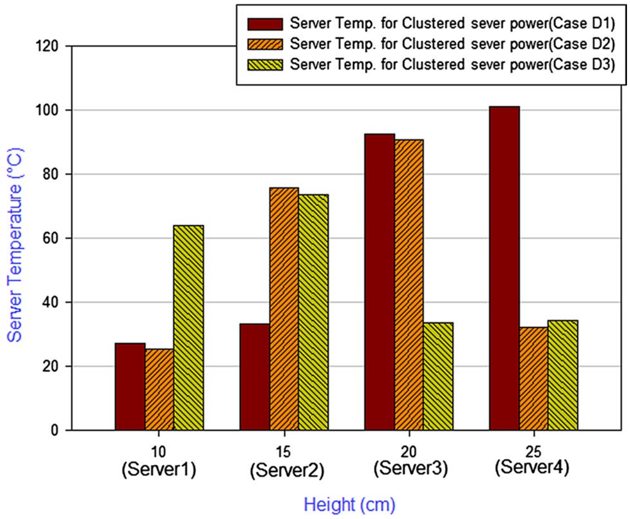


Fig. 18 Servers temperature distribution for clustered power scheme (case D)

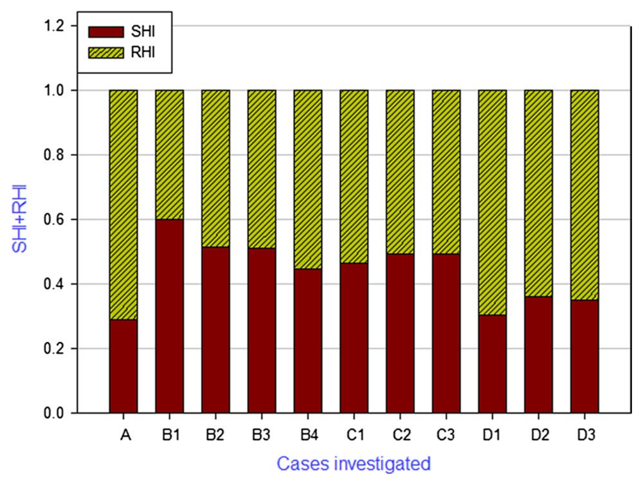


Fig. 19 variations in SHI/RHI for the various cases of servers powers schemes

5 Conclusions

In the present paper, a scaled physical model of data centers was designed and constructed to experimentally study and evaluate data centers performance. A parametrical study of the effects of the operational and geometrical design parameters on data centers thermal management and performance was conducted. Front and rear rack temperatures distributions, server's temperatures and supply and return heat indices parameters are measured and used to study and evaluate the performance and thermal management efficiency of data centers. The conducted parametrical study included the effects of perforated tiles opening ratio, the

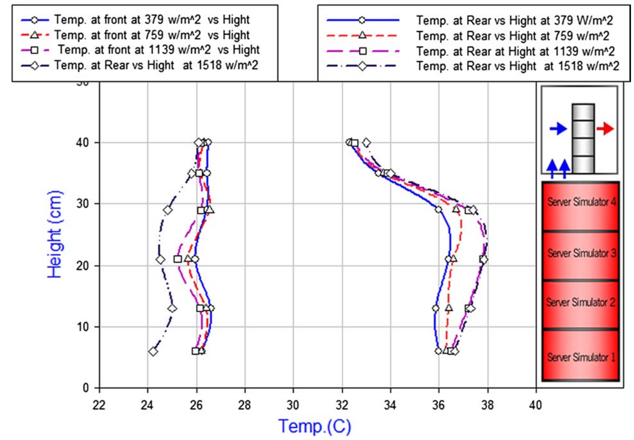


Fig. 20 Temperature profile at front and rear of the rack at different power densities

