

Synthetic Jet Flow Control in the Indoor Environment

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B.S., Illinois Institute of Technology, 2011

A thesis submitted to the Faculty of the
Graduate School of the University of Colorado
in partial fulfillment of the requirement for the degree of
Master of Science
Architectural Engineering
2013

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The final copy of this thesis has been examined by the signatories, and we
Find that both the content and the form meet acceptable presentation standards
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Abstract

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Synthetic Jet Flow Control in the Indoor Environment

Thesis directed by Assistant Professor Lupita Montoya and Associate Professor Jean Hertzberg

Experimental flow visualization study was used to assess the ability of synthetic jets to be adapted for control of air flows and particulates in an indoor environment. Flow visualization was used to determine whether paired synthetic jet modules installed onto the surface of a supply diffuser could significantly impact room air distribution through changing the angle at which supply air left the diffuser when mixing into the room air. Control over the supply jet angle is directly related to how well the supply air mixes with the room air and the overall air quality of the room. A lab with a high air exchange rate (21 ACH) was selected to act as the environment to test the synthetic jets in. This lab space is representative of occupational indoor environments that may require ventilation strategies beyond typical systems to ensure the safe and efficient operation of the space. Three synthetic-jet modules were tested including two pairs of small one-inch diameter jets used in a previous small-scale ventilation study^[1] and two larger two-inch diameter jet pairs constructed specifically for this study. Statistical methods were used to compare the visualized supply flow with active synthetic jet flow control versus a baseline case (no flow control). A significant increase in the angle of mixing of the supply air of up to 4° or 50% of the original supply jet angle was achieved.

Acknowledgements

Thank you to Lupita Montoya and Jean Hertzberg for all their advising and support both in terms of time, space and thought through this work from the beginning to the end.

A special thanks to John Zhai and the Building Systems Department for providing the support to accomplish all the required measurements and understand the fundamentals.

Thanks to James McNeil for his instruction and advice in learning the lab equipment.

Thanks to all my family and friends for their support through sickness and health and the inspiration to continue to pursue my education.

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Introduction

Active flow control has been used to improve the performance of mechanical systems across a wide variety of fields. One type of active flow control, synthetic jets, have been used to impact turbulent structures on a scale of 1 to 2 magnitudes larger than the characteristic length of the jets and generate momentum fluxes without injecting mass into the flow ^[2]. Synthetic jets have been used for flow control purposes in mechanical systems from small computer electronics ^{[3] [4] [5]} to large systems such as wind turbines ^[6] with promising results. Synthetic jets have been used for convective cooling ^{[3] [4] [7]}, sorting of particulates ^[8], vectoring of larger jets ^{[9] [10] [11] [12]} and increasing or decreasing distance of attachment ^{[2] [13]} of larger interacting jets. The use of synthetic jets to improve air distribution and indoor air quality in buildings is largely unexplored.

Active flow control enables applications that go beyond the scope of passive systems. Active systems can be turned on or off to meet the demands of different system conditions; however, they can also add energy to the system in the form of unwanted noise or heat ^[14]. Indoor environments often require active systems for at least part of their operating cycle. Critical indoor environments such as hospitals or laboratories have a greater need for active systems due to the wide range of operating conditions they undergo, including emergency conditions ^[14].

The advantages of synthetic jet active flow control over traditional active control methods include low energy consumption ^[15] and compact size ^{[2] [16]}. Synthetic jets operate using time periodic motion of an actuator inside a cavity. A “synthetic jet” is formed at the orifice of the cavity from the ambient fluid surrounding the cavity through the suction and expulsion strokes of the internal actuator as shown in Figure 1 ^[17].

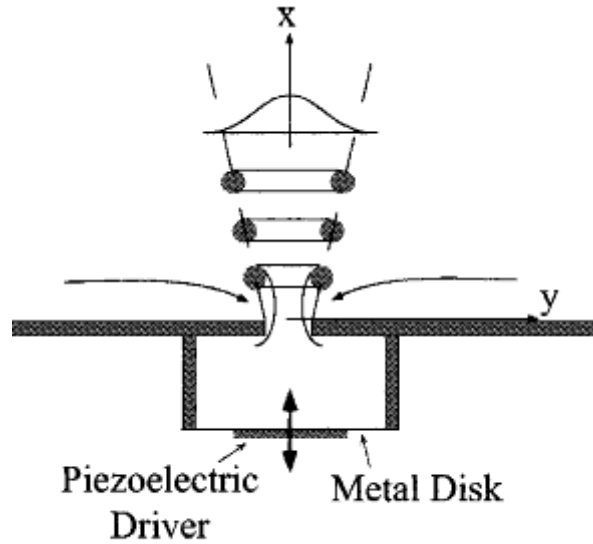


Figure 1: Synthetic Jet Flow Evolution Diagram

Synthetic jets can be classified as zero net mass flux devices due to their interaction with the ambient fluid. Flow separation occurs at the edges of the cavity orifice creating a rollup of vortices on the external edges of the orifice during the expulsion stroke. The self-induced velocity of these vortices continues to carry them forward enough to not be affected significantly by the suction stroke of the actuator/cavity system. This continual periodic rollup of vortices creates a non-zero momentum of fluid from the synthetic jets even though there is a zero net mass flux across the orifice of the synthetic jet cavity^{[2][18]}.

One of the earliest-studied indoor flow control applications of synthetic jets was their potential use in cooling electronics. The earliest publication of a study on synthetic jets for the purpose of indoor cooling was a conference paper by Lagorce et al in 1997^[5]. Since then dozens of papers have been published focusing on using synthetic jets for the cooling of electronics^[19]^[16]. The compact size and low cost of components make synthetic jets optimal for electronic cooling^[16]. Synthetic jets have been found to have an enhanced heat transfer coefficient greater than 10 times that of natural convection over small surfaces (less than 1.5 x 1.5m)^[16]. Some

acoustic abatement may be required as synthetic jets can produce sound pressure levels of over 70 db as measured in an anechoic chamber. Mufflers may reduce unwanted noise by 20-40 db^[16]. Cooling of larger subjects (such as people) using synthetic jets is largely unexplored likely due to the acoustic issues of the jets and the lack of commercially available piezoelectric actuators of larger sizes (above 2 inches in diameter). However, non-piezoelectric actuators such as pistons are available for synthetic jet studies^[18].

