AIR FLOW PATTERN AND PATH FLOW SIMULATION OF AIRBORNE PARTICULATE CONTAMINANTS IN A COLD-AISLE CONTAINMENT HIGH-DENSITY DATA CENTER UTILIZING AIRSIDE ECONOMIZATION

by

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Abstract

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The energy used by Information Technology Equipment (ITE) and the supporting data center equipment keeps rising as data center expansion continues worldwide. To contain the rising operation costs, data center administrators are resorting to cost cutting measures by not adhering to the ambient data center environment standards. In many cases, free cooling techniques are adopted to partially or completely relieve the usage of refrigeration units, which adds to huge cost savings but also allows for the increased risk of particulate and gaseous contaminations. The ASHRAE TC9.9 subcommittee, on Mission Critical Facilities, Data Centers, Technology Spaces, and Electronic Equipment, has provided the temperature-humidity envelope primarily targeting data centers utilizing free air cooling or air-side economizers, to manage the contamination risk. According to ASHRAE Standard (2009b), to manage the contamination risk, it was recommended to have the air entering the data center to be continuously filtered with MERV 11 or preferably MERV 13 filters to achieve ISO Class 8 cleanliness standards.

The HVAC systems in the data center operate with high supply flow rates to maintain the server inlet temperatures within the ASHRAE recommended limits and is continuously changing the air in the server space. This air change causes for different levels of air speed, temperature difference and contaminant concentration at different regions of the white space. The spread of contamination from such a turbulent airflow leads to unanticipated stagnant regions or areas of dense accumulation of contaminants in the cabinet aisles, thereby increasing the risk of failure due to airborne particulate contamination. This paper uses 6SigmaRoom, a data center CFD (Computational Fluid Dynamics) tool, to study the airflow pattern and flow path of sub-micron contaminants in a high-density data center with both hot/cold aisle containment configurations. In particular, it addresses the behavior of particulate (dust) contaminants which are characterized by their spherical shape and of diameters 0.05, 0.1 and 1 micron. The sub-micron particles have little slip relative to the air, which allows for these particles to be considered as completely airborne. For heavier particles of size 1 micron, the properties of dense carbon particle are considered for simulating contamination in the white space.

The data obtained from this study can be helpful in predicting the nature of contaminants and their extent of contamination when utilizing air-side economizers. Further, identifying the region of deposition of contaminants can help data center operators to implement design strategies or simply reinforce the regions which have a potential to fail from particulate contamination. MERV filters with higher efficiency ratings can be used to solve the contamination problem, but this leads to added installation and operation costs .With the help of results from this study, data centers utilizing air-side economizers can tightly control the risk of contamination and also save on operational costs from allowing the IT equipment to operate outside the recommended and allowable ASHRAE envelopes.

Keywords: air-side economizer, contamination, data center, 6SigmaRoom, Cold-aisle configuration.

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Chapter 1

Introduction

Data centers are not mission critical facilities anymore, they are business critical facilities in the year of 2018. Cloud computing and bitcoin mining are the major commercial success attributing to the significance of data center development and their efficient operations. Since information is transferred continuously, there is a need to ensure zero downtime and provide the computing resources to be available on demand. With the booming advancements of information technology over the last couple of decades, there is a rapid growth in the number and size of data centers. Companies throughout the world have data centers that have grown from single rooms within large office spaces into enormous standalone buildings.

This rapid growth for data centers has changed the notion that data center belong only to large organizations of the world as smaller business are beginning to set up modular data centers or in-house server rooms to rely on the benefits of running a data center that can assist with their operational efficiency. A significant challenge faced is the cooling of data centers due to the increase in power consumption and the increasing load of the IT (Information Technology) equipment in the data center.

This loading of IT equipment is expected to increase with improved semi-conductor technology discoveries. Most of the energy requirements in the data center are towards the IT hardware and cooling requirements. Shah, M **[1]** (Shah J. M., et al., 2017) explains the energy usage allocation observed commonly in data centers. In reference with his journal article, cooling units consume up to 31% of the overall data center energy, as displayed in Figure 1-1.

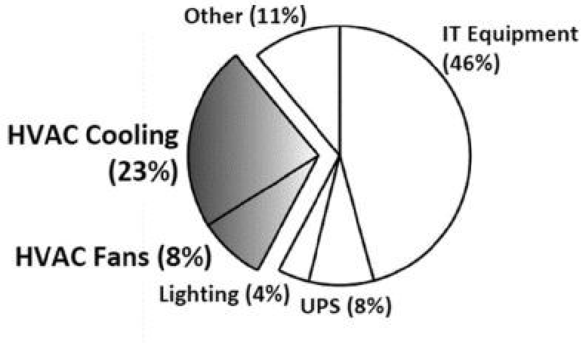


Figure 1-1 Power Distribution in a Data Center [1]

Typically, data center or colocation facilities operate in tightly controlled environment parameters such as, dew point, temperature and relative humidity, and they utilize very efficient filtration systems. Different methods of cooling such as, liquid cooling, and immersion cooling **[2-5]** and free cooling are usually employed. In emerging countries, for the interest of energy saving and reducing costs, a small number of data center operate using free cooling techniques, where available. To allow for small and medium sized data centers to efficiently use this method, American Society of Heating Refrigeration and Air Conditioning Engineers (ASHRAE) recommended an allowable envelope to define the limits under which the IT equipment would operate most reliably, mainly with reduced energy consumption interests. The recommended envelope defined by ASHRAE **[6]** are as follows: 18-27^{0}C (64.4-80.6^{0}F) dry bulb temperature, 5.5-15^{0}C (41.9-59^{0}F) dew point temperature, and less than 60% relative humidity. This ambient environment envelope with recommended air quality levels will ensure reliable operation of IT equipment in the data center space.

1.1 Air Side Economization

As defined by ASHRAE **[7]** in its Energy Standard edition for buildings, air-side economizers as a simple duct and damper arrangement with an automatic control system to allow for a cooling system to supply the outdoor free cool air to reduce/eliminate the loading on refrigeration systems during mild or cold weather, which is illustrated in Figure 1-2. Unlike the refrigeration units where the air is re-circulated and cooled, the return air from the servers is directed outside. The ASE unit is integrated into the air-handling system of the facility, with ducting structures for both supply and return air. Efficient filters reduce the entry of particulate and gaseous contaminants, however, there is a predictive risk of server failures due to contamination from sub-micron sized airborne particulate contaminants. Field study indicate that the server racks act as recirculation units which lead to the failure of circuit boards. The objective of this study is to deal only in the effect of concentration of airborne particulate contaminants at the surface walls of the servers at different rack heights in a cabinet column **[8].**

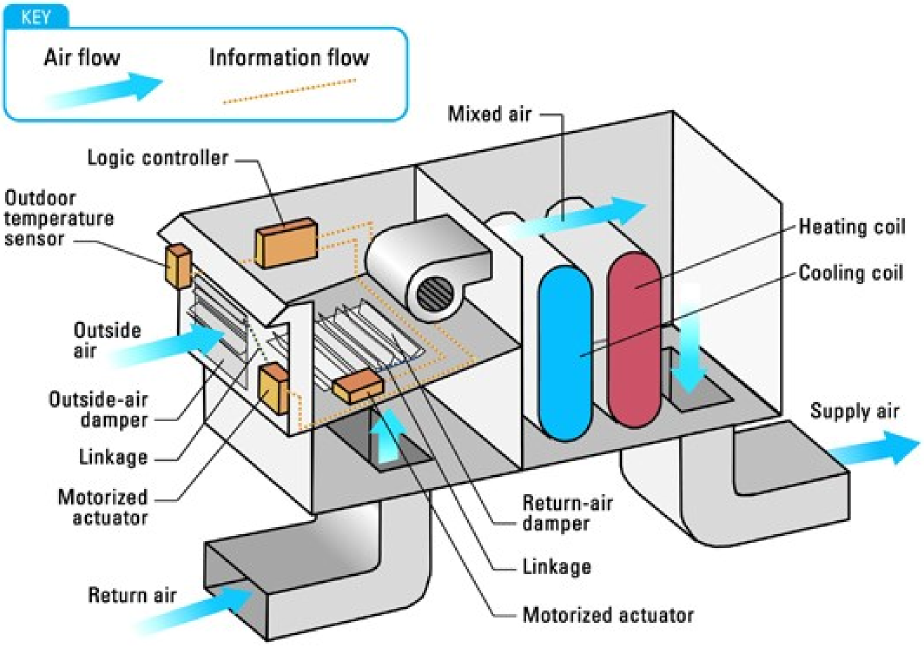


Figure 1-2 Layout of Air-Side Economizer

1.2 Thesis Outline

This study begins with Chapter 1, an introduction outlining the scope and purpose of this study with intended results to be achieved. Chapter 2, gives the cfd literature review of the previous work with CFD modelling of air-cooled data centers and its progress throughout the years and also contains the basic theory about particle tracking and CFD modelling. Chapter 3, continues to describe the particulate contaminants and their selection criteria. Chapter 4, explains the simulation methodology with the geometry, mesh and boundary conditions for the problem setup. Finally, Chapter 5-6 contains discussion and conclusions.

