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Effect of data center servers' power density on the decision of using in-row cooling or perimeter cooling

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Abstract Heat propagation and servers' temperature increase inside data centers racks is a vital issue. So, selecting the proper cooling architecture is an important step during the design of data centers. Traditional cooling systems, called perimeter cooling, consume huge amounts of electricity. A more recent effective cooling architecture of data centers, called in-row cooling where the cooling units are inserted between racks, is commercially suggested to reduce cooling power consumption. The current study numerically investigates the performance of in-row cooling architecture compared with the traditional cooling architecture of data centers of different power densities. Temperature distribution and performance parameters indices such as Supply/Return Heat Indices (SHI/RHI), Return Temperature Index (RTI), Index of Mixing (IOM), Energy Utilization Coefficient (ηr), and Beta Index (β) are used to conduct this comparative study. The study was performed at different rack's power densities to determine the overall better cooling architecture for the different power densities. The results show that (i) in-row cooling architecture has better thermal performance as observed in temperature contours (ii) SHI, RHI, RTI, ηr, β and IOM have better values in case of in-row cooling, especially at high power densities, which indicates less hot air recirculation and cold air bypass and completely benefit from cooling capacity of CRACs, (iii) perimeter cooling is suitable for low power densities while in-row cooling can be used for high power densities, and (iv) maximum velocity values are obtained for 10 kW rack's power which dramatically affects the thermal performance of perimeter cooling architecture as indicated by the dramatic decrease of the energy utilization coefficient to 1.4 while it increased for in-row cooling to 1.9.

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1. Introduction

Data centers are computing structures that contain servers or Information Technology (I.T) equipment which store, process, and manage digital data information. Any data center contains five main components, which are (1) switches to allow and regulate the pass of electricity, (2) uninterruptible Power Supply

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Nomenclature

CFD	Computational Fluid Dynamics
CRAC	Computer Perimeter Air Conditioning
CRAH	Computer Perimeter Air Handling
Q	Total power dissipation from data center components (W)
$\dot{m}$	Mass flow rate (kg/s)
T	Temperature (°C)
U	Average velocity (m/s)

SHI	Supply Heat Index
RHI	Return Heat Index
IOM	Index of Mixing
RTI	Return Temperature Index
β	Beta Index
ηr	Energy Utilization Coefficient
I.T.	Information technology

Systems (UPSs) to switch the power supply between batteries and generators, (3) Power Distribution Units (PDUs) to receive power from UPS and distribute it to the racks, (4) I.T. equipment including servers and racks that store and process the data, and (5) cooling equipment including Computer Room Air Conditioning (CRAC) units.

Data centers are considered one of the major sources that consume electrical power worldwide. Fig. 1 shows the rapid increase in USA data centers power consumption over the past twenty years. The figure shows that, data centers consumption was about 70 billion kilowatt-hours in 2013, and in 2020 it reached to the double (140 billion kilowatt-hours) [1]. The cooling power consumptions is shared between the different cooling equipment including computer room air conditioning (CRAC) units, chillers, cooling towers and condensing units. Díaz et al. [2] performed a thermodynamic analysis that measures the power consumption percent of each component of the cooling system. They reported that about 38% of total input power to the data center is only used for cooling. They found that the chiller represents the highest power consumption component in case of high-density racks. While for low-density racks, the cooling tower consumes most of the input power.

Data centers must be constructed such that enough cooling air is provided to the racks entrance to absorb the servers' generated heat and avoid servers overheating. As data centers servers normally operate 24 h a day, the cooling system should perform optimally to avoid downtime and increase servers' life. Excessive unremoved servers' heat leads to slow down and failure of servers. The design of any cooling system of a data center must satisfy two main functions; the first one is to assure that the capacity of the cooling system is sufficient for removing the heat generated in the I.T. equipment and the second one is to distribute the CRAC cold air to reach and enters the racks for removing their heat generation. The first function is achieved by proper calculation of the required cooling capacity, and it is easy to be assured, but the second function which is related to the proper distribution of the cold air inside the data center is the most important issue. The main reason of the un-efficiency of the cooling system of a data center is normally related to the method of distributing the cold air in the data center room and how long the path between CRACs units and data center racks.

Conventional methods used for data centers cooling depend on using cold air as a primary cooling medium. The racks are positioned on the plenum of the raised floor, and there is a perforated tile in front of each rack from which the cold air is supplied. The computer room air conditioning (CRAC) units are located on the periphery of data center room perimeter. The fans of the CRAC units draw the hot air from the room and cool it and then they push the cold air to the racks through underfloor plenum until it reaches the perforated tile of the cold aisle. The floor is raised to specific height to form the cold air plenum and it is accompanied by the per-

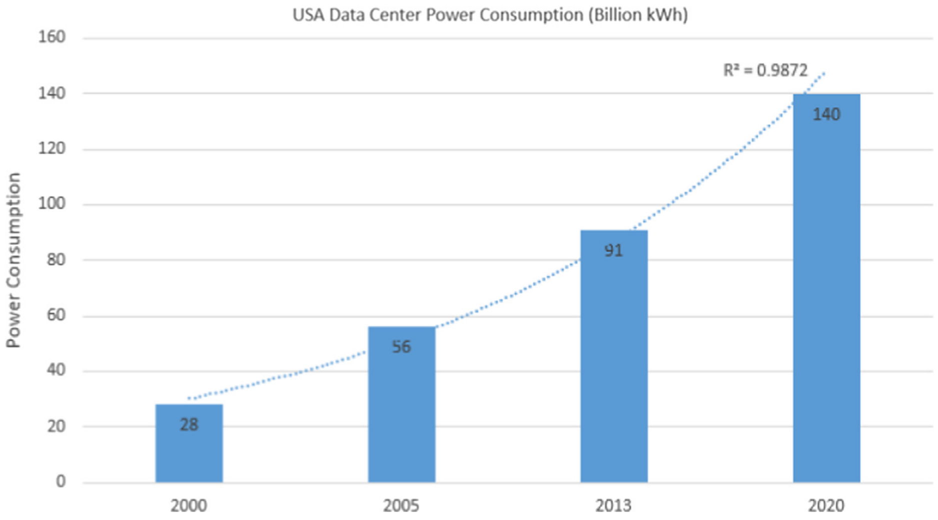
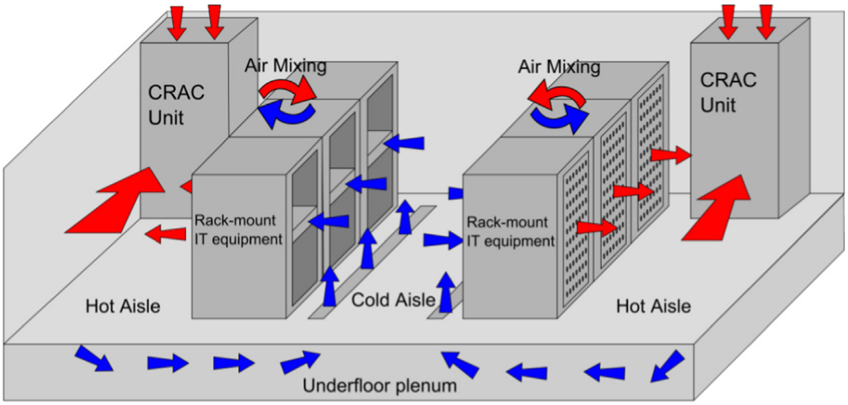


