Applied Thermal Engineering 118 (2017) 339–344

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Effect of CRAC units layout on thermal management of data center

S.A. Nada *, M.A. Said

Department of Mechanical Engineering, Benha Faculty of Engineering, Benha University, Benha, P.O. 13511, Egypt

HIGHLIGHTS

- CFD study of thermal management in data centers.
- Effects of layout arrangements of the CRACs units relative to the racks array on data center performance.
- Design guide liens for data centers energy efficiency improvements.

ARTICLE INFO

Article history:
Received 21 November 2016
Revised 16 January 2017
Accepted 1 March 2017
Available online 2 March 2017

Keywords:
Data centers
CFD investigations
Thermal management
Layout arrangements of CRAC units

ABSTRACT

Comprehensive numerical studies of thermal management of data centers were presented by several investigators for different geometric and operating conditions of data centers. In the present work, a technical note regarding the effect of the computer room air conditioning (CRAC) units layout arrangements is presented. Two arrangements of CRAC units layouts are investigated; namely locating CRACs units in line with the racks row and locating the CRACs units perpendicular to the rack row. Temperature distributions, air flow characteristics particularly air recirculation and bypass and thermal management in data centers are evaluated in terms of the measureable overall performance parameters: supply/return heat indices (SHI/RHI) and return temperature indices (RTI). The results showed that locating CRAC units perpendicular to the racks row has the following effects: (i) enhances the uniformity of the air flow from the perforated tiles along the rack row, (ii) reduces the hot air recirculation at the ends racks of the row and the cold air bypass at the middle rack of the row and (iii) enhances the data center performance parameters RTI, SHI and RHI.

1. Introduction

Increasing data centers servers density, reducing servers sizes and maintaining energy efficiency represent a challenge of the air conditioning designer of data centers. Efficient air distribution and thermal management in data centers are the key factors to solve this challenge. In recent years, energy consumption by data centers servers and their cooling system was doubled leading to a critical concern of the electricity usage [1]. The increase of server's power density led to the increase in energy consumption of cooling systems to approximately 40% of data center's energy consumption [2,3]. Hot air recirculation and cold air bypass around the server's racks are the main problems to reliable operation and energy consumption of data centers (see Fig. 1).

Servers located at the bottom of servers racks are expected to receive cold air and servers located at the top of racks and ends of racks row may receive hot recalculated (see Fig. 1). Hot air recirculation results in high server's intake air temperature leading to hot spots in servers. Typically, pushing more air flow through the perforated tile or lowering the tile air flow temperature is used to avoid high servers intake temperature. In this case, the bottom servers will be over-cooled resulting in wasted cooling energy. Maintaining efficient airflow distribution for cooling of IT servers can provide high cooling efficiency with minimal effort. Servers racks and CRAC units layout arrangements strongly affect air flow and temperature distribution inside the data center.

Most of recent data centers studies are devoted to solve hot air recirculation problem and minimize cooling system energy consumption. There is a recent interest in performing data center studies using CFD tools validated with experimental data. Kang et al. [4] showed that a simple model of the volume of data center raised floor using the technique of flow network modeling (FNM) can predict the air flow distribution exiting from the various tiles. Schmidt et al. [5] numerically investigated the effect of raised-floor plenum depth and percentage of tiles perforation area on airflow rates through the perforated tiles for different arrangement of data center. They showed that 20% opening ratio and 60 cm plenum depth

* Corresponding author.
E-mail address: samehnadar@yahoo.com (S.A. Nada).

