CFD Letters

Journal homepage:
https://semarakilmu.com.my/journals/index.php/CFD_Letters/index
ISSN: 2180-1363

A Comparative Numerical Study of Effectiveness of Cold Aisle Containment in Data Centers by Varying Rack Porosity Using Computational Fluid Dynamics

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ARTICLE INFO

Article history:
Received 18 October 2023
Received in revised form 20 November 2023
Accepted 17 December 2023
Available online 30 April 2024

Keywords:
Cold aisle containment; Data center; Numerical study; Porosity

ABSTRACT

Depending on specific needs and workloads, several racks with varied component densities may be used in a data center. As server density increases, porosity decreases, and the opposite is also true. A frequently used method called cold aisle containment separates hot air and cold air flows in data center settings to improve cooling effectiveness. In this paper, the performance of a data center is investigated using computational fluid dynamics, and the influence of porosity on cold aisle containment is evaluated using well-established non-dimensional performance parameters. The value of RTI without containment increased with an increase in porosity and a maximum RTI of 217 was found with a porosity of 0.75. Regardless of the rack number and porosity, containment provides the optimal RTI values. The results indicate that the SHI and RHI values for rack 1 for all porosities, without confinement, are outside of the permissible range and at higher porosities containment has no significant effects on SHI and RHI. RCILO values for racks 2, 3, and 4, with or without containment, fall within the 80-85% range, indicating temperatures below 13°C. RCIHI value is 1 for all cases considered indicating no rack is out of the recommended temperature of 25°C.

1. Introduction

A data center is a building that houses essential computer systems and associated hardware, such as servers, networking equipment, storage systems, and infrastructure for cooling and electricity. Information Technology (IT) equipment performs efficiently in the controlled and secured environment data centers provide. Data centers are required to handle the growing demand for digital services. Given the increasing cost of energy, data center operations must be improved to be more environmentally friendly and energy efficient. Data centers use a significant portion of their energy to meet the cooling demand and the energy distribution within a data center. Excessive

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https://doi.org/10.37934/cfdl.16.9.94113

energy use might be a result of ineffective cooling systems and poor airflow management. They need effective cooling systems that are capable of maintaining the right temperature and humidity levels, as well as dependable electrical systems that can guarantee a consistent supply of electricity [1–4]. Figure 1 represents the typical layout of a room-based, raised floor air-cooled data center. The most effective way of air distribution inside a data center is by supplying cold air through the raised floor and extracting the return air through the ceiling. A standard raised floor design with a plenum space beneath is used in air-cooled data centers to distribute conditioned air. Perforated tiles that are strategically positioned on the elevated floor enable conditioned air to go from the plenum into the data center room. The cold aisle and hot aisle are designated spaces for server racks. The IT equipment in a data center receives cool air from the cold aisle while hot air after absorbing heat is expelled to the hot aisle. The cold air that is drawn into the server rack from the front circulates inside the rack absorbing heat produced by the servers. After passing through the equipment racks and absorbing the heat, the cold air warms up and changes into hot air. The hot air is subsequently expelled from the equipment racks' backside into the hot aisles, where it is further directed towards the Computer Room Air Handling (CRAH)) units for removal and cooling. However, this method frequently leads to inefficient airflow, mixing of hot and cold air streams, and higher energy usage [5–7].

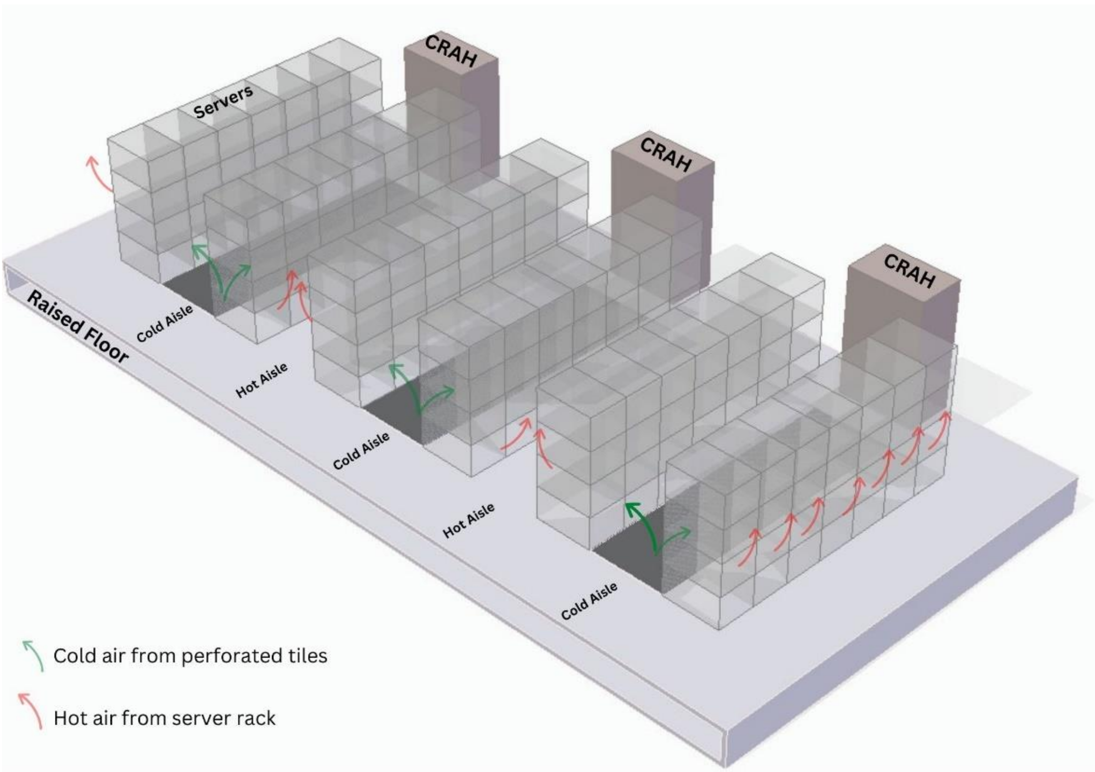


Fig. 1. Typical layout of raised floor air-cooled data centers

1.1 Challenges in Traditional Air Cooling

The main drawbacks of raised floor data centers are that hot air coming from the hot aisle can enter the cold aisle again, which is termed hot air recirculation, and cold air can enter the return air duct without passing through the server rack is termed cold air bypass [8]. However, there is little that can be done in an open space to efficiently prevent this. Figure 2 shows recirculation and bypass zones.

