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Thermal management and performance enhancement of data centers architectures using aligned/staggered in-row cooling arrangements

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ABSTRACT

This research investigates the effects of using aligned/staggered arrangements of cooling units and top aisles containments on the performance of in-rows cooling architectures of data centers. Four different configurations of cooling architectures are numerically set up inside identical data centers of aligned/staggered cooling-units arrangements and with/without top aisles containments. ANSYS IcePak CFD software is used to build models for the four configurations. A scaled physical module of the data center is experimentally constructed and tested for model validation. Air streamlines, velocity vectors and temperature distributions in addition to two-thermal perfromance indices (SHI and IOM) and two-energy efficiency metrics (β and η_r) are used to evaluate and compare thermal environmental and energy efficiency performances of the different configurations. Results show that (i) aligned arrangement has better thermal and energy efficiency performance, (ii) thermal perfromance and energy efficiency indices of intermediate racks of the racks array are better than those of end racks, especially in the staggered arrangements, (iii) thermal environment problem of end racks can be solved by starting and ending racks row by CRAC units, and (iv) using top aisles containment improves the thermal and energy efficiency perfromance indices of data centers racks, especially for intermediate racks.

1. Introduction

Data centers are computing structures that contain servers and racks (IT equipment) which store, process, and manage digital data information. Any data center also include cooling equipment computer room air conditioning (CRAC) units to cool the servers and maintain them within the allowable temperature limit. Cooling of data centers can be considered as one of the major sources that consumes electrical power worldwide. The traditional method used for cooling data centers (known as room cooling system) depends on supplying cold air through perforated tiles that are installed in the raised floor of the data centers. The supply air travels a long journey in the raised floor plenum along its path form the computer room air conditioning units (CRAC) until it reaches the racks. This leads to high-pressure drop (ΔP) due to cables blockage and heat losses (Q_{loss}) for the supply air. Other drawbacks are also exist in the traditional data centers cooling method, such as hot air circulation and cold air bypass.

Recently, many researchers have focused their interest in using different cooling systems strategies and techniques for data center

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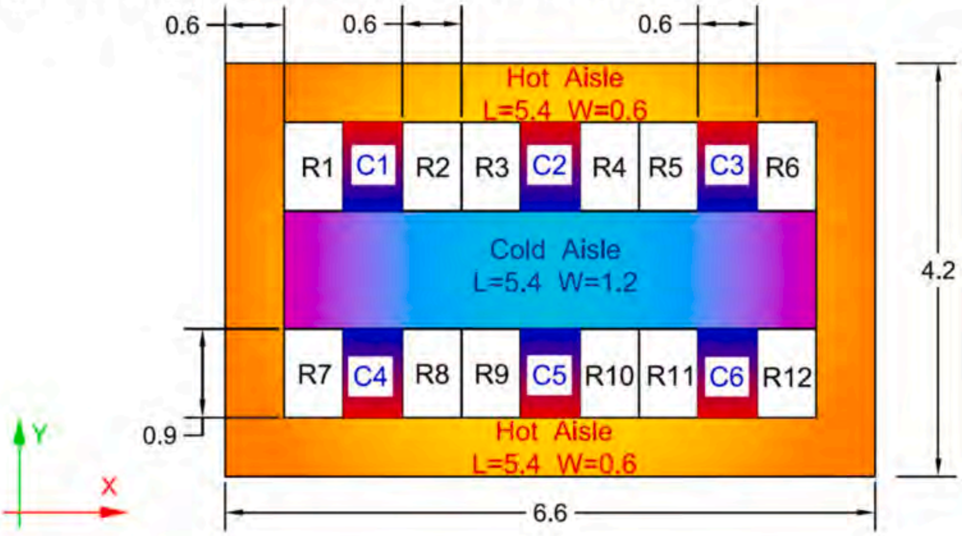
cooling process. A recent developed data center cooling systems using in-row architecture in which CRAC units are periodically distributed and inserted in-between the served racks (see Fig. 1) are rapidly sprit. This arrangement leads to shorter air paths and accordingly less pressure drop losses and heat dissipation.

1.1. Design configuration and advantages of in-row cooling system

The main goal of any data center cooling system is to remove the heat generated by the IT equipment in energy efficient way. The data centers must be constructed such that enough cool air is provided to the inlet of the racks such that this heat can be absorbed without equipment overheating. The promising usage of In-Row Cooling Units (IRUs), presented by Ilal in CANOVATE White paper 101 [1] who compared between newly developed In-row Cooling system (IRUs) with traditional Room based cooling system (Perimeter cooling). They reported that in-row cooling system is the best cooling option for high-density data centers while traditional perimeter cooling systems can be a good solution for densities below 5 kW.

a) **Aligned Configurations A.1 (H = 3 m) and B.1 (H = 2 m)**



b) **Staggered Configurations A.2 (H = 3 m) and B.2 (H = 2 m)**

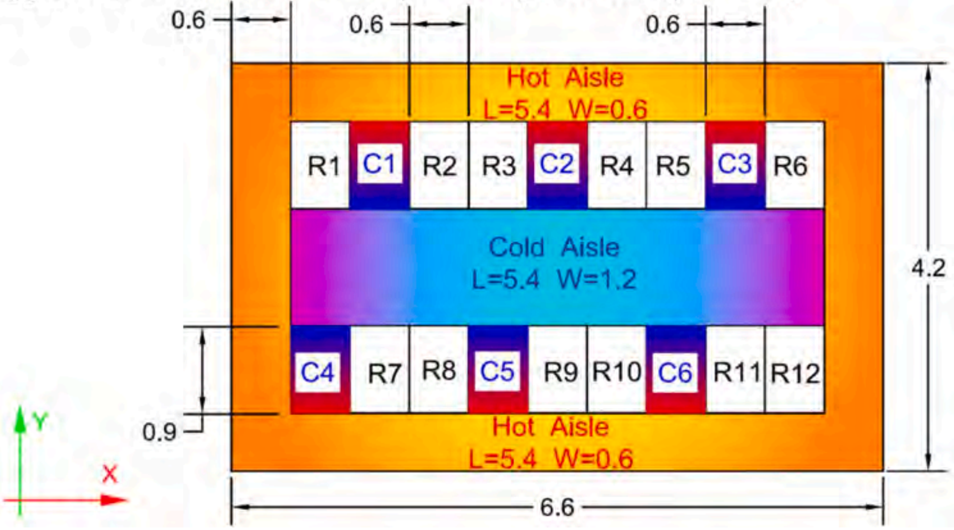


Fig. 1. Plan Views for DC room dimensions equipped with In-Row cooling units for (a) Aligned arrangement and (b) staggered IRUs Arrangement.

Schneider electric white paper 130, conducted by Dunlap and Rasmussen [2], compared between the three levels of cooling system in data centers: room, row and rack level cooling system. They found that row-based cooling is the most flexible and recommended to avoid row-end locations. They reported that the room-based cooling is to cool the entire room and the in-row cooling systems the CRAC units are associated with cooling of racks rows with a shorter airflow paths while the rack-based cooling is to cool a rack with the minimum amount of air volume and cooling capacity. Lin and Avelar [3] presented the idea of in-row cooling and how it is suitable for balancing the cooling capacity with the heat loads. The using of in-row architectures for data centers cooling are encouraged as next generation technology by Server Racks Australia (SRA) [4]. They stated that in-row cooling systems help in reducing air mixing, in addition to the expected reduction and saving for construction time of the data center.

Gong et al. [5] have classified the researches of dada centers cooling in their conducted literature review into four groups which were: (i) air management, (ii) cooling technology, (iii) air conditioning systems, and (iv) energy performance. Zhang et al. [6] presented a review study on the recent advancement on thermal management evaluation for data centers. They classified their interests into three sections, which are: (i) thermal management strategies, (ii) energy conservation techniques such as free cooling and heat recovery, and (iii) currently used thermal evaluation metrics. They reported that there are still short of statistical studies on the thermal management and evaluation of associated cooling systems for data centers.

