Numerical Investigation of Novel Underfloor Air-Directors Effect on Data Center Performance

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Abstract

Most of the thermal management technologies concentrate on managing airflow to achieve the desired server inlet temperature (supply air operating set point) and not to manage/improve the amount of cool air (CFM) that each computer rack (i.e. IT servers) should receive in order to remove the produced heat. However, airflow is equally important for quantifying adequate cooling to IT equipment, but it is more challenging to obtain a uniform airflow distribution at the inlet of computer racks. Therefore, as a potential option for improving airflow distribution is to eliminate the sources of non-uniformities such as mal-distribution of under-floor plenum pressure field caused by vortices. Numerous researchers focus on the adverse effects of under-floor blockages. This study focused to numerically investigate the positive impact of selectively placed obstructions (on-purpose air-directors); referred as partitions; Quantitative and qualitative analysis of under-floor plenum pressure field, perforated tiles airflow rate and racks inlet temperature with and without partitions using two Computational Fluid Dynamics (CFD) models, which were built using Future Facilities 6SigmaRoom CFD tool. First, a simple data center model was used to quantify the partitions benefits for two different systems; Hot Aisle Containment (HAC) compared to an open configuration. Second, the investigation was expanded using a physics-based experimentally validated CFD model of medium size data center (more complicated data center geometry) to compare different types of proposed partitions. Both models results showed that partition type I (partitions height of $\frac{2}{3}$ of plenum depth measured from the subfloor) eliminates the presence of vortices in the under-floor plenum and hence, more uniform pressure differential across the perforated tiles that drives more uniform airflow rates. In addition, the influence of proposed partitions on the rack inlet temperature was reported through a comparison between open versus hot aisle containment. The results showed that the partitions have a minor effect on the rack inlet temperature for the hot aisle containment system. However, the partitions significantly improve the tiles flowrate. On the other hand, for the open system, the presence of partitions has improved the tiles airflow rate, rack inlet temperature and hence eliminate the hot spots formation at computer rack inlet.

1. Introduction.

We are living in a computer age. Most of our daily activities/interaction are fully computerized. Information search on the internet, airline travel e-tickets reservation, getting boarding passes, online banking, instantaneous verification and approval of credit cards transactions and the list goes on. Furthermore, large industrial companies have computerized their inventory, communication commands for purchase orders and invoices. Health care is another example of the need of storing medical records on computers. Therefore, the whole systems ensure functionality if and only if all relevant data is stored at one location and the requests processed at very high speeds, and hence, the small visible actions/transactions processed in a large and powerful computer servers deployed and operated in single building/facility and such a huge mission critical facility is called data center.

Data centers (cloud computing nowadays) have become an essential part of any modern life and large industrial business needs. Thus, leads to growth in power densities, which means more heat will be dissipated and exhausted by servers and telecommunication equipment to their rooms. Subsequently, to maintain the room temperature and humidity (room environmental conditions) for such equipment within the recommended vendor specifications and the ASHRAE thermal guidelines in order to meet functionality and reliability requirements. For those reasons data centers thermal consideration became a first-class citizen in the design, deployment, and operation of the next generation servers. In addition, data center cooling energy efficiency is critical to the successful operation of modern large data centers.

Although, the growth rate of data centers energy consumption slowed significantly from 2006 - 2016 due to improved management of the installed server design and energy efficiency best practices compared to the growth rate that prevailed between 2000 and 2006. Recently, Shehabi et al. [1] showed that the consumed energy in data centers increased by 4% from 2010 – 2014. In addition, they estimated an increase of 4% in the near future. Based on the current trend, the warehouse-sized computer facilities will approximately consume 73 billion kWh in 2020 compared to 70 billion in 2014 which accounts for 2% and 1.8% of the total U.S. electricity consumption respectively. Given that, the cooling infrastructure can average 40% of the total data centers energy consumption [2, 3]. Therefore, energy conservation measures and design of energy efficient cooling systems are important factors in achieving improvements. In addition, the data center cooling energy consumed in 2014 can be approximated at 28 billion kWh.

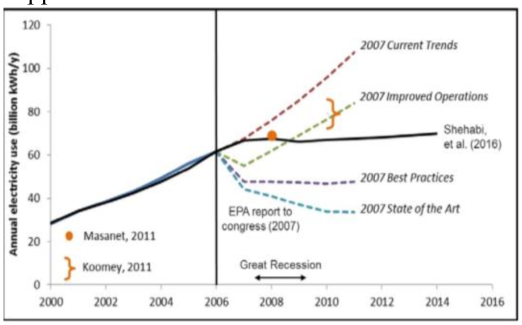


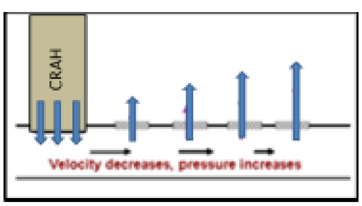
Figure 1. Projected data centers total electricity use. [1].

