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Experimental investigations of air conditioning solutions in high power density data centers using a scaled physical model

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ABSTRACT

The widespread use of data centers, the dramatical increase of the data center power density and the need for improving cooling system efficiency to maintain reliable operation temperature and save cooling energy make the study of data center thermal management an urgent issue. In the current paper, three different configurations for thermal management solution of high power density data centers are investigated, compared and evaluated. A scaled physical model data center has been designed and constructed for the sake of the study using the theory of scale modeling of air flow experiments. The results showed that (i) by using aisle partition and aisle containment the rack inlet temperature can be reduced by 3–13% and 13–15.5% for aisle partition and aisle containment configurations, respectively; (ii) the intake air temperature reduction increases with increasing power density; and (iii) using aisle partitions and aisle containment with raised floor improves the data center cooling performance.

Études expérimentales des solutions de conditionnement d’air dans des centres de données à forte densité électrique en utilisant une maquette

Mots clés : Centre de données ; Conditionnement d’air ; Modélisation physique ; Gestion thermique ; Partition d’allées ; Confinement d’allées ; Frigorigène ; Monocouche auto-assemblée ; Mouillage

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Nomenclature

Q	heat dissipation [W]
Cp	specific heat of air at constant pressure [$J\cdot kg^{-1}\cdot k^{-1}$]
$\dot{m}$	mass flow rate [$kg\cdot s^{-1}$]
T	temperature [°C]
T_{ref}	reference temperature [°C]
CRAC	computer room air conditioning
RHI	return heat index
SHI	supply heat index
U	velocity [$m\cdot s^{-1}$]
L	length [m]
ν	kinematic viscosity [$m^2\cdot s^{-1}$]
α	length scale = L_m/L_R
τ	time scale
Re	Reynolds number
Ar	Archimedes number
Pr	Prandtl number

Superscripts

r	rack
c	CRAC

Subscripts

in	inlet
out	outlet
m	for model
R	for real data center
i,j	Cartesian direction

1. Introduction

Data centers are widely used in different industrial applications where large/high-speed data processing is necessary, such as telecommunications, data storage and processing in banks, market transactions and other special and private applications. Recent studies showed that data center consumes a huge amount of the total power consumption of modern cities. It was reported that data centers consumed 61 billion kWh or about 1.5% of U.S. total electricity consumption in 2006 (EPA, 2007). A large portion of this consumed energy (almost 50%) is necessary for cooling of servers to maintain their temperature within the allowable limits (ASHRAE, 2008). The properly managed data center cooling process would reduce this portion of energy. Consequently, a much more detailed understanding of air flow and temperature distributions for proper thermal management in data centers is a vital issue to operate the data centers within the required specifications while avoiding excessive use of cooling. Layout and features of all data centers are similar; mostly they use raised-floor configuration. Fig. 1 shows a typical schematic view of open aisle data centers (Patankar, 2010). The racks are arranged in a hot-/cold-aisle configuration with standard alignment like that shown in Table 1 (ASHRAE, 2004). The cold aisle contains perforated tiles that supply cold air to the inlets of the server racks from the underfloor plenum. The hot air leaving the racks is extracted by the Computer Room Air Conditioning (CRAC) unit to re-cool and supplies it as cold air to data center plenum to complete the cycle. This concept of energy management for data centers

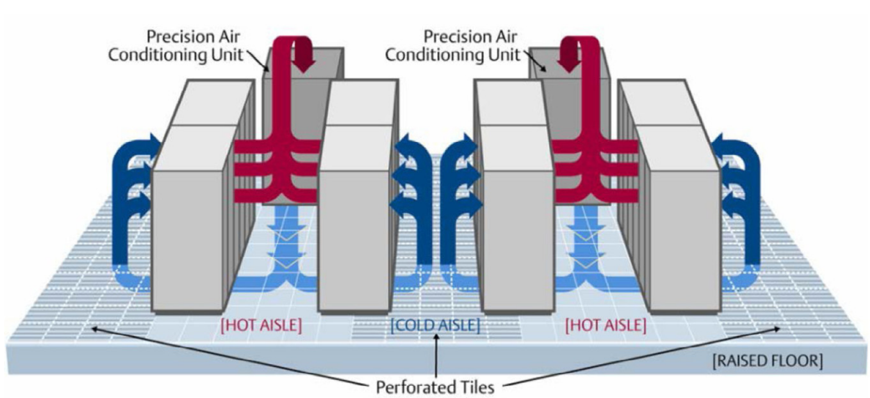
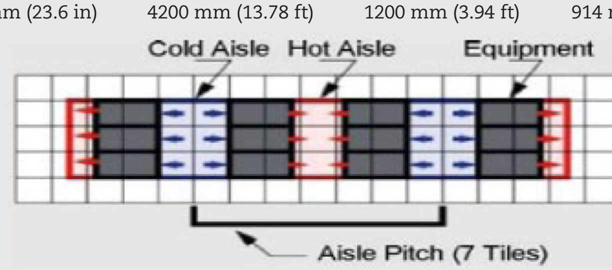


Fig. 1 – Typical open aisle data center (Patankar, 2010).

Table 1 – Aisle pitch allocation and rack arrangements with separation (ASHRAE, 2004).

	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				



prevents the unwanted mixing of the hot air expelled from the servers with the cooling air coming from the perforated tiles. However, hot air recirculation and cold air bypass must be considered in design and operation stage in order to prevent a drop in the servers cooling efficiency.

Efficient thermal management of data centers can be maintained by using proper air distribution in the room that would reduce or prevent the hot air recirculation and/or the cold air bypass. For this purpose, physical separation (aisle partition) of hot and cold aisles has been suggested (Cho and Kim, 2011). Containment of air throughout the data center is an important thermal management and energy saving strategy that results in the data center optimization especially in high power density data center. Most of the modern energy efficient data centers use some kind of containment system (Gondipalli et al., 2008; Saurabh et al., 2012; Vaibhav et al., 2013; Vikneshan et al., 2013). Generally, the major benefit of aisle partition and containment is the mitigation of server air inlet temperatures due to the minimum mixing of cold air with hot air. Data center thermal management performance and effectiveness are normally evaluated in terms of performance dimensionless metrics: Supply Heat Index (SHI) and the Return Heat Index (RHI) (Herrlin, 2006; Sharma et al., 2002). Using these indices, heat transfer and thermal management inside the data centers can be understood and evaluated.

One of the relevant works in this area is that from Cho et al. (2009) who studied air distribution inside high compute density (Internet) data centers. Cho et al. (2009) observed that the air velocity is not an important factor for the data center designers where human thermal comfort is not a significant factor. Shrivastava et al. (2005) reported that supplying the cold air from the raised floor and extracting the return air from ceiling is the most efficient air distribution system. On the other hand, the ceiling supply with under floor return leads to the worst air distribution and the worst thermal management in data centers (Nakao et al., 1991). Other works cited in the literature (Herrlin and Belady, 2006; Sorell et al., 2005) were used to evaluate and compare the under floor supply and the overhead supply configurations. They reported that although under floor supply is recommended for proper air distribution and thermal management, it can result in hot spots at the servers located at the rack top due to hot air recirculation.

More recently, VanGilder and Schmidt (2005) studied the uniformity of air flow through the raised floor perforated tile and they reported that perforated tiles of 25% opening ratio give the best flow uniformity. Karlsson and Moshfegh (2005) 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. Patterson (2008) studied the effect of data center temperature on energy efficiency. It was reported that the efficiency of the overall cooling system is strongly related to the efficiency of the data center room cooling which in turn depends on the data center air temperature. Estebe et al. (2014) studied the simulation of a temperature adaptive control strategy in a data center. It was reported that the increase in blown air temperature allows the system to raise the evaporator loop temperature reducing the load on the heat pump. It was found that the servers reduce their energy needs by about 78% when the blow air temperature (CRAC output air temperature) rises from 16 °C to 24 °C (Nada et al., 2015).

