Effect of Operational Parameters and Inlet Duct Design on ECM Fan Performance of a Push-Through Residential Air Handling Unit

By

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Effect of Operational Parameters and Inlet Duct Design on ECM Fan Performance of a Push-Through Residential Air Handling Unit

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Dedicated to my father who left me during this journey.

—Md Yeam Hossain

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Title of Study: Effect of Operational Parameters and Inlet Duct Design on ECM Fan Performance of a Push-Through Residential Air Handling Unit

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Abstract: The current trend in HVAC industry is to use increased air flowrate to increase the air conditioners' efficiency compared to when testing standards were originally developed. Manufacturers tend to achieve this increased efficiency by increasing the coil surface area and thus increases the equipment size. While this has indeed reduced environmental footprint it also has led to issues for the testing of units. In particular, increased indoor air handling unit height leads to conflicts between dictated inlet and outlet duct lengths and actually available total height of legacy testing facilities.

The issue is, that the current standard (ASHRAE 37) has limited guideline about inlet ductwork design while testing an air handling unit. It does not mandate using one but just recommends using one if the space permits. As there is no specific length (only the minimum length) for the inlet ductwork is provided in the standard, testing of the air handlers at different inlet duct length could lead to change in measured performance of the fan, in extreme cases resulting in 'false testing failures'. This theses work studies the experiments conducted to evaluate the effects of changes in inlet ductwork configuration to the fan performance and highlights some of the constraints applicable to units with up-to-date Electronically Commutated Fan (ECM).

The purpose of this study is to develop an inlet duct design guideline with reduced length while maintaining the reliability of AHRI and ASHRAE standards and also it will reduce the risk of false testing failures and will lead to higher integrity of the testing results at different laboratories. Here we studied the fan performance of a 3-ton ECM blow through fan coil unit for a number of parameters such as flow rate, inlet duct length, unit capacity, fan type and motor configuration. An additional objective of this work is to reduce the overall height of the testing setup (inlet duct + test unit + outlet duct) by reducing this inlet duct length while maintaining the equivalent fan performance as of the minimum inlet duct length (standard case) as per ASHRAE 37.

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ABBREVIATIONS

Acronym	**W**hat (it) **S**tands **F**or
HVAC	**H**eating **V**entilation and **A**ir **C**onditioning
ASHRAE	**A**merican **S**ociety of **H**eating **R**efrigerating and **A**ir **C**onditioning **E**ngineers
CFM	**C**ubic **F**eet per **M**inute
ANSI	**A**merican **N**ational **S**tandards **I**nstitute
AHU	**A**ir **H**andling **U**nit
FCU	**F**an **C**oil **U**nit
AHRI	**A**ir conditioning **H**eating and **R**efrigeration **I**nstitute
CFR	**C**ode of **F**ederal **R**egulations
EIA	**E**nergy **I**nformation **A**dministration
NIST	**N**ational **I**nstitute of **S**tandards and **T**echnology
CAD	**C**omputer **A**ided **D**esign
DOE	**D**epartment of **E**nergy

CHAPTER I

Introduction

In recent years residential air conditioning systems have gained public interest due to their large energy consumption and the expenditure it causes. In the United States about 87% household uses air conditioning system and in 2015 it was responsible for about 12% for total home energy expenditures (EIA,RECS, 2015). Also, this air conditioning system consumes 8% of total and 17% of electricity consumption (EIA,RECS, 2015). Due to this high energy consumption and expenditure the HVAC industry is now manufacturing energy efficient air handling equipment. Current testing standards are ASHRAE 37 (ANSI/ASHRAE-37, 2009) and DOE (DOE, 2017). Both of these standards provide requirements for testing unitary air handling equipment with some variations.

ASHRAE 37 recommends installing an inlet duct if the space in the testing chamber permits while DOE suggests to install one when testing a coil only indoor unit, a ducted blower coil indoor unit, or a single-package system. Both of these standards provide guidelines about the size of the inlet and outlet ducts and also the location and construction of static pressure measurement locations. The inlet duct duct is optional per ASHRAE 37 (ANSI/ASHRAE-37, 2009) standard. Due to these different requirements in different standards, there is always a possibility that the testing facility could test the units with different configurations and conditions. False testing failures in this context are differences between measured performance data by third party accreditation laboratories relative to a manufacturers own laboratory that exceed the allowable tolerances given in the applicable standards and are caused by reasons that are unrelated to the actual performance of the equipment.

Height limitations in the testing chambers were one of the motivations for this project. We had some opportunity to visit some of the testing locations and have seen limited height in vertical direction in some testing chambers. As the industry is now trying to develop energy efficient equipment, the air handling units are increasing in size with larger coil surface area and air flowrate for a given cooling capacity. As a matter of fact the test setup size is also increasing as the inlet and outlet duct sections dimension is based on the air handling units upstream and downstream duct cross sectional area. This increased unit size along with the inlet and outlet duct size causes testing facilities with vertically limited height to compromise with the standard. The overall height of the test setup sometimes exceeds existing testing chambers height. In that case companies choose either an extensive modification of the testing chamber (which is not always feasible) or they have to test the unit without following the testing standard. In that case the risk of false testing occurs.

This project, ASHRAE RP-1743 is created to address these issues in the current testing standard and develop guideline of for testing residential air handling unit.The scope of this project is limited to the inlet duct of the tested unit. Our goal is to develop a guideline for reduced inlet duct length that will reduce the overall height of the setup (that includes the height of test unit and outlet duct) while maintaining the reliability of ASHRAE testing standard. Also we want to increase the repeatability in testing results among different test facilities. This means if a unit is tested in a testing chamber and the same unit is tested in another third part test facility with all the test conditions unchanged, they will have similar result or result with very small difference.

CHAPTER II

Literature Review

ASHRAE research project 1581 (Pate et al., 2013) similarly to RP 1743 addressed overall testing "stack" height of inlet duct – AHU (Air Handling Unit)– outlet duct during testing in vertical configuration. Figure 2.1 shows the schematic of the test setup and the stack height of the setup. However, their focus was to investigate the effect of a reduction of outlet plenum length with the goal to maintain the reliability of ASHRAE Standard 37 (ANSI/ASHRAE-37, 2009) testing method. Two approaches to accomplish that goal were employed. The first approach was to change the air flow direction after the AHU outlet from vertical to horizontal, substantially reducing the height of the test apparatus. This was accomplished using an elbow at the unit outlet and placing the outlet duct in a horizontal position. Secondly, they reduced the height of the outlet duct by inserting a passive resistive device between the unit and the static pressure measurement location.

ASHRAE Standard 37 (ANSI/ASHRAE-37, 2009) establishes a uniform method for testing unitary air conditioning and heat pump equipment and specifies how to measure static pressure and air flow. Minimum inlet and outlet plenum length are specified based on the tested AHU's inlet and outlet cross section. However, ASHRAE 37 (ANSI/ASHRAE-37, 2009) does not strictly require the use of an inlet plenum if the available space does not permit its use. ASHRAE 37 (ANSI/ASHRAE-37, 2009) also includes the specifications for the air flowrate measuring apparatus commonly known as code tester or flow measurement nozzle box.

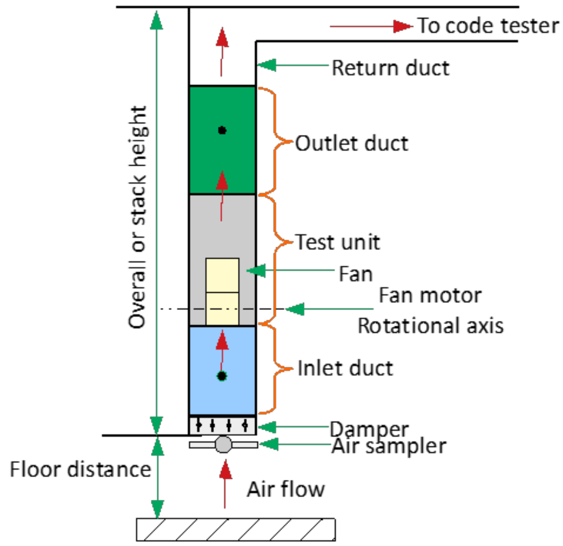


Figure 2.1: Schematic of test setup

ANSI/AHRI Standard 210/240(ANSI/AHRI-210/240, 2008) specifies the operational conditions for rating indoor and outdoor units. Air inlet conditions to the indoor and outdoor unit are specified in terms of target dry bulb and wet bulb temperature. Additionally, test operating and condition tolerances for nozzle pressure drop, external voltage, external resistance to airflow and temperatures are specified to ensure sufficient quality of the obtained performance date. A minimum external static pressure to be maintained across the test units is specified based on nominal cooling or heating capacity. However, this requirement of external static pressure differs from the updated DOE requirements (DOE, 2017). DOE recommends external static pressure (Implementation date January 1, 2023) higher than the ANSI/AHRI Standard(ANSI/AHRI-210/240, 2008), e.g. 0.50" w.c. (water column) for 3-ton split systems instead of 0.15 w.c. as given in (ANSI/AHRI-210/240, 2008). Figure 2.2 shows the external static pressure required according to two standards.

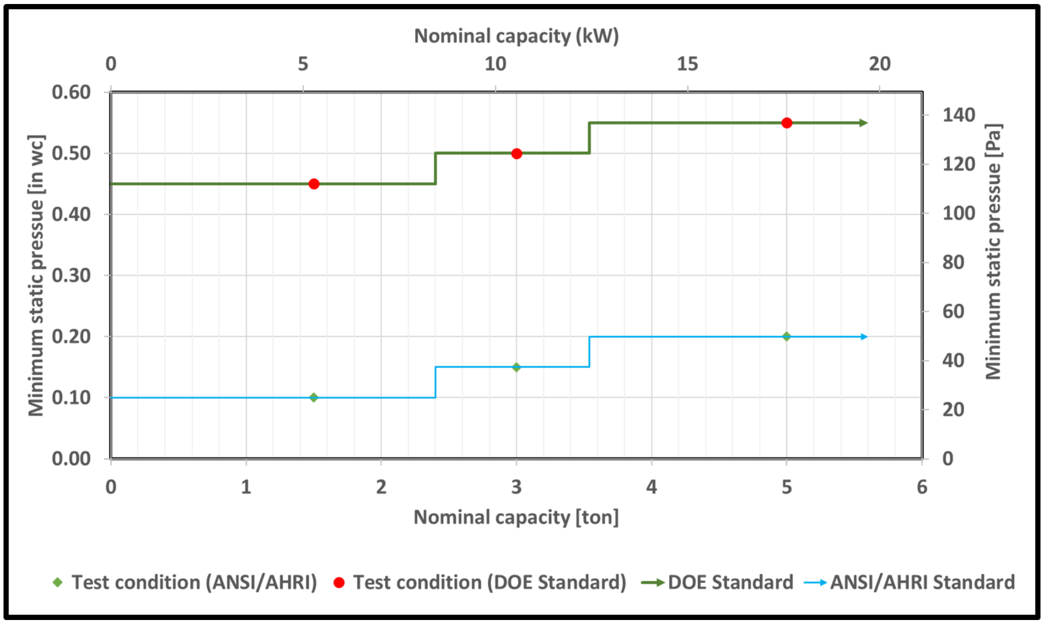


Figure 2.2: External static pressure requirement

In ASHRAE 37 it is required that the leakage rate should be within 1% of the air flowrate that is going to be tested. The current updated ASHRAE 41.2-2018 (ANSI/ASHRAE-41.2, 2018) requires that the leakage rate will be within 0.25%.

For uncertainty calculation the technical note 1297 of NIST (Taylor and Kuyatt, 1994) is considered. NIST provides guideline for uncertainty analysis of measurement results. It provides guideline to calculate standard uncertainty and measurement uncertainty of results from an experimental study. Also it gives guideline about how to report the uncertainty.

For the specification of OSU psycrometric chamber the these work Osgur Aslan (Ozgur Aslan, 2005) is used. In the theses work, OSU psycrometric chamber description is provided. Indoor and outdoor psycrometric chamber dimension, specifications, schematics of bay areas are provided. Also position of nozzles in the code tester or the position of booster fans, heaters is also provided in the theses work. The specifications of the pressure sensors in both indoor and outdoor chambers are also discussed in the theses. Also the theses work of Pedro Pablo Perez Paez (Pedro Pablo Perez Paez , 2009) provides the model and specifications of all other instrumentations such as RTD, barometer, used in OSU psychrometric chamber. These specifications of the instruments helped us calculating the uncertainty in air flow measurement and based on that we selected our nozzle sets for the 3 ton fan coil unit.

For predicting pressure losses and sources and noise and heat dissipation, numerous experimental and computational studies were done to investigate the flow behavior across a ducting system (Launder and Ying (1972), Melling and H. (1976), Nakayama and Koyama (1986)). It is also studied that to have better or higher energy efficiency of fans, the pressure losses across the duct networks, elbows and joints should be minimized (Liu and Chen, 2012). ASHRAE Handbook Fundamentals (ASHRAE, 2013) provides necessary guidelines for designing a HVAC system.

CHAPTER III

Experimental Setup and Test Plan

3.1 Introduction

For the experimental study of this project a test setup was built with the test unit, inlet and an outlet duct which is shown in Figure 3.1. This test setup is connected with a return duct and the return duct is connected with a code tester or nozzle air flow measurement device with a flexible duct. For the experiment we have considered the floor distance from the damper inlet to the floor. But DOE also specifies the minimum floor distance that is required and according to DOE the minimum floor distance for testing is 2" from the air sampler. Figure 3.1 shows the floor distance measurement for our experiment ans also the minimum floor distance specified by DOE.

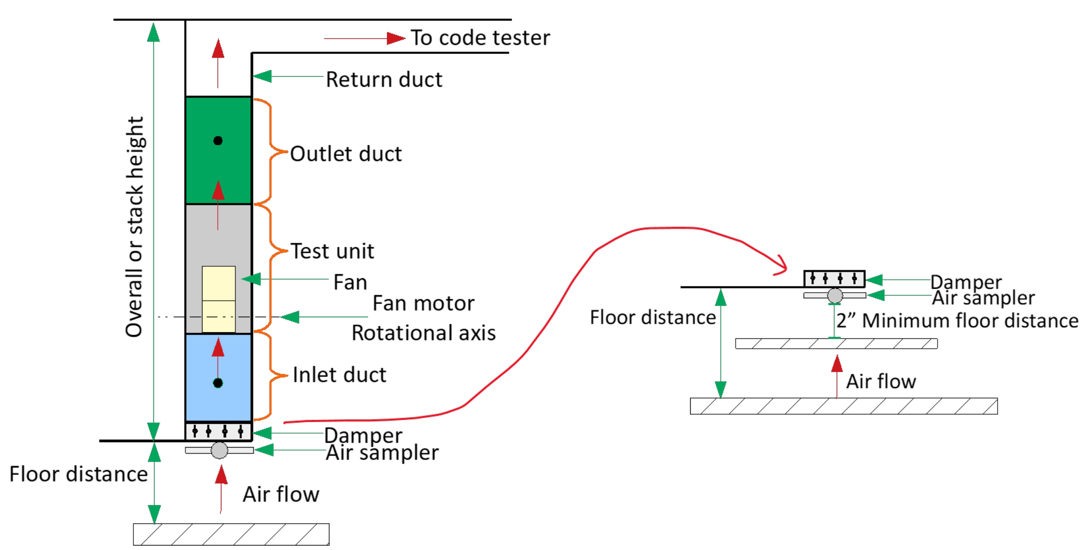


Figure 3.1: Floor distance measurement

3.2 Test Unit Matrix

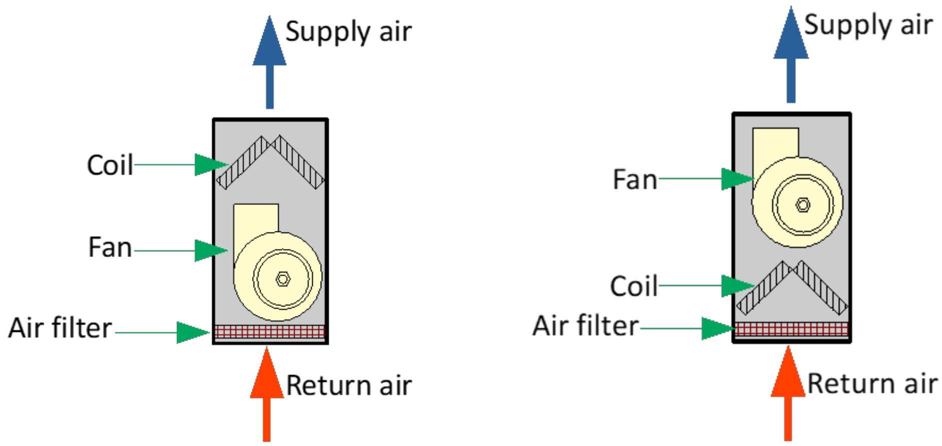
In Table 3.1, the test unit matrix for this project is shown. We plan to test units of different capacity and also of different fan configuration and motor type. Motor types that we plan to test are- ECM (Electronically Commutated Motor) and CTM (Constant Torque Motor). Each unit will also be tested at two different flowrates. The fan types are- blow or push through and draw or pull through (Figure 3.2). Also, to have variety in the test matrix we will test both fan-coil unit and air handling unit. At this point we have tested only the 3-ton ECM (Electronically Commutated Motor) blow through type fan coil unit and it is marked as red in the Table 3.1. Our main focus will be on the 3-ton capacity unit. That's why for a 3-ton unit we will also test a CTM (Constant Torque Motor) blow through type unit.

Table 3.1: Test unit matrix

Nominal Capacity (ton)	Fan Type				Flowrate (cfm/ton)	
	Blow Through		Draw Through			
	Motor Type					
	ECM	CTM	ECM	CTM	Low	High
1.5				x	350	450
3	**x**	x	x			
5	x					

3.3 Blow Through vs Draw Through Configuration

The difference between a blow and draw through configuration is in the location of fan with respect to the coil and filter. Blow and draw through fans are also termed as push and pull through respectively. The name indicates that one fan is pushing and other one is pulling air. In case of blow through configuration the fan is mounted before the coil and for draw through configuration the orientation is opposite, the fan is mounted after the coil and filter. Figure 3.2 shows the schematic of blow and draw through configuration. Till now we have tested a 3-ton ECM blow through fan coil unit.



(a) Blow or push through (b) Draw or pull through

Figure 3.2: Fan configurations

3.4 Inlet Duct Designs

The goal of this project is to reduce the overall height of the test setup by reducing the length of the inlet duct. Thus our main focus is only on the inlet side of the test setup. While reducing the length of inlet duct we also have to maintain the reliability of ASHRAE 37 standard, e.g. maintain for power and flowrate as close as possible to the current standard duct.

3.4.1 Standard and Straight Duct Configurations

ASHRAE 37 specifies the minimum length of the inlet and outlet duct that is constructed based on equation 3.1 and 3.2. In addition to the minimum standard duct length we will also investigate some duct configurations with reduced length. In Figure 3.3 some of the inlet configurations with reduced duct length is shown that we have considered. We kept the outlet duct length unchanged for all the case. The floor distance that is shown is measured between the ground floor and the damper inlet. As the duct length is reduced, floor distance increases.