In a typical air-cooled raised floor data center the Computer Room Air Handler (CRAH) supply cold air into the under-floor plenum that distributes the cooling airflow to cold aisles and hence, to computer racks through perforated tiles. Therefore, the cooling performance of the cooling system (energy usage) is influenced by improved airflow distribution; which is driven by many design factors such as, under-floor plenum geometry, CRAH's nominal supply/location, perforated tiles openness, …etc.

The cooling airflow rates through perforated tiles must satisfy the demand of the IT equipment located next to them to ensure its proper functionality and reliability. As the cooling air emerges from the tiles, the velocity of horizontal flow in the plenum decreased and hence the pressure increased. These pressure variations in the horizontal plane under the raised floor lead to non-uniform flow rates from different tiles. An example of perforated tiles non-uniform flow rates is illustrated in Figure 2 (c) where the furthest tile from the perimeter CRAH gets the largest amount of air. This behavior of tiles delivery is noticed when the tiles are aligned with the cooling unit supply jet. In addition, the airflow delivery through perforated tiles depends on the under-floor plenum geometry, relative location from CRAH unit. Another factor that will cause a mal-distribution of the flow field is vortices existence. Alissa et al. [4] reported a non-uniform flow rate of perforated tiles. Figure 2 (b) presents a new set of measured data of the tiles flow rate which shows a variation among the vertical distance from CRAH 1, the behavior was approximated by a second-order polynomial and it agrees with what Alissa et al. reported in their study. They related this non-uniformity to the presence of a vortex under the raised floor that causing a pressure wake as shown in Figure 2 (c) which shows the top view of pressure field 12 inches under the raised floor using an experimentally validated physics-based CFD model of the data center. On that account, the amount and uniformity of the delivered cooling air are mainly governed and affected by flow field and pressure distribution in the under-floor plenum, which is considered a very important element amongst other challenging tasks in data centers. Considering under-floor plenum depth, modified perforated tiles open area and selectively located partitions and air-directors under the raised floor will influence the plenum pressure field and thus more uniform tiles delivery.

More in-depth studies on the presence of under-floor blockages that related to data center infrastructure (chiller pipes, cables, and conduits) received the interest of many researchers. While, the conducted research on deliberated partitions that selectively installed in the under-floor plenum (solid or perforated, tilted/inclined or vertical/straight) is scarce in the literature. Karki et al. [5] used a mathematical model to discuss a number of techniques to modify airflow distribution in raised floor data centers. Their numerical results showed the control of the airflow distribution was more flexible with the use of thin partitions. While VanGilder and Schmidt [6] analyzed over 240 CFD models to estimate the effects of different parameters on the uniformity of tiles airflow. The results showed that tile's type and the existence of under-floor obstructions have the greatest influence. They recommended keeping outlet region of cooling unit free of pipes and cables among other design recommendations to gain uniform tile's airflow. Shrivastava et al. [7] built a multi-scale 3-D model of air-cooled data center including under-floor plenum to improve data centers cooling system efficiency, and hence energy consumption. Bhopte et al. [8-10]. Characterized the impact of under-floor blockages on data center (DC) performance and established guidelines by introducing a colored code for the plenum using experimentally validated models. Their results showed a significant reduction (19% less) in the perforated tiles airflow rates when the blockages are located in the critical zones. A set of published articles, recommendations and guidelines related to the cooling of data centers including the placement of under-floor blockages and partitions that lead to best practices were reviewed and presented by Schmidt et al. [11]. Suhas V. Patankar [12] used CFD modeling to discuss and investigate the effect of different factors on the airflow distribution in raised floor data center. Among the factors, the quantitative and qualitative analysis of under-floor obstructions effect on the tiles airflow delivery. Their results showed that under-floor obstructions could be used to positively affect the distribution of airflow. Fakhim et al. [13] used CFD simulation to study the impact of under-floor obstructions location on data center airflow distribution. Their results showed more uniform tiles airflow when the obstructions are placed under hot aisle (HA) compared to cold aisle (CA). In contrast, VanGilder et al. [14] analyzed and showed numerically a significant effect of obstructions on airflow distribution. The authors recommend keeping obstructions within a distance away from tiles and the cooling unit.