The effect of the schemes of server's power loadings on data center thermal management was studied. It was found that uniform power loading provides the best results for (SHI/RHI) and the optimum benefit of cold air in server and clustering of active servers lead to better air flow management compared to discretely individual active servers and segmented distributions of active servers.

Cho and Kim (2011) observed that the data center cooling efficiency can be improved by installing a simple partition wall on the rack server. Gondipalli et al. (2008) conducted a computational study on the effect of using cold aisle 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. In this regard, Vikneshan et al. (2013) reported that the fully provisioned contained aisle is preferred in case of no geometrical or cost limitations; otherwise the partial containment is a good accepted option. Vaibhav et al. (2013) showed that the containment of the cold aisle tends to significantly improve the temperature uniformity in the cold aisle, as well as at the server inlets temperature. Saurabh et al. (2012) found that a containment system reduces the overall cooling energy cost by preventing or reducing the mixing of cold and hot air streams.

Actually, most of these investigations were conducted on a real data center which is not an easy task due to high cost and difficulty to be controlled. Fernando et al. (2012) studied the viability of design and constructed 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.

In the present work, we focus on the thermal characteristics of separation and contained cold aisle by comparing three air distribution system configurations: typical under floor air cooling system configuration, typical configuration with aisle partition system and typical configuration with aisle containment. It is important to investigate the influence of these air distribution system configurations on the rack temperature distribution, the server temperature distribution and the performance metrics (SHI and RHI) at different power densities. For purpose of the study, a physically modeled data center with a single rack and four server simulators is constructed following the under floor supply-ceiling return airflow entering through perforated plate of 25% opening ratio.

2. Experimental facility and procedure

2.1. *Scale modeling of air flow and temperature*

The above literature revealed that a scale modeling theory is needed to achieve a physical scale and air flow modeling of real data centers for the purpose of testing and study (White, 2001). The proposed model is based on the use of under floor supply-ceiling return configuration as it provides the best cooling performance (Herrlin and Belady, 2006; Nakao et al., 1991; Shrivastava et al., 2005; Sorell et al., 2005). From the limited literature available regarding the data center modeling, there are three papers: one for testing the scaled model of data centers (Fernando et al., 2012), the second for testing the air flow in the scale modeled room (Awbi and Nemri, 1990) and the third for testing the effect of the rack intake temperature on the energy consumptions of the computer room air conditioning unit (Estebe et al., 2014). Flow conditions are completely similar if all relevant dimensionless parameters have the same corresponding values for the model and the real data centers. It was verified (Awbi and Nemri, 1990; Fernando et al., 2012) that such similarity can only be achieved if geometric, kinematic and thermal similarities between the modeled and real data centers exist. From dimensional analysis, this complete similarity can only be attained if Prandtl (Pr – ratio of momentum diffusivity to thermal diffusivity), Reynolds (Re – ratio of momentum force to viscous force), and Archimedes (Ar – ratio of gravitational force to viscous force characterizing fluid motion due to density differences) numbers are equal for both modeled and real data centers while geometric and boundary conditions similarities are attained. In fact, achieving complete similarity is very difficult, so it is often more reasonable to try to achieve a particular type of similarity: geometric, kinematic, dynamic, and/or thermal similarities (White, 2001). Assuming that geometric and boundary similarities exist, then equality of Pr, Re and/or Ar must be obtained to achieve particular types of similarities. Applying this similarity criterion to the supply air from perforated tile means:

1 Equality of Prandtl number is achieved when the same working fluid (i.e. air) in the scaled model and real data centers is used.
2 Equality of Reynolds number (Re) for both model and real data centers while using the same working fluid (i.e. identical kinematic viscosity or $\nu_m = \nu_R$) provides:

$$\mathrm{Re} = \left[\frac{UL}{\nu}\right]_m = \left[\frac{UL}{\nu}\right]_R \tag{1}$$

then a time scale factor can be defined as:

$$\tau = \frac{U_m}{U_R} = \frac{L_R}{L_m} = \frac{1}{\alpha} \tag{2}$$

3 Equality of Archimedes Number (Ar) for model and real data centers is given by:

$$\mathrm{Ar} = \left[\frac{g\beta L\Delta T}{U^2}\right]_m = \left[\frac{g\beta L\Delta T}{U^2}\right]_R \tag{3}$$

where g is the gravitational acceleration (9.81 m/s^2), β is the expansion coefficient ($\beta = 3.43\times10^{-3}\ K^{-1}$ for air at 20 °C), and ΔT is the temperature rise throughout room (typically, air going through a server increases 10 °C in temperature), L is the characteristic vertical length scale (2 m standard rack height), and U is the characteristic velocity (average tile flow velocity). It is common in real data centers to have a value of Ar greater than 1; thus natural convection dominates the data center cooling and so buoyancy must be taken into account.

In scaling velocity, a fully open perforated tile velocity is considered. If the temperature change is similar between the model and real data centers, then the time–scale ratio based on Archimedes similarity gives:

$$\tau = \frac{U_m}{U_P} = \sqrt{\frac{Lm}{Lp}} = \sqrt{\alpha} \tag{4}$$

It can be seen that the time–scale ratios based on Re equality (in Eqn. 2) and that based on Ar equality (in Eqn. 4) do not agree unless the length–scale ratio is 1. Therefore, a completely similar model of a data center is impossible to be created. For non-isothermal flows, Awbi and Nemri (1990) recommend that the time–scale factor based on the equality of Ar and Re can be used when Archimedes number is greater than and less than 0.001, respectively.

The experimental facility of the present work is constructed using a scaled model of a full size standard dimension data center based on a length–scale ratio of α equals 1/6. Using this length scale ratio and taking typical values of real rack height and tiles air velocity as $L_R = 2$ m and $U_R = 1$ m/s, respectively, then Re and Ar for the scaled model data center can be estimated as:

$$R_e = \left[\frac{U_m L_m}{\nu}\right]_m, \quad \mathrm{Ar} = \left[\frac{g\beta L_m \Delta T}{{U_m}^2}\right]_m \tag{5}$$

where U_m is the average inlet velocity of the air jet from the tiles (calculated from Eqn. (2) as $U_m = U_R/\alpha = 6$ m/s for Re equality and from Eqn. (4) as $U_m = \sqrt{\alpha}\ U_R = 0.4082$ m/s for Ar equality) and L_m is a characteristic vertical length scale ($L_m = \alpha\ L_R = 0.334$ m), i.e.:

$$R_e = \left[\frac{U_m L_m}{\nu}\right]_m = \left[\frac{6*0.334}{15.69*10^{-6}}\right] = 1.2747\times10^5$$

$$\mathrm{Ar} = \left[\frac{g\beta L\Delta T}{U^2}\right]_m = \left[\frac{9.81*3.448*10^{-3}*0.3334*10}{0.4082^2}\right] = 0.676$$

As $\mathrm{Ar} = 0.676$ is greater than 0.001, then the time–scale factor based on Ar equality will be used to achieve the similarity analysis in the present study.

Considering the one-sixth geometrical scaled model and a time scale factor based on Archimedes number equality, Table 2 summarizes the modified boundary conditions, flow rates and heat generation for the scaled model data center. The table also gives the necessary equations used to study heat transfer in the modeled data center. The heat generation is determined from the server flow rate and prescribes the temperature difference of the air flowing through the server ($\Delta T = 11$°C (Rasmussen)).