http://dx.doi.org/10.1016/j.applthermaleng.2017.03.003
1359-4311/

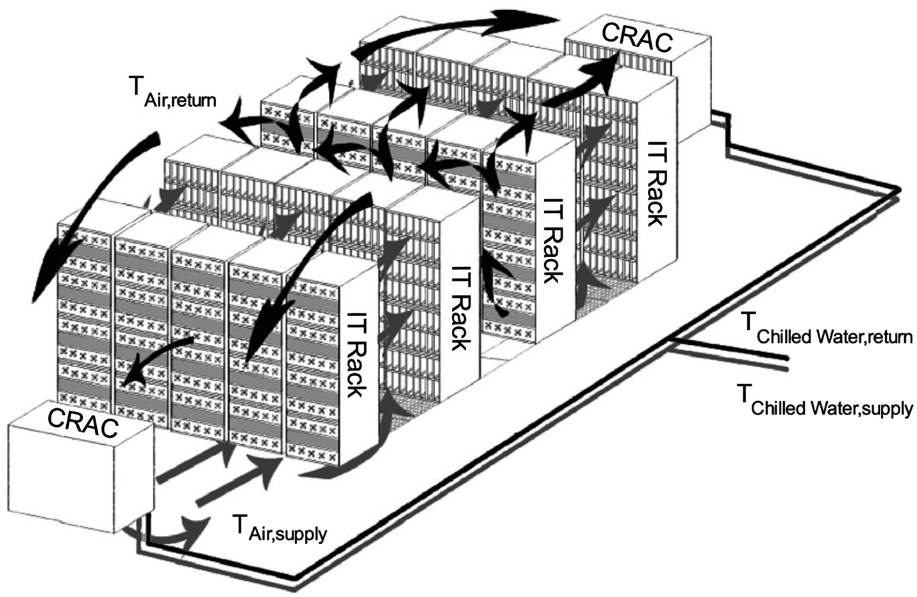

Fig. 1. Example of a typical data center [3].

leads to data center optimum performance. Karki et al. [6] presented a CFD model for predicting perforated tiles airflow rates in raised-floor data centers. To limit the calculation to only the raised floor space, the pressure in the space above the raised floor is assumed to be uniform. Abdelmaksoud et al. [7] reported that including of correct tile flow model, buoyancy, and realistic turbulent boundary conditions in the model are strongly improve data centers CFD simulation results. A momentum source model for tile flow was developed to correct mass and momentum modeling of air jets from the perforated tiles. Kim [8] presented a CFD study for air flow distribution in data centers for fan-assisted floor tiles and floor tiles with louvers. The fan-assisted tile was used to enable a variable local tile flow rate. The study recommended a control system for the active tile to avoid hot spots at a particular severs of the racks. Schmidt and Cruz [9] studied the effect of the distribution of airflows exiting the perforated tiles on rack inlet air temperatures. A computational fluid dynamics (CFD) tool called Tileflow (trademark of Innovative Research, Inc.) was used to generate the flow distribution exiting the perforated tiles. The effects of raised floor depth and perforated tile-free areas on rack inlet temperatures were also investigated. Cho et al. [10] conducted CFD simulation analysis in order to compare the heat removal efficiencies of various air distribution systems in a high heat density data center. Schmidt [11] numerically studied the effect of datacenter design parameters of actual data center floor plans on the uniformity of the perforated tile airflow using CFD model verified by experimental test data. It was found that decreasing the plenum depth leads to a reverse flow at perforated tiles near the CRAC units. Bhopte et al. [12] conducted a numerical parametric study to the effect of plenum depth, floor tile placement and ceiling height on the air flow distribution and thermal management of 12 kW racks power density. Karki et al. [13,14] used an idealized one-dimensional CFD model to study the effects of plenum depth and the opening ratio of the perforated tiles on the airflow distribution. The results showed significant variations in airflow distribution when changing plenum height or tile open areas. Sharma [15] studied the effects of cold aisle and hot aisle widths and ceiling space on data centers thermal performance. The study showed that data centers can be optimized not only based on geometric parameters but also based on heat loads using the non-dimensional parameters supply heat index (SHI) and return heat index (RHI) to evaluate the thermal design and performance. Ibrahim [16] conducted numerical study to investigate the effects of power density and IT servers thermal mass on airflow and thermal management of data center. The results showed that servers mass dictates how slowly or quickly the facility temperature rises or falls. More recently, Nada et al. [17–24] presented comprehensive numerical and experimental studies suing scale physical model to investigate the effects of power density, floor tiles opening ratio, lateral space between the CRAC unit and cold aisle, power loading conditions of servers and the using of cold aisles containments and partitions on the uniformity of the air flow, cold air bypass and hot air recirculation, temperature distribution around the servers of the racks, and the thermal management performance parameters (RTI, SHI, RHI and RCI). It was shown that (i) using cold aisle partitions with raised floor decreases the recirculation and bypass of air flow around the middle and first racks in a rack row, respectively and improves the performance of data center cooling system, (ii) using control of servers fans speeds improve the data center performance parameters and eliminate the possibility of hot spots existence.

