QUANTIFYING AIR FLOW RATE THROUGH A SERVER IN AN OPERATIONAL DATA CENTER AND ASSESSING THE IMPACT OF USING THEORETICAL FAN CURVE

by

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Abstract

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Cooling is one of the major cost factors in data centres that accounts for 37% of the total data centre electricity consumption. Demands on cooling systems have increased substantially in recent years, due to increasing server densities. To avoid the overheating of servers, cooling aisles are over provisioned, but little attention is paid to the actual scenario at the server level. Cooling requirements of the servers is calculated on the basis of fan manufacturer's published data for the air flow capacity of the server fan and system impedance data obtained from the server designer put together. Thus, the air flow rate through the system is assumed to be the theoretical air flow rate delivered by the server fans that can overcome the system impedance of the server.

The following experimental work analyses the impact of different flow conditions on the volumetric flow rates through the server .Operating points are obtained at various fan duty cycles. The air flow rates through the server at various operating points are quantified in ideal and operational data centre conditions. The study predicts that this data will be useful to quantify the actual air flow rate across the racks and might be useful in controlling the facility parameters that will modulate the airflow distribution and in turn the power consumption due to cooling.

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Chapter 1

Introduction

1.1 Data Center Cooling

Data centers are facilities that centralize an organization's IT operations and equipment. The web servers present in the data center are used as a medium to store, manage, process and disseminate the data one can access on the internet.

Cooling is one of the major issues in data center. It accounts for 37% of the total electricity consumed by a data center. [1] Increased computing and increased density of servers is leading to increased generation of heat loads. Measures are taken to avoid the mixing and recirculation of the cold conditioned air provided to the servers and the hot air exhausted from the servers.

Air flow supply to the data center is calculated based on the air flow rate required to cool the heat load generated by one server which is provided by server designers. Conditioned air is provided to the servers through a CRAC unit. The conditioned cold air flows through the under floor plenum and enters the server inlets through the perforated tiles placed in front of the server racks in the cold aisle. The hot air from the server exhaust is collected using different kinds of containment. The hot air moves in the upward direction and returns back to the CRAC unit through the upper false ceiling. Despite of the calculation of the air flow rate required for all the servers, hot spots are observed in data centers especially in the servers at the top of the racks. Lowering the temperatures of the CRAC unit or increasing the number of air handlers are the common methods used to get rid of these hot spots. These methods only lead to increased consumption of electricity and do not eliminate the hot spots. All this leads to questioning the only possibility that is, the calculated air flow rate supplied to the utility.

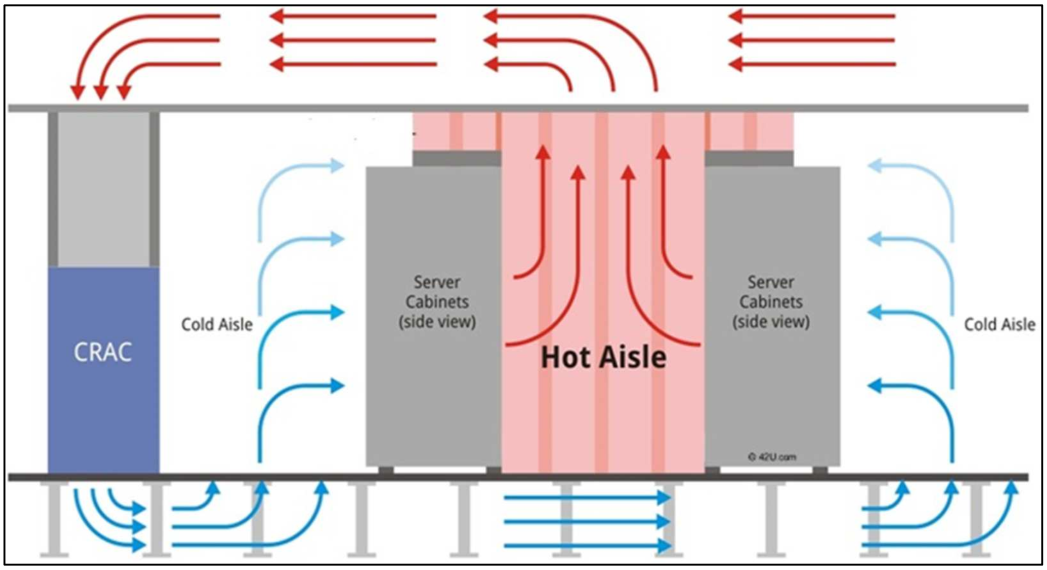

Figure 1-1: Schematic representation of air flow in a data center [2]

1.2 Air Flow Rate through Servers

The air flow rate through the server depends upon the air flow capacity of the server fans and the impedance offered by the server to the flow delivered by the fans. Server is tested for its system impedance as per ANSI/ASHRAE standard 51. A system impedance curve is generated which graphically represents the resistance offered by the server to the flow through it. Using standard 51, server fan is tested for its air moving capacity. A fan curve is generated which graphically represents the air flow rate through the fan against a static pressure drop across the fan. The server designers select the fans based on the ability of the fan to overcome the system impedance. The operating point of the system is obtained by overlaying the fan performance curve obtained from the fan manufacturer with the system impedance curve. The operating point or the performance point of the system is the point where the fan overcomes impedance offered by the system; graphically it is the point of intersection of the fan performance curve and system impedance curve.

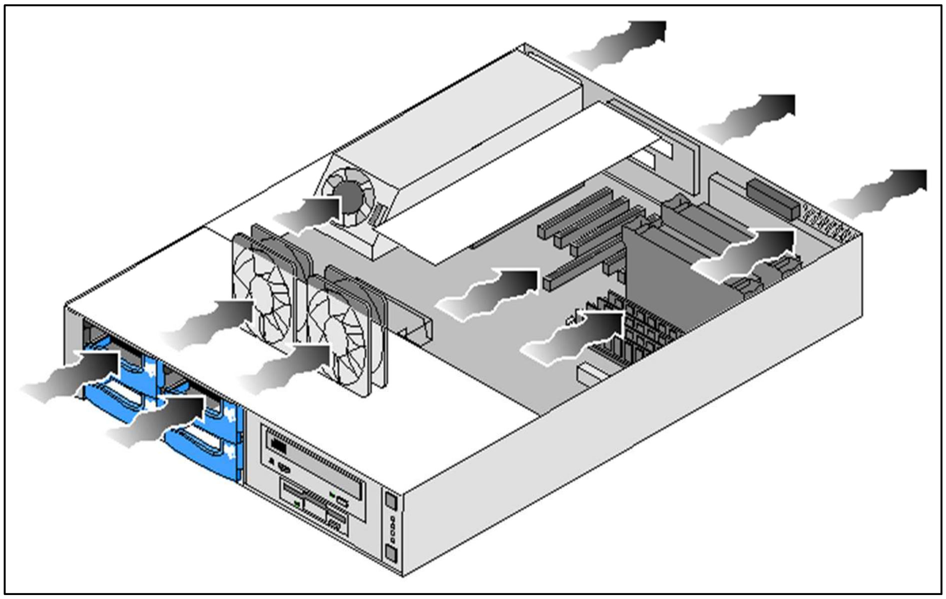

Figure 1-2 : Air flow rate through the server [3]

1.3 Motivation

The air flow rate through the server, when experimentally quantified was found to be lesser than the expected air flow rate as per the manufacturer’s data. The fans and servers are individually tested and are never tested as a system together. Thus, the air flow rate across the system is assumed to be the air flow rate delivered by the fans. The actual air flow rate across the system is never quantified. The set points on the CRAC unit are set as per this assumed flow rate. The cold aisles in data center are over provisioned in order to get rid of hot spots. Quantifying the right amount of air will enable one to set the set points on the CRAC unit accordingly, manage the air flow rate and thus, help reduce the power consumption due to effective air flow rate management.