3.4.2 Standard Duct Length Calculation

Figure 3.3(a) shows the standard duct length or the base case for the current 3-ton unit. Standard case means the duct lengths are calculated and built according to the standard. The standard case is the 32.11" duct length. This length is the minimum inlet duct length as per the standard ASHRAE 37 (ANSI/ASHRAE-37, 2009). The minimum length of inlet and outlet duct is calculated as -

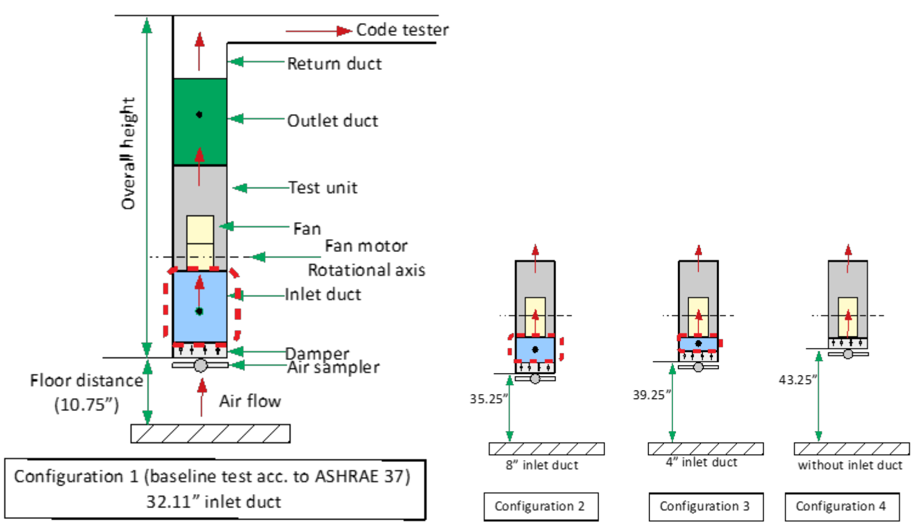
$$L_{min,in} = 1.5\sqrt{CD} \tag{3.1}$$

where, CD = Cross-sectional area from the equipment inlet.

Similarly the minimum length of the outlet duct is calculated as -

$$L_{min,out} = 2.5\sqrt{AB} \tag{3.2}$$

where, AB = Cross-sectional area from the equipment outlet.



(a) Base test (b) Inlet duct configurations

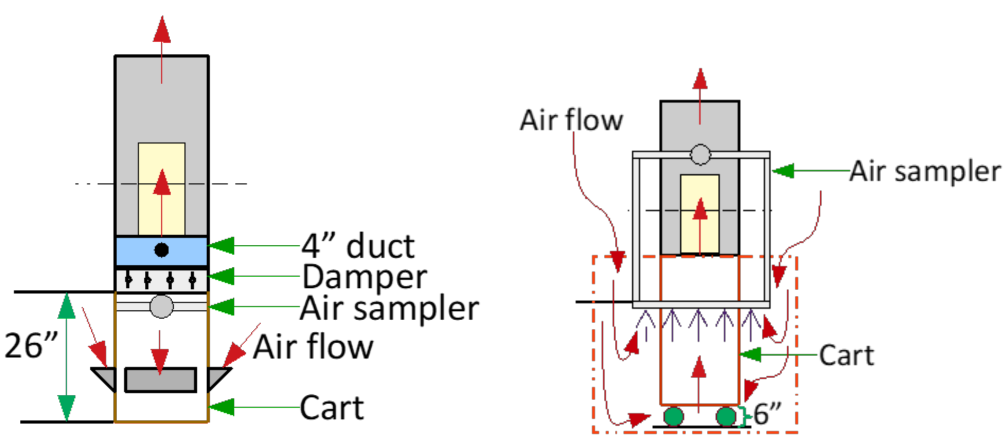
Figure 3.3: Test plan with varying inlet duct length and floor distance

3.5 Alternative Duct-works

Besides the inlet duct configurations shown in Figure 3.3 we have also tested the unit with two unconventional ductworks. Figure 3.4 shows the schematic of two alternative ductworks that we have tested. Figure 3.5 and Figure 3.7 show the actual picture of the test setup. We have named these two ductworks as alternative ductwork 1 and 2.

In case of the alternative ductwork 1 we attached a 4" duct between the test unit and the damper followed by the air sampler. Then we have attached a closed box which has openings at four sides of the box. Thus the air flows into the air handling unit from the sides of the box and not from the bottom.

For alternative ductwork 2 we have not used any damper and central trunk air sampler. Rather we have placed our test unit on a boxed cart and air sampler is placed around the test unit, not at the bottom center of the unit. Then this inlet duct is enclosed by a secondary duct to prevent side flow and create a thermal siphon for cyclic tests. Cyclic tests in this context means a test where the unit's compressor is cycled on and off for specific time intervalsThe floor distance from the upstream of air flow is 6".



(a) Alternative ductwork 1 (b) Alternative ductwork 2

Figure 3.4: Schematc of alternative ductwork

In case of alternative ductwork 1 the air sampler is embedded into the closed

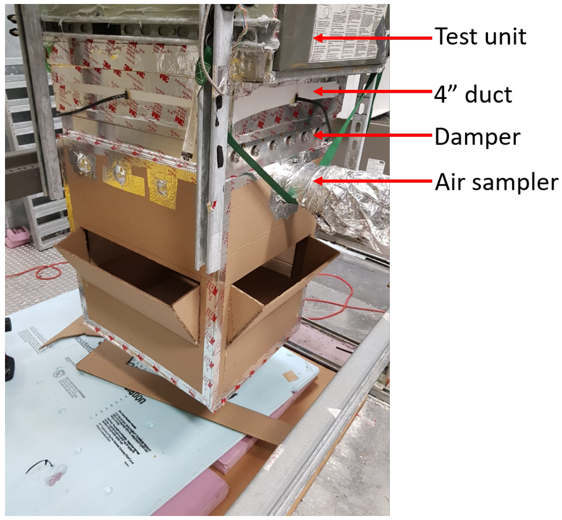


Figure 3.5: Alternative ductwork 1

box with the openings and we used the conventional central trunk air sampler as shown in Figure 3.6. And for alternative ductwork 2 we developed an air sampler that surrounds the unit as show in Figure 3.7. The picture of air sampler is shown in Figure 3.8.

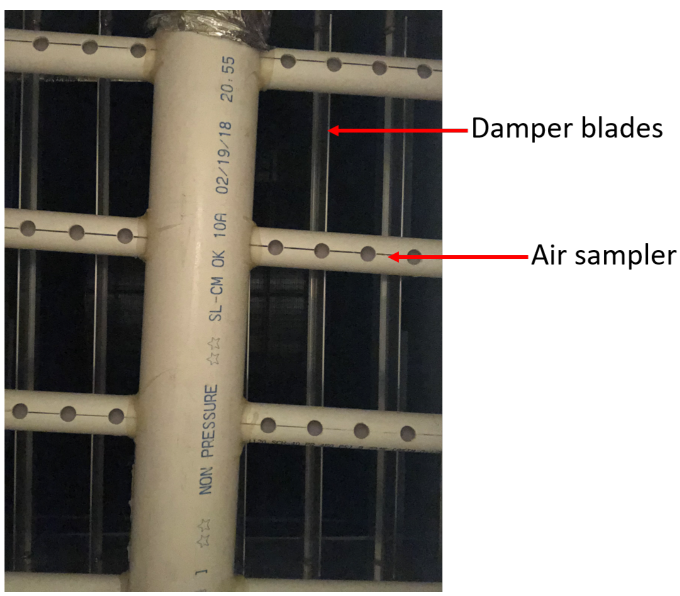


Figure 3.6: Central trunk air sampler

(a) (b)

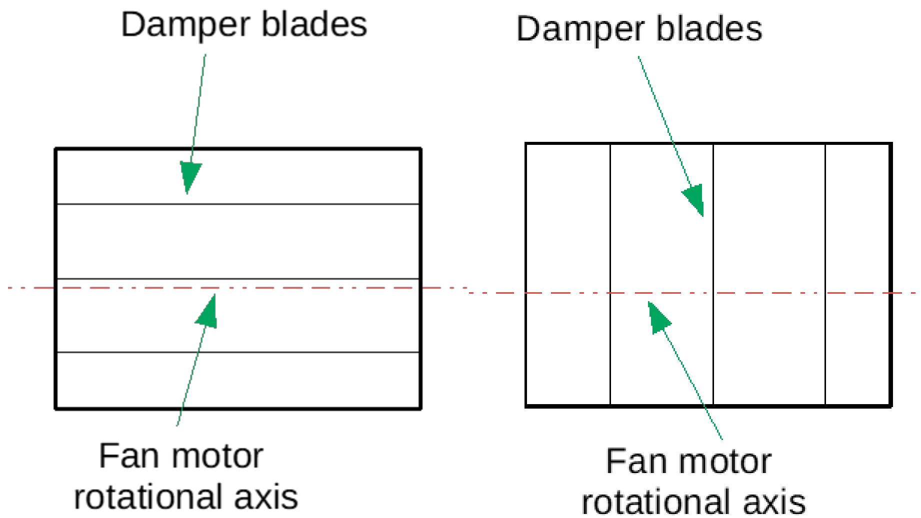
Figure 3.7: Alternative ductwork 2

(a) (b)

Figure 3.8: Air sampler design for alternative ductwork 2

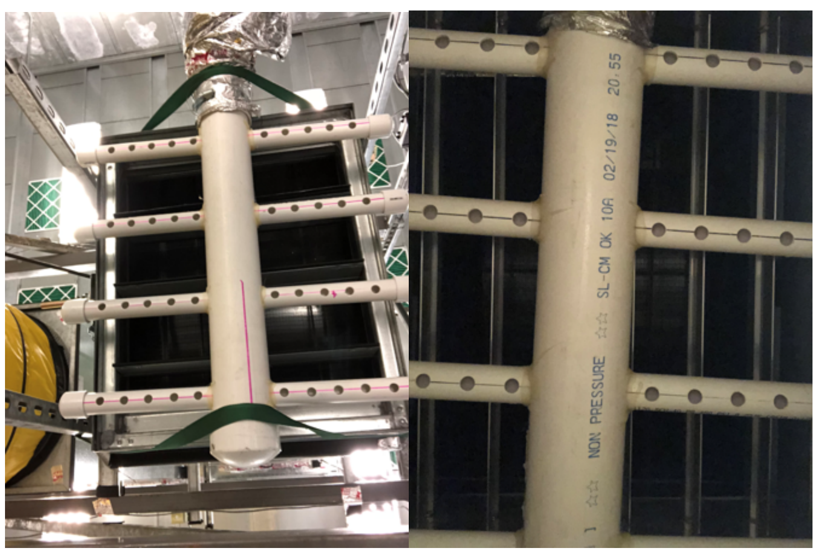
3.6 Damper Orientation

Dampers of of two different blade orientation with respect to the fan motor axis are considered. Figure 3.9 and Figure 3.10 show the damper blade orientation with respect to the fan motor rotational axis.



(a) Parallel (b) Perpendicular

Figure 3.9: Damper blade w.r.t. fan motor axis (air flow into the page)

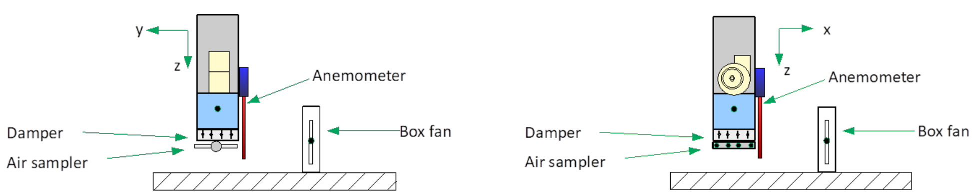


(a) Parallel (b) Perpendicular

Figure 3.10: Damper orientation (air flow into the page)

3.7 Side Flow

DOE allows to use a "de-stratification" fan in the testing chamber to minimize the magnitude of temperature distribution non-uniformity. But the fan speed should be below 500 fpm at the "vicinity" of the test unit. We have therefore investigated the effect of side flow in the vicinity of the test unit. In the standard DOE does not quantify ”vicinity”. It does not clearly indicate the area around the test unit within which the velocity should be below 500 fpm. As the vicinity is not clearly defined we adjusted our box fan in front and right of the test unit unit the velocity is within the DOE specified limit. Figure 3.11 shows the schematic of the side flow set up. We used a box fan to create the side flow at the vicinity of the test setup and also used an anemometer to measure the side flow velocity of the fan. The velocity is measured without running the test unit and the core tester. During this we maintained our side flow velocity within the DOE limit of 500 fpm. We tested our unit with side flow of parallel and perpendicular to the fan motor axis. Figure 3.12 shows a picture of actual test setup with side flow that is created with the box fan in front of it.



(a) Parallel (b) Perpendicular

Figure 3.11: Side flow w.r.t. fan motor axis

Figure 3.12: Side flow

3.8 Naming of Test Cases

As we have already discussed in our test plan, we have decided to test units of different types of motor, fan, and flowrate. The naming of the test cases (Figure 3.13) is based on the fan and motor type, flowrate, floor distance, unit type and any other inlet configurations.

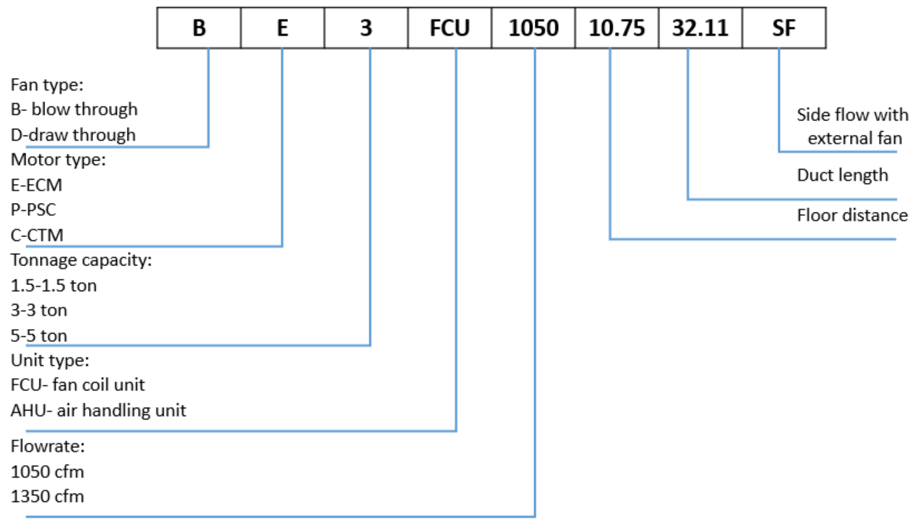


Figure 3.13: Naming convention for tests

CHAPTER IV

External Static Pressure Measurement

The unit is tested for a series of external static pressure (ESP) levels. At first the unit is tested from a high static pressure (0.55” wc) to low static pressure (0.10” wc) then the testing procedure is repeated from low to high static pressure. The external static pressure across the unit is controlled by the code tester fans speed at the downstream of the unit. DOE recommends minimum static of 0.50” wc (applicable from 2023) and ANSI/AHRI recommends 0.15” wc across the unit for a 3 ton unit. Thus by selecting 0.55” wc as our high static and 0.10” wc as the low static we have covered current and future standards requirements. The static pressure across the unit is measured with a differential pressure transducer as shown in Figure 4.1. On side of the transducer is connected at the outlet duct and other side is at the inlet duct section. The positions of the pressure taps are calculated according to ASHRAE 37 standard. ASHRAE 37 provides necessary formula and schematics about how to construct the pressure taps for static pressure measurement and where to place the pressure taps on the inlet and outlet duct of the test setup. We constructed our pressure taps following the standard and as shown in Figure 4.2. Figure 4.3 shows the schematic of external static pressure measurements. The pressure tap locations are calculated based on the inlet and outlet opening of the test unit.

In case of an air handling unit the position of the pressure tap is calculated by equation 4.1.

$$L_{tap,out} = 2\sqrt{AB} \tag{4.1}$$

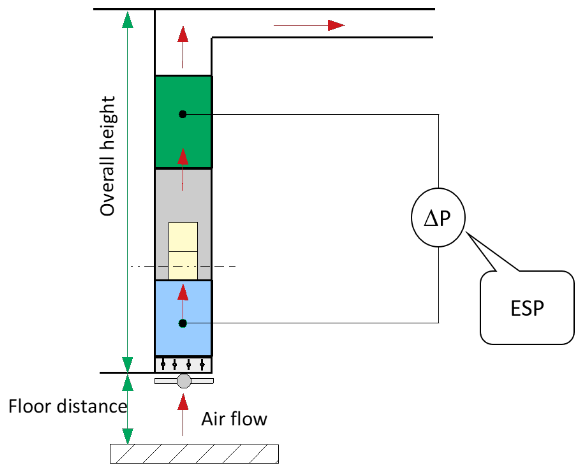


Figure 4.1: External static pressure (ESP) measurement

where, AB = Cross-sectional area from the equipment outlet.

For a fan coil unit the pressure tap locations for inlet duct is calculated as -

$$L_{tap,in} = 0.5\sqrt{CD} \tag{4.2}$$

where, CD = Cross-sectional area from the coil inlet

For outlet duct the location of the pressure tap is calculated as-

$$L_{tap,out} = 0.5\sqrt{AB} \tag{4.3}$$

where, AB = Cross-sectional area from the coil outlet

As currently we are testing a 3 ton fan coil unit, we have constructed our pressure taps according to equation 4.2 and 4.3.

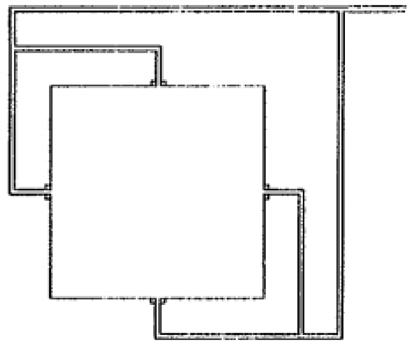
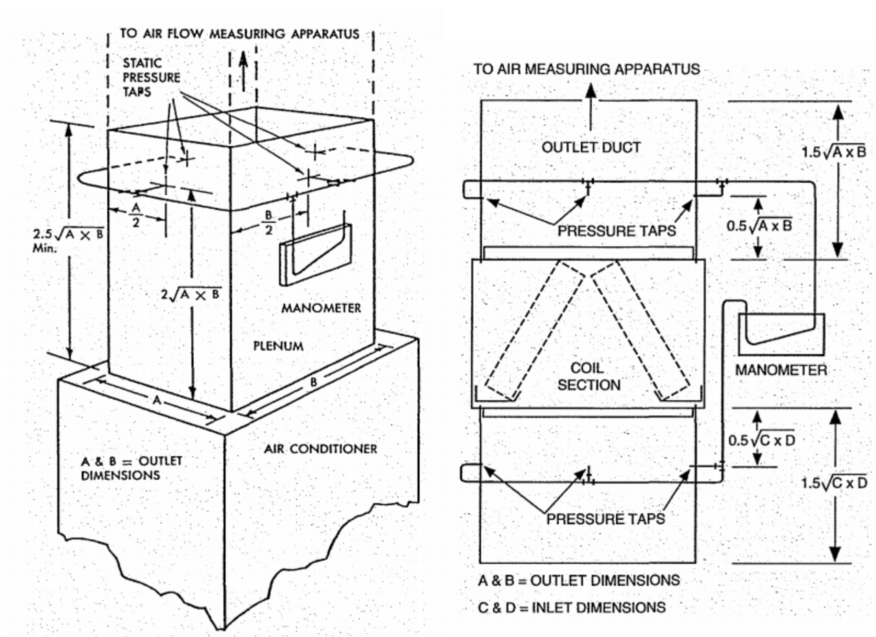


Figure 4.2: Connection of pressure taps (ANSI/ASHRAE-37, 2009)



(a) Outlet duct (b) Inlet duct

Figure 4.3: External static pressure (ESP) measurement (ANSI/ASHRAE-37, 2009)

Thus for the standard case we followed the standard pressure tap measurement. As mentioned before we have tested our unit for ducts with reduced length and also we have tested some alternative ductworks. In case of those we made the pressure taps at the center of the duct. Figure 4.4 shows how the surface around the pressure tap looks from the inside of the duct.