The current literature illustrates that studies on the effects of CRAC units location, layout and arrangements inside the data center on air distribution, temperature distribution and thermal management of data centers are not available. In the present technical note, the effects of CRAC units layout arrangements on the air flow characteristics and thermal performance of the data centers are investigated. Supply/return heat indices (SHI/RHI) and return temperature indices (RTI) are used as measureable performance parameters of data center.

2. Physical model

A raised floor data center room of dimensions $6.71\ \text{m} \times 5.49\ \text{m} \times 3.0\ \text{m}$ is considered as the physical models of the present study. The data center houses 14 servers racks, each dissipating power of 3.5 kW. The racks are arranged in two rows with a spacing 1.22 m between the two rows. The racks rows are arranged to be at 1.22 m distance from the room wall. Typical raised floor plenum of depth 0.6 m and perforated tiles of size $0.6\ \text{m} \times 0.6\ \text{m}$ with an opening ratio of 25% are used for the analyses. Fourteen perforated tiles are used in the cold aisle to provide the supply cold air to the 14 racks. Two CRACs units are used to supply cold air to the plenum of data center. Two layout arrangements (Layout 1 and 2) of the CRAC units in the data centers are investigated. Fig. 2 shows these two arrangements. In layout 1, the CRAC units are located in the two opposite sides of the data center to be in line with the racks row. In layout 2, the two CRACs units are located in the other sides of the data center to be perpendicular to the racks row. The total cooling capacity of the CRACs unit(s) in the two arrangements are the same.

The CRACs units discharge the cold air at 12 °C to the plenum underneath the raised floor. All tiles are assumed to give the air flow rate to the racks at the same temperature (12 °C) and inlet velocity 1 m/s. The cold air pass through the racks to cool it. The hot air discharged from the rack servers flows out from the room through ceiling vents. Table 1 gives the boundary conditions for the physical model. The heat generation is estimated using the server flow rate and the air temperature difference across the server (approximately 10.19 °C [2]).

3. Mathematical formulation, numerical techniques and model validations

The governing equations (mass, momentum and energy equations) [17], boundary conditions given in the above sections and numerical solution techniques using finite volume discretization and considering were applied to solve the resulting coupled partial differential equations with in the three-dimensional data center computational domains. The results simulate fluid flow, temperature distribution and heat transfer in the physical model. CFD-Fluent-Solver is used for simulation. All simulations were run with the k-Epsilon turbulence model and the results were analyzed on CFD-Post. The two commercial CFD packages ANSYS FLUENT 14 and grid-generation software GAMBIT 2.4.6 are used for data processing, analysis and presentation. The convergence criterion for the root mean square values of the equation residuals was set to 0.001.

Table 1
Boundary conditions for physical model.

Boundary condition	Symbol	Formula	Value
Air inlet velocity	U_0	–	1.0 m/s
Air flow rate from tiles	Q_t	$Qt = U_0 A_{tile}$	0.294 m^3/s
Air inlet temperature	T_0	–	12.0 °C
Air flow rate through server	Q_s	$Qs = Q_t/4$	0.0735 m^3/s
Server heat generation	P_s	$Ps = \rho\, c_p\, Q_s\, \Delta T$	875.0 W
Tile opening ratio	σ_t	–	25.0%
Rack porosity	σ_r	–	35.0%

4. Performance parameters indices

A lot of non-dimensional performance-key parameters, RTI, SHI, RHI were previously used as indices parameters for the data centers performance. *RTI* is defined as the ratio of the airflow through CRACs over airflow through IT racks. RTI is used as a measure of data center energy performance. A value of RTI above 100% means existence of hot air re-circulation and the rise of racks intake temperatures. RTI below 100% means cold air by-passed the racks and returned directly to the CRAC. The optimum RTI target value as a measure of the energy performance is 100%.

The supply heat index (SHI) is defined as the ratio between heat gained by the air in cold aisle before entering racks and heat gain by air after leaving the rack exhausts. Assuming equal mass flow rates at inlet and outlet of racks, SHI can be rewritten as the ratio between air temperature rise before racks inlet, total air tempera-