Chu et al. [7] classified the airflow in data center into long and short paths in their review study of airflow management in data centers. They reported that the long paths technologies such as room cooling suffer from hot air recirculation, cold air bypass, and leakages, while the short paths of airflow help in the reduction of losses. Watson and Venkiteswaran [8] conducted a CFD analysis for universal cooling of data center. Nada and Said [9,10] conducted numerical researches studying the effect of plenum depths on airflow thermal management inside the data centers, and the effect of CRAC units layout on thermal management of the data center. In this study, a comparing between locating the CRAC units in line with the racks row and locating them perpendicular to the racks row was conducted. Nada et al. [11,12] studied the effect of using different configurations of CRACs, and the effect of changing the space between CRACs and the Racks. Fernando et al. [13] demonstrated how data center heat flow can be scale down modeled. Huang et al. [14] performed numerical simulation and comparative analysis of different airflow distributions in data centers. Hassan et al. [15] conducted CFD analysis to monitor temperature distribution inside data center. Macedo et al. [16] studied numerically the air flow and thermal performance in their case study conducted on real data center to improve sustainability. Nada et al. [17] performed numerically simulation of the air flow distribution and energy efficiency in raised floor air conditioning system using different angles of supplying cold air from the perforated tiles.

Nada et al. [18] studied experimentally the effect of using different perforation ratios for the raised floor perforated tiles to get the optimum temperature distribution at 25% perforation ratio. Nada and Elfeky [19] also 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, respectively. Meng et al. [20] experimentally analyzed the effect of the thermal environment of a small-scale data center located in china. Nada et al. [21,22] conducted an experimental study that solves the thermal heterogeneity problem of the room cooling architecture. In these studies, they conducted experimental investigations on thermal management of electronic servers under different power conditions. Bhopte et al. [23] studied the effect of under-floor blockages used in traditional cooling architectures on the performance of data centers. Cho et al. [24] performed an experimental study for replacing a room-based cooling system with row-based cooling one in Korea, using six performance indices in their study to compare between the two systems. Cho and Woo [25] conducted an experimental study on the newly developed row-based cooling system for improving thermal performance of data center. Zhang et al. [26] investigated experimentally the effects of using of T-shaped underfloor air ducts on the airflow uniformity and its optimization inside modular data center.

Recently, Jin et al. [27] compared the thermal management and energy efficiency between raised floor and row based systems used for data centers cooling. Moazamigoodarzi et al. [28] studied the influence of cooling architecture on data center 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. Moazamigoodarzi et al. [29] used machine learning principle to model temperature distribution in IT with row-based cooling architecture. Yuan et al. [30] demonstrated the design validation for tilted server placement to improve the airflow management system in data center. Yuan et al. [31] investigated the effects of lower side terminal baffles for servers on airflow management in their experimental and numerical study performed.

1.2. Thermal evaluation metrics

For evaluating the thermal performance of a data center, there are several parameters were used in the literature. Most of these parameters concern with supply and return temperature of CRACs and racks units. Jin et al. [32] listed and grouped most of those thermal evaluation metrics in grouped indices according to each indication parameters, and function to monitor the thermal behavior and the power efficiency of cooling system used for data centers. Sharma et al. [33] defined two dimensionless parameters to analyze and evaluate the degree of deviation from ideal situation of actual computer rooms. Their parameters are named as SHI and RHI with which the mixing degree of the air supply in the cold aisle can be quantified with the surrounding hot air before entering the IT server. Herrlin [34,35] proposed the rack cooling index (RCI) and return temperature index (RTI) in 2005 and 2007, respectively. These metrics directly address whether the CRAC can efficiently cool the IT equipment. The optimum value of RTI is 100%; an RTI higher than 100% signifies recirculation, and an RTI less than 100% signifies bypassing.

To obtain the performance of airflow pattern; the beta index **(β)** had been defined by Schmidt et al. [36]. 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. Xu [37] defined the Energy Utilization Coefficient **(ηr)**, which is used for calculating the thermal efficiency of airflow in data centers. 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 thermal management of data centers. Tian et al. [38] presented the Index of Mixing (IOM), which is used to indicate the thermal performance of the data center. Lower values of IOM indicate a better thermal environment. A higher value of IOM indicates a greater the possibility of a local hot spot at the location of the rack. Van Gilder and Shrivastava [39] proposed the capture index (CI) and the recirculation index (RI) to capture the cooling performance based solely on the airflow associated with the supply of cooling air to, or the removal of hot air from, a rack. Table 1 depicts the definition and the explanation of the different thermal environment metrics used to evaluate the thermal perfromance of data centers.

1.3. Motivation of the present study

The present literature review concludes that the new hired data centers cooling architectures, known as in row cooling, proved better perfromance comparing to other traditional data centers cooling systems. However, researches regarding the enhancement of the thermal and energy performances of the in-row cooling architectures using different arrangement of cooling units and top aisles containments are not totally investigated and available in the literature. The aim of the present paper is to study the effects of using different cooling units arrangements (namely: aligned and staggered arrangements) in the data centers racks on the thermal and energy efficiency of the in-row cooling architectures. The study also aims to investigate the effects of using top aisles containments on the perfromance of the different configurations of the in-row cooling architectures. The effects on the different racks of the racks row including intermediate and ends racks are individually studied. The study aims to set guidelines for the cooling units' distributions relatives to the cracks arrangement that gives enhanced thermal environments and energy efficiency perfromance. Air streamlines, velocity vectors and temperature distribution in addition to two-thermal perfromance indices (SHI and IOM) and two-energy efficiency metrics (β and η_r) are used to evaluate and compare thermal environmental and energy efficiency perfromance of the different configurations of the in-row cooling architectures in order verify the aim of the present paper.

2. Numerical experiments methodology

2.1. Physical model and numerical experiments setup

Typical size of DC room with dimensions (L = 6.6 m x W = 4.2 m x H = 3 m) is designed to be investigated with aligned arrangement of CRACs units (denoted as arrangement A) and with staggered arrangement of CRACs units (denoted as arrangement B). The investigation is conducted without using Top containments of the racks row (denoted by Configuration 1, where the height of the room is 3 m) and with using top containments (denoted by configuration 2, where the cold and hot aisles are covered at height 2 m). Accordingly four different configurations A.1, A.2, B.1 and B.2 are considered in this study with arrangements and dimensions as summarized in Table 2. The number of In-row cooling units (IRUs) which supplies air the racks of the data center are kept the same (6 IRUs) in all the four configuration. The number of served racks in the data center is kept the same (12 racks) for all configurations A.1, A.2, B.1 and B.2. Fig. 1 demonstrates the two different arrangements of IRUs, Aligned and Staggered, in horizontal plan views for the

Table 1
Data Center Thermal Evaluation Indices listed in Literature Review [34–40].