Chapter 2 Literature Review

The study on air flow distributions has progressed in the last two decades. This has paved a path for accurate predictions in air flows and temperature distributions in many air-conditioned spaces. This illustrated in a study by Chow **[9]**, where computational fluid dynamics was used as a study tool to illustrate the air flow in large ventilated buildings. The literature on air flow modelling which is available, only address the temperature distributions and path flow of free cooling air but fail to address the risk of contaminations and its direct impact on reliability of IT hardware. Awbi and Gan **[10]**, used a CFD program to calculate thermal comfort and airflow in naturally and mechanically ventilated offices and Schmidt **[11]** in one of his studies describes the flow rate and temperature measurements in data center space. The literature on study of airflow and contaminants in a data center is scarce and the research interest on temperature distribution and operational efficiency of data centers has gained momentum only in the previous decade.

Measurements for equipment power consumption, airflow through the CRAC and its power usage, ITE inlet temperature, etc., were recorded and these values were then presented and compared with the CFD results airflow through perforated tiles; Gugary **[12]** et al., through their study reported the best practices to design a data center. This study reports the importance of analytical and simulation tools to improve the energy efficiency of the Data center. This was done by performing a flow analysis of raised floor and then deciding the layout based on the flow distribution results. A CFD model of the data center was then developed to verify the required cooling airflow characteristics. Patankar and Karki **[13]** state in their research about the airflow distribution and cooling in a raised floor data center. This study illustrated the effect of various parameters that effect the airflow distribution in such a configuration like floor height and open tile area. In another study by Karki **[14]**, CFD analysis was used for calculating the flow rate through perforated tiles in a raised floor configuration data center. This study used the k-e model of turbulence and a finite volume method approach to calculate airflow rates through the perforated tiles, assuming pressure distribution to be uniform in the data center server space above the raised floor.

It is also discussed by Patankar **[15]**, that the archival literature available on airflow in data center discuss only on temperature flow distributions in various large engineering buildings. To highlight, the only research author who has prescribed a method to mitigate contamination was by Seymour **[16]** where a method of application of CFD was used to calculate the trajectory of airborne organisms being produced either by a patient coughing or sneezing in a hospital space. This modelling simulated the motion of sneeze droplets in clean rooms where there transmission can be reduced by exposing them to ultraviolet irradiation. A very similar logic, suggested my Seymour, was applied in the study of this paper. The predictive air flow simulation of micron sized fine particles and extending their trajectories inside the data center space to increase the reliability of hardware in data centers using airside economization.

2.1 Role of CFD Simulation

CFD modelling is the process of representing a fluid flow problem by mathematical equations based on the 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 **[17]**. Eulerian or Lagrangian approaches are one of the most popular methods for flow visualization and particle tracking, the difference in both the methods is that the Eulearian method treats the particles as continuum and the Lagrangian method focuses on the particle frame of reference, treating each particle individually. Two studies which closely relate to the type of particle transport model with the present study were by Chen and Zhang **[18]** which evaluate the flow using RANS (Reynolds-Averaged Navier Stokes) and LES (Large Eddy Simulation). The other important study by Seymour **[16]** used the Lagrangian approach, where the assumption that the volume fraction of particles is very less than that of total airflow and the particles do not influence the flow of air. This describes, more closely, the exact behavior of particulates in the data center space.

Governing Equations

The governing equations of fluid mechanics are the conservation laws for mass, momentum and energy. These equations can be stated in differential or integral form by applying the conservation laws to a point or an extended region of the fluid (air) respectively. The point of the fluid is considered to be an infinitely small volume element, but not so small that individual molecules influence the macroscopic properties. The fluid is considered to be a continuum and all fluid properties are functions of space and time. The governing equations for incompressible Newtonian fluid, as given below. Derivation of the governing equations is available in many fluid mechanics books such as **[19]**

the exact behavior of particulates in the data center space.

Conservation of mass:

$$\nabla \cdot u = 0$$

Conservation of momentum:

$$\rho \frac{dV}{dt} = \rho f + \nabla p + \mu \nabla^2 V$$

Conservation of energy:

$$\rho \frac{de}{dt} = \frac{\partial Q}{\partial t} + \kappa \nabla^2 T + \phi$$

The particle trajectories by Lagrangain method are computed by solving the momentum equation is given as:

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

The complete equation for the particle motion is detailed in **[8]**. The primary objective of the current study is the simulation and analysis of the airflow inside the data center. An elaborate background study has been done on the physics that controls and affects the flow of gases and particles inside the ventilated rooms like Data centers. Computational Fluid Dynamics, when applied to air flow distribution within data centers have the potential to predict the velocity and temperature distributions. It is also possible to predict the spatially and temporally varying distribution of particulate contamination within the space and hence evaluate IT equipment reliability **[20]**. In order to perform air flow path calculations in the data center space, it is necessary to define the boundary conditions, which is necessary for each of the turbulence transport equation to be solved. By specifying the geometry of the data center and overlaying with a mesh of control volumes, it is then necessary to identify on the mesh of the locations of any supply and return terminals, the flow rates of the supply and the return air, the velocity and the temperature of the supply air, the heat transfer process occurring at surfaces and within the space, and if required, the location and release rates of any indoor air pollutants. The complex iterative nature of the calculation methods and solving the equations needed to represent a reasonably detailed description of the flow distribution in the room means that a substantial computing power and time duration is needed. Realistically, this is interpreted and analyzed using a graphics-based post-processor. The CFD package 6SigmaRoom is used as the simulation tool and the technique of simulating the air flow distribution in a high-density data center with both hot/cold-aisle configuration is used to illustrate its capability.

Turbulence Modelling

Reynolds number is a measure of the relative inertia forces and viscous forces, It is expressed as,

$$Re = \frac{\rho U L}{\mu}$$

At values of Reynolds number below some critical value, the flow is smooth and steady. This regime is called laminar flow. Above the same critical value, this flow changes drastically and is called turbulent flow. This flow is characterized by random, chaotic fluctuation and motions. Most of the industrial relevant flows are turbulent, however, most often the time-averaged properties are of importance. The governing equations for this flow are called Reynolds-Averaged Navier Stokes (RANS) equations. They are obtained by introducing the Reynolds decomposition where the flow variables are decomposed into a steady fluctuating component according to

$$u(t) = \bar{u} + u'(t) \qquad v(t) = \bar{v} + v'(t) \qquad w(t) = \bar{w} + w'(t) \qquad p(t) = \bar{p} + p'(t)$$

The RANS equation are obtained by substituting the above relations into momentum equation and taking time average. The RANS equation include additional The turbulence model based on the RANS equation focus on the mean flow and the effect on the flow properties. The k-ε model is a turbulence model which solves the additional transport equations for the two quantities, turbulent kinetic energy and the rate of dissipation of turbulent kinetic energy. It is a very widely used turbulent model.

Discretisation Method

The governing equation of fluid mechanic seldom have analytic solution. Therefore, CFD modelling is used to solve them. The differential equations are approximated as a system of algebraic equations by using a discretization method. The most common methods are the finite difference method, the finite element method and the finite volume method. 6SigmaRoom used the element based finite volume method. It iteratively solves the many simultaneous equations representing the Conservative equations or Navier-Stokes equations. These equations define mass, momentum and energy on a three dimensional array of points, defined by the superimposed grid or mesh, with a view to solving the equations numerically.

2.2 Data Center

Many commercial CFD packages are 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.