Numerical based study and analysis of the effects of under-floor obstructions on the thermal and flow fields for open and contained environments presented by Alissa et al. [15]. A comparison between parallel and perpendicular blockages distribution for both cases (i.e. critical and safe zones). The perpendicular critical location and improper distribution of infrastructure blockages found to have severe effects on the hydrodynamic and thermal behavior due to the reduction of the air feed to IT equipment and operating points. Seven CFD models generated by Falpagare et al. [16] to investigate the effect of under-floor blockages among other factors on CRAH airflow rates and distribution. The results showed that under-floor obstructions could reduce the airflow rate by 80% and increase exit air temperature by 2.5 ℃. Khalaja and Halgamugeb [17], reviewed the articles related to thermal management of air-cooled, liquid-cooled and free cooling technologies in data centers. Based on their review the under-floor partitions as one of the most efficient methods for balancing the perforated tiles airflow rates. Yuan et al. [18] studied the impact of installing inclined under-floor baffles (UFB) on the airflow pattern of a DC with Cold Aisle Containment (CAC) was investigated using CFD simulation by different inclination angles of UFB with respect to the CRAH's outlet air were considered. The results revealed that deploying CAC can relief the hotspots and reduce the rack's average outlet temperature by (1-2) ℃. In addition, applying under-floor baffles can further reduce the rack's outlet temperature and make its distribution uniform. The highest value of temperature drop of local hot spots of 2.1 ℃ was observed with the 45° tilt angle of the baffles. Khalili et al. [19] conducted a parametric simulation of three types of floor tiles with different open area, opening geometry, and understructure considered. They used an experimentally validated detail model of tiles implemented in CFD simulations to address the impact of tile design on the cooling of IT equipment in both open and enclosed aisle configurations. Zhang et al. [20] investigated the influence of different raised floor heights on airflow distribution for three different configurations (HA-CA, CAC, and HAC) using commercial CFD software.



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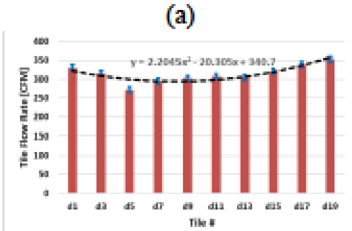

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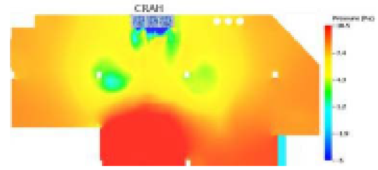


(c)

Figure 2. (a) Tiles flow rate non-uniformity. (b) Experimental tiles flow rate measurements at BU DC Lab.(c) Pressure field 12" under the raised floor.

One of the keys to modify flow rates through perforated tiles is to influence the pressure field in the under-floor plenum. This study focused to present a quantitative and qualitative analysis of under-floor pressure field, airflow rates through perforated floor tiles and rack inlet temperature with and without partitions using two different CFD models.

2. Simple Data Center Model with Deliberated Obstructions.

A representative simple data center CFD model was developed first using Future Facilities 6SigmaRoom CFD tool. The room that houses the data center in the numerical model includes an under-floor plenum that feeds the 12 perforated tiles with cold air supplied from single chilled water-based down flow perimeter CRAH unit and a ceiling return ducted to hot aisle containment for HAC case. In addition, the model consists of two cold aisles and one enclosed hot aisle. The 12 computer racks divided equally into two rows dissipating 100 kW as heat to the hot aisle as shown in Figure 3 below and a detailed description of the model layout is shown in Appendix A. Table 1 shows a detailed description of the simple data center model used. In this section of the study, two main benchmark cases are considered and then applied to both configurations open and HAC system. The first one is the baseline case (i.e. with no partitions). The second benchmark case is when selective deliberated air-directors (i.e. partitions) are introduced and placed under the cold aisles (parallel to cold aisle and perpendicular to cooling unit) as shown in Figure 4. The partitions porosity was fixed at 50% which was based on a thorough CFD analysis. In addition, the partitions height was assumed to be $\frac{2}{3}$ of the distance that separate raised floor to the subfloor.

Figure 5 (a) illustrates under-floor plenum pressure distribution on the horizontal plane located 3 inches under the raised floor for the first benchmark case (i.e. with no partitions) and for HAC system. The cold air that leaves the cooling unit at high velocity hit the opposite wall and as a result of that two low-pressure regions (Pressure wake) are obvious and observed near the walls that opposite to cooling unit. Since the room pressure is equalized then one can suspect that the condition causing this behavior is the high air supply jet from CRAH and the small size of the room that forcing the cold air to turn when hits the opposite wall as shown in Figure 5 (c). Figures 5 (a) and (c) that show the developed vortices (pressure wake) under the farthest tiles relative to CRAH. Subsequently, deficiency of those tiles airflow rate predicted as shown in Figure 5 (e). In addition, a sample of streamlines plot that emerging to such tiles is shown in Figure 5 (g) in which the developed vortex in the under-floor plenum is obvious.

To capture the positive impact of the deliberated partitions and their influence on the plenum pressure field, eliminating vortices and thus improving airflow uniformity. The obtained results for the second benchmark case (i.e. with installed partitions under the cold aisle) are shown in Figures 5 (b), (d), (f), (h). To facilitate the comparison between the two main benchmark cases in this section of the study. From Figure 5 it can be noted that both vortices are eliminated between the LHS and RHS figures. Furthermore, the perforated tiles airflow rate uniformity significantly improved as shown in Figure 5 (f).

Table1. Simple model details.