Fig. 1 USA data center power consumption [1]

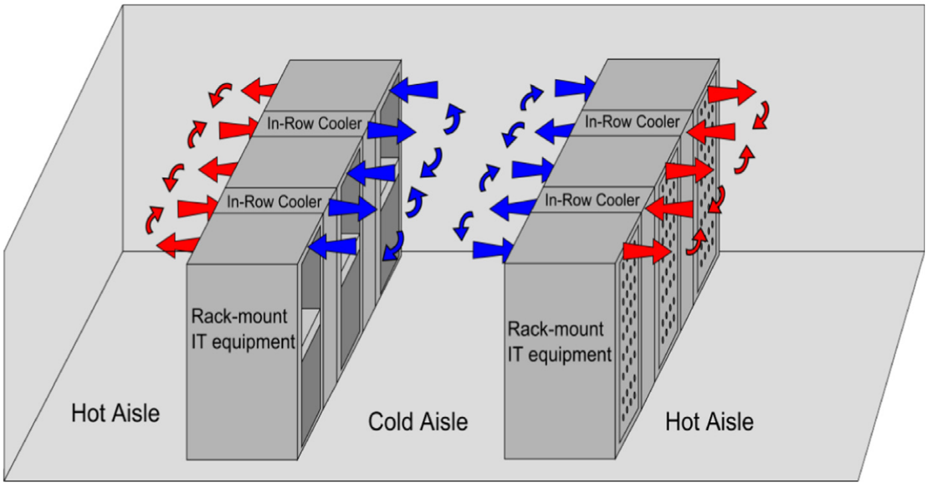
forated tiles to discharge the cold air in front of the racks to go from the bottom of the racks towards the top. The hot air that goes out form racks enters the CRAC again to be cooled as shown in Fig. 2-a. This traditional architecture which, called raised floor or perimeter cooling, has many disadvantages such as the air pressure drop occurred in the plenum due to the blockages of cables and the heat losses in this long path. The second main source of losses for this system is the air mixing between cold and hot air that occurs due to the hot air recirculation and cold air bypass. So it was necessary to look for shorter air paths' cooling architecture such as in-row cooling, in which the cooling units are inserted between the racks as shown in Fig. 2-b.

In-Row cooling has many advantages over the traditional cooling architectures (i) the airflow has to travel small distances and so it is less probable to recirculate, (ii) as air flow expense shorter paths, smaller fans power is required to push the air from the CRACs to Racks, which leads to energy savings and reduction of costs, and (iii) hot air recirculation and cold air bypass don't have a chance to occur in this architecture. The major benefit of this system is the flexibility of redesign the data center. Paul Lin and Victor Avelar [3] reported about the idea of in-row cooling and how it is suitable for balancing the cooling capacity with the heat loads. They also noticed the necessity of cooling redundancy which means it is important to add a redundant cooling unit in every data center pod. Server Racks Australia (SRA) [4] encouraged the in-row architectures for in-row cooling data centers as they help in reducing air mixing and consume less time for the construction of the data center. Dunlap and Rasmussen [5] conducted a comparison between perimeter, row, and rack-based cooling based on the commercial use and they found that row-based cooling is the most flexible and also recommended it to avoid row-end locations. Cho et al. [6] performed an experimental study of replacing a perimeter-based cooling system with row-based cooling one in Korea. The study used six performance indices to compare between the two systems. The results showed an improvement of SHI and RHI by 37.1% and 20%, respectively. It was also concluded that, in-row cooling requires lower flow rates than perimeter cooling and the required supply air temperature was higher than that required in case of perimeter cooling. It was also concluded that in-row cooling architectures reduced the cooling power by about 29% over perimeter cooling architecture.

Nada et al. [7] studied the effect of using different configurations of CRACs on the cooling performance and they found that using distributed layout of CRACs gives better thermal performance than using concentrated CRACs. Also, Nada et al. [8] numerically studied the effect of cooling units' layout on the thermal management of data centers. The study com-



a- Traditional raised floor cooling system



b- In-row cooling Architecture

Fig. 2 Different cooling architectures of data centers [4] pared between locating the CRAC units in line with the racks row and locating them perpendicular to the racks row. The results proved that locating the CRACs in perpendicular arrangement enhances the uniformity of airflow through the perforated tiles along with the racks and also improves the overall thermal performance. In another numerical study, Nada et al. [9] studied the effect of changing the spaces between CRACs and the Racks. They found that, with increasing the distance between CRACs and the cold aisle, the flow rates of perforated tiles decreased, which in turn adversely affects the performance parameters indices as the increase of SHI and the decrease of RHI. Bhopte et al. [10] studied the effect of under-floor blockages used in traditional cooling architectures on the performance of data centers. They mainly found that the chiller pipes in raised floor adversely affect the data center performance and cause high air pressure losses. Macedo et al. [11] studied numerically the air flow and thermal performance in their case study conducted on real data center to improve sustainability. They assured that inappropriate CRAC positioning causes ineffective refrigeration of the data center which leads to existing of hot spots. Sheth and Saha [12] recently conducted a numerical study on thermal management of data center using porous medium approach for servers simulation. They concluded that the porous medium approach is effective for simulating servers and can be used for designing the data centers. Nada et al. [13] also conducted numerical research studying the effect of plenum depths on airflow thermal management inside the data centers. The results showed that increasing the plenum height increases the uniformity of the air and the optimum plenum depth is 60 cm. In another experimental work, Nada et al. [14] conducted an experimental investigation of high-power density data centers using a scaled physical model to study the effect of adding aisle partition and aisle containment systems. They found that both aisle partition and aisle containment reduces the rack inlet temperature; the aisle partition reduces it by 3–13%, while the aisle containment reduces it by 13–15.5%. Nada et al. [15] also experimentally studied the effect of using different perforation ratios for the raised floor perforated tiles and reported that using 25% perforation ratio gives the best performance and the optimum temperature distribution; also they found that top of the racks suffers from the low thermal performance. Later, Nada et al. [16] computationally analyzed the effect of the thermal environment of a large space cooled through raised floor system. They found that controlling the openings under the perforated tiles using guide vanes for the air improves thermal performance. Moazamigoodarzi et al. [17] studied the influence of cooling architecture on the data center performance by comparing the amount of airflow rate required by each architecture at fixed supply air temperature and the required supply air temperature at different airflow rates. Later, Moazamigoodarzi et al. [18] used machine learning principle to model the temperature distribution in I.T. The results showed that increasing the airflow rate by 10% increases the cooling power consumption by 7%. They also recommended increasing utilization of all servers rather than increasing the number of servers and not using its full load. Gupta et al. [19] performed a comparison study between different cooling architectures depending on the value of exergy destruction of each case and the results showed that in-row cooling achieves lower exergy destruction than perimeter cooling architecture. Chu et al. [20] performed a review study of airflow management in data centers; they classified the airflow paths to long and short. They reported that the long paths technologies such as perimeter cooling suffer from hot air recirculation, cold air bypass, and leakages, while the short paths of airflow help in the reduction of losses.