Data Center Environment

The rack server in a data center can be closely modeled to the fundamental functioning of a home based PC (personal computer unit). There is a very unusual concentration of hear load generated, when high computing applications are used. This requires some air conditioning to handle the heat load concentration. Scaling this to comparison of a data center housing hundreds of server, the size of server rooms and heat load that is dissipated 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 forces 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. To relate our results closely and more accurately with the conditions in a real-life data center, both configurations of hot-aisle (HAC) and cold-aisle (CAC) configurations were considered for this study.

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 configures 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 serves at separate locations for effective cooling.

Containment

Containment configuration has allowed for increased energy efficiency and also allows for uniform IT inlet temperatures, eliminating hot spots typically observed in traditional data centers. John Neimann, in his white paper summaries that hot aisle containment is the most preferred solution, but this comes as an expensive option for existing data center. Cold-aisle containment, although not optimal, is the best feasible option in some cases. Both the types of containment provide energy savings over traditional uncontained configurations. The main advantages of containment systems are discussed in a white paper by John Neimann et al., **[22]** are:

- Uniformity in supply air temperature from CRAC to inlet at the racks.
- Increase in economizer hours.
- Humidification and dehumidification costs are reduced due to elimination of flow mixing.

HAC: Hot aisle containment encloses the hot exhaust air from the IT hardware, this allows the rest of the data center to act like a large cold-air room. Figure 2-1 shows a basic hot-aisle containment setup.

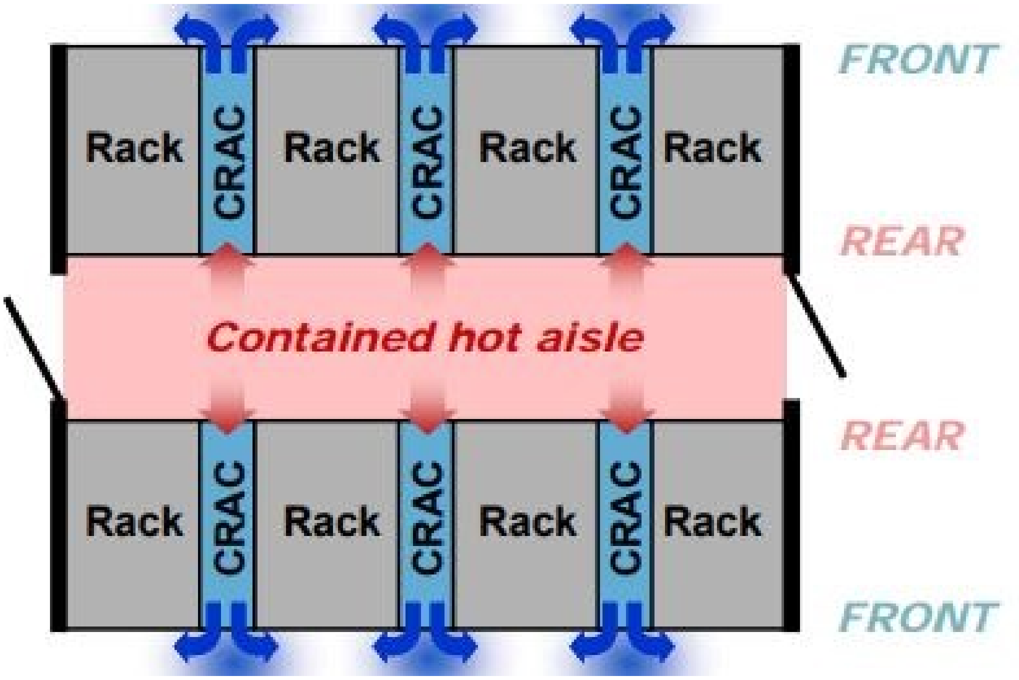


Figure 2-1 Configuration of Hot-Aisle Containment

CAC: A cold-aisle containment system is one in which the cold aisle is enclosed, and the rest of the Data center becomes a hot air return space The aisle maybe separated from the rest of the data center by means of plastic curtains, plastic or plexi-glass doors.

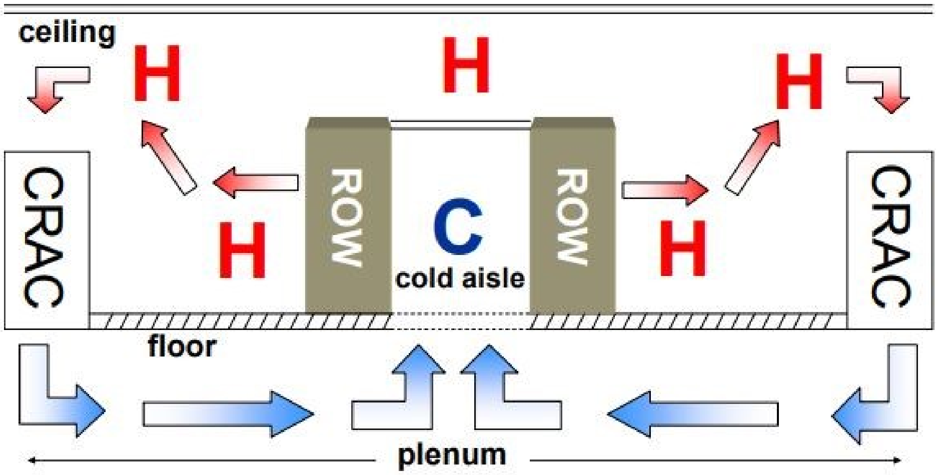


Figure 2-2 Configuration of Cold-Aisle Containment

Figure 2-2 shows a general layout of the cold-aisle containment in the data center room with a raised floor configuration.

Cooling Airflow in Raised Floor

The need for data center cooling in server racks arise from the facts that these servers consume electrical energy and in turn dissipate a large amount of heat. To maintain proper functionality of the servers, they must be maintained under optimum operating temperature range, exceeding which may lead to equipment malfunction or even failure in some cases.

The traditional way server cooling works in Data Center is that the cold air through the ACU (Air Conditioning Unit) enters the server racks from the front face, flows over the hot ITE and, exits from the rear face. This technique although is limited to rooms with small area. In larger data center spaces, raised floor concept is used where the server racks are cooled by the air coming out from the perforated tiles placed next to them. The cool air enters the plenum and forces its way through the perforated tiles, thus cooling the equipment inside the racks. For efficient execution of this concept the ITE racks are arranged in cold aisle-hot aisle configuration. A hot aisle is the region between the rear sides of two ITE racks and conversely, cold aisle is the region from where the cold air enters the ITE racks from the perforated tiles. The main advantage of such an arrangement is that it prevents mixing of hot and cold flows.

Data Center Description

In this study, the data center model investigated is adopted from the one that has been used as standard representation for data centers across the market. Using this standard model, the data center was modelled in 6SigmaRoom. Its 3-D representation of the physical data center combined with the CFD solver allows for safe simulations of data center physical capacity and cooling efficiency. The layout of the data center is as follows. The through row concentration is chosen for simple design model of the data center space with four rows of cabinets in the cold-aisle configuration and a cabinet power limit of 5.6kW, making this model a high-density data center design. The layout of the cabinets in the model data center considered is tabulated in Table 1.

The data center has a total of 486 servers distributed into four rows of each unit. There are four CRAC (Computer Room Air Conditioner) units placed along the perimeter of the data center room. These units supply cooling air at 12.80^0 C from the pressurized 2ft raised floor plenum. The modelled data center was designed using the best practices of cold aisle arrangements.

Chapter 3 Particulate Contaminants

The trend of intermittent, short-circuit failure mode in servers of data centers have increased since their rapid pace of being established in regions where there is a presence of high levels of fine particulate matter in the ambient air and with the increased using of free cooling method (air-side economization), these failures are mainly due to particulate matter. It is explained by Prabjit. S **[23]** that the source of particulate matter is both natural and anthropogenic. In terms of size, the contaminants can be classified into two distinct categories: fine and coarse particles.

Fine particulates (<2.5um), are found in motor vehicle exhaust, diesel particulate matter, smoke and haze, which are further classified into primary and secondary types. Primary particulates are emitted from a source, such as forest fire, volcanoes, construction sites, unpaved roads, fields or smokestacks. Secondary fine particulates, which make up for the most of the fine particulate contamination, are a result of photochemical reactions in the atmosphere. Table 1, as explained by Jimil. M, **[24]** illustrates the particulate matter generally found in the nearby surroundings of industrial area similar to the experiment site and their sources. The experiment site data center was surrounded by diesel generators, gas welding and manufacturing process environments which are responsible for different kinds of particulate matter as detailed in Figure 3 **[24]**.