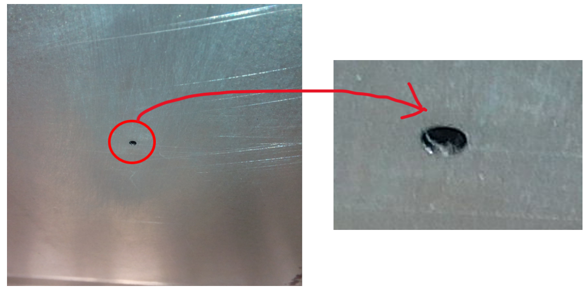


Figure 4.4: Pressure tap surface from the inside duct

CHAPTER V

Leak Testing and Sealing

According to the ASHRAE 37 the air leakage from the test equipment should not exceed 1% of the air flow rate being measured. On the other hand as per the new ASHRAE 41.2 standard the required air leakage rate will be 0.25% of the desired air flowrate. But as per out PMS suggestion we followed the ASHRAE 37 standard and kept the air leakage rate within 1%. For our current 3-ton unit our target air flowrates are 1050 cfm and 1350 cfm. Table 5.1 shows the allowable air leakage rate for different standards-

Table 5.1: Maximum air leakage rate according to the standard

Sources	**Flowrate (cfm)**	
	1050	**1350**
	Leakage rate (%)	
ASHRAE 41.2-2018	2.63	3.38
ASHRAE 37-2009	10.5	13.5

There are three sections of our experimental setup-

1. Test setup,
2. Flexible duct, and
3. Code tester or nozzle air flow meter

Table 5.2 shows the desired static pressure at each section during the leak testing.

Table 5.2: Desired external static

Test section	**ESP(in wc)**
Test unit	0.55
Code tester	0.50
Flex duct	0.55

These values are determined from the maximum static pressure at which the actual test is done. As mentioned in section 5.1.2, we do our testing from high static pressure of 0.55” wc across the unit, thus we chose this static pressure to achieve during our leak testing of different sections. We did some tests before doing this leak test and after analyzing those data we selected the static pressure at which we wanted to measure the leakage rate. At first we did the leak test of each section individually and got the leakage rate within the standard requirement. Initially the static pressure was very low due to the leaks and as the leaks were reducing the static pressure was increasing. We reduced the leaks until we reached at our desired static pressure of the system. After reducing the leaks from each section then we connected all the three parts of the system and did the same procedure again until we reached our desired leakage rate and static pressure. Table 5.3 shows the leakage rate of each section and also the leakage rate of the whole test setup. From the table it can be seen that for the sum of all sections we achieved our desired leakage rate that is within 1% of actual flowrate which will be tested and also we did the leak test at the static pressure at which the units will be tested.

Table 5.3: Leakage rate of test sections

Test section	Leak test before		Leak test after		Target	Predicted leakage rate at target ESP (old)(CFM)	Predicted leakage rate at target ESP (new) (CFM)	% Leakage rate relative to 1050 CFM
	ESP (in wc)	Leakage rate (CFM)	ESP (in wc)	Leakage rate (CFM)	ESP (in wc) (in operation)			
Test unit + sheet metal duct	0.130	4.400	0.560	2.300	0.55	9.05	2.27	0.22
Code tester	0.310	4.640	0.520	2.830	0.50	5.89	2.77	0.26
Flex duct	0.010	0.150	0.610	1.370	0.55	1.11	1.30	0.12
					Total	16 CFM	6 CFM	
					Total - relative to 1050 CFM	1.53%	0.61%	
Whole test setup	0.43	4.35	1.06	7.08	0.55	4.90	5.10	
					% Leakage rate relative to 1050 CFM	0.47	0.49	

Table 5.4 shows the leakage rate for the current 3-ton unit at the ASHRAE and DOE required minimum static pressure. Leakage rate is less that 1% for both values of ESP. Figure 5.1 shows the iterations that we did during our leak testing. Two

Table 5.4: Leakage rate for 3-ton capacity unit

	ESP (in wc)	**Leakage rate (CFM)**	**Leakage rate - relative to 1050 CFM**
Whole test setup	0.158	3.055	0.29%
	0.566	6.109	0.582%

horizontal lines indicate the 1% and 0.25 leakage rate respectively. As mentioned before 1% leakage rate was our target. 1% of 1050 cfm is 10.5 cfm, thus we wanted the velocity to be within 10.5 cfm and the static pressure to be at or above 0.55" wc (also shown in the figure with vertical line). The circles in the figure indicates the iterations. Initially we were below 1% leakage rate but our static pressure was low. But we gradually achieved our target pressure and leakage rate. The curves in the figure are plotted based on-

$$V^2 = C.\Delta P \tag{5.1}$$

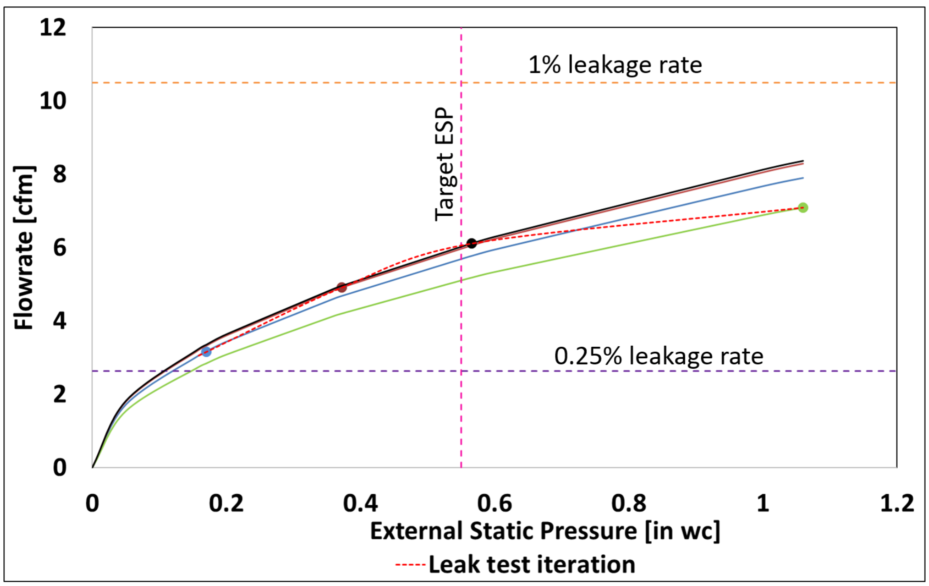


Figure 5.1: Leak testing iterations

In Figure 5.2 the test setup for leak testing for flex duct is shown. For the flex duct section we closed both side of the flex duct at first. Then on one of the side we attached a pvc pipe and inserted an anemometer into the pipe. Then the end of the pipe which was open to the ambient, we inserted a small blower fan to create the static pressure inside the pipe and flex duct. After inserting the fan the tube end was also closed. The static pressure across the flexible duct increased as the air leakage was reducing. A similar test setup was also used for leak testing other parts of the test setup.

(a) (b)

Figure 5.2: Leak testing setup

CHAPTER VI

Uncertainty Calculation

An uncertainty analysis was conducted for the experimental data sets recorded from the experiment. The data that is of our interest are flowrate, static pressure, dry and wet bulb temperature, and power. The speed (rpm) of the fan in the unit is recorded to evaluate the ECM motor behavior. The total uncertainty u_{tot} of each data is composed of two uncertainties,

- random, and
- measurement

$$u_{tot} = \sqrt{u_{rand}^2 + u_{meas}^2} \tag{6.1}$$

where, u_{rand} = random uncertainty, and
u_{meas} = measurement device uncertainty

Random uncertainty includes the uncertainty that originates form the environmental noise fluctuations of the measured variable and electrical interference. Measurement device uncertainty includes the uncertainty that is associated with the instruments. Random uncertainty u_{rand} is calculated using the standard deviation of the data recorded, e.g.

$$u_{rand} = k \cdot S_x, \tag{6.2}$$

where
k= coverage factor and

S_x= standard deviation of the data x

The value of coverage factor k is considered 2 assuming that the data are normally distributed and a 95 % confidence interval is required.

Measurement uncertainties include the uncertainties associated with the measurement devices that is used during the experiment. This includes differential pressure transducer for static pressure measurement, RTD (Resistance Temperature Detector) for dry and wet bulb temperature, barometer for ambient pressure, gauge pressure measurement device, and a power meter. Air flowrate is determined as volumetric flowrate (ANSI/ASHRAE-41.2, 2018),

$$Q = 1.414Y\sqrt{\frac{\Delta P}{\rho}}\sum(CA_s) \tag{6.3}$$

where

Δp= static pressure across nozzle,

ρ= air density,

C= nozzle discharge co-efficient,

A_s= nozzle throat area, and

Y= expansion factor

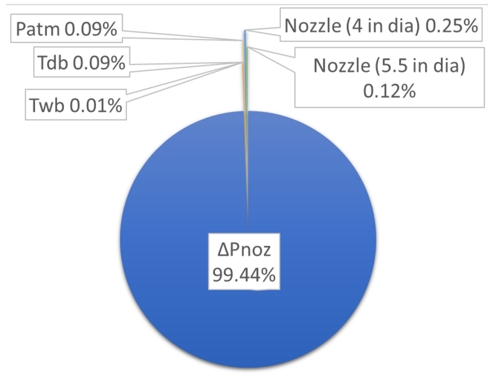
For the experimental setup of this project we selected a number of sensors, e.g. RTD, differential pressure sensors, power meter, barometric pressure sensor. We also needed to select the nozzle combinations for air flow measurement. For this before the instrumentation of the setup we did a preliminary uncertainty analysis. For the uncertainty analysis we mainly focused on the uncertainty of the air flow measurement. We focused on selecting the nozzle sets for different air flow rate based on our test unit and we looked at the uncertainty of the air flowrate and the velocity across each nozzle. ASHRAE 37 (ANSI/ASHRAE-37, 2009) requires the velocity across each nozzle will be between 15 m/s (3000 fpm) to 35 m/s (7000 fpm).

So, while selecting the nozzle sets we had to maintain this velocity range. As we have plan to test unit of 1.5-ton, 3-ton and 5-ton at two different flowrates of 350 cfm/ton and 450 cfm/ton, we selected different nozzle sets for different units. Also we selected our differential pressure transducer after doing a preliminary uncertainty analysis. We used Engineering Equation Solver (EES) to calculate the uncertainties of the flowrate. Table 6.1 shows the selected nozzle sets for different units and their flowrate. The nozzle sets are selected in such a way that it reduces the uncertainty in flowrate. Instruments nominal range and uncertainty is given in the Table 6.2. This preliminary uncertainty analysis is done based on the measurement uncertainty of the instruments selected for the project. Figure 6.2 shows the VI of nozzle sets that are located in the indoor psychrometric chamber of Oklahoma State University and the blue ones are the nozzle set that is being used for testing the current 3-ton fan coil unit.

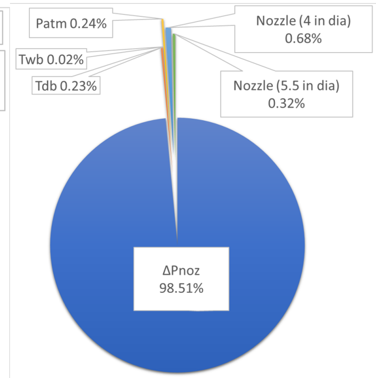
Table 6.1: Selection of nozzle sets

Nominal capacity [tons]	Nominal flowrate [cfm/ton]	Desired flowrate [cfm]	Calculated flowrate [cfm]	Uncertainty of air flowrate [%]	Nozzle differential pressure [in w.c.]	Nozzles used [diameter in inches]
1.5	350	525	523	0.33	0.95	3,4
	450	675	675	0.2	1.58	
3	350	1050	1053	0.5	0.62	4,4,5.5
	450	1350	1352	0.31	1.02	
5	350	1750	1756	0.4	0.78	4,4,5.5,5.5
	450	2250	2251	0.25	1.28	

The uncertainty analysis allowed the evaluation of the effect of different instrument parameters. The results show that the differential pressure measurement across the nozzles has, with 96% to 99%, the highest contribution to the uncertainty of the airflow measurement. Figure 6.1 shows a graphical representation of different properties contribution in uncertainty measurement of air flow for the case of 3-ton unit at 350 cfm/ton and 450 cfm/ton.



(a) 3-ton at 350 cfm/ton



(b) 3-ton at 450 cfm/ton

Figure 6.1: Contribution of measurement devices to overall uncertainty of measured air flow

Table 6.2: Instrumentation list

Parameter	**Manufacturer**	**Model**	**Nominal value**	**Uncertainty**
Differential Pressure Across Nozzles	Setra	Model 264	0 to 3 in wc	± 0.25% FS
Differential Pressure Across Unit	Setra	Model 265	0 to 3 in wc	± 0.25% FS
Barometer	Valsala	PTB110	0.002 to 0.004 in wc	± 0.12 in wc
Pressure at Nozzle Inlet	Setra	Model 266	-1.5 to 1.5 in wc	± 0.25% FS
Unit Supply Dry Bulb RTD	Omega	PR-10	5 to 140 (°F)	± 0.2 (°F)
Unit Supply Wet Bulb RTD	Omega	PR-10	5 to 140 (°F)	± 0.2 (°F)
Electrical Power (45-65 Hz)	Camille Bauer Metrawatt AG	APLUS 2111-0E1	Adjustable using the current transformer	± (0.02% FS+0.08% Reading)
Electrical Voltage	Camille Bauer Metrawatt AG	APLUS 2111-0E1	57.7-400 VLN	± (0.02% FS+0.08% Reading)
Electrical Current	Camille Bauer Metrawatt AG	APLUS 2111-0E1	1-5 Amp Max 7.5 Amp	± (0.02% FS+0.08% Reading)
Current Transformer	Ohio Semitronics	Model-12974	Current Ratio: 150:5	± 0.3% FS
Humidity Sensor	Omega	HX71-MA	15% to 85%	± 3.5% RH

Figure 6.2: Indoor psychrometric room nozzle sets

We have also selected our differential pressure (DP) transducer to measure the external static pressure across the test unit. ASHRAE 37 (ANSI/ASHRAE-37, 2009) requires the static pressure measurement device to be accurate within ± 2.5 Pa (± 0.01 in wc). We have done the uncertainty analysis of differential pressure transducer for a range of static pressure and for a number of transducers with different full scale and uncertainty. After analyzing the uncertainty, cost and our target static pressure we selected a DP transducer of full scale 0-1.5 in wc and accuracy of 0.4%. Figure 6.3 shows the plots of uncertainty for different DP transducers.

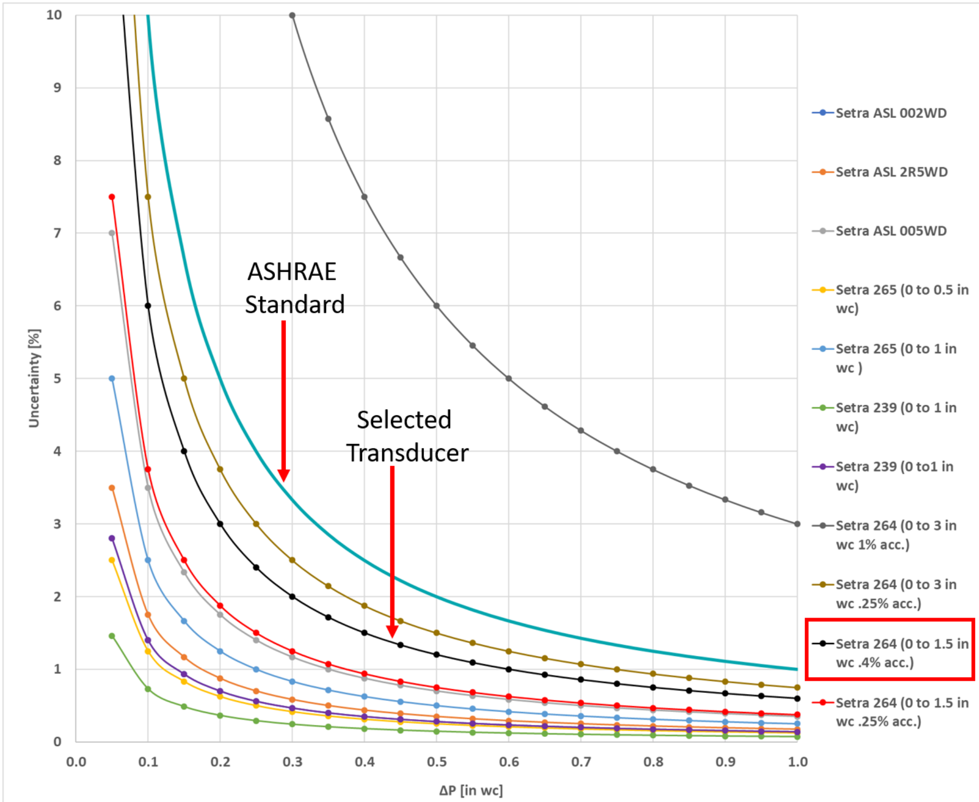
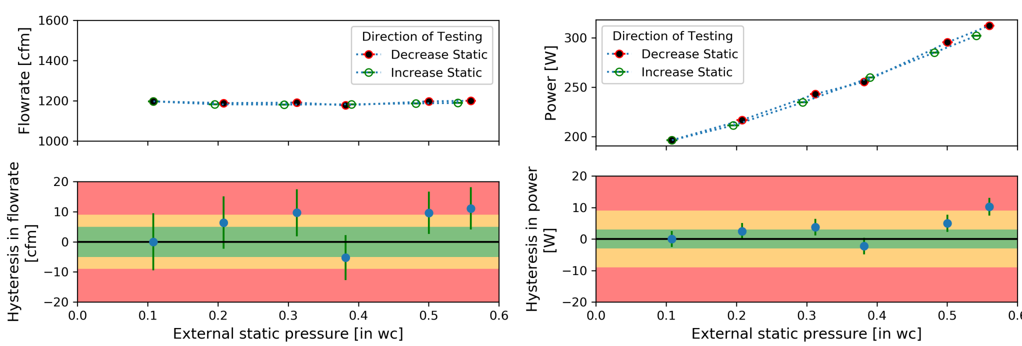


Figure 6.3: Differential pressure transducer selection

CHAPTER VII

Data Analysis and Visualization

We conduct our testing for a series of external static pressures. We start the unit with a high ESP of 0.50” wc and gradually decreases to low ESP of 0.10” wc. After that the whole process is reversed from low to high ESP. During this two directional testing we maintained all the conditions unchanged including the code testes blowe fan speed. But we noticed that even though all the conditions were unchanged at the same code tester blower fan speed there is always some difference in ESP which results in difference in power anf flowrate as well. So, we decided to investigate the behavior of the ECM motor of the unit and thus did some transient data analysis. We wanted to know whether it is an issue with motor electronics or our instrumentation. We termed the directional difference in power, ESP and flowrate hysteresis. Figure 7.1 shows this hysteresis in flowrate and power.



(a) Hysteresis in flowrate (b) Hysteresis in power

Figure 7.1: Hysteresis effect

To investigate this fan hysteresis we installed an rpm sensor inside the test unit. We noticed that actually the fan speed does not match during this two directional test and thus resulting a difference in ESP, power and flowrate. Figure 7.2 shows the hysteresis in fan speed.

