AIRFLOW PATH AND FLOW PATTERN ANALYSIS OF SUB-MICRON PARTICULATE CONTAMINANTS IN A DATA CENTER WITH HOT-AISLE CONTAINMENT UTILIZING DIRECT AIR COOLING

by

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Abstract

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The percentage of the energy used by data centers for cooling their equipment has been on the rise. With it has been the necessity for exploring new and more efficient methods, both from an engineering as well as business point of view, to contain this energy demand. The PCB boards are becoming more densely populated with multitude of smaller hardware on them, thereby, increasing its cooling requirements. Literature suggests that almost 40% of the total energy consumption in a typical Data Center is used for cooling purposes. Air cooling has always been the first choice for IT companies to cool their equipment in data centers, but it has its demerits as well.

Data centers which use Airside Economizers (ASE's) to reduce cooling costs by giving a relief to their CRAC (Computer Room Air Cooling) units for some time are particularly at risk of gaseous and particulate matter contamination. In doing so, mostly the IT companies tend to operate outside the ASHRAE recommended cooling envelope, thereby, reducing the equipment reliability. The objective of this study is to analyze the effect of particulate contaminants on data center equipment with the help of CFD simulation in 6SigmaRoom. This study deals with determining the airflow pattern and flowpath of the particulate contaminants emanating from the ACU. The particles are

assumed to be spherical in shape and are classified based on their size as 0.05µm, 0.1µm and, 1µm. The smaller particles represent fine particulate contaminants like dust and salts, and the 1µm particles represent carbon black particles emitted in vehicle exhaust. To better understand the results obtained from the simulation, a mathematical model was referred which also has been presented in this work. The result plots provide the information about the most vulnerable locations, where the particle concentration is the most. The streamline plot gives the velocity vectors and helps in depicting the airflow pattern and flowpath of the contaminants.

The results of this study can be combined with best practices for data center design, which will not only improve the energy efficiency of the data centers but will also help in subsequent cost savings by improving equipment reliability.

Table of Contents

List of Illustrations

List of Tables

Chapter 1

Introduction

1.1 Data Centers:

Data centers are centralized facilities that house networking and computing equipment for remote data storage, distribution and processing. This equipment plays vital role in running the daily tasks of any IT or government organization. Apart from this Data Centers are particularly important for cloud service providers for backing up huge amounts of user data and to keep critical applications up and running during nominal and peak demand periods.

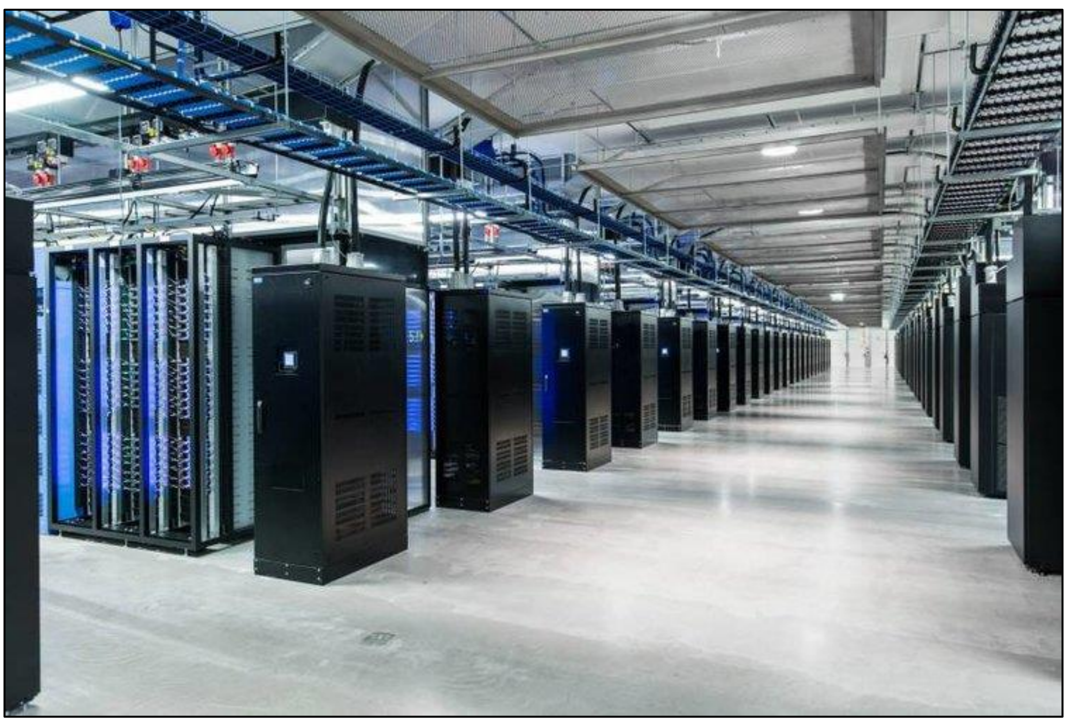


Figure 1-1 Facebook’s Data Center

With increasing IT loads and packaging densities the power consumption requirements of the ITE has been increasing. With this, the cooling requirements are also increasing, and the literature suggests that almost 40% of the total power consumption in a typical data center is used for cooling purposes. To ensure that all the ITE works reliably under all loading conditions, the ITE should be cooled continuously for effective operation. The air temperature standards of cooling air entering the ITE are set by ASHRAE (American Society of Heating, Refrigeration and Air-conditioning Engineers) T.C.9.9. This technical committee is mainly concerned with various aspects related to data center white spaces, ITE and mission critical facilities. ASHRAE TC 9.9 created the first edition of the 'Thermal Guidelines for Data Processing Environments' in 2004. Prior to that the environmental parameters necessary to operate data centers were anecdotal or specific to each IT manufacturer. In the second edition of the Thermal Guidelines in 2008 ASHRAE TC 9.9 expanded the environmental range for data centers so that an increasing number of locations throughout the world were able to operate with more hours of economizer usage [1].

With increasing need of higher computing efficiencies, the stress on using cost saving cooling techniques like airside economization year-round has increased. The second edition of the thermal guidelines for data centers (2008) laid down emphasis on the recommended envelope to maintain high ITE reliability and at the same time operating the data center with highest efficiency. Figure 1-2 shows the psychometric chart describing ASHRAE's allowable and recommended ranges of temperature and humidity conditions for data centers. It defined the recommended temperature-humidity range as 18-27°C dry bulb temperature range, 5.5-15°C dew point range and relative humidity less than 60% [2]. The recommended envelope defines the best set of conditions for highest ITE reliability as stated by the manufacturers. However, due to increasing computing demands and high packaging densities in ITE, data center administrators are always looking for expanded recommended and allowable ranges. This expansion if left unchecked can severely reduce the equipment reliability.

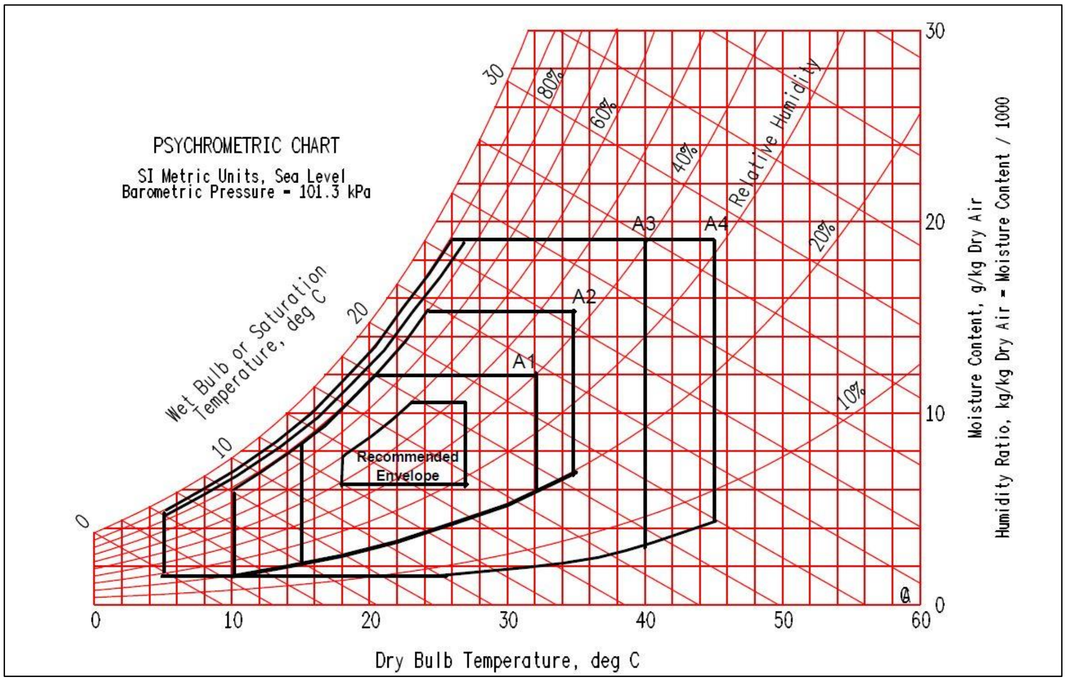


Figure 1-2 Psychometric chart for ASHRAE recommended and allowable classes

1.2 Data Center Cooling

Heat removal from a data center white space is perhaps the most essential task for proper functioning of all the ITE in the white space. Cooling in a Data Center white space can be achieved by various methods. Some these are shown in Fig.1-3**.** All these methods have their advantages and disadvantages and a myriad of other factors like geographical location, the size of the data center, power density requirements etc. Other important factors on which cooling depends is the distribution of airflow and the location of cooling units.