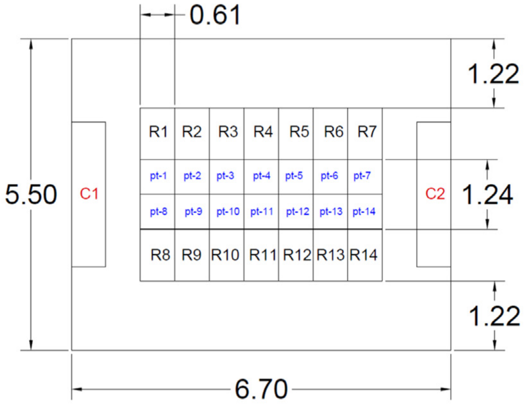
The above literature review reveals that there a gap in the research area comparing between the raised floor and the in-row cooling architectures of data centers; where all the conducted studies did the comparison in general. A comparative studies for different data centers powers densities is not available in the literature. This study is needed to know the preferred system for a specific power density of the data center. The aim of the present research is to investigate and evaluate the performance of the in-row cooling architectures of data centers against the traditional cooling architecture for the same data center physical model and the same boundary and operating conditions at a wide range of power density. Different performance indices of data centers were used in the present study to evaluate and compare the thermal performance of in row data center with traditional cooling architecture from different aspects. The study also aims to (i) compare the temperature distribution and the velocity vectors of air flow around the data centers racks/servers between in-row and perimeter cooling architectures, (ii) use the different performance indices to evaluate the performance of the in-row cooling architectures against the traditional cooling architectures.

2. Methodology

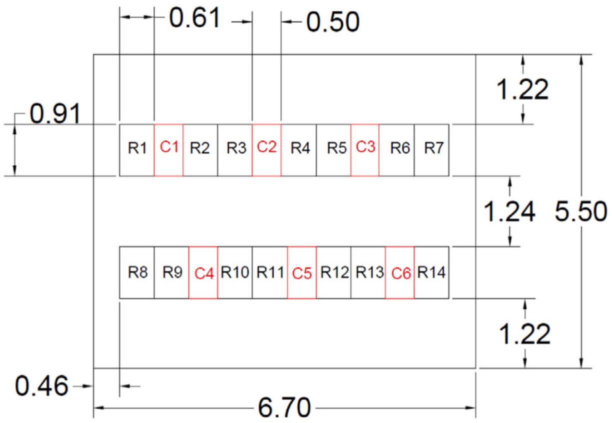
Computational Fluid Dynamics (CFD) proved a success in simulating the thermal performance of data centers as the experimental work requires a lot of time and costs. Using CFD to simulate the data center requires many steps; the first step is to build the computational domain that contains all the components of the physical model; CFD interests in the space between solid objects, where the flow moves. The second step is to divide the computational domain into small cells where the governing equations are solved; it is important to get a well-structured mesh for reducing the solution time. Then, the governing equations are solved at each cell using an iterative solution due to the inexistence or complexity of exact solution. To get meaningful results, the residual that arises from cumulative error of each equation must be within an acceptable value which is called residual error.

2.1. Physical model

The present study contains two configurations of perimeter and in-row cooling. Each of them consists of fourteen racks with the same room dimensions of (6.7 × 5.5 × 3.0) m. In-row architecture contains six CRACs placed vertically between the racks. While perimeter cooling architecture contains two CRACs distributed on the sides of the room. Both of the models has the same total cooling capacities. For the sake of comparison, the racks, CRACs numbers and the room dimensions of the present study were selected to be the same of the perimeter cooling architecture. Also, the heat loads or racks power density, the amount of cold air flow rate, and the supply air temperature of the present study are selected to be the same as the perimeter cooling architecture to perform an accurate comparison. Fig. 3 shows a plan view for the perimeter cooling



(a) Perimeter cooling model



(b) In-row cooling

Fig. 3 Plan views for the CFD model (All dimensions in m).

and in-Row cooling simulated models used in the present study. In perimeter cooling (Fig. 3.a) there are two cooling units supply cold air to the raised floor plenum and this cold air is discharged in the cold aisles through the perforated tiles. For in-row cooling (Fig. 3.b) there are six cooling units that were inserted between racks in a staggered configuration to achieve the requirements of the In-Row Cooling principle. Each of the fourteen racks of the data center has dimensions of (0.91 × 0.61 × 2) m, inserted in two rows.

The required mass flow rate of the air can be calculated from the following formula

$$Q = \dot{m}c_P(T_R - T_S) \quad (1)$$

where Q is the amount of the heat removed from the air, $\dot{m}$is the mass flow rate of the air, $C_{.P.}$ is the specific heat of air, $T_{.R.}$ is the return temperature to CRAC and $T_{.S.}$ is the Supply temperature from CRAC. The difference between return and supply temperatures can be considered ~10℃ [21]. The air mass flow rate changes according to rack heat generated. Table 1 represents data center boundary conditions and the required mass flow rate at each rack's power and Table 2 gives the characteristics of the air conditioning units for the different racks power densities needed to satisfy the boundary conditions given in Table 1.

As given in Table 1, the supply air flow rates and the cooling capacity varies according to the server power density and accordingly the CRAC unit size and specification should be selected according to each rack power densities to satisfy these boundary conditions.

Table 1 Boundary conditions for both CFD models.

DC Boundary Conditions	Perimeter cooling	In-row cooling
No. of Racks	**14**	**14**
No. of CRACs	**2**	**6**
Supply Air temperature (°C)	**17**	**17**
Power per Rack (kW)	**3.5–10**	**3.5–10**
Mass flow rate per CRAC (kg/s)	**2.46–6.96**	**0.82–2.32**

2.2. Grid independency study and model validation

Since the grid generation step is very important as the proper structured mesh makes the solution convergence faster and easier. The proper fine mesh for the domain (see Fig. 4) with the optimum number of cells has to be found in order to solve the problem with the best accurate results and consumes the minimum time. A mesh independency study with six different sizes and numbers of cells beginning with 600,000 cells and ending with 3,000,000 cells were considered in this study. In each case, four parameters were calculated (SHI- RHI- Beta Index- Energy Utilization Coefficient) for each of the fourteen racks to get the optimum number of cells that will be used for further calculations of this study.

Table 3 and Fig. 5 show the variation of the calculated parameters with the different number of generated cells for in-row cooling architectures as a case study. The figure and table indicate that the optimum number of cells to be used is 2,500,000 cells. At this number, the values of each (SHI-RHI- Beta Index- Energy Utilization Coefficient) are almost become fixed, and any further increase of the number of cells will lead to a very slight change of the indices. Accordingly, the calculations based on this number will be accurate enough and there will be no need for increasing the number of cells, for avoiding the long solution time.

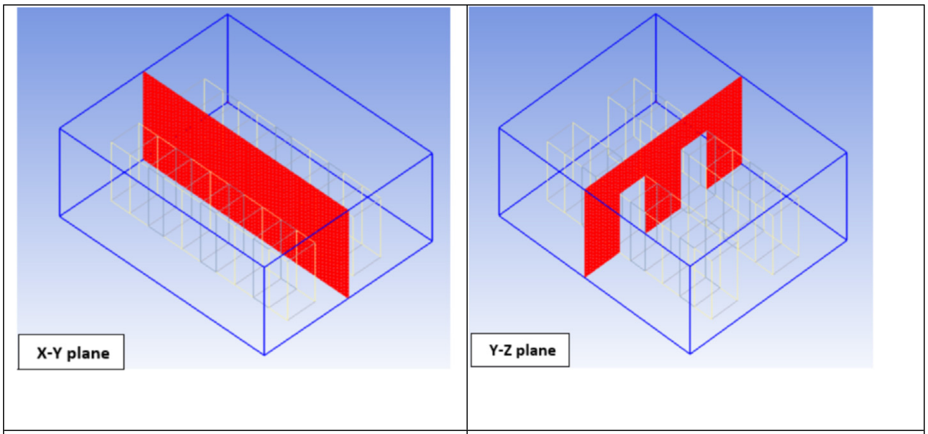
For model validation, kindly refer to Abbas et al. [22] where the present used model and code were experimentally validated.