The objective of this experimental work is to quantify the actual air flow rate across the server in ideal versus actual data center environments. The operating points of the system are obtained at various fan duty cycles in both the environments and air flow rate at these operating points is obtained experimentally.

Chapter 2

Terminologies Used For Measuring Fan And System Perfomance

2.1 Ideal Data Center setup

3000-5000 cfm chamber, also known as the air flow bench is used to measure the fan and system performances. Equipment is tested on the air flow bench as per ANSI/ASHRAE standard 51.

The air flow bench is assumed to be the ideal data center because there are no pressure variations across the chamber, the air velocity can be controlled, the air flow rate is uniform, and there are no leakages. The equipment under consideration is sealed to the inlet of air flow bench. The air flow bench can be used in pressure or suction mode. The pressure tap present near the inlet of the air flow bench is static pressure tap; it measures the static pressure drop across the equipment. Nozzles are present in the mid section of the air flow bench. Nozzle selection depends on the air flow rate range requirement. The pressure taps present on either side of the nozzles are the differential pressure taps; they measure the air flow rate through the equipment. The blast gate and the counter blower present at the end of the air flow bench are used to vary the air velocities across the unit.

The pressure taps are connected to pressure transducers which convert pressure readings to voltage. The range for static pressure transducer is 0-2.5 VDC and that for differential pressure is 0-5 VDC. The flow sensor for the differential pressure reading and the pressure sensor for static pressure reading are connected to a multiplexer in an Agilent 34972A LXI Data Acquisition /Switch Unit. The Agilent unit is connected to a computer unit and Agilent interface software- BenchLink Data Logger is used to read the pressure readings. The gain in the Agilent interface for pressure sensor is set to 0.5 to get a full scale reading; that for differential pressure is 1 by default. The air flow bench is calibrated by keeping the blast gate open and letting it stabilize. The Agilent 34972A is turned on to scan mode and the readings for the pressure and flow sensors are recorded for certain number of scans. The averaged values are then negated from the offsets so as to get a zero VDC readings to begin the scan with for any test.

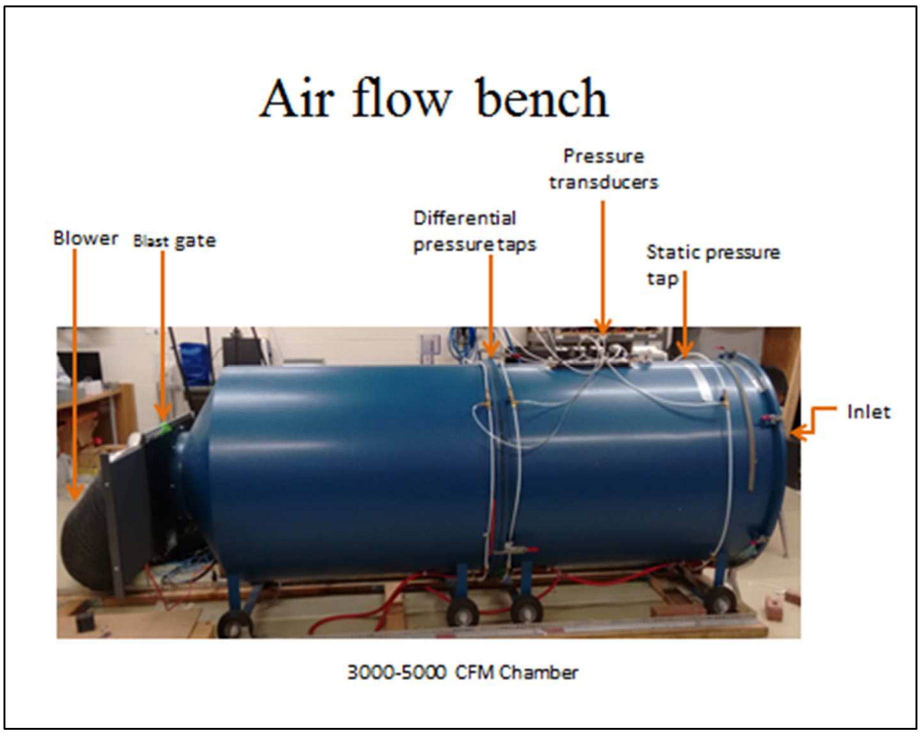

Figure 2-1: Air flow bench

Figure 2-2: Nozzles present in the mid-section of the air flow bench

2.2 Fan Curve

Fan curve is the graphical representation of the air moving capacity of the fan. The graph represents the air flow rate delivered by the fan, which is plotted on the x- axis, corresponding to the static pressure drop, which is plotted on the y-axis. The point, at which the static pressure drop across the fan is at maximum, is called the point of 'no flow'. The air flow rate across the fan at this point is zero as it cannot add any more air to the system. The point at which the flow rate delivered by fan is at maximum and the pressure drop across the fan is zero is called the 'free flow' condition.

The fan curve can be a curve for a single fan or a combination of fans. Fans are pressure adding devices. When 'n' fans are placed in series they multiply the static pressure 'n' times. Fans in series are used in dense servers where the flow resistance is high. When 'n' fans are placed in parallel they multiply the air flow rate 'n' times. Fans in parallel are used to achieve higher air flow rate through low flow resistance servers.