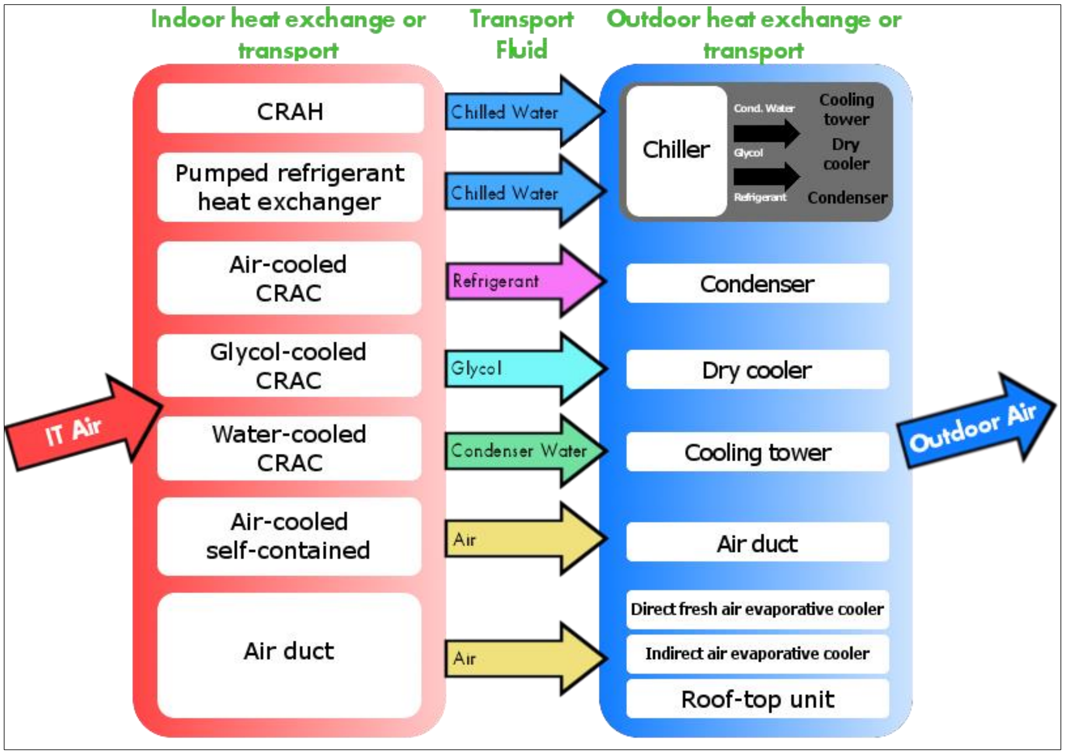


Figure 1-3 Data Center cooling methods

This study deals with modeling of a data center which uses airside economizers/ direct and indirect evaporative cooling, therefore, our focus will be on the above-mentioned cooling technique.

1.3 Airside Economizer

Data center owners are resorting to cost saving measures, primarily owing to the increasing demand for cooling due to more densely packed PCB boards and rising cloud data storage and faster computing needs. To keep the critical applications and effectively provide users with their data stored on the cloud, the IT load has increased manifolds. While, a lot of research and successful small-scale application has been done on liquid immersed cooling, air cooling remains the most popular choice for most of the data centers for cooling ITE, especially smaller data centers.

Airside Economizer (ASE) helps to partly relieve the cooling load off the CRAC (Computer Room Air-Conditioning) units. The ASE work on the principle that when the device senses that the outside temperature and humidity conditions are favorable as per the operating conditions inside the data center, it shuts down the condenser and allows free air to enter the data center facility. Fig. 1-4 shows the working of a typical Airside Economizer. A major drawback of this process is that, along with this free air, it also allows particulate contaminants to enter the data center space that are near the facility which was the main motivation behind this study. While some larger particles are filtered by the air filters, the sub-micron and fine particles do enter the data center space and are detrimental in long term reliability of the ITE. The sources and effects of this contamination will be explained in the following section.

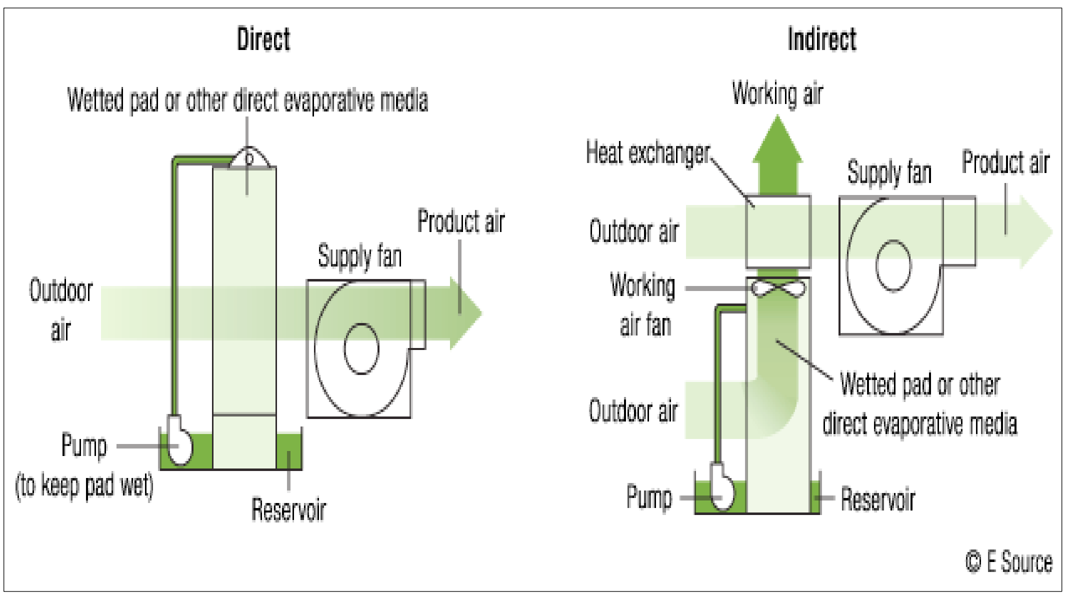


Figure 1-4 Working of an Airside Economizer

1.4 Particulate Contaminants

Most of the data centers have cleaner geographical locations and are well equipped with state of art filter systems to prevent contamination from particulate matter. To deal with the increasing server densities and the associated cooling costs, data center operators are resorting to cost cutting measures such as not tightly controlling the temperature and humidity levels as per ASHRAE recommended envelope and often turning to Airside Economizers with the related danger of bringing particulate and gaseous contaminants into their data centers [22]. Using ASE puts these data centers at the risk of being prone to airborne particulate contamination. There is an urgent need to determine the reliability of IT equipment as a function of temperature, humidity, and gaseous and particulate contamination so that algorithms can be generated for the most cost-effective operation of data centers without adversely affecting the reliability of IT equipment [22].

It is incumbent on data center managers to do their part in maintaining hardware reliability by monitoring and controlling the dust and gaseous contamination in their data centers. Data centers must be kept clean to Class 8 of *ISO 14644-1, Cleanrooms and Associated Controlled Environments—Part 1: Classification of Air Cleanliness* (ISO 1999). This level of cleanliness can generally be achieved by an appropriate filtration scheme as outlined in the following.

- The room air may be continuously filtered with MERV 8 filters as recommended by *ANSI/ASHRAE Standard 127-2007, Method of Testing for Rating Computer and Data Processing Room Unitary Air Conditioners* (ASHRAE 2007a).
- Air entering a data center may be filtered with MERV 11 or MERV 13 filters as recommended by *Particulate and Gaseous Contamination in Datacom*

Environments (ASHRAE 2009a) [4].

The above guidelines are meant to be standard for all data centers for maintaining high equipment reliability. While MERV 11-MERV 13 filters can filter most of the heavy particulate contaminants, sub-micron particles still escape and accumulate on PCB boards over longer period and cause equipment failure. While one might think that its easier to use higher efficiency filters to prevent fine particles from entering data center white space, this leads to further increase in costs incurred for purchase and scheduled maintenance and repair of these filters.

Table 1 ISO 14644-1 (ISO 1999) Air Cleanliness Classification vs. Maximum Particle Concentrations Allowed (particles/m^3)

ISO CLASS	Maximum Number of Particles in Air (Particles in Each Cubic Meter Equal to or Greater Than the Specified Size)					
	Particle size, μm					
	>0.1	>0.2	>0.3	>0.5	>1	>5
Class 1	10	2				
Class 2	100	24	10	4		
Class 3	1000	237	102	35	8	
Class 4	10,000	2370	1020	352	83	
Class 5	100,000	23,700	10,200	3520	832	29
Class 6	1,000,000	237,000	102,000	35,200	8320	293
Class 7				352,000	83,200	2930
Class 8				3,520,000	832,000	29,300
Class 9					8,320,000	293,000

Note: Uncertainties related to the measurements process require that data with no more than three (3) significant figures be used in determining the classification level.

Figure 1-5 ISO cleanliness standards

The sources of particulate matter are both natural and anthropogenic. According to P.Singh et al [5] the particulate matter can be broadly classified on the basis of size as fine and coarse particles. Fine particles are those whose particle diameter is less than 2.5 µm and coarse particles are those which have particle diameter raging between 2.5-15 µm. Table-1 describes the sources of the most typical particulate matter found inside a data center. The particulate matter accumulates on PCB and causes open and shot circuits which will be explained in the following section on the effects of the particulate contaminants.

Table 1-1 Sources of some typical contaminants

Contaminant	**Source**
Zinc Whisker	Zinc coated ICT, steel building tuds
Tin Whisker	Components and products with electroplated tin
Oxide Flake Off	Magnetic media
Natural and Artificial Fibers	Paper, cardboard, etc.
Water Soluble Ionic Salts	Chemical reaction
Sulphates Nitrates and Sea Salts	Wind
Lime Dust with Water	Concrete material
Dust	Farms (especially during plowing)
Toner Dust	Toner
Smoke	Cigarette, wind
Cellulose Fragments	Traditional ceiling tiles and space

1.5 Effect of particulate contaminants

The effects of particulate contaminants on data center ITE, as per ASHRAE 2009b, can be classified as:

i. Mechanical effects

ii. Chemical effects

iii. Electrical effects

The white paper also describes that most kind of dust is harmless for ITE. The sources of fine particles include ionic sea salts, volatile organic carbon compounds from vehicle exhaust, zinc whiskers from floor plenum etc. Most of the fibrous and whisker type particles are larger in dimeter and are filtered easily. The particles which are detrimental to equipment reliability are salts mixtures and mixture of salts with other

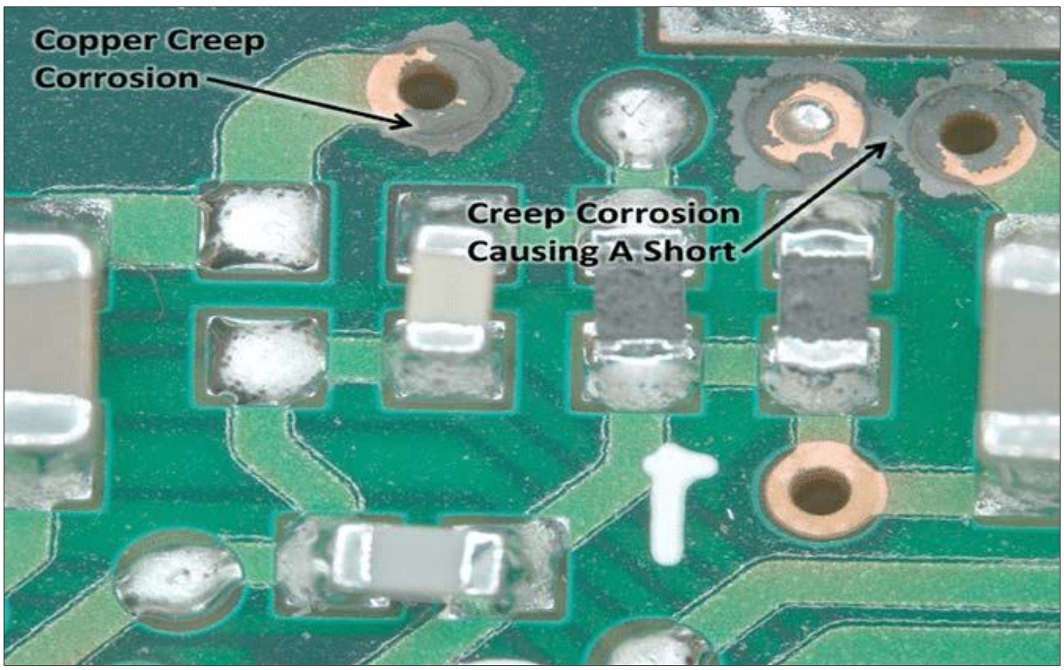


Figure 1-6 Example of copper creep corrosion on lead-free PCB

organic compounds as dust. These compounds, otherwise harmless, become conductive in presence of moisture. DRH (Deliquescent Relative Humidity) is a term frequently used and is defined as the threshold value of humidity above which the particulate matter absorbs moisture from air to form an ionic solution, thus, becoming conductive in nature. This causes electrical short circuit failures in PCB by reducing the resistance between closely space hardware features as shown in Fig1-6 [6]. Jimil Shah et al [23] carried out a computational study on the reaction mechanism of the PCB undergoing corrosion in gaseous contaminant environment as in an actual data center. In another study he goes on to study the effects immersing PCB in mineral oil and concluding that there was no effect on equipment reliability although the board did become stiffer. [25]