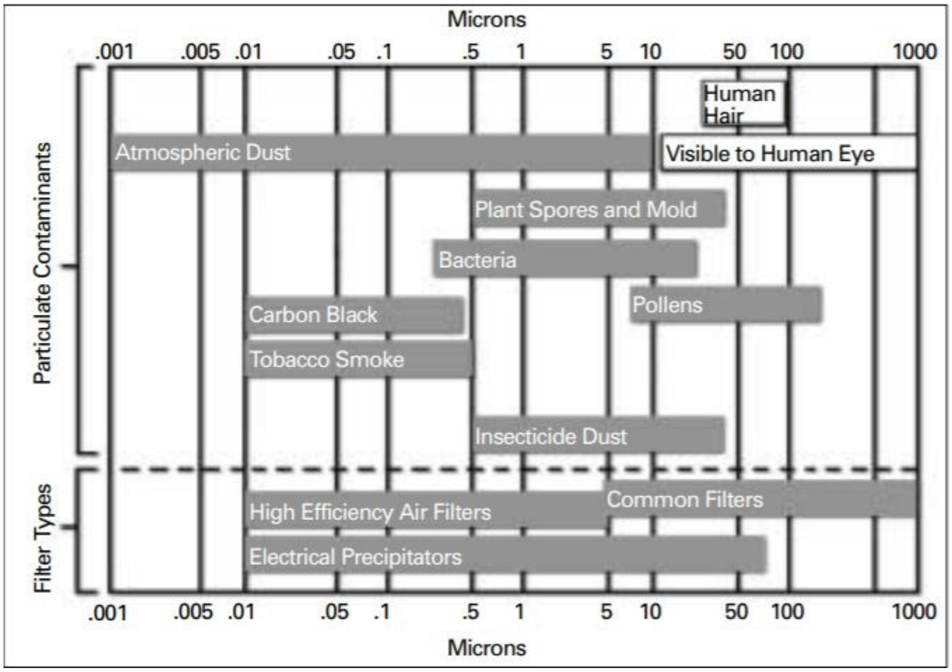
Table 3-1 Source of Particulate Contaminants

Contaminant	Source
Zinc Whiskers	Zinc Coated ICT equipment, steel building studs
Tin Whiskers	Components and products having electroplated Tin
Oxide flake off	Magnetic media
Natural and Artificial Fibers	Paper, Cardboard, etc.,
Water-soluble ionic sale	Chemical Reaction
Sulfate, nitrate, sea salts	Winds
Lime dust with water	Concrete Materiak
Dust	Farms, especially during plowing
Toner Dust	Toner
Smoke	Cigarette Wins
Cellulose Fragments	Traditional ceiling tiles and space

As explained by Seymour, M **[16]**, that in any contamination control applications, the particles are of sub-micron level and at this size, there is little slip relative to the air in which they are situated. As a result, the particulates are considered to be completely airborne and treated as if they are gaseous.

By using this as a base assumption, our study uses the physical properties of air (molecular weight of 28.9 kg/mol and density equalts to 1.19 kg/m^3) for 0.05U and 0.1U particles. To simulate the flow of 1μm particles, we assumed the properties of VOC (volatile organic compounds) like carbon black particulates which are among the prominent particulate contaminants.

Table 3-2 Classification of Particulate Contaminants by their size

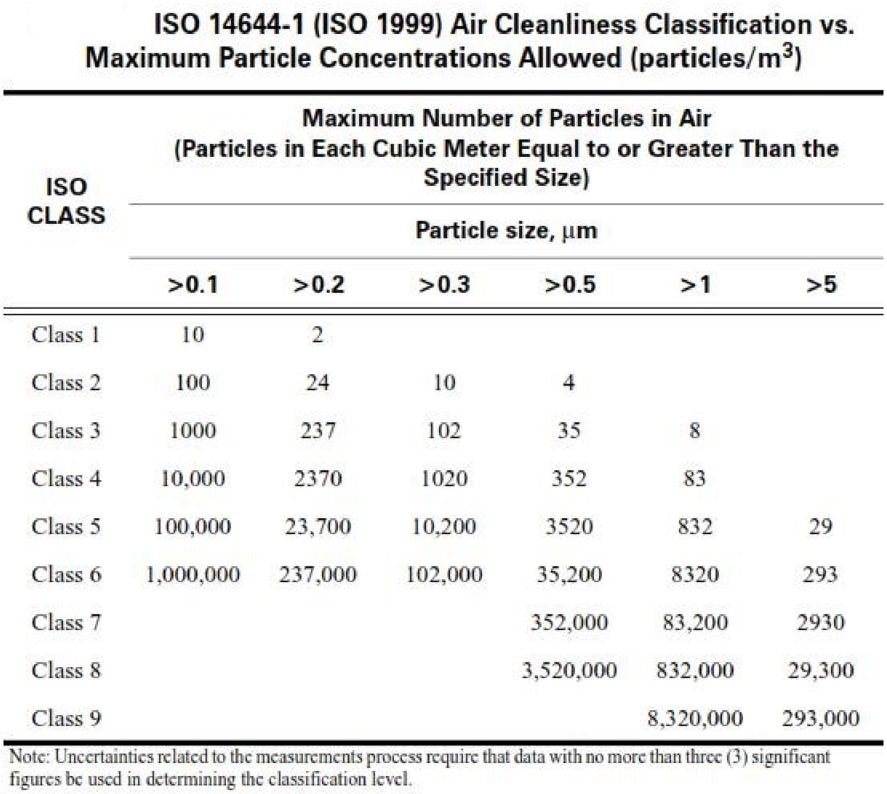


The considered sub-micron particulates are approximated as a concentration which excludes the particle slip. This allows for the assumption that the particles are of low concentration (10000ppm) where the air flow affects their motion, but their presence is insignificant to the flow path of air. This intake air is filtered as per ASHRAE standard which has been outlined in the Indoor Air Quality Guide **[22]**. The filtration of particulates is as outlined: ISO 14644-1 has become the dominant, worldwide standard for classifying the cleanliness of air in terms of concentration of airborne particles (ISO 1999). Figure # provides maximum concentration levels for each ISO class (ASHRAE 2009b). ASHRAE recommends that data centers be kept clean to ISO Class 8 with the strictness of the

95% upper confidence limit. For data center without economizers, the ISO class 8 cleanliness levels may be achieved simply by specifying the following means of filtration:

- The room air maybe continuously filtered with MERV 8 filter as recommended by ASHRAE Standard 127 (ASHRAE 2007) [19].
- Air entering a data center maybe filtered with MERV 11 or Merv 13 filters as recommended by ASHRAE (2009b) [20].

Table 3-3 ISO 14644-1 Air Cleanliness Classification



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.

For data centers utilizing free air cooling or air-side economizers, the choice of filters to achieve ISO class 8 level of cleanliness depends on the specific conditions present at that data center. In general, air entering a data center may require use of MERV 11 or, preferably, MERV 13 filters. **[22]**

Chapter 4 Methodology

The main components of this model data center room setup are four CRAC units and 35 cabinet server units arranged in parallel rows. All the server racks are facing the same direction and this geometry is built in the 6SigmaRoom. The server room size in 135 m^2 with a room height of 3.44m. The geometry of the data center is illustrated in Figure 4-1. The problem setup is simplified by assuming that the 520 server racks are rectangular boxes acting as recirculating units. All the other components in the gray space are neglected.