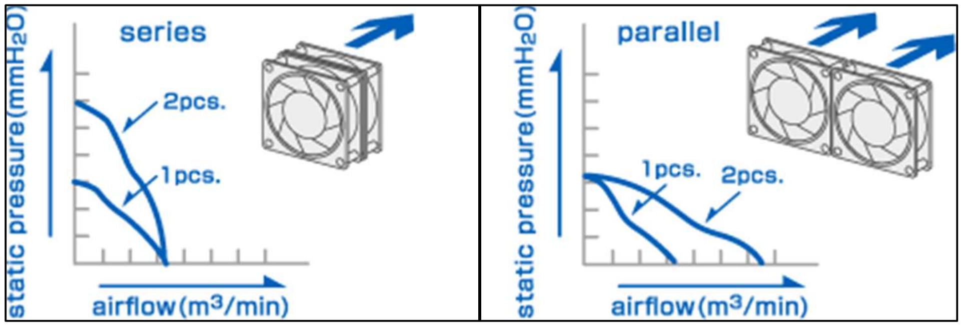

Figure 2-3: Fans in series v/s fans in parallel [4]

2.3 System Impedance Curve

A server is populated with electronic components like capacitors, heat sinks, electrical cables and processors. These components offer resistance to the air flowing through the server. System impedance curve is the graphical representation of the resistance the system offers to the flow through it. System impedance increases with the increase in density of server. The graph represents the flow resistance offered by the system in terms of air flow rate, which is plotted on the x- axis, at that particular static pressure drop, which represents the impedance, is plotted on the y-axis. The system impedance is the property of the system alone.

2.4 Operating Point

Operating point is the point where the air flow rate delivered by the fan is able to overcome the system impedance. It represents the amount of air flow rate consumed by the system. It is obtained overlaying the fan performance curve with the system impedance curve. The point of intersection of the curves is called the operating point of the system. The fan performance curve provided by the fan manufacturer is used by the server designers to get the operating point by the above method and the fan is selected based on this operating point obtained.

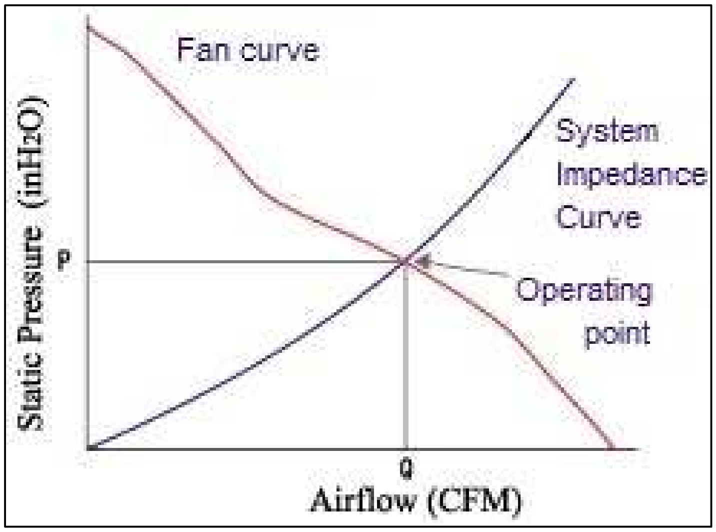

Figure 2-4: Operating point obtained by overlaying fan performance curve with system impedance curve [5]

Chapter 3

Experimental Characterization Of Fans And Server In Ideal

Data Center Conditions

3.1 Fan under consideration

The fan under consideration is a Sunon PMD1204PJB1-A DC brushless fan. It is a 40×40×48 mm unit consisting of two fans in series. The front fan runs in clockwise direction and rear fan in counter-clockwise direction. The manufacturer power specifications for the fan unit are 12W, 1A. The front fan runs at a 15000 RPM and the rear fan runs at 14000 RPM at 100% PWM (Pulse width modulation). The two fans form a push and pull configuration where the front fan pulls the air from the surrounding and the rear fan pushes the air into the system. The two fans being in series combination develop a higher static pressure as compared to each individual fan. The fan unit cools the system via forced draft. The maximum air flow rate in ft^3/min that a fan unit delivers at 100% PWM is 27 ft^3/min at a static pressure drop of 1.97" of H_2O.

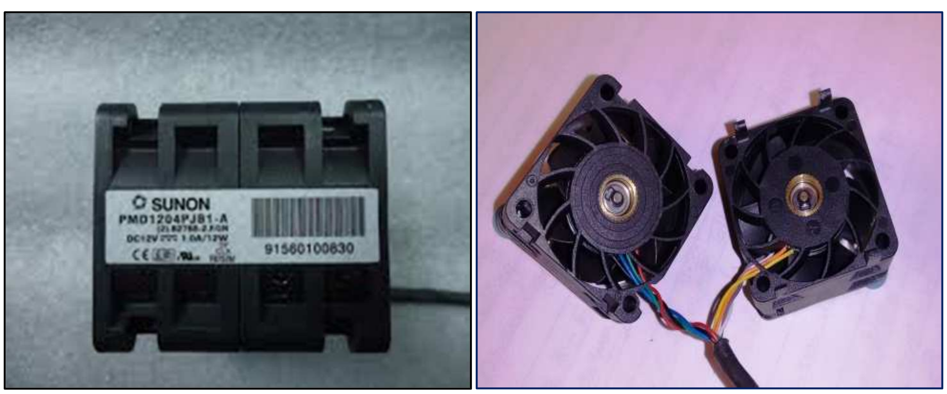

Figure 3-1: SUNON fan unit

As the fan unit consists of two separate fans the power cables, the ground cables and the control cables from both fans are clubbed together. The sense cables for both fans are separate. The sense cables are used to read the RPM values of both the fans. The PWM signal is given to the fan unit through Agilent 33210A function generator. The fan unit is powered using Agilent E3633A DC power supply.

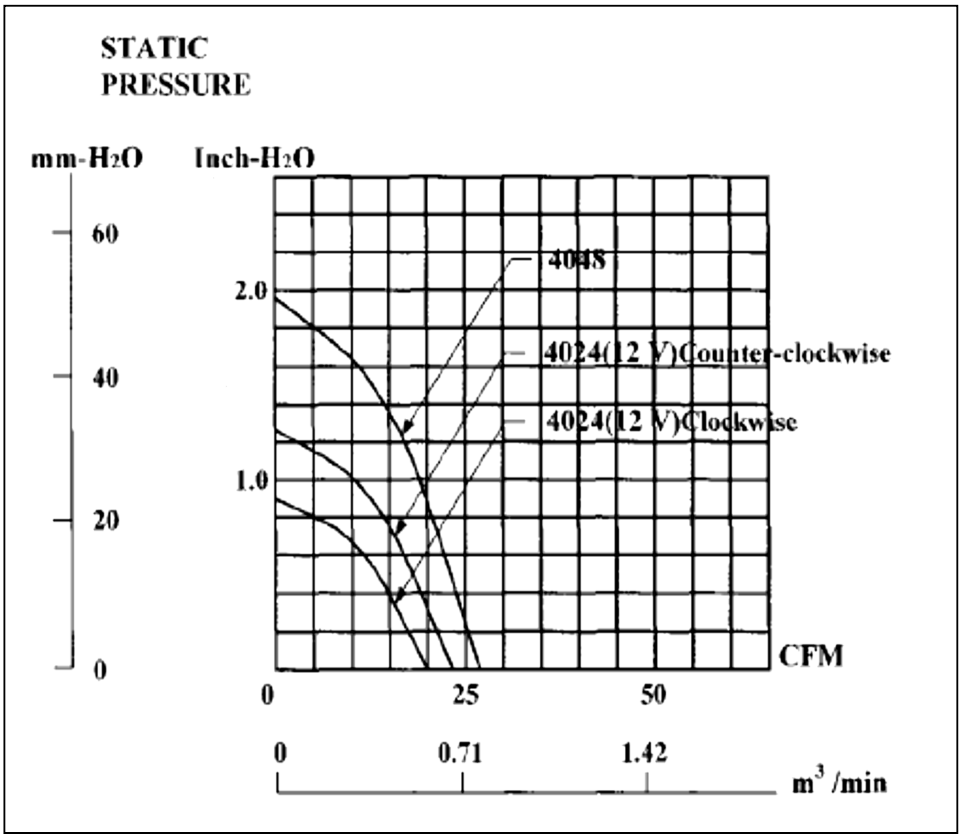

Figure 3-2: Manufacturer's data sheet for Sunon fan unit [6]