Environmental factors such as temperature, relative humidity, and gaseous and particulate contaminants can cause PCBs to fail in two major ways:

- Electrical open circuits occurring due to corrosion, for instance corrosion of silver terminations in surface mount segments, surface mount resistors endure open circuits because of the consumption of their silver terminations by sulfur bearing gaseous contaminants in polluted geographies [6-10]
- Electrical short circuiting due to copper creep corrosion, by electrochemical reactions such as ion migration and cathodic–anodic filamentation [5,6,9]

In 2006, the European Union’s restriction of hazardous substance (RoHS) directive banning the use of lead in solders led to changes in PCB finishes and the elimination of lead from solders. These progressions significantly expanded the PCB failure rates because of creep corrosion [5,6]. The settled, hygroscopic particulate matter contaminations reduce the surface insulation resistance between closely spaced structures on PCBs. In humid environments, it becomes very difficult to deal with the electrical short circuiting caused by the accumulated particulate matter. The difficulty arises from the intermittent electrical nature of these particles and the fact that the failure leaves no visible evidence besides the presence of deposited particulate matter [5,6]

The is a first of its kind of study which shows the airflow path and flow patter of airborne particulate matter inside the data center white space. The results of this thesis research can be collaborated with the experimental results to corroborate the locations of maximum particle accumulation with those obtained experimentally. If both the results are in congruence then, the results can be incorporated with best data center design practices to not only improve data center energy efficiencies but also improve its equipment reliability. The effect and extent of corrosion due to different salts and their combination is discussed in a study by Anand R. [27].

To partly overcome the challenges faced in air cooling, research is still ongoing in the field of oil immersion cooling of ITE. Although this will still take some time to overcome the dominance of air cooling techniques which are most prevalent in present day data centers. Jimil Shah, Ashwin S. et al [24] discuss the effects of immersion in mineral oil on the reliability of ITE in data centers.

1.6 Data center layout and ITE heat load generation

(Reprinted with permission © 2018 ASME) [26]

An IT server in a data center can be closely related to the fundamental functioning of a standard home-based PC (personal computer) unit. It produces a very unusual and concentrated head load and when running at high computing speeds, it requires some air conditioning to handle the heat load concentration. When scaling this comparison to a data center, the size of server rooms and the load of heat dissipated is very large and the need for cooling is also very large. The IT hardware equipment are very sensitive to changes in temperature and humidity, and with the introduction of free air cooling, standard design conditions would strain the operations of a data center using air-side economizations. Tackling the increasing costs because of high energy expenditures has forced data center engineers and professionals to come up with strategies which can minimize these costs. Aisle containment is one of these strategies which has become a proven measure for building energy efficient Data Centers.

The rack-mounted servers are designed to draw in cool air at the front and exhaust it out at the back of the unit. They are positioned in such a way that their back sides are facing to form hot aisles, while the front sides, which receive cool air from the perforated floor tiles, form the cold aisles. This set-up divides the draw air and the exhaust air of the IT equipment into separate hot-aisle and cold-aisle containments. The best standard practice observed is to configure the data center room into alternating hot and cold aisles. Containment of the hot and/or cold aisle can be configured to best suit the operational standards. Cold aisles contain the floor tiles or diffusers and the racks stacked with server fronts (intake) facing the cold aisles. This practice of having all rows arranged in a similar manner allows for easy configuration of air distribution throughout the entire data center space. Many large data centers have the practice of implementing the air inlets and outlets of the servers at separate locations for effective cooling.

Chapter-2

Literature Review

An extensive literature review was carried out to corelate the results of the present study with existing research. Although, there are no studies on flow path and airflow pattern of particulate matter inside a data center white space, there are some studies on particle transport and flow distribution in closed and ventilated rooms. These studies closely represent the particle and flow distribution conditions in the present data center model. Another challenge that was faced during this study was lack of any analytical CFD model to represent particle transport inside a data center, so a math model was referred and has been presented in this section. The purpose of presenting a math model is that it helps in comprehending the post processing results obtained from CFD software package.

There have been many researches on temperature and airflow distribution in the data center white space. Of these studies, Awbi and Gan [11] calculated thermal comfort and airflow in office space which is naturally ventilated using CFD program. Flow rates and measurement of temperature in a data center were presented by Schmidt [12]. This study describes the detailed thermal conditions, power usage, airflow distribution through units and heat dissipation measurement in server racks. A detailed CFD model was also presented in the study and the experimental results were compared with those obtained from the CFD model. Guggari et al [13] used CFD as analytical tool to check the for the airflow distribution and desired cooling levels in a data center. the study used a data center with a raised floor design and performing a flow analysis. Based on the results from the flow analysis, the data center layout was decided in such a way that cabinets were placed in the areas with maximum cooling airflow. The purpose of the study was energy efficient and design layout optimization of a data center. Patnakar and Karki [14] describe the use of principles of fluid mechanics govern the airflow distribution in a data center with raised floor for reliable operation of ITE. Patnakar [15], in one of his studies also describes the key parameters that affect the airflow and pressure distributions in a raised floor data center. The parameters used in this case were variation in plenum height and changing the open area of the perforated tiles. The study also demonstrated how the presence of under-floor obstructions influences the airflow through the floor grilles.

All the studies mentioned above were related to the thermal environment mapping or airflow distribution in the data center. The study which was the closest to present work was done by Seymour M. [16]. This study deals with modeling cough

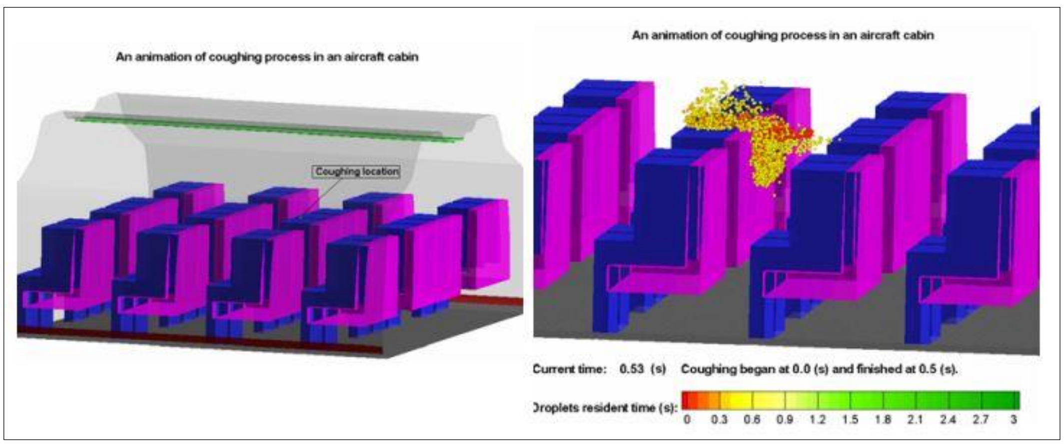


Figure 2-1 Cough droplets dispersion

particle trajectories, in a hospital space, using a CFD model. The objective of the study was to simulate the motion of the droplets containing bacteria and minimizing it by exposing the droplets to ultraviolet irradiation. A similar analytical study on particle transport was done by Chen and Zhang [17] to predict the particle dispersion in an airplane cabin and a building with six rooms. The paper discusses two different particles and flow models and compares their shortcomings. It then uses the RANS (Reynolds Averaged Navier-Stokes) flow model and Lagrangian approach to track the particle droplets as shown in Figure 2-1.

CFD modeling is the process of representing a fluid flow problem by mathematical equations based on fundamental laws of physics and solving those equations to predict the variation of velocity, pressure and temperature, and other variables such as turbulence parameters and concentrations which are discussed by Jone [18]. Analytical modeling in a CFD study is as important as the computational model, especially in particle transport studies, to effectively visualize the relation between particles and the carrier. To relate the results of the simulation more closely to a mathematical model of past research literature, the Lagrangian model for particle transport was referred. The CFD solver in 6SigmaRoom, the CFD package used in this study, iteratively solves many simultaneous equations representing Conservation of Momentum Equations or Navier-Stokes Equations. The mathematical model presented below most closely relates to the existing study and helped in visualizing the post-processing results from the simulations.

The particle trajectories by Lagrangian method are computed by solving the momentum equation, which is given as:

$$\sum F_i = d(m_p v_i) / dx$$

Momentum force is transferred between air and particles through inter-phase drag and lift forces, which can be divided into, but not limited to, the following parts: the drag force, pressure gradient force, unsteady forces which include Basset force and virtual mass force, Brownian force, and body force, such as gravity force and buoyancy force [19].

$$\sum F_i = F_{drag\ i} + F_{grav\ i} + F_{saf\ i} + F_{b\ i}$$

The drag force on the particle is expressed as

$$F_{drag\ i} = -C_D \frac{\pi}{8} \rho d_p^2 |\vec{u} - \vec{v}| (v_i - u_i)$$

The drag coefficient, C_D, in this equation depends on the particle shape as well as flow parameters like flow velocity, turbulence level Reynolds number etc.