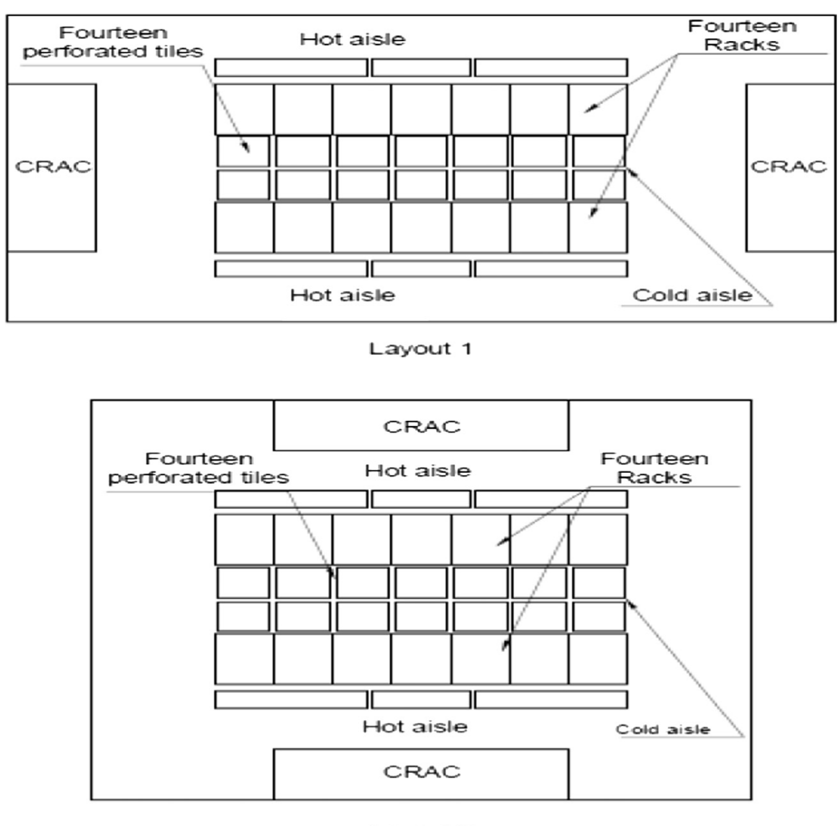

Fig. 2. Two layout arrangements of CRAC units distributions in data centers.

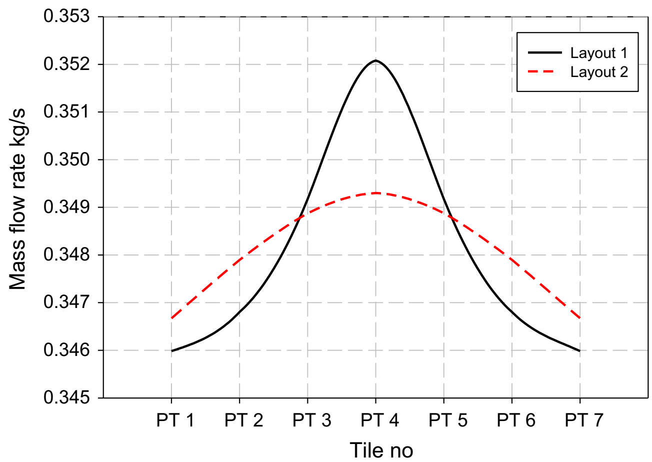

Fig. 3. Air flow rates distributions in perforated tiles for Layouts 1 and 2.

ture rise after rack exits. SHI is used as an indicator of thermal management and energy efficiency of racks. *RHI* is considered as a complement to *SHI*; *i.e.* $SHI + RHI = 1$. The ideal optimum values of SHI and RHI are 0 and 1 but the target practical values are 0.2 and 0.8.

Extensive grid refinement study has been carried out to determine the effect of grid size on the accuracy of the numerical solution and insure grid independent results. The index of overall performance parameters (SHI, RHI and RTI) were used to analyze the results of different levels of meshes to find the grid independent solution [17]. The capability of the present numerical model in predicting actual data of data center is checked by comparing the results of the present model with the results of previous experimental and numerical work [25–27].

5. Results and discussion

Numerical experiments were conducted for the two arrangements layouts of the CRACs units. In each layout, air flow and temperature distributions in the data center are obtained and analyzed. The data center performance index matrices SHI, RHI and RTI are calculated from the temperature distribution results.