Figure 3-3: Agilent 34972A LXI Data Acquisition

Figure 3-4: Agilent 33210A function generator

Figure 3-5: Agilent E3633A DC power supply

The fan curve for the fan unit is obtained as per ANSI/ASHRAE standard 51. The fan is sealed to the inlet of air flow bench and tested from 'no flow' to 'free flow' condition. For the no flow condition, all the nozzles are closed and the fan is energized. The fan is allowed to stabilize and the readings at Agilent interface for static pressure are recorded. The static pressure drop at the 'no flow' condition is the maximum static pressure drop across the fan unit and the air flow rate at this point is zero. The maximum static pressure drop across the fan unit as per the manufacturer's data is 1.97" of H2O. The nozzle of 1" diameter is then opened. The blast gate is then slowly opened by some increment. The air flow rate delivered by the fan can now be measured via the differential pressure tap which is also the flow sensor. The differential pressure readings correspond to the air flow rate delivered by the fan. The blast gate is opened by increments till it is completely open. After this point the counter blower is started and the velocity of air across the air flow bench is increased through suction. The frequency of the counter blower is increased till a point the static pressure is near to zero. The air flow rate delivered by the fan at this point is at maximum and this point is called the 'free flow 'condition. The pressure readings and the flow sensor readings at every increment are recorded. A curve for the fan is generated using these readings. The fan unit tested on the air flow bench was found to comply with the manufacturer's published data.

The server under consideration consists of four such fan units placed in parallel. Using fan laws the fan performance curve for four fans was obtained. This fan performance curve is the theoretical fan performance curve as it is obtained using fan laws.

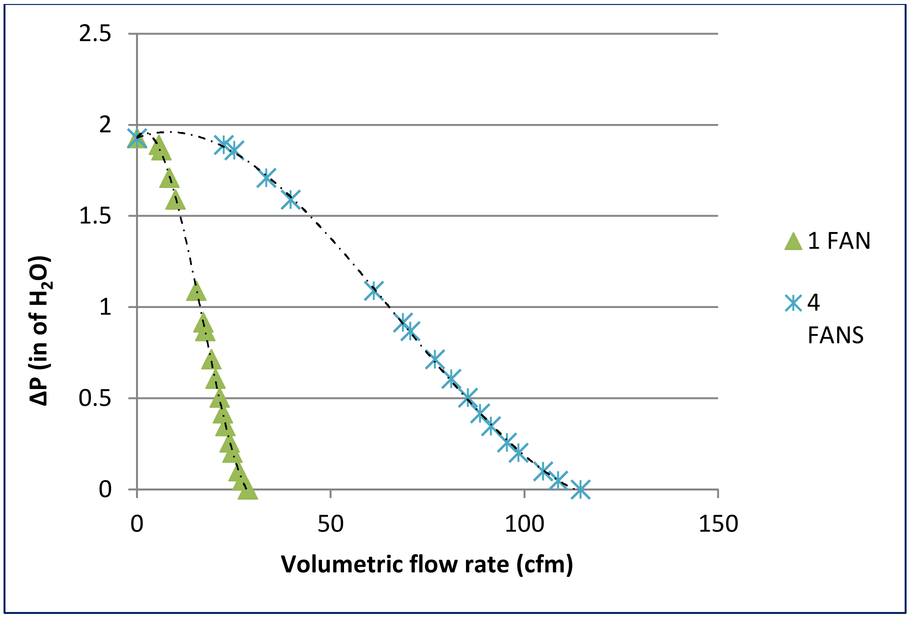

Figure 3-6: Theoretical fan curve

3.2 System under consideration

The system under consideration is HPSE1102 1U server. 1U is equal to 1.719'' server. The server consist four disk bases; the mother board consists of two xeon processors. The server is cooled by four Sunon fan units placed in parallel to each other.

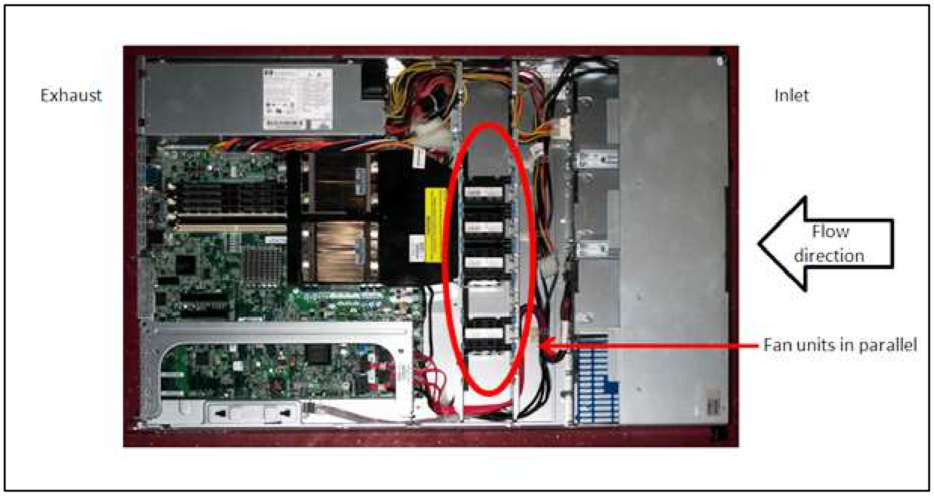

Figure 3-7: HPSE1102 server top view

The server is tested for system impedance as per ANSI/ASHRAE standard 51. The rear end of the server is sealed to the inlet of the air flow bench. The air flow bench is used in the suction mode. The blast gate is kept completely open and the counter blower is turned on to create varying air flow rates through the unit; the corresponding pressure drops are measured. A graph of the air flow rate versus the pressure drop is plotted where the pressure drop represents the impedance to the flow through the system. The fans do not run in this test as system impedance curve is the property of the system alone.