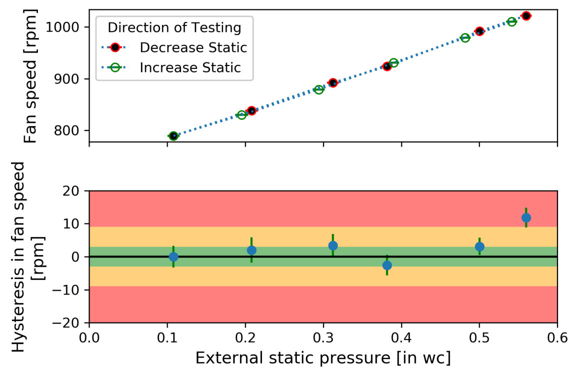


Figure 7.2: Hysteresis in speed

During the time of testing each time after changing the code tester blower fan speed we used to wait for 4-5 minutes and then recorded data for 5-6 minutes. After investigating the hysteresis in fan speed of the test unit we decided to see whether our waiting and recording time is good enough to get a steady state data. Thus we recorded data for 2.5 hours time period and after that we calculated the moving average and uncertainty of moving average of our data. We wanted to see whether the data that we record for 5 minutes is within 10% of measurement uncertainty. Moving average is calculated using equation 7.1.

$$S_{avg_i} = \frac{\sum_{i=1}^{i=N} S}{N_i} \tag{7.1}$$

where

$S=$ parameter (speed or power)

$N=$ number of data point

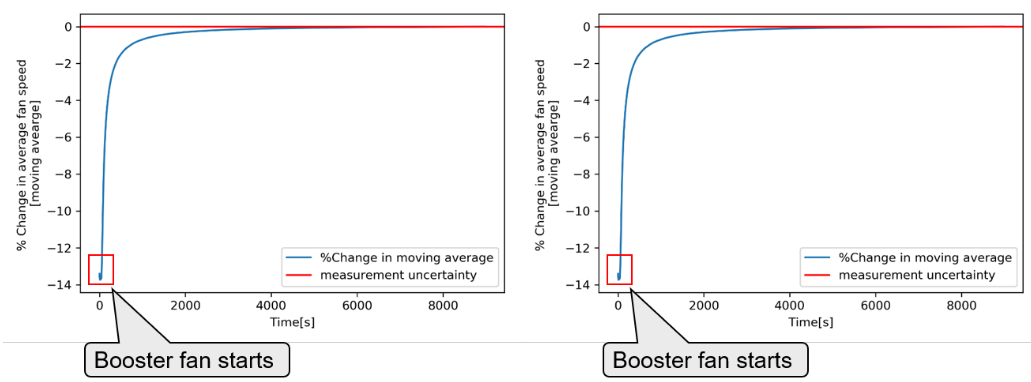
Percentage change in moving average is calculated using the following equation 7.2. Figure 7.3 shows the % change in moving average for the speed and power. The measurement uncertainty is calculated using the instruments uncertainty (Table 6.2).

$$\Delta S_{avg}[\%] = \frac{(S_{avg})_N - (S_{avg})_i}{(S_{avg})_N}, i = 1, 2, ..N \tag{7.2}$$

Measurement uncertainty of speed (u_{rpm})and power (u_{power}) are calculated using the following formulas-

u_{rpm}= 0.005%, and

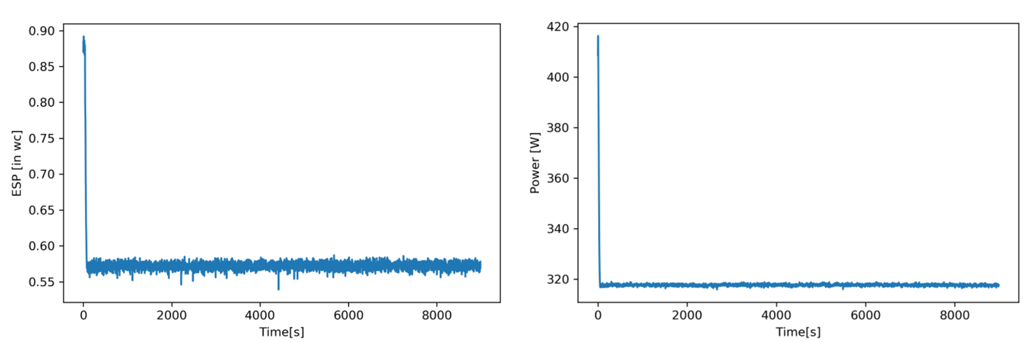
u_{power}=0.16% of measured value + 0.04% of maximum range



(a) Fan speed (b) Fan power

Figure 7.3: Percent change in moving average

In the above Figure 7.3 the 0 in the axis indicates when the code tester blower fan is started. And this speed and power is at 0.55" wc. Figure 7.4 shows the recorded of external static pressure, power and speed for the time period of 2.5 hour.



(a) ESP (b) Power

Figure 7.4: Data over 2.5 hour period

This test of transient data is done at the steady state condition. ANSI/AHRI 210-240 (ANSI/AHRI-210/240, 2008) provides the required operating condition for testing unitary equipment and that 80°F dry bulb and 67°F wet bulb temperature. The test condition tolerance fro dry bulb is 0.5°F and for wet bulb is 0.3°F. We maintained this operating conditions for all of our tests. Figure 7.5 shows the steady state condition during the test time. The red horizontal lines are indicator of the the dry and wet bulb temperature limit. All the plots here are shown after the test unit was shut down for 8-9 hours.

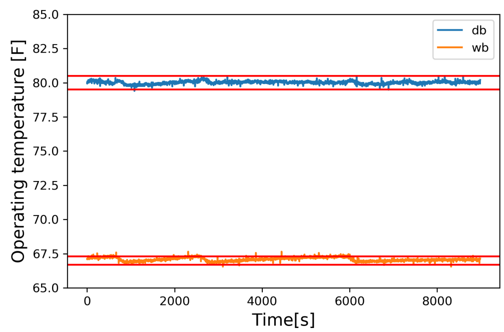


Figure 7.5: Operating temperature

We have also done a 5-minute moving average and percentage change to investigate how the average value changes over a 5 minute time period. Figure 7.6 shows the 5 minute moving average for power and the percentage change of average power. The moving average and percentage change is calculated as similar way of equation 7.1 and 7.2, only difference is that in this case we calculated the average over 5 minute period of time.

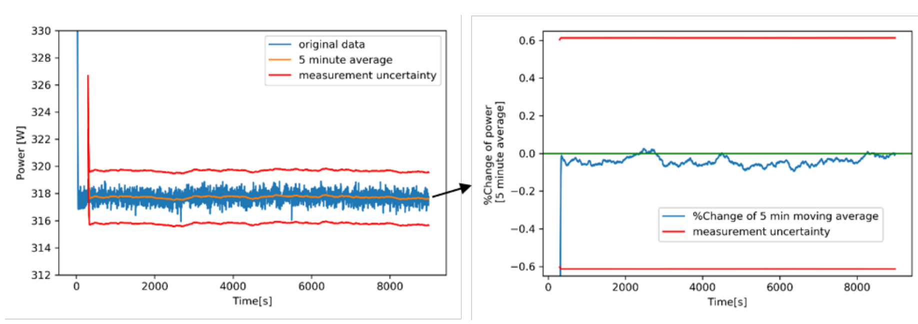


Figure 7.6: 5 minute moving average and percentage change

Figure 7.7 shows the data with 95% confidence interval.

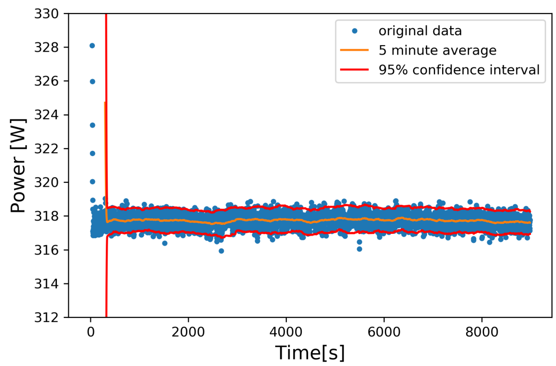


Figure 7.7: Power data within 95% confidence interval

Figure 7.8 shows the case for fan speed. Measurement uncertainty of speed sensor is 0.005%, within linewidth of the 5-minute average value. During this transient test we did not see any significant motor warmup effects. Change over time is within noise band for fan speed, power, and ESP.

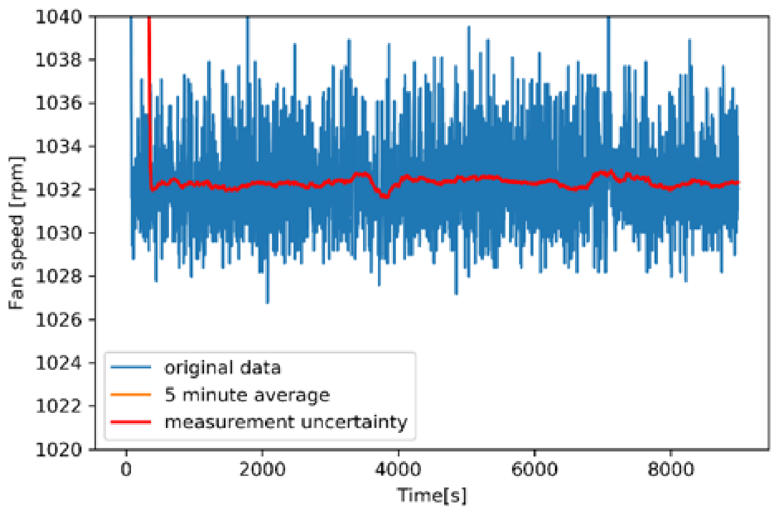
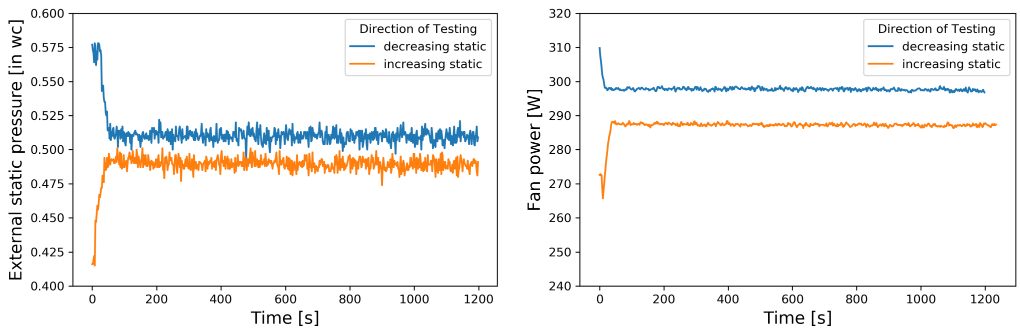


Figure 7.8: 5 minute moving average and percentage change

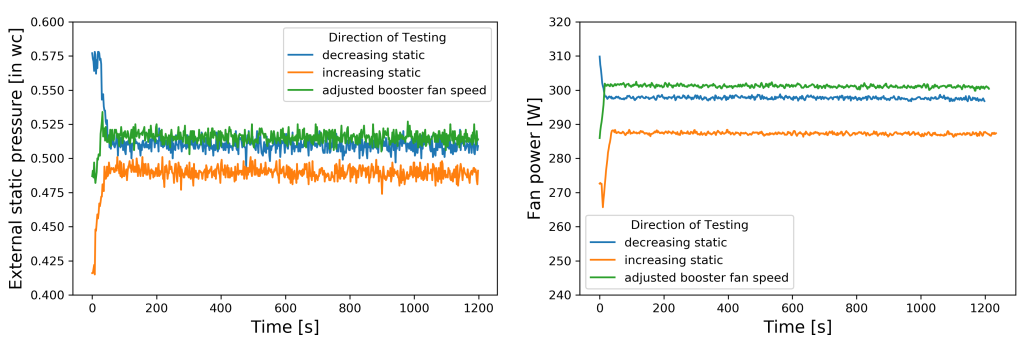
As mentioned before, we noticed that the ESP, power and fan speed does not match properly while testing the unit in increasing and decreasing static pressure direction. Even though all the conditions kept unchanged. Figure 7.9 shows this hysteresis effect for 0.50" wc. Even though we kept all the conditions unchanged while going from high to low static pressure or low to high static pressure, ESP and power does not match completely. There is always some lagging in values at a certain ESP and power.



(a) ESP (b) Power

Figure 7.9: Hysteresis of fan motor

During our test we have noticed that this hysteresis effect can be reduced by ramping up the booster fan speed above the target value (0.50” wc) and then going back to the target value. This hysteresis effect may cause issues if attempt to control static pressure using conventional PID loop on booster fan. This ramping up of the booster fan reduces the hysteresis effect and it gives closer value as like the target value. In Figure 7.10 this reduction if hysteresis is shown after adjusting the code tester booster fan speed.



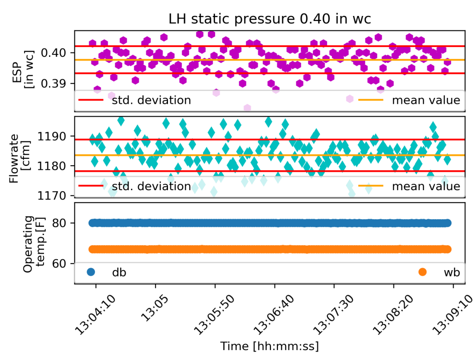
(a) ESP (b) Power

Figure 7.10: Hysteresis of fan motor

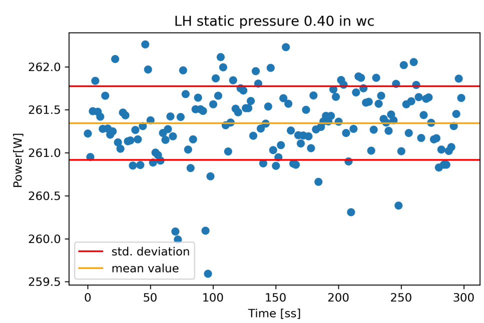
CHAPTER VIII

Results

To compare the results of different cases we needed a reference test and we considered the standard duct length case (Figure 3.3a) with parallel damper orientation (Figure 3.9a) as our base or reference case. Mainly we compared the fan power of all different tests with the reference test. For each test case we also looked the fan hysteresis and operating conditions whether that is within the tolerance limit or not. Figure 8.1 shows some visualization of data for external static pressure of 0.40” wc.



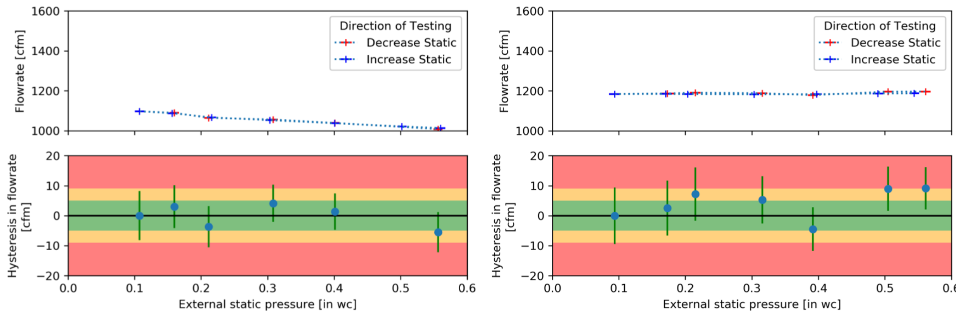
(a) ESP, Flowrate and Operating temperature



(b) Power

Figure 8.1: Data visualization for 0.40” wc (Increasing ESP case)

We compared the results for base case before and after fixing all the leaks including test setup and pressure taps leak. Figure 8.2 shows the result of flowrate before and after the leak test is done. Before leak test the flowrate was going downward with ESP and after fixing the leaks it became flatter.



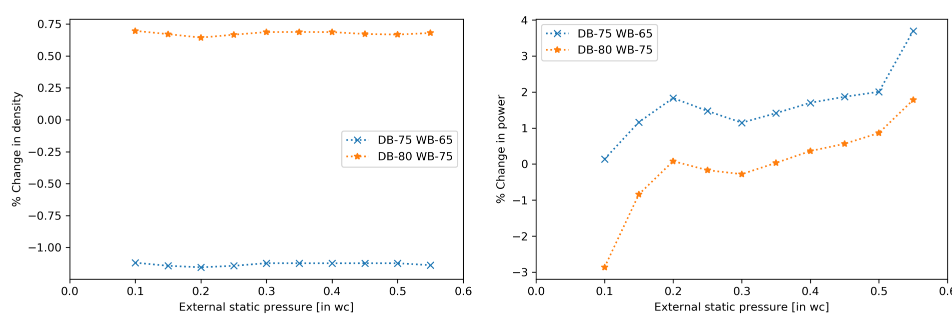
(a) Before fixing leaks (b) After fixing leaks

Figure 8.2: Flowrate

We have done a density sensitivity analysis of the unit. Our standard operating condition is DB-80°F WB-67°F. Other than that we tested the unit for two different operating conditions-

- DB-80°F WB-75°F
- DB-75°F WB-65°F

Figure 8.3 shows the percentage change in density and power for different operating conditions over the base power and operating condition.



(a) Density (b) Power

Figure 8.3: Percent change in density and power over standard test

From the density sensitivity analysis we have noticed that when the dry bulb temperature is fixed and wet bulb temperature is increased to 75°F, the density decreases and it decreases the power. As the density is going down it requires less power for the fan for air flow through the unit. The power also decreases when we reduce both dry and wet bulb temperature and in that case it increases the density. Figure 8.4 shows the percentage change of power over the percentage change of density. For the increased in density the percentage change increases and vice versa.

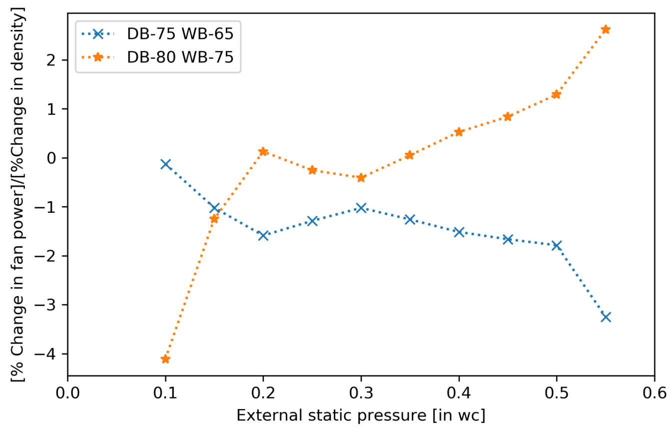


Figure 8.4: Density sensitivity of ECM fan

As mentioned before we have compared our test results for different duct configurations with the standard duct configuration case with damper blade orientation parallel to the fan motor axis. We tested the unit at 1050 cfm and 1350 cfm. Figure 8.6 and 8.7 show the comparison of power for the straight duct cases. The results are shown in terms of unit to floor distance (Figure 8.5) as x axis. The plots also show the result for the side flow cases. Size of the markers indicate the side flow around the test unit which is created using the external box fan. DOE recommends the side flow to be within 500 fpm in case any external fan is used. The black dotted line indicates the 5% limit within the base case. We intend to find the test configuration that gives power within 5% of the base test and we have found quite a few configurations that gives us our desired result. In case of no duct cases we received higher power than the base cases. The reason behind that without the inlet duct the air flow directly hits the fan of the unit and that could create more turbulence near the fan. Another reason could be the pressure measurement.