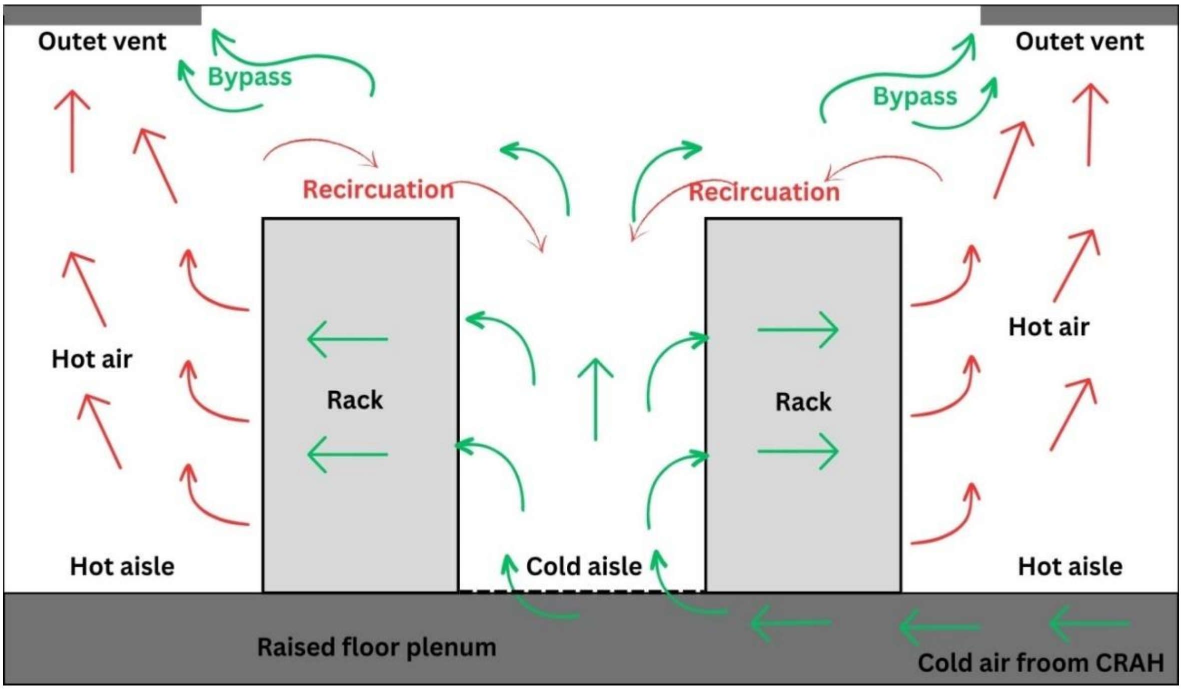


Fig. 2. Challenges encountered in raised floor air-cooled data centers

The following paragraph summarizes several studies that have been conducted to enhance a data center's thermal performance. Cho *et al.,* [9] have conducted a Computational Fluid Dynamics (CFD) study on a data centre and suggested installing aisle partition walls up to a particular height to divide cold and hot aisles which considerably increased cooling effectiveness. It was concluded that temperature differences with height may be decreased to 10^0 C with partition walls, compared to 15^0 C without partition and return temperature drops by 1.4 C. Cho *et al.,* [10] have examined the efficiency of Hot Aisle Containment (HAC) for hard floor and raised floor data center. They discovered that employing a raised floor in combination with HAC increased cooling efficiency by 28%, leading to a 40% decrease in recirculation and significant energy savings. As a result, HAC with a raised floor is a useful method for preserving the ideal operating conditions for data centers. Shrivastava *et al.,* [11] The advantages of a Cold Aisle Containment (CAC) system are demonstrated in this study article. Compared to the typical arrangement, test findings show that CAC consistently produces low cabinet inlet air temperatures and saves around 22% on cooling energy. Lee *et al.,* [12] have studied a CAC with an overhead downward flow cooling system with a heat exchanger and an evaporative water chiller as a part of the design. The power usage effectiveness of 1.38 demonstrates the substantial energy savings potential offered by this approach. Three configurations namely open, side containments (semi-enclosed) and sides and top containments (fully enclosed)were examined by the authors Nada *et al.,* [13] and Gondipalli *et al.,* [13, 14] and they concluded that thermal management and energy efficiency were enhanced using both containment configurations CAC significantly enhanced the energy efficiency and thermal performance of a data centre. Choo *et al.,* [15] focused on an experimental, numerical and simulation study of a medium-sized data center. Conclude that CAC was a useful energy-saving strategy for improving thermo-fluid flow and lowering energy usage. Muralidharan *et al.,* [16] Study demonstrate the advantages of using CAC, showing a significant cooling energy savings of 22% compared to the standard configuration. A CAC system was installed in their data center to reduce inlet temperatures, but the findings were unreliable. CFD simulation was employed to evaluate the performance of the data center by Goren., [17]. The findings of the modelling and measurement were in agreement, pointing to two airflow problems: an airflow deficit and faulty installation of the rear fan doors. The CACS was optimized by using CFD-guided recommendations that reduced temperature fluctuations and energy usage. Wang *et al.,* [18] studied the effectiveness of a container data center with ten racks supplied by a drop ceiling, the consequences of various obstacle layouts, and cold-aisle confinement were explored in this study. Testing indicated hot air recirculation at the entrance to the cold aisle. The configuration with the enclosing door at the entry of the cold aisle, but with the cold aisle left open, significantly improved the temperature distribution, and the RCI of 99% because of a good balance between the pressures in the hot and cold aisles. Sheth *et al.,* [19] investigated the thermal performance of a data center using a porous media approach with servers having uniform volumetric heat generation. Tiles are also modelled as porous media having porosity of 0.25 and Fans are modelled as momentum sources. It was concluded that by moving the outlet vent from the ceiling to the bottom of the wall facing the hot aisle side, the maximum temperature was reduced by up to 8.3 °C. The fluid flow and recirculation were significantly impacted by the fan speed and different porosities. They concluded that a certain amount of recirculation is inevitable without containment solutions since servers at the end are subject to a high level of recirculation.

Even though few works of the literature include experimental techniques for getting results within the data center it is found to be expensive and also impractical due to their continuous operation [20–22]. The technique that is consistently employed for simulating fluid flow and studying heat transfer inside data centers is CFD modelling [23, 24]. The majority of the literature that has used CFD to predict performance has used black box modelling, reduced order modelling, energy analysis modelling, the Galerkin approach and flow network modelling. The approaches described have their advantages and limitations in computation. One of the most important aspects of data center design and operation is data center density, or the concentration of computing devices in a certain area. Depending on the requirements and load of the equipment it holds, a data center's density may vary. Depending on the demands and load of a given data center, multiple racks with varied component densities are employed. Higher and more complicated computations can create more heat and may call for more sophisticated equipment, which in turn may increase the density of the data server, resulting in less porosity and ultimately a higher cooling load. Sheth *et al.,* [19] and Narasimhan *et al.,* [25] recently proposed a porous media approach which was found to be computationally effective and offers valuable insights into the data center’s thermal performance. To balance performance and operational efficiency, the precise density level should be carefully selected to fit the needs of the equipment and the resources at hand. Porosity is a representation of server density. As porosity changes, volumetric heat production varies, and lower porosity indicates higher density while higher porosity indicates lower density. In the current study, CAC and its effect on the data centers thermal performance using a porous media approach for various porosity ranging from 0.35 to 0.75 is studied numerically.

1.2 Non-dimensional Performance Parameters

Non-dimensional performance parameters, such as Return Temperature Index (RTI), Supply/Return Heat Index (SHI/RHI), and Rack Cooling Index (RCI), are used during the design and operating phases to evaluate the effectiveness of the DC airflow and thermal management [26–28]. A value of 100% is the target for RTI, values below 100% indicate a cold air bypass, whereas RTI values above 100% indicate recirculation. Higher or lower RTI readings that differ from the ideal value of 100% are a sign of a poor thermal management system. SHI indicates the sensible heat that air in the cold aisle acquires before it enters the racks. The target for SHI is 0, but 0.2 is considered to be acceptable; the target for RHI is 1, but 0.8 is considered to be acceptable. The RCI is used to quantify the extent to which the rack intake temperatures lie in the allowable range recommended by the

American Society of Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE) [29–33]. Recommended and allowable temperature ranges defined by AHSRAE are depicted in Table 1. The range of target and acceptable non-dimensional performance parameters are shown in Table 2.

$$RTI = \frac{T_{return} - T_{supply}}{\Delta T_{sever}} \times 100\ \% \tag{1}$$

$$SHI = \frac{T_{intake} - T_{supply}}{T_{exit} - T_{supply}} \tag{2}$$

$$RHI = \frac{T_{return} - T_{supply}}{T_{exit} - T_{supply}} \tag{3}$$

$$RCI_{HI} = \left[1 - \frac{\Sigma(T_{intake} - T_{max-rec})\ _{T_{intake} > T_{max-rec}}}{(T_{max-all} - T_{max-rec})n}\right] \times 100\% \tag{4}$$

$$RCI_{LO} = \left[1 - \frac{\Sigma(T_{min-rec} - T_{intake})\ _{T_{intake} < T_{min-rec}}}{(T_{min-rec} - T_{min-all})n}\right] \times 100\% \tag{5}$$

Table 1
ASHRAE thermal guidelines

Parameter	Representation	Value
Minimum recommended temperature	$T_{min-rec}$	13^0 C
Minimum allowed temperature	$T_{min-all}$	10^0 C
Maximum recommended temperature	$T_{max-rec}$	25^0 C
Maximum allowed temperature	$T_{max-all}$	32^0 C

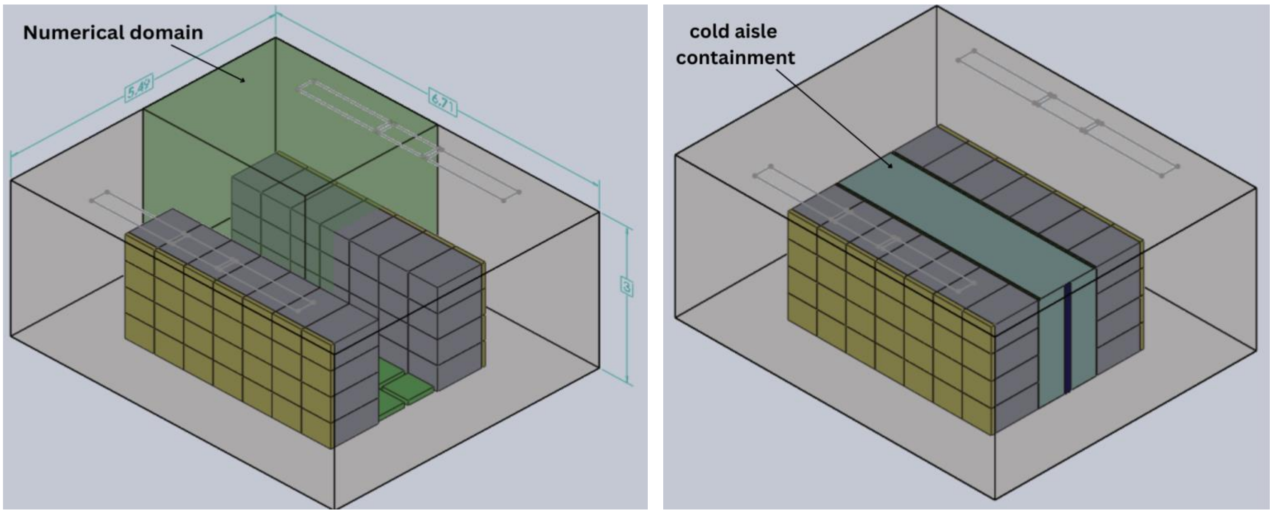
Table 2
Range of non-dimensional performance parameters