2.2. *Experimental setup*

A physical scale room model was used to conduct the experimental investigation of the present work to avoid the required exhaustive construction, measurement costs and time–length efforts of actual data centers. Scale modeling theory was utilized to design and construct the scale room model as per Section 2.1. 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

Table 2 – Boundary conditions and necessary calculations of sever load of modeled data center.

Boundary condition	Symbol	Equation	Value
Inlet airflow velocity	U_O	Eqn. (4)	0.4083 m s^{-1}
Tile flow rate	Q_t	$Q_t = U_o A_{tile}$	$4.215\times10^{-3} m^3 s^{-1}$
Inlet air temperature	T_O	–	22 °C
Rack temperature rise	ΔT	–	Assuming (ΔT = 10 °C)
Server flow rate	Q_S	$Q_S = Q_t/4$	$1.0534\times10^{-3} m^3 s^{-1}$
Server heat generation	P_S	$P_S = \rho c_p Q_s \Delta T$	12.969 W
Tile porosity	σ_t	–	0.25
Rack porosity	σ_r	–	0.65

conditions and arrangements of actual standard data centers. The built-up test facility was equipped with different measuring devices and instrumentations to measure different parameters needed for later analysis such as temperatures, powers, and air flow rates. Fig. 2 shows a schematic diagram of the whole test facility and measuring instruments. As a scenario of operation, the 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 is sucked to flow throughout the cooling passage of server with the help of specific fan. 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. In the current test facility, a single rack including four servers is used to simulate the actual rack of a real data center located at the center of the room and surrounded by hot and cold aisles. To measure temperature distribution at different locations within scaled data center, a number of thermocouples (type T) were installed, typically twenty-eight thermocouples. 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 (DAQ, model NI cDAQ-9178 with NI 9213 16-Channel Thermocouple Input Module) connected with PC and controlled by LabView program. Reading of all thermocouples received by DAQ has been corrected against calibrated thermometer from normal temperature up to 150 °C.

2.3. *Scale model overall design*

The data center room used in the current experimental facility is a scale model of a full size standard dimension data center room with a length–scale ratio $\alpha = 1/6$ based on Archimedes number equivalence (see Fig. 3 for more details). It is made from Plexiglas wall of thickness 1 cm, air tight assembled using silicon. The room dimensions are $400 \times 329.5 \times 500$ 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.

A single rake of dimensions $101.6 \times 152.6 \times 334$ mm (height) located at the center of the data center room was designed

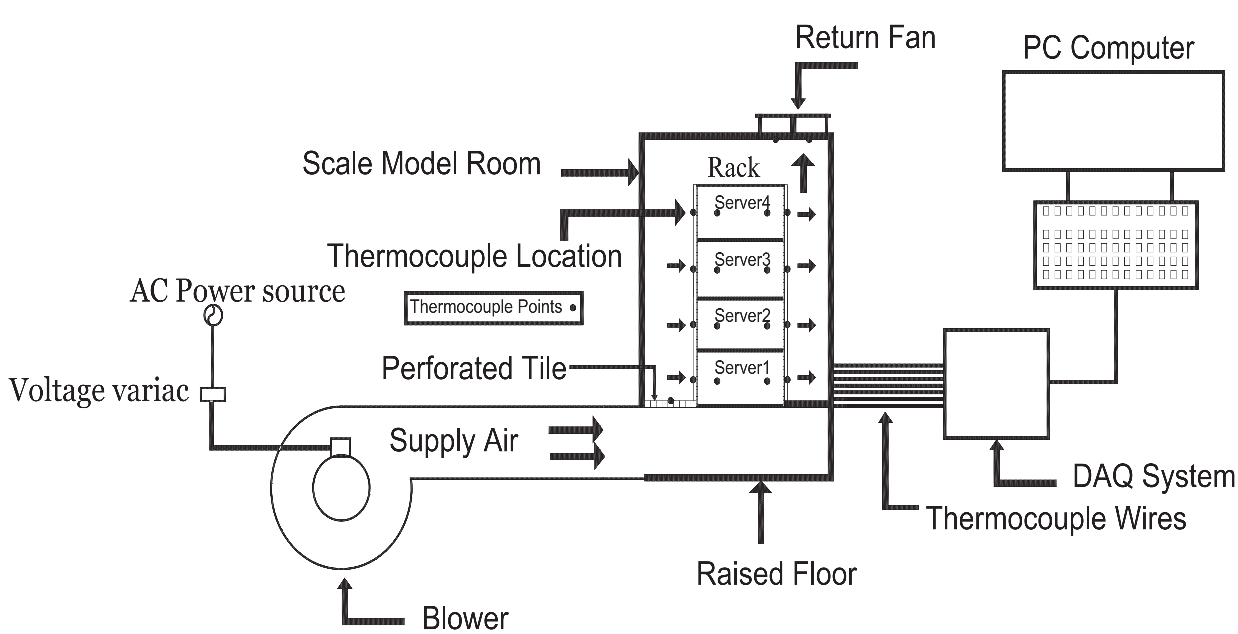


Fig. 2 – Schematic diagram of the experimental setup.

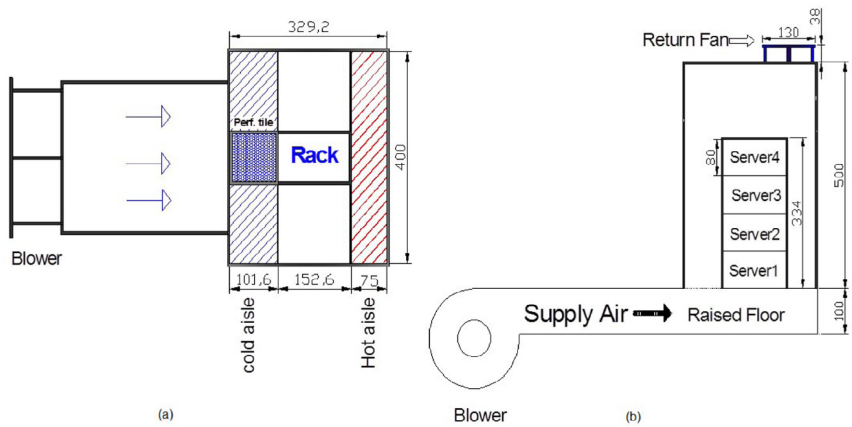


Fig. 3 – Scale model data center (a) top view, (b) side view (dimensions in millimeters).

and built to accurately simulate a rack in actual data center located at the middle of racks matrix. In order to simplify the modeling, the rack was designed to house four servers accommodating four server simulators (Smith et al., 2011). To ensure that there is no internal recirculation, server intake and exhaust face are attached to the rack perforated doors made of screen mesh of 65% opening ratio simulating actual servers opening ratio. The dimensions of each server cabinet simulator are 101.6 mm wide and 80 mm high and 152.6 mm deep. 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 server 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 supplied power using Variable AC transformer (variac – that regulate voltage in the range of 0–220 volts). The fans flow rates are measured by using hot wire anemometer (Model: Testo 435, of measuring range 0 to 20 m/s). 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. Fig. 4 shows a top view of the server heater. In order to obtain a

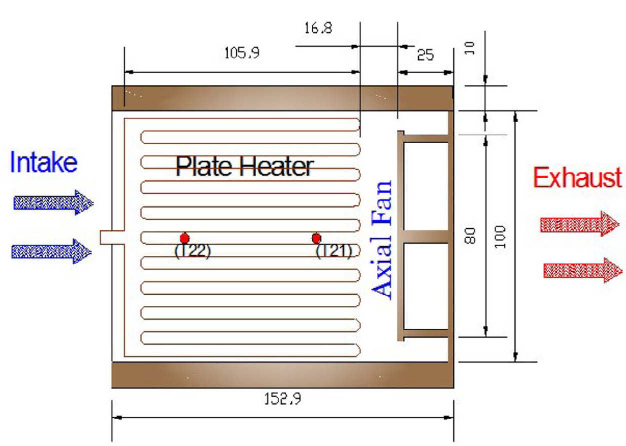


Fig. 4 – This figure shows a top view of the server (dimensions in millimeters).