Fig. 3 shows air flow rates throw the perforated tile in front of each rack of the racks row for the two layouts. The air flow rates distributions were obtained from modeling of the air plenum with the perforated tiles. For the two layouts, the figure shows that the air flow rate is symmetric around the middle rack due to the symmetric of the problem (equal distribution of the CRAC units on both sides of the racks row and CRAC units perpendicular to the rack row) where the air flow rates and consequently the air discharging velocity appears small in the tiles near the CRAC units and increases until it reaches its maximum in the middle perforated tile (PT4). This air flow distribution agrees with the results of Schmidt et al. [5] and Nada et al. [17] which show the same trend. This distribution of the air flow rate causes bypass of the cold air from the cold aisle to the hot aisle at the middle rack in layouts and causes recirculation of the hot air from the hot aisle to the cold aisle at the first and last racks of layouts. Fig. 3 also shows that air flow distribution in layout 2 is more uniform than layout 1. This uniformity reduces both of cold air bypass in the middle racks and hot air recirculation in the ends racks of the racks row.

Fig. 4 shows the temperature distribution around the first and middle racks of the racks row for layouts 1 and 2. As shown in the figure, in layout 1 a high recirculation of the hot air from the hot aisle to the cold aisle and cold air bypass occurs at the ends rack and middle racks, respectively. This causes hot spots at the upper servers of the ends racks and lower servers in the middle rack. This can be attributed to the air flow distribution along the racks row (see Fig. 3) where high air flow rates exists at the middle

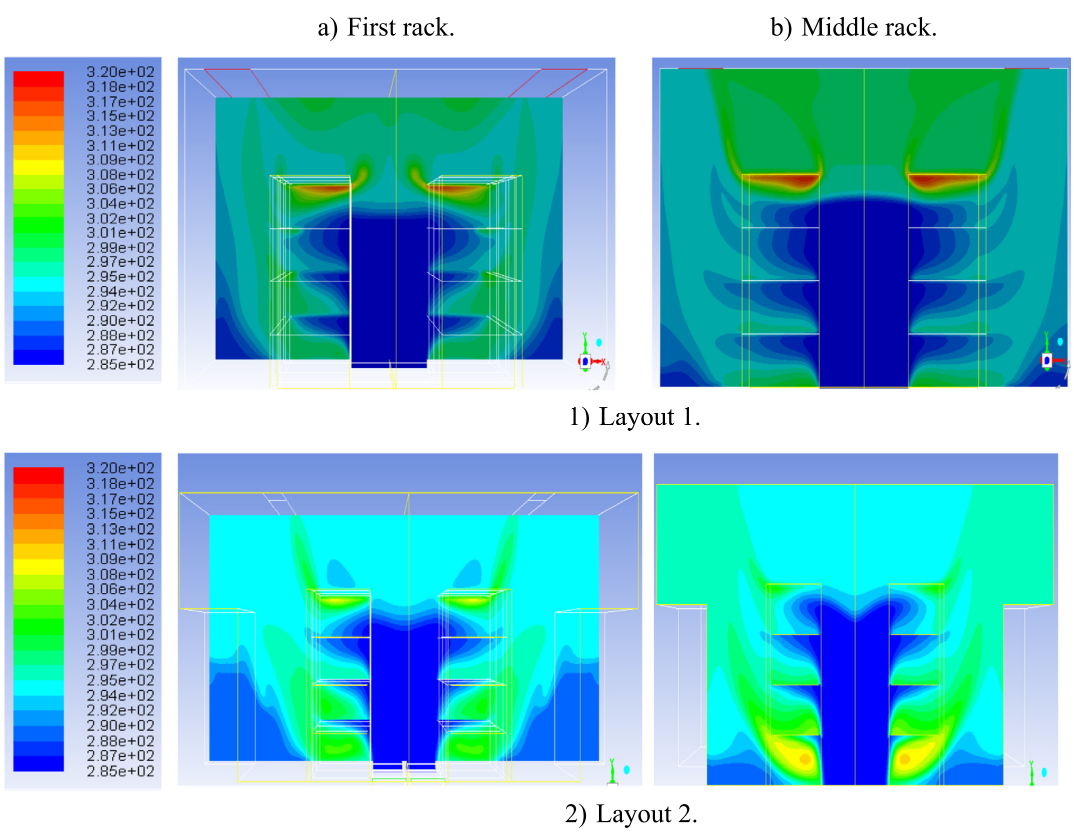

Fig. 4. Temperature distribution at the first and middle in layout 1 and 2.