More recently, in 2006, the ability to direct particulate motion using synthetic jets has shown another potential use of synthetic jets in the indoor environment. Aerodynamic Vectoring Particle Sorting (AVPS) is a technique used to sort particles by size demonstrated by Humes and Smith in 2006. Particles experience varying drag forces depending on their size which allow jet vectoring techniques to concentrate particles within certain size ranges by a factor of 10^[8]. This same effect has been observed in 4-6 lpm water spray vectoring studies using synthetic jets for indoor applications^[9]. Paired synthetic jet vectoring was used to accomplish significant AVPS in a chamber study of 20 and 40 lpm air flows that are more representative of indoor environmental air flows^[20]. AVPS has the advantage of a reduced risk of damage or contamination when compared to more traditional impaction techniques of particulate sorting^[8]. These promising steps forward demonstrate the potential for using synthetic jets as part of the solution of particulate removal in the indoor environment.

Flow control in an air distribution system is a relatively unexplored use of synthetic jets in the indoor environment. Vectoring of larger traditional jets from diffusers using synthetic jets has potential applications in laboratories and hospitals where air contamination is a major concern^[14]. Flow control and jet vectoring studies have demonstrated the ability of synthetic jets to affect the dispersion, exit angle^[10], ability to attach to nearby surfaces^[13], and generation of

turbulence in larger jets ^[10]. This study examines the impact of synthetic jets on a supply air jet in an indoor environment.

First, this section provides background on the common characteristics of indoor jets and their impact on room air distribution. The fundamental forces that govern synthetic jet behavior relevant to indoor flows are then described. The next section (1 B) describes how new jets were constructed based upon these principles and compared against synthetic jets previously used in a study for AVPS. Section 2 documents how both jets were calibrated and tested to determine their peak operating conditions based on the driving frequency of their actuators. Section 3 presents results from testing both sets of jets in a laboratory setting using flow visualization techniques.

Room Air Diffusion

Indoor environmental quality is driven by the air distribution patterns in the space of interest. These patterns are directly affected by the type of air terminals in the space. Air diffusion patterns are generally categorized as fully-mixed, fully-stratified, partially-mixed or task-conditioned systems as summarized in Figure 2. The supply airflow and heat load configuration of an air diffusion system determines what category the system falls into. The room air temperature, supply flow quantity, and terminal type dictate the distribution of the supply air flow. The overall heat load is affected by the quantity, location, distribution (point or distributed) and type (radiative/convective split) of individual heat loads. This experimental study focuses on altering the room air diffusion by manipulating the supply air flow at the terminal.

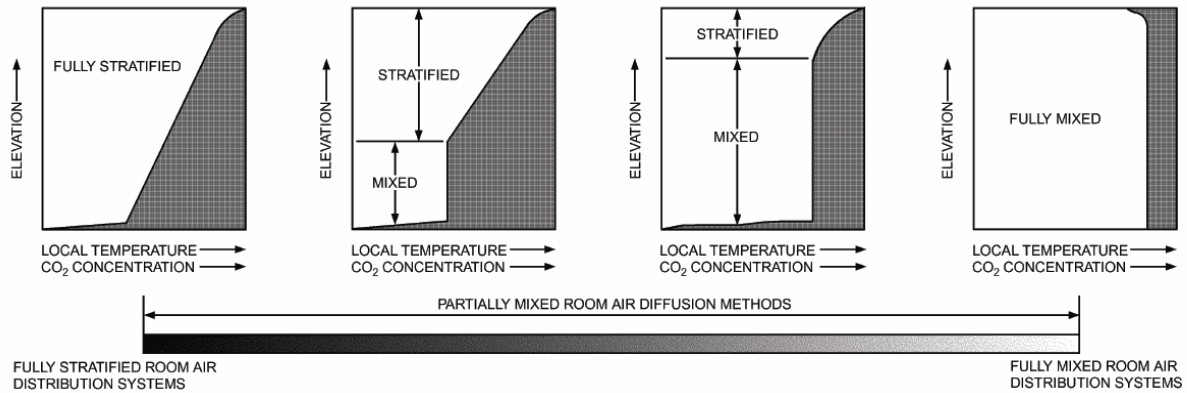


Figure 2: Room Air Distribution ^[21]

Stratified systems have mostly linear temperature and contaminant profiles, with the highest temperature and level of contaminants near the heat and contaminant sources, respectively. Fully mixed systems have flatter temperature and contaminant profiles. Mixing air distribution systems are the most commonly used in North America. Commonly, the area in a room from the floor to approximately seven feet above it is referred to as the “occupied” zone. Environmental qualities such as contaminant concentrations and air velocity are primarily considered for the occupied zone. ^[14]

The room air distribution system also affects the overall energy distribution of the building by means of the air change effectiveness. Air change effectiveness is defined as age of air occupants breathe in a mechanically ventilated space to the age of air that would occur in the space if the air was perfectly mixed. The age of air is the average time elapsed since each molecule of air in a given volume had entered the space from the outside. The air change effectiveness of a room is a function of the air distribution system’s design, construction and operation ^[22].