3. Numerical solution techniques

Computational Fluid Dynamics (CFD) is becoming a powerful tool in designing the data centers; this is due to the high cost of performing experiments on data center. By using the CFD, airflow distribution and its thermal profile are simulated in the data center, in addition to identifying the performance of the cooling system. ANSYS-IcePak software which is specialized in cooling of electronic devices is used in the present study to simulate the data center. Solving the equations (Conservation of mass – Momentum- Energy – K- epsilon) for each cell, using finite volume method and ANSYS-Fluent as a solver, is firstly conducted by the software. Then the post-processing step was conducted where the results are presented using graphic tools such as temperature contours and velocity vectors in addition to calculating the performance parameters indices.

Table 2 Characteristics of Air Conditioning units for the different Racks power densities.

Rack Power density (kW)	Characteristics of Air Conditioning units			
	Air Flow Rate (kg/s)		Cooling Capacity (kW)	
	Perimeter cooling	In-row cooling	Perimeter cooling	In-row cooling
3.5	**2.46**	**0.818**	**24.5**	**8.17**
5	**3.51**	**1.168**	**35**	**11.67**
7	**4.92**	**1.635**	**49**	**16.33**
10	**7.13**	**2.345**	**70**	**23.33**



(a) x-y section for the mesh

(b) y-z section for the mesh

Fig. 4 Structured mesh of the domain.

Table 3 Grid independence study for in-row cooling architectures.

Performance parameter	Number of grid cells					
	6000,000	1,000,000	1,500,000	2,000,000	2,500,000	3,000,000
SHI	0.18	0.19	0.2	0.21	0.22	0.22
RHI	0.82	0.81	0.8	0.79	0.78	0.78
β	0.15	0.16	0.17	0.18	0.19	0.19
ηr	1.81	1.80	1.79	1.78	1.78	1.78

3.1. Governing equations

The basic equations that the fluid dynamics depend on are; mass conservation, momentum conservation, and energy conservation. Continuity and momentum equations are almost being applied in most of the problems and the energy equation is also applied in the present case as there is a variation in temperatures, or there is a heat source. Air is regarded as an incompressible fluid, and the flow is turbulent. Also the effects of radiation were ignored. For the finite volume method, the following differential equations are integrated and converted to the algebraic form.

- **Mass Conservation:**

If the Mass Conservation law is applied to a fluid passing through a fixed control Volume, it yields the following equation:

$$\frac{\partial \rho}{\partial t} + \mathrm{div}(\rho \mathbf{u}) = 0 \tag{2}$$

Assuming the density of the fluid element is constant for incompressible flow, Eq. (2) is reduced to:

$$\mathrm{div}\mathbf{V} = 0,\ \ \mathrm{alternativewaytowritethis}\ \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \tag{3}$$

A suitable approximation of incompressibility assumption is valid in the present work where the steady airflow speed is less than 100 m/s or Mach number is less than 0.3.

- **Momentum Conservation:**

Applying Newton’s second law on a fluid passing through a fixed control volume, it yields the following momentum equation:

$$\rho \frac{\partial \vec{u}}{\partial t} + \rho \vec{u} \cdot \vec{\nabla} \vec{u} = -\vec{\nabla} P + \vec{\nabla} \cdot \tau + (\rho - \rho_\infty) g \tag{4}$$

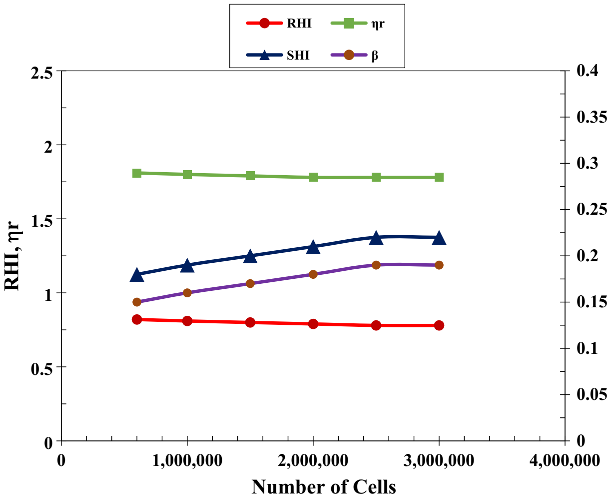


Fig. 5 Grid independency study for in-row cooling architectures.

Which can be written in a three dimensional form as follows:

$$x-\text{momentum}: \frac{\partial(\rho u)}{\partial t}+\text{div}(\rho u\mathbf{u}) = -\frac{\partial p}{\partial x}+\text{div}(\mu\ \text{grad}\ u)+S_{Mx} \tag{5}$$

$$y-\text{momentum}: \frac{\partial(\rho v)}{\partial t}+\text{div}(\rho v\mathbf{u}) = -\frac{\partial p}{\partial y}+\text{div}(\mu\ \text{grad}\ v)+S_{My} \tag{6}$$

$$z-\text{momentum}: \frac{\partial(\rho w)}{\partial t}+\text{div}(\rho w\mathbf{u}) = -\frac{\partial p}{\partial z}+\text{div}(\mu\text{grad}w)+S_{Mz} \tag{7}$$

- **Energy Conservation:**

Applying the first law of thermodynamics to a fluid passing through a fixed control volume, it yields the following equation for energy:

$$\rho\frac{DE}{Dt} = -\text{div}(p\mathbf{u})+[\frac{\partial(u\tau_{xx})}{\partial x}+\frac{\partial(u\tau_{yx})}{\partial y}+\frac{\partial(u\tau_{zx})}{\partial z}+\frac{\partial(v\tau_{xy})}{\partial x}+\frac{\partial(v\tau_{yy})}{\partial y}+\frac{\partial(v\tau_{zy})}{\partial z}+\frac{\partial(w\tau_{xz})}{\partial x}+\frac{\partial(w\tau_{yz})}{\partial y}+\frac{\partial(w\tau_{zz})}{\partial z}]+\text{div}(k\text{grad}T)+S_E \tag{8}$$

Noting that $S_{E.}$ is a source term that may include sources such as (potential energy, sources due to heat production from Chemical reactions, etc.).