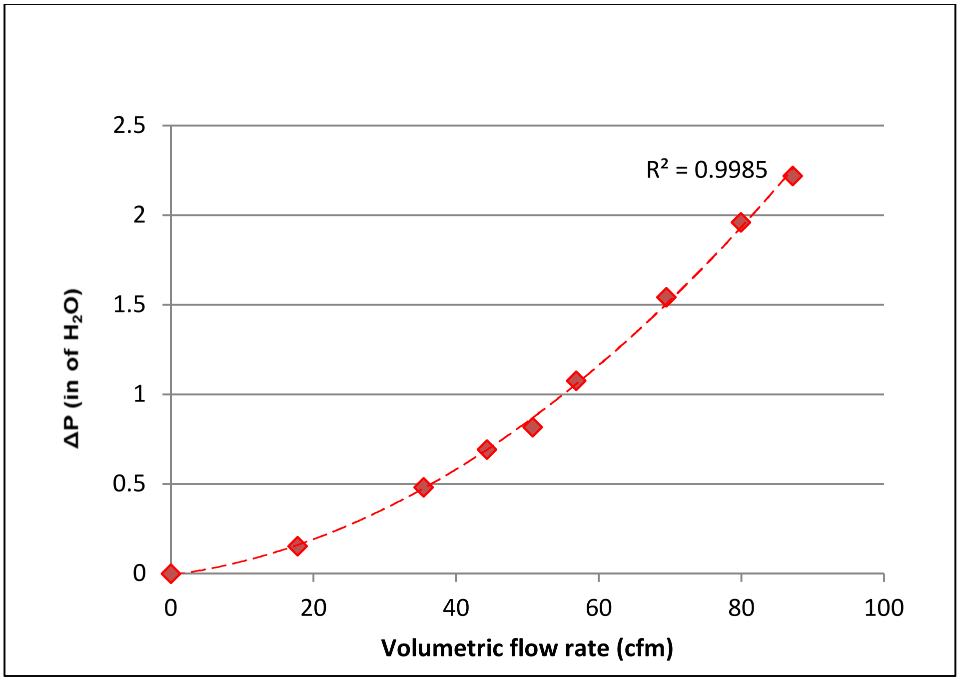

Figure 3-8: System impedance curve

3.3 Operating point of the system

The operating point of the system is obtained by overlaying the fan performance curve with the system impedance curve. This is the theoretical operating point of the fan in the system as the fan's performance may be affected when placed in the server. To get the actual operating point, the system is attached to the air flow bench like in the previous section and the fans are the externally powered. The counter blower is started and the frequency is increased till the static pressure drop reading reads zero. [7] This condition represents a free delivery operation, where the flow rate delivered by the fan is the flow rate consumed by the system. This point is then plotted on the system impedance curve and is the actual operating point that corresponds to the actual air flow rate through an operating system.

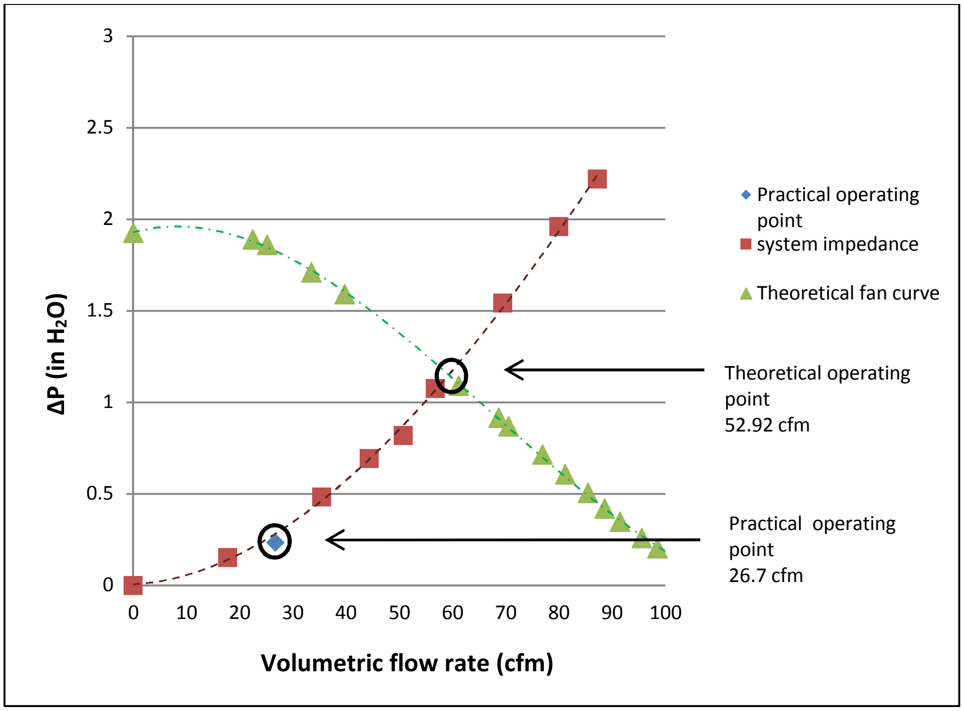

Figure 3-9: Theoretical and Practical operating point

3.3.1 Reasons for shift in operating points

The fans tested for performance are tested with open inlets and straight duct outlets as per ANSI/ASHRAE standard 51. If the inlet and outlet conditions are obstructed it can alter the fan performance. Hence the theoretical operating point is an over estimate because the inlet and outlet conditions of the fan when placed in a server are not taken into consideration. [8] The practical operating point is the actual amount of air flow rate consumed by the server and the amount of air flow rate that needs to be delivered by the fans in the server to overcome the system impedance.

3.3.2 Operating points at different fan duty cycles

The system was tested for different fan duty cycles and the corresponding air flow rates were measured. Different fan duty cycles correspond to the various modes at which the fans operate when internally controlled by the system, which change with the change in temperature of the server in order to cool the system accordingly. It also enables one to quantify the amount of air flow rate through the system at a particular fan duty cycle provided the inlet and exhaust pressures of the server are the same.

The server was mounted on the air flow bench like in the previous section and the fans were externally controlled using a function generator. The fans were then operated at different fan duty cycles and the corresponding air flow rates were measured. In order to check if the increase in temperature across the server affected the air flow rates, the server was powered and loaded with a Lookbusy program. The operating points at different fan duty cycles were obtained and the corresponding air flow rates were measured. The readings showed a slight increase in the air flow rates when the server was powered. The points are plotted alongside the system impedance curve as a reference; the actual pressure drop across the system at all operating points is zero.