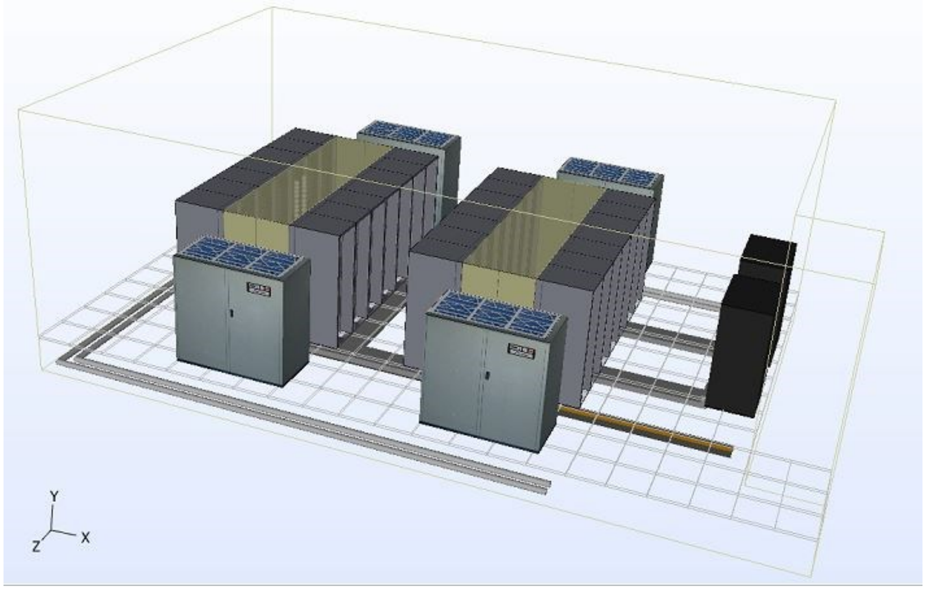


Figure 4-1 Layout of the Data Center modelled in 6SigmaRoom

Contaminants in 6SigmaRoom can be used to specify pollutants in the model, they can be created from projects, environments or vents. These pollutants can be attached to a vent, ACU or environments and specify the concentration of that contaminant as a percentage of the total airflow. In the present study, the ACU (Air Cooling Unit) has been chosen as the source of contaminants to simulate free air cooling during economizer hours. To show that the CFD results are converged, the default termination criteria that the 6SigmaRoom package uses for executing results is that it specifies a degree of acceptable error in the calculation to end the simulation. The default value of this factor is 1. Once the CFD residuals have reduced to this factor, the solver executes the simulation.

4.1 Modelling

The mesh is auto-generated in the 6SigmaRoom. The computational domain is divided into rectangular blocks which are inter-connected with each other by edges and vertices. The edges and vertices of the blocks are associated with the curves and points of the geometry. The blocks are then divided into small hexahedral cells. The mesh with the maximum cell size during the rest of the simulation is illustrated in Figure 4-2. The aspect ratio is kept as close as one as possible but there are deviations at some locations as a result of the dimensions of the geometry.

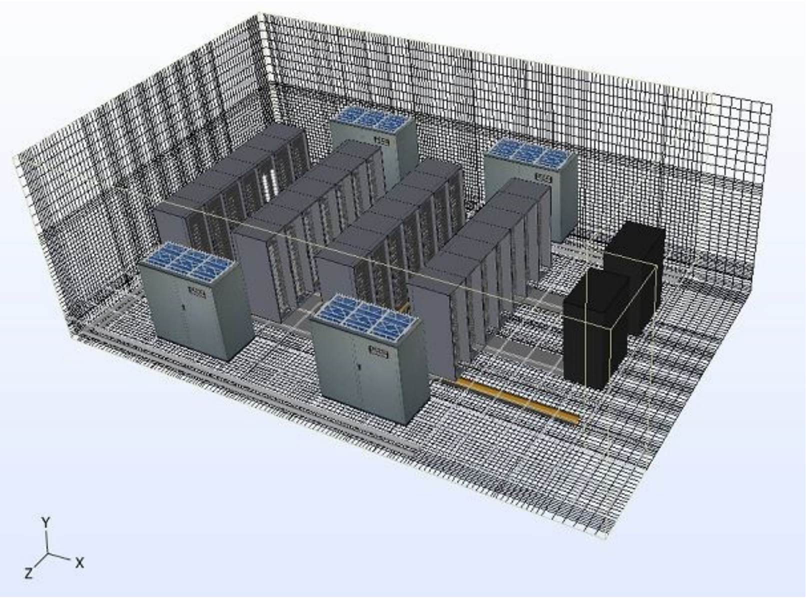


Figure 4-2 Mesh generated 744648 cells

Chapter 5 Results and Discussion

The contour plots and the streamline plots shows the concentration of the contaminants in the room at a height of 1 meter off the raised floor. The number of particles per million (ppm) is chosed to be 10000 particles for 0.05um and 0.1um and 900 particles for 1um, based on the ISO 14644-1 air classification. The results include a comparison of the streamline plots of the smaller 0.05 and 0.1 micron particle with the streamline plots of the larger 1 micron sized particles. The concentration plots clearly outline the dense accumulation regions of the contaminants, as seen from the top view. The result plane, when viewing from the cabinet front view, gives the location of the contaminants on the cabinet server surface.

5.1 Particulate Contaminant 0.05μm

The Figure 5-1 shows the streamlines of 0.05um particulate contaminant in the cold-aisle configuration model. For a total transient time of 420 seconds, to simulate the extent of migration of contamination was simulated. We observe that during the first 5 seconds of the cycle of air change, there is a significant distribution of contaminants on the cabinet server surface, as seen in Figure 5-2. It is clearly observed the accumulation of the contaminants of the 0.05um are higher in the first 3 cabinet servers, which allows us to comfortably assume that these servers are at higher risk to fail under contamination than the other farther placed cabinet servers.