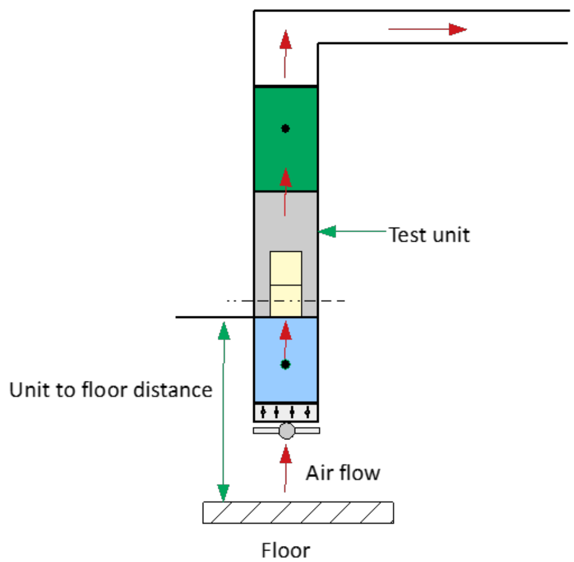
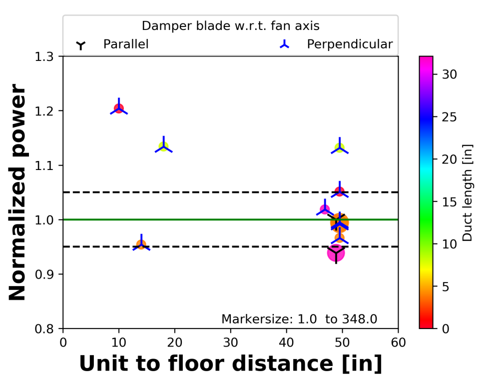
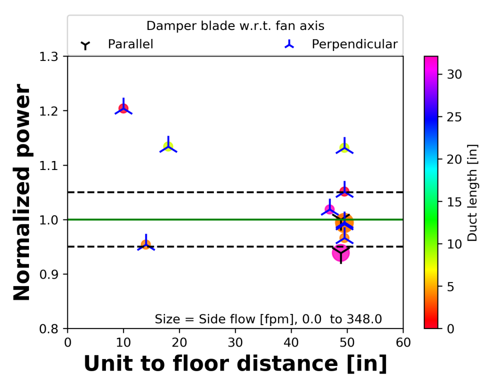


Figure 8.5: Unit to floor distance



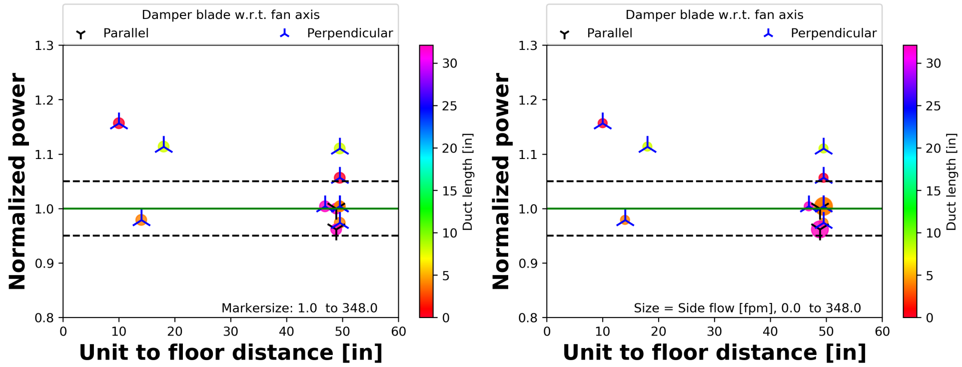
(a) 1050 cfm



(b) 1350 cfm

Figure 8.6: Straight duct power comparison over base case (0.15" wc)

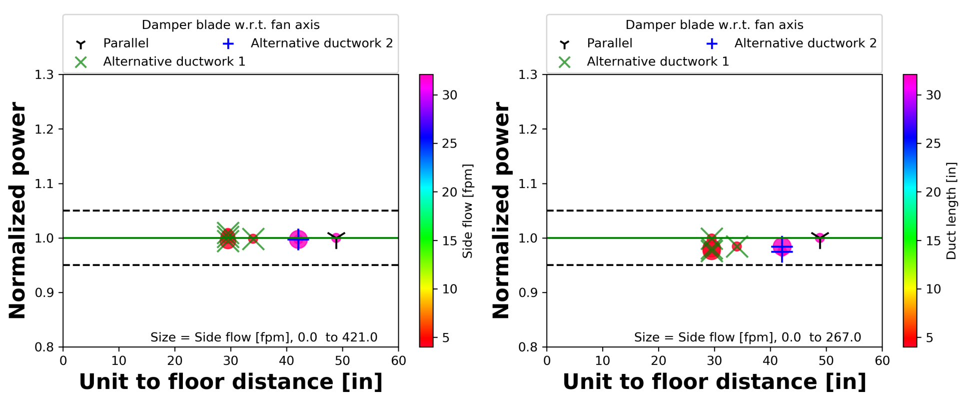
In case of the ducted configurations it is recommended to put pressure taps on the four sides of the duct but in case of no duct case we measured the pressure with respect to the ambient. This could affect the pressure measurement of the system which eventually leads to high power consumption of the fan.



(a) 1050 cfm (b) 1350 cfm

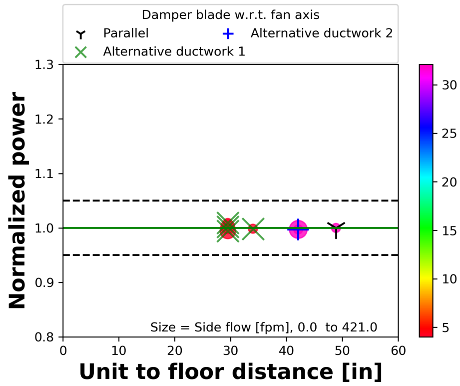
Figure 8.7: Straight duct power comparison over base case (0.50" wc)

After investigating the fan performance of different straight duct, we also investigated the fan performance for alternative ductworks. We tested the alternative ductworks both with and without side flow. Figure 8.8 and 8.9 show the comparison of power for the alternative ductwork cases. We noticed that all the alternative ductwork cases give us power within 5% of the base test. Even with the side flow it gives us power within our desired range. Figure 8.10 to 8.13 show the comparison of flowrate for both straight duct and alternative duct cases. In cases of the flowrate we considered 2.5% of base test result as our limit. This 5% limit for power and 2.5% limit for air flowrate with respect to the base test is adopted from the ASHRAE research project 1581 (Pate et al., 2013).

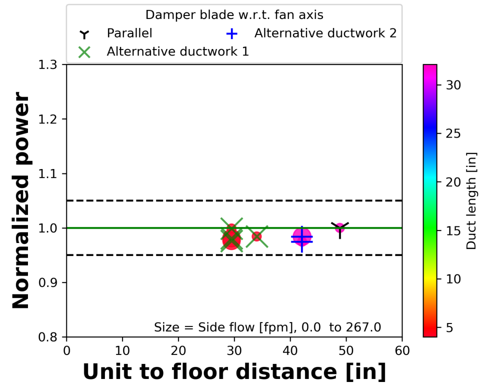


(a) 1050 (b) 1350

Figure 8.8: Alternative ductwork power comparison over base case (0.15" wc)

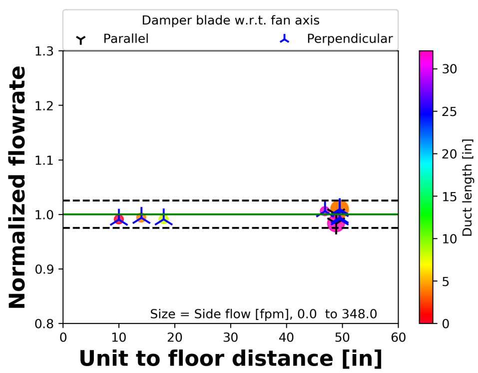


(a) 1050

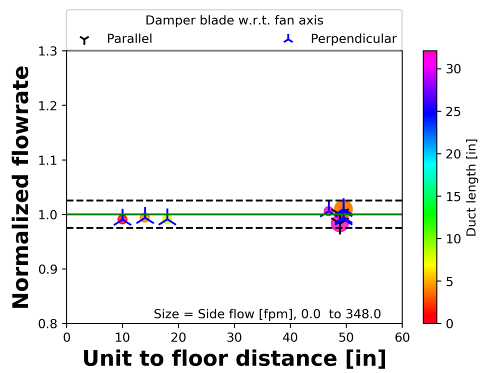


(b) 1350

Figure 8.9: Alternative ductwork power comparison over base case (0.50" wc)

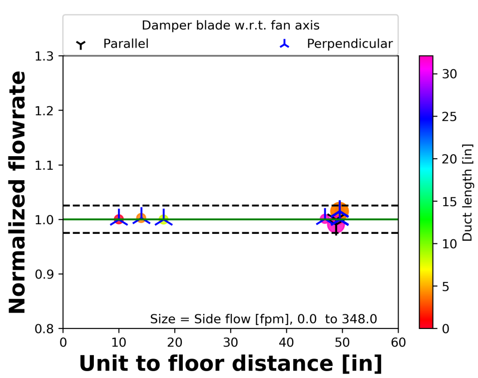


(a) 1050 cfm

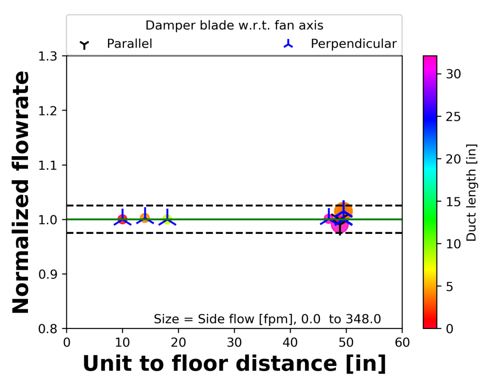


(b) 1350 cfm

Figure 8.10: Straight duct flowrate comparison over base case (0.15" wc)

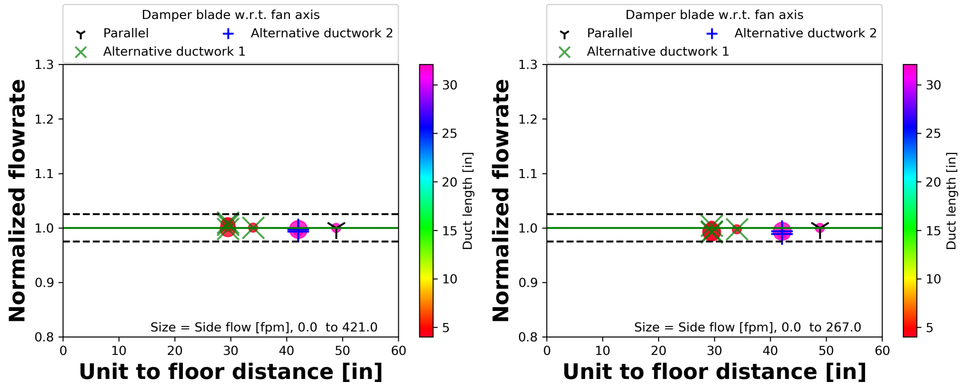


(a) 1050 cfm



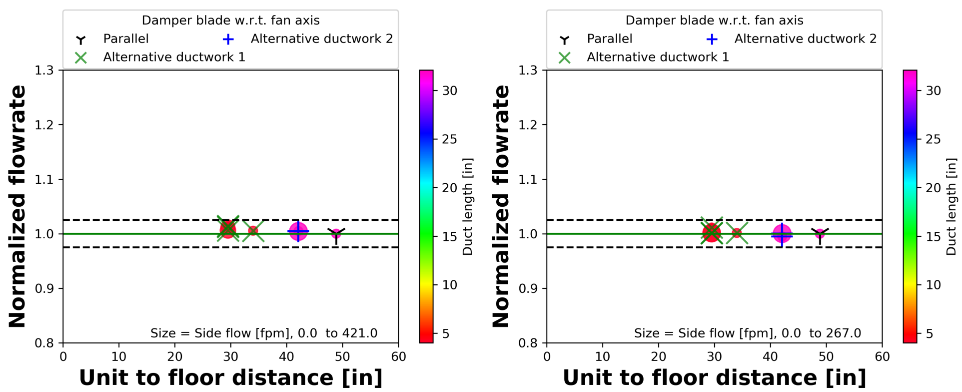
(b) 1350 cfm

Figure 8.11: Straight duct flowrate comparison over base case (0.50" wc)



(a) 1050 cfm (b) 1350 cfm

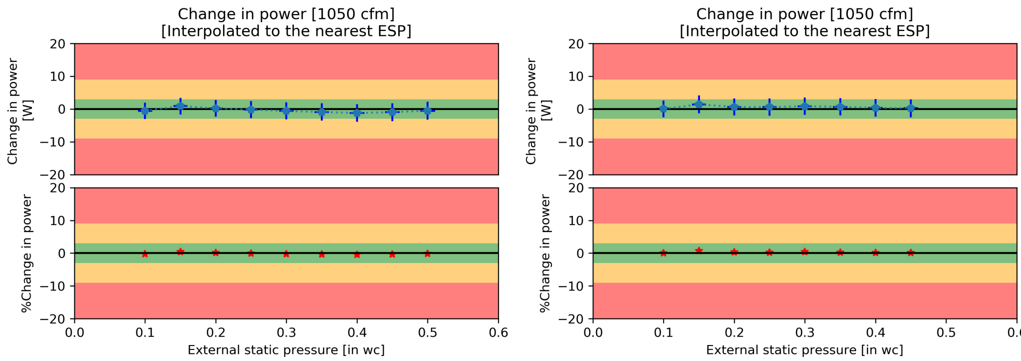
Figure 8.12: Alternative ductwork flowrate comparison over base case (0.15” wc)



(a) 1050 cfm (b) 1350 cfm

Figure 8.13: Alternative ductwork flowrate comparison over base case (0.50” wc)

We have also done some repeated test to investigate the repeatability of our test reults that we did a certain time ago. We repeated two tests. We repeated the test with a 4” duct, perpendicular damper blade orientation with respect to fan axis and air sampler. We repeated the test with and without side flow. We repeated the side flow case where the flow is parallel to fan axis. The without side flow case is repeated after about one and half month of the original test was done. And the side flow case us repeated after one week of the original test. Figure 8.14 shows the results for the repeated test. In both cases we obtained identical results. The difference is less than 0.5% comparing with the original test.



(a) Without side flow

(b) With side flow

Figure 8.14: Repeated test with 4” duct

CHAPTER IX

Conclusion

The goal of this project is to reduce the overall or stack height of the setup by reducing the inlet duct length maintaining the power similar to that if the standard test or with very small difference. Also we have to maintain the reliability of ASHRAE testing standard. We tested an ECM 3 ton blow through unit with different duct lengths and also with some alternative ductworks. As our goal is to reduce the overall height as much as possible, we also tested the unit with minimum floor distance required by the DOE standard for different duct lengths. 5% difference over the base test is considered as our acceptable limit and we noticed that testing the unit without duct is giving us power out of our acceptable range in both smaller and larger floor distance cases. The same also goes for the 8" duct length. The 4" duct case gave us less value than the base test. The only configurations that gave us closer value to the base test was the alternative ductworks. Both of the alternative ductworks gave us power within 2-3% of the base test. Also these configurations are very effective against the side flow. As in both of the scenarios the inlet section of the unit was enclosed, any external flow was less likely to affect the air flow field near the test unit inlet. The flowrates are all within 1% of the base test. The reason behind increased power while reducing the floor to minimum distance could be the turbulence at the inlet of the fan.

We also performed the sensitivity analysis and noticed that increasing the wet bulb temperature while keeping the dry bulb temperature fixed reduces the density as well as power with increasing external static pressure. Also the power decreases while reducing the dry bulb temperature even though the density was increasing.

We also wanted to make sure that our test is repeatable and that is why we did two repeated test. We did one repeated test within one and half month apart and another one after one week. Our tests were repeatable as it gave us power within less that 0.5% of the base test.

The goal of this theses work is to reduce the overall height of the setup by reducing the inlet duct length and at the same time maintain the ASHRAE standard reliability. After investigating the fan performance of the 3 ton ECM push through fan coil unit, I think using the alternative ductwork 1 full fill all the criteria. This configuration reduces the overall height of the setup as well as gives most closest fan performance as like the base or standard case. Another reason behind my recommendation is that this configuration could be also very effective against side flow and can reduce the side flow effect at the vicinity of the test unit. For reducing the side flow effect alternative ductwork 2 would be also a good candidate but in terms of smaller overall height I would not recommend that configuration. For standard duct case the unit to floor distance was 48.86" for the alternative dctwork 1 it was 29.5". Thus we were able to reduce the distance between the test unit inlet to floor by about 39.6%.
For side flow it is necessary to quantify the distance within which the velocity should be within 500 fpm. Other wise the side flow around the chamber may affect the fan performance of the unit by distorting the flow profile across the duct.
Another recommendation would be using at least an inlet duct rather that using no duct with the test unit. The least could a 4" skirt like duct and then damper, air sampler. In case of without duct there is a possibility of higher turbulence at the inlet near the fan. That could lead increased vibration and noise in the system. As a result it could lead wrong performance of the system.

CHAPTER X

Future Work and Recommendations

10.1 Future Work

We have tested the 3 ton ECM blow through fan coil unit. Our future plan includes testing draw through unit and of different fan and motor type. We will also test an air handling unit. The draw through units should be tested for different duct lengths and also for the alternative ductworks cases. Fan performance of the unit will be also investigated for minimum floor distance required by DOE. By analyzing the results from the draw through unit, may be we will be able to finalize our test configurations that will reduce the overall height of the setup.

10.2 Recommendations

10.2.1 Leakage Test

During the testing of air side of an air conditioning system air leakage adversely affects the fan performance of the unit. Though we reduced our air leakage f the system and also the leakage from the pressure measurement taps, we achieved the 1% air leakage rate as per the PMS members suggestion and also according to the ASHRAE 37 standard. The current updated ASHRAE 41.2-2018 (ANSI/ASHRAE-41.2, 2018) standard requires the air leakage rate be within 0.25%. So, in future it may be useful to reduce the leakage rate and that may be give more reliable fan performance. Also it would be a good idea to do the leakage test after switching each unit to make sure that the all the connections of test unit is leak tight.

10.2.2 Installing Additional Pressure Tap

The pressure tap leak was also a major issue during this type of air side testing. So, one recommendation would be doing the pressure tap leak testing after some interval of time and testing, so that we don't have to remove the unit and then find out there is some discrepancy in the test result due to pressure tap leaks. Also it could be a good idea to install an extra pressure tap at one side of the inlet duct. In case of any air leakage there will be different value in pressure measurement between the actual pressure tap and the extra installed pressure tap.

10.2.3 Pressure Tap Position

Another recommendation should be about the position of the pressure tap leaks on the inlet side of the duct. Though the ASHRAE 37 provides the guideline for making pressure taps and the position of it, it is in terms of the standard duct and also it is given in terms of the inlet cross sectional area of the test unit. But in case of reduced duct length there should be new guideline about pressure tap making and its position. During our testing except the standard duct length we positioned the pressure tap at the center of the each side of the duct.

10.2.4 Fixing Flexible Duct

During this test one thing we noticed that in case of the 1050 cfm flowrate the ESP was more stable than the 1350 cfm case. Here stable means fluctuation of the pressure. Though the pressure was within the tolerance limit of the ASHRAE 37 standard, it fluctuates more in case of 1350 cfm case than the 1050 cfm case. This could be an issue associated with the vibration of flexible duct that we used to connect the test setup with the code tester. Also at the elevated flowrate the test test unit and the associated structures vibrates more. That could have also affected the measurement of the static pressure and thus affects the fan performance or power.

10.2.5 Investigation of Velocity Profile Across Duct

During this testing we did some air velocity profile across the inlet duct and we saw that the air velocity profile was not fully developed near the fan of the unit and also the side flow around the unit distorts the profile. As a result the fan does not receive uniform velocity profile and which could be affect the fan performance. In future it may be a good idea to look the development of velocity profile across the ducting system used to test air handling unit and also how to improve the uniformity of the profile. One idea could be installing a horizontal elbow type duct instead of vertical duct and using a guide vane or air straightener for the stratification of the air. That may also help in reducing the height of the test setup.