The particle Reynolds number is expressed as:

$$Re_p = \frac{|\vec{u} - \vec{v}| d_p}{\nu}$$

The buoyancy and gravity forces on the body in a fluid are given as

$$F_{grav\ i} = (\rho_p - \rho) \frac{\pi}{6} d_p^3 g_i$$

The Saffman lift force on the body is given as:

$$F_{saf\ i} = K \frac{\pi}{3} \sqrt{v} d_p^2\, \rho \frac{d_{ij}}{(d_{lk} d_{kl})^{1/4}} (u_j - v_j)$$

After substituting these values in the equation 1 and dividing both sides by particle mass m_p, the complete equation for the particle motion becomes:

$$\frac{dv_i}{dt} = -\frac{3}{4} \frac{\rho C_D}{d_p \rho_p} |\vec{u} - \vec{v}| (v_i - u_i) + (\rho_p + \rho)\ \frac{\pi}{6} d_p^3 g_i + (1 - \frac{\rho}{\rho_p}) g_i + (\frac{2K\rho\sqrt{v} d_{ij}}{\rho_p d_p (d_{lk} d_{kl})^{1/4}})\ (u_j - v_j)$$

For particle size less than 1µm, the Brownian force can also be included to calculate the diffusion:

$$F_{bi} = \zeta_i \sqrt{\frac{216 \rho v \sigma T}{\pi \rho_p^2 d_p^5 C_c \Delta t}}$$

Where ζ, is Gaussian random number given by,

$$u_i = \zeta \sqrt{\frac{2k}{3}}$$

Chapter-3

Methodology

3.1 Data Center Configurations

As mentioned earlier, a data center houses various type of ITE required for storing and back up of company's as well as the users' data. Architecture of a data center includes not only the ITE but also infrastructure facilities required to keep the ITE functionable and running. The facility infrastructure includes power components like PDU's (Power Distribution Units) and UPS (Universal Power Supplies), cooling components as per the data center design like CRAC units and economizer units, cabling and power routes etc. The investment in data center architecture and infrastructure can thus be significant, especially for IT giants like Google, Microsoft, Amazon etc. Therefore, majority of the companies are constantly researching and developing techniques to reduce the expenditure on data centers and at the same time, maximizing the computing efficiency.

These high computing costs have led to development of containment systems in data centers viz. hot-aisle containment system and cold-aisle containment systems. The primary pre-requisite for a containment system is that the data center layout should be in the form of alternate hot and cold aisles. The advantage of containment systems is that it maximizes energy efficiency by allowing uniform inlet temperatures and preventing the mixing of hot and cold flows. This in turn allows the IT administrators to set the CRAC temperatures higher than in a data center without containment because all the cold flow reaches the ITE. A typical layout of hot aisle containment and cold aisle containment is shown in Fig 3-1. A detailed description of both the layouts is presented in the following sections. There are various advantages of containment systems, some of which are listed below:

- A containment system allows to set the supply temperatures higher, thereby, reducing the cooling costs while supplying sufficient cold airflow for safe operation of ITE.
- Since, the containment prevents mixing of hot and cold flows, this provides and even temperature profile in the data center white space and uniform ITE inlet temperatures.
- Due to separation of hot and cold flows, the CRAC unit temperature can be set higher than the dew point temperature of the CRAC supply air. In such a case, the requirement of dehumidifying and again humidifying the air is eliminated. This in turn reduces energy costs too.

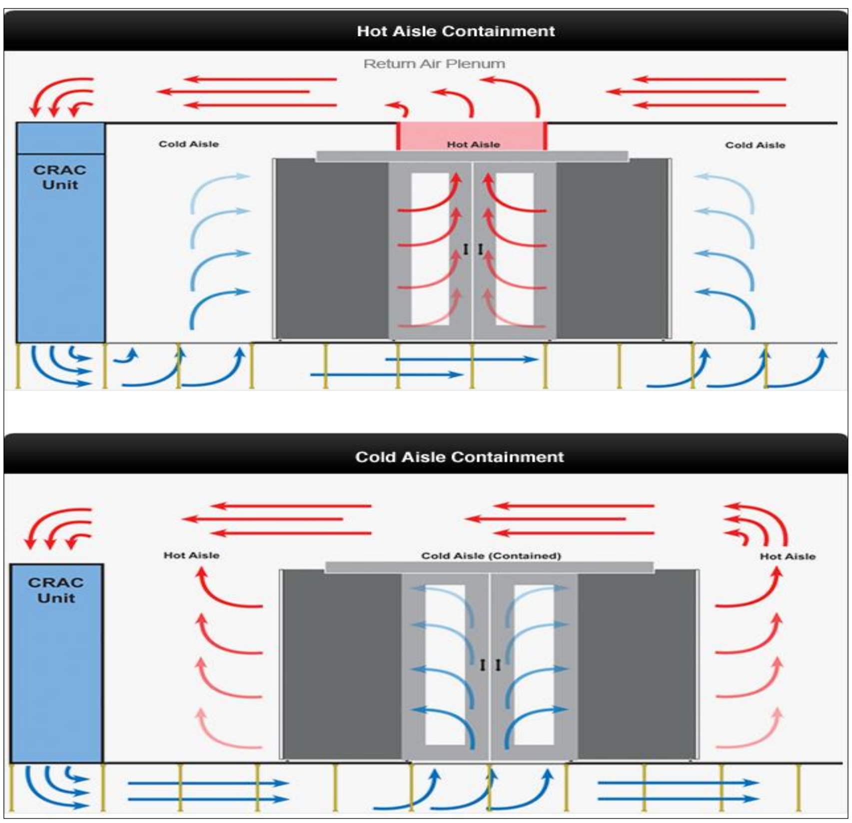


Figure 3-1 Hot-aisle and cold-aisle containment layout

3.1.1 Hot-aisle containment:

A hot aisle containment system is one in which the hot-aisle is contained, and the rest of the data center white space behaves as a big cold aisle space. The hot air is returned to the CRAC return through air ducts and roof panels.

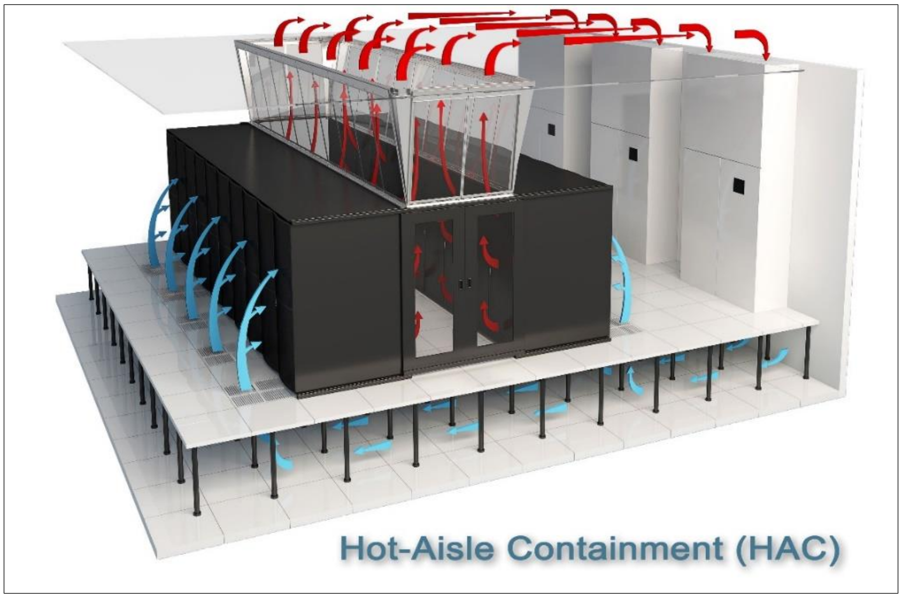


Figure 3-2 Hot-aisle containment system

A HAC system can be used in different variations as per the size of the data center. For smaller data centers, the given layout in Figure 3-1 can be used in which the hot air is returned to the CRAC unit, conditioned and supplied back as cold airflow. For larger data centers, the hot airflow can be directed to a CRAH (Computer Room Air Handler) unit which unlike a CRAC unit uses chilled water, cooling coils and fans to condition hot air. Such an arrangement can be used in data centers in conjunction with ASE and further reduce the cooling costs. Another practical advantage of a HAC system is that by containing the hot flow, the temperature of the working area stays reasonably cold and well in agreement with OSHA (Occupational Safety & Health Standards) regulations.

3.1.2 Cold-aisle containment

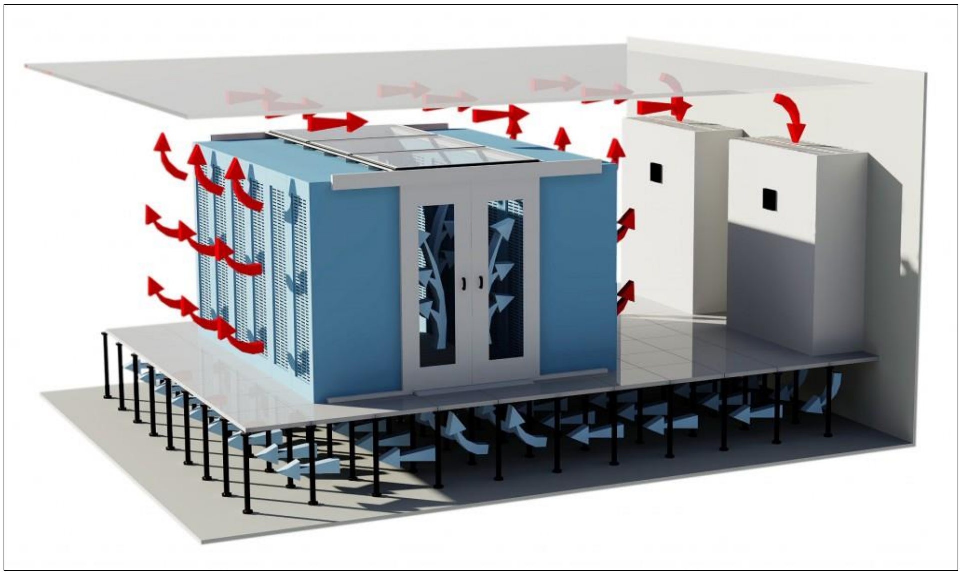


Figure 3-3 Cold-aisle containment system

A cold-aisle containment (CAC) system is one in which the cold aisle is enclosed, and the rest of the data center becomes a hot aisle return. Some small-scale data centers use curtains made of cellophane plastic or plexi-glass to contain the cold flow, although this s only suitable for lower flow rates due to high amount of leakage. Also, now-a-days, a lot of manufacturers are making sealed cold-aisle enclosures and doors that can be mounted with the racks. This is particularly suitable for high density data centers. As discussed in literature review section, analysis of energy savings by both type of containment systems was done by John Neimann et al [20] in a white paper. Their analysis showed that the HAC system yielded 40 annual savings in cooling cost and a 13% reduction in annual PUE (Power Usage Effectiveness). Since, the rest of the data center is hot in CAC system, with temperatures reaching 38°C in big data centers, it can be detrimental for safe operation of unracked ITE. Therefore, considering all these points, it can be concluded that a HAC can be a better choice in case of energy savings.