The supply air terminal into the room may create various types of jets depending on the terminal configurations and the room conditions. Completely unobstructed jets are known as “free jets”; however, more commonly supply air jets attach to a nearby surface due to the

Coanda effect and hence are known as “attached jets” Manufacturers often measure the “throw” of a jet for design purposes. The throw of a jet is the horizontal or axial distance an airstream travels from an air terminal before the maximum centerline stream velocity is reduced to a specified terminal velocity. The specified terminal velocity is determined by an appropriate standard (such as ASHRAE standard 70) and is often chosen based on occupant comfort needs. Throw is most often listed by supply terminal manufacturers for attached jets. Attached jets are often preferred for design purposes to free jets because they have longer throws and therefore fewer terminals are required to provide the specified terminal air velocity in the occupied zone throughout the room. Attached jets are able to provide greater throw because they have a lower induction rate of ambient air due to a smaller area exposed to the ambient air. Attached jets are preferred for mixing air distribution systems because they provide supply air more time to mix with ambient room air before entering the occupied zone. An attached jet may detach due to buoyancy forces if they exceed inertia of the moving air stream. Early separation of attached jets may lead to drafts and poor mixing in rooms due to a reduced time for the supply air to mix with the ambient room air before entering the occupied zone. Supply air jets are commonly non-isothermal, meaning they have a different temperature than the ambient room air and are susceptible to buoyancy forces ^[21].

The angle of divergence of a supply air jet affects the jet’s expansion into the room. ASHRAE defines four jet expansion zones. The first zone is a short core of relatively unchanged velocity or temperature from the exit of the supply terminal. Zone 2 is a transitional zone dictated by the air terminal properties and initial turbulence of the flow. The third zone is fully established turbulent flow and is the zone the jet is designed to be in when

it reaches the occupied zone. Zone 4 is marked by rapid deterioration of the jet velocity below 50 feet per minute ^[21]

Synthetic Jet Design

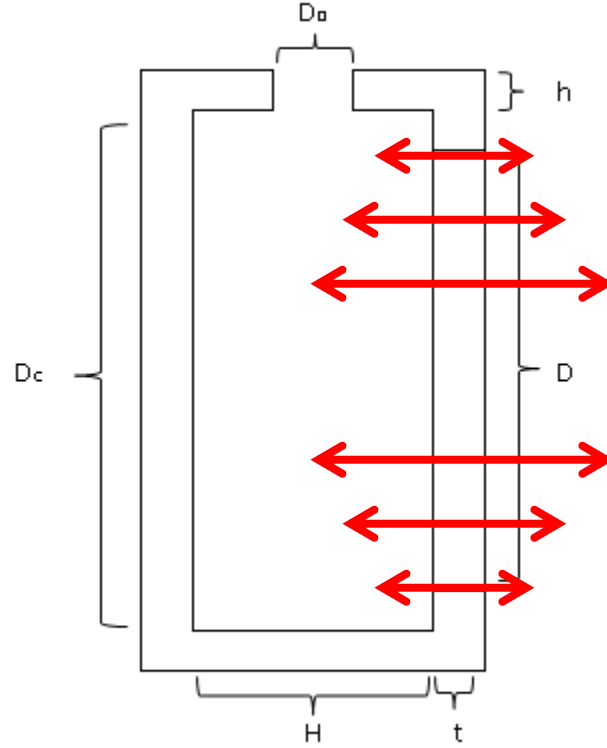
Synthetic jets have been successfully used for various flow control applications including in flow over airfoils ^{[13] [23]}, cooling of electronics ^[16], underwater propulsion ^[24] and improving the power coefficient of wind turbines ^[6]. This study investigates the potential flow control application of synthetic jets for indoor ventilation.

Unlike conventional jets, synthetic jets are formed from the ambient fluid of the system in which they are installed. This unique feature allows the jets to impart a forward transfer of momentum without a net transfer of mass to the flow system. Synthetic jets are commonly formed by an oscillatory solid boundary within a small cavity with an orifice open to an ambient fluid. If the motion of the oscillatory boundary is large enough, it will induce flow separation at the orifice of the cavity causing periodic pairs (planar jets) or rings (circular jets) of vortices to form outside the cavity. These vortices are propelled downstream from the cavity orifice by the self-induction of the vortex pairs. The vortex pairs eventually break down due to turbulent instability and become indistinguishable from the mean flow from the synthetic jet (Figure 1).

When the synthetic jet interacts with external flows, it can generate closed recirculation regions, which can impact external flows of one to two magnitudes greater than the characteristic length scale of the synthetic jet ^{[17] [2]}.

Synthetic jet designs are driven by the properties of three main elements: the orifice, the cavity and the oscillating boundary or actuator. The orifice is characterized by the width (D_o) and depth (h). The cavity can be characterized by the depth (D_c), width (H) and the length (not shown). The actuator is primarily characterized by material properties but also by size (D). Each

of these elements has several parameters that can be modified to achieve a different effect on the operation of the synthetic jet. These parameters are shown in Figure 3.



D_o = Orifice Width
 h = Orifice Depth
 D_c = Cavity Depth
 D = Actuator Diameter
 H = Cavity Width
 t = Wall Thickness

Figure 3: Synthetic Jet Dimensions

The orifice geometry drives the vortex formation of the jets. Orifices of various shapes have been studied but the most common are round or rectangular^[2]. Usually rectangular jets are used for 2-dimensional studies. High aspect ratios in rectangular jets decrease the width in one direction and minimize edge effects in the 2-dimensional view. Lower aspect ratios increase the width of the produced jets due to increased induced velocities towards the jet orifice^[25]. The orifice depth (h) also plays a role in the evolution of synthetic jet flow. The deeper the orifice,

the larger the dampening effect on the expulsion stroke of the jet is. This dampening narrows the width of the jets and accelerates the flow. If the orifice is long enough for the flow to reattach to its walls, it will suppress the flow width and slow the expulsion due to shear action along the wall. These two fluid phenomena can be optimized to yield a depth that provides the highest orifice exit velocity at a given orifice width. Optimization studies have found this depth to be approximately twice the diameter or width of the jet ^[26].