Index	Equations	Limitations	Ref
SHI	$SHI = \frac{\delta Q}{Q + \delta Q} = \frac{\text{Enthalpy rise due to infiltration in cold aisle}}{\text{Total Enthalpy rise at the rack exhaust}}$	Ideal (min) = 0 Good < 0.2 Poor (max) = 0.2 Target = 0.1	Sharma et al. [34]
RHI	$\text{RHI} = \left(\frac{Q}{Q + \delta Q}\right)$ $= \frac{\textit{Total heat extracted by the CRAC units}}{\textit{Total Enthalpy rise at the rack exhaust}}$	Ideal (max) = 1 Good > 0.8 Poor (max) = 0.8 Target = 0.9	Sharma et al. [34]
RCI	$RCI_{HI} = \left[1 - \frac{\textit{Totalovertemperature}}{\textit{Maxallawableovertemperature}}\right] 100\%$ $RCI_{lo} = \left[1 - \frac{\textit{Total under temperature}}{\textit{Maxallawable under temperature}}\right] 100\%$	Ideal (max) = 1 Good > 96% Acceptable = 0.91–0.95 Poor < 90%	Herrlin [35]
RTI	$RTI = \left[\frac{T_{return} - T_{supply}}{\Delta T_{equipment}}\right] \times 100\%$	Ideal = 100% Good = 95–105% Target = 98–102%	Herrlin [36]
β	$\beta = \frac{T_{in} - T_{ref}}{T_{out} - T_{in}}$	Ideal = 0	Schmidt et al. [37]
ηr	$\eta_r = \frac{T_{out} - T_{ref}}{\frac{r_{out+T_{in}}}{2} - T_{ref}}$	The more the better	Xu [38]
IOM	$\text{IOM} = \frac{T_{i,max} - T_{i,min}}{T_o - T_i}$	The less the better Poor >1 Close to 1	Tian et al. [39]
CI	$\text{CI} = \frac{\textit{mass of species}}{\textit{total mass of fluid}}$	Ideal = 1	VanGilder & Shrivastava [40]
RI	RI = 1- CI	Ideal = 0	

Table 2
Different configurations and arrangements of In-Row Cooling Units.

Configuration	IRUs Arrangement	Cold/hot Ailes Height (m)
A.1	Aligned without top containment	3
A.2	Staggered without top containment	3
B.1	Aligned with top containment	2
B.2	Staggered with top containment	2

data center room layout. The cold and hot aisles are also highlighted in Fig. 1. Each rack has been simulated to generate 5 KW, therefore, it should be clear that the total heat dissipation inside the DC room is kept constant at 60 kW.

The racks heat loads, supply airflow rate, and the supply temperatures are kept the same in all studied configurations to perform an accurate CFD comparative study between them. The supply inlet air temperature (T_{in}) supplied from the IRUs to the cold aisle of each model is kept at 17 °C, however, the delta T on the rack sides (ΔT_{equip}) are kept equal to 10 °C. After the supplied air entering the racks to carry out their disssipated heat, its temperature rises, and then become as returned air leaving the racks from the hot aisles, then will be ready to re-enters the IRUs to be cooled again.

All the physical models have their mesh generated using the commercial CFD package of Ansys IcePak 18.1. This software has been commonly used by many authors (Mulay [40], Tan et al. [41]) to investigate the thermal behavior inside data center using CFD analysis. Ansys IcePak can be considered as powerful simulation tool for electronics cooling; in addition, it easily represents data center components through macro icons. It can specify the heat load of racks, flow direction and rate. This software produces highly accurate, conformal meshes that represent the true shape of electronic components.

2.2. Governing equations and numerical technique

Applying the basic equations (mass conservation, momentum conservation, and energy conservation) result in the govern equation for the fluid dynamics and heat transfer. Air is regarded as an incompressible fluid, and the flow is turbulent. In addition, the effect of radiation is ignored. For the finite volume method, the resulting differential and partial differential equations are integrated and converted to algebraic equations. The set of obtained governing equations and solution method are given in the supplementary material. The operating conditions for performed numerical experiments are listed in Table 3(see Table 4).

2.3. Mesh independence study

Mesh independence study with six different number of cells beginning with 600,000 cells and ending with 3,000,000 cells have been performed before starting the current CFD investigation on the four investigated configurations. In each case, three parameters were calculated (SHI- Beta index- Energy Utilization Coefficient) for each of the racks in all of the tested configurations, to get the optimum number of cells that will be used for the rest of the calculations. The following tables show the values of the obtained results at different numbers of cells for the first rack (R1) and the intermediate rack (R4) tested in configuration A.1. The values of these parameters indicate that the optimum number of cells to be used is 2,500,000 cells where further increase of the cells number do not affect the results.

2.4. Model validation and experimental setup

For validating the numerical work, a scaled experimental module of in-row data center was constructed with a plexi-glass room of dimensions (45 × 42 × 33 cm). The module contains two racks with one simulated In-row cooling unit inserted between them to formulate in-row cooling Architecture. The idea of using scaled model of a full sized standard dimensions using a length-scale ratio of 1/6. the scaled model theory was approved by Fernando et al. [13] and previously showed its validity of achieving thermal similarity [18–22] to take the advantage of cost reduction for building a real prototype. A refrigeration unit is connected with a test rig where a cold air is supplied by a blower at temperature of 22.5 °C.

The racks contain plate heaters inside them to simulate the servers. A suction fan was fixed at racks rear for hot air suction. Fig. 2 shows a picture of the experimental setup and a schematic of the side view of the experimental setup. An AHU supplies cold air to the simulated in-row cooling unit (IRU) that inserted between the racks. The cold air exiting from the IRU in the cold aisle enters the racks through perforated inlets. This cold air cools the servers and is withdrawn by fans installed at racks outlet to the hot aisle. Then, this air

Table 3
Operating conditions for numerical experiments performed in current CFD study.

Boundary Condition	Value	Units
Supply air Temperature, $\mathbf{T_{supply}}$	17	^{o}C
Temperature difference on Equipmnet, $\mathbf{\Delta T_{equip}}$	10	^{o}C
Inlet air volume flowrate, $\mathbf{V^{o}}$	4.97	m^3/s
Power Distribution	2.16	$[kW/m^2]$

Table 4
The influence of grid size on performance indices in current CFD study.

Mesh (Nodes)	SHI @ R1	SHI @ R4	β @ R1	β @ R4	η_r @ R1	η_r @ R4
600,000	0.18	0.10	0.21	0.11	1.70	1.82
1,000,000	0.19	0.11	0.24	0.12	1.67	1.81
1,500,000	0.20	0.12	0.26	0.13	1.66	1.80
2,000,000	0.21	0.12	0.27	0.13	1.65	1.79
2,500,000	0.22	0.13	0.28	0.14	1.64	1.79
3,000,000	0.22	0.13	0.29	0.14	1.63	1.79

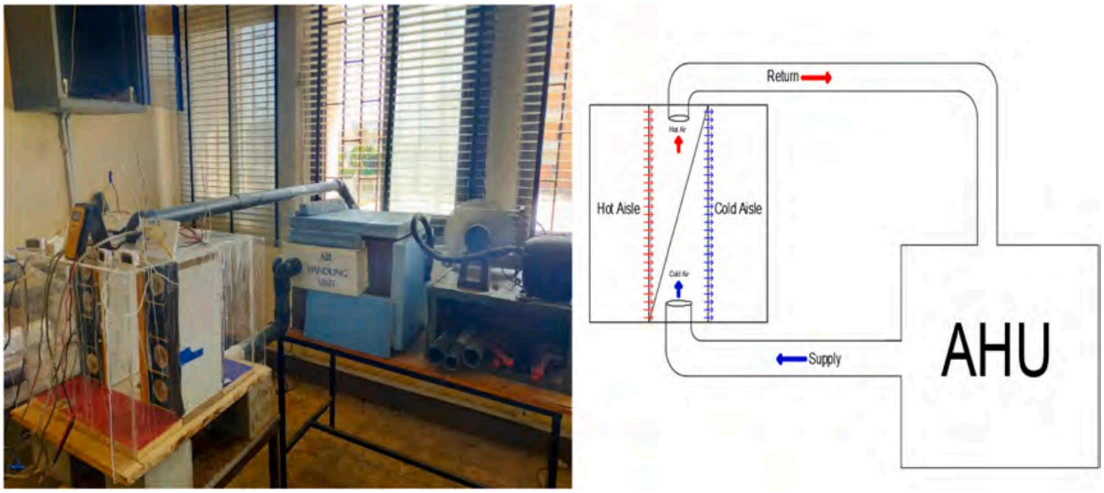


Fig. 2. Photo picture of the experimental setup and schematic of a side view.

enters the IRU to be cooled again in the AHU. Temperatures were measured along the racks heights in both cold and hot aisles after reaching steady state to evaluate the thermal performance of the air at the inlet and outlet of the racks.