3.2 Data Center Description

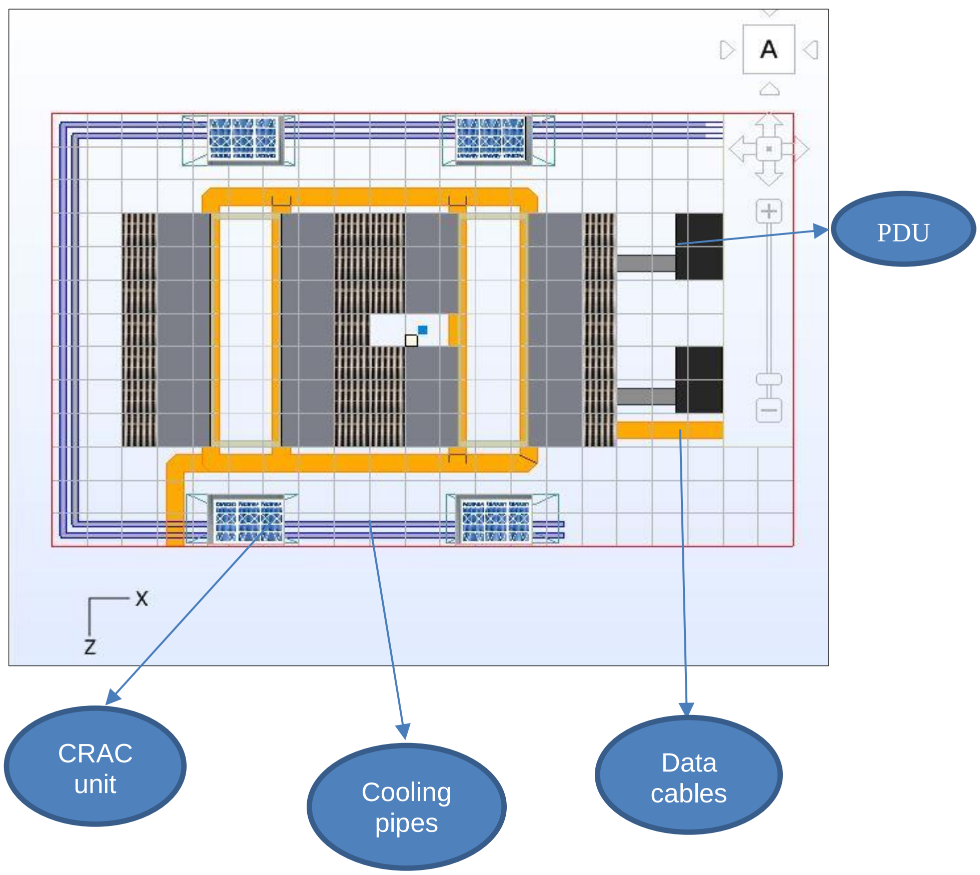
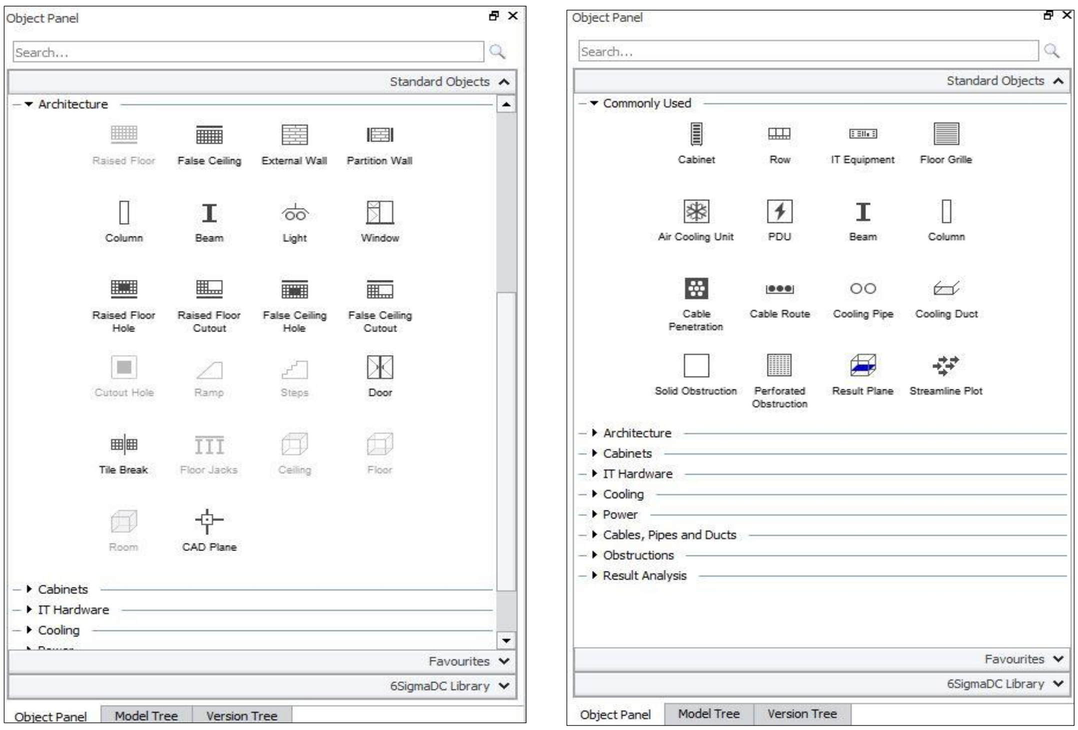


Figure 3-4 Data center layout

Figure 3-4 shows the layout of CAD model of the data center with HAC used in the present study as modelled in 6SigmaRoom. Many commercial CFD packages are



(a) (b)

Figure 3-5 Object panel in 6SigmaRoom

available which can effectively predict the flow pattern of air which are induced by mechanical devices and thermal sources. Most of them, including 6SigmaRoom [21] can be executed on personal computers. 6SigmaRoom, by Future Facilites, can predict the air flow and heat transfer explicitly for Data Center using CFD techniques. It provides a fast mean of predicting the indoor data center environment as an alternative or supplement to the physical model. It acts as an easy tool which allows the user to generate a virtual facility model that is used to assess and compare new designs, to model and troubleshoot existing facilities and to provide a basis for ongoing change management; this practice is known as predictive simulation. Applications including design, ventilation and air-conditioning system for data centers of all types and sizes, from small to high-density data centers. The approach is very similar to that of a field model for predicting the turbulent convective air flow path within the data center space.

Figure 3-5 shows the object panel as available in 6SigmaRoom. As seen from the figure, this software allows the user to model a virtual data center with the finest of details giving access to various architectural and cooling options exactly as in a real-life data center. Thus, the airflow and thermal analysis results. Table 3-1 gives a description of the hardware used, cooling and equipment power consumed in the data center model

Table 3-1 Large Table in Landscape Orientation

Object	Description
Room Size	91.08 m^2
Raise floor height	640 mm
ACU supply temperature	12.8°C
Number of servers	486
Cabinet power limit	5.6 kW
Server type	2U-600W
Number of cabinets	27
Cabinets per row	7
ITE power	175.2 kW
Total power used	151.2 kW
PUE	1.156

obtained from post-processing in 6SigmaRoom can be considered very precise.

3.3 CAD modeling of the data center

There are a variety of commercial data center design packages available in the market but 6SigmaRoom offers extensive vendor libraries items including ACU's, PDU's ITE, fans etc. which makes data center design a simple and quick task.

Figure 3-6 Hot-aisle containment infrastructure layout

In this section, we will be briefly going through the steps that were followed while creating the CAD model as shown in Figure 3-6.

1. A room layout is sketched wherein the dimensions of the room are given which act as the room boundaries or walls. All the technical space containing power supplies, cooling equipment and ITE is contained within this space.
2. Once the technical space is defined, the raised floor option is chosen from the object panel as shown in Figure 3-5 and the required raised floor height is

specified the supporting structures like a column or a beam can also be added during this step depending upon the design requirement. A column was added in the current model to support the false ceiling.

3. Once the flooring and room dimensions are specified, cabinets are laid out as per the design requirement. The cabinet power limit and the servers to be stacked is also decided in this step which are available in 6SigmaRoom vendor library representing real equipment from specific manufacturers.
4. After laying out the cabinets and stacking them with servers, the cooling requirement of the room can be estimated and the ACU units are laid out. In the current model, four 40 kW Centrifugal Blower type ACU's were used. Once all the ACU's were laid out, the cooling pipes were added which run under the raised floor. Two 100 kW PDU's are then put at specific locations as per best data center design practices and the data cables running from the PDU's to cabinets are placed as per the design specifications.
5. The last step was containing both the hot aisles. A false ceiling is first selected from the architecture node in the object panel as shown in Figure 3-5 and the height from the raised floor is specified. After this, an aisle enclosure is provided, and the roof panel and roof ducts holes are made. The last step is connecting the ACU's in the aisle to the false ceiling so that all of the hot flow is returned to the ACU without getting mixed with the cold airflow.

This completes the CAD modeling part of the present study. In the following section the pre-processing and post processing steps undertaken for the CFD simulation will be explained.

3.4 Simulation Methodology

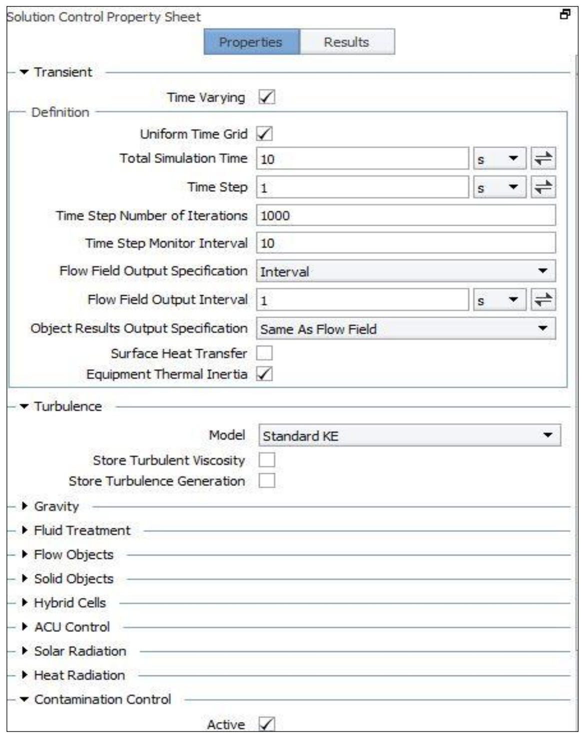


Figure 3-7 Solution control panel in 6SigmaRoom

Given below are the steps that were followed to for the CFD simulation of the contaminant flow:

1. The first pre-processing step was to set the contamination control feature active from the solution control tab as seen in Figure 3-7. This helps to specify the pollutants in the model. The contaminants can be attached to a supply/return vent, an ACU or directly in an environment. 6SigmaRoom has gaseous contaminants library as well as ability to attach user defined contaminants by assigning the physical properties like density and molecular weight. In the current model, ACU was chosen as the source of contamination to model the effect of particulates entering due to airside economization.