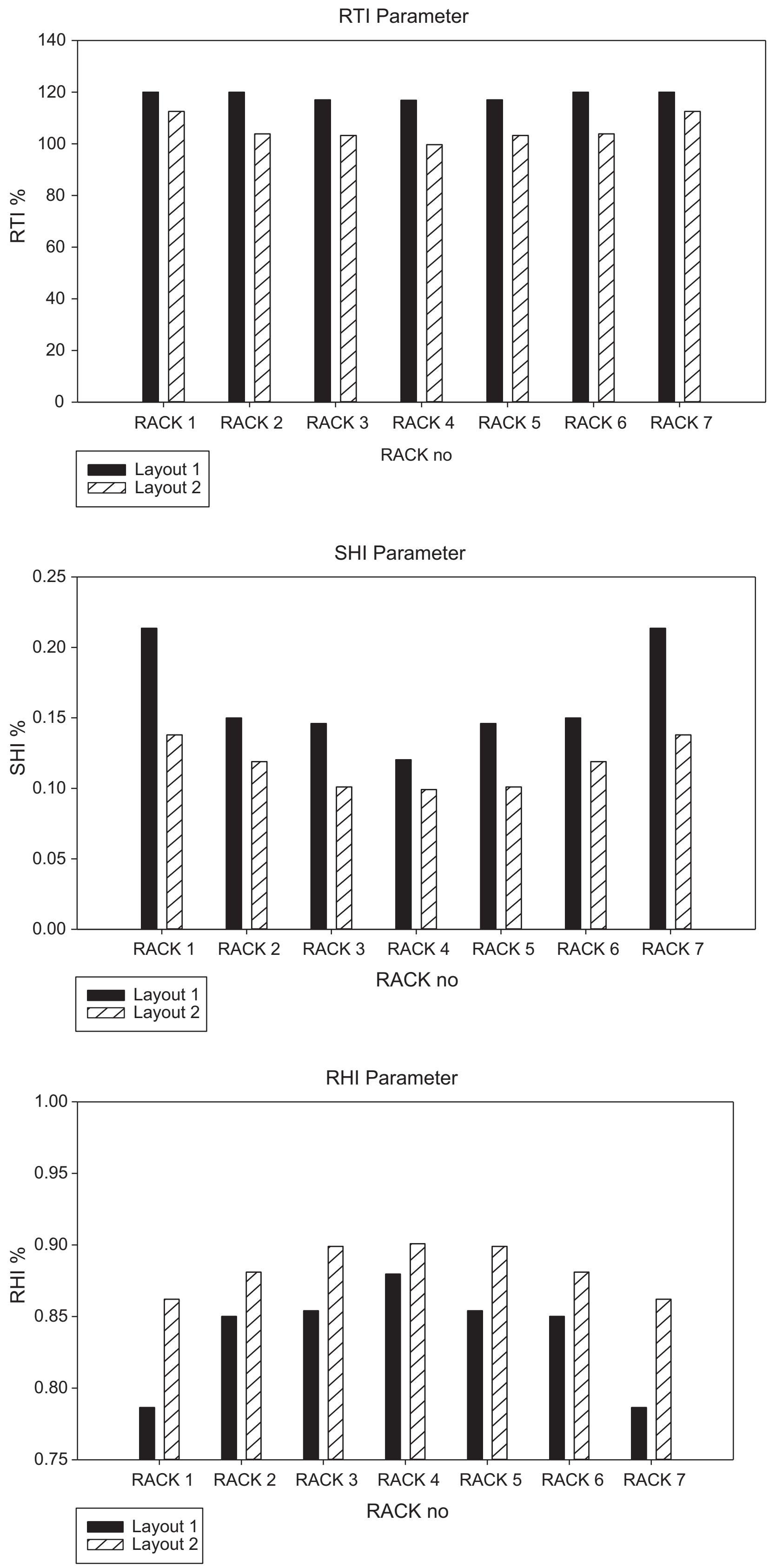

Fig. 5. Effect of rack numbers on RTI, SHI and RHI for Layouts 1 and 2.

rack and low air flow rate exists at the ends racks. However in layout 2, the air flow distribution along the racks row becomes more uniform where the air flow rate at the middle rack decreased and the air flow rate at the ends racks increased eliminating the cold air bypass and the hot air recirculation at the middle and ends racks, respectively. Eliminating the cold air bypass at the middle rack in layout 2 eliminates the hot spots formed at the bottom server of the middle rack but may create hot air recirculation at the top of the middle rack as shown in Fig. 4-b for layout 2.