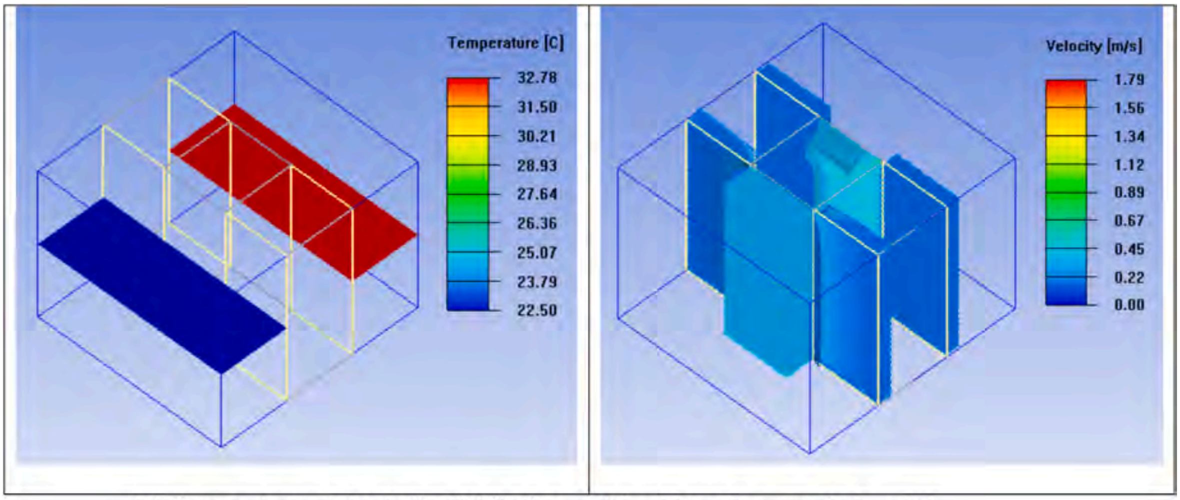
A typical simulated model was constructed using Ansys-IcePak software. The model has the same dimensions and boundary conditions of the experimental model to validate the numerical results with the experimental work. Fig. 3-a shows that temperature and velocity distributions obtained by the numerical model, while Fig. 3-b compares the temperature distribution with the experimental data. The figure shows that the average temperature in the cold aisle is 22.5 °C, while it is 32.7 °C in the hot aisle. The temperature difference is compatible with the experimental results as shown in Fig. 3-b. The comparison shows that the error is about 3% (1 °C out of 32.7 °C). The homogeneity in velocity vector and air temperature in the aisles as shown in Fig. 3-a assure the smoothness of air paths inside data centers due to using in-row cooling Architecture.

3. Results and discussion

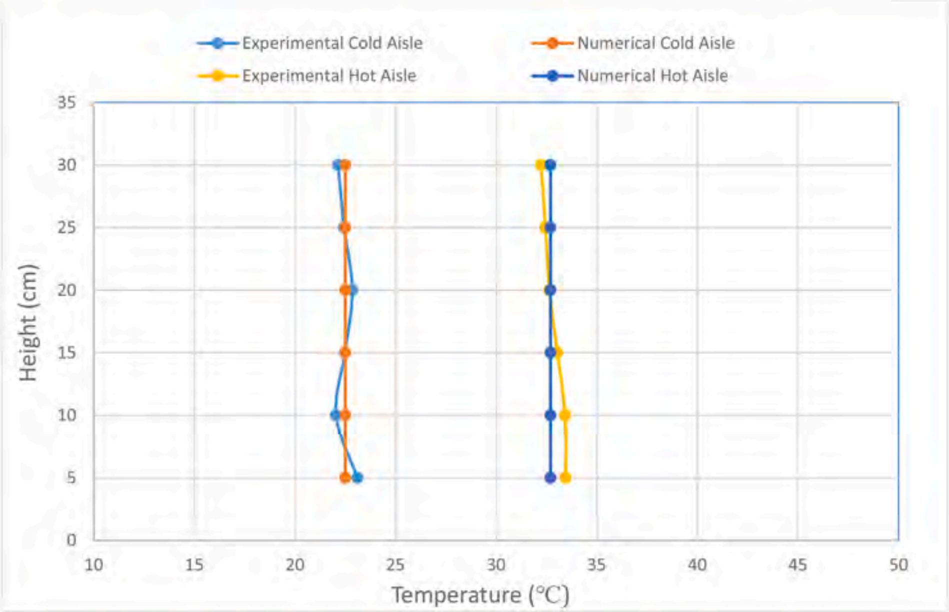
3.1. Characteristics of flow

3.1.1. 1Air streamlines

Fig. 4 shows the air streamlines and velocity magnitudes (using coloured scale) in 3D views for the four different In-Row configurations. Effects of using top contaminants of the data centers racks by lowering the ceiling height to the level of the cracks height ($H = 2$ m) in configurations B.1 and B.2 are clearly noticed by disappearing of air streamlines of the flow that by-passes the row of racks from their top, as can be seen on Fig. 4-b. However air flow and circulation above the racks rows are observed for the cases A1 and A2 (without using top containments; i.e. using standard ceiling height; $H = 3$ m), as shown on Fig. 4-a. This flow enhancement due to using top containments improves the health of thermal environment between the racks in the cold aisle and keeps the total amount of supplied cold air from IRUs inside cold aisles without any percentage of exfiltrated air from the cold aisle to the hot aisles at the racks top. These observations are also discussed in section 4.2 during discussing the effect of using top containments for cold aisles on the temperature distribution. It should be clear that using top containments of the cold aisles is pronounced on the smoothness of air streamlines passes from IRUs supply air outlets until reaching the rack intakes (configurations B.1, and B.2) comparing to the case of opening the cold aisles to the standard room ceiling (configurations A.1, and A.2.). As shown in Fig. 4, the maximum velocities are observed at the IRUs return air intakes facing the hot aisles and their range is around 0.9 m/s for all configurations A.1, A.2, B.1 and B.2 while the velocities at the IRUs supply air outlets increase is around 0.65 m/s for all configurations. As can be seen on Fig. 4-a,b, the by-



(a) Temperatures and velocity distributions obtained from the numerical model



(b) Comparison of cold and hot aisles temperature distribution along the racks heights

Figure 3. Model validation (Comparison between experimental and numerical results)

Fig. 3. Model validation (Comparison between experimental and numerical results).

passing flow around the ends of each racks row were observed which might increase the degree of mixing between supplied cold air from IRUs and the return air from racks backsides. These observed interactions between supply air streams and return air streams at end racks are capable to generate hot spots in corners of data centers array. In configurations of using top containments of data centers aisles (Configurations B.1, and B.2) most of these hot spots phenomenon occurs locally at the data centers corners.