The cavity geometry drives the exit velocity of the jets in two ways: 1) through its depth or volume and 2) through its Helmholtz frequency. Reducing the chamber volume proportionately increases the peak exit velocity of the jets. This effect is due to the increased effect of the actuator movement on a smaller cavity volume ^[26]. The frequency response of the synthetic jet is dependent on the relationship between the actuator resonant frequency and the Helmholtz resonant frequency of the cavity ^[27]. When the two resonant frequencies are close in value, they couple creating a single resonant peak producing higher peak exit velocities than they would create otherwise. Although the actuator resonant frequency tends to dominate between the two, the Helmholtz frequency has a significant impact and can produce exit velocities near those of the actuator resonance when they are decoupled. ^[25]. The Helmholtz frequency (f_H) is driven by the orifice depth (neck length), the orifice area and the cavity volume. Increasing the cavity volume or neck length decreases the Helmholtz frequency while increasing the orifice area will increase it. This relationship is described in Equation 1 ^[28].

$$f_H = \frac{v_{sound}}{2\pi} \sqrt{\frac{A}{V_o L}} = \text{Helmholtz frequency}$$

$$v_{sound} = \text{speed of sound}$$

$$L = \text{neck length}$$

$A = \text{orifice area}$

$V_o = \text{cavity volume}$

Equation 1: Helmholtz Frequency

Small synthetic jets commonly use piezoelectric discs as their transducers due to their efficient conversion of an electrical signal to mechanical motion ^[2]. Piezoceramics are ceramic elements that contain polycrystalline ferroelectric metals that respond mechanically to an electrical field. By applying an electric voltage to a piezoceramic element, it undergoes physical stress ultimately causing it to buckle in a periodic fashion (inverse piezoelectric effect). The most commonly used piezoceramic is lead zirconate titanate (PZT). PZT properties vary between manufacturers but have a Young's modulus in the range of $6-9 \times 10^{10}$ and Curie points over 300 degrees Celsius ^[29].

This study uses the basic slug flow model, which considers the fluid from the jets to be ejected intermittently in the form of cohesive “slugs”. These slugs have a diameter equal to the orifice, and “stroke length” (L) representative of the length of the slug such that the slug volume equals the expelled volume. Analyzing the synthetic jets using the slug flow model, the periodic jet slug can be defined by the dimensionless stroke length ^{[17] [30]}.

$$\frac{L_o}{D_o} = \frac{\int_0^\tau u(t)dt}{D_o} = \frac{u_{peak}}{\pi \cdot f \cdot D_o} = \text{dimensionless stroke length}$$

$$\text{Where } \tau = \frac{T}{2} \text{ and } T = \frac{1}{f}$$

$T = \text{actuator cycle period (s)}$

$f = \text{jet's driven frequency (Hz)}$

$u(t) = \text{centerline stream velocity}$

$$u_{peak} = \text{peak exit velocity}$$

Equation 2: Dimensionless Stroke Length

The Reynolds number using this model for the synthetic jets is defined as ^[17]:

$$Re = \frac{U_o D_o}{\nu} = \text{Reynolds Number}$$

$$U_o = \text{Average orifice velocity}$$

$$\nu = \text{Kinematic Viscosity}$$

$$\text{Where } U_o = \frac{u_{peak}}{\pi}$$

Equation 3: Reynolds Number

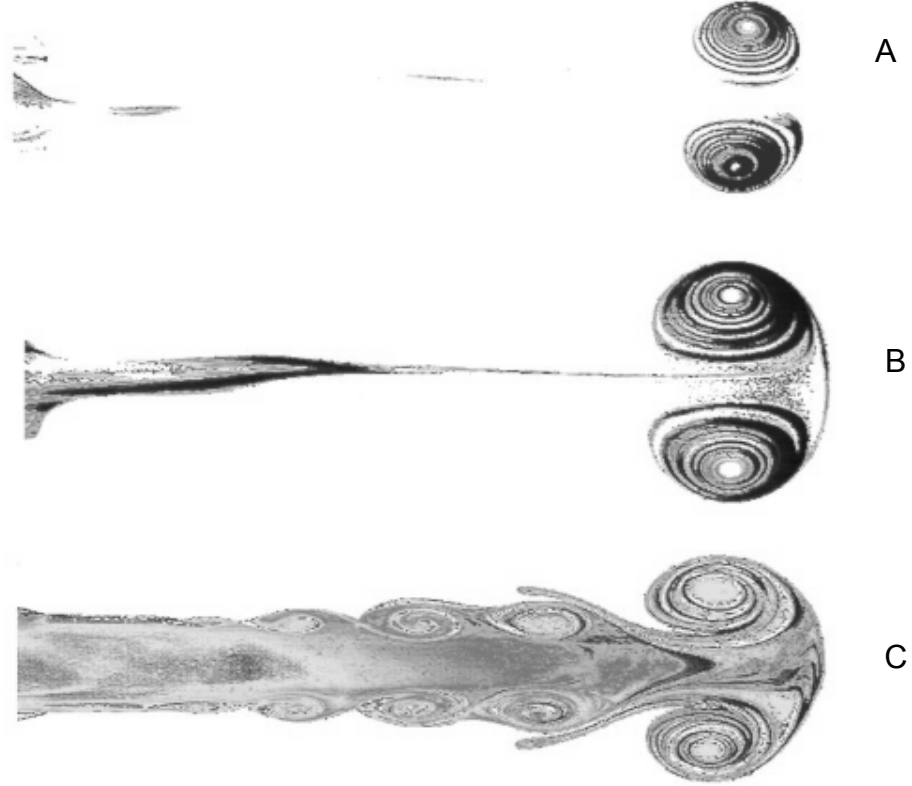
The slug model assumes that the flow is laminar in the orifice and that the effect of the boundary layer of the flow along the edges of the orifice is negligible. ^[17]

Due to the oscillating nature of the synthetic jet flow, it is convenient to use the Strouhal Number for comparisons between jets. The Strouhal Number is defined as ^{[17] [31]}:

$$St = \frac{f * D_o}{U_o} \text{ Strouhal Number}$$

The Strouhal number is the reciprocal of the dimensionless stroke length assuming that the driven frequency of the actuator (f) is the same as the frequency of vortex shedding. Large (magnitude of 1 or greater) Strouhal Numbers (or low dimensionless stroke lengths) are characterized by viscosity-dominated fluid flow resulting in a collective oscillatory movement of the fluid “slug”. Smaller Strouhal numbers correspond to a buildup of vortices followed by rapid shedding ^[31]. The dimensionless stroke length is sometimes referred to as the “formation number” of vortex rings because of its role in impulse jet formation. The Kelvin-Benjamin principle predicts that steady axis touching vortex rings have a maximum state of kinetic energy due to their circulation ^[30]. It has been confirmed through numerical and experimental studies

that maximum jet formation resulting from vortex pairs occurs at stroke lengths of 3.6-4.5 over a broad range of flow conditions. Below this range, most of the fluid ejected is entrained in the initial vortex formation as shown in part A and B of Figure 4^[32]. Above this critical dimensionless stroke length, a trailing jet forms behind the initial pair of vortices with subsequent vortex pairs entrained in the jet flow^[32].