Non-dimensional performance parameters	Range
RTI	Target 100% , Acceptable > 100% ± 5%
SHI	Target 0, Acceptable < 0.2
RHI	Target 1, Acceptable > 0.8
RCI_{HI}	Target 100 % Acceptable > 96 %

2. Data Center Modeling

2.1 Physical Model

The physical model for the present investigation is a raised floor data center with the following measurements: 6.71 m 5.49 m and 3.0 m. The data center under consideration has 14 server racks that are placed in two rows, with a 1.22 m distance between each row. The racks are positioned 1.22 meters apart from the room's wall. To give cold air to the 14 racks in the cold aisle, fourteen perforated tiles are used. Figure 3 shows the traditional and cold aisle-contained data center model. Fernando *et al.,* [34] have conducted a CFD study of a data center and found that between the scaled model and the full-scale prototype, thermal equivalence in terms of temperature distribution may be reached with a 5% error margin. This implies that there is a strong similarity between the temperature patterns in the scaled model and those in the real data center. Prior research has demonstrated scaled-down model theory and its viability in obtaining thermal similarity [13, 35]. Due to the geometric model's symmetrical characteristics, the numerical domain is reduced to one-fourth of the whole data center area, as illustrated in Figure 4.



(a) (b)

Fig. 3. Physical model of a full data center (a) Without containment (b) With containment

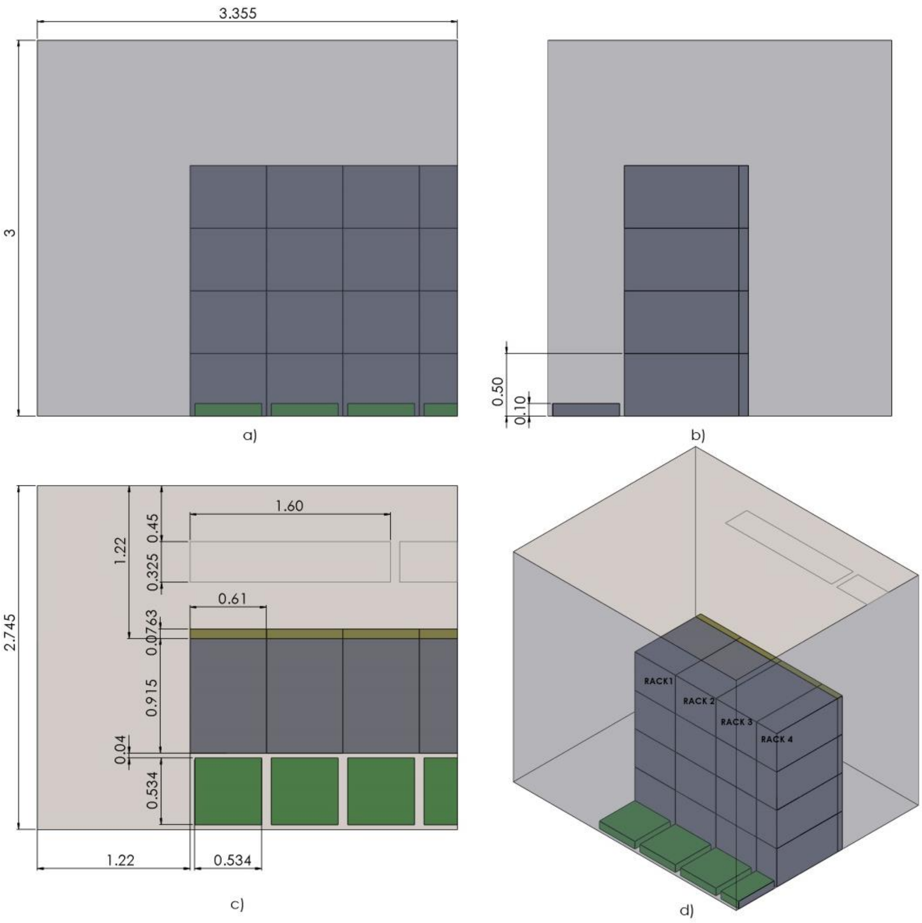


Fig. 4. Physical model of a quarter data center (a) Front view (b) Side view (c) Top View (d) Isometric view

2.2 Governing Equations

To reduce the computational cost the effect of radiation, buoyancy and air leakages are neglected. The flow is assumed to be steady, turbulent and incompressible. The governing equations used to simulate fluid motion and heat transmission are continuity, momentum, and energy equations as shown in Eq. (6) to Eq. (8).

Continuity equation:

$$\rho\nabla \cdot (\vec{u}) = 0 \tag{6}$$

Where $\vec{u}$ the fluid velocity vector and ρ is the fluid density

Momentum equation:

$$\rho(\vec{u} \cdot \nabla\vec{u}) = -\nabla p + \mu\nabla^2\vec{u} + \rho\vec{g} + S \tag{7}$$

where μ is the viscosity coefficient, p is the pressure, $\rho\vec{g}$ is the body force and S represents the heat source term.

Energy equation:

$$\rho Cp[(\vec{u} \cdot \nabla)T] = k\nabla^2 T + S \tag{8}$$

Where k is the thermal conductivity, Cp is the specific heat

Reliable simulation results can be obtained by the traditional k-Ɛ model as mentioned by referred literature [36–38], the same has been used in the current study, and Eq. (9). and Eq. (10). describe the same.

Turbulent kinetic energy equation:

$$\rho(\vec{u} \cdot \nabla)\kappa = \nabla \cdot \left[\left(\mu + \frac{\mu_T}{\sigma_k}T\right)\nabla\kappa\right] + G_k - \rho\varepsilon + S_k \tag{9}$$

Turbulent kinetic energy dissipation rate equation:

$$\rho(\vec{u} \cdot \nabla)\mathcal{E} = \nabla \cdot \left[\left(\mu + \frac{\mu_T}{\sigma_{\mathcal{E}}}\right)\nabla_{\mathcal{E}}\right] + C_{\mathcal{E}1}\frac{\mathcal{E}}{k}\,G_k - C_{\mathcal{E}2}\rho\frac{\varepsilon^2}{k} + S_{\mathcal{E}} \tag{10}$$

Where G_k is the turbulence kinetic energy due to the average velocity gradient.

The value of constants are $C_{\mathcal{E}1}$= 1.44, $C_{\mathcal{E}2}$ =1.92, C_μ =0.09, σ_k = 1.0 and σ_ϵ = 1.0 as mentioned in Ref. [39, 40]

Boundary conditions are derived from Sheth *et al.,* [19] and Fernando *et al.,* [34]. The volumetric heat generation in a server is 3136.29 W/m^3 at porosity 0.35 using an assumed temperature differential of 10.19^0 C and a designed mass flow rate of 0.0713m^3/s. The volumetric heat generation term is approximated linearly while accounting for server porosity equal to Ø make the servers homogenous. Eq. (11) is used to linearly modify the heat production term using the reference values of 3136.29 W/m^3 for the volumetric heat generation term and 0.35 as the reference porosity[19]. Calculated volumetric heat generation using Eq. (11) is shown in Table 3.

$$Q_{s,\emptyset} = Q_{s\,ref} \frac{(1-\emptyset)}{(1-\emptyset_{ref})} \tag{11}$$

Table 3
Volumetric heat generation

Porosity	Volumetric heat generation (W/m^3)
0.35	3136.290
0.45	2653.784
0.55	2171.278
0.65	1688.772
0.75	1206.265

2.3 Boundary Conditions

Boundary conditions used to solve the numerical models are shown in Table 4.