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APPENDIX A

Test setup

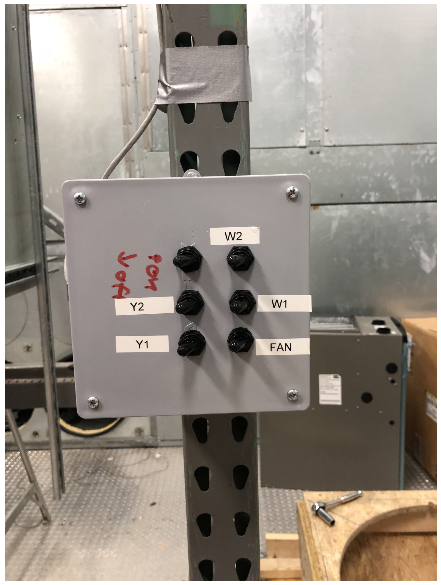

Figure A.1: Test unit control switch

Figure A.2: Aplus meter for power measurement

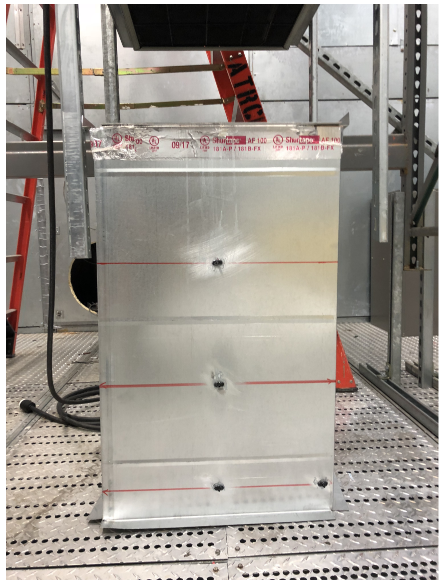

Figure A.3: standard inlet duct

Figure A.4: Experimental test setup

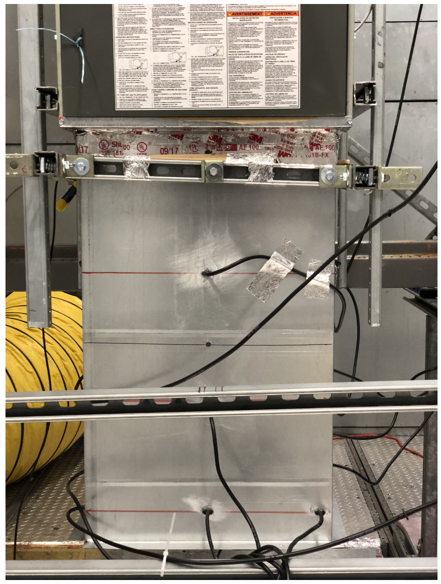
Figure A.5: Pressure tap connections


Figure A.6: Anemometer for velocity measurement

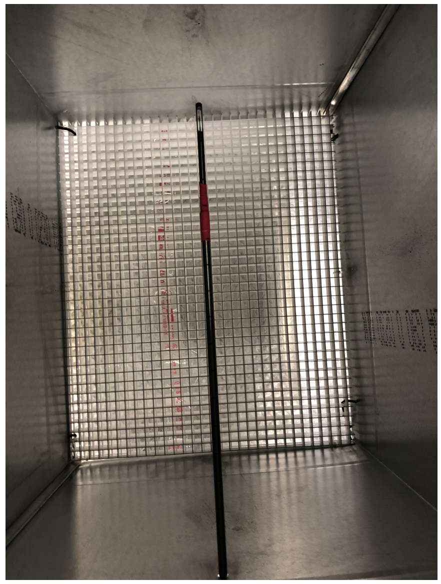

Figure A.7: Duct with air straightener

Figure A.8: Test setup with front air straightener

Figure A.9: Test setup without duct

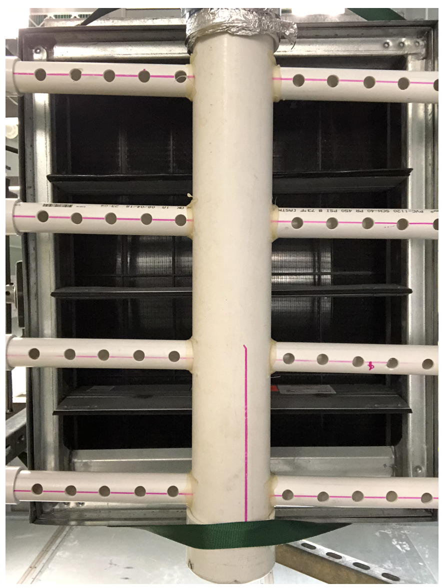

Figure A.10: Bottom side view of test setup without duct

Figure A.11: Reduced floor distance with cardboard (no duct case)

Figure A.12: Test unit with 8” duct

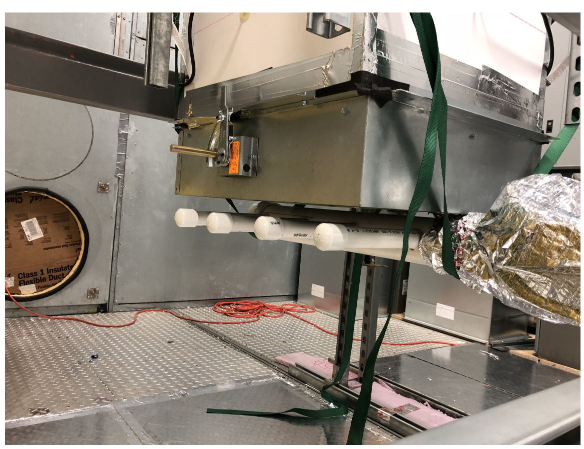

Figure A.13: Damper and air sampler orientation for 8” duct case

Figure A.14: Indoor psychrometric chamber nozzle sets

Figure A.15: Setra differential pressure transducer (unit side)

Figure A.16: Test setup for leak testing (code tester side)

Figure A.17: Coil section of test unit

Figure A.18: Furnace section of test unit

Figure A.19: Leak testing setup (unit side)

Figure A.20: Sealing of code tester section

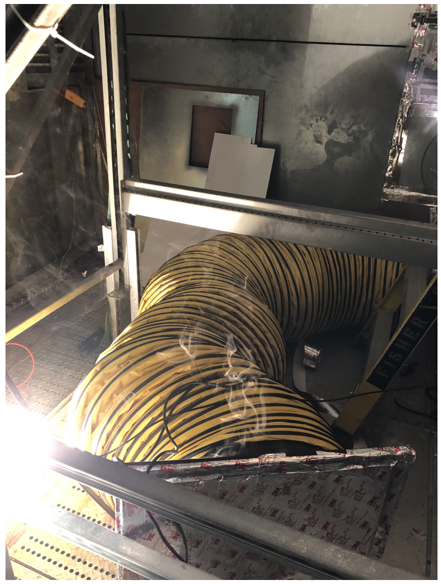

Figure A.21: Leak testing of flexible duct

Figure A.22: Reduced floor distance with cardboard (standard duct case)

Figure A.23: Side flow for alternative ductwork 2

Figure A.24: Air sampler position for alternative ductwork 2

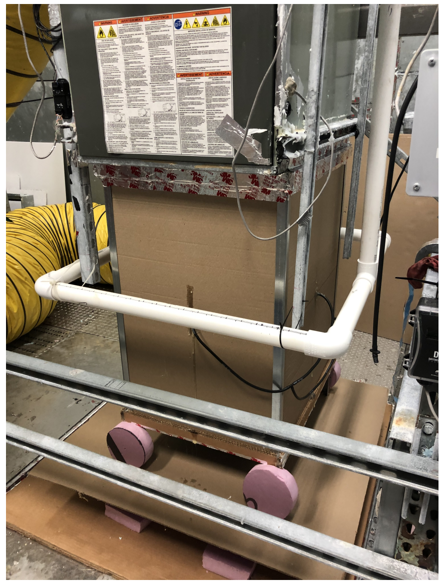

Figure A.25: Alternative ductwork 2

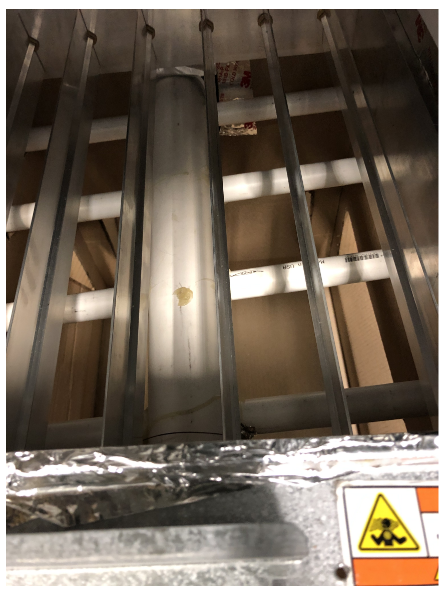

Figure A.26: Damper and air sampler orientation (alternative ductwork 1)

Figure A.27: Side flow measurement (alternative ductwork 1)

Figure A.28: Alternative ductwork 1

Figure A.29: Side flow for 4” duct case

APPENDIX B

Average Experimental Data- 1050 cfm

This section provides interpolated data that is obtained by averaging the interpolated power and flowrate values for the increasing and decreasing pressure at several fixed static pressures. The data is intended for the estimation of fan power for building simulation. Table B.1 shows the external static pressure at which the static pressures are interpolated to calculate the average values.

Table B.1: ESP at which the average values are calculated by interpolation

ESP [in wc]
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
0.55

2.1 Average Data for Standard Case With Parallel Blade Damper

Table B.2: Before fixing air leakage

ESP [in wc]	Flowrate [cfm]	u(Flowrate) [cfm]	Power [W]	u(Power) [W]
0.1	1097.74	5.81	180.74	1.84
0.15	1090.36	5.19	192.64	1.85
0.2	1071.64	4.9	201.99	1.81
0.25	1061.69	4.67	214.59	1.82
0.3	1055.52	4.44	228.63	1.85
0.35	1047.36	4.33	242.25	1.87
0.4	1038.78	4.26	255.75	1.89
0.45	1029.93	4.29	269.05	1.92
0.5	1021.07	4.31	282.34	1.94
0.55	1012.59	4.66	295.64	1.97

Table B.3: After fixing test setup air leakage

ESP [in wc]	Flowrate [cfm]	u(Flowrate) [cfm]	Power [W]	u(Power) [W]
0.1	1191.05	6.53	191.34	1.91
0.15	1193.47	6.2	204.71	1.9
0.2	1194.03	6.57	216.79	1.97
0.25	1194.72	6.4	228.94	1.97
0.3	1195.92	6.06	241.36	1.95
0.35	1197.93	5.58	254.99	1.97
0.4	1199.91	5.4	268.75	2
0.45	1202.54	5.44	282.79	2.03
0.5	1205.13	5.46	296.87	2.05
0.55	1206.35	5.4	310.86	2.08

Table B.4: After fixing test setup and pressure tap air leakage

ESP [in wc]	Flowrate [cfm]	u(Flowrate) [cfm]	Power [W]	u(Power) [W]
0.1	1184.54	6.66	188.65	1.91
0.15	1185.52	6.53	200.92	2.01
0.2	1186.84	6.38	212.65	2
0.25	1186.71	6.02	224.88	1.93
0.3	1185.69	5.64	237.12	1.88
0.35	1183.55	5.36	249.01	1.89
0.4	1181.89	5.14	261.14	1.9
0.45	1186.67	5.17	276.39	1.93
0.5	1191.28	5.21	291.54	1.95
0.55	1191.98	5.03	304.41	1.97

2.2 Average Data With Perpendicular Blade Damper With Air Leakage Fixed

Table B.5: Standard case

ESP [in wc]	Flowrate [cfm]	u(Flowrate) [cfm]	Power [W]	u(Power) [W]
0.1	1196.77	6.7	196.48	1.79
0.15	1191.62	6.47	204.34	1.84
0.2	1185.83	6.19	213.85	1.89
0.25	1185.5	5.9	225.86	1.88
0.3	1185.68	5.61	238.14	1.86
0.35	1182.51	5.38	249.54	1.87
0.4	1181.52	5.18	262.01	1.89
0.45	1186.98	5.11	277.32	1.91
0.5	1192.31	4.97	292.72	1.94
0.55	1194.27	4.96	305.75	1.96

Table B.6: 0" duct with 45.5" floor distance

ESP [in wc]	Flowrate [cfm]	u(Flowrate) [cfm]	Power [W]	u(Power) [W]
0.1	1198.16	6.48	200.93	1.85
0.15	1193.48	6.13	211.23	1.87
0.2	1198.6	5.54	225.71	1.86
0.25	1200.73	5.43	239.1	1.87
0.3	1202.07	5.39	252.22	1.88
0.35	1204.08	5.32	266.08	1.91
0.4	1206.09	5.21	280.07	1.94
0.45	1207.34	5.22	294.04	1.97
0.5	1208.49	5.26	308	2
0.55	1209.33	5.21	321.6	2.03

Table B.7: 0" duct with 6" floor distance

ESP [in wc]	Flowrate [cfm]	u(Flowrate) [cfm]	Power [W]	u(Power) [W]
0.1	1172.15	7.82	232.54	2.93
0.15	1174.5	8.81	241.89	3.03
0.2	1177.76	8.62	255.15	3.37
0.25	1180.48	7.52	268.19	2.88
0.3	1183.21	6.42	281.23	2.38
0.35	1184.7	5.81	294.26	2.15
0.4	1186.07	5.35	307.52	2.02
0.45	1188.46	5.2	322.21	2.04
0.5	1191.33	5.03	337.23	2.06
0.55	1194.25	4.88	350.59	2.1

Table B.8: 8" duct with 37.5" floor distance

ESP [in wc]	Flowrate [cfm]	u(Flowrate) [cfm]	Power [W]	u(Power) [W]
0.1	1175.03	6.48	217.8	1.94
0.15	1174.98	6.51	227.38	1.94
0.2	1180.26	6.52	241.64	1.96
0.25	1184.66	6.3	255.9	1.97
0.3	1189.05	6.07	270.16	1.97
0.35	1190.15	5.88	283.56	1.98
0.4	1190.12	5.68	296.61	1.99
0.45	1189.97	5.32	309.88	2.01
0.5	1190.6	5.05	323.7	2.04
0.55	1192.39	5.21	336.63	2.09

Table B.9: 8" duct with 6" floor distance

ESP [in wc]	Flowrate [cfm]	u(Flowrate) [cfm]	Power [W]	u(Power) [W]
0.1	1173.94	6.52	221.57	2.05
0.15	1174.8	6.58	227.86	2.07
0.2	1175.96	6.4	240.52	2.11
0.25	1178.34	6.09	254.03	2.11
0.3	1180.74	5.84	267.58	2.1
0.35	1183.61	5.49	281.56	2.1
0.4	1186.74	5.09	295.76	2.11
0.45	1189.04	4.89	310.2	2.12
0.5	1190.88	4.8	324.7	2.15
0.55	1193.14	5.14	339.1	2.19

Table B.10: 4" duct with 41.5" floor distance

ESP [in wc]	Flowrate [cfm]	u(Flowrate) [cfm]	Power [W]	u(Power) [W]
0.1	1183.3	6.07	190.11	1.81
0.15	1178.87	6.23	194.13	2.04
0.2	1180.18	5.79	206.39	1.82
0.25	1182.19	5.75	219.35	1.84
0.3	1184.12	5.73	232.32	1.86
0.35	1185.9	5.43	245.44	1.88
0.4	1187.69	5.16	258.6	1.91
0.45	1189.85	5.12	272.35	1.93
0.5	1191.8	5.12	283.91	1.94
0.55	1192.21	5.07	290.81	1.96

Table B.11: 4" duct with 41.5" floor distance and front side flow

ESP [in wc]	Flowrate [cfm]	u(Flowrate) [cfm]	Power [W]	u(Power) [W]
0.1	1198.4	6.02	192.82	1.77
0.15	1196.79	5.81	199.87	1.79
0.2	1196.31	5.59	211.8	1.81
0.25	1198.61	5.53	224.95	1.83
0.3	1200.74	5.45	238.12	1.85
0.35	1201.82	5.47	251.34	1.87
0.4	1202.97	5.53	264.64	1.9
0.45	1205.82	5.59	278.67	1.92
0.5	1208.64	5.63	292.73	1.95
0.55	1211.03	5.44	306.16	1.97

Table B.12: 4” duct with 41.5” floor distance and right side flow

ESP [in wc]	Flowrate [cfm]	u(Flowrate) [cfm]	Power [W]	u(Power) [W]
0.1	1199.17	6.3	192.89	1.77
0.15	1197.01	6.12	199.18	1.79
0.2	1196.18	5.72	211.08	1.81
0.25	1198.62	5.43	224.44	1.83
0.3	1201.02	5.26	237.81	1.85
0.35	1202.91	5.38	251.24	1.88
0.4	1204.58	5.44	264.67	1.91
0.45	1206.83	5.54	278.51	1.93
0.5	1209.59	5.49	292.72	1.96
0.55	1211.96	5.28	301.65	1.97

Table B.13: Alternative ductwork 1 with 26” rectangular box height

ESP [in wc]	Flowrate [cfm]	u(Flowrate) [cfm]	Power [W]	u(Power) [W]
0.1	1188.83	6.88	190.34	1.84
0.15	1186.1	6.18	198.6	1.82
0.2	1186.46	6	210.17	1.82
0.25	1188.11	5.97	223.05	1.84
0.3	1189.69	5.89	236.03	1.86
0.35	1191.12	5.71	249.19	1.88
0.4	1192.71	5.56	262.45	1.9
0.45	1194.86	5.54	276.49	1.93
0.5	1197.79	5.49	291.1	1.95
0.55	1205.36	6.04	307.92	1.98

Table B.14: Alternative ductwork 1 with 21” rectangular box height

ESP [in wc]	Flowrate [cfm]	u(Flowrate) [cfm]	Power [W]	u(Power) [W]
0.1	1199.11	7	193.88	1.81
0.15	1197.24	6.6	200.82	1.87
0.2	1197.34	6.27	213.05	1.84
0.25	1198.11	6.19	225.8	1.85
0.3	1199.38	6.06	238.87	1.87
0.35	1201.24	5.74	252.19	1.89
0.4	1203.8	5.5	265.98	1.91
0.45	1206.89	5.51	280.39	1.93
0.5	1208.02	5.23	294.2	1.96
0.55	1209.86	5.32	300.69	1.97

Table B.15: Alternative ductwork 1 with 21” rectangular box height and front side flow

ESP [in wc]	Flowrate [cfm]	u(Flowrate) [cfm]	Power [W]	u(Power) [W]
0.1	1188.66	6.12	187.48	1.79
0.15	1183.41	6.61	195.64	1.79
0.2	1185	6.32	208.6	1.8
0.25	1186.74	5.97	221.42	1.82
0.3	1188.39	5.65	234.32	1.85
0.35	1190.85	5.68	248.01	1.87
0.4	1193.44	5.73	261.81	1.89
0.45	1196.1	5.63	275.9	1.92
0.5	1198.47	5.49	289.93	1.94
0.55	1199.4	5.62	300.11	1.97

Table B.16: Alternative ductwork 1 with 21” rectangular box height and right side flow

ESP [in wc]	Flowrate [cfm]	u(Flowrate) [cfm]	Power [W]	u(Power) [W]
0.1	1197.89	6.55	192.76	1.81
0.15	1192.71	6.48	198.43	1.82
0.2	1194.47	6.29	211.21	1.84
0.25	1196.46	6.11	224.41	1.85
0.3	1198.01	5.98	237.61	1.88
0.35	1199.73	5.81	250.96	1.91
0.4	1201.73	5.52	264.45	1.93
0.45	1204.09	5.27	278.31	1.95
0.5	1206.23	5.22	292.18	1.97
0.55	1208.06	5.51	305.17	1.99

Table B.17: Alternative ductwork 2

ESP [in wc]	Flowrate [cfm]	u(Flowrate) [cfm]	Power [W]	u(Power) [W]
0.1	1179.68	6.08	183.39	1.77
0.15	1177.82	6.06	194.7	1.79
0.2	1177.5	5.8	206.78	1.8
0.25	1179.67	5.55	219.76	1.82
0.3	1181.86	5.34	232.82	1.84
0.35	1183.96	5.26	246.36	1.86
0.4	1186.33	5.23	260.14	1.89
0.45	1191.55	5.24	275.39	1.91
0.5	1196.99	5.22	290.74	1.94
0.55	1193.59	5.26	301.61	1.97

Table B.18: Alternative ductwork 2 with side flow

ESP [in wc]	Flowrate [cfm]	u(Flowrate) [cfm]	Power [W]	u(Power) [W]
0.1	1186.39	6.11	186.57	1.82
0.15	1182.16	6.21	196.74	1.8
0.2	1183.54	5.55	208.81	1.8
0.25	1185.19	5.25	222.04	1.82
0.3	1187.51	5.33	235.51	1.84
0.35	1189.59	5.38	248.93	1.87
0.4	1191.59	5.32	262.41	1.9
0.45	1193.72	5.07	276.39	1.92
0.5	1196.2	5.13	290.74	1.94
0.55	1199.49	5.53	302.07	1.96

2.3 Actual Test Data

This section provides average data that is obtained by time averaging the power and flowrate values for the increasing and decreasing static pressure at several fixed static pressures.