$$A: \frac{L_0}{D_o} = 2, B: \frac{L_0}{D_o} = 3.8, C: \frac{L_0}{D_o} = 8$$

Figure 4: Formation Number of Vortex Pairs

The synthetic jets used in this study were operated in a condition of vortex ring formation well above the formation number. As shown in part C of Figure 4, trailing jets produced by vortex rings are characterized by buildup and shedding of subsequent vortices, which have been observed at low Strouhal numbers^{[30] [31] [32]}.

The interaction of a pair of adjacent synthetic jets can result in a single jet that can be tilted to either side by varying the operating conditions of the two jets ^[12]. This process is known as “synthetic jet vectoring” and is used in flow control applications. The combined jet stream is wider than a single jet and can move more than twice the amount of fluid. This synergistic effect is due to the low pressure caused by two adjacent jets. Vectoring can be achieved by offsetting the stroke length of the jets or by creating a phase difference between the frequencies at which the two jets are being driven. The jet leading in phase dictates the direction of the combined jet flow by entraining the flow of the lagging jet into its vortices. The effect becomes more pronounced as the phase difference is increased. Three different operating regimes have been observed in synthetic jet vectoring and are characterized by the phase difference between the pair of jets ^[12] [[HYPERLINK "" \l "Zie07" 1](#)] :

1) Phase difference of less than 70 degrees. This mode is characterized by suction of the lagging jet during the start of the expulsion phase of the leading jet. The lagging jet increases the vorticity of the leading jet and creates a stronger entrainment towards the leading jet, which drives the vectoring of the fluid being expelled from the jets.

2) Phase difference between 70 and 110 degrees. This mode of operation is characterized by significantly weaker downstream velocities from the paired jets. A strong vortex also develops between the leading jet and the surface around the orifice, adding to the vorticity of the expelled fluid from the leading jet.

3) Phase difference between 110 and 180 degrees. This case is easily distinguished by reattachment of the leading jet to the nearby exterior wall due to greater strength of the recirculation vortex on this side of the jets. This mode has the lowest downstream velocities.

Experimentally, synthetic jets with peak exit velocities of up to 130 m/s^[26] have been produced. The actual peak exit velocity of a synthetic jet can vary sometimes dramatically from the predicted velocities^[33]; therefore, experimental results were used to help guide the design of the synthetic jets used in this study. The peak synthetic jet exit velocities from various studies are summarized in Table 1 and were used as a guide of expected ranges. It can be observed in Table 1 that larger synthetic jets have been observed to have lower peak exit velocities. This may be in part due to the limit selection of larger piezoceramic actuators for synthetic jets.

Table 1: Sample of Synthetic Jet Peak Velocities

Disc D (cm)	Operating f	u_{peak}	Investigator
2.0	3000 Hz	130 m/s	Gomes, Crowther, Wood ^[26]
1.8	3800 Hz	85.8 m/s	Arik ^[16]
3.7	630 Hz	65 m/s	Gallas, Wang, Papila, Sheplak, Cattafesta ^[34]
6.4	25-100 Hz	25-50 m/s	Mane, Mossi, Bryant ^[11]
6.4	25-100 Hz	25-50 m/s	Mane, Mossi, Bryant ^[11]
5.0	25-100 Hz	25-50 m/s	Mane, Mossi, Bryant ^[11]
2.5	600 Hz	35-45 m/s	Ziegler ^[1]
2.4	2115 Hz	30 m/s	Gallas, Wang, Papila, Sheplak, Cattafesta ^[34]
2.5		30 m/s	Allard ^[20]
3.1	1100 Hz	23 m/s	Pavlova, Otani, Amitay ^[4]
4.0	1500 Hz	7 m/s	Milanovic, Zaman ^[35]
37.0	33 Hz	6.95 m/s	Milanovic, Zaman ^[35]

Experimental Set-Up

Synthetic Jets

Two synthetic jet sizes were used in this study. The small jets used a rectangular orifice of 0.5 mm by 27.5 mm with a 25 mm circular actuator. These jets were part of a 16 synthetic jet module used in previous studies^{[20][1]}. In the current study, the 4 synthetic jets on the top of the 16-jet module were used, as shown in Figure 4A. The small jets are referred to as S1, S2, S3 and S4 in this study, with jets S1 and S2 on the top of the module and jets S3 and S4 below them.^[1] Figure 4B shows the small jet array attached to the diffuser. All four small jets were operated

concurrently in the ventilation experiments presented here. The jets emerge horizontally at the top of the module (S1).