Items	Description	Value
Room	Size	61.8 m^2
	Height	3.3 m
	Raised floor height	0.33 m
	Containment type	HAC
	Total number of perforated Tiles	12
	Perforated tile dimensions	24" x 24"
	Tiles open area	22 %
CRAHs	Number of CRAHs	1
	Nominal cooling capacity	103 kW
	Maximum flow rate	5.85 m^3/s
Deliberated Obstructions	Height from floor slap	2/3 of plenum height
	Porosity in all direction	50%
	Thickness	150 mm

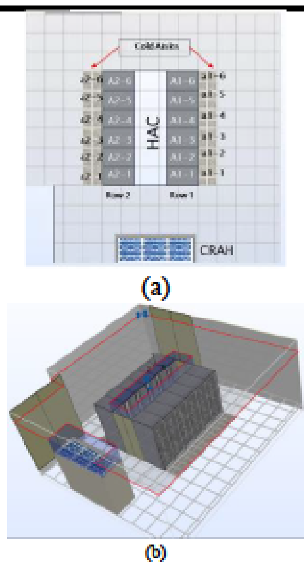


Figure 3. Schematic for the simple data center model

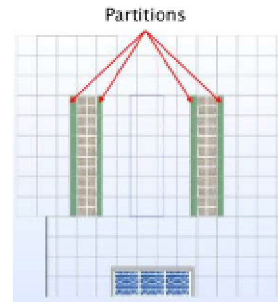


Figure 4. Deliberated air-directors.

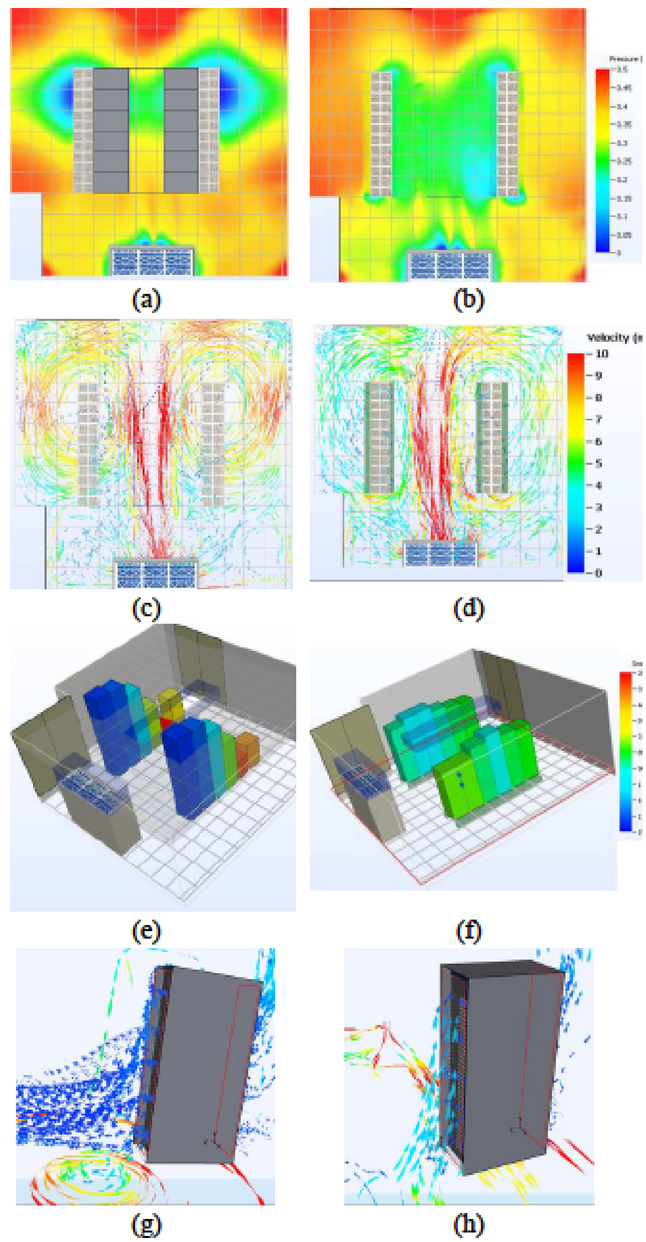
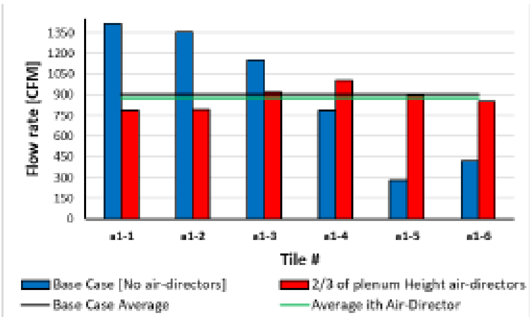


Figure 5. (a, b) Pressure distribution (c, d) Streamlines plot under floor. (e, f) 3-D tiles flow simulation. (g, h) A sample of streamlines under rack A2-5.

To quantify the benefits of the proposed partitions and their effect on under-floor plenum pressure distribution and flow field (i.e. eliminating the developed vortex) on both hydrodynamic and thermal performance. First, the tiles airflow rate for both cold aisles are shown in figures 6 (a) and (b). The tiles flow rate differ up to 775 and 629 CFM increase and decrease in tiles a2-5 and a1-1 respectively between both cases. More uniform airflow through perforated tiles results in less hot air recirculation for the adjacent computer racks to the tiles with less airflow rate. Consequently, improving the thermal behavior by receiving more cold air at rack inlet.