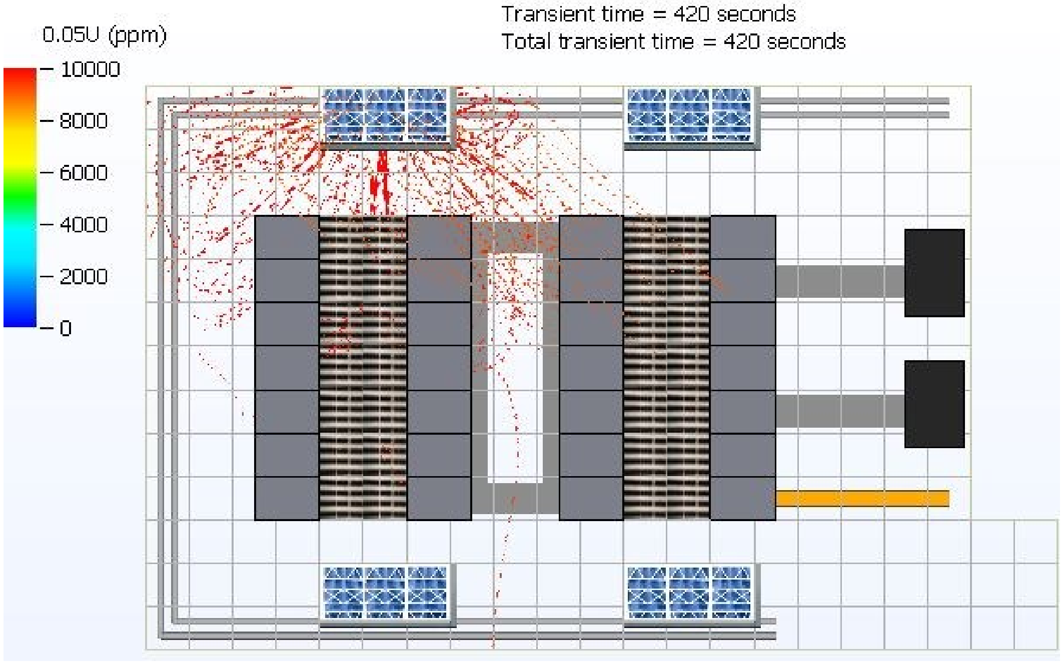


Figure 5-1 Streamlines for 0.05 micron Particulates of 10000ppm

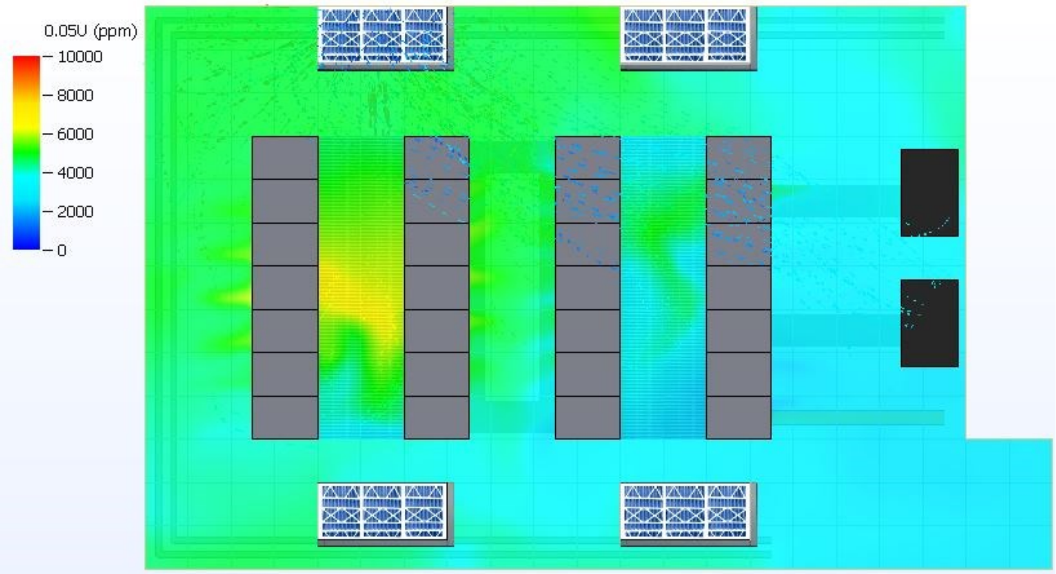


Figure 5-2 Concentraion Plot at a height of 1m off the floor plenum

The Result plane plot, Figure 5-3, shows the concentration of the contaminants at the 45 second transient time step. This progress of migration of contaminants steadily increases, until the entire room is filled with contaminants at the end of the simulation time duration. The key finding is the identifying the first susceptible location of the flow of contaminants when the airside economiser is switched on. This first cycle of the air change in the data center plays an important role as it brings in the contaminants with the free cool air.

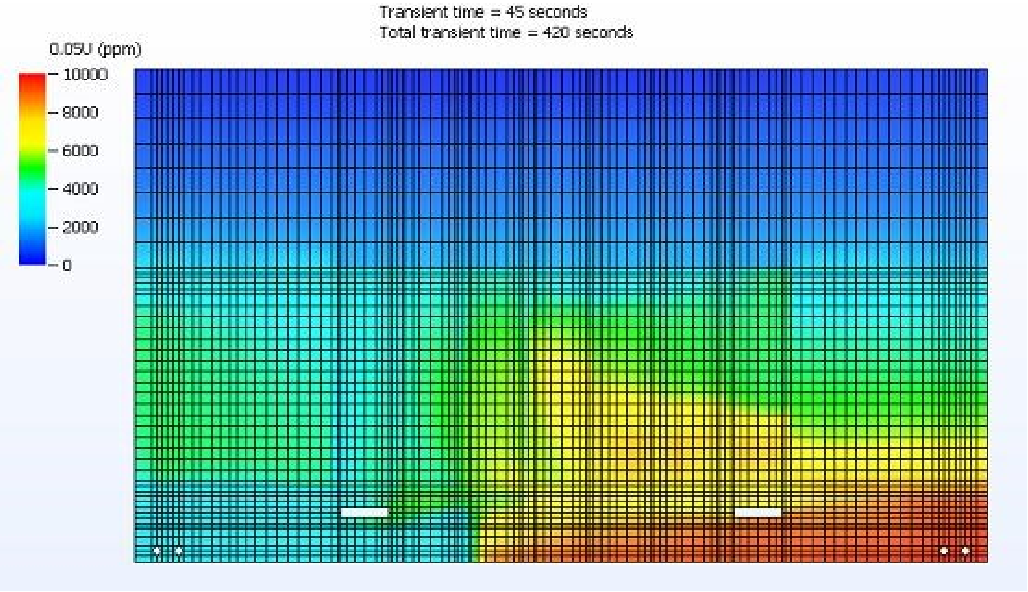


Figure 5-3 Result Plane showing the concentration of contaminants

5.2 Particulate Contaminant 0.1μm

The sub-micron size particulates of size 0.1μm are specified when simulating the predictive contamination in the cold-aisle configured model. Our assumption, based from Seymour **[9]** that these sub-micron particles behave with the flow of fluid (air) is clearly observed in the previous and current simulation figures. In Figure 5-4, the streamline for 0.1um is plotted. The path distribution of the contaminants is the same as that of air.

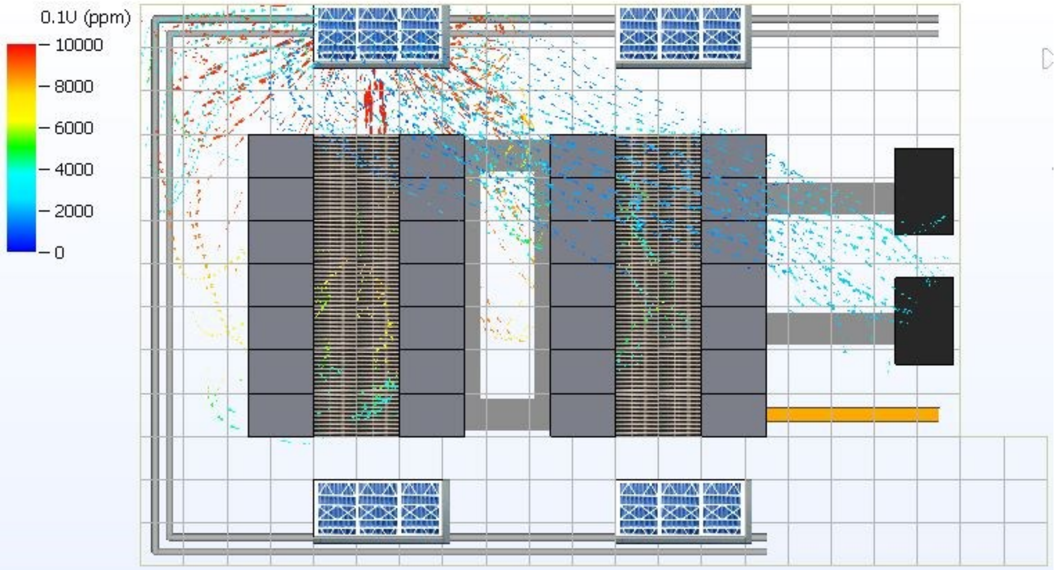


Figure 5-4 Streamlines for 0.1 micron particles of 10000ppm

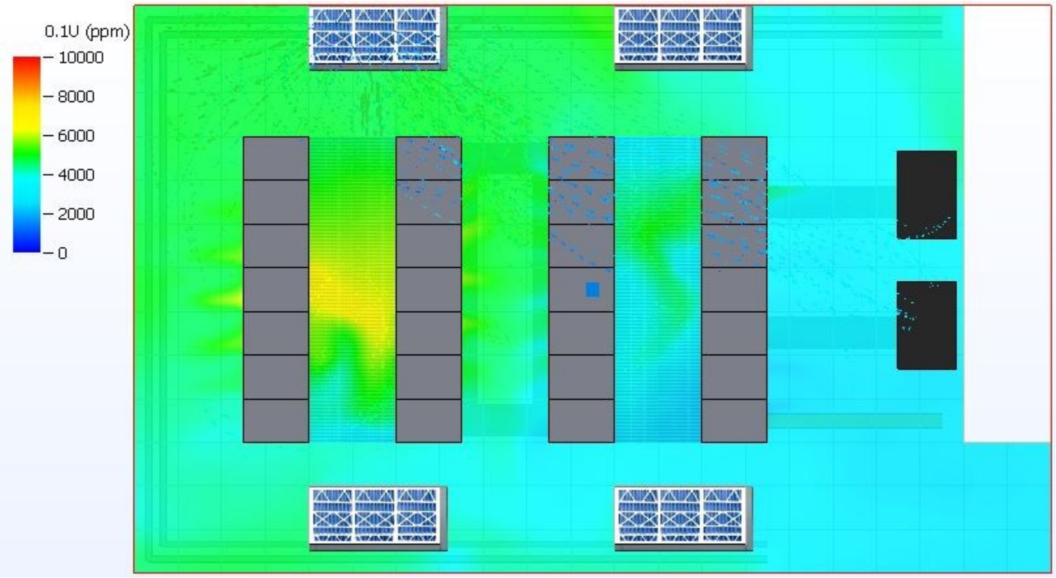


Figure 5-5 Concentration Plot at a height of 1m off the floor plenum

Figure 5-6, shows the result plane concentration plot on the cabinet server surface. This plot remains the same as that of the 0.05μm, as the 0.1μm particulate behaves in the same way as the sub-micron size particulate.