- **k-ε turbulence model**

The k-ε turbulent had proved its agreement with experimental results for such problems [23]. This model is used for solving Reynolds' stress in the turbulence momentum equations. The k transport equation was obtained from an exact equation, while the ε transport equation was conducted using physical assumptions. The k-ε equations used for this model are:

$$\frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_i}[(\mu+\frac{\mu_t}{\sigma_k})\frac{\partial k}{\partial x_j}]+G_v+G_b-\rho_\varepsilon \tag{9}$$

$$\frac{\partial}{\partial x_i}(\rho\varepsilon u_i) = \frac{\partial}{\partial x_i}[(\mu+\frac{\mu_t}{\sigma_\varepsilon})\frac{\partial\varepsilon}{\partial x_j}]+C_{1\varepsilon}\frac{\varepsilon}{k}(G_v+C_{3\varepsilon}G_b)-C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} \tag{10}$$

3.2. Data center performance indices

For evaluating the thermal performance of a data center, several parameters are used to evaluate the temperature distribution. Most of these parameters concern with supply and return temperature of CRAC, rack inlet temperature, and rack outlet temperature. The first parameter used is the supply heat index (SHI), which is a dimensionless parameter introduced by Sharma [24] and is defined as the ratio of heat gained by the air in the cold aisle before entering the racks and the total heat gained by the air after leaving the racks. The SHI can be written as a function of rack inlet & outlet temperatures and CRAC outlet temperature as follows:

$$SHI = \left\{\frac{\sum_j\sum_i((T^r_{in})i,j-T_{ref})}{\sum_j\sum_i((T^r_{out})i,j-T_{ref})}\right\} \tag{11}$$

where T_{ref} is the outlet air temperature of CRAC, T_{in} is the average intake temperature of the rack and T_{out} is the average outlet temperature of the rack. A high value of SHI indicates that the inlet temperature of racks is high, which is caused by hot air recirculation and a lower value for SHI indicates a better thermal management.

The second parameter is the Return Heat Index (RHI) which is the complement of SHI; it can be written as:

$$\mathbf{SHI}+\mathbf{RHI}=1 \tag{12}$$

The higher the values of RHI, the better. This indicates that most of that heat is extracted by the Racks.

The third parameter is called Return Temperature Index (RTI) that is conducted by Herrlin [25]. This parameter measures the thermal performance for the air management system by showing the level of cold air bypass and hot air recirculation inside the data center. RTI can be defined as the ratio of temperature difference through the CRAC over the temperature difference through the rack and can be written as follows:

$$RTI = \left[\frac{T_{return}-T_{supply}}{\Delta T_{equipment}}\right]\times 100\% \tag{13}$$

where T supply is the supply air temperature from the CRAC and T $_{return}$ is the return air temperatures to the CRAC, respectively. $\Delta T_{eqipment}$ is the difference between intake and exhaust rack temperatures. The best value of RTI is 100%, which means all the supply air is drawn by the rack while the value over 100% means hot air recirculation occurs, and the value lower than 100% means cold air bypass occurs.

To obtain the performance of airflow pattern; the beta index (β) which was Produced by Schmidt [26] is recommended and it can be defined as:

$$\beta = \frac{T_{\mathrm{in}} - T_{\mathrm{ref}}}{T_{\mathrm{out}} - T_{\mathrm{in}}} \tag{14}$$

where T_{in} is the average inlet temperature of the rack, T_{out} is the average outlet temperature of the rack and T_{ref} is the airflow outlet temperature from the CRAC. The range of β values is between 0 and 1. If the value of β is 0, this means no air recirculation, while if the value of β is above 1, this indicates self-heating.

The energy utilization coefficient ηr [27] is used for calculating the thermal efficiency of airflow in the data center; it can be defined as:

$$\eta_r = \frac{\mathrm{T}_{\mathrm{Out}} - \mathrm{T}_{\mathrm{ref}}}{\frac{\mathrm{T}_{\mathrm{out}}+\mathrm{T}_{\mathrm{in}}}{2} - \mathrm{T}_{\mathrm{ref}}} \tag{15}$$

where T_{out} is the average outlet air temperature, T_{in} is the average inlet air temperature and T_{ref} is the outlet air temperature of the CRAC. This parameter is used as a reference to measure the percent of mixing between hot and cold air. The larger the value of energy utilization coefficient, the better the cooling system performance.

Index of Mixing IOM [28] is used to indicate the thermal performance of the data center and it can be defined as:

$$\mathrm{IOM} = \frac{T_{i,max} - T_{i,min}}{T_o - T_i} \tag{16}$$

where $T_{i,max}$ is the maximum intake air temperature of the rack, $T_{i,min}$ is the minimum intake air temperature of the rack and To is the average outlet air temperature of the rack and T_i is the average intake air temperature of the rack. If the value of IOM is more than 1, this indicates, there is a self-loop in the exhaust air area. Lower values of IOM indicate a better thermal environment.

These performance indices parameters are used in the present study in evaluating and comparing the thermal performance of the data centers for different cooling architectures where each of them refers to a specific phenomenon. Also, the temperature contours that show all temperature values inside data center are presented to indicate the hot spots locations, if any.

4. Results and discussion

Both of perimeter and in-row cooling architectures were numerically modeled in the present study using ANSYS. The results were analyzed, evaluated and compared using Six performance parameters indices (SHI- RHI- RTI- β index- Energy utilization coefficient ηr – IOM). In addition to the temperature contours and velocity vectors that show the variation in air temperature and velocity values inside the data center were presented in each case. The tests were performed at different racks power densities of 3.5, 5, 7 and 10 kW for each rack.

4.1. Temperature contours and velocity vectors

Fig. 6 shows temperature contours of the racks for in-row and perimeter cooling architectures, respectively, at different racks' power densities of 3.5, 5, 7 and 10 kW per rack. The figure shows the homogeneity of temperature distribution for in-row cooling compared to the perimeter cooling whatever the value of the rack power. In the case of perimeter cooling, the figure shows that the air distribution is less homogenous with the possibility of appearing hot spots at different locations of the racks servers which leads to higher values of air temperature that may exceed the allowable limits. These hot spots were noticed at the top servers in the case of 3.5 kW, at the lower servers in case of 5 kW and in all the servers in case of 7 and 10 kW. This may be attributed to that at low power density the air flow exits the perforated tiles is at low flow rate and its velocity and momentum are not high enough to reach the air to the top servers. In contrast, for in-row cooling, the CRACs are inserted between racks and the cold air is uniformly distributed along the rack's height causing uniform cooling and uniform temperature distributions along all the servers of the racks. Increasing the power density of the racks to 5 kW is accompanied with increasing the mass flow rate of the cold air in order to overcome the added heating load. Increasing the air flow rate increases air velocity and it was noticed that this high air velocity in the case of perimeter cooling moves the air up with high momentum and doesn't give the air a chance to be in contact with the bottom rack servers to be cooled completely. This also doesn't occur in case of in-row cooling as the CRACs are inserted between racks and the air directly enters the racks servers with uniform distribution after leaving the cooling units. Increasing the power density from 7 kW to 10 kW causes more increase of the air flow rates and air velocity making the air moves with high momentum in case of perimeter cooling. This high momentum adversely affects the air to be in good contact with the racks causing the increase of the possibility of cold air circulations and high temperature levels. In contrast to perimeter cooling, in-row cooling hadn't been affected by increasing the air flow rate as occurred in-perimeter cooling. Despite increasing the rack power density with in-row cooling, there is always homogeneity of temperature distribution. The results of the effects of the server power density on the thermal management of data centers in case of using raised floor cooling agree well with previous results [9,15] where both of them showed the increase of the possibility of cold air circulations and high server temperature levels with increasing power densities.

Using velocity vectors, the airflow paths can be indicated everywhere inside the data centre. Fig. 7 represents the velocity vectors at vertical plane for the racks. These vectors were produced for in-row and perimeter cooling configurations. The Figure confirms the homogeneity of air distribution for in-row cooling architecture compared with perimeter cooling architecture, as there is neither cold air bypass nor hot air recirculation. Referring to boundary conditions listed in table 1; with increasing power density, the required mass flow rate for supplied cold air increases. So the velocity value increase as long as CRACs' outlet areas are the same. As shown in Fig. 7, the maximum velocity vectors were obtained for 10 kW rack's power and the minimum for 3.5 kW. In-row cooling architecture has lower indicated values, as the total supplied mass flow rate is divided over six cooling units. While it is divided over two cooling units in case of perimeter cooling.