Fig. 5 shows the comparison between the performance indices RTI, SHI and RHI of the two CRAC units layouts arrangements. The figure shows the symmetry of RTI, SHI and RHI around the fourth rack for the two layouts. This can be attributed to the symmetry in air flow rates around the fourth rack (see Fig. 3). Fig. 5 also shows the decrease of RTI and SHI and the increase of RHI in the two layouts as the rack number in the rack row increases until the fourth rack. This can be attributed to the increase of the air flow rate and air velocity with increasing the number of the rack in the row which leads to recirculation of the hot air from the hot aisle to the cold aisle at the first and second racks and bypass of the cold air at the middle rack. Increasing the air flow rate at the middle rack decreases the temperature of the zone around the rack servers and increases the possibility of the cold air bypass above the rack and this decreases SHI to the recommended value <0.2 (good) and decreases RTI (118% for layout 1 and to 100% to layout 2). Fig. 5 shows that SHI of end and middle racks in layout 2 lie in the recommended range (<0.2) and is lower than those of layout 2. The figure also shows that RTI of layout 2 lies in the recommended range (100%) and is lower than that of layout 1 which lies above the recommended range (>118%). This can be attributed to the decrease of the air flow rate at the middle rack and the increase of the air flow rate at the ends rack of layout 2 as compared to layout 1 which lead to the decrease of the cold air bypass at the middle rack and the hot air recirculation at the ends racks. However, in layout 1, increasing air flow rates at the middle of racks and consequently the reduction of the air flow rates in ends racks lead to hot air recirculation from the hot aisle to the cold aisle at the first and second racks leading to the increase of RTI and SHI of the ends racks to be outside the recommended range (RTI becomes more than 100% and SHI becomes more than 0.2).

The trends of RTI, SHI and RHI shown in Fig. 5 are supported by the temperature distribution around the first, middle and last rack that are shown in Fig. 4 where (i) hot air recirculation at the ends racks and cold air bypass with the appearance of hot spots at the bottom server of the middle racks are noticed for layout 1, and (ii) hot air recirculation at the first rack and cold air bypass at the middle rack were eliminated for layout 2 with the appearance of hot air recirculation at the middle rack.

6. Conclusions

Numerical investigations of the performance of high density data centers using perforated air tiles have been carried out for different layouts arrangements of the CRAC units. Temperature distribution, air flow characteristics particularly hot air recirculation and cold air bypass, cooling efficiency and thermal managements in data centers are evaluated in terms of the performance parameters (RTI, SHI and RHI). The results showed that locating the CRACs units perpendicular to the racks row (i) enhances the uniformity of the air flow from the perforated tiles along the rack row, (ii) reduces hot air recirculation at the ends racks and the cold air bypass at the middle rack of the row and (iii) enhances the overall performance parameters RTI, SHI and RHI of the data center.

References

[1] Jonathan G. Koomey, Worldwide electricity used in data centers, Environ. Res. Lett. 3 (3) (2008).

[2] Emerson Network Power, Energy Logic: Reducing Data Center Energy Consumption by Creating Savings that Cascade Across Systems, a White Paper from the Experts in Business-Critical Continuity, 2008.

[3] T.J. Breen, E.J. Walsh, J. Punch, et al., From chip to cooling tower data center modeling: chip leakage power and its impact on cooling infrastructure energy efficiency, J. Electron. Packag. 134 (4) (2012) 041009, http://dx.doi.org/10.1115/1.4007744.

[4] S. Kang, R.R. Schmidt, K.M. Kelkar, A. Rdmehr, S.V. Patankar, A Methodology for the Design of Perforated Tiles in Raised Floor Data Centers Using Computational Flow Analysis, ITherm, 2000.

[5] R. Schmidt, K. Karki, K. Kelkar, A. Radmehr, S. Patankar, Measurements and predictions of the flow distribution through perforated tiles in raised floor data centers, in: Advanced in Electronic Packaging 2001, Proceedings of IPACK'01, and the Pacific Rim/ASME International Electronic Packaging Technical Conference and Exhibition in Kauai, vol. 2, Paper IPACK2001-15728, 2001b, pp. 905–914.

[6] K.C. Karki, A. Radmehr, S.V. Patankar, Use of computational fluid dynamics for calculating flow rates through perforated tiles in raised-floor data centers, Int. J. Heat. Vential. Air-Condit. Refrig. Res. 9 (2) (2003) 153–166.