2. Once all three particles and their properties and concentration were assigned, the number of iterations to be performed and total transient simulation time can be assigned. In this study, 1000 iterations were chosen for a total simulation time of 10 minutes. Once these values are assigned, the CFD solver generates the solution grid automatically based on the number of obstructions present in the white space.
3. The CFD solver completes the given number of iterations and terminates the solution based on the default value (which is 1) or the assigned value of the termination factor as seen in Figure 3-8. The termination factor decides the degree of acceptable numerical error in the calculation to end the simulation.
4. After the solution is executed, there are various post processing options that can be used depending on the requirement of the study.

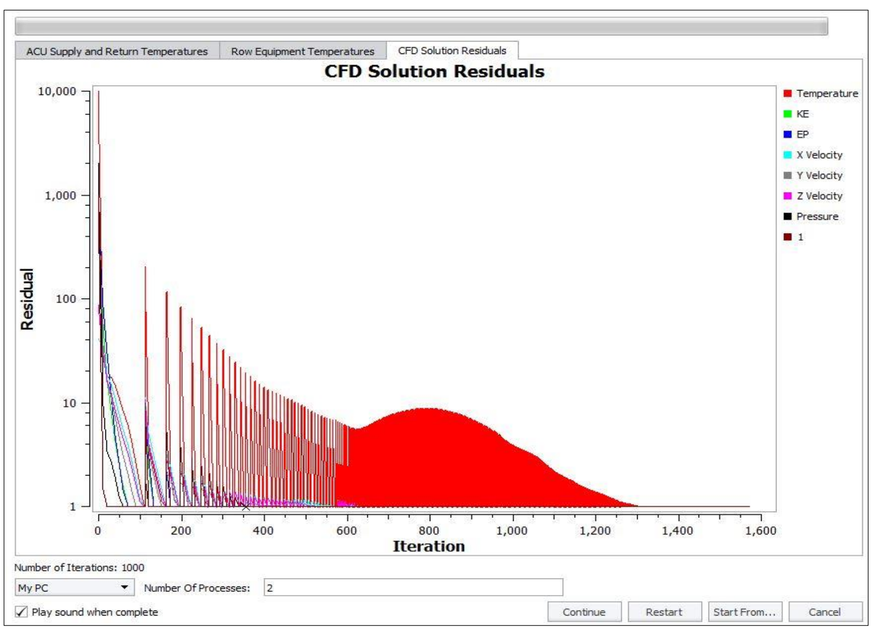


Figure 3-8 6SigmaRoom solution termination strategy

5. The temperature plots for cabinet and ITE were checked to see if the cooling flow kept the equipment within the ASHRAE recommended or allowable temperature envelope as seen in Figure 3-9 and 3-10.

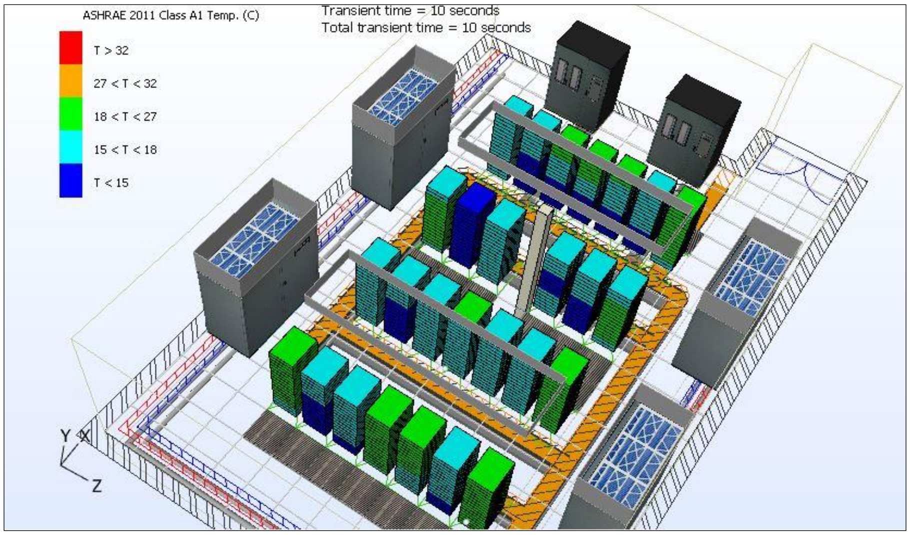


Figure 3-9 ASHRAE equipment temperature compliance plot

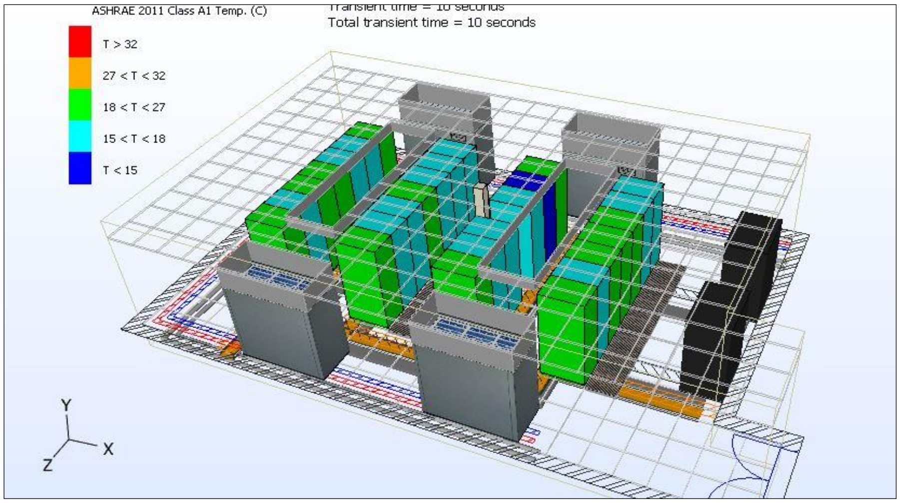


Figure 3-10 ASHRAE temperature compliance cabinet plot

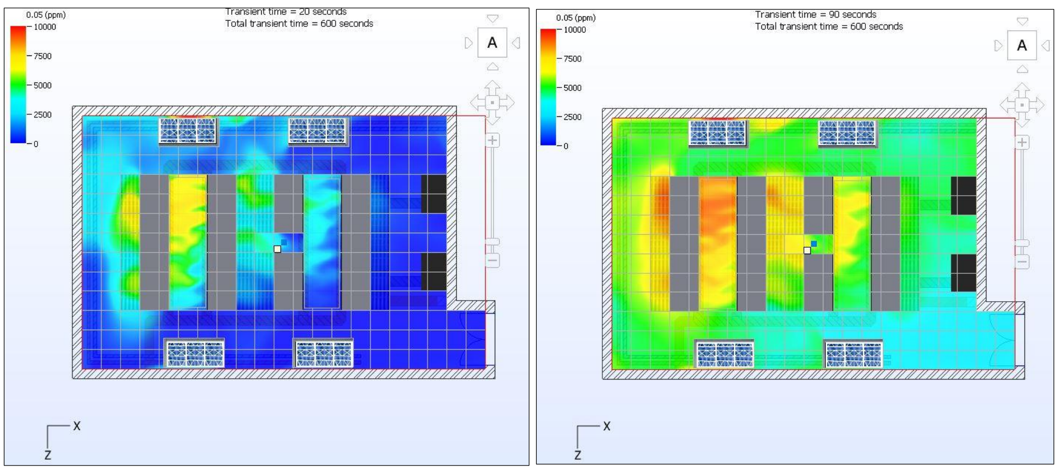
6. Once it was checked that the data center temperatures were in accordance to that ASHRAE temperature compliance, the concentration plots showing the distribution of contaminants on a plane at a height of 1 m from the raised floor height were plotted for all three particle sizes.
7. Streamline plots were then plotted, which describe the velocity vectors of the particles at different instances of time with the help of result animations that help in easily visualizing the flow path of the particles from ACU towards the server racks.
8. In the end, six sensors were used to monitor the rise in concentration of the particles in the hot aisle.

Chapter-4

Results and discussion

4.1 Plots for 0.05 μm particles

Figure 4-1 shows the concentration and streamline plots for the smallest particle size of 0.05 μm. The concentration or the contour plot shows particle accumulation on a plane at a height of 1 m from the raised floor plenum.



(a) (b)

Figure 4-1 (a) concentration plot at 20 seconds and (b) at 90 seconds

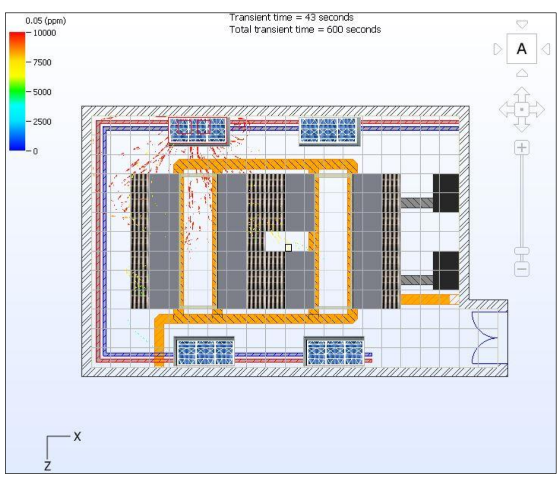


Figure 4-2 Streamline plot of 0.05 µm particles

Figure 4-1 (a) and (b) show the particle concentration at 20 second and 90 second interval of time. The stream line plot in Figure 4-2 shows the velocity vectors of the particles emanating from the ACU. After close examination of the concentration plots, it was found that the regions of maximum concentration were in the first three cabinets on either side of the hot aisle.