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 variac. Two thermocouples located on the heater surface of each server (see Fig. 4) are used to measure the temperature of the heaters.

2.4. *Experimental conditions*

The experiments were conducted at different operating and geometric parameters to study the effects of these parameters on the thermal and air flow management inside the scaled model data center. The studied parameters and ranges include:

Room power density (W/m^2): 379, 759, 1139, 1518 and 1898
Blower air discharge temperature: 22 °C
Data center system configuration: typical under floor, typical under floor with aisle partition and typical under floor with aisle containment system.

The room power density is the sum of active servers' power per unit area of the data center room. The comparison involves five heat densities (379 W/m^2, 759 W/m^2, 1139 watt/m^2, 1518 W/m^2 and 1898 W/m^2) and three room configurations (open, aisle partition, and aisle containment). The open configuration does not use physical barriers to enhance the separation of hot and cold air in the equipment room (see Fig. 5a). The aisle partition system vertically divides the cold aisle and the hot aisle with a height of 100 mm, as shown in Fig. 5b, and the aisle enclosure system that blocks off the upper part of the cold aisle, as shown in Fig. 5c. Fig. 5 shows side views of the three room configurations. All experiments were conducted at 25% perforated plate opening ratio as this ratio is the most widely used in data center applications and is also recommended by previous investigators (Abdelmaksoud et al., 2010; Radmehr et al., 2007; Smith et al., 2011; VanGilder and Schmidt, 2005) who reported that 25% opening ratio gave the more uniform air flow distribution and bitter supply heat index along the rack servers as compared to other opening ratios. It is important to state that the power supplied to blower is synchronized with the predefined server power, as actually done in real data centers to maintain server temperature within specific range of operating temperature.

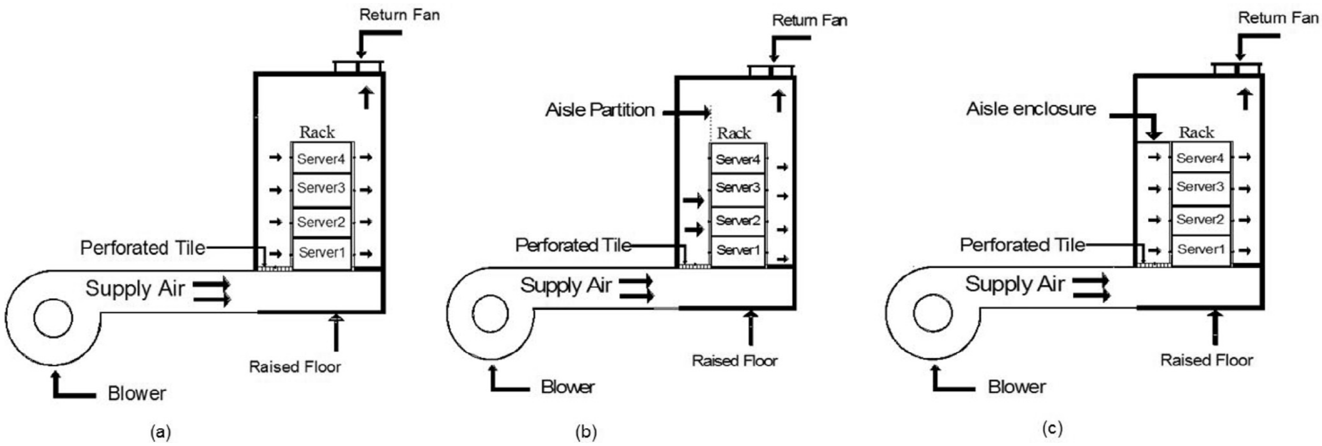


Fig. 5 – Comparison of three air distribution systems. (a) Typical under floor air cooling system configuration, (b) typical configuration with aisle partition system, and (c) typical configuration with aisle containment system.

2.5. *Experimental procedure and program*

The procedure and experimental program were performed 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. Steady state conditions were assured when the heater surface temperature of each server was maintained constant (variation within ±0.2 °C for 5 min). Steady state conditions were normally achieved after about forty minutes.
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).

Repeat steps 3–8 at different power density for specific data center configuration systems. Then these steps are repeated at other configurations of data center system in accordance with experimental program. 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.

2.6. *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 center recirculation, bypass or infiltration phenomena may occur (see Fig. 6). Accordingly, airflow ingested by a rack is a mixture of cold and hot airflow coming from surrounding. In case of re-

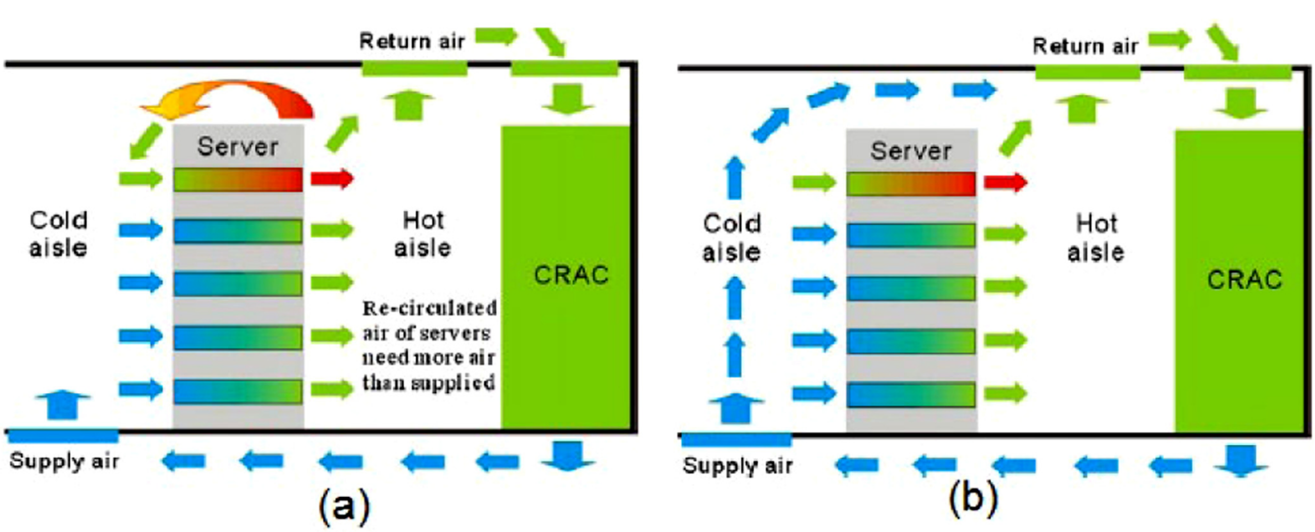


Fig. 6 – Typical data center airflows. (a) Re-circulation airflow and (b) by-pass airflow.

circulation, the exhaust hot air travels back into the server's intake air stream leading to rise of intake air temperature and so to unsafe servers operating temperatures. In case of bypass airflow, the supply cold source air bypasses the active servers and moves directly into the hot exhaust air stream. It has been reported that only about 40% of supplied air passes through the servers due to the occurrence of bypass and/or leakages (Awbi and Nemri, 1990). In general, thermal metrics depend on the geometric and physical parameters of the data centers.