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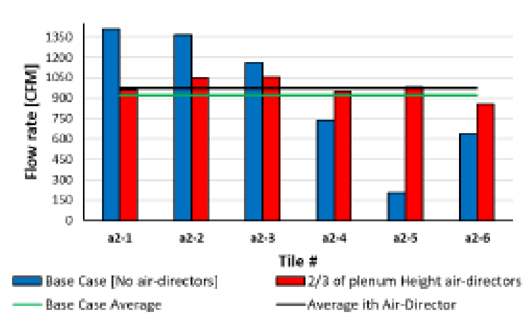
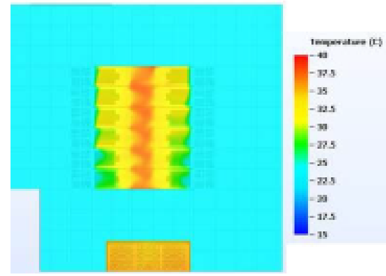


(b)

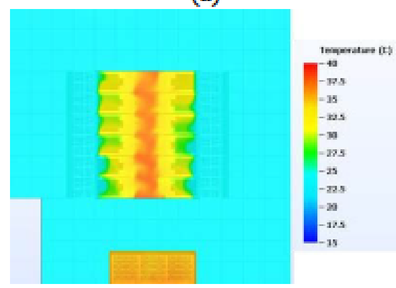
Figure 6. Tiles flow rate delivery.

2.1 Effect of Deliberated Obstruction on Thermal Performance (Rack Inlet Temperature)

For the case of hot aisle containment, a comparison of thermal behavior of racks for hot aisle enclosure system is shown in Figure 7 (a) and (b) and Figure 8 (a) and (b). It can be noted that introducing deliberated partitions has no major effect on rack inlet temperature. Although, they have a significant impact on the airflow distribution. This can be related to the fact that the hot aisle is enclosed and ducted to the return face of the CRAH with no recirculation is taking place in computer racks driven by backpressure as shown by Khalili et al. [21]. Then, to capture the benefit of the proposed partitions. A comparison of temperature contours at rack inlet for an open system shown in Figure 9 (a) and (b) and Figure 10 (a) and (b).

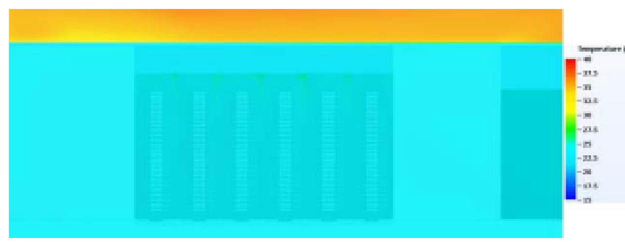


(a)

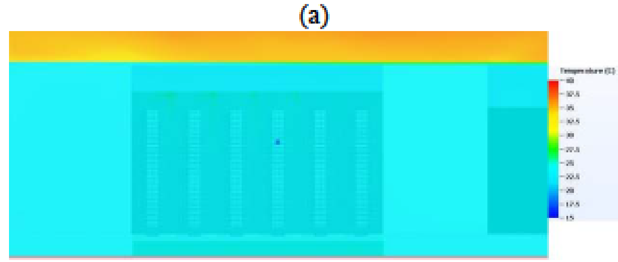


(b)

Figure 7. Contained system temperature contour at 79 inches above raised floor. (a) With no partitions. (b) with deliberated partitions.

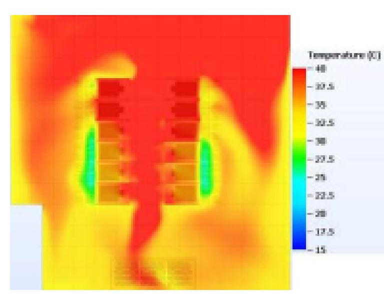


(a)

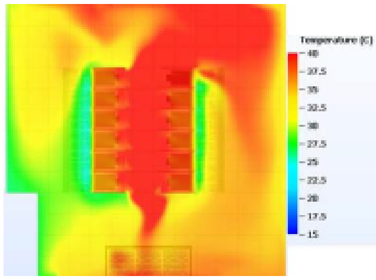


(b)

Figure 8. Temperature contour of the contained system at rack inlet of row 2. (a) With no partitions. (b) with deliberated partitions.

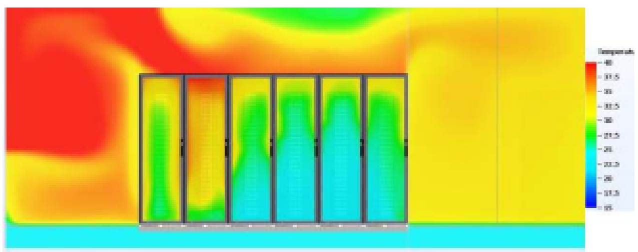


(a)



(b)

Figure 9. Open system temperature contour at 79 inches above raised floor.