Table 4
Boundary conditions

Parameter	Value	Parameter	Value
Room size	6.79 x 5.49 x 3m	Tile size	0.534 x 0.534 x 0.1m
Number of racks	14	Tile porosity	0.25
Rack size	0.61 x 0.915 x 2 m	Inlet temperature	12.3^0 C
Rack porosity	0.35 to 0.75 (Step size 0.1)	Inlet velocity	1m/s
Cooling fan size	0.61 x 0.5 x 0.0763m	Mesh size	0.05 m
Fan momentum	25 N/m^3	CFD solver model	k-Epsilon turbulence

The physical model is created using ANSYS Design Modeler 15. Mesh creation and numerical simulations are done using the mesh package and fluent that comes with ANSYS Workbench 15. The SIMPLE approach for pressure-velocity coupling was used as the method of solution. Various equations were spatially discretized utilizing techniques including least squares cell-based, second-order, and first-order upwind. For continuity, momentum, kinetic energy, and dissipation, the convergence equations, limit was set at 10^{-3}. The convergence criterion was set to 10^{-6} for the energy equation. To make the computation simpler, cooling fans are treated as a source of momentum [19, 34, 41].

2.4 Grid Independence Study

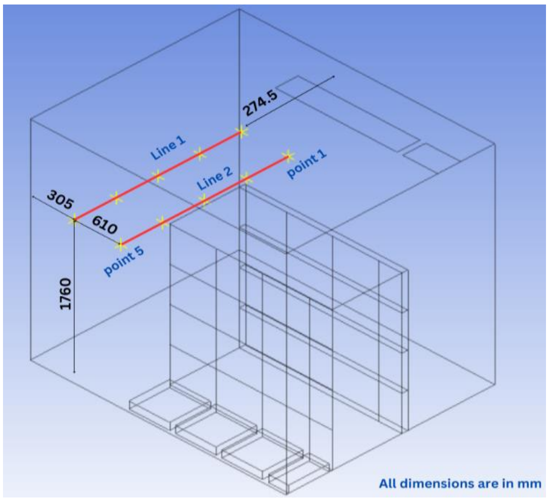
The mesh was created using structured hexahedral elements. A grid refinement was done to determine the smallest grid size that has a lesser impact on the computational solution. To get the different mesh density maximum face size is varied from 0.1m to 0.02m. Different mesh sizes, from a coarse grid of 936802 elements to the finer grid size of 3,520457 elements, are used to model grid-independent solutions as shown in Table 5. For subsequent simulations, fine mesh is chosen because it requires relatively less computational time.

Table 5
Effect of different grid sizes on maximum temperature

Mesh	Maximum face sizes	Nodes	Elements	Maximum temperature (°C)	Error (%)
Coarse	0.1	983209	936802	33.95	9.83
Medium	0.05	1872931	1823247	36.18	3.90
Fine	0.03	2677784	2621065	37.50	0.39
Finer	0.02	3594701	3520457	37.65	-

2.5 Validation

Validation of the numerical model was done at 10 distinct points on two lines as shown in Figure 5(a) and compared to the results with Fernando *et al.,* [34]. A comparison between the results of the current numerical model and the findings of Fernando's earlier numerical study is shown in Figure 5(b). The temperatures derived from the current simulations and those reported, with the largest error at 6.9 %, are in fair agreement, The error may have been caused by treating servers and tiles as porous blocks rather than momentum sources, which would have considered the impacts of the fans' resistances.



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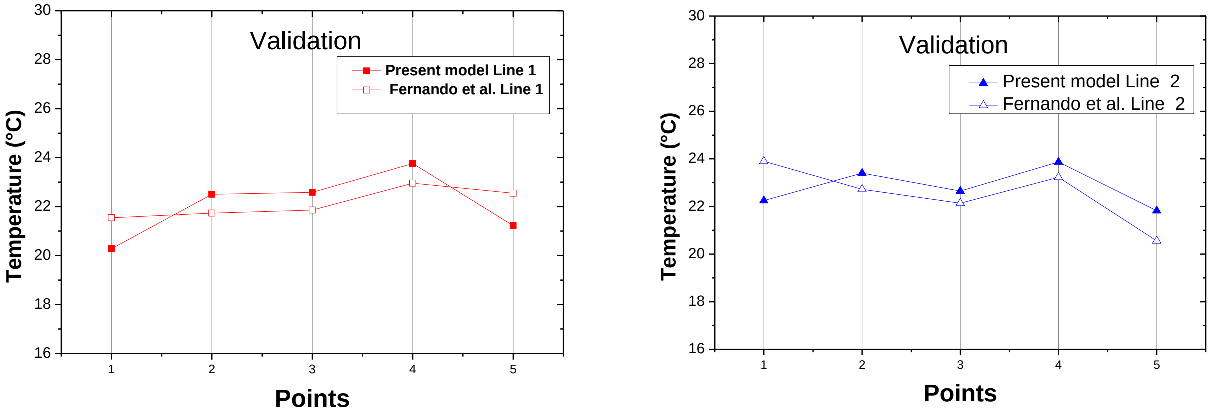
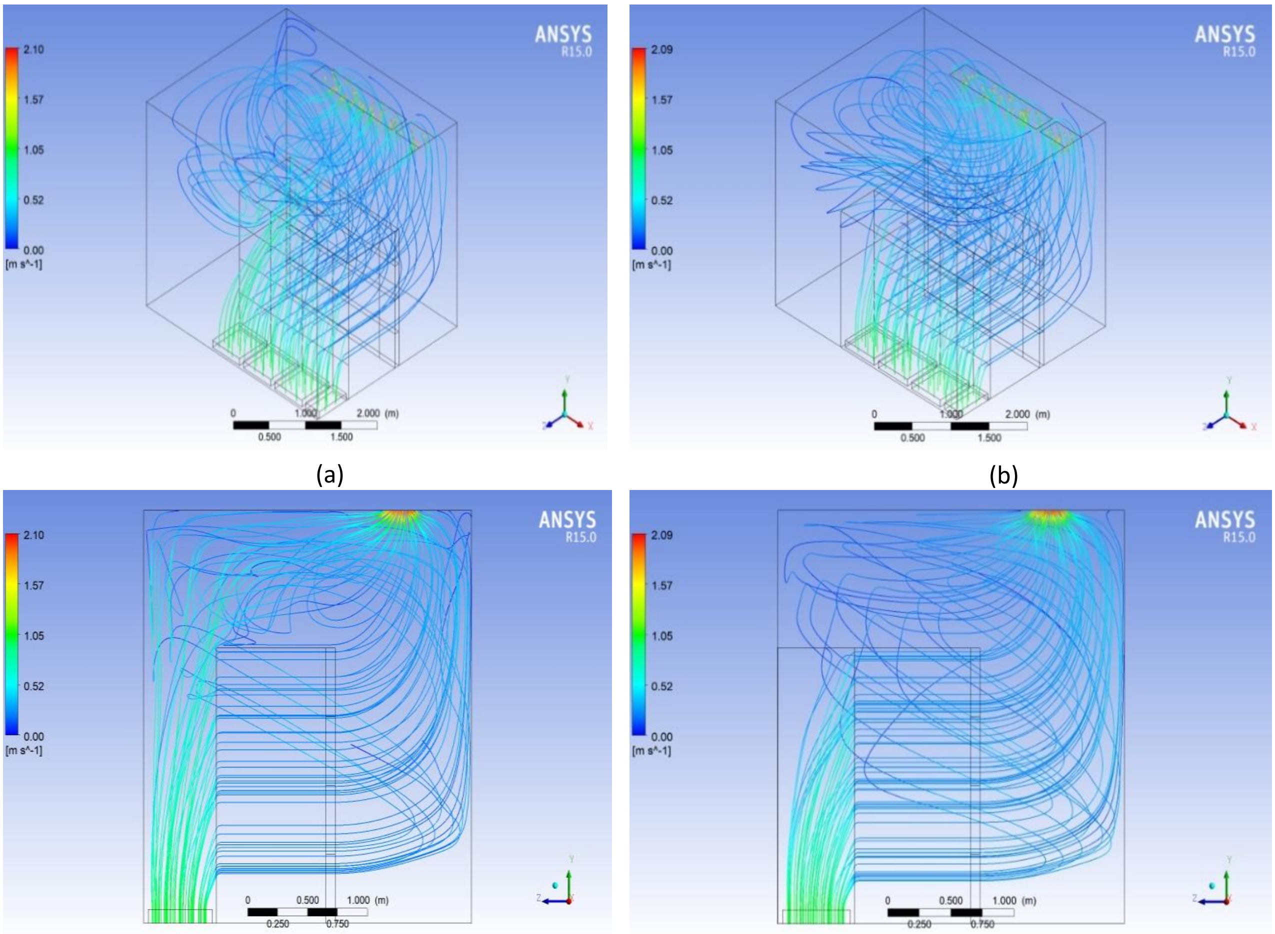


(b)

Fig. 5. Validation of present results (a) Points considered for validation (b) Comparison of results with Fernando *et al.,* [11]

3. Results and Discussions

Numerical simulations were used to examine the impact of CAC at various porosities on airflow and temperature distribution within a data center. The results of this analysis were used to compute and assess RTI, SHI, RHI and RCI which reflect cooling efficiency and temperature management. The velocity streamlines in the isometric and YZ planes, both with and without containment, are shown in Figure 6. It can be seen from Figure 6(c) that cold air is reaching the outlet without entering the rack which is a clear case of bypass. Figure 6(d) illustrates how containment limits the ability of cold air to bypass. Figures 6(a) and (b) show that streamlines are recirculating to rack 1 in the absence of containment, but they are confined in the presence of containment.