4.2. Cooling system performance indices

In the present study, the performance of the data center's cooling systems is measured, evaluated using six performance indices that are widely used in the literature of the data centers

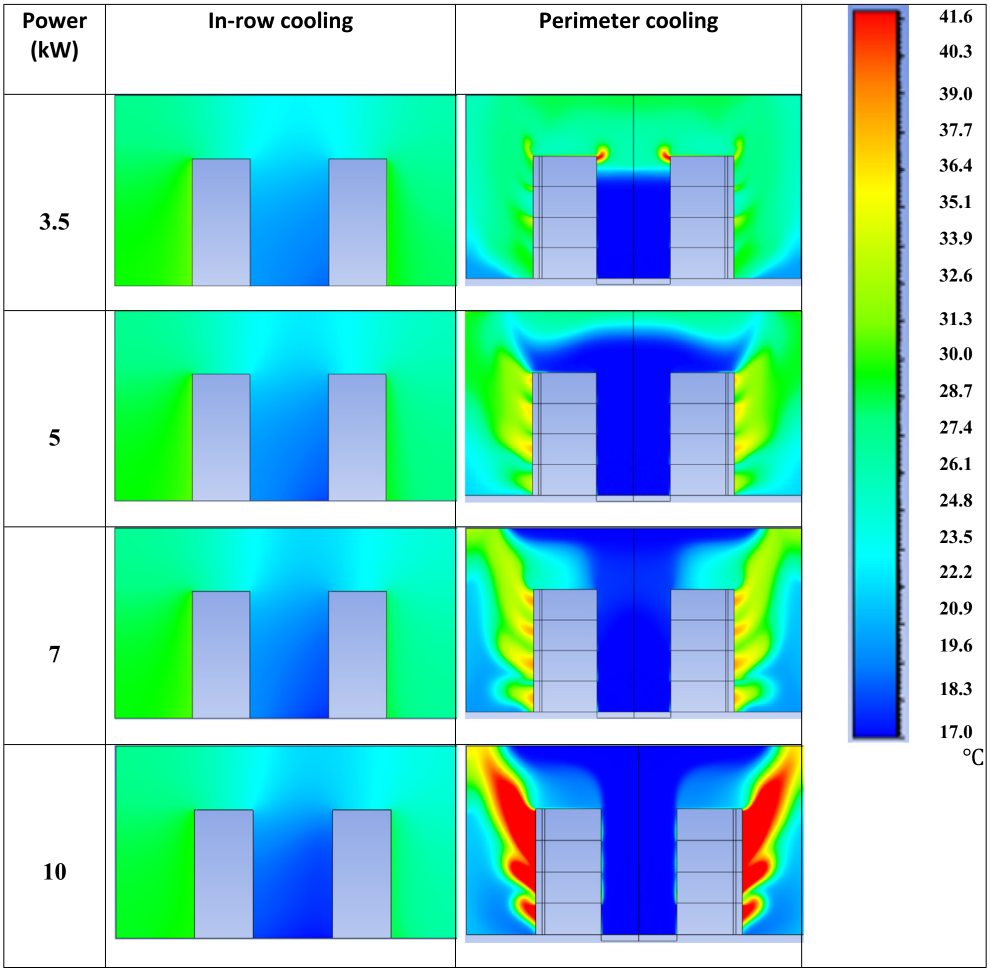


Fig. 6 Comparison of temperature contours at vertical plans between in-row and perimeter cooling architectures.

works. Each index is used to indicate a certain phenomenon that affects the data center performance. In the following sections these data centers' performance indices of perimeter and In-row cooling architectures are studied, evaluated and compared for different power densities.

4.2.1. SHI and RHI of perimeter and In-row cooling architectures.

Figs. 8 and 9 compare the SHI and RHI for perimeter and In-row cooling architectures at different racks' power densities. Fig. 8 shows that at any racks' power densities the SHI values of the in-row cooling architecture are smaller than those of the perimeter cooling architecture and are very close to the required optimum value. This means less heat gained by the cooling air in the cold-aisle before entering the racks for In-row cooling compared to perimeter cooling. Less values of SHI leads to the reduction of the required cooling capacity from cooling units. Smaller values of SHI in case of in-row cooling architectures comparing to those of perimeter cooling architectures can be attributed to (i) the short path of the cooling between cooling units' exits and the racks' inlet compared with the long path of the perimeter cooling architecture, and (b) the high possibilities of existence hot air recirculation in case of perimeter cooling which leads to more heat gain by the cooling air before entering the racks.

Fig. 8 also shows that (i) due to increasing the power density from 3.5 kW to 5 kW per rack, SHI had been reduced from 0.21 to 0.14 in case of perimeter cooling, and from 0.15 to 0.10 in case of in-row cooling and this is a good result for both systems, and (ii) increasing the power density from 5 kW to 10 kW per rack adversely affect the SHI in case of perimeter cooling, while there is a slight increase in case of in-row cooling. This can be investigated to that at low and high power densities, i.e. low and high air flow rates, more heat is expected to be gained by the cold air before entering the racks due to the hot environment and spots and the hot air circulation which is expected to exist at low and high air flow rates, respectively. Fig. 8 also shows the enhancement of SHI in-row cooling in case of 7 and 10 kW compared to the enhancements in perimeter cooling which can be attributed to the high cold air bypass and hot air circulation which is expected in perimeter cooling in case of high power densities due to the high momentum of air but for in-row cooling the effect of increasing momentum isn't noticeable as the cooling units are inserted between the racks. Increasing rack's power to 10 kW represents the best value of SHI, compared to the rest powers, in case of in-row cooling. While it dramatically increases SHI value for perimeter cooling. This clearly assures the validity of using in-row cooling for high-densities and perimeter cooling for low-densities.