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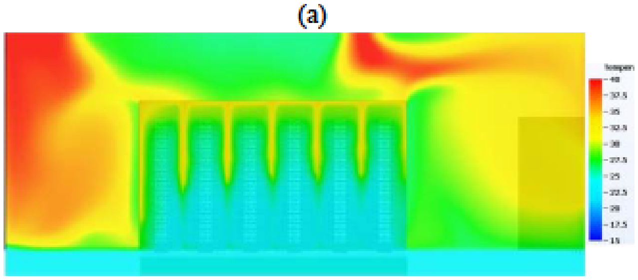


(b)

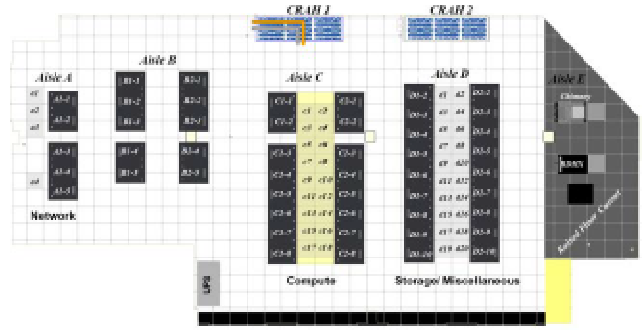
Figure 10. Temperature contour of the contained system at rack inlet of row 2. (a) With no partitions. (b) with deliberated partitions.

3. Effect of air-directors in a medium size data center.

In this section further analysis and investigations of the effect of deliberated under-floor partitions (air directors) in more complicated physics based experimentally validated CFD model. Different configurations of deliberated partitions were installed.

3.1 Representative data center laboratory

The data center laboratory profiled in the center for Energy-Smart Electronic Systems (ES2) located at the State University of New York at Binghamton. Figure 11 (a) shows the overall map view of the data center lab. Where it has a slap to slab height of 4.37 m (14.33 ft), which is broken down as follows: 0.91 m (3 ft) under-floor plenum depth, 3.45 m (11.3 ft) from the ceiling down to the raised floor, room air return to two-chilled water-based cooling units. A traditional arrangement of hot aisle/cold aisle used in the laboratory. The data center has a variable distance from one cold aisle center to the next cold aisle center (aisle pitch). The aisle pitch varies between 7 and 9 raised floor (2 ft x 2 ft) panels. Furthermore, cold aisles (A, C and D) perforated tiles have 22% open area. There are a few infrastructure blockages (chiller pipes), then it makes sense to consider empty under-floor plenum as shown in Figure 11 (b).



(a)

(b)

Figure 11. (a) Map view of ES2 DC lab. Racks and tiles matrix. (b) ES2 DC under-floor plenum.

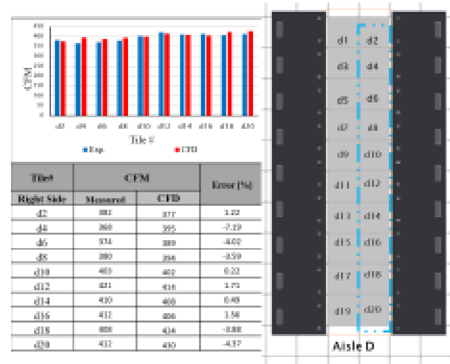
3.2 Measurements and Validation.

Considering the strength of Computational Fluid Dynamics (CFD) in parametric and sensitivity studies. Then, the real data center laboratory is replicated in a physics-based CFD model which was developed using Future Facilities 6SigmaRoom (Facility level CFD tool) for more visibility of complex airflow pattern and pressure distribution. Experimental measurements of both perforated tiles airflow rate and plenum/room pressure differential were conducted and used to validate the CFD model which used to expand the investigation of deliberated under-floor partitions. As shown in Figure 12 (a) and (b) the CFD model predicted the experimentally collected data with a maximum mismatch of < 8% in both pressure and flow fields. Therefore, the model can be used for additional sensitivity analysis.

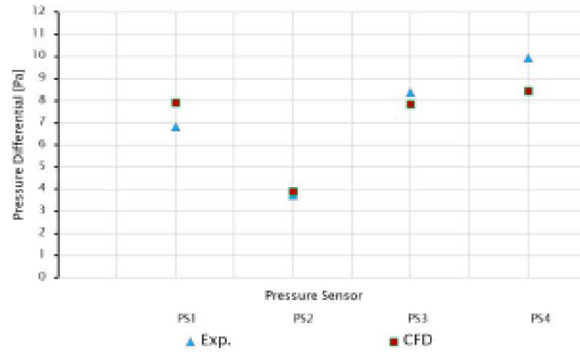
3.3. Effect of deliberated Partitions (air-directors).