To evaluate cooling performance of data centers, Gondipalli et al. (2008) proposed the dimensionless parameters for thermal indices. These indices evaluate the extent of cold and hot air mixing in data center. They are scalable metrics and potentially applicable at racks, rows or at wide data center level. Supply heat index parameter is defined as the ratio of the heat gained by cold aisle air before it enters the racks to the heat gained by the air leaving the racks and return heat index parameter is defined as the ratio of the total heat extraction by the CRAC units to the heat gained by the air leaving the racks. The utilization of dimensionless parameters allows these formulas to be scalable for any size system. These indices are defined as:

$$SHI = \left(\frac{\delta Q}{Q + \delta Q}\right) = \frac{\text{Enthalpy rise due to infiltration in cold aisle}}{\text{Total Enthalpy rise at the rack exhaust}} \tag{6}$$

$$RHI = \left(\frac{Q}{Q + \delta Q}\right) = \frac{\text{Total heat extraction by the CRAC units}}{\text{Total Enthalpy rise at the rack exhaust}} \tag{7}$$

$$Q = \sum_j \sum_i m^r_{i,j} Cp\left((T^r_{out})_{i,j} - ((T^r_{in})_{i,j}\right) \tag{8}$$

$$\delta Q = \sum_j \sum_i m^r_{i,j} Cp\left((T^r_{in})_{i,j} - ((T_{ref})_{i,j}\right) \tag{9}$$

$$SHI + RHI = 1 \tag{10}$$

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). Neglecting the heat transfer in the plenum, the temperature of the air exit from the vent tile and CRAC supply air temperature are considered to be equal. These temperatures are denoted by the reference temperature in the enthalpy calculations. According to mass conservation at rack inlet and exit, SHI can be rewritten as a function of rack inlet, rack outlet and CRAC outlet temperatures.

For a single rack data center, these metrics are evaluated using the following relations:

$$SHI = \left(\frac{\sum (T^r_{in} - T_{ref})}{\sum (T^r_{out} - T_{ref})}\right) \tag{11}$$

Equations (7) and (9) reveal 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 problems exist. 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.

A low RHI indicates the mixing of rack exhaust air with the cold air due to bypass air flow. Target values of SHI and RHI are 0 and 1 respectively, and typical benchmark of recommended acceptable ranges of SHI and RHI are SHI < 0.2 and RHI > 0.8.

3. Results

To study the effect of using the three air distribution system configuration on thermal management (temperature distribution, and SHI and RHI) at different power densities, the experiments were conducted at different power levels in the room from 379 W/m^2 to 1898 W/m^2 by step 380 W/m^2 for a typical under-floor air cooling system of 25% perforated tile opening ratio and uniform servers power schemes configuration. The four servers are equally powered and the speed setting of their fans is identically set to discharge the sum of uniform air flow rate of 0.0042 m^3/s across the entire rack for the first case. The results shown in Figs. 7–11 provide the rack temperature profile and servers' surface temperature distribution at the studied range of power density for the three configurations superimposed on the same plots for the sake of comparison. For all the three configurations, temperatures are monitored along the rack at different heights above the raised floor and at the surfaces of the servers. Average of these temperatures is used as a comparison parameter for aisle partition and aisle containment with typical under floor air cooling system configuration.

As observed from Figs. 7–11, for the three configurations there is a significant increase of the temperature at the rack back and the servers' surface temperatures with the increase of the power density. This can be attributed to fact that increasing the power density increases the air 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 this leads to the increase of the server's surface temperature and the exit fans temperature (temperature at rack back). It is also noticed that the server located at the rack bottom cabinet always has lower temperature compared to the upper servers no matter the value of the power density. Moreover, along the height of the rack, there is a remarkable increase in the server's surface temperature reaching the maximum value at the highest location, server 4 (located at height 25 cm). The increase of the surface temperature of servers with the increase of its location height can be attributed to the buoyancy effect that makes the environment of the server at higher levels in the rack hotter than those at lower levels of the rack.

The discussion of the behavior in the previous section reveals that increasing the perforated tile flow rate (configuration 1)

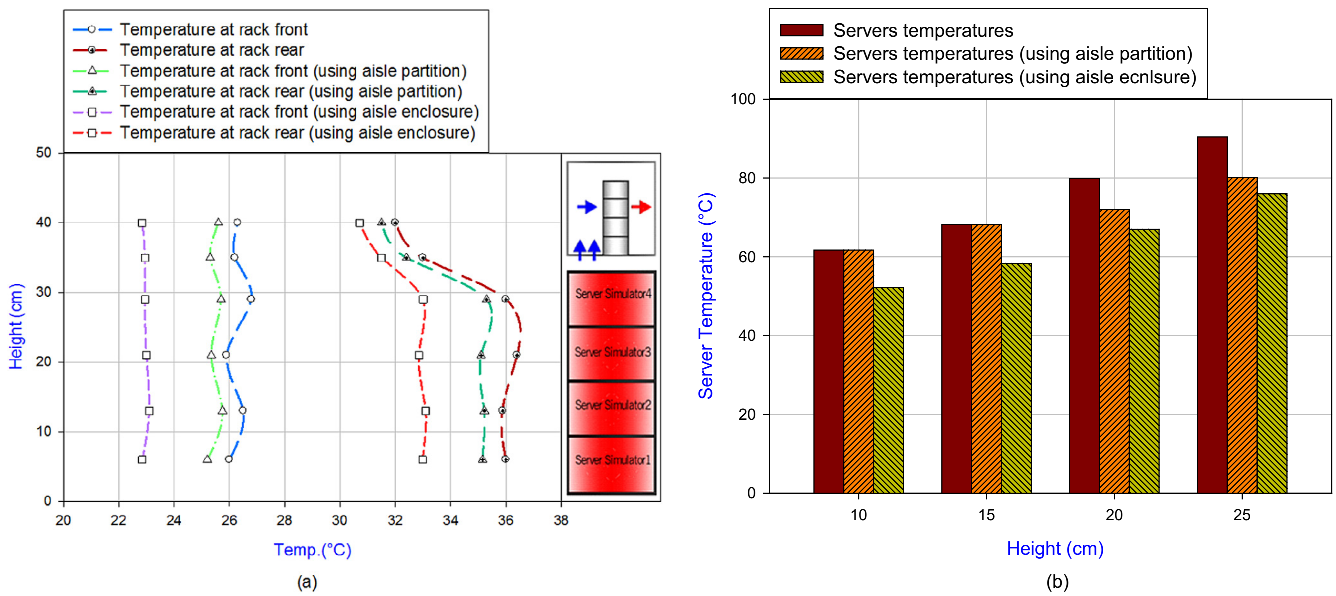


Fig. 7 – Comparison of the different configuration systems at 379 watt/m² power density. (a) Temperature profile at front and rear of rack for and (b) servers surface temperature distribution.

by using active tiles (tiles with fans to increase the air flow rate) will not resolve the increase in the needed cooling demand. In fact, increasing the perforated tile supply flow rate would adversely impact rack cooling due to the increase of the server's temperature. Techniques to prevent re-circulation and by-pass in case of high power density is needed. Two alternative techniques are used: aisle partition system configuration and aisle containment system configuration to contain the air in cold aisles and hot aisles and prevent the by-pass or the recirculation.