3.2. *Characteristics of temperature distribution*

3.2.1. *Horizontal temperature distributions on XY plans*

The temperature distribution on different XY horizontal plan views are deduced and analyzed to know the temperature distributions along the racks height. For example the temperature distributions at horizontal plane taken at rack top level (Z = 2 m) is presented in Fig. 5-a, b for the four studied configurations A.1, A.2, B.1 and B.2. It is clearly shown on the figures that the temperatures levels of the staggered arrangements at the end racks of the right side of the row racks (R12; see Fig. 1) are higher than the temperature

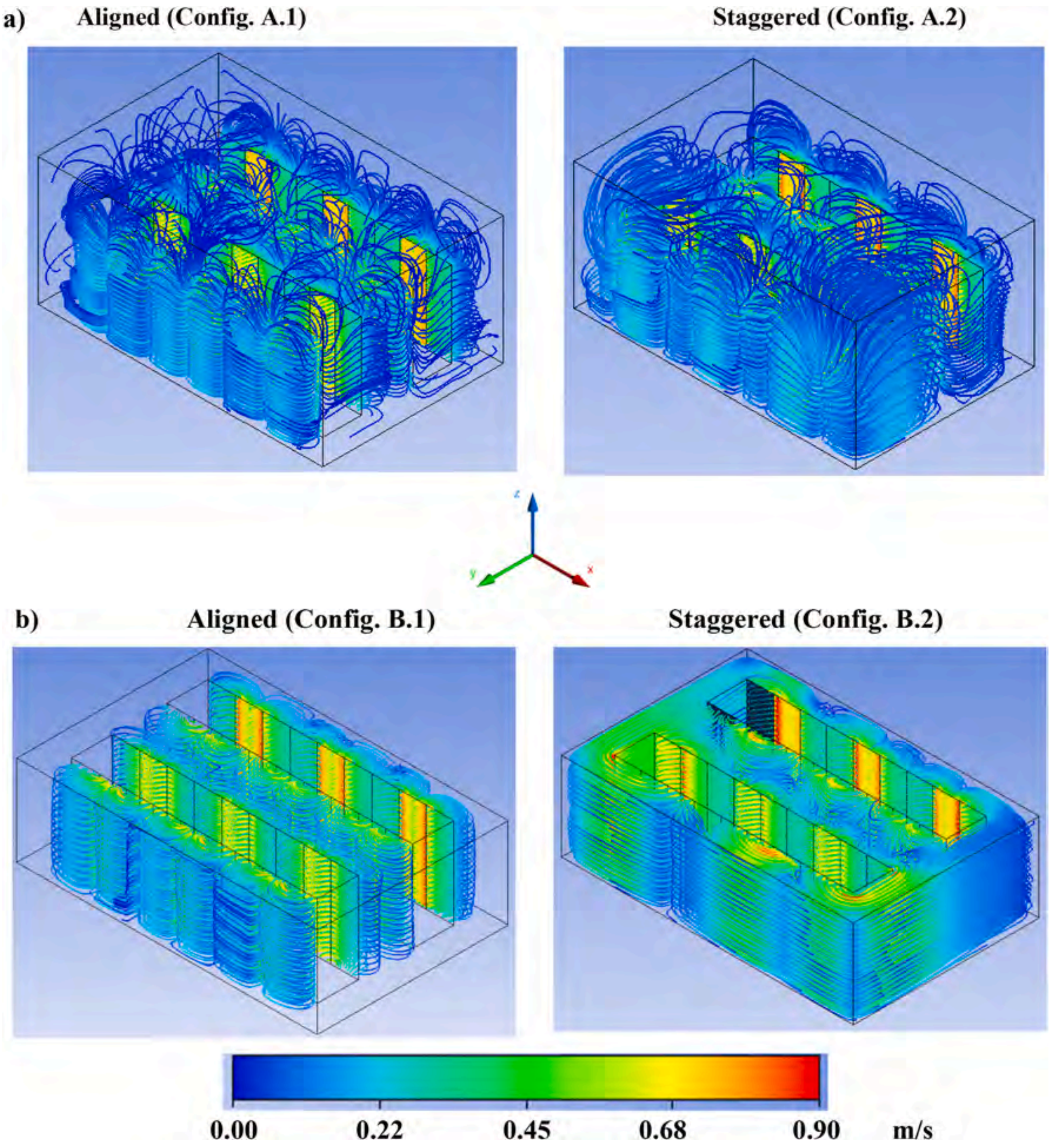


Fig. 4. Air Streamlines and Velocity magnitudes in 3D Views for the four studied configurations A.1, A.2, B.1 and B.2.

levels of the end racks at the left hand side of the staggered arrangements (R7) and is higher than those of the ends racks of the aligned arrangements (R1, R6, R7 and R12). This can be attributed to the location of the closest CRAC units to the ends racks of the racks row in the two arrangements where in configuration A2 and B2 there are two end racks (R11 and R12; see Fig. 1) on the right of the latest CRAC unit (C6; see Fig. 1) while in configuration A1 and B1 of the aligned arrangement there are only one end rack (R1, R6, R7 and R12; See Fig. 1) after the latest CRACs units (C1, C3, C4, C6; respectively). This means that (a) locating the end racks away from the nearest CRAC of it as R12 in Configurations A2 and B2 will lead to high temperature levels comparing to the case of locating the end rack closer to the nearest CRAC unit to it as R1, R6, R7 and R12 in configuration A1 and B1, and (b) Ending the racks row with a CRAC unit as C4 in A2 and B2 is better than ending it with a rack units as R1, R6, R7 and R12 in configuration A1 and B1and R1, R6, R12 in configurations A2 and B2. This can be attributed to the increase of the distance between the rack and the nearest CRAC unit. Fig. 5-b shows that configurations B.1 and B.2 with using top aisles containments by lowering the ceiling height (H = 2 m) have lower cold aisles temperatures and higher hot aisles temperature comparing to Configurations A1 and A2 of the standard ceiling heights (H = 3 m; i. e without using top aisles containments). This can be attributed to the expected cold air bypass and hot air recirculation from the top of racks in the case of without using top aisles containments (A1 and A2). This means that for Configurations B.1, and B.2, the inlet

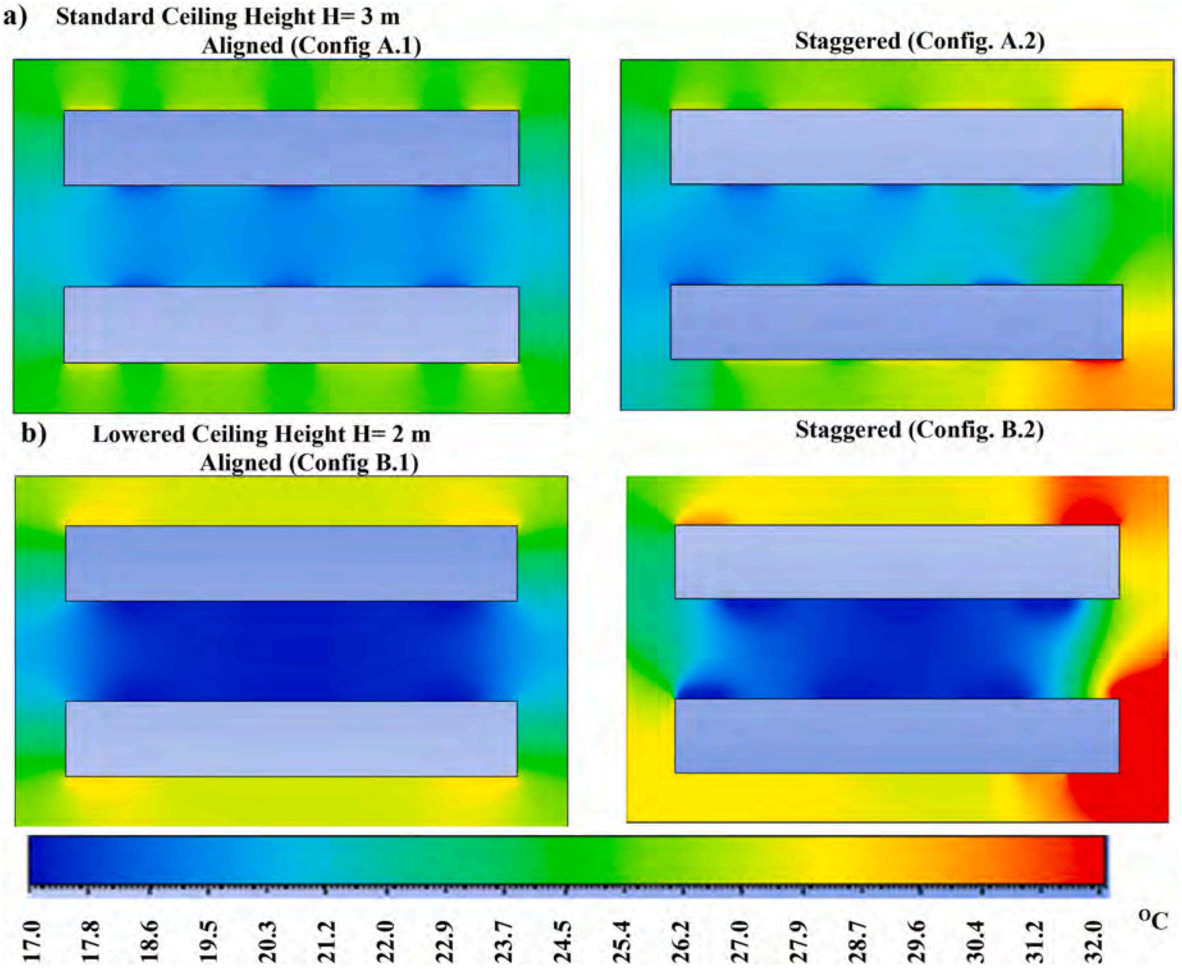


Fig. 5. Temperature Distribution shown on XY Horizontal Plan Views (at rack top horizontal plans) for the four studied In-Row configurations.