In the attempt of expanding the investigation, a set of proposed obstructions that varies in geometry and location relative to CRAH units and cold aisles is introduced The porosity and thickness of all partitions are fixed to 50% and 150 mm respectively. While the length, inclination angle with respect to the CRAH unit and cold aisle were varied as illustrated in table 2 below. Furthermore, the partitions height was assumed to vary to facilitate more generic guidelines. Two main heights were considered. First, when the height is equal to the whole depth of the under-floor plenum referred to as scenario 1. Second, when it is equal to $\frac{2}{3}$ of plenum depth referred to as scenario 2. Finally, in all studied cases, the partitions were placed vertically on the subfloor.

Table 2. Summary of proposed deliberated obstructions. [Data center top view]



(a)



(b)

Figure 12. Experimental vs CFD results. (a) RHS tiles airflow rate. (b) Plenum/room pressure differential.

Case Study: CRAH 1 OFF and CRAH 2 ON.

a. Under-Floor Plenum Pressure Distribution.

Figure 13 (a) displays plenum pressure distribution on the horizontal plane 12 inches under the raised floor for the base case #1 (i.e. with no partitions) and hence, considered as a reference frame to decide up to what extent the pressure distribution improved. Scenario 1 is shown on the LHS for each type, while scenario 2 is shown on the RHS. It can be noted from Figure 13 that the vortex moves around in the plenum and vanishes as long as alternating between scenario 1 and some types with scenario 2 respectively. The figure and based on pressure distribution report that type A scenario 1 and type I scenario 2 are the worst and the best-deliberated partitions among the studied cases. The next step was to compare and quantify the perforated tiles airflow rate.

b. Aisle level Total Tiles Delivery Comparison.

Table 3 summarizes the total perforated tiles flow rate per aisle for all proposed partitions of the two investigated scenarios. All computed results shown in table 3 were compared to the base case (i.e. with no partitions) in which the computed total tiles flow rates for aisles A, C, and D were 1258, 6350 and 7948 respectively. In addition, table 4 presents the maximum and minimum airflow rates among all individual tiles. Again, it can be noted that type A scenario 1 and type I scenario 2 are the worst and the best-deliberated partitions among the studied cases.

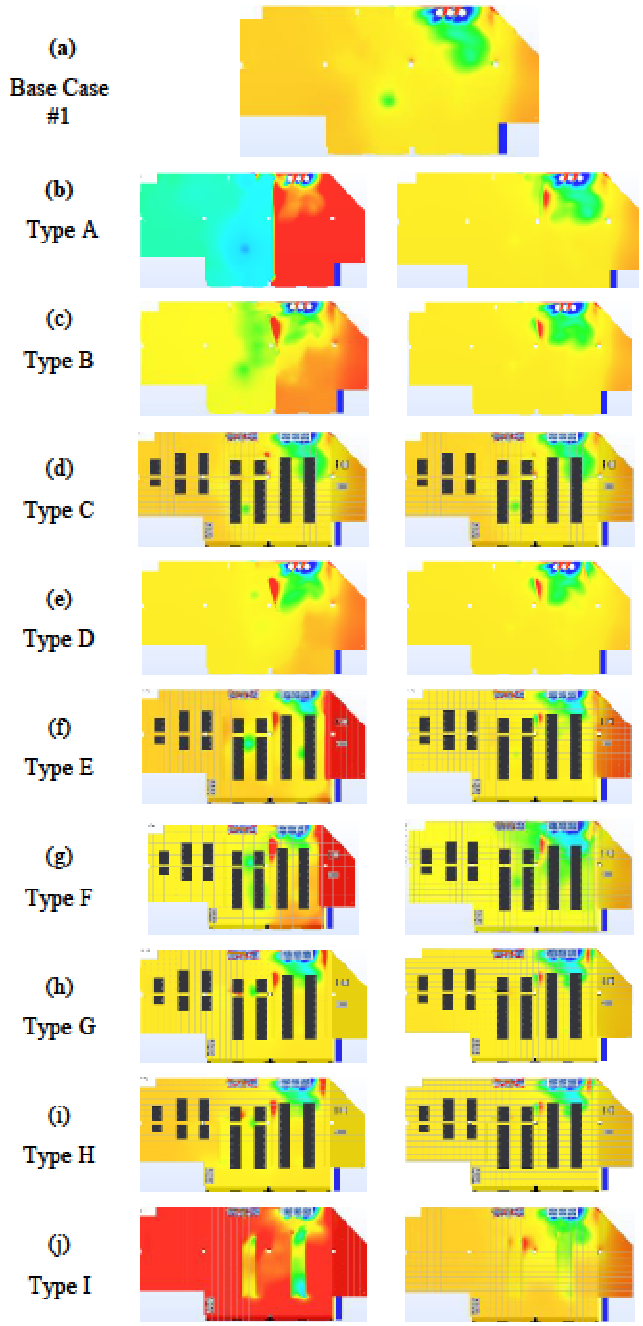


Figure 13. Plenum pressure distribution 12" under the raised floor.

c. Effect on perforated tiles airflow rate uniformity.