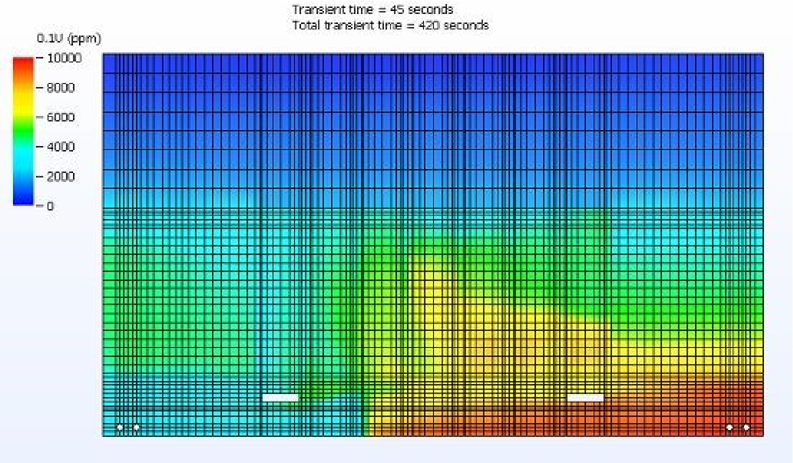


Figure 5-6 Result Plane showing the concentration of contaminants

5.3 Particulate Contaminant 1µm

For simulation of 1µm particulate contaminants, the amount of particles entering the white is restricted to 900 ppm to keep the volume fraction of the contaminants far less than that of air. This is also in agreement with the ISO Class 8 cleanlines standard which gives the maximum amount of particulates in the white space to be less than 900 ppm. Figure 5-7, illustrates the streamline of the particulates. The trajectory is fairly similar but the number of trajectories are reduces, accounting to the amount of particulates which enter the data center space.

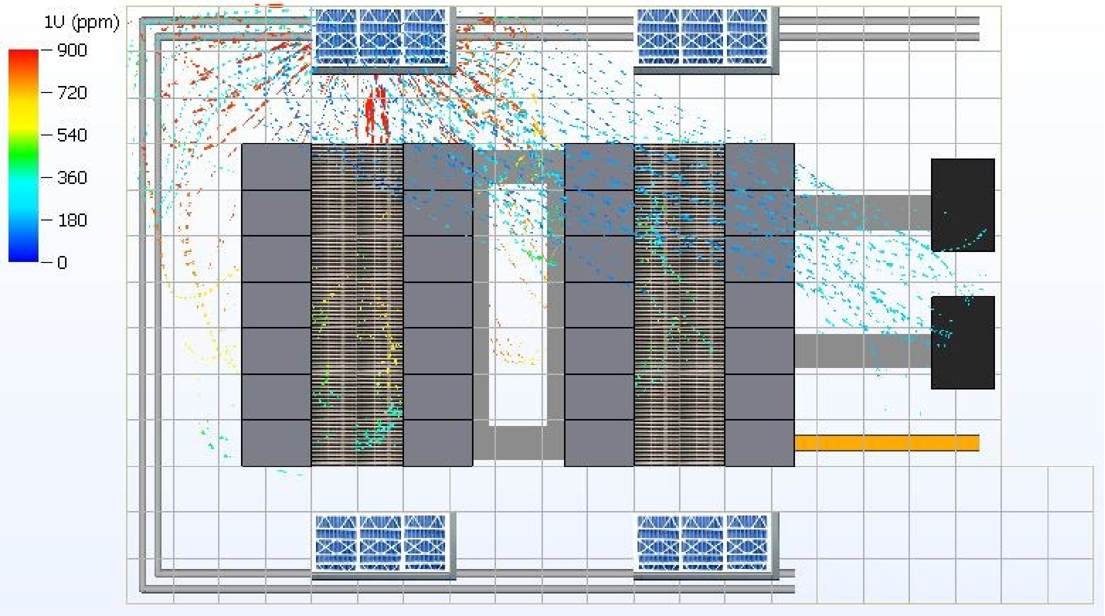


Figure 5-7 Streamlines for 1 micron particles of 900 ppm

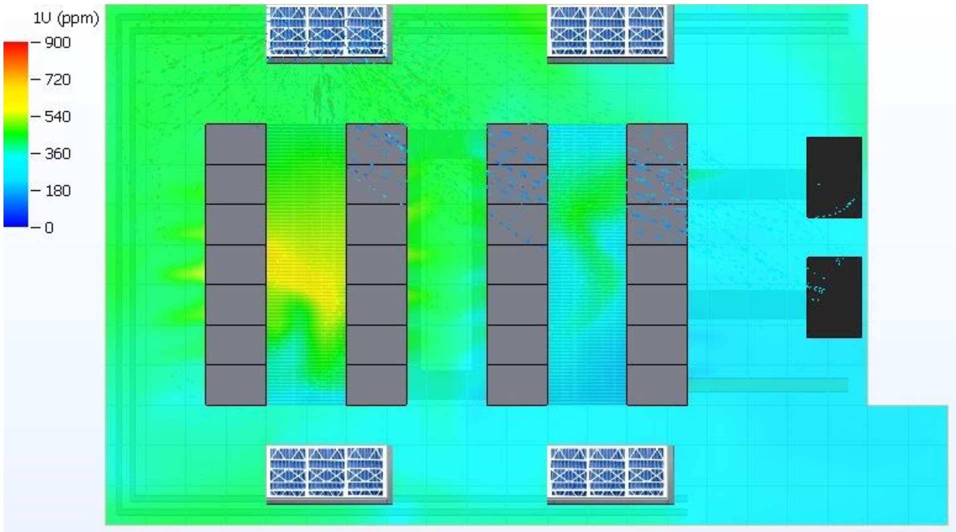


Figure 5-8 Concentration Plot at a height of 1m off the floor plenum

Figure 5-8, illustrates the concentration plot at 1m height off the floor plenum, where the concentration of the contaminants is highest in the first 3 cabinet servers. This is as seen in Figure 5-9, the result plot also gives the same idea of concentration of contaminants from the front view.