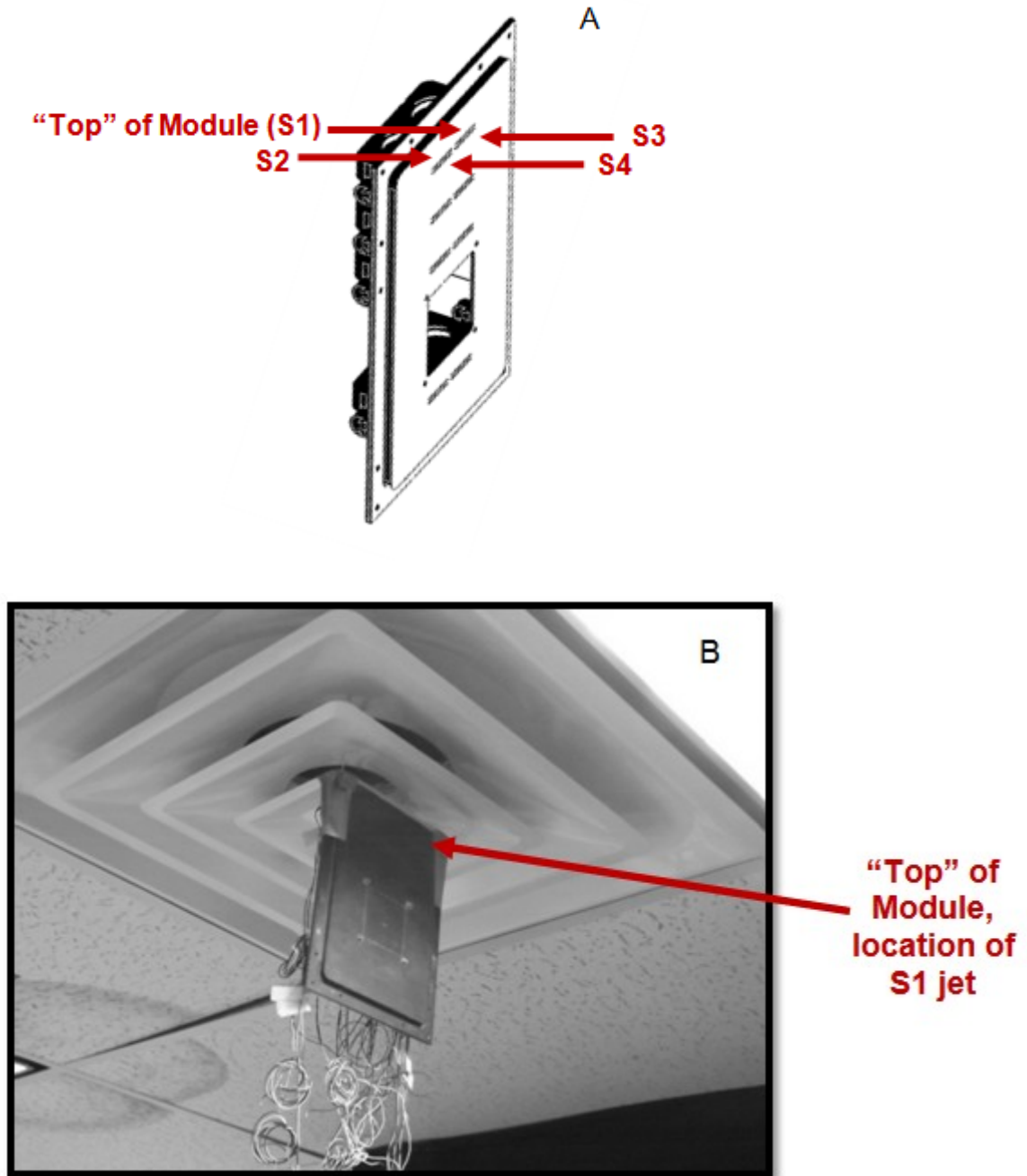


Figure 5: Small Synthetic Jets

The large jets have rectangular orifices of 0.5 mm by 55 mm and circular actuators of 50 mm in diameter and are referred to as L1, L2, L3 and L4. Jets L1 and L2 were located at the top of the module while jets L3 and L4 were located at the bottom, as shown in Figure 5B. Large jets L1 and L3 were paired and operated together during the ventilation studies. Likewise, L2 and L4 are paired and operated together in another set of experiments.

The large synthetic jets were constructed specifically for this study. Their design was informed by the performance of the smaller jets and expert advice^[36]. The prototype for the large synthetic jets is shown in Figure 6A.