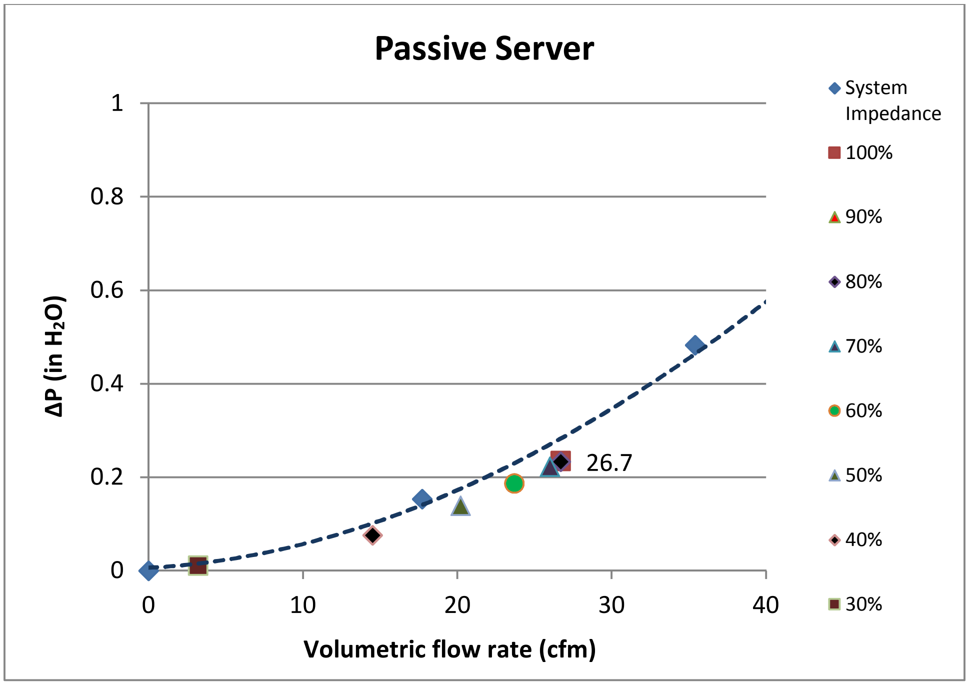

Figure 3-10: Operating points in passive server

Fan Duty cycle (%)	Air flow rate through a passive server (ft^3/min)
100%	26.7
90%	26.7
80%	26.7
70%	26
60%	23.7
50%	20.2
40%	14.5
30%	3.2

Table 3-1: Air flow rate through a passive server at different fan duty cycles

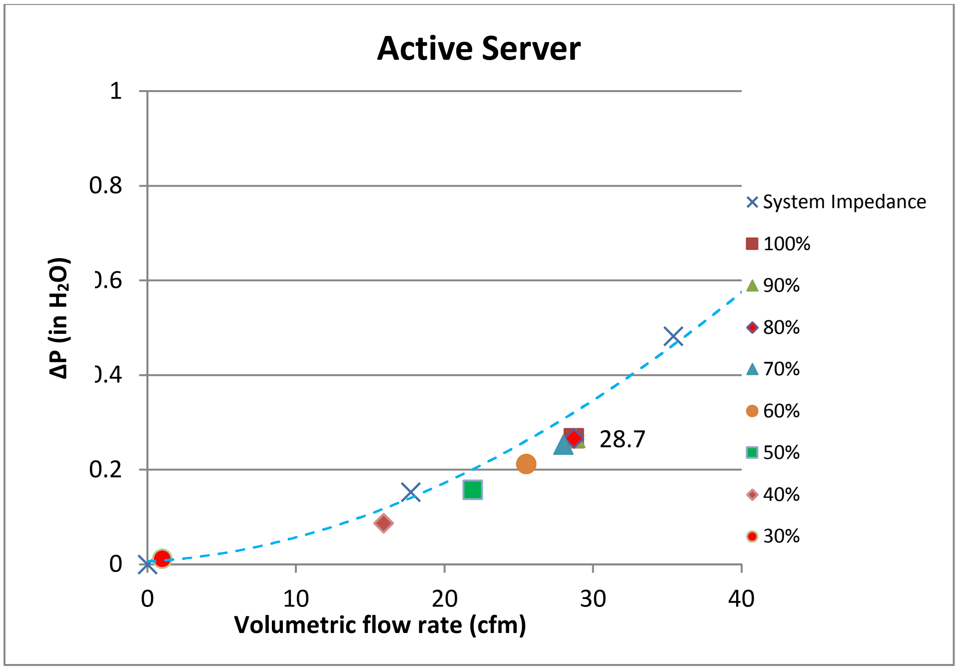

Figure 3-11: Operating points in an active server

Fan Duty cycle (%)	Air flow rate through a passive server (ft^3/min)
100%	28.7
90%	28.8
80%	28.7
70%	28
60%	25.5
50%	21.9
40%	15.9
30%	4.6

Table 3-2: Airflow rate through active server at different fan duty cycles

Chapter 4

Experimental Characterization Of The System In Data Center

4.1 Experimental setup in data center

The lab at NH114 is a representative data center. It is a 625 square foot test-bed data center facility equipped with a 12 inch raised floor and a 44 ton computer room air conditioning (CRAC) unit for cooling. The room consists of three racks populated with Facebook servers and four of HPSE1102 servers. The cold aisle consists of three perforated tiles, one each for a rack. The hot aisle is contained using plastic curtains. The area of the racks not consisting of any servers is blanked off using blanking panels. The CRAC unit set points are set in order to match the temperature and humidity conditions of the ideal data center setup. The server under consideration is situated in the middle rack.

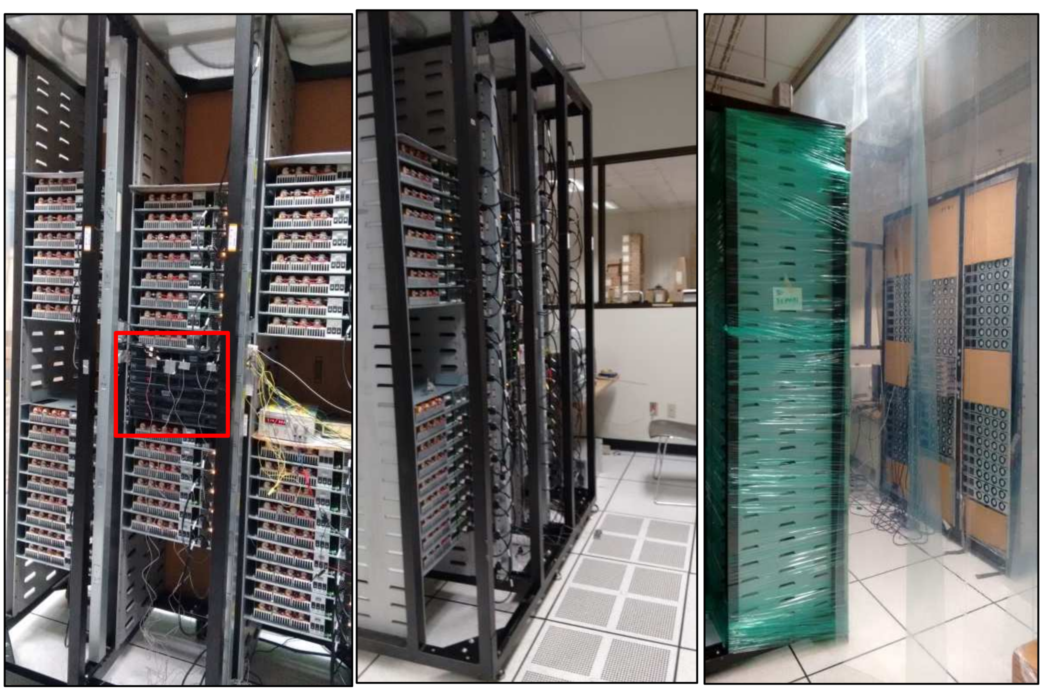

Figure 4-1: HPSE1102 servers; cold aisle; hot aisle

Velocity anemometers ATM 2400 are attached to the face of the server. The anemometers are plugged into an ACCUSENSE USB hub. The AccuTrac software interface is used to record the velocities of air at the anemometers.