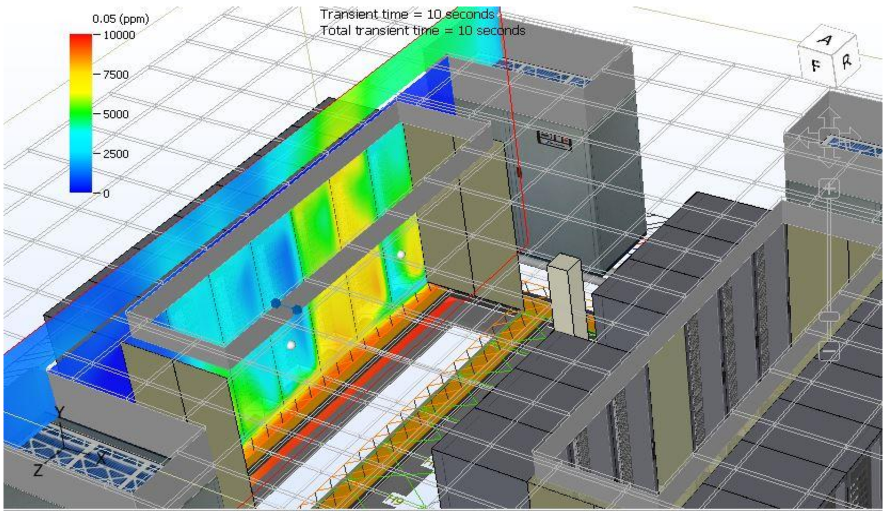
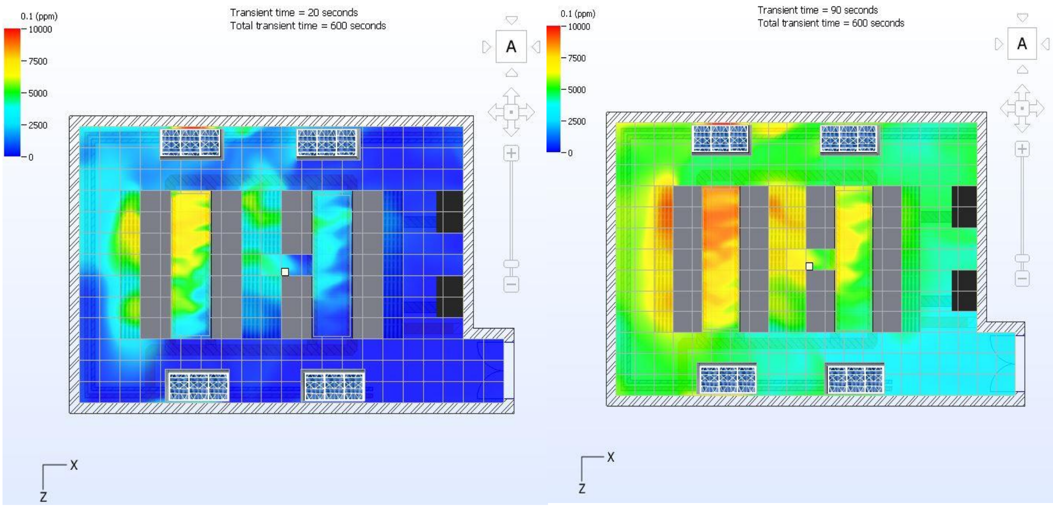


Figure 4-3 Concentration plot along cabinet height for 0.05 µm particles

A concentration plane was also plotted along the rear face of the cabinet to check the variation of contamination along the cabinet height. It is clearly shown in Figure 4-3 that the concentration decreases with increasing height and is maximum in the 2nd and 3rd cabinets. The height at which maximum concentration was found was around 0.9 m height from the raised floor. The minimum concentration is in the cabinet located at the far end of the aisle.

4.2 Plots for 0.1 μm particles

The second case for particle size simulated was for 0.1 μm particle size. As assumed, the physical properties for these particles were kept same as that of air as they are considered as concentration i.e. there is not particle slip with respect to the airflow.



(a) (b)

Figure 4-4 (a) concentration plot at 20 seconds and (b) at 90 seconds for 0.1 µm particles

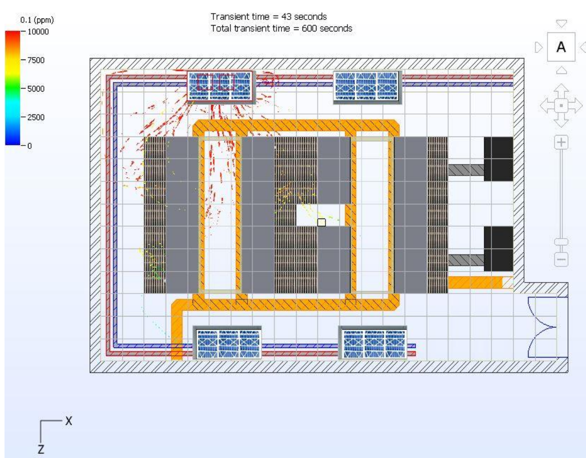


Figure 4-5 Streamline plot of 0.1 µm particles

The concentration plane was plotted at a height for 1 m for this particle size as well and exactly similar concentration plot was obtained as for 0.05 μm particles. The streamline plot in Figure 4-5, showing the velocity vectors, was also observed to be the same as that for 0.05 μm particles. The locations of maximum particle concentrations remain the same on both the intervals as seen in Figure 4-4 (a) and (b). The change in particle concentration with height is also plotted and the concentration in this case also decreases with increasing height in the aisle as seen in Figure 4-6.

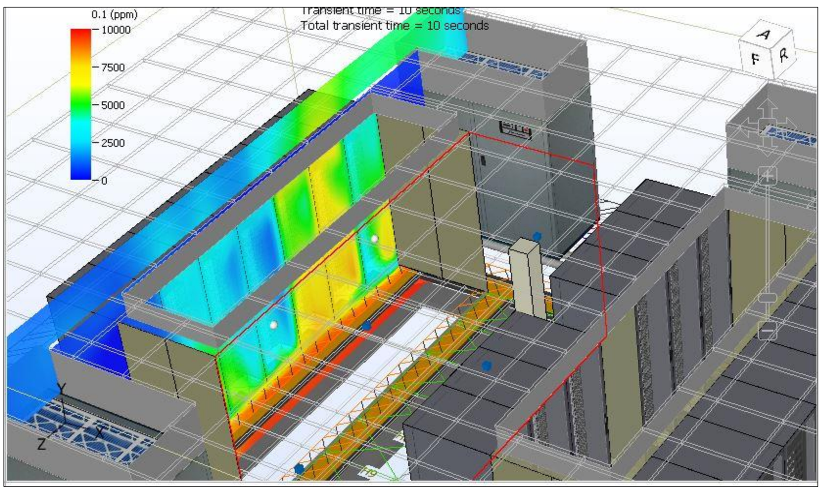


Figure 4-6 Concentration plot along cabinet height for 0.05 µm particles

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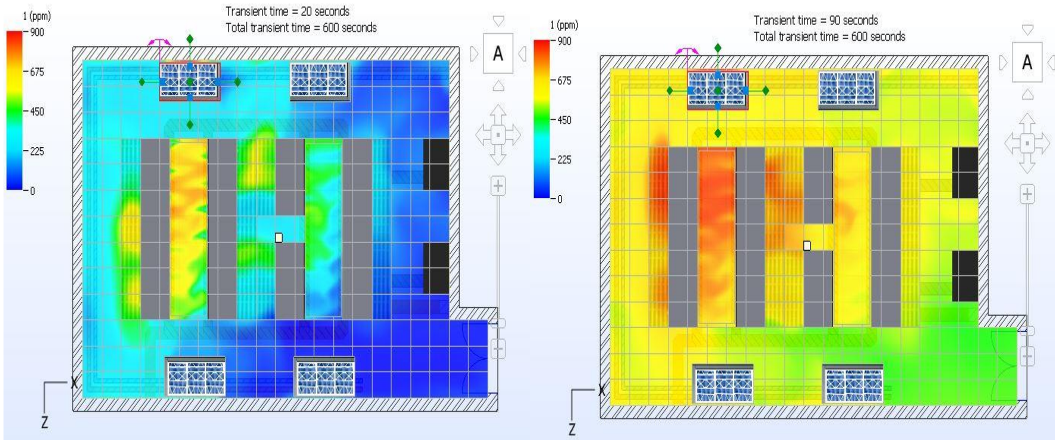
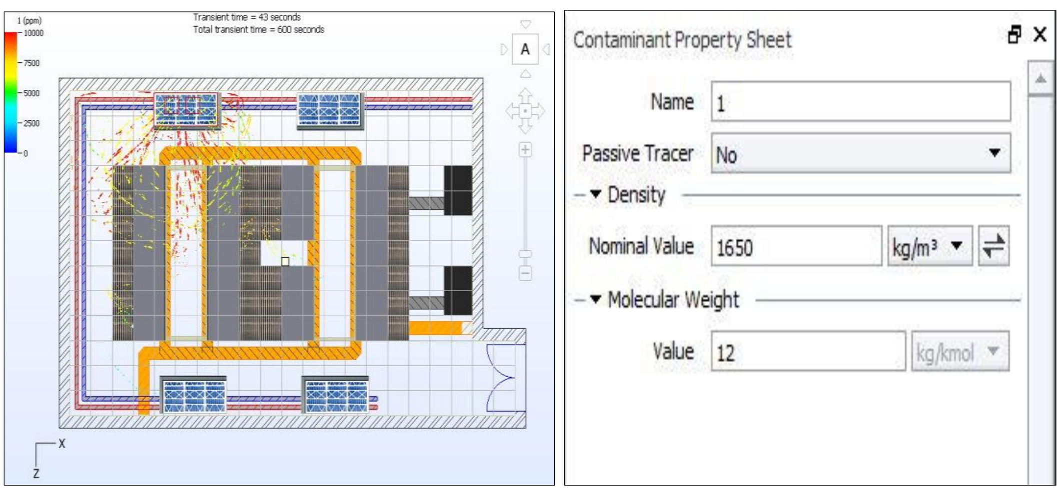
4.3 Plots for 1 μm particles

To simulate the airflow path for 1 μm particles the properties of dense carbon black particles, as found in vehicle exhaust, are used as shown in Figure 4-8 (b). To keep the volume fraction of particles low as compared to that of air, the number of particles entering were restricted 900 ppm. This concentration was chosen as per our assumption of Lagrangian approach. As seen from Figure 4-7, the concentration plane shows the same locations of maximum particle accumulation i.e. first three cabinets on each side of



(a) (b)

Figure 4-7 (a) concentration plot at 20 seconds and (b) at 90 seconds for 1.0 µm particles



(a) (b)

Figure 4-8 (a) Streamline plot for 1µm particle and (b) contaminant property sheet the hot-aisle. The concentration plots look different because the particle concentration was kept low. The streamline plots showing the velocity vectors are also like that of sub-micron particles.