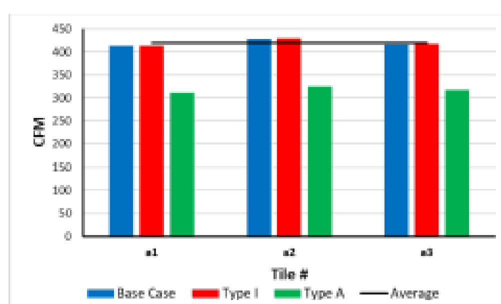
Based on the previously mentioned comparison between all proposed partitions, it can be noted that the best and the worst of all proposed air-directors are type I –scenario 2 and type A scenario 1 respectively. This conclusion is based on the improved pressure distribution and vortex elimination in under-floor plenum resulting in a more uniform flow rate through the perforated tiles as shown in Figure 14.

Table 3. Aisle level total perforated tiles flow rate [CFM]

Air-Director type	Scenario 1			Scenario 2		
	Aisle A	Aisle C	Aisle D	Aisle A	Aisle C	Aisle D
Type A	953	4688	10030	1209	6464	7935
Type B	1159	6004	8441	1218	6513	7887
Type C	1260	6396	7945	1255	6361	7946
Type D	1209	6321	8023	1221	6528	7892
Type E	1260	6278	7949	1227	6411	7951
Type F	1232	6275	8072	1216	6464	7937
Type G	1188	5979	8386	1211	6464	7929
Type H	1234	6347	8065	1222	6490	7924
Type I	1421	6719	7170	1260	6653	7640

Table 4. Individual tiles maximum, minimum and average airflow rate [CFM]

Air-Director type	Scenario 1			Scenario 2		
	Max.	Min.	Ave.	Max.	Min.	Ave.
Type A	534	209	382	421	351	381
Type B	457	319	381	421	346	381
Type C	429	313	380	427	301	380
Type D	437	337	379	420	344	381
Type E	429	276	378	418	335	380
Type F	431	294	380	414	436	381
Type G	442	286	379	415	350	381
Type H	424	308	382	416	348	381
Type I	484	292	373	429	356	379



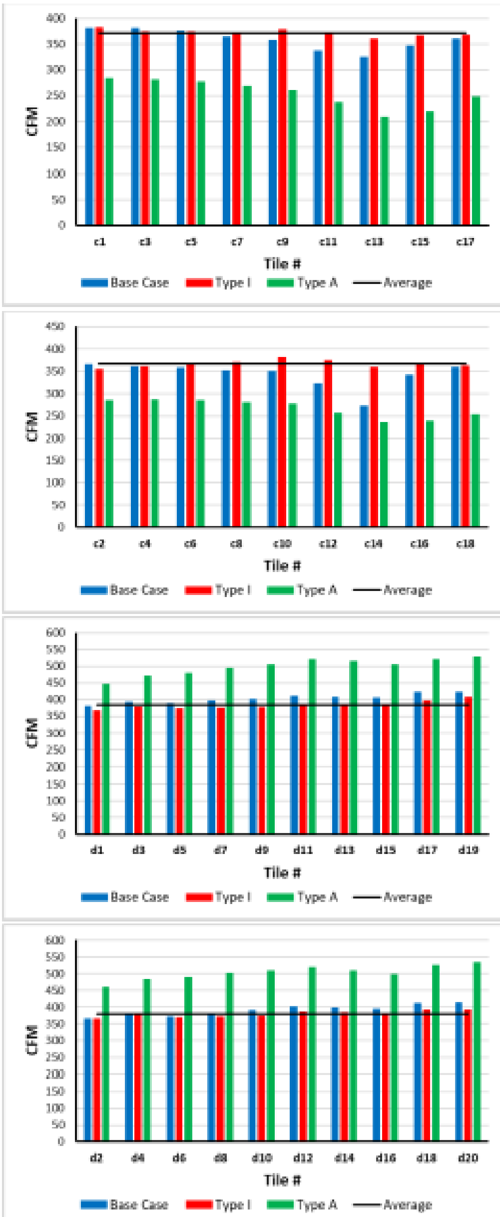


Figure 14. Perforated tiles flow rate.

Conclusions

In this study focused on a numerical investigation of the effect of novel air-directors placed selectively in the under-floor plenum referred as partitions, Quantitative and qualitative analysis of under-floor pressure field, perforated tiles airflow rate and rack inlet temperature with and without partitions using two different data center CFD models. First, a simple data center model was used to quantify the partitions benefits for two different systems; hot aisle containment system compared to the open system. Second, the investigation was expanded using a physics-based experimentally validated CFD model of medium size data center (more complicated geometry data center) to compare different types of proposed partitions. Both models results showed that partition type I ($\frac{2}{3}$ of plenum depth measured from the subfloor) eliminates the presence of vortices in the under-floor plenum and hence, more uniform pressure differential across the perforated tile. In addition, the influence of proposed partitions on the rack inlet temperature was reported through a comparison between open versus hot aisle containment. It was shown that the partitions have a minor effect on the rack inlet temperate for the HAC system. However, the partitions significantly improved the tiles flow rate. On the other hand, for the open system, the presence of partitions has improved the tiles flowrate and hence rack inlet temperature.

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Appendix A – Simple data center model layout.