From Figs. 7–11a, the average inlet temperature is improved no matter the value of the power density due to the existence of aisle partition as aisle partition prevents air re-circulation to some extent in comparison with the case where no partition is used. In this case, the inlet average temperature drops from 26 °C to 22.6 °C showing an improvement of 13% at 1898 W/m² power density for aisle partition. The results presented in Figs. 7–11 for aisle partition are in a good agreement with that obtained by Cho and Kim (2011). A similar effect has been found for the average surface temperature of servers (see Figs. 7–11b); for example, the top server's surface temperature is improved by 11% at 1898 W/m² power density. This effect of aisle partition regarding the surface temperature is not significant for bottom servers where the cooling air tem-

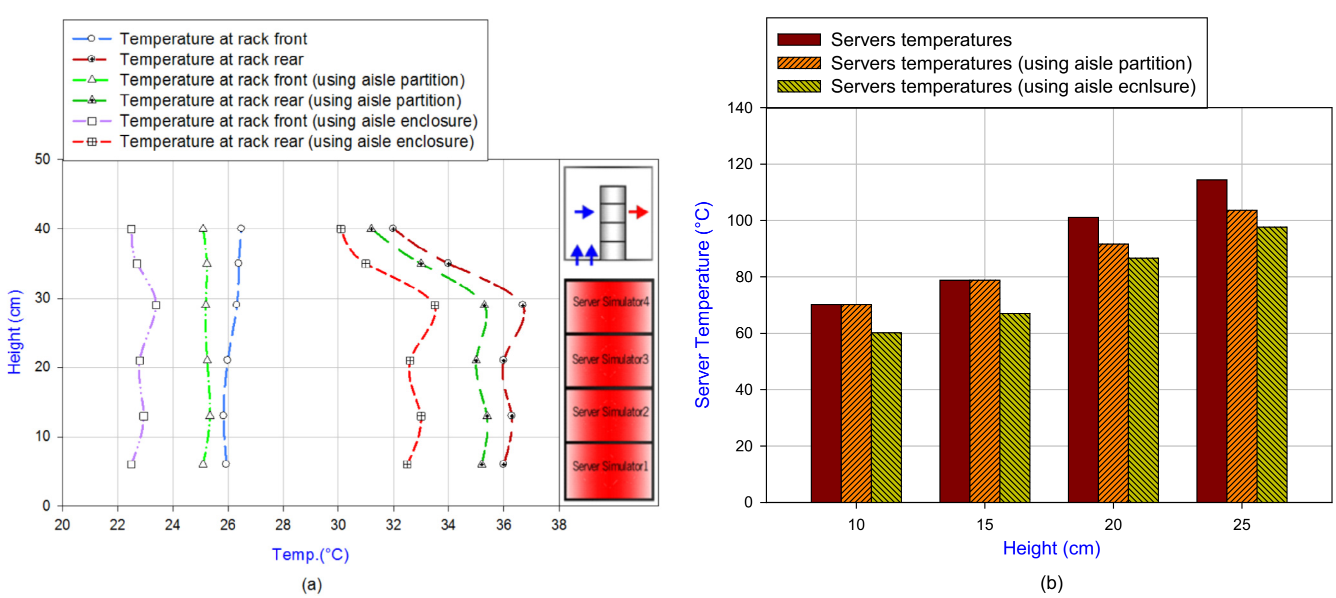


Fig. 8 – Comparison of the different configuration systems at 759 watt/m² power density. (a) Temperature profile at front and rear of rack for and (b) servers temperature distribution.

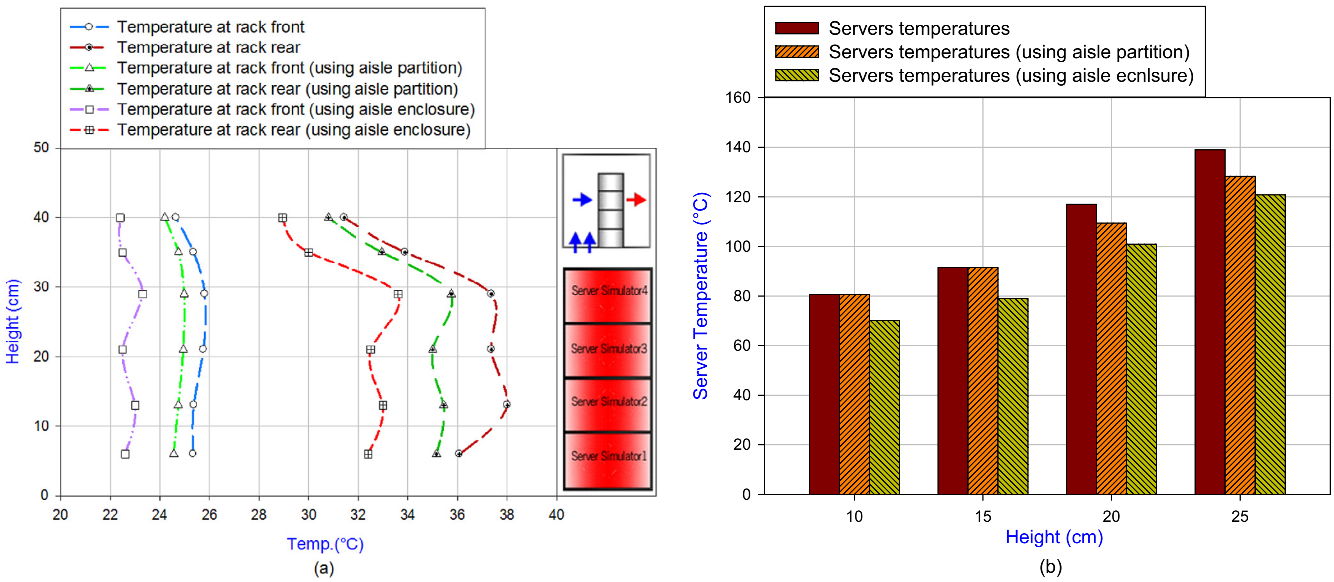


Fig. 9 – Comparison of the different configuration systems at 1139 watt/m² power density. (a) Temperature profile at front and rear of rack for and (b) servers temperature distribution.

perature is already low and the uncontrolled phenomenon has low tendency to occur. But at high altitude, the buoyancy effect of natural convection makes hotter gases at the top leading not only to higher surface temperature of servers at the top, but also increase the tendency for mixing both hot and cold air above the top server.

By installing cold aisle enclosure (cold aisle containment) instead of aisle partitions, the average inlet temperature is additionally improved for all studied range of power densities (see Figs. 7–11a) because the aisle enclosure completely blocks the top recirculation. The inlet average temperature drops from 26 °C to 22.1 °C for 1898 W/m² power density for aisle enclosure. In this case, greater enhancement of servers' cooling is attained for all servers along the height of the rack with overall improvement around 15.5%. The results presented in Figs. 7–11 for aisle enclosure are in a good agreement with that obtained by Gondipalli et al. (2008). Generally, the improving effect in thermal management when aisle enclosure is used primarily comes from the full obstruction of the top circulation.

Fig. 12 shows the air-management and energy performance as expressed by SHI and RHI at different power densities for the studied three configurations. Generally as the power density is increased, there is a remarkable decrease in the values of SHI and a remarkable increase in the values of RHI, which directly reflects the improving of heat transfer and cooling efficiency for all studied air distribution system configurations.