temperatures of racks are the temperature of the supply cold air while in configurations A1 and A2 the inlet temperature is a little bit higher than the supply cold air due to the mixing with the recirculated hot air at the top of the racks. Accordingly, lowering of ceiling height of the cold and hot aisles of the data center by using top containments can be considered as one of the most advanced techniques which are widely used in order to diminish the smoothness of air streamlines and to enhance of flow conditions and to avoid heterogeneity of supply and return air temperatures inside DC room.

The similarity of the temperature distribution and temperatures levels at the top and median horizontal plans in case of using top aisles containments, as shown in Fig. 5 b assures the achievement of the thermal homogeneity over the racks height. However, in case of un-using top aisles containments as in cases A1 and A2, the temperature levels at the median horizontal plans are lower than those at the top horizontal plane as clearly seen in Fig. 5-a. This can be attributed to hot air circulation from top of racks in case of un-using top aisles containments.

3.3. *Thermal Evaluation and energy efficiency indices*

In Post-processing stage of the current CFD investigation for the studied four configurations on ANSYS (Icepak), two thermal evaluation indices Supply Heat Index (SHI) and Index of Mixing (IOM) are computed for all racks of the data centers. Also, the energy efficiency metrics Beta index (β), and the Energy Utilization Coefficient (η_r) are estimated for all racks of all configurations with both arrangements of aligned and staggered IRUs. The results of the thermal evaluation indices (SHI & IOM) and of tho energy efficiency indices (β & η_r) are presented here in sections 3.3.1 to 3.3.4, respectively.

3.3.1. *Supply Heat Index (SHI)*

Fig. 6 compares the SHI of the twelve racks of the two rows of the data center in the studied four configurations A1, A2, B3 and B2. The figure also include the legends of the aligned and staggered racks distribution to show the position of each rack in the racks rows for easily understand the trends of the figure. The figure shows that for the aligned distributions (A1 and B1) the SHI values for the

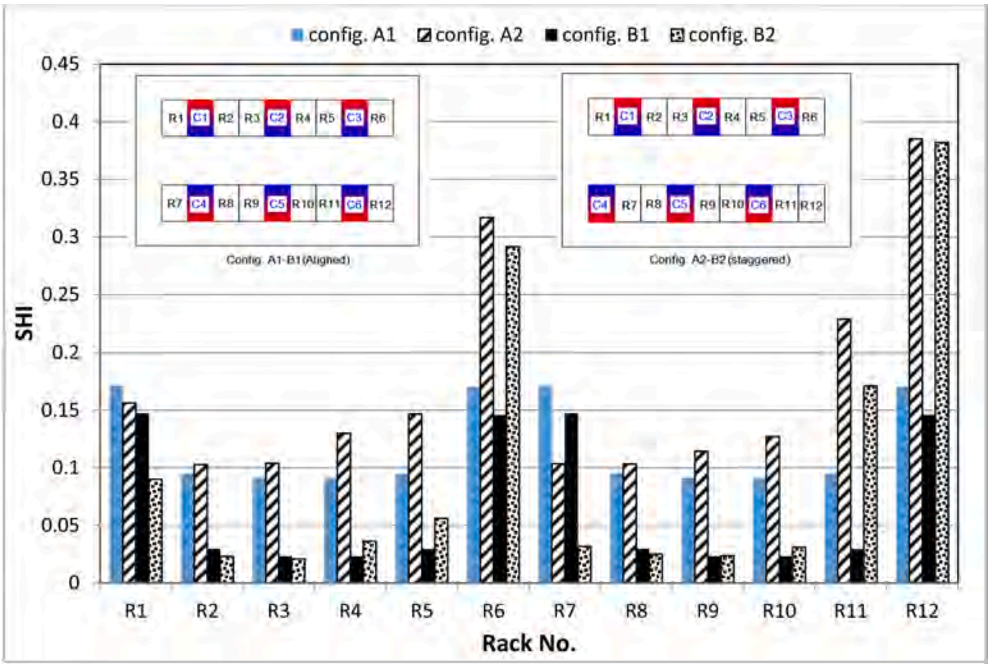


Fig. 6. SHI for the different racks in the four In-Row configurations.

racks R1-R6 are typical to the SHI values for the racks R7-R12, respectively. This can be attributed to the symmetrical distributions of the racks and CRACs in the two racks rows in case of aligned distributions. Fig. 6 also shows that the values of SHI for all the intermediate racks (R2-R5 and R7-R10 in A2 and B2, R8-R10 in A1 and B1) are very low compared to the terminal/end racks (R1, R6, R7 (in A1 and B1) and R12) where the values tend to be zero for aligned arrangement (A1 and B1) and tends to be close to 0.1 for staggered arrangement (A2 and B2). However, for the terminal/ends racks of the racks rows (R1, R6, R7 (in A1 and B1) and R12), some increase for the values of SHI are observed for both arrangements; for example the SHI values can reach up to 0.18 in R1, R6, R7 and R12 in the aligned configuration (A1 and B1) and it can reaches 0.3 in R6 and 0.38 in R12 in the staggered arrangement. The high values of the SHI in the terminal/end racks compared to those of the intermediate racks can be attributed to the hot air circulation and cold air by-