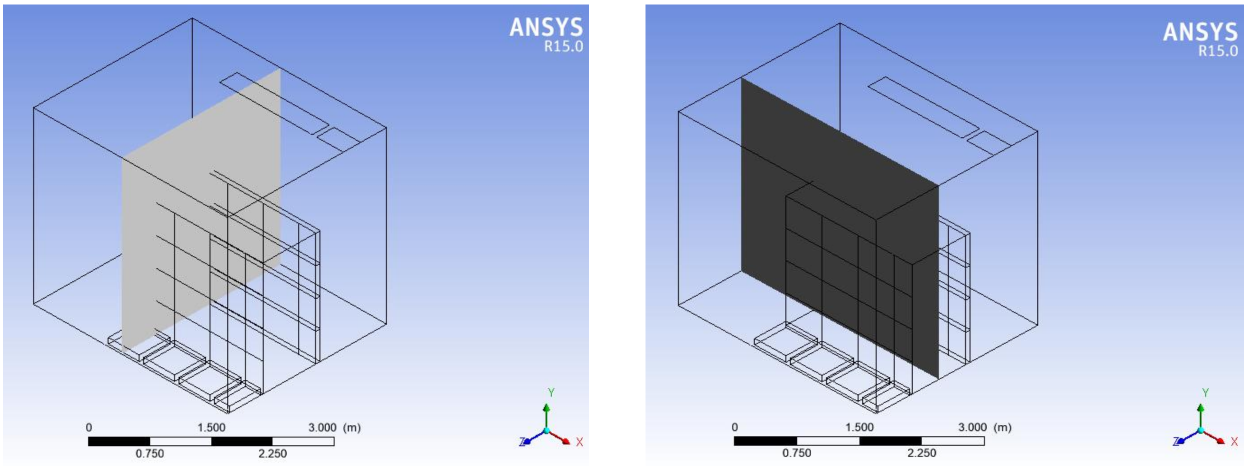


(a) (b)

(c) (d)

Fig. 6. Velocity streamlines (a) Velocity streamlines without containment isometric view (b) Velocity streamlines with containment isometric view (c) Velocity streamlines without containment YZ plane (d) Velocity streamlines with containment YZ plane

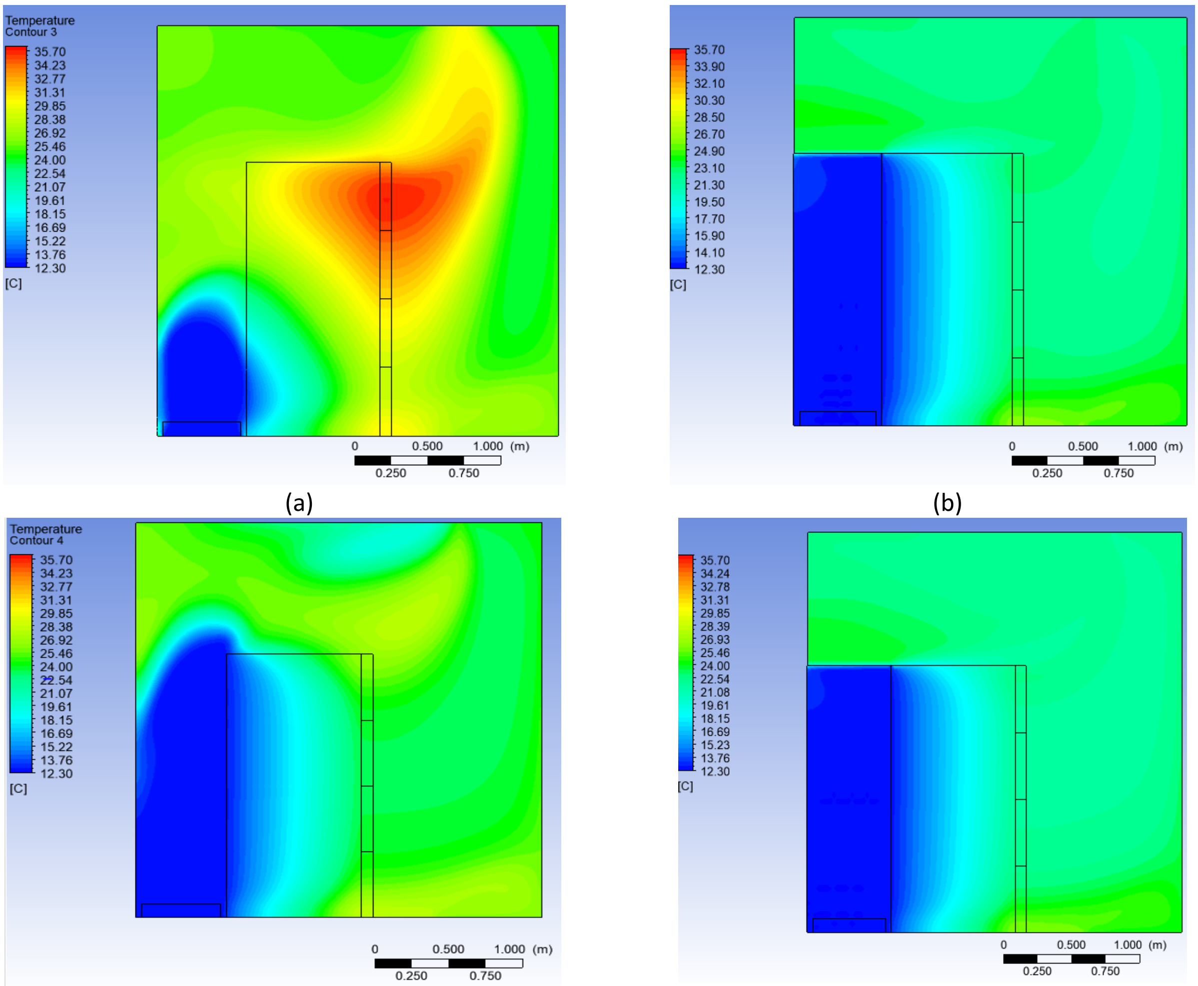
Two planes are considered to visualize the temperature profile with and without the containment data center. (i) Figure 7 (a) shows the YZ plane in the centre of all four server racks, a similar YZ plane is drawn for all racks to visualize temperature ii) Figure 7 (b) depicts the XY plane at the middle of the racks.



(a) (b)

Fig. 7. Contour plane considered for temperature visualization (a) Rack 1 (b) XY plane

Figure 8 and Figure 9 depict temperature contours on the YZ plane, XY plane and isometric view for all racks. It is evident that without containment the high temperature zone is formed near rack 1 because of recirculation and bypass is seen in the remaining racks. The higher temperature is caused by hot air leaving the racks returning to rack 1 instead of reaching the outlet, creating a local hotspot. However, the temperature in a containment system is far lower and appears to be uniform across all cross sections.



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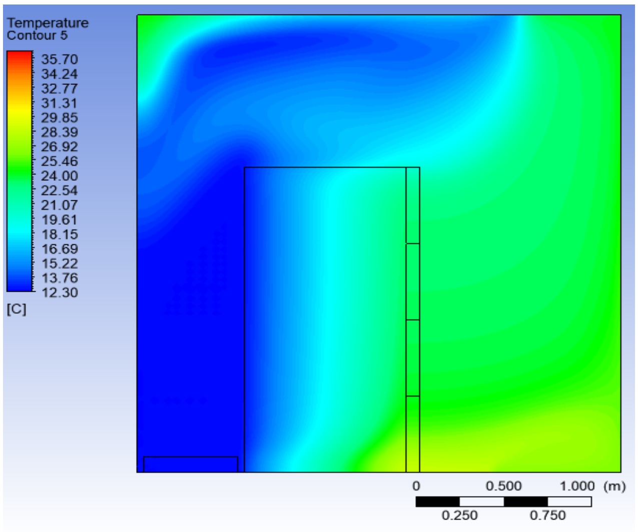

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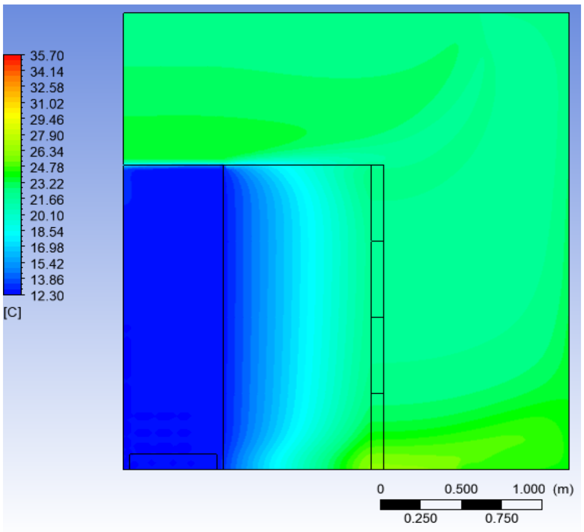