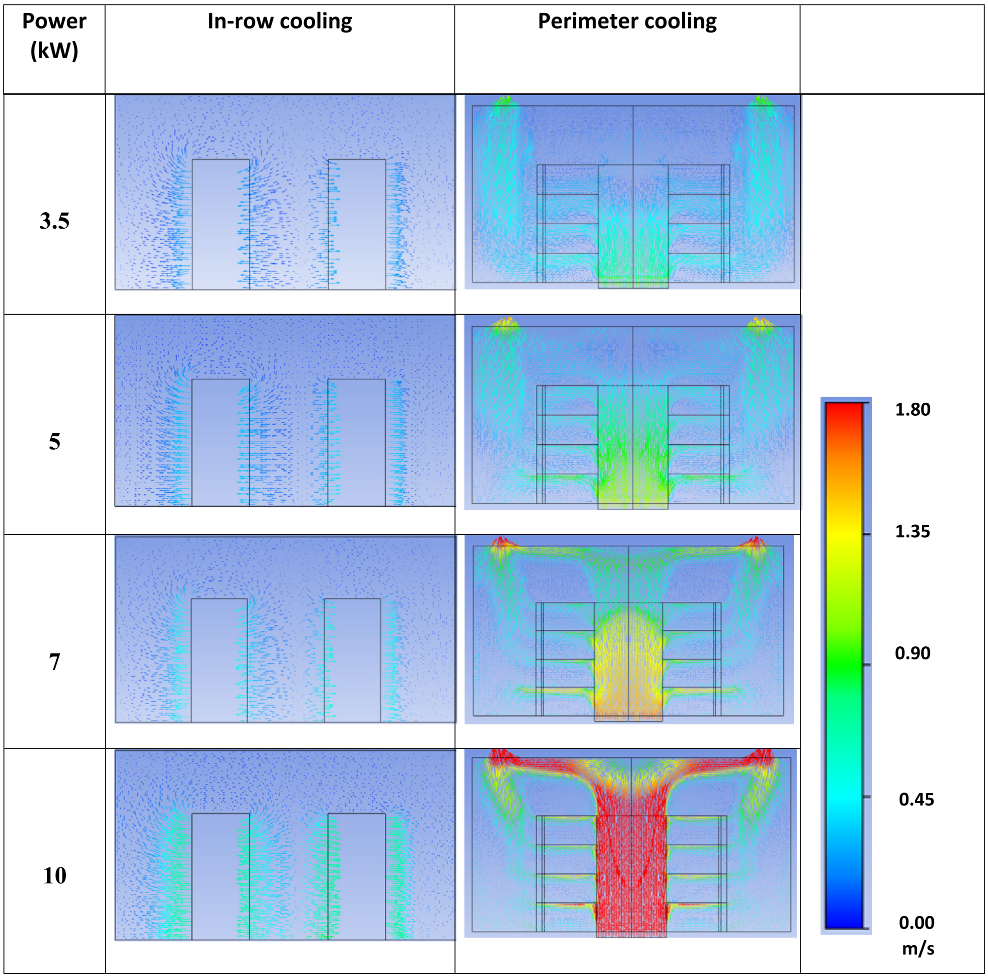


Fig. 7 Comparison of velocity vectors at vertical plans between in-row and perimeter cooling architectures.

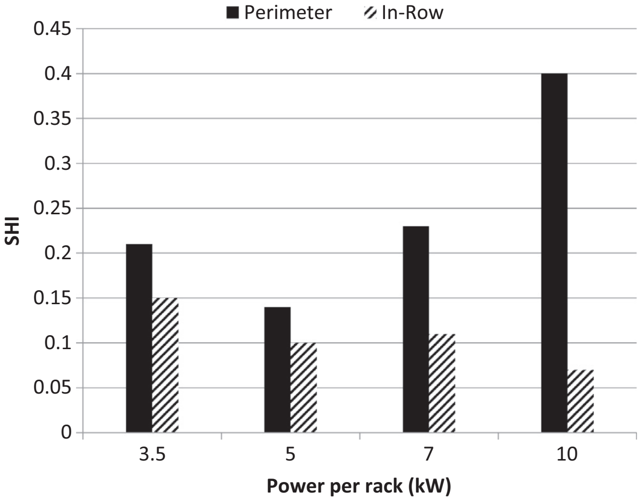


Fig. 8 SHI at various power densities for Perimeter and In-Row Cooling.

Fig. 9 shows that the RHI of the row cooling architectures is larger than those of the perimeter cooling architectures due to the same reasons discussed in Fig. 8, as RHI is the complement of the SHI as (SHI + RHI = 1).

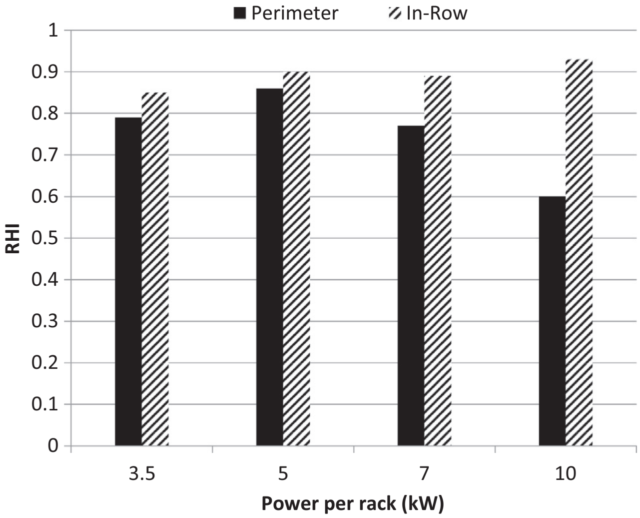


Fig. 9 RHI at various power densities for Perimeter and In-Row Cooling.

The range of values of SHI obtained in the present results for raised floor cooling are compared with those of previous results [9,15,29] and both show the RHI values lies in the range 0.25–0.4 for rack power densities in the range **3.5–7 kW**

4.2.2. RTI of perimeter and In-row cooling architectures.

As the RTI value is an indication of the hot air recirculation and the cold air bypass, it is used for comparing between the performance of the perimeter cooling and in-row cooling architectures. The absence of hot air recirculation and cold air bypass is achieved when the value of RTI nears from 1. Fig. 10 shows that for all power densities RTI values for in-row cooling architectures is closer to 1 more than those of perimeter cooling architectures, which means a better thermal performance is achieved. This can be attributed to the expected absence of hot air circulation and cold air bypass for in-row cooling due to the insertion of the cooling units between the racks. While for perimeter cooling architectures cold air by pass and hot air circulation are expected. Fig. 10 also shows that for perimeter cooling architectures, RTI decreases and become far from 1 with increasing the power density while for in-row cooling, the effect of the power density is limited where RTI is almost fixed and close to 1 whatever the value of the power density. With increasing the power density from 3.5 kW, 5 kW to 7 kW, the RTI decreased from 1.12, 10.7 to 1.01 and finally equals 1 for 10 kW in case of in-row cooling, while it was dramatically decreased from 1.19, 0.72 to 0.492 in case of perimeter cooling. The decrease of the RTI with the power density in the perimeter cooling can be attributed to the increase of the air flow rate and the air momentum with the increase of power density which leads to more hot air circulation and cold air bypass.

4.2.3. Beta index of perimeter and In-row cooling architectures.

Beta index is one of the parameters that measures the thermal performance of the data center. It measures how the inlet rack temperature closes to the CRAC outlet temperature. The closer means that the highest efficiency is achieved. As the Beta index is expressed in terms of the temperature difference between inlet rack temperature and the CRAC outlet temperature over temperature difference of rack's outlet and inlet, this implies that beta index value is close to zero for high efficiency cooling system. Fig. 11 shows that the Beta index for in-row cooling system is closer to zero than that of perimeter cooling system and this can be attributed to the long path of the cooling air from CRAC exit to the racks inlet for perimeter cooling system. This long path leads to more heat gain which rises the temperature of air at racks' inlet leads to an increase of beta index. Increasing racks' power to 10 kW shows more decrease of β index for in-row cooling and high increase for perimeter cooling, which assures that perimeter cooling is insufficient at high power densities.

4.2.4. Energy utilization coefficient of perimeter and In-row cooling architectures.

Energy utilization coefficient is an indication of the percent that the racks benefit from the cooling capacity of the cooling units. The increase of this value indicates that a higher useful percent is achieved with less wasted cooling energy. Fig. 12 shows that, the value of the energy utilization coefficient for in-row cooling is larger than that of the perimeter cooling. The figure shows that increasing the power density from 3.5 kW to 5 kW per rack, the energy utilization coefficient increased from 1.66 to 1.76 in case of perimeter cooling and from 1.7 to 1.8 in case of in-row cooling. This copes with the results of SHI, RTI and beta index presented earlier. At 10 kW racks' power, the energy utilization coefficient slightly increased for in-row cooling and rapidly decreased for perimeter cooling. This dramatic decrease in case of perimeter cooling is attributed to the high hot air circulation and cold air bypass occurs in the perimeter cooling at high power density.