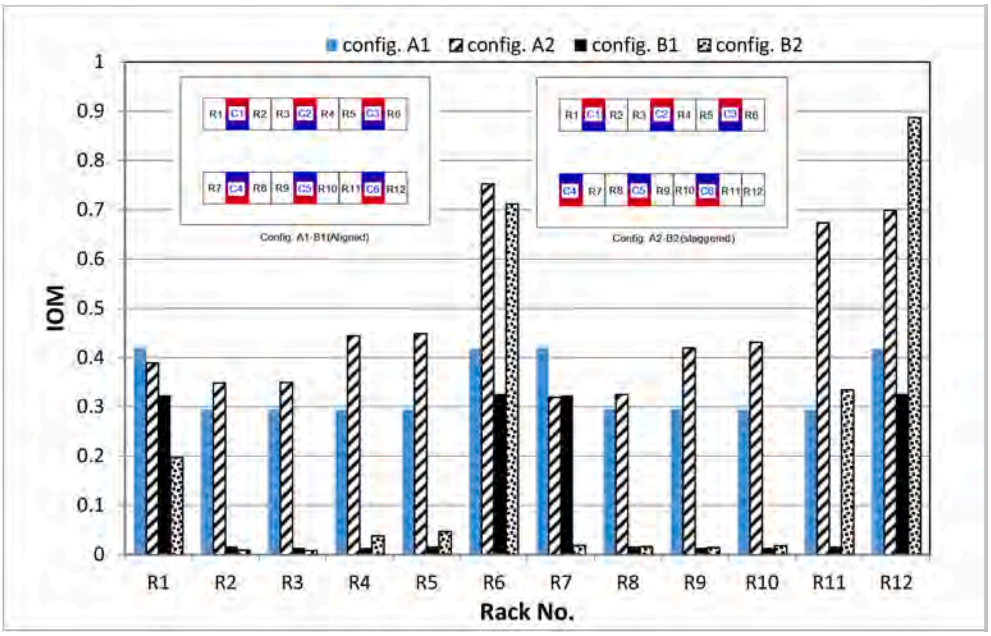
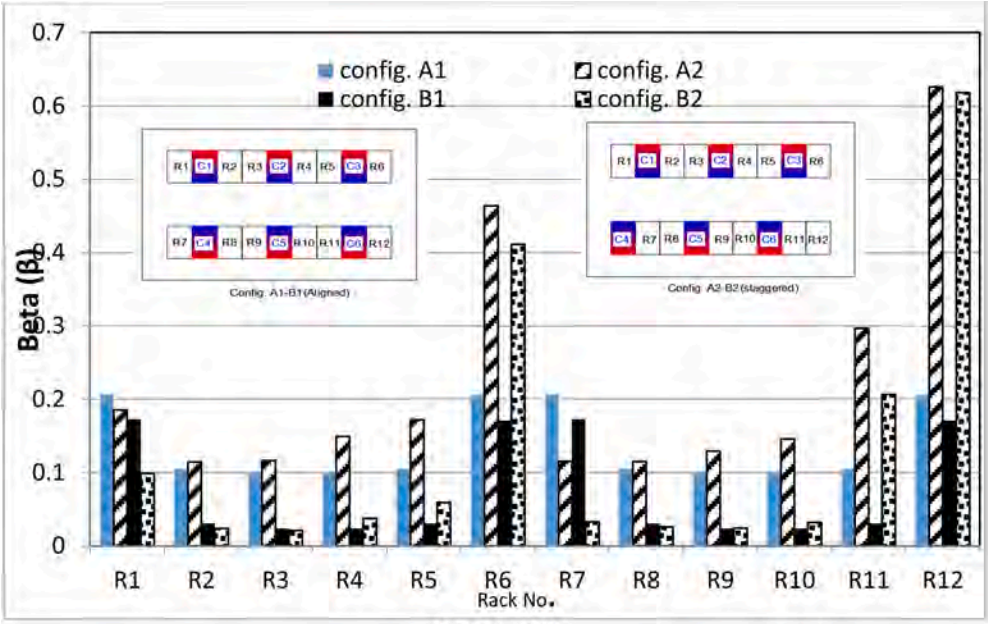


Fig. 7. IOM for the different racks in the four In-Row configurations.

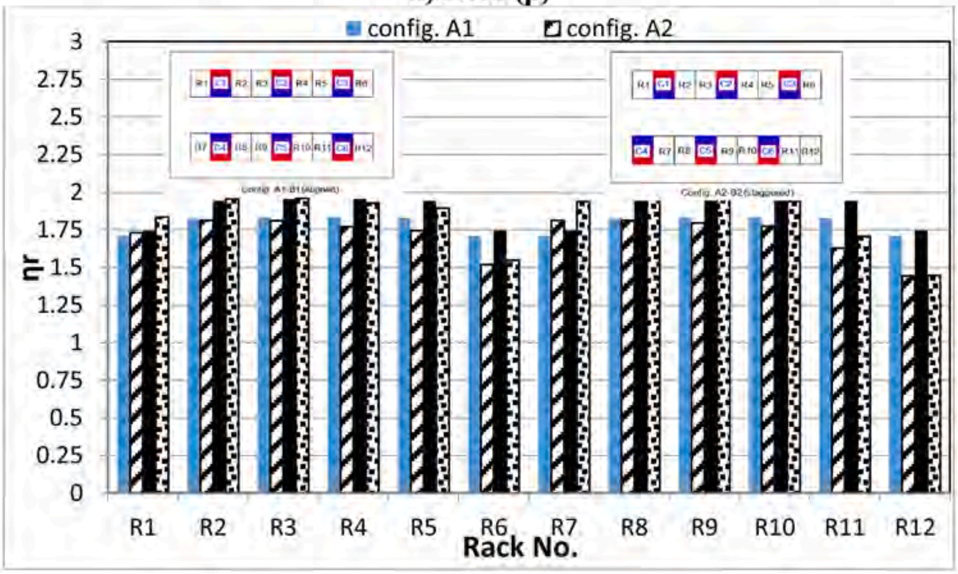
pass that occurs around the end racks that rise the intake air temperature of the racks and accordingly the SHI values.

Fig. 6 also shows that the SHI values of the racks in the aligned arrangements (A1 and B1) are smaller than those of the staggered arrangements. For example the SHI of R6 and R12 (Terminal racks) in A1 and B1 are smaller than their values in A2 and B2 and the SHI values of R2-R5 and R8-R11 (Terminal racks) in A1 and B1 are smaller than their values in A2 and B2. This indicates that the thermal environment in case of aligned arrangement is better than that of the staggered arrangements and this also confirm the temperature distributions results presented in Fig. 5.

Fig. 6 also confirms that the thermal environment can be improved by using top aisles containments where the SHI values of the racks in configurations B1 and B2 are smaller than those of configurations A1 and A2, respectively. This can be attributed to the hot air circulation and the cold air bypass that are expected to occurs at the top of the racks in case of un-using top aisles containment as in configurations A1 and A2. Fig. 6 shows that the value of SHI for the terminal racks (R2-R5, R8-R11) in case of using top aisles containments (B1 and B2) are very close to the optimum value of SHI (SHI = 0) indicating that there is no hot air circulations and cold air



a) Beta (β)



b) Energy utilization coefficient (ηr)

Fig. 8. Beta (β) and energy utilization coefficient (ηr) for the different racks in the four In-Row configurations.

bypass occurs at these racks. However the values of the SHI of the terminal racks (R1, R6 and R12) in case of using top aisles containments (B1 and B2) increases to be higher than those of the intermediate racks indicating the occurs of hot air circulation and cold air bypass around the sides of the racks.

Fig. 6 shows that the worst rack that has the highest value of SHI is R12 in A2 (SHI = 0.39); the next worst rack is R6 (SHI = 0.31) in A2. This can be attributed to that this rack is a terminal racks without using top containment and at the same time it separated from the nearest CRAC (C8) unit by another rack (R11) which dramatically rise the intake temperature of the supply air to this rack. This problem can be solved by putting terminal CRAC unit adjacent to R12 similar to C4 that is adjacent R7. Doing so, will dramatically decrease the values of SHI of R12 and R6 in A2 to be similar to R7 and R1 in A1.

3.3.2. *Index of Mixing (IOM)*

Fig. 7 represents the IOM values of the twelve racks for all configurations A.1, A.2, B.1, and B.2. Fig. 7 shows that the minimum values for IOM, which tend to the optimal value (IOM = 0), are recorded and observed for all the intermediate racks R2-R5, R8-R11 in all configurations including R7 of Configurations A.2 and B.2. However, an increase of IOM up to 0.3–0.4 are observed for the terminal/end racks R1, R6, R12 for all configurations and R7. This can be attributed to the hot air circulations and cold air bypass occurring around the sides of the terminal racks. A sudden decrease in IOM value to be close to zero is observed for the first rack R7 in configuration B.2; where locating just adjacent CRAC (C4) at the start of second rack row, in the staggered arrangement dramatically improve the thermal environment of R7 in B2 comparing to R12 in B2.