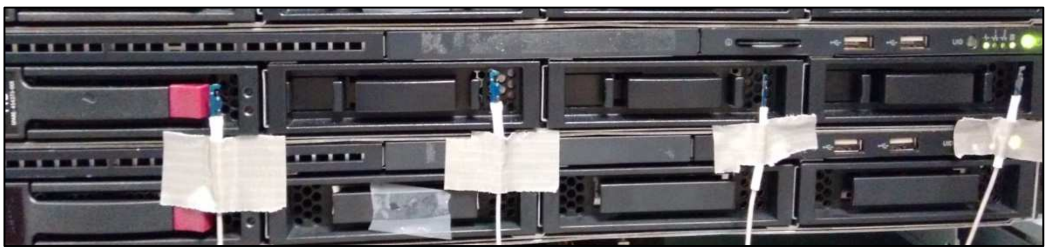

Figure 4-2: Anemometers attached to the server face

Figure 4-3: USB hub used to plug in the anemometers

4.2 Measuring air flow rate across the server

The air flow rate across the server is measured using the formula $Q = V \times A$ where Q is the air flow rate through the server, V is the velocity of the air measured at the face of the server and A is the effective cross sectional area of the server.

The fans are externally controlled via a function generator. Operating points of the system are obtained at different fan duty cycles. The system is allowed to stabilize at every duty cycle reading. Three runs of the test are carried out to get repeatability of results. A graph of air flow rate versus fan duty cycles is plotted. A reduction of approximate 50% is observed in the air flow rate measured at the data center. The reduction in the air flow rate in the data center is due to the pressure variations across the rack owing to the presence of other servers, bypass flow, non-uniformity in the rack and leakages in the rack. These all factors lead to increased impedances that affect the pressure drop across the server and in turn air flow rate through the servers.

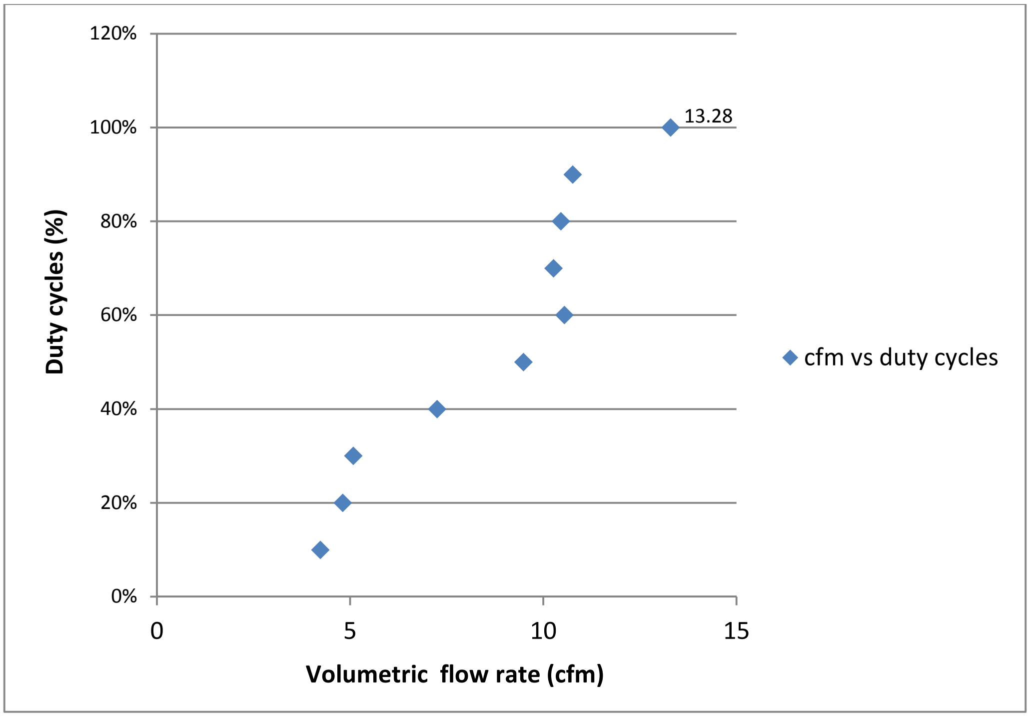

Figure 4-4: Operating points at various fan duty cycles in data center condition

Fan duty cycle (%)	Air flow rate through server (ft^3/min)
100%	13.28239
90%	10.75339
80%	10.44498
70%	10.25993
60%	10.5375
50%	9.478609
40%	7.244318
30%	5.071693
20%	4.800988
10%	4.221867

Table 4-1: Air flow rate through a server in data center

Chapter 5

Literature Review

5.1 Fan Laws

Fan laws are the basic proportional relationships between fan speed, air flow rate, pressure drop, and power. They are most useful for determining the impact of extrapolating from a known fan performance to a desired performance. The process of arriving at the affinity laws assumes that the two operating points that are being compared are at the same efficiency. The affinity laws were developed using the law of similitudes which provide three basic relationships; flow vs. diameter and speed, total head vs. diameter and power vs. diameter and speed.

Fan law 1: $(Q_1/Q_2) = (D_1/D_2)^3 (N_1/N_2)$

Fan law 2: $(P_1/P_2) = (D_1/D_2)^2 (N_1/N_2)^2 (\rho_1/\rho_2)$

Fan law 3: $(W_1/W_2) = (D_1/D_2)^5 (N_1/N_2)^3 (\rho_1/\rho_2)$

Fan laws are applicable to aerodynamically similar fans with same flow conditions. Fans are tested for their performance in ideal data center conditions where there are no obstructions in the path of the air flow, there are no pressure variations, the flow is uniform and the velocity of air flowing through the fan unit can be controlled. On the other hand when fans are mounted in a server the inlet and the outlet conditions to the fan are obstructed by the presence of electric cables and other electronic components, this affects the fan performance. As the two flow conditions differ the fan laws cannot be applied to the fan curve published by the manufacturer to obtain the actual air flow rate through the system. [8][9]

5.2 CFD Modelling

Compact fluid dynamics (CFD) modelling is governed by the continuity, momentum and energy equations. It is a widely used method to predict the flow velocity, temperature, density, and chemical concentrations for any region where flow occurs. It can predict performances of a system before having to modify or install it. It is widely used to create thermal/airflow models of data centers.