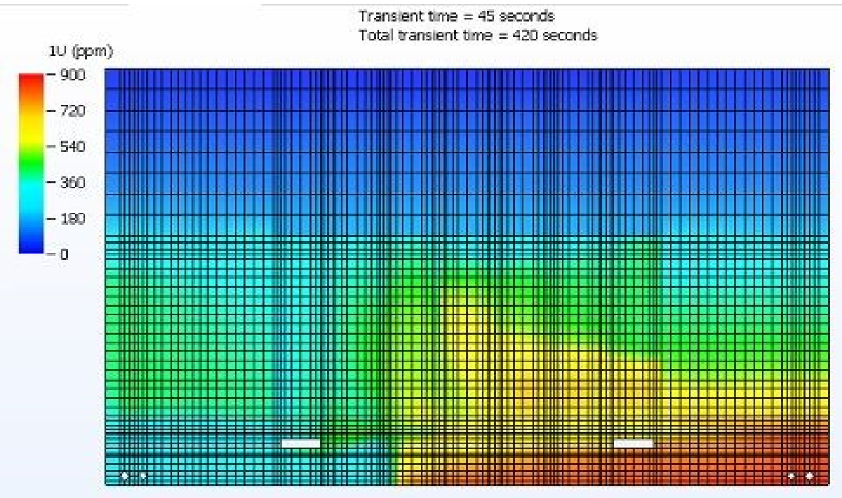


Figure 5-9 Result Plane showing the concentration of contaminants

5.4 Contamination Sensor Plots

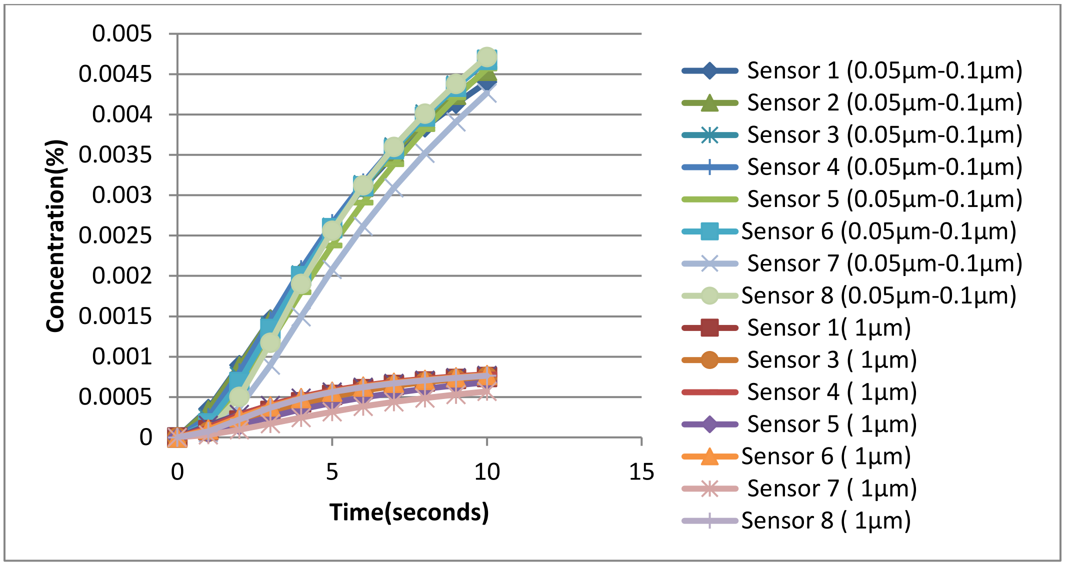


Figure 5-10 Sensor Contamination Plot

For accurately identifying the percentage of concentration accumulating on the cabinet server surfaces, contamination servers are placed exactly on the server cell face. The Sensors are placed on the third cabinet, which is the most susceptible server to fail under particulate contamination. From the sensor graph, it allows us to predictively identify the most susceptible server in the third cabinet. In Figure 5-10, the contamination concentrations are illustrated. In Figure 5-11, the sensor 7 placed on the highest risk shows less accumulation of contaminants than the other servers in the cabinet which are at a higher risk of contamination. Although, this concentration of particulates is minor, there continued accumulation leads to potential failure of the PCB's. The extent of corrosion of the PCB's from the accumulation of particulate contaminants is discussed in **[27].**

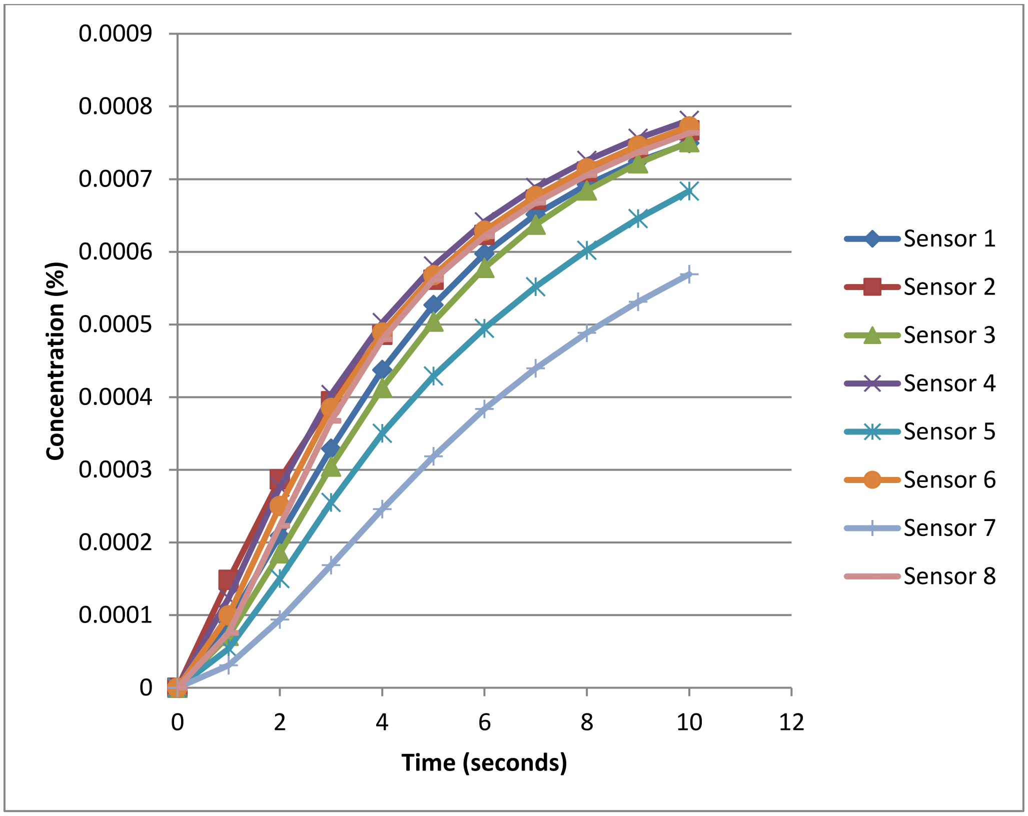


Figure 5-11 Sensor Contamination Curve at the 3rd Cabinet

Chapter 6 Conclusion

This study aimed to identify the flow-path distribution of sub-micron sized airborne particulate contaminants in data center using air-side economization, as well as a transient study to predict the location of the highest concentration of these particulate contaminants. This study concludes that, the particles of size 0.05 and 0.1 micron follow the same path of the air flow inside the data center space, this is observed in the concentration plots for the respective contaminants in the previous chapter. It is recommended to implement design changes to the placement of the servers at the regions of high concentration in the cold cabinet aisles. High-density servers tasked with high importance can be installed in locations where the concentration of contaminants is significantly less, this would reduce the failure of the servers from contamination. Also, installing higher rating MERV filters can allow the facilities to operate energy free, but this adds to higher installation costs. With IT equipment renewal rate every 3-4 years, data center operators need to keep in mind the high cost of installing and running high efficient filtration system along with the energy usage of the IT equipment. The definitive goal is to allow data center to operate energy free by utilizing cooler night air or whenever the ambient conditions permit, without risking the reliability of the IT hardware. However, since the failure from contamination has been increasing, this study identifying the trajectories of particulates and their accumulation location proves useful in helping operators to implement design strategies

In terms of containment configuration, it should be realized that these design configurations have already proven to be advantageous by preventing mixing of flows. This plays in favour with contamination, where the reliability of units in the grey space and facilty operators are shielded away from the contaminants. Thus, in times of rising demand over the cloud, the demand for data centers is projected towards a high growth.

The air-side economizers can potentially reduce the cost from loading of refrigeration units during ambient environment. The risk from particulate contamination, although seems minor they play a very critical role in the reliability of the hardware over time. In a time, where data center trend is on the rise and their capacity increasing by the year, apparently small savings in power locally can amass to significant number cost saving annually.

6.1 Future Scope

This current study only dealt with the predictive simulation of identification of flow path distributions of contaminants and their regions of accumulations. The impact of contamination can be further verified by experimental test methods to determine the corrosivity of the particulate contaminants on the PCB’s. This predictive study was carried out in 6SigmaRoom CFD package and can be verified using ANSYS Fluent or Mentor Graphic FloVent to simulate the particulate distribution. From this, the flow of contaminants into the servers can be further studied in ANSYS Icepack or 6Sigma ET to identify their location of deposition. Also, using the Lagrangian approach, a CFD analytical model can be developed to verify the path trajectories from this study. This study was based on a model designed using standard data center design practices and not any other factors. It is therefore recommended to consider.

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Gautham Thirunavakkarasu received his Bachelor of Engineering degree in Mechanical Engineering from Reva Institute of technology, Bangalore, Karnataka, India in 2015.In May 2018, he received his Master of Science degree in Mechanical Engineering from The University of Texas at Arlington, Texas. His research focuses on thermal and energy efficient systems. Since October 2016, he has been an active member of the Electronic, MEMS and Nanoelectronics Packaging Center (EMNSPC) and has been working on NSF I/UCRC projects for “Energy Efficient Data Centers”. His thesis focused on exploring the extent of contamination from sub-micron particulates in collocation facilities. Key research and career interests are in the field of design, simulation and development of energy efficient systems to solve the problems of the world today.