2.3.1 Actual Test Data for Standard Case With Parallel Damper Blade

Table B.19: Before fixing air leakage- decreasing ESP

	ESP[in wc]	Flowrate[cfm]	DB[F]	WB[F]	DeltaPnozzle[in wc]	Barometer[in wc]	Voltage[V]	Power[W]	Current[A]	Density[lb/ft3]
0	0.11	1097.74	80.03	67.02	0.64	394.15	120.07	180.74	2.09	0.0699
1	0.16	1089.9	79.99	66.99	0.63	394.17	120.08	195.63	2.27	0.06992
2	0.21	1065.04	79.99	66.94	0.6	394.19	119.99	203.13	2.36	0.06992
3	0.31	1056.55	79.99	67.16	0.6	394.05	120.02	232.07	2.72	0.06988
4	0.4	1039.21	79.93	67.14	0.58	394.05	120.11	256.9	3.03	0.06989
5	0.56	1008.77	79.86	67.09	0.54	394.04	119.9	296.47	3.55	0.0699

Table B.20: Before fixing air leakage- increasing ESP

	ESP[in wc]	Flowrate[cfm]	DB[F]	WB[F]	DeltaPnozzle[in wc]	Barometer[in wc]	Voltage[V]	Power[W]	Current[A]	Density[lb/ft3]
0	0.11	1097.74	80.03	67.02	0.64	394.15	120.07	180.74	2.09	0.0699
1	0.16	1088.04	80.01	67.09	0.63	394.15	120.08	194.27	2.25	0.0699
2	0.22	1067.16	79.99	67.11	0.61	394.14	120	205.52	2.39	0.0699
3	0.3	1053.17	79.98	67.13	0.59	394.16	120.06	228.65	2.67	0.0699
4	0.4	1037.99	80	67.16	0.57	394.17	119.91	255.17	3	0.0699
5	0.5	1021.97	80.01	67.19	0.56	394.2	120.04	283.17	3.36	0.0699
6	0.56	1013.73	80.02	67.21	0.55	394.22	120.05	299.24	3.56	0.0699

Table B.21: After fixing test setup air leakage- decreasing ESP

	ESP[in wc]	Flowrate[cfm]	DB[F]	WB[F]	DeltaPnozzle[in wc]	Barometer[in wc]	Voltage[V]	Power[W]	Current[A]	Density[lb/ft3]
0	0.09	1190.37	80	67.16	0.75	391.56	119.74	187.62	2.17	0.06943
1	0.17	1197.55	80	67.17	0.76	391.56	119.75	212.14	2.46	0.06942
2	0.21	1195.32	80	67.17	0.76	391.56	119.72	219.16	2.55	0.06942
3	0.32	1201.01	79.98	67.15	0.76	391.57	119.75	247.88	2.91	0.06943
4	0.38	1201.59	79.98	67.14	0.76	391.62	119.62	264.44	3.12	0.06944
5	0.51	1209.37	80.01	67.13	0.77	391.66	119.68	301.17	3.6	0.06944
6	0.56	1209.91	80.05	67.12	0.78	391.81	119.71	315.96	3.79	0.06947

Table B.22: After fixing test setup air leakage- decreasing ESP

	ESP[in wc]	Flowrate[cfm]	DB[F]	WB[F]	DeltaPnozzle[in wc]	Barometer[in wc]	Voltage[V]	Power[W]	Current[A]	Density[lb/ft3]
0	0.09	1190.37	80	67.16	0.75	391.56	119.74	187.62	2.17	0.06943
1	0.17	1191.63	80.01	67.16	0.75	391.56	119.75	207.98	2.41	0.06942
2	0.2	1192.18	80	67.15	0.75	391.53	119.75	216.59	2.52	0.06942
3	0.3	1191.77	79.99	67.14	0.75	391.51	119.69	240.06	2.81	0.06942
4	0.37	1195.76	80	67.13	0.76	391.47	119.69	259.55	3.05	0.06941
5	0.49	1201.26	80	67.12	0.76	391.47	119.63	293.41	3.49	0.06941
6	0.55	1203	79.99	67.12	0.77	391.44	119.66	310.28	3.72	0.06941

Table B.23: After fixing test setup and pressure taps air leakage- decreasing ESP

	ESP[in wc]	Flowrate[cfm]	DB[F]	WB[F]	DeltaPnozzle[in wc]	Barometer[in wc]	Voltage[V]	Power[W]	Current[A]	Density[lb/ft3]
0	0.09	1184.41	79.81	66.98	0.74	393.18	119.88	187.09	2.17	0.06975
1	0.17	1187.19	80	67.32	0.75	393.21	119.94	206.78	2.38	0.06971
2	0.22	1191	79.99	67.27	0.75	393.17	119.85	217.55	2.51	0.06971
3	0.32	1188.14	79.87	67.12	0.75	393.16	119.93	242.3	2.8	0.06973
4	0.39	1178.95	79.88	67.09	0.74	393.14	119.88	257.55	2.99	0.06973
5	0.5	1196.15	80.03	67.09	0.76	393.11	119.91	294.83	3.46	0.06971
6	0.56	1196.57	80.1	67.04	0.76	393.11	119.89	310.72	3.73	0.06971

Table B.24: After fixing test setup and pressure taps air leakage- decreasing ESP

	ESP[in wc]	Flowrate[cfm]	DB[F]	WB[F]	DeltaPnozzle[in wc]	Barometer[in wc]	Voltage[V]	Power[W]	Current[A]	Density[lb/ft3]
0	0.09	1184.41	79.81	66.98	0.74	393.18	119.88	187.09	2.17	0.06975
1	0.17	1184.74	80.01	67.13	0.75	393.1	119.91	205.77	2.39	0.06971
2	0.2	1183.97	80.09	67.23	0.74	393.1	119.82	212.35	2.47	0.06969
3	0.3	1182.76	80.1	67.29	0.74	393.09	119.89	236.67	2.78	0.06968
4	0.4	1183.49	79.94	67.04	0.74	393.12	119.85	261.34	3.09	0.06972
5	0.49	1187.06	79.91	67.1	0.75	393.14	119.88	287.1	3.42	0.06973
6	0.54	1187.46	79.97	67.16	0.75	393.13	119.83	301.33	3.61	0.06971

2.3.2 Cases With Perpendicular Damper With All Air Leakages Fixed (Test Setup+ Pressure Taps)

2.3.2.1 Standard Duct

Table B.25: Decreasing ESP

	ESP[in wc]	Flowrate[cfm]	DB[F]	WB[F]	DeltaPnozzle[in wc]	Barometer[in wc]	Voltage[V]	Power[W]	Current[A]	Speed[rpm]	Density[lb/ft3]
0	0.11	1196.77	80.07	66.94	0.76	393.67	119.89	196.48	2.26	789.52	0.06982
1	0.14	1195.33	79.93	66.85	0.76	393.66	119.99	204.59	2.36	809.73	0.06984
2	0.21	1188.62	79.98	67.24	0.75	393.66	119.78	216.84	2.51	838.09	0.0698
3	0.31	1190.75	79.89	67.17	0.75	393.67	119.86	243.18	2.83	892.28	0.06982
4	0.38	1177.01	79.93	67.17	0.74	393.71	119.86	255.35	3	923.91	0.06982
5	0.5	1197.17	80.12	67.2	0.76	393.68	119.81	295.33	3.52	991.84	0.06979
6	0.56	1200.04	80.18	67.18	0.77	393.71	119.84	312.27	3.74	1021.94	0.06979

Table B.26: Increasing ESP

	ESP[in wc]	Flowrate[cfm]	DB[F]	WB[F]	DeltaPnozzle[in wc]	Barometer[in wc]	Voltage[V]	Power[W]	Current[A]	Speed[rpm]	Density[lb/ft3]
0	0.11	1196.77	80.07	66.94	0.76	393.67	119.89	196.48	2.26	789.52	0.06982
1	0.2	1182.45	79.99	66.96	0.74	393.66	119.87	211.43	2.44	829.73	0.06982
2	0.29	1180.77	79.97	66.99	0.74	393.65	119.83	234.66	2.73	879.1	0.06982
3	0.39	1182.45	79.98	67.01	0.74	393.64	119.81	259.84	3.04	931.08	0.06982
4	0.48	1186.87	79.99	67.03	0.75	393.64	119.85	284.99	3.36	979.02	0.06982
5	0.54	1188.96	80.02	67.05	0.75	393.63	119.81	302.03	3.59	1010.14	0.06981

2.3.2.2 0" Duct

Table B.27: Decreasing ESP- Floor distance 6"

	ESP[in wc]	Flowrate[cfm]	DB[F]	WB[F]	DeltaPnozzle[in wc]	Barometer[in wc]	Voltage[V]	Power[W]	Current[A]	Speed[rpm]	Density[lb/ft3]
0	0.11	1172.15	80.04	67.1	0.73	393.4	120.04	232.54	2.71	873.63	0.06976
1	0.15	1174.03	80.04	67.03	0.73	393.37	120.06	242.73	2.84	895.03	0.06976
2	0.19	1176.15	80.06	66.97	0.74	393.35	120.09	252.56	2.96	914.21	0.06976
3	0.31	1186.69	79.98	67.24	0.75	393.23	120.07	284.46	3.37	973.53	0.06972
4	0.4	1189.71	79.99	67.17	0.75	393.26	120.02	310.82	3.71	1022.09	0.06973
5	0.55	1198.2	80.09	66.99	0.76	393.19	119.96	354.92	4.3	1095.48	0.06973

Table B.28: Increasing ESP- Floor distance 6"

	ESP[in wc]	Flowrate[cfm]	DB[F]	WB[F]	DeltaPnozzle[in wc]	Barometer[in wc]	Voltage[V]	Power[W]	Current[A]	Speed[rpm]	Density[lb/ft3]
0	0.11	1172.15	80.04	67.1	0.73	393.4	120.04	232.54	2.71	873.63	0.06976
1	0.16	1175.67	80	67.13	0.74	393.4	120.03	243.71	2.85	895.47	0.06976
2	0.2	1178.54	80.06	67.19	0.74	393.4	119.92	254.4	2.98	917.18	0.06975
3	0.39	1182.12	80.03	67.22	0.74	393.45	119.97	302.22	3.6	1011.07	0.06976
4	0.48	1185.71	79.95	67.19	0.75	393.34	119.99	328.06	3.94	1055.32	0.06975
5	0.54	1190.33	80.02	67.21	0.75	393.25	119.9	346.43	4.2	1085.08	0.06973

Table B.29: Decreasing ESP- Floor distance 45.5"

	ESP[in wc]	Flowrate[cfm]	DB[F]	WB[F]	DeltaPnozzle[in wc]	Barometer[in wc]	Voltage[V]	Power[W]	Current[A]	Speed[rpm]	Density[lb/ft3]
0	0.09	1199.71	79.59	66.99	0.77	393.69	119.78	198.17	2.28	794.6	0.06987
1	0.15	1190.57	80.01	66.9	0.76	393.75	119.88	208.89	2.41	823.54	0.06984
2	0.21	1205.82	80.25	67.07	0.77	393.77	119.81	230.61	2.67	865.92	0.06981
3	0.31	1208.04	80.16	67.09	0.78	393.76	119.8	258.36	3.02	923.72	0.06981
4	0.41	1211.24	79.99	66.97	0.78	393.74	119.78	285.57	3.37	974.91	0.06984
5	0.53	1213.09	79.93	67.24	0.79	393.81	119.79	318.29	3.79	1032.94	0.06983
6	0.58	1215.27	79.86	67.13	0.79	393.83	119.75	332.17	3.97	1056.84	0.06985

Table B.30: Increasing ESP- Floor distance 45.5"

	ESP[in wc]	Flowrate[cfm]	DB[F]	WB[F]	DeltaPnozzle[in wc]	Barometer[in wc]	Voltage[V]	Power[W]	Current[A]	Speed[rpm]	Density[lb/ft3]
0	0.09	1199.71	79.59	66.99	0.77	393.69	119.78	198.17	2.28	794.6	0.06987
1	0.19	1192.83	79.93	67.11	0.76	393.66	119.82	219.72	2.54	847.54	0.06982
2	0.29	1196.07	79.9	67.08	0.76	393.65	119.84	247.88	2.88	907.95	0.06982
3	0.39	1201.06	79.81	67.13	0.77	393.62	119.82	275.41	3.23	960.97	0.06982
4	0.51	1204.72	79.84	67.17	0.77	393.61	119.79	309.27	3.67	1022.38	0.06981
5	0.56	1204.64	79.89	67.18	0.77	393.55	119.7	321.95	3.84	1044.64	0.0698

2.3.2.3 4" Duct

Table B.31: Decreasing ESP- Floor distance 41.5"

	ESP[in wc]	Flowrate[cfm]	DB[F]	WB[F]	DeltaPnozzle[in wc]	Barometer[in wc]	Voltage[V]	Power[W]	Current[A]	Speed[rpm]	Density[lb/ft3]
0	0.13	1183.3	79.89	67.16	0.74	393.64	119.94	190.11	2.19	774.76	0.06981
1	0.16	1184.08	79.92	67.14	0.75	393.63	119.9	199.19	2.3	797.4	0.06981
2	0.21	1186.43	79.87	67.09	0.75	393.62	119.88	210.12	2.43	822.61	0.06982
3	0.41	1193.16	80.03	67.03	0.76	393.64	119.81	263.47	3.1	934.32	0.06981
4	0.5	1197.94	79.97	66.96	0.76	393.64	119.85	289.24	3.43	982.13	0.06982
5	0.56	1198.75	79.91	66.89	0.77	393.65	119.91	305.21	3.63	1011.65	0.06984

Table B.32: Increasing ESP- Floor distance 41.5"

	ESP[in wc]	Flowrate[cfm]	DB[F]	WB[F]	DeltaPnozzle[in wc]	Barometer[in wc]	Voltage[V]	Power[W]	Current[A]	Speed[rpm]	Density[lb/ft3]
0	0.13	1183.3	79.89	67.16	0.74	393.64	119.94	190.11	2.19	774.76	0.06981
1	0.15	1174	79.94	67.2	0.73	393.64	119.99	191.59	2.21	781.72	0.06981
2	0.18	1173.54	79.96	67.21	0.73	393.64	119.97	200.03	2.31	803.73	0.0698
3	0.29	1178.47	79.92	67.23	0.74	393.64	119.96	228.33	2.65	867.27	0.06981
4	0.39	1182.3	79.83	67.21	0.74	393.64	119.92	254.58	2.98	921.56	0.06982
5	0.48	1185.82	79.89	67.27	0.75	393.66	119.95	279.49	3.29	969.28	0.06981

Table B.33: Decreasing ESP- Floor distance 41.5” with front side flow

	ESP[in wc]	Flowrate[cfm]	DB[F]	WB[F]	DeltaPnozzle[in wc]	Barometer[in wc]	Voltage[V]	Power[W]	Current[A]	Speed[rpm]	Density[lb/ft3]
0	0.12	1198.4	80.03	67.13	0.76	393.83	119.97	192.82	2.22	781.84	0.06984
1	0.16	1201.49	79.99	67.1	0.77	393.83	120.03	203.4	2.34	806.89	0.06984
2	0.2	1202.07	80	67.1	0.77	393.83	120.01	213.08	2.46	829.49	0.06984
3	0.31	1206.43	79.98	67.06	0.77	393.84	119.97	242.73	2.82	892.16	0.06985
4	0.41	1207.84	79.95	66.99	0.78	393.84	119.89	268.88	3.15	944.38	0.06986
5	0.51	1213.87	79.91	66.94	0.78	393.84	119.82	296.79	3.52	995.3	0.06987
6	0.57	1219.25	80	66.93	0.79	393.85	119.89	315.79	3.77	1027.43	0.06986

Table B.34: Increasing ESP- Floor distance 41.5” with front side flow

	ESP[in wc]	Flowrate[cfm]	DB[F]	WB[F]	DeltaPnozzle[in wc]	Barometer[in wc]	Voltage[V]	Power[W]	Current[A]	Speed[rpm]	Density[lb/ft3]
0	0.12	1198.4	80.03	67.13	0.76	393.83	119.97	192.82	2.22	781.84	0.06984
1	0.17	1188.94	79.99	67.12	0.75	393.72	119.91	202.25	2.31	809.75	0.06982
2	0.29	1195.09	80.01	67.11	0.76	393.71	119.91	232.71	2.68	876.36	0.06982
3	0.39	1197.66	80	67.09	0.76	393.72	119.92	259.96	3.01	931.71	0.06982
4	0.49	1203.68	79.98	66.74	0.77	393.72	119.89	287.93	3.36	983.75	0.06985
5	0.54	1204.55	80.32	66.85	0.77	393.74	119.78	302.65	3.57	1011.6	0.06981

Table B.35: Decreasing ESP- Floor distance 41.5” with right side flow

	ESP[in wc]	Flowrate[cfm]	DB[F]	WB[F]	DeltaPnozzle[in wc]	Barometer[in wc]	Voltage[V]	Power[W]	Current[A]	Speed[rpm]	Density[lb/ft3]
0	0.12	1199.17	79.97	66.97	0.76	391.1	119.98	192.89	2.22	781.56	0.06936
1	0.17	1202.1	80.05	67.23	0.76	390.83	119.91	204.84	2.37	809.82	0.06928
2	0.2	1203.53	80.04	67.27	0.76	390.58	119.95	214.36	2.48	831.81	0.06924
3	0.32	1208.96	79.94	67.15	0.77	390.59	119.94	245.18	2.86	896.89	0.06926
4	0.42	1211.76	79.89	67.2	0.78	390.48	119.93	272.06	3.2	950.05	0.06924
5	0.52	1219.85	80.1	67.2	0.79	390.53	119.83	302.39	3.6	1004.29	0.06923
6	0.55	1222.63	79.92	67.04	0.79	390.46	119.81	311.35	3.71	1019.16	0.06924

Table B.36: Increasing ESP- Floor distance 41.5” with right side flow

	ESP[in wc]	Flowrate[cfm]	DB[F]	WB[F]	DeltaPnozzle[in wc]	Barometer[in wc]	Voltage[V]	Power[W]	Current[A]	Speed[rpm]	Density[lb/ft3]
0	0.12	1199.17	79.97	66.97	0.76	391.1	119.98	192.89	2.22	781.56	0.06936
1	0.17	1187.64	80.03	67.09	0.75	391.27	119.99	201.7	2.32	808.97	0.06938
2	0.29	1193.48	80.04	67.12	0.75	391.35	119.99	232.32	2.69	876.1	0.06939
3	0.39	1197.64	80.02	67.14	0.76	391.4	119.9	259.55	3.03	931.55	0.0694
4	0.48	1200.26	79.99	67.13	0.76	391.37	119.89	284.39	3.35	979.5	0.06939
5	0.51	1201.28	79.97	67.13	0.76	391.41	119.94	291.95	3.45	993.6	0.0694

Table B.37: Decreasing ESP- Floor distance 6”

	ESP[in wc]	Flowrate[cfm]	DB[F]	WB[F]	DeltaPnozzle[in wc]	Barometer[in wc]	Voltage[V]	Power[W]	Current[A]	Speed[rpm]	Density[lb/ft3]
0	0.11	1183.32	80.05	67.16	0.74	393.86	119.86	183.2	2.1	759.86	0.06984
1	0.15	1184.29	80.03	67.07	0.75	393.86	119.86	194.2	2.23	784.82	0.06985
2	0.19	1185.25	79.98	66.98	0.75	393.86	119.83	203.35	2.34	807.28	0.06986
3	0.3	1190.48	79.92	67.27	0.76	393.86	119.82	233.49	2.7	873.83	0.06984
4	0.41	1196.23	80.07	67.19	0.76	393.86	119.84	262.24	3.09	930.71	0.06983
5	0.5	1198.72	79.99	67.03	0.77	393.86	119.8	288.1	3.42	980.06	0.06985
6	0.57	1205.81	79.93	67.22	0.77	393.86	119.76	308.72	3.7	1015.64	0.06984

Table B.38: Increasing ESP- Floor distance 6”