Fig. 7 shows that for both aligned and staggered arrangements, using top aisles containment has a positive effect on the IOM values where the values of IAM of the twelve racks in configurations B1 and B2 (using top aisles containments) are lower than those of configurations A1 and A2 (using standard height of the room). As mentioned before, using top aisles containments can help in avoiding the airflow by pass above the racks top which improve the heterogeneity of temperatures inside cold aisle, and also in hot aisles. On the other side, using top aisles containments may compress the air streamlines below the level of racks top, which may facilitate ex-filtrated air to pass around both ends of racks row, as can be seen in previous Fig. 4 b for the movement of air streamlines, and in Fig. 5 b for temperature distributions indicating the hot spots in some racks row end. This tendency of increasing the possibility/strength of ex-filtration at the terminal sides (R1, R6 and R12) in case of using top aisles containments makes the IOM values of the terminal racks (R1, R2 and R12) in case of using top aisles containments (B1 and B2) are higher than those of A1 and A2 that use the standard height of the room.

3.3.3. *Beta index (β) and Energy Utilization Index (η_r)*

Fig. 8 shows the Beta perfromance index (β) and the Energy Utilization Index (η_r) of the twelve racks for all the racks configurations A.1, A.2, B.1, and B.2. As discussed in section 1 and summarized in Table 1, the β express the performance of airflow pattern and the air circulations around the racks. The range of β is between 0 and 1; the less values of (β) are the better values and the optimal value is zero. Fig. 8-a shows that in the case of using the standard height of the room (without top aisles containments) the values of Beta index (β) for all the intermediate racks (from R2 to R5) in the aligned arrangement (Configuration A.1) are less than 0.05 and are less than 0.1 in the staggered arrangement (Configuration A.2). However, the values of β recorded some increase in the first and the last racks for both arrangements and the β values can reach up to $\beta = 0.2$ at the first rack for Configuration A.2. The increase of the β in the terminal/ends racks can be attributed to the hot air circulations that are expected to occur around the sides of the terminal racks. In the case of using top aisles containments (configurations B1 and B.2), Also all the intermediate racks (from R2 to R5) recorded very small values for (β), which almost tends to $\beta = 0.05$. Nevertheless, local slight increases in (β) values (β from 0.1 to 0.2) might be observed at the first rack R1 of Configurations B.1, and at the last racks R6 for configurations B.1, and B.2 due to the air recirculation around the terminal racks. The maximum observed value for $\beta = 0.65$ is locally recorded at R12 for B.2, due to the large separating distance between it and the nearest CRACs and also due to the hot air recirculation that are expected to occurs around the sides and top of this rack. This problem can be solved by putting a CRAC unit at this end of this racks row like C4 in the other and of the row. Figure 12 also shows that the β of R6 in case of staggered arrangement are very high compared to its value in the aligned arrangement can be attributed because the distance between R6 and the nearest CRAC unit in the opposite row (C6) in case of staggered arrangement is higher than that in aligned arrangement. This problem also can be solved by putting a CRAC unit adjacent to R12 in the staggered arrangement.

The trends of the values of (β) shown in Fig. 8-a for the different configurations are in good agreements with the trends of SHI and IOM that are shown in Figs. 6 and 7 due to the same reasons of hot air recirculation and the cold air bypass.

The Energy Utilization Coefficient **(ηr)** is used for calculating the thermal efficiency of airflow in data centers and to measure the percent of mixing between hot and cold air. The larger the value of energy utilization coefficient, the better the thermal management in data centers. Fig. 8-b shows the Energy Utilization Index (η_r) values for the twelve racks in the four different studied configurations. Fig. 8-b shows that the values (η_r) for the intermediate racks in the configurations A1 and A2 (without using top aisles containments) are approximately constant around 1.75 and almost equal 1.8 for configurations B1 and B2 (with using top aisles containments). The figures also shows that for the intermediate racks the η_r values are approximately the same for the aligned and the staggered arrangements. However, a slight decrease of η_r are observed in the terminal racks of the different arrangements; namely at the first rack R1 and the last rack R6 of configuration B.1 and at the last racks R6 and R12 of configurations A.2 and B.2. In addition, Fig. 8-b reports that the worst racks which has the smallest value of η_r is R12. All of these observations confirm the privilege of having top aisles containments (configurations B.1 and B.2) which can be well utilized during the design stage of the data center room to help the smoothness of air streamlines and to enhance the air flow conditions by avoiding air by pass above the racks top as can be observed for standard ceiling configurations A.1 and A.2. The results also lead to eliminating hot spot problems inside the data center room corners that can be seen at R12 in the staggered configurations (A.2 and B.2) by having a CRAC unit at the end of the racks row like R7 in configurations A2 and B2.

4. Conclusions

In-rows cooling architectures of data center is a recent efficient technique replacing the traditional room based cooling systems to solve the problems of thermal managements and energy efficiency in data centers. The main purpose of the present paper is to study, analysis and compare the performance of different configurations of in row cooling architectures, namely aligned and staggered arrangements of the data centers racks and CRACs units with and without top aisles containments to reach the optimum distribution of CRACs units between the racks. The results of the present study can be concluded in the following points:

- Air streamlines, velocity vectors/magnitudes and temperature distributions showed that the aligned arrangement has better thermal environment and performance especially for the terminal/end racks.
- The thermal perfromance (presented by SHI and IOM) and the energy efficiency (represented by Beta index β and Energy Utilization Coefficient η_r) indices of the intermediate racks of data center are better than those of terminal/end racks, especially in the staggered arrangements.
- The thermal environment problem of the end/terminal racks of the data centers racks rows, especially in the staggered arrangement, can be solved by starting and ending each racks row by a CRAC unit.
- Using top aisles containments can help in improving the smoothness of air streamlines and diminishing the hot air recirculation and the ex-filtration of the supply air from the racks top level. Nevertheless, some hot spots might be appeared in the hot aisle at the DC corners, due to the unexpected supply air and return air mixing phenomenon at the terminal sides of the racks rows.
- Using top aisles containments improves the perfromance indices of the thermal environment and energy efficiency of the data centers racks, especially the intermediate racks, for both aligned and staggered configurations of in-row cooling.
- Using top aisles containments can adversely affect the thermal environment of the terminal/ends racks, especially in the staggered arrangement and the problem can be solved by starting and ending the racks rows by a CRAC unit.

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.

Nomenclature

H	Height of DC Room(m)
L	Length of DC Room(m)
m^o	mass flow rate(QUOTE QUOTE kg/s kg/s kg/s)
Q	The total power dissipated from the rack (kW)
δQ	the amount of heat gained in the cold air before entering the racks(kW)
Q_{cc}	Cooling Capacity of Refrigeration machine(TR)
T	Temperature(°C)
T_{ref}	the outlet air temperature of CRAC/IRU(°C)
T_{in}	the average intake temperature of the rack(°C)
T_{out}	the average outlet temperature of the rack(°C)
T_{supply}	the supply air temperatures to CRAC/IRU (°C)
T_{return}	the return air temperatures to CRAC/IRU(°C)
ΔT_{equip}	difference between intake and exhaust rack temperatures(°C)
$T_{i,\ max}$	the maximum intake air temperature of the rack(°C)
$T_{i,\ min}$	the minimum intake air temperature of the rack(°C)
T_i	the average intake air temperature of the rack(°C)
T_o	the average outlet air temperature of the rack(°C)
V^o	Air volume flow rate(m^3/s)
V_{in}	Inlet Air velocity of IRUs(m/s)
W	Width of DC Room(m)

Greek Symbol

β	Mean Temperature Difference Index of Rack Intake and Exhaust Air()
η_r	Energy Utilization Index()

Abbreviations

ASHARE	American Society for Heating, Air Conditioning, and Refrigeration Engineers
CRAC	Computer Room Air Conditioning

CRAH	Computer Room Air Handling
IRU	In-Row Cooling Unit
IT	Information Technology
R	Rack number
RCI	Return Cooling index
RHI	Return heat index
RTI	Return Temperature index
SHI	Supply Heat index
SRA	Server Racks Australia

CRediT authorship contribution statement

A.M. Abbas: Software, Data curation, methodology.

A.S. Huzayyin: Final review and check.

T.A. Mouneer: Data curation, methodology.

S.A. Nada: Conceptualization, Methodology, Writing - original draft, Writing - review & editing.

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