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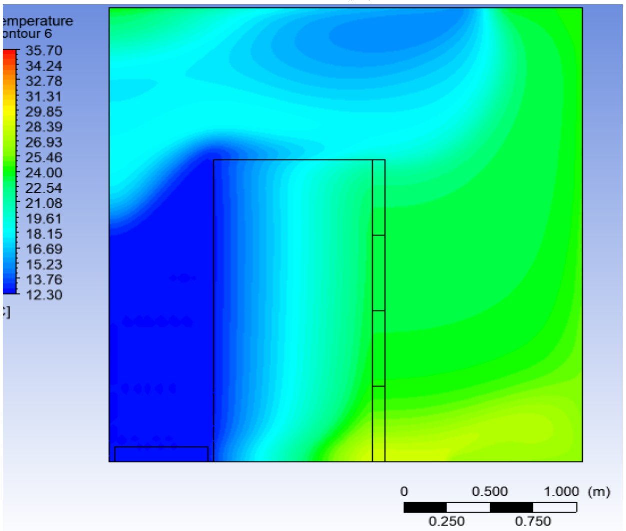

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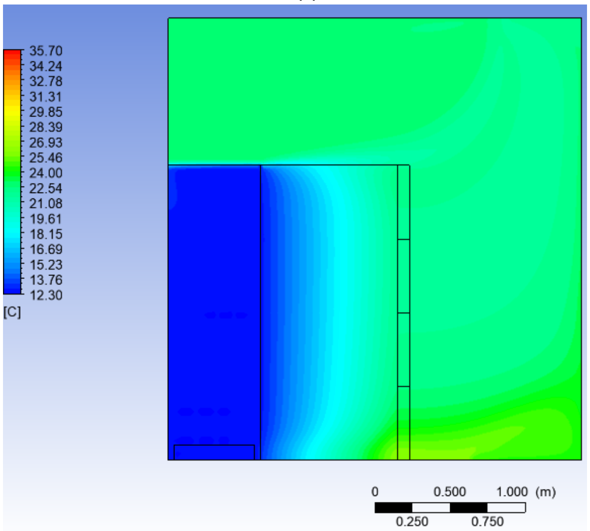


(h)

Fig. 8. Temperature contours on the YZ plane at the center of various racks (a) Temperature contour on the YZ plane Rack 1 without containment (b) Temperature contour on the YZ plane Rack 1 with containment (c) Temperature contour on the YZ plane Rack 2 without containment (d) Temperature contour on the YZ plane Rack 2 with containment (e) Temperature contour on the YZ plane Rack 3 without containment (f) Temperature contour on the YZ plane Rack 3 with containment (g) Temperature contour on the YZ plane Rack 4 without containment (h) Temperature contour on the YZ plane Rack 4 with containment

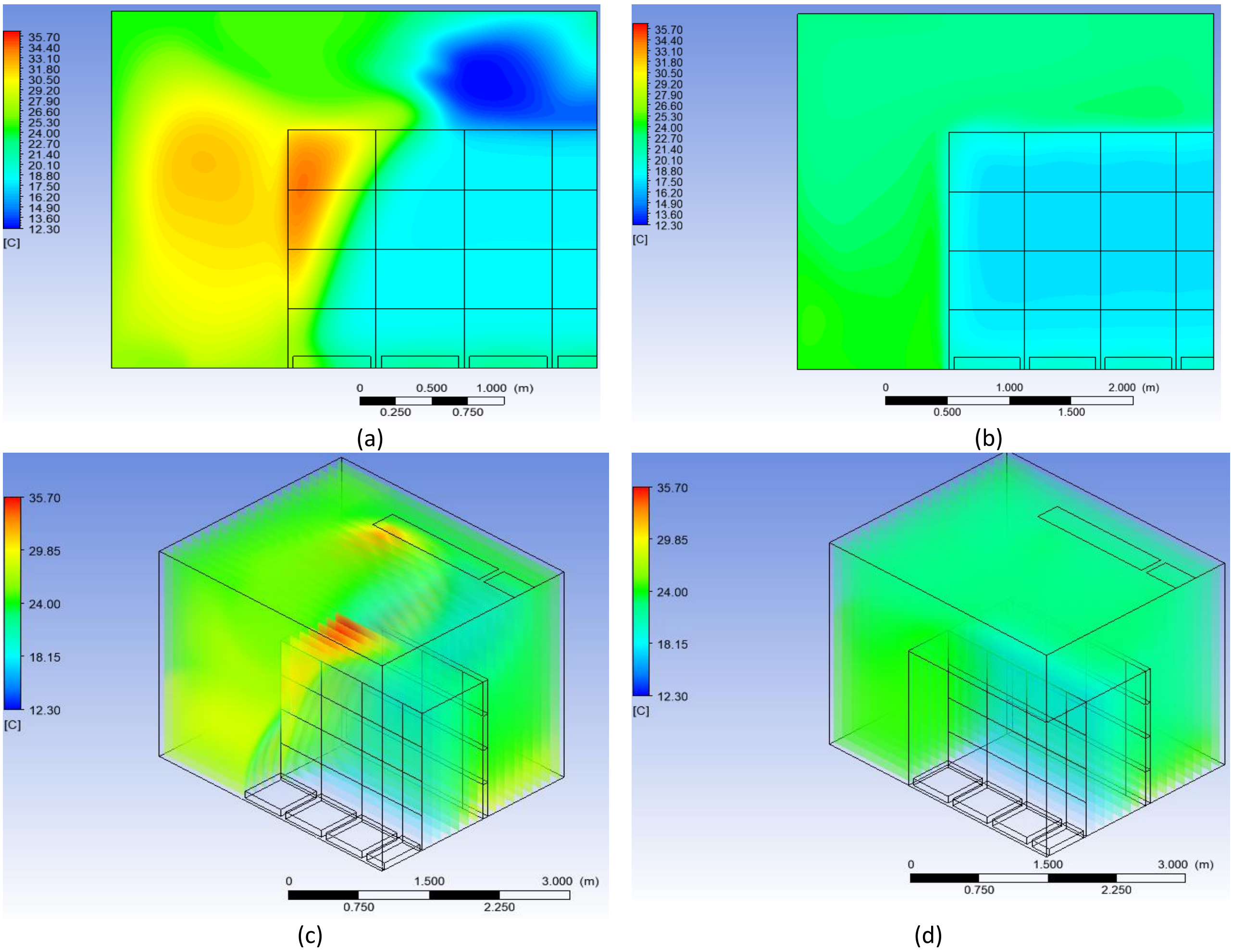


Fig. 9. Temperature contours at different planes, with and without containments (a) Temperature contour on XY plane without containment (b) Temperature contour on XY plane with containment (c) Temperature contour in isometric view without containment (d) Temperature contour in isometric view with containment

The average inlet temperature of rack 1 at various porosities with and without containments is shown in Figure 10. It can be seen that at 0.35 porosity the difference in inlet temperature of rack 1, with and without containment is 8.4^0 C, which is marginally large and it reduces as porosity is increased. More fluid is drawn through the server racks with increased porosity, which might be the cause of the temperature decrease. The average inlet temperature of rack 1 with containment is observed uniform at all porosities.