	ESP[in wc]	Flowrate[cfm]	DB[F]	WB[F]	DeltaPnozzle[in wc]	Barometer[in wc]	Voltage[V]	Power[W]	Current[A]	Speed[rpm]	Density[lb/ft3]
0	0.11	1183.32	80.05	67.16	0.74	393.86	119.86	183.2	2.1	759.86	0.06984
1	0.13	1172.52	80.02	67.19	0.73	393.85	119.82	183.58	2.11	764.9	0.06984
2	0.16	1172.52	80.02	67.22	0.73	393.85	119.85	193.06	2.22	788.2	0.06983
3	0.28	1178.54	79.99	67.25	0.74	393.85	119.85	223.58	2.58	857.15	0.06983
4	0.39	1184.75	79.99	66.86	0.75	393.85	119.79	253.17	2.95	917.6	0.06987
5	0.48	1188.69	80.03	66.93	0.75	393.84	119.75	278.94	3.28	967.63	0.06986
6	0.55	1192.63	80.03	66.97	0.76	393.76	119.76	296.65	3.51	1000.21	0.06984

2.3.2.4 8” Duct

Table B.39: Decreasing ESP- Floor distance 6”

	ESP[in wc]	Flowrate[cfm]	DB[F]	WB[F]	DeltaPnozzle[in wc]	Barometer[in wc]	Voltage[V]	Power[W]	Current[A]	Speed[rpm]	Density[lb/ft3]
0	0.13	1173.94	80.13	66.82	0.73	392.84	119.96	221.57	2.54	847.71	0.06967
1	0.17	1177.18	79.95	66.77	0.74	392.83	119.93	233.48	2.68	872.7	0.06969
2	0.21	1178.56	80.02	66.8	0.74	392.9	119.95	243.52	2.81	894.46	0.0697
3	0.32	1182.91	80.05	66.82	0.74	392.94	119.92	272.66	3.17	952.72	0.0697
4	0.42	1189.97	80.03	66.82	0.75	392.98	119.97	302.56	3.55	1006.03	0.06971
5	0.51	1193.21	79.93	66.76	0.76	392.99	119.91	328.8	3.89	1051.04	0.06973
6	0.57	1195.65	80	66.79	0.76	393.04	119.92	345.97	4.12	1079.62	0.06972

Table B.40: Increasing ESP- Floor distance 6”

	ESP[in wc]	Flowrate[cfm]	DB[F]	WB[F]	DeltaPnozzle[in wc]	Barometer[in wc]	Voltage[V]	Power[W]	Current[A]	Speed[rpm]	Density[lb/ft3]
0	0.13	1173.94	80.13	66.82	0.73	392.84	119.96	221.57	2.54	847.71	0.06967
1	0.2	1173.57	80.21	66.83	0.73	392.76	120.02	239.22	2.78	889.05	0.06965
2	0.41	1185.68	80.2	66.8	0.75	392.74	119.93	298.7	3.54	1001.25	0.06965
3	0.5	1189.05	80.17	66.77	0.75	392.62	119.96	324.61	3.88	1045.9	0.06963
4	0.56	1192.05	80.24	66.82	0.75	392.61	119.95	341.38	4.1	1074.62	0.06962

Table B.41: Decreasing ESP- Floor distance 37.5”

	ESP[in wc]	Flowrate[cfm]	DB[F]	WB[F]	DeltaPnozzle[in wc]	Barometer[in wc]	Voltage[V]	Power[W]	Current[A]	Speed[rpm]	Density[lb/ft3]
0	0.11	1175.03	80.13	66.76	0.74	393.81	119.94	217.8	2.5	841.06	0.06985
1	0.15	1180.35	80.1	66.78	0.74	393.81	119.95	230.36	2.65	867.55	0.06985
2	0.2	1182.41	80.06	66.8	0.74	393.81	120.01	241.64	2.78	891.88	0.06986
3	0.31	1188.04	80.01	66.81	0.75	393.82	120.02	271.12	3.15	950.19	0.06986
4	0.41	1192.5	80.03	66.85	0.76	393.82	119.97	299.39	3.51	1001.23	0.06986
5	0.5	1195.98	80.03	66.86	0.76	393.82	119.85	325.81	3.85	1046.17	0.06986
6	0.56	1199.03	80	66.89	0.77	393.83	119.83	344.57	4.1	1075.02	0.06986

Table B.42: Increasing ESP- Floor distance 37.5”

	ESP[in wc]	Flowrate[cfm]	DB[F]	WB[F]	DeltaPnozzle[in wc]	Barometer[in wc]	Voltage[V]	Power[W]	Current[A]	Speed[rpm]	Density[lb/ft3]
0	0.11	1175.03	80.13	66.76	0.74	393.81	119.94	217.8	2.5	841.06	0.06985
1	0.13	1166.99	80.09	66.72	0.73	393.8	119.94	220.25	2.53	850.81	0.06986
2	0.18	1175.52	80.28	66.71	0.73	393.8	119.93	234.75	2.7	880.92	0.06984
3	0.31	1192.03	80.23	66.74	0.76	393.79	119.91	274.91	3.2	956.26	0.06984
4	0.48	1184.52	80.08	66.78	0.75	393.79	119.94	314.98	3.71	1033.2	0.06985
5	0.54	1186.22	80.04	66.82	0.75	393.79	119.79	331.55	3.93	1061.11	0.06985

2.3.2.5 Alternative Ductwork 1

Table B.43: Decreasing ESP

	ESP[in wc]	Flowrate[cfm]	DB[F]	WB[F]	DeltaPnozzle[in wc]	Barometer[in wc]	Voltage[V]	Power[W]	Current[A]	Speed[rpm]	Density[lb/ft3]
0	0.12	1199.11	80.04	67.13	0.76	391.3	119.93	193.88	2.24	785.21	0.06938
1	0.16	1202.9	80	67.09	0.76	391.33	119.89	205.48	2.38	811.94	0.06939
2	0.2	1201.31	80.08	67.26	0.76	391.32	119.9	214.93	2.49	834.04	0.06937
3	0.28	1203.06	80.09	67.22	0.77	391.39	119.9	235.37	2.75	878.13	0.06938
4	0.4	1210.06	80.01	67.16	0.77	391.37	119.85	267.59	3.16	941.45	0.06939
5	0.5	1217.15	80.01	67.07	0.78	391.43	119.82	299.28	3.57	998.64	0.06941
6	0.54	1220.59	79.95	66.95	0.79	391.42	119.77	311.25	3.72	1018.24	0.06942

Table B.44: Increasing ESP

	ESP[in wc]	Flowrate[cfm]	DB[F]	WB[F]	DeltaPnozzle[in wc]	Barometer[in wc]	Voltage[V]	Power[W]	Current[A]	Speed[rpm]	Density[lb/ft3]
0	0.12	1199.11	80.04	67.13	0.76	391.3	119.93	193.88	2.24	785.21	0.06938
1	0.14	1192.55	80.03	67.14	0.75	391.24	119.92	197.9	2.29	797.81	0.06937
2	0.18	1193.16	79.96	67.13	0.75	391.28	119.94	207.66	2.4	822.23	0.06938
3	0.26	1193.91	79.95	67.12	0.75	391.27	119.88	226.35	2.63	863.09	0.06938
4	0.37	1195.41	79.92	67.1	0.76	391.26	119.84	254.09	2.98	921.39	0.06938
5	0.47	1201.52	79.91	67.1	0.76	391.25	119.9	283.87	3.36	977.14	0.06938
6	0.5	1199.13	79.98	67.09	0.76	391.24	119.82	290.13	3.44	991.11	0.06938

Table B.45: Decreasing ESP- with front side flow

	ESP[in wc]	Flowrate[cfm]	DB[F]	WB[F]	DeltaPnozzle[in wc]	Barometer[in wc]	Voltage[V]	Power[W]	Current[A]	Speed[rpm]	Density[lb/ft3]
0	0.11	1188.66	80.02	67.13	0.75	393.57	119.85	187.48	2.15	768.77	0.06979
1	0.15	1190.87	80.01	67.15	0.75	393.57	119.81	197.46	2.26	792.73	0.06979
2	0.19	1191.55	80	67.15	0.76	393.58	119.83	209.06	2.4	819.66	0.06979
3	0.31	1193.3	80.05	67.14	0.76	393.43	119.67	237.7	2.77	883.01	0.06976
4	0.42	1200.12	80.13	67.13	0.77	393.45	119.72	270.21	3.18	945.22	0.06976
5	0.52	1205.19	80.07	67.06	0.77	393.35	119.64	298.39	3.54	997.83	0.06975
6	0.56	1209.33	80.03	66.98	0.78	393.33	119.62	310.51	3.71	1017.95	0.06976

Table B.46: Increasing ESP- with front side flow

	ESP[in wc]	Flowrate[cfm]	DB[F]	WB[F]	DeltaPnozzle[in wc]	Barometer[in wc]	Voltage[V]	Power[W]	Current[A]	Speed[rpm]	Density[lb/ft3]
0	0.11	1188.66	80.02	67.13	0.75	393.57	119.85	187.48	2.15	768.77	0.06979
1	0.12	1174.94	80.01	67.1	0.73	393.53	119.89	184.85	2.12	768.09	0.06979
2	0.16	1176.27	80	67.04	0.74	393.49	119.87	196.18	2.25	795.91	0.06979
3	0.28	1182.87	80.01	67.01	0.74	393.48	119.85	227.93	2.63	867.17	0.06979
4	0.4	1187.75	80.01	66.98	0.75	393.46	119.84	257.97	3	928.34	0.06978
5	0.5	1193.08	80.05	66.94	0.76	393.4	119.81	286.68	3.36	982.63	0.06977
6	0.52	1190.37	80	66.86	0.75	393.38	119.84	292.37	3.44	994.29	0.06978

Table B.47: Decreasing ESP- with right side flow

	ESP[in wc]	Flowrate[cfm]	DB[F]	WB[F]	DeltaPnozzle[in wc]	Barometer[in wc]	Voltage[V]	Power[W]	Current[A]	Speed[rpm]	Density[lb/ft3]
0	0.12	1197.89	80.03	67.23	0.76	391.96	119.86	192.76	2.22	783.37	0.06949
1	0.16	1199.79	80.07	67.2	0.76	391.94	119.76	204.37	2.36	809.97	0.06948
2	0.28	1201.58	79.99	67.03	0.77	391.94	119.75	234.9	2.74	877.43	0.06951
3	0.4	1206.28	79.99	67.28	0.77	391.96	119.71	265.42	3.13	940.11	0.06949
4	0.5	1210.94	79.91	67.19	0.78	391.99	119.8	294.07	3.49	991.75	0.06951
5	0.57	1214.22	80.01	67.06	0.78	392	119.77	313.57	3.75	1025.42	0.06951

Table B.48: Increasing ESP- with right side flow

	ESP[in wc]	Flowrate[cfm]	DB[F]	WB[F]	DeltaPnozzle[in wc]	Barometer[in wc]	Voltage[V]	Power[W]	Current[A]	Speed[rpm]	Density[lb/ft3]
0	0.12	1197.89	80.03	67.23	0.76	391.96	119.86	192.76	2.22	783.37	0.06949
1	0.14	1185.8	80	67.18	0.75	391.93	119.84	193.32	2.23	789.05	0.06949
2	0.18	1187.27	79.97	67.21	0.75	391.95	119.83	203.15	2.34	812.76	0.06949
3	0.26	1192.75	80.01	67.23	0.75	391.96	119.86	226.19	2.62	862.92	0.06949
4	0.37	1195.75	80.01	67.24	0.76	391.94	119.8	255.34	2.99	923.49	0.06949
5	0.48	1200.78	79.97	67.24	0.76	391.94	119.88	283.59	3.34	977.18	0.06949
6	0.54	1202.64	79.88	67.22	0.77	391.95	119.87	301.18	3.56	1009.53	0.0695

2.3.2.6 Alternative Ductwork 2

Table B.49: Decreasing ESP

	ESP[in wc]	Flowrate[cfm]	DB[F]	WB[F]	DeltaPnozzle[in wc]	Barometer[in wc]	Voltage[V]	Power[W]	Current[A]	Speed[rpm]	Density[lb/ft3]
0	0.09	1180.16	79.91	67.2	0.74	393.31	119.9	180.46	2.08	751.66	0.06975
1	0.17	1183.63	80.01	67.23	0.74	393.35	119.95	200.25	2.32	799.86	0.06974
2	0.21	1184.88	80.11	67.23	0.75	393.38	119.89	210.89	2.44	823.77	0.06974
3	0.32	1188.41	79.95	67.11	0.75	393.39	119.82	239.26	2.79	884.89	0.06977
4	0.41	1190.85	79.72	66.96	0.76	393.4	119.87	265.43	3.12	937.08	0.06981
5	0.5	1196.3	80.09	67.03	0.76	393.38	119.83	291.57	3.47	986.06	0.06976
6	0.57	1200.41	79.84	66.81	0.77	393.36	119.83	310.18	3.71	1018.33	0.0698

Table B.50: Increasing ESP

	ESP[in wc]	Flowrate[cfm]	DB[F]	WB[F]	DeltaPnozzle[in wc]	Barometer[in wc]	Voltage[V]	Power[W]	Current[A]	Speed[rpm]	Density[lb/ft3]
0	0.09	1180.16	79.91	67.2	0.74	393.31	119.9	180.46	2.08	751.66	0.06975
1	0.18	1169.23	79.95	67.21	0.73	393.29	119.88	199.21	2.3	801.98	0.06974
2	0.29	1175.3	80	67.23	0.74	393.29	119.92	227.92	2.65	867.35	0.06973
3	0.39	1181.08	80.12	67.26	0.74	393.24	119.82	256.08	3	924.16	0.06971
4	0.51	1199.54	80.07	66.95	0.77	393.14	119.86	294.52	3.5	990.36	0.06972
5	0.54	1187.86	80.06	66.95	0.75	393.1	119.86	298	3.54	1003.47	0.06972

Table B.51: Decreasing ESP- Front Side Flow

	ESP[in wc]	Flowrate[cfm]	DB[F]	WB[F]	DeltaPnozzle[in wc]	Barometer[in wc]	Voltage[V]	Power[W]	Current[A]	Speed[rpm]	Density[lb/ft3]
0	0.1	1186.39	80.02	66.82	0.75	392.62	119.84	186.57	2.15	765.85	0.06964
1	0.18	1190.97	80.01	66.84	0.75	392.69	119.86	206.9	2.4	813.79	0.06965
2	0.22	1189.85	80.11	66.86	0.75	392.77	119.9	215.57	2.5	833.81	0.06966
3	0.33	1195.32	80.16	66.89	0.76	392.79	119.83	245.75	2.87	897	0.06965
4	0.43	1199.84	80.11	66.87	0.76	392.84	119.83	272.86	3.22	950.33	0.06967
5	0.49	1201.5	79.98	66.83	0.77	392.83	119.82	290.68	3.45	983.14	0.06969
6	0.55	1207.99	80.23	66.93	0.78	392.89	119.8	310.59	3.71	1017.44	0.06966

Table B.52: Increasing ESP

	ESP[in wc]	Flowrate[cfm]	DB[F]	WB[F]	DeltaPnozzle[in wc]	Barometer[in wc]	Voltage[V]	Power[W]	Current[A]	Speed[rpm]	Density[lb/ft3]
0	0.1	1186.39	80.02	66.82	0.75	392.62	119.84	186.57	2.15	765.85	0.06964
1	0.15	1174.39	80.18	66.86	0.73	392.61	119.85	194.82	2.25	791.76	0.06962
2	0.19	1176.35	80.39	66.93	0.73	392.6	119.82	203.89	2.36	814.04	0.06959
3	0.3	1181.31	79.98	66.77	0.74	392.59	119.82	234.22	2.73	879.39	0.06965
4	0.4	1184.59	80.09	66.79	0.75	392.57	119.86	259.42	3.04	931.2	0.06963
5	0.46	1187.64	80.21	66.82	0.75	392.49	119.85	277.2	3.27	965.55	0.0696
6	0.52	1191.41	80.06	66.75	0.75	392.42	119.74	294.82	3.5	997.37	0.06961

2.3.2.7 Repeatability Test- 4" Duct

Table B.53: Decreasing ESP- Front Side Flow

	ESP[in wc]	Flowrate[cfm]	DB[F]	WB[F]	DeltaPnozzle[in wc]	Barometer[in wc]	Voltage[V]	Power[W]	Current[A]	Speed[rpm]	Density[lb/ft3]
0	0.13	1187.17	80.24	66.96	0.75	394.03	120.04	190.05	2.2	773.34	0.06987
1	0.15	1182.23	80.38	67.05	0.74	394.03	120.09	194.71	2.25	787.39	0.06984
2	0.2	1189.18	80.09	66.95	0.75	394.04	120.09	209.62	2.43	819.08	0.06988
3	0.31	1191.33	80.04	66.99	0.76	394.03	119.97	237	2.77	879.85	0.06988
4	0.41	1196.97	80.03	67.03	0.76	394.03	120.01	264.77	3.12	934.92	0.06988
5	0.51	1203.2	80.02	67.07	0.77	394.03	119.94	292.69	3.48	985.71	0.06988
6	0.54	1206.56	80.02	67.11	0.78	394.03	119.96	303.16	3.61	1003.81	0.06988

Table B.54: Increasing ESP

	ESP[in wc]	Flowrate[cfm]	DB[F]	WB[F]	DeltaPnozzle[in wc]	Barometer[in wc]	Voltage[V]	Power[W]	Current[A]	Speed[rpm]	Density[lb/ft3]
0	0.13	1187.17	80.24	66.96	0.75	394.03	120.04	190.05	2.2	773.34	0.06987
1	0.14	1172.84	80.03	66.84	0.73	394.03	120.01	187.47	2.17	773.49	0.0699
2	0.17	1172.28	80.32	66.86	0.73	394.03	120.11	196.49	2.27	795.22	0.06986
3	0.29	1179.7	80.13	66.75	0.74	394.03	120.09	226.42	2.64	862.63	0.06989
4	0.39	1183.41	80.27	66.77	0.75	394.02	120.11	253.07	2.96	917.8	0.06988
5	0.49	1190.07	80.32	66.75	0.75	394.02	120.02	279.82	3.31	968.94	0.06987
6	0.52	1191.83	80.35	66.74	0.76	394	120.08	288.58	3.42	985.27	0.06987

Table B.55: Decreasing ESP- With Right Side Flow

	ESP[in wc]	Flowrate[cfm]	DB[F]	WB[F]	DeltaPnozzle[in wc]	Barometer[in wc]	Voltage[V]	Power[W]	Current[A]	Speed[rpm]	Density[lb/ft3]
0	0.12	1199.54	80.01	67.18	0.76	391	119.95	193.42	2.24	782.32	0.06932
1	0.16	1201.56	79.99	67.19	0.76	391.08	119.94	203.54	2.36	806.48	0.06934
2	0.2	1203.05	80.05	67.23	0.76	391.11	119.95	214.39	2.49	830.78	0.06933
3	0.31	1207.58	80.04	67.24	0.77	391.29	120.01	244.33	2.85	894.98	0.06936
4	0.42	1212.21	80.07	67.25	0.78	391.34	119.98	272.65	3.21	950.01	0.06937
5	0.51	1215.25	79.99	67.22	0.78	391.32	120	298.46	3.54	998.43	0.06938
6	0.56	1229.26	80.07	67.16	0.8	389.73	119.89	316.29	3.78	1025.54	0.06909

Table B.56: Increasing ESP- With Right Side Flow

	ESP[in wc]	Flowrate[cfm]	DB[F]	WB[F]	DeltaPnozzle[in wc]	Barometer[in wc]	Voltage[V]	Power[W]	Current[A]	Speed[rpm]	Density[lb/ft3]
0	0.12	1199.54	80.01	67.18	0.76	391	119.95	193.42	2.24	782.32	0.06932
1	0.13	1184.38	79.99	67.15	0.74	390.96	119.9	190.59	2.21	782.44	0.06932
2	0.18	1188.99	79.98	67.11	0.75	390.98	119.95	202.88	2.35	810.82	0.06933
3	0.29	1195.54	80	67.1	0.76	390.96	119.87	232.85	2.72	876.86	0.06932
4	0.39	1200.22	80	67.06	0.76	390.96	119.85	261.44	3.08	934.05	0.06932
5	0.49	1203.54	80	67.01	0.77	390.93	119.79	287.87	3.43	984.05	0.06932
6	0.54	1205.11	79.98	66.94	0.77	390.91	119.79	303.05	3.63	1012.25	0.06933

VITA

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