[7] W.A. Abdelmaksoud, H.E. Khalifa, T.Q. Dang, B. Elhadidi, R.R. Schmidt, M. Iyengar, Experimental and computational study of perforated floor tile in data centers, in: ITherm, 2012.

[8] Sang Kim, Effectiveness of Specialized Floor Tile Designs on Air Flow Uniformity, BS, State University of New York at Binghamton, 2009.

[9] R.R. Schmidt, E. Cruz, Cluster of high-powered racks within a raised-floor computer data center: effect of perforated tile flow distribution on rack inlet temperatures, ASME J. Electron. Packag. 126 (2004) 510–518.

[10] Jinkyun Cho, Taesub Lim, Byungseon Sean Kim, Measurements and Predictions of the Air Distribution Systems in High Compute Density (Internet) Data Centers, Yonsei University, Seoul 120-749, South Korea, 2009.

[11] Roger R. Schmidt, Airflow uniformity through perforated tiles in a raised-floor data center, in: Proceedings of IPACK2005, 2005.

[12] S. Bhopte, R. Schmidt, D. Agonafer, B. Sammaika, Optimization of data center room layout to minimize rack inlet air temperature, J. Electron. Packag. 128 (4) (2006) 380–387, http://dx.doi.org/10.1115/1.2356866.

[13] Kailash C. Karki, Suhas V. Patankar, Airflow distribution through perforated tiles in raised-floor data centers, Innovative Research, Inc., 3025 Harbor Lane North, Suite 300, Plymouth, MN 55447, USA, 2005.

[14] Kailash C. Karki, Suhas V. Patankar, Amir Radmehr, Techniques for controlling airflow distribution in raised-floor data centers, in: Proceedings of IPACK03 the Pacific Rim/ASME International Electronic Packaging. Technical Conference and Exhibition. July 6–11, 2003, Maui, Hawaii, USA, 2003.

[15] Ratnesh K. Sharma, Dimensionless Parameters for Evaluation of Thermal Design and Performance of Large-Scale Data Centers, Hewlett-Packard Laboratories, 2002.

[16] Mahmoud Ibrahim, Dynamic Thermal Management of Data Centers, Binghamton University, State University of New York, 2012.

[17] S.A. Nada, M.A. Said, M.A. Rady, Numerical investigation and parametric study for thermal and energy management enhancements in data centers' buildings, Appl. Therm. Eng. 98 (2016) 110–128.

[18] S.A. Nada, M.A. Said, M.A. Rady, CFD investigations of data centers' thermal performance for different configurations of CRACs units and aisles separation, Alex. Eng. J. (2016), http://dx.doi.org/10.1016/j.aej.2016.02.025.

[19] S.A. Nada, M.A. Rady, M. Elsharnoby, M.A. Said, Numerical investigation of cooling of electronic servers racks at different locations and spacing from the data center cooling unit, Int. J. Curr. Eng. Technol. 5 (5) (2015).

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

[21] S.A. Nada, K.E. Elfeky, A.M.A. Attia, Experimental investigations of air conditioning solutions in high power density data centers using a scaled physical model, Int. J. Refrig. 63 (2016) 87–99.

[22] S.A. Nada, K.E. Elfeky, Experimental investigations of thermal managements solutions in data centers buildings for different arrangements of cold aisles containments, J. Build. Eng. 5 (2016) 41–49.

[23] S.A. Nada, A.M.A. Attia, K.E. Elfeky, Experimental study of solving thermal heterogeneity problem of data center servers, Appl. Therm. Eng. 109 (2016) 466–474.

[24] S.A. Nada, K.F. Elfeky, A.M.A. Attia, W.G. Alshaer, Experimental parametric study of servers cooling management in data centers buildings, Heat Mass Transfer (2017), http://dx.doi.org/10.1007/s00231-017-1966-y.

[25] Magnus K. Herrlin, Rack cooling effectiveness in data centers and telecom central offices: the Rack Cooling Index (RCI), ASHRAE Trans. 111 (Part 2) (2005), American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, GA.

[26] W. Abdelmaksoud, Experimental and Numerical Investigations of the Thermal Environment in Air-Cooled Data Centers Ph.D. thesis, Department of Mechanical and Aerospace Engineering, Syracuse University, Syracuse, NY, 2012.

[27] H. Fernando, Can a Data Center Heat-Flow Model be Scaled Down, The University of Melbourne, Parkville, Melbourne, Australia, 2012.