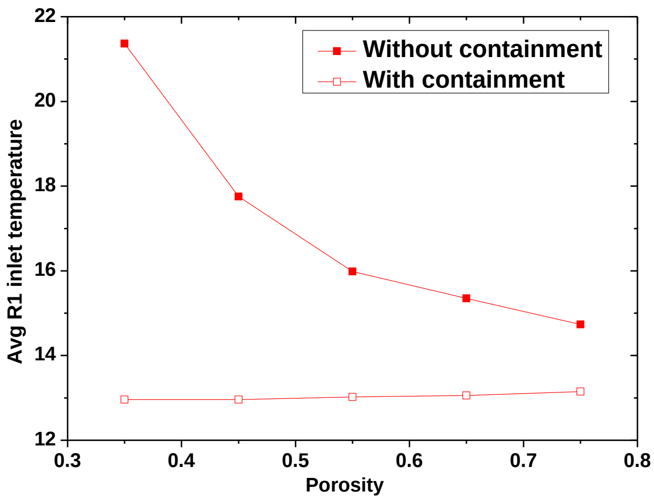
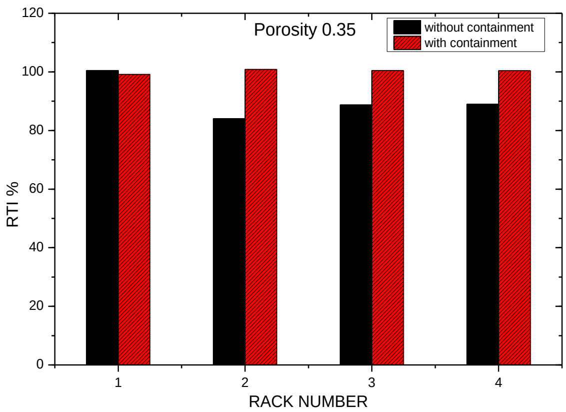


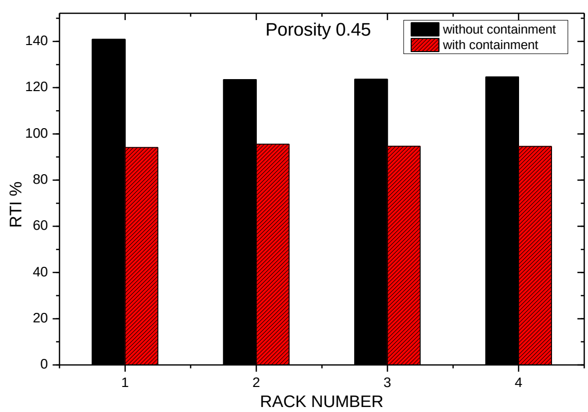
Fig. 10. Average inlet temperature of rack 1 at different porosities, with and without containments

3.1 Effect of Porosity and Containment on RTI

The RTI percentage for various porosities, both with and without CAC, is shown in Figure 11. At a porosity of 0.35 without containment, rack1 has an RTI value of 100% as racks 2, 3, and 4 have RTI values under 100%, indicating that cold air is bypassing in these racks. For all the porosities without containment, rack 1 has the highest RTI values because of higher recirculation compared to other racks. RTI values without containment have considerably increased with increasing porosity, highlighting the enormous amount of recirculation present. The maximum value of 217 is observed in the first rack with a porosity of 0.75 highlighting the increased porosity leads to an increased amount of recirculation. However, the bypassing effect is reduced at larger porosities because the fans' suction allows cold air to pass through the racks. While RTI values with containment are almost 100% for larger porosities, showing reduced recirculation and bypass. Regardless of rack numbers or porosities, containment has produced optimum RTI values, which shows that containment lowers recirculation and bypass.



(a)



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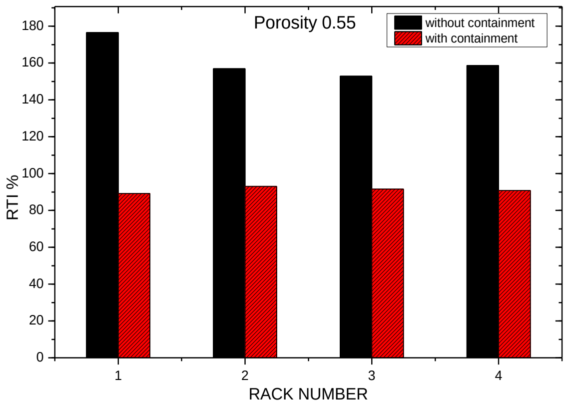

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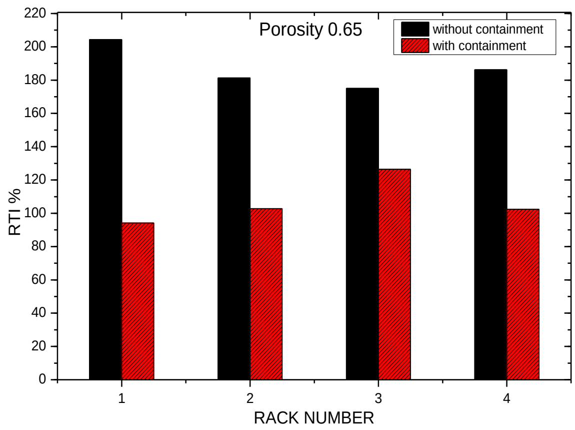

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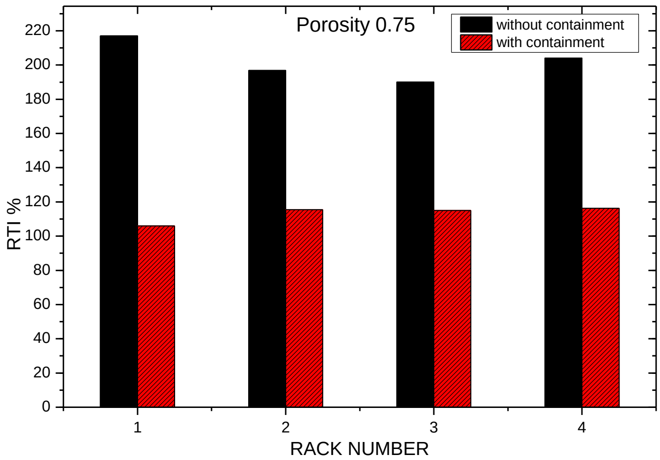

(e)

Fig. 11. Variation of RTI (a) Porosity 0.35 (b) Porosity 0.45 (c) Porosity 0.55 (d) Porosity 0.65 (e) Porosity 0.75

3.2 Effect of Porosity and Containment on SHI & RHI

SHI measures the degree of mixing of return air and RHI quantifies the degree of supply air bypass. When the SHI stays below 0.2 and the RHI rises over 0.8, it is typically regarded as acceptable. The design gets more in line with the ideal cooling system configuration for a data center when the SHI declines and the RHI tend to rise. This situation suggests less mixing of the warm air released from the equipment racks with the surrounding cold air. Variation of SHI & RHI is presented in Figure 12. It can be seen from the figures that without containment SHI values for rack 1 for all porosities are greater than the acceptable range. The principal observation of recirculation is supported by SHI measurements. With increasing porosities, both with and without containments, the SHI value increases while the RHI value decreases. For porosity 0.35, 0.45 and 0.55 the SHI is below 0.2 and RHI above 0.8 for all racks and RHI values are in the acceptable range with containment. At increased porosities, the values have deviated from the ideal values indicating a greater level of mixing. At higher porosities containment has no significant effect on SHI & RHI.