4.2.5. IOM of perimeter and In-row cooling architectures.

Index of mixing is an important parameter that shows whether the self-loop of the air which causes hot air circulation and cold air bypass occurs or not. As IOM value is low, this refers to a better thermal environment is exists. Fig. 13 shows that IOM of in-row cooling is very low compared to that of the perimeter cooling. This indicates that there is neither hot air circulation nor cold air bypass in case of in-row cooling due to the insertion of cooling units directly between the racks. Fig. 13 also shows that racks' power density of 5 kW has the optimum IOM value in case of perimeter cooling architecture

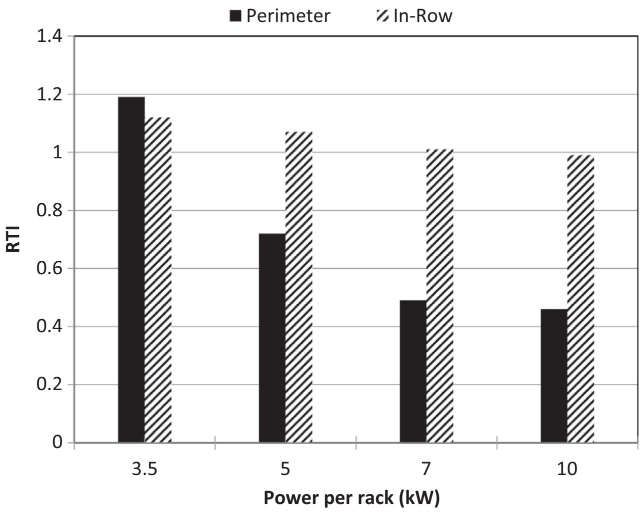


Fig. 10 RTI at various power densities for Perimeter and In-Row Cooling.

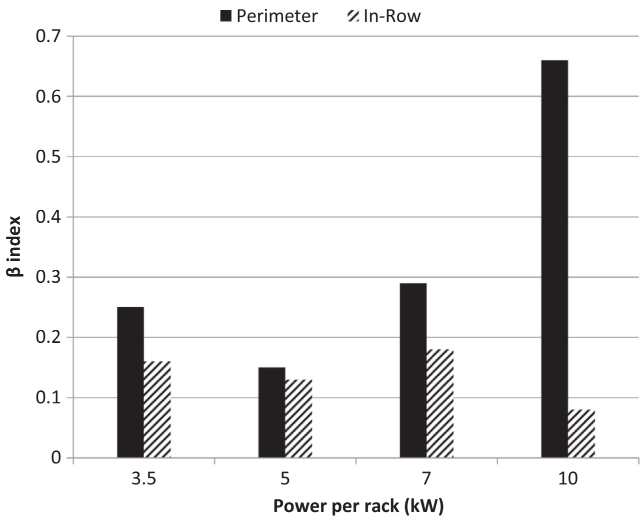


Fig. 11 Beta index at various power densities for perimeter and in-row cooling.

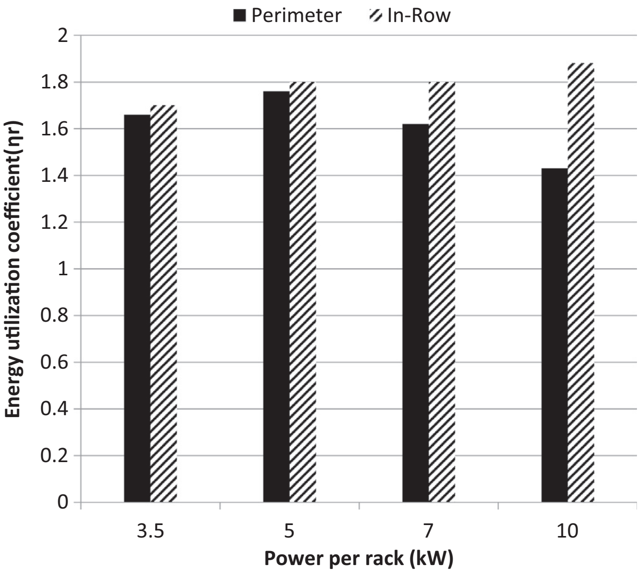


Fig. 12 ηr at various power densities for perimeter and in-row cooling.

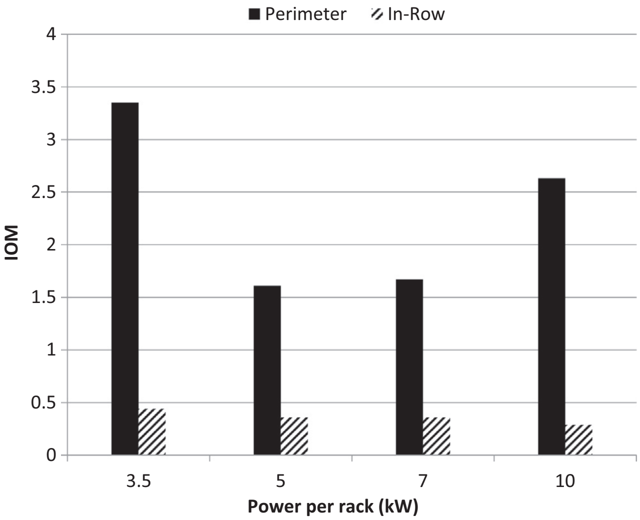


Fig. 13 IOM at various power densities for perimeter and in-row cooling.

however it has approximately no effect for in-row cooling architecture. This supports not using perimeter architecture for high rack's power density.

5. Conclusions

A CFD study was performed to evaluate the performance of in-row and perimeter cooling architectures used in data centers at different rack power densities. The performance was evaluated for both configurations under the same geometric and boundary conditions. The comparison depended on temperature contours, velocity vectors and the performance indices that judge the thermal behavior of air inside the data center. The following points summarize the results:

- Perimeter cooling suffers from hot air recirculation and cold air bypass, especially at high power densities, while in-row cooling hasn't been affected by increasing the racks' power density. This assures that in-row cooling is better for high-power densities and perimeter cooling is only suitable for low-power densities.
- Perimeter cooling architecture exposes un-efficient cooling for the bottom of racks due to the high momentum of the air leaving perforated tiles. While, this doesn't occur in case of in-row cooling as the cold air is uniformly distributed along the racks' height.
- SHI values of in-row cooling architecture are lower than those of perimeter cooling. Their values don't exceed 0.15 for in-row cooling, while they reach 0.4 in case of perimeter cooling.
- RTI of in-row cooling is closer to 1 compared to the perimeter cooling indicating that hot air recirculation and cold air bypass vanish with in-row cooling whatever the servers' power densities.
- Maximum values of beta index doesn't reach 0.2 for in-row cooling; while it reaches 0.6 for perimeter cooling due to higher values of rack's inlet temperatures.
- In-row cooling architecture has higher values of energy utilization coefficient and lower values of IOM, compared to perimeter cooling, which means that the data centers' racks completely benefit from the cooling capacity of the cooling units.

As in-row cooling architecture shows its excellence over perimeter cooling especially at high power densities, it is recommended to proceed further studies for future works for the optimum CRACs and racks distributions for in-row cooling architectures.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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