Data centers face the most inherent challenges due to the inefficient and unpredictable air distribution in the room. But while modelling a data center certain assumptions are made in the boundary conditions. Data center thermal designers assume the cooling units and the IT equipment as fixed-flow devices, which are based on the assumption that the pressure drop inside these devices is much greater than in the room, so that the flow rate from these units does not change significantly. Fixed flow assumption is also used in comparative studies in data centers with different layouts. [9]

CFD techniques used to analyze the flow field around the server rack and the air flow rate through the racks make the assumptions that the air flow rate provided by the perforated tile in front of the rack is equal to the air flow rate needed by all the servers in the rack. It is assumed that the maximum flow rate that the server fan can deliver is 70% of the original flow in a large testing room owing to the internal losses and the server inlet and exhaust pressures are the same. CFD models for the CRAC and the server fans are calibrated using the manufacturer fan curves. [10][11] The actual air flow rate through the server is never measured.

5.3 Thermal design considerations

The key parameters that are taken into consideration for thermal design of the data center are air flow rates and heat loads in the room. In order to calculate the total airflow rate into the room, the measurements of flow rates from perforated tile openings, cable openings, and other openings are taken into consideration. Measurements of power and airflow rate obtained from CRAC unit located in the room and the above measurements are deemed critical to thermal profiling of the data center. [12] Air flow rate needed to be supplied to the cold aisles is predicted by the thermal load of the rack. Thermal load of the rack is considered to be variable from peak consumption to idle state. The airflow rate provisioning should vary according to the needs of the rack. The newer data centers can vary the air flow rate supplied but the air flow rate supplied in legacy data centers is constant. If the air flow rate is kept constant cold air not used by the servers bypasses the servers and enters the hot aisles. Thus, if the air flow rate that actually consumed by the servers is not quantified it might lead to wastage of the conditioned air and thus increase the power consumption. [13]

Chapter 6

Conclusions

The results obtained experimentally vary from the theoretically obtained operating point. The air flow rate measured at the practical operating point is 49.54% lesser than the air flow rate calculated at the theoretical operating point obtained by overlaying the theoretical fan curve and the system impedance curve. The reduction in the air flow rate obtained in data center conditions is 74.9% lesser than the theoretical air flow rate.

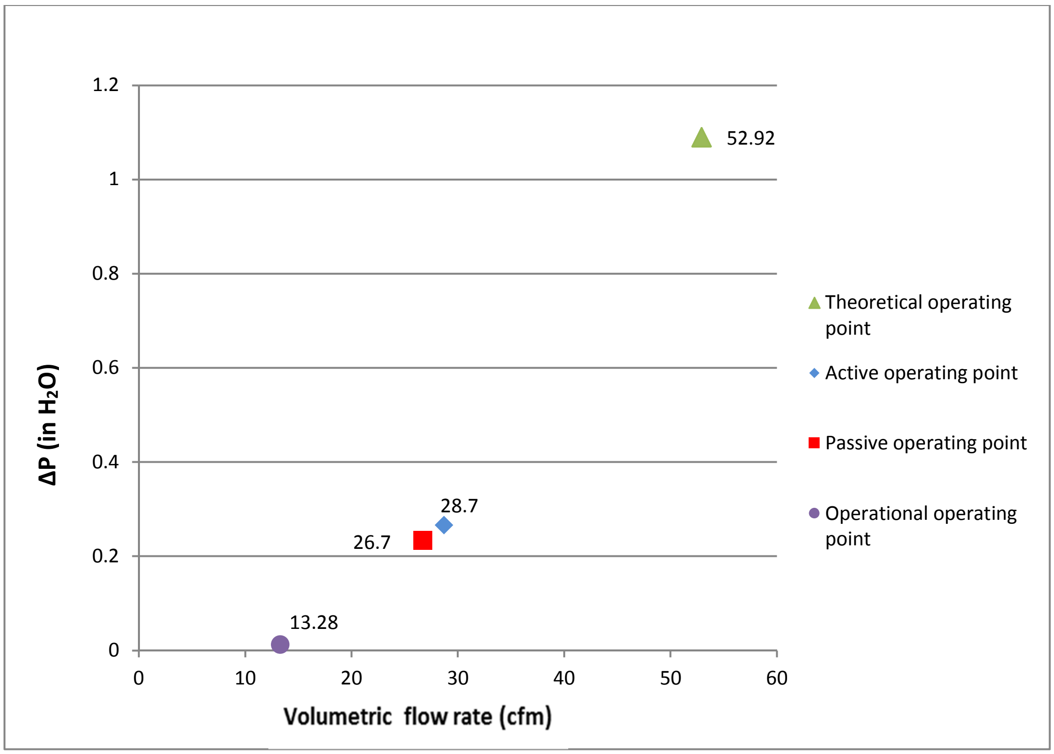

Figure 6-1: Theoretical operating point and Operating points in different flow conditions, at 100% fan duty cycles

6.1 Variations in flow conditions

The fan is tested with open inlets and a section of straight ducts when tested as per ANSI/ASHRAE standard 51. The performance of fan can degrade owing to various fan/system combinations like improper inlet outlet connections, non-uniform inlet and swirl at the fan inlet. [8]

The fan performance of a server fan degrades because of the change in flow conditions. The fan curve published by the fan manufacturer is for a fan tested per ANSI/ASHRAE standard 51. Using this fan curve to generate a fan curve for four fans applying fan laws does not provide the actual flow rate through the system. This is because of difference in the flow conditions. The difference in the flow rates obtained at the theoretical and practical operating point is due to the difference of the flow conditions.

The practical operating point is obtained in an ideal data center setup. The operating conditions in an ideal data center setup are controlled. There are no pressure variations, no air leakages, no bypass airflow and the flow is uniform as the velocity of the air through the air flow bench can be controlled. Also, the server being tested is assumed to represent all the servers in the rack.

The actual data center flow conditions are again different from the flow conditions in an ideal data center setup. The presence of other servers, pressure variations in the rack, pressure differences in both the aisles, leakages in the rack, bypass airflow are all the factors that act as external impedances and affect the flow rate through the system. The fans have to work more to overcome these impedances and cool the servers.

6.2 Future work

This experimental data may be useful to quantify the airflow rate through the rack provided the servers are of the same type. The impact of aisle pressure in an operational data center on the server fan performance can be studied. The effect of presence of different types of servers in the rack can affect the fan performance, as with different densities and different configurations the air flow rates through each server is going to be different. The clearances in the rack due to presence of cables, clearance between the cabinet door and the servers can affect the flow uniformity and should be taken into consideration for future studies.

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She worked as a Quality engineer for a period of one and half years in an automotive sector in Mumbai, India.

During her master's program she was a part of the Sustainable cooling team and her work was focused on experimentally quantifying the air flow rate through an operating server and studying the impact of operational data center conditions on the air flow rate through the server. She has gained knowledge about ANSI/ASHRAE standard 51 and has characterized fans and server using the technique.