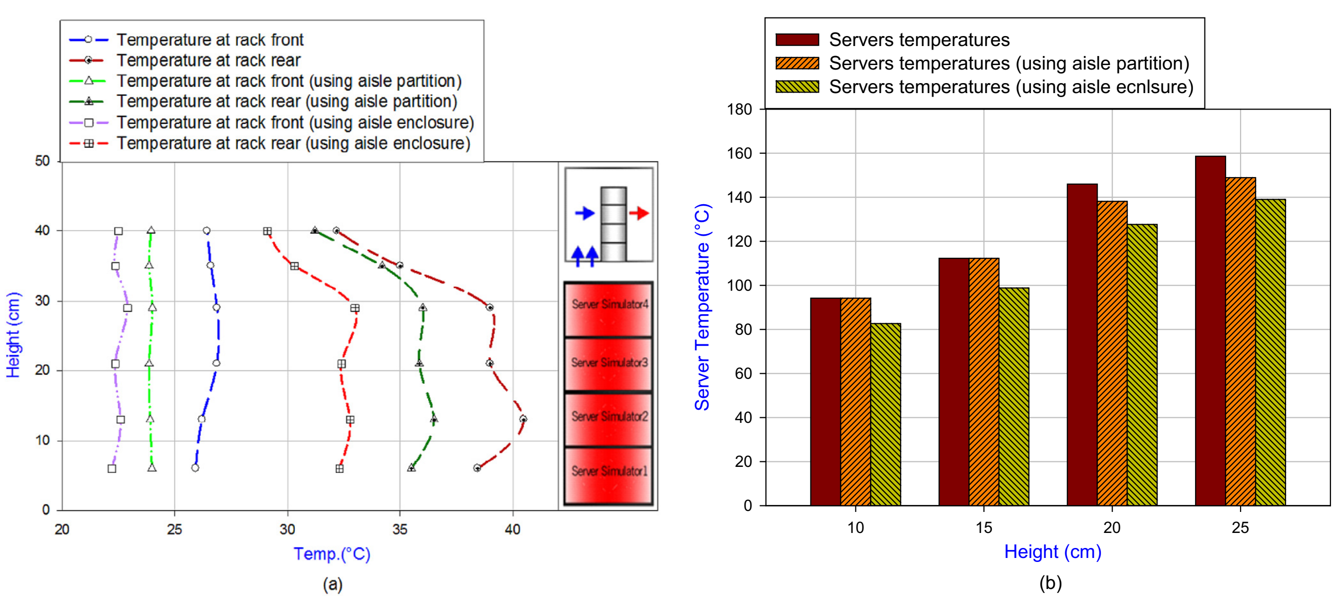


Fig. 10 – Comparison of the different configuration systems at 1518 watt/m² power density. (a) Temperature profile at front and rear of rack for and (b) servers temperature distribution.

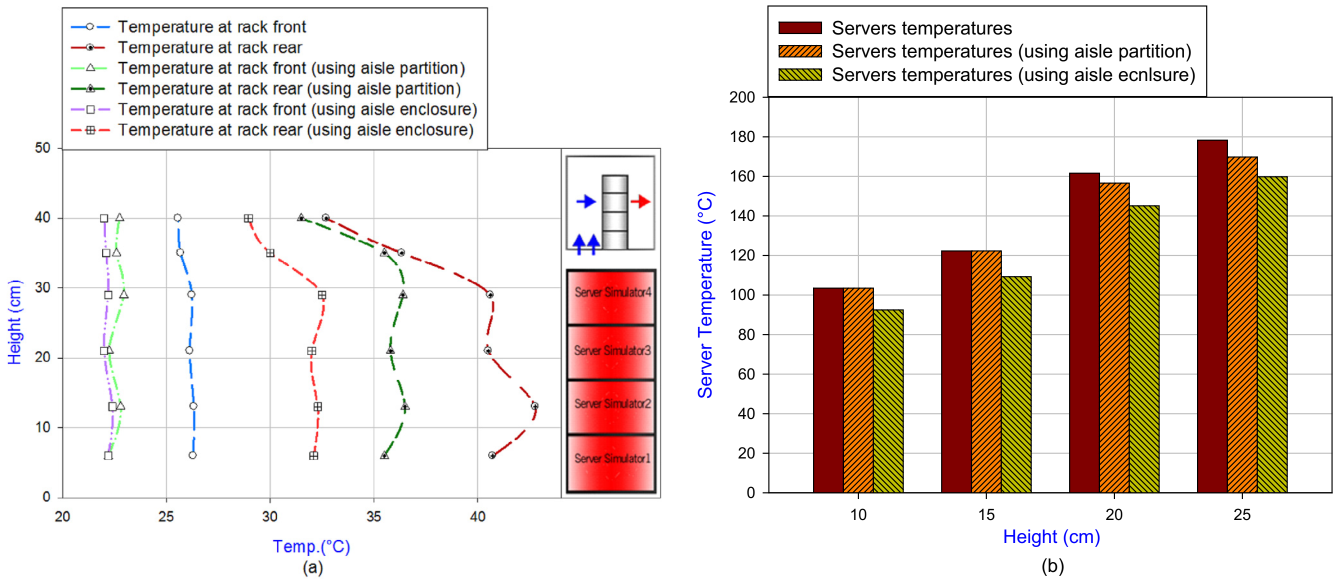


Fig. 11 – Comparison of the different configuration systems at 1898 watt/m² power density. (a) Temperature profile at front and rear of rack for and (b) servers temperature distribution.

A slight improvement in the thermal management efficiency is received when aisle partition is used and this effect is increased with the increase of power density (SHI is improved from 13% to 62%, and RHI is improved from 4% to 7% as power density varied from 379 to 1898 W/m²). On the other hand, the best improvement in cooling efficiency is attained when aisle enclose is used. This enhancement effect due to the use of aisle enclosure is increased (over the case where no enclosure or partition were used) with the increase in power density (SHI is improved by a fixed value of order 70%, and RHI is improved from 8% to 25% as density varied from 379 to 1898 W/m²). Even at the 1898 watt/m² power level, the RHI is elevated approximately to 1 (ideal). Many data centers are running out of capacity due to limited raised-floor heights. Raised-floor heights can be reconfigured with cold-aisle containment to allow very significant heat densities. This should provide a welcome relief for many data centers. Finally, it should be noted that the aisle containment may be more vulnerable to catastrophic cooling outages, and engineered thermal solutions are often required to safeguard the servers.

4. Conclusion

In this paper, the effect of three air distribution systems on rack temperatures profile and thermal management have been studied in detail by using two performance metrics for analyzing air-management systems in data centers. Two performances, the supply heat index (SHI) and the return heat index, were computed experimentally to evaluate the thermal performance of the scaled model data center at five different

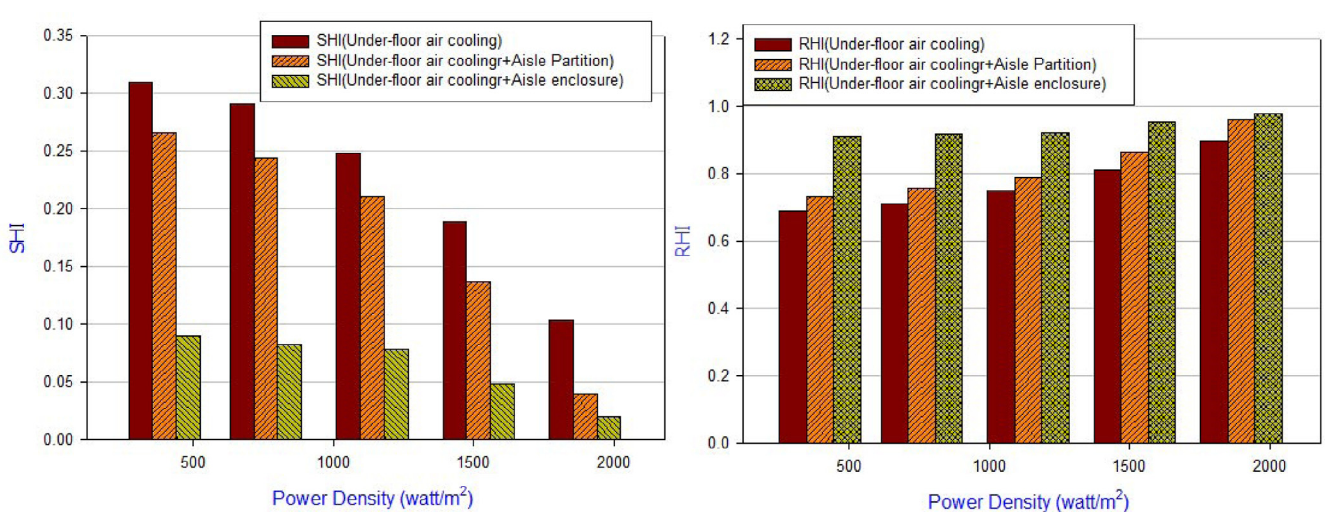


Fig. 12 – Variations of SHI and RHI with power density for the three air distribution system configurations.