To check for particle contamination at different positions in the hot aisle, 2 sensors were added on either side of the hot aisle on the cabinets at a height of 0.5 m from the raised floor height as seen in Figure 4-9 and figure 4-10. These sensors gather data for increasing percentage of contamination with time and gives an idea about how

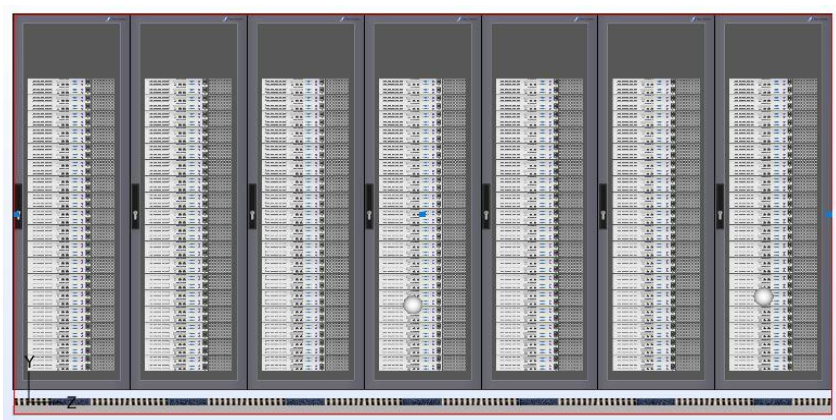


Figure 4-9 Sensor location on left side of the hot-aisle

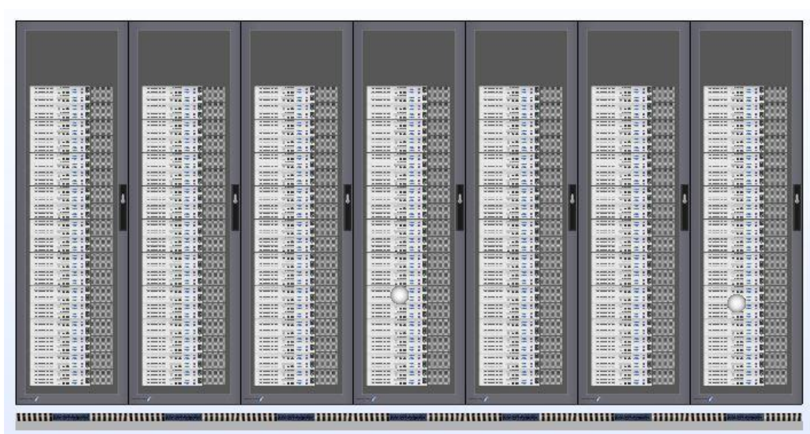


Figure 4-10 Sensor location on the left side of the hot-aisle

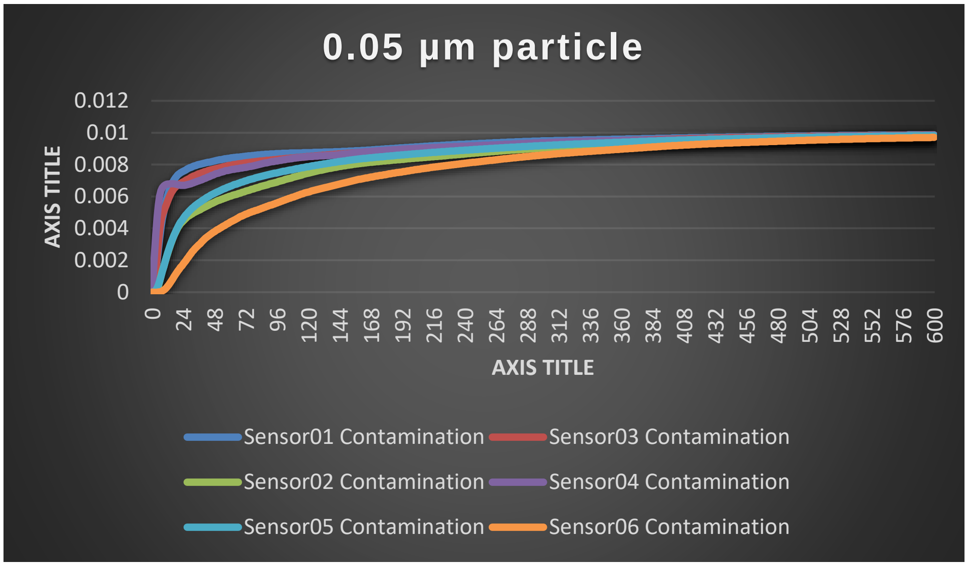


Figure 4-11 Sensor plot for 0.05 µm particles

the contamination is increasing at different locations and reaching a steady state. Two sensors were attached to the cold aisle as well to monitor the contamination level outside the hot aisle. The sensor plots were obtained for the three particle sizes considered in

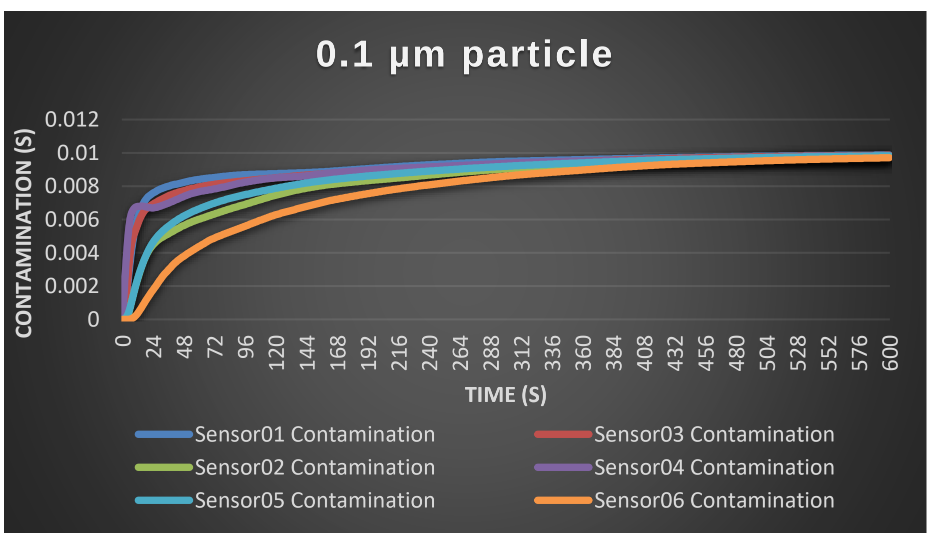


Figure 4-12 Sensor plot for 0.1 µm particles

this study and compared. It is seen that the percentage increase in concentration is

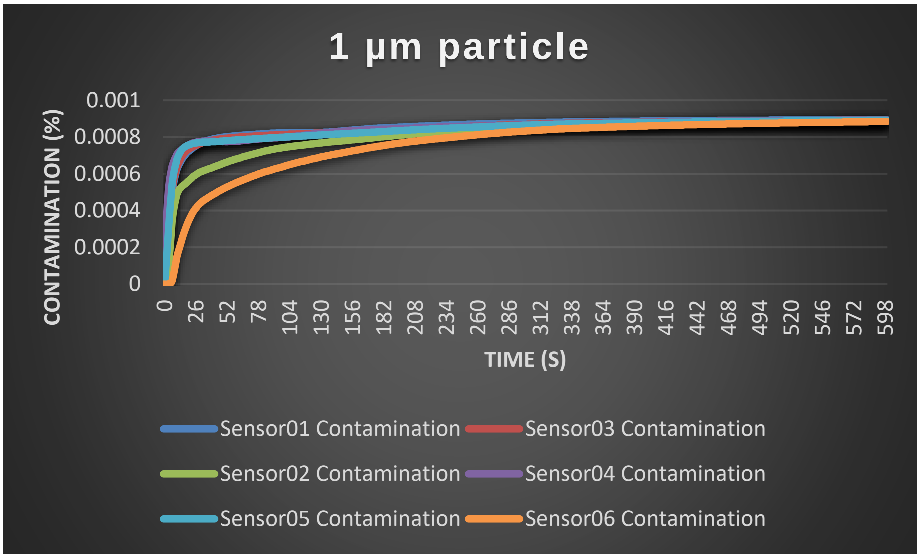


Figure 4-13 Sensor plot for 1.0 µm particles

similar in both the sub-micron particles as evident from the sensor plots in Figure 4-11, Figure 4-12 and Figure 4-13. The contamination percentage reached almost 85% and then it started reaching to steady state. The percentage of contamination does not reach 100% due to default filter efficiency of the ACU supply in 6SigmaRoom which was around 95%. The sensor plot for 1 μm is also same as that of sub-micron particles, apart from sensor 4, which does not show a sudden bent around 50 second interval of time. This is due to lesser particle concentration due to which the sensor plot behaves rather smoothly.

Chapter-5

Conclusion

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The flow-path and concentration plots were obtained for three different sizes of the contaminants. The CFD results were obtained for transient analysis of the hot-aisle containment system for a total time of 10 minutes. From the simulations and the result plots obtained, the following conclusions were drawn:

- As assumed, the particles of size 0.05 and 0.1 followed the same path as of air since they have the same physical properties as air.
- The streamline plots obtained show the velocity vectors of the particles emanating from the ACU and entering the Server racks which describes the flow pattern and path. The concentration plots, which is a plane at 1m height in the room, shows the region of the most particle concentration. Result animations show that the most affected area are the first three cabinets on either side of the aisle in the hot-aisle containment model.
- The sensor plot, as seen in Figure 16 for contamination percentage is obtained by placing 6 sensors at 0.5 m height from the raised floor on 3 cabinets on either side of hot aisle describe the variation of contamination with increasing time at that height. It was also observed that the contamination level reduced with increasing height in the containment region. As we know, that while containment systems are proven to reduce cost expenditure on ITE cooling, they may also be helpful in preventing the contamination of the ITE. Firstly, the CAC might prevent the direct entry of contaminants from human sources in the Data center facility.

As this study assumes that the sub-micron particles have similar properties to that of air, based on the streamline plots obtained for HAC, it is proved that these particles rise up with hot return air. This return air can be then filtered with filters of appropriate efficiency, like filters with rating above MERV 13. There are several strategies that can be used to prevent important servers and other IT equipment using the results obtained from such simulations. If the most vulnerable locations of particle contamination are known for a given Data Center, depending on the critical use and utilization of servers, the servers can be placed accordingly in the regions where the least amount of contamination is predicted. Another way is adding an obstruction to the flow near the critical ITE, based on the knowledge of the results from simulation, to alter the flow-path of contaminants away from the cabinets.

Chapter-6

Future Work

A major challenge faced while completing this study was lack of existing literature on computational model of particulate contaminants or particulate matter transport inside data center white space. Therefore, I hope that this study will be a pioneering work and pave way for many other research studies in this field. The current study only dealt with developing a simulation model for studying the airflow pattern and flowpath of the particulate contaminants in CFD software package 6SigmaRoom. A comparative study can be done in on ANSYS Fluent or ANSYS Icepak for flow visualization with a similar configuration of data center. I believe that the study on ANSYS platform can be more detailed as it gives a wide variety of user defined options for flow type and in regard to physical properties of the particles.

A simplified CFD analytical model of the data center can also be developed for particle tracking using Lagrangian approach. This will help us to verify the streamline plots obtained from the computational study with those obtained from analytical model. As the present study was done in a data center with hot aisle containment system, the same flow can also be visualized in a data center with same dimensions and ITE but with a cold aisle containment system. We know that the flow pattern is fundamentally reversed by changing the containment type. This will help us to make this study more generic and widen its scope to two of the most popular data center configurations.

Appendix A

Nomenclature

C_c Cunningham correction factor

C_D drag coefficient

d_p particle diameter

ρ_p particle density

σ Boltzmann constant

$F_{drag\ i}$ component of the drag force in the xi direction

F_{bi} component of the Brownian force in the xi direction

$F_{grav\ i}$ component of the gravity force in the xi direction

F_i forces in the xi direction

$F_{saf\ i}$ component of the Saffman lift force in the xi direction

g_i component of the gravitational acceleration in the xi direction

k turbulence kinetic energy

m_p particle mass

$\vec{u}$ fluid velocity

$\vec{v}$ Particle velocity

u_i component of filtered fluid velocity in the xi direction

u_j component of filtered fluid velocity in the xj direction

v_j component of particle velocity in the xj direction

v_i component of particle velocity in the xi direction

ζ Gaussian random number

Δt the time step

ρ air density

v fluid kinetic viscosity

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