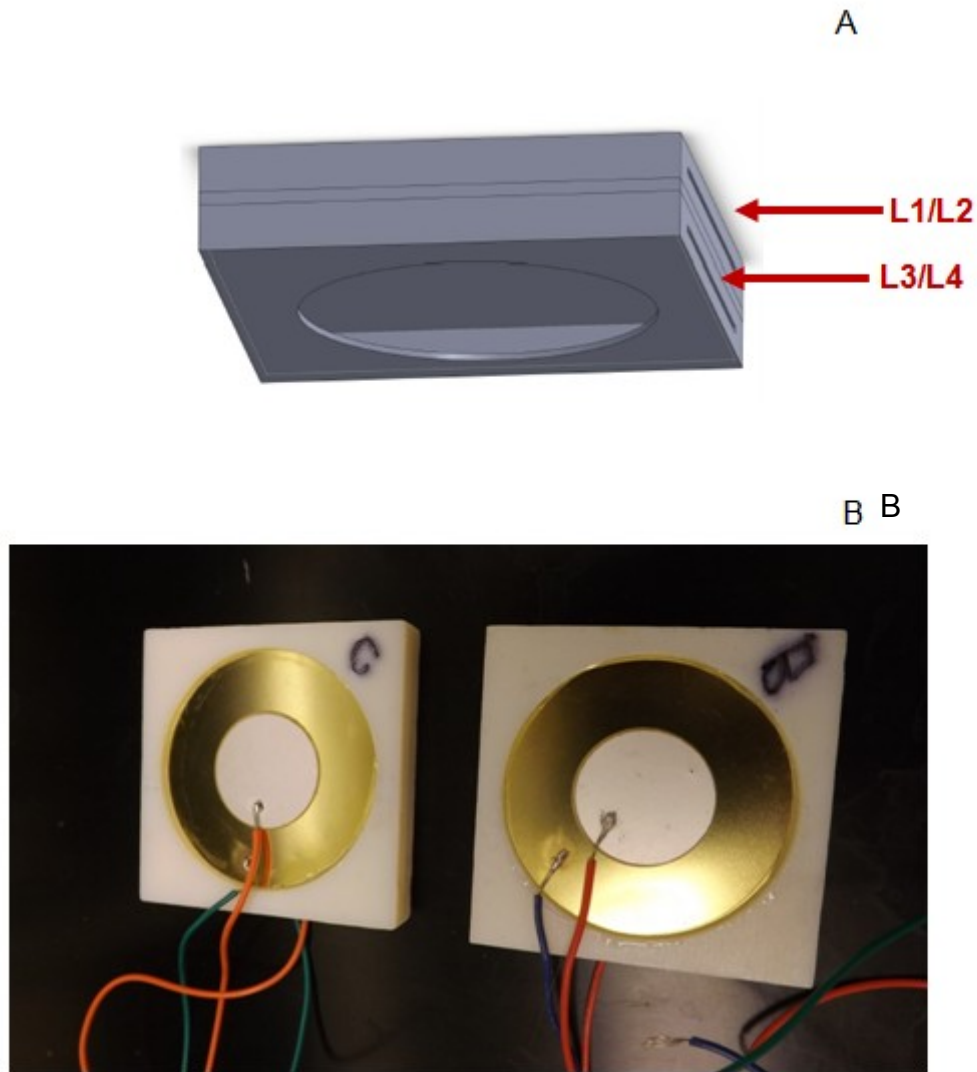


Figure 6: Large Synthetic Jets

The finished product is shown in (insert figure reference). The synthetic jet module and cavity were built using an Objet 30 3D prototyping printer (Stratasys, Eden Prairie, Minnesota) in the Integrated Teaching and Learning Laboratory at the University of Colorado. A computer model and 3D prototype was used to minimize deformations and irregularities in the construction of the synthetic jets. The performance of the synthetic jets is especially sensitive to the cavity parameters and orifice geometry ^[1], as previously discussed. The printer can create layers as small as 28 μm with a tolerance of 0.1 mm. The material used for printing was a proprietary

translucent plastic-like rigid material offered by Stratasys/Objet called VeroWhitePlus. Each module contained one pair of synthetic jets and required three hours of printing time for 33.4 cm³ of material and then an additional hour to clean each module. Some deformation occurred due to thermal stresses on the material during the cleaning process. At the centerline of the jet orifice this caused deformation was over 2mm (50% of the original size). This deformation was minimized in subsequent designs by allowing the modules to cool for 2 to 3 hours after printing and before removing printing residue. The deformation on the final cavities used did not exceed 0.5 mm.

A piezoceramic disc model 20-1235 manufactured by the American Piezo Corporation was selected as the synthetic jet actuator for the larger jets. These discs were selected because their cost (~\$0.50/disc) and shipping time were acceptable. Similarly, the resonant frequency (1.7 +/- 0.5 kHz) and maximum drive voltage (30 V_{pp}) for these units were appropriate for our applications. The selected disc has a capacitance of 80,000 pF at an operating frequency of 1 kHz and a maximum impedance of 1000 ohms. Other experimental studies have used custom made actuators^[11]; however, this study chose not to use them since the cost for small quantities (less than 100) of custom actuators, in some cases, exceeded the cost of readily available ones by 200 times (\$100+/disc). Various tradeoffs in performance were made due to cost restrictions. The ideal actuator would have a high deflection and a resonant frequency outside the human audible range. Most manufacturers report the capacitance and resonant frequency of their discs but not the deflection. The deflection decreases with higher capacitance given all other variables being the same. The deflection is also dependent on the size of the disk and material properties^[29]. Unfortunately due to a lack of other readily available options, a disc with a high capacitance and an operating frequency in the near the most sensitive part of the human audible range was

selected. No readily available (shipped in less than 5 weeks) discs were available in the size range desired that had operating frequencies outside the human audible range from the piezoceramic disc suppliers that responded including American Piezo, Seacor Piezo, PI Ceramics, and ISL Products. Ideally, a custom disc should be ordered for future experiments. The dimensions for the selected piezoceramic disc as provided by the manufacturer are shown in Figure 7^[37]. The outside diameter of the discs used was 50.0 mm, while its thickness was 0.23 mm.

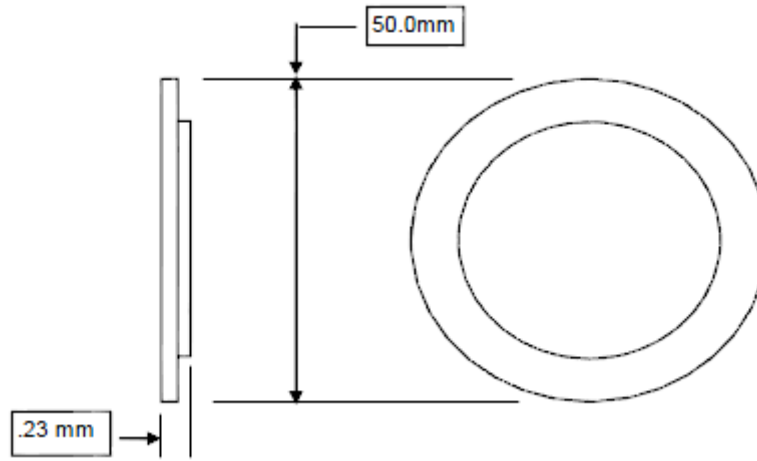


Figure 7: APC Actuator Dimensions

The synthetic jet dimensions for both jet sizes are summarized in Table 2.

Jet Type	Large	Units	Small	Units
Orifice Width $D_{c,o}$	0.5	mm	0.5	mm
Orifice Length L	55	mm	27.5	mm
Orifice Depth h	2.0	mm	1	mm
Cavity Depth H	2	mm	1.5	mm
Cavity Width $D_{c,c}$	60	mm	28	mm
Wall Thickness t	1	mm	1	mm
Jet Separation w	3.5	mm	3.5	mm
Actuator Diameter D	50	mm	25	mm

Table 2: Synthetic Jet Dimensions

The cavity width, D_c , for the large synthetic jets was increased to 60 mm to accommodate the larger actuator diameters; however, a small cavity (2 mm) and orifice depth (2.1 mm) were used

to maintain a high centerline exit velocity from the jets. The orifices of both the small and large jets had high aspect ratios (55 and 110, respectively) to minimize edge effects on the synthetic jet flow and maintain a mostly 2-dimensional planar flow^[25].