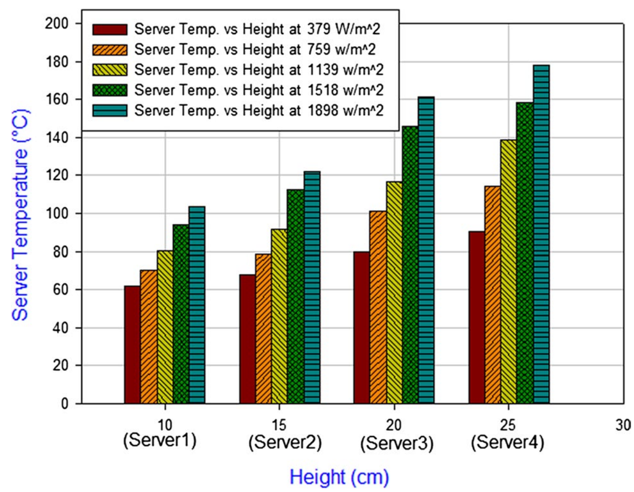


Fig. 21 Servers temperature distribution at different power densities

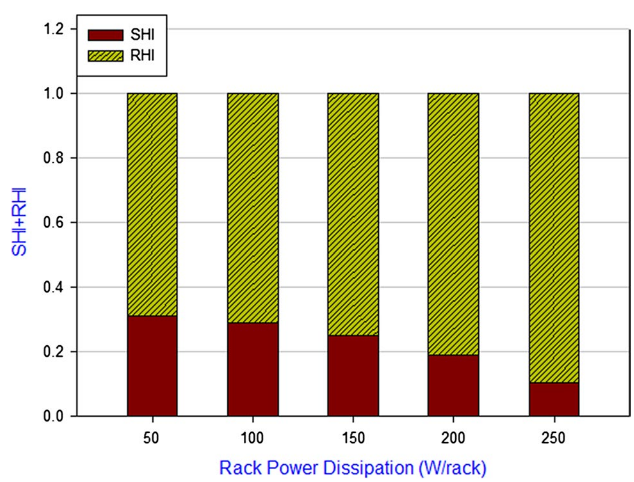


Fig. 22 Sum of heat indices (SHI/RHI) at different rack power densities

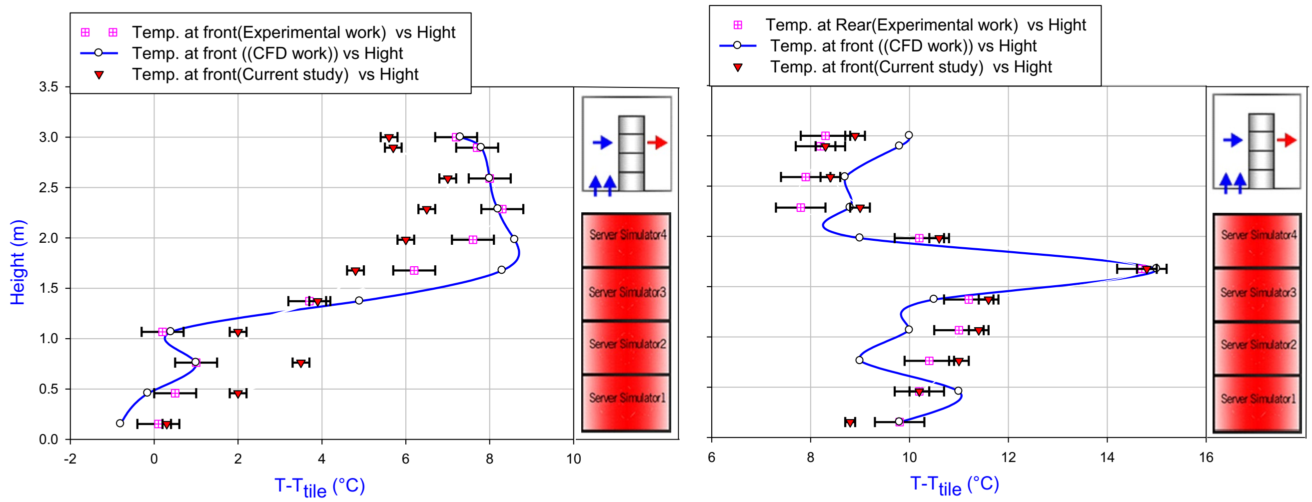


Fig. 23 Comparison of the temperature profiles with pervious work [35, 36]

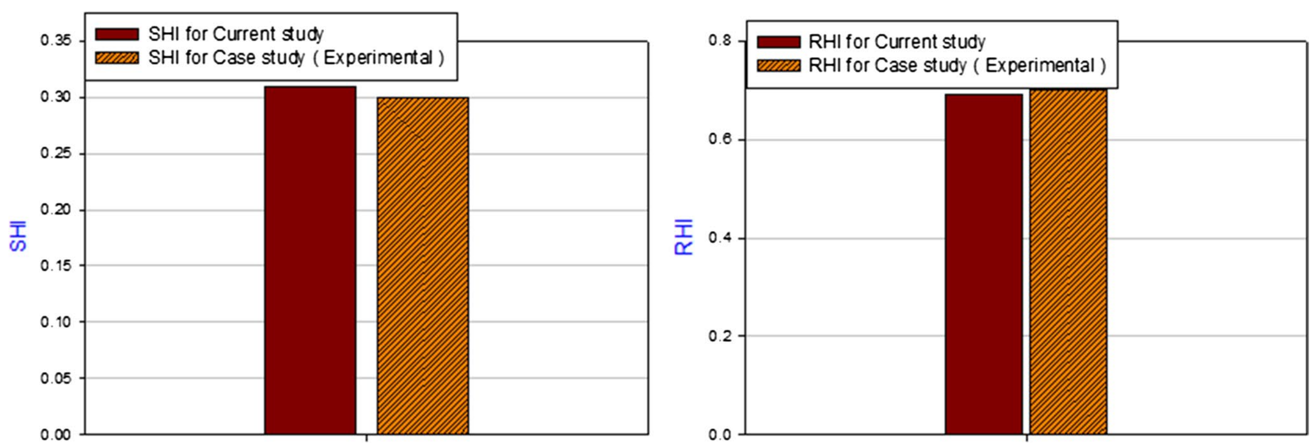


Fig. 24 Comparison of Supply heat index and Return heat index with pervious experimental work [36]

server's loads variations schemes and the data center power density. The presented results will aid the thermal-fluid design of future Data Centers as follows:

- The 25% perforated tiles opening ratio has the best temperature distribution, supply and return heat indices and energy saving as compared to 50, 75%, and fully opened perforated tiles.
- Racks 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.
- Increasing data centers power density and supply air flow rates decrease air re-circulation but increase air bypass and servers temperature.

Comparing the present results with previous experimental and CFD results of real data centers, reveals that conducting investigations and studies on scale physical model of data centers can fairly simulate and predict the results of real data centers.

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