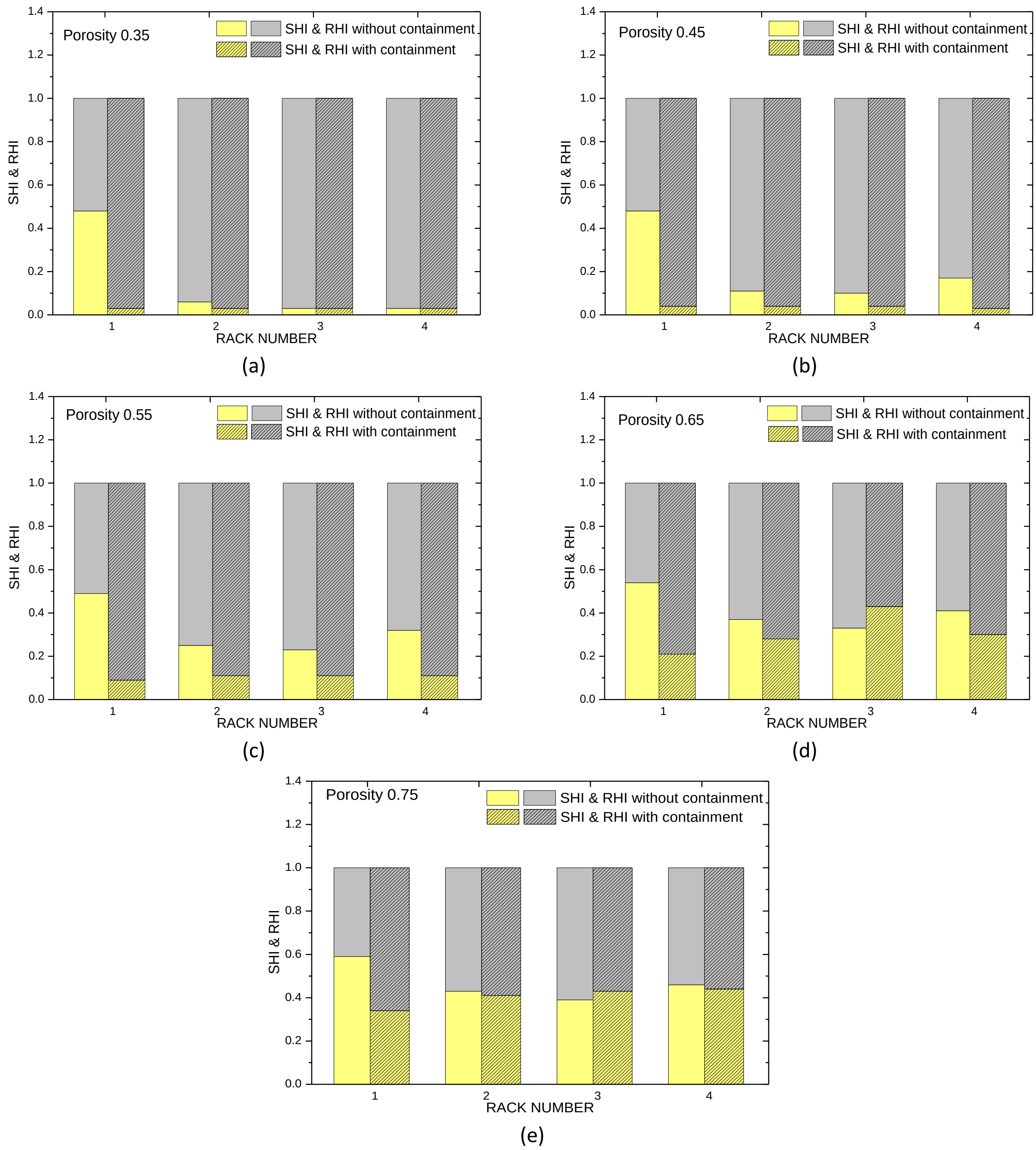

Fig. 12. Variation of SHI & RHI (a) Porosity 0.35 (b) Porosity 0.45 (c) Porosity 0.55 (d) Porosity 0.65 (e) Porosity 0.75

3.3 Effect of Porosity and Containment on RCI

The variation of RCI for porosity and containment is shown in Figure 13. Containments have no effect on the RCI_{HI} values for all cases under examination as the value observed is 100%. Consequently, no rack is receiving air that is higher than what is considered appropriate. RCI_{LO} for the first rack is close to 100 % for all the cases with and without containment. RCI_{LO} value for racks 2, 3 and 4 with and without containment is in the range of 80-85%, meaning that temperatures in these racks are below the minimum necessary temperature of 13^0 C. This is not dangerous given the temperature of the air entering the rack, since colder air can absorb more heat than hotter air.

Containment has a significant effect only on rack 1 as the RCI_{LO} values for the other racks, both with and without containment, are almost identical. RCI_{LO} and RCI_{HI}, don't show large variations because they depend on the temperatures at which racks pull in air, which are subject to significant alterations as heat generation levels fluctuate.

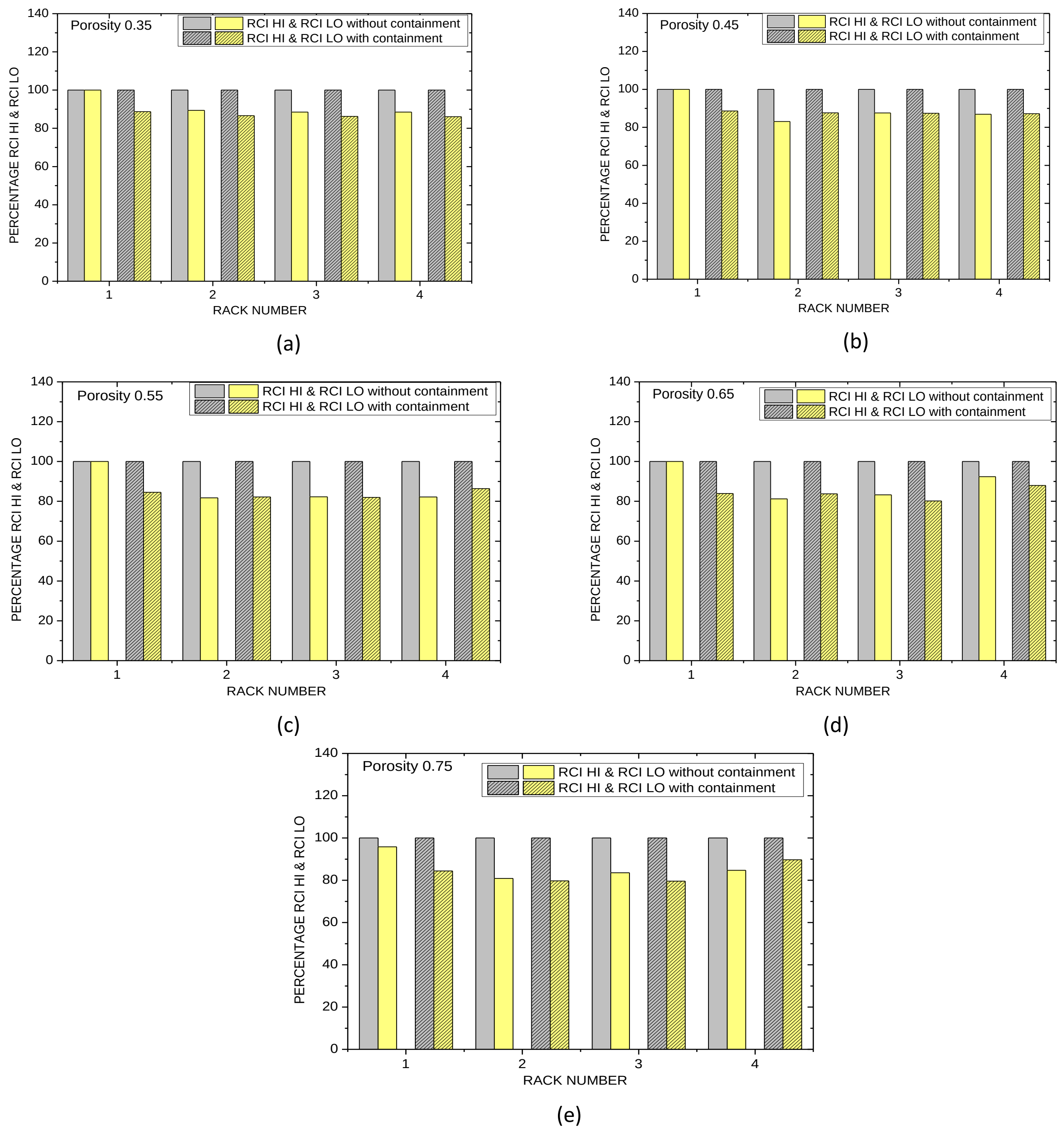

Fig. 13. Variation of RCI (a) Porosity 0.35 (b) Porosity 0.45 (c) Porosity 0.55 (d) Porosity 0.65 (e) Porosity 0.75

4. Conclusions

With the advance of technology, the load per rack is increasing extensively and maintaining uniform temperature across all server racks is imperative to save energy. A numerical analysis was performed to evaluate the effectiveness of porosity in cold aisle-contained data centers. Thermal management, air flow characteristics (such as air recirculation and bypass), and temperature distribution were the main focuses of the investigation. RTI, SHI/RHI, and RCI are three quantifiable parameters that were used to evaluate the performance. A certain amount of recirculation becomes inevitable in the absence of any containment techniques, especially since servers at the ends have noticeable recirculation impacts. According to the study's findings, containment leads to a uniform temperature distribution within the data center, which reduces recirculation and bypass in racks, and porosity affects the distribution of temperature in the data center. When compared to racks with higher porosity, those with low porosity add more airflow resistance, increasing the magnitude of recirculation in high-porosity racks. As a result, the RTI value rises along with porosity. SHI/RHI and RCI values, however, are unaffected by the variation of porosity because these parameters primarily depend on fluid flow dynamics. The results of these investigations indicate that porosity and containments have an impact on the data center's temperature distribution, which in turn affects how well the cooling works. These findings contribute to the ongoing efforts to optimize the design of data centers for better equipment reliability and energy efficiency.

Following are the results of the study

i. With containment rack 1 inlet temperature is 8.4^0C less at 0.35 porosity and the difference in inlet temperature of rack 1 with and without containment decreases as porosity increases,
ii. RTI values without containment increase with higher porosities, peaking at 217 for rack 1 at a porosity of 0.75, indicating increased recirculation and RTI values with containment remain consistently close to 100%, indicating a reduction in recirculation and bypass effects.
iii. SHI and RHI values for rack 1 are beyond acceptable values for all porosities without containment. At porosities of 0.35, 0.45, and 0.55, the SHI remains below 0.2, and the RHI is consistently above 0.8 for all racks, while RHI values fall within the acceptable range when containment is employed. At higher porosities containment has no significant effect on SHI & RHI.
iv. RCILO values for racks 2, 3, and 4, regardless of containment, consistently fall within the 80-85% range, signifying temperatures below 13°C, while RCIHI remains at 1 for all scenarios, indicating that no rack exceeds the recommended temperature of 25°C.

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