power densities and three room architectures. Based on the dimensional analyses, 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 temperature distributions, server's temperatures and supply and return heat indices are measured and used to study, compare and evaluate the performance of the three air distribution system configuration in the scaled data center and its efficiency in simulating actual data centers. Efficient thermal management of data centers can be improved by using proper isolation technique in data center. Both isolation techniques aisle partition and aisle containment reduce the rack inlet temperatures at critical locations (top portions of server racks) significantly. Improvement in thermal management primarily comes by obstructing top circulation. Isolation technique with just aisle partition has marginal merits and may improve the thermal performance of top server racks as aisle partition prevents air re-circulation to some extent in comparison with the existing system. But blocking the cold aisle gives the best thermal performance because the aisle enclosure blocks top recirculation completely.

The results showed that:

- Both isolation techniques aisle partition and aisle containment reduce the rack inlet temperatures at critical locations (top portions of server racks) significantly. Isolation technique with aisle partition and aisle containment can reduce the rack inlet temperature by ~3%–13% for aisle partition and by ~13%–15.5% for aisle containment at different power density.
- Isolation technique with just aisle partition improve the thermal performance of top server racks only.
- Blocking the cold aisle give the best thermal performance because the aisle containment block top recirculation completely.

REFERENCES

Abdelmaksoud, W., Khalifa, H.E., Dang, T., Iyengar, M., Schmidt, R., 2010. Experimental and computational study of perforated floor tile in data centers. In: Proceedings of the Inter Society Conference on Thermal Phenomena (ITherm). Las Vegas, Nevada, USA.

ASHRAE, 2004. TC 9.9, Mission Critical Facilities, Technology Spaces, and Electronic Equipment, Thermal Guidelines for Data Processing Environments. American Society of Heating, Refrigerating and Air-Conditioning Engineers Inc.

ASHRAE, 2008. Environmental Guidelines for Datacom Equipment. ASHRAE, Atlanta, GA, USA.

Awbi, H., Nemri, M., 1990. Scale effect in room airflow studies. Energy Build. 14 (3), 207–210.

Cho, J., Kim, B., 2011. Evaluation of air management system's thermal performance for superior cooling efficiency in high-density data centers. Energy Build. 43, 2145–2155.

Cho, J., Lim, T., Kim, B.S., 2009. Measurements and predictions of the air distribution systems in high compute density (internet) data centers. Energy Build. 41 (10), 1107–1115.

EPA, Report to congress on server and data center energy efficiency, Public Law 109-431, USA, 2007.

Estebe, B.D., Bot, C.L., Mancos, J.N., Arquis, E., 2014. Study the simulation of a temperature adaptive control strategy for an IWSE economizer in a data center. Appl. Energy 134 (1), 45–56.

Fernando, H., Siriwardana, J., Halgamuge, S., 2012. Can a data center heat-flow model be scaled down? In: 2012 IEEE 6th International Conference on Information and Automation for Sustainability (ICIAfS). IEEE, Beijing, pp. 273–278.

Gondipalli, S., Bhopte, S., Sammakia, B., Iyengar, M., Schmidt, R.R., Effect of isolating cold aisles on rack inlet temperature. In: Proceeding of the 11th IEEE ITHERM Conference 2008, Orlando, FL, USA, 2008.

Herrlin, M., Belady, C., Gravity assisted air mixing in data centers and how it affects the rack cooling effectiveness. In: Proceedings of the Inter Society Conference on Thermal Phenomena (ITherm), San Diego, CA, 2006, 30 May–2 June, 2006.

Herrlin, M.K., A new tool for evaluating and designing the thermal environment in telecom central offices. In: Proceedings of Telecommunications Energy Conference 2006; 1–5, 2006.

Karlsson, J.F., Moshfegh, B., 2005. Investigation of indoor climate and power usage in a data center. Energy Build. 37, 1075–1083.

Nada, S.A., Elfeky, K.E., Attia, A.M.A., Alshaer, W.G., 2015. Thermal management of electronic servers under different power conditions. Int. J. Emerg. Trends Electr. Electron. 11 (4), 145–150.

Nakao, M., Hayama, H., Nishioka, M., 1991. Which cooling air supply system is better for a high heat density room: underfloor or overhead. In: Proceedings of International Telecommunications Energy Conference (INTELEC), vol. 12, 4. pp. 393–400.

Patankar, S.V., 2010. Airflow and cooling in a data center. J. Heat Transfer 132 (7), 073001.

Patterson, M.K., 2008. The effect of data center temperature on energy efficiency. In: 11th Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems, 2008. ITHERM 2008. Orlando, FL. ISBN: 978-1-4244-1701-8.

Radmehr, A., Karki, K.C., Patankar, S.V., Analysis of airflow distribution across a front-to-rear server rack. In: Proceedings of the ASME InterPACK '07 Conference, Vancouver, British Columbia, Canada, paper IPACK2007-33574, 2007.

Rasmussen, N., Cooling strategies for ultra-high density racks and blade servers (White Paper), American Power Conversion, Washington, DC.

Saurabh, K.S., Andrew, R.C., Mahmoud, I., Quantitative comparison of air containment systems. In: Proceedings of the Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems (ITherm). San Diego, CA, 2012, 30 May–1 June, 2012.

Sharma, R.K., Bash, C.E., Patel, C.D., Dimensionless parameters for evaluation of thermal design and performance of large scale data centers. In: Proceedings of AIAA2002-3091, American Institute of Aeronautics and Astronautics Conference, 2002.

Shrivastava, S., Sammakia, B., Schmidt, R., Iyengar, M., Comparative analysis of different data center airflow management configurations. In: Proceedings of the ASME/Pacific Rim Technical Conference and Exhibition on Integration and Packaging of MEMS, NEMS, and Electronic Systems: Advances in Electronic Packaging, PART A. 329–336 2005.

Smith, J.F., Abdelmaksoud, W.A., Erden, H.S., Dannenhoffer, J.F., Dang, T.Q., Khalifa, H.E., et al., Design of simulated server racks for data center research. In: Proceedings of ASME InterPACK, Portland, OR, 2011 6–8 July, 2011.

Sorell, V., Escalante, S., Yang, J., 2005. Comparison of overhead and underfloor air delivery systems in a data center environment using CFD modeling. ASHRAE Trans. 111 (2), 756–764.

Vaibhav, K.A., Vikneshan, S., Yogendra, J., 2013. Thermal characteristics of open and contained data center cold aisle. J. Heat Transfer 135, 061901.

VanGilder, J., Schmidt, R., Airflow uniformity through perforated tiles in a raised floor data center. In: Proceedings of the ASME InterPACK ″05 Conference, San Francisco, CA, paper IPACK 2005-73375, 2005.
Vikneshan, S., Vaibhav, K.A., Yogendra, J., Experimental characterization of cold aisle containment for data centers. In: 29th IEEE SEMI-THERM Symposium, Atlanta, GA 30332, USA, 2013.
White, F.M., 2001. Fluid Mechanics, fourth ed. McGraw Hill, New York.