The small synthetic jets generated a peak exit jet flow velocity when operating at around 600 Hz and a smaller resonance peak at around 1200 Hz as shown in Figure 8 A, B, C and D. The larger jets had peak velocities at the cavity Helmholtz frequency of around 1100 Hz and at the actuator resonance frequency around 1700 Hz as shown in Figure 8 parts E, F, G, H. The jet pair L2/L4 was operated at 1100 Hz while the L1/L3 pair was operated at 1700 Hz to compare the performance between operating at the Helmholtz resonant frequency of the cavity versus the resonant frequency of the actuator. Jets L1 and L3 were chosen to operate together at 1700 Hz since they generated consistent peak exit velocities as shown in Figure 8. Both pairs of large jets had well-defined peaks closer the theoretical Helmholtz frequency of 2.2 kHz. The higher peak attributed to the Helmholtz resonance of the cavity occurred at a driving frequency of approximately 23% less than Equation 1 predicts.

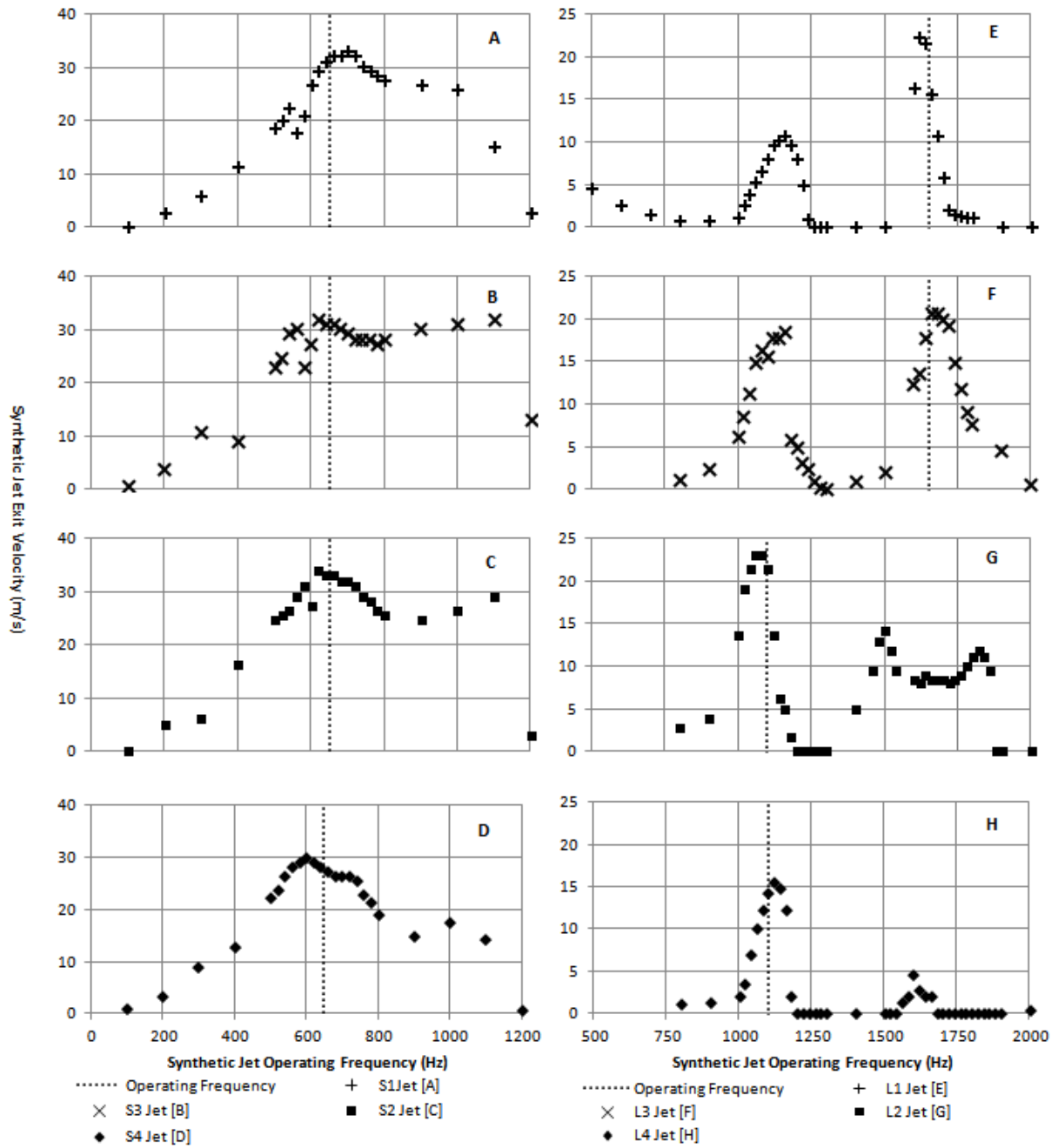


Figure 8: Synthetic Jet Peak Exit Velocity at Various Actuator Frequencies

The theoretical Helmholtz resonant frequency of the small synthetic jets was about 4 kHz but exit velocities were negligible at frequencies above 2 kHz; therefore, their Helmholtz resonant frequency was not measured. Previous studies found that when the actuator resonant frequency and the Helmholtz resonant frequency are decoupled, operation of the synthetic jets at

the Helmholtz frequency produced lower jet exit velocities ^{[26] [33]}. The farther the actuator and Helmholtz resonant frequencies are apart, the lower each resonant peak is.

The large synthetic jets have a lower theoretical Helmholtz resonant frequency of 2.2 kHz. The actual Helmholtz resonant frequency response of the large synthetic jets was found experimentally to be 1.7 kHz. The Helmholtz resonant frequency of cavities found experimentally is typically lower than the theoretically-derived Helmholtz resonant frequency due to dampening effects of real materials ^[33]. For synthetic jets, the Helmholtz resonant frequency can be even lower due to extra dampening effects of the actuator. The experimental testing of the large synthetic jets indicated that the Helmholtz and actuator resonant frequency responses were partially coupled.

The large synthetic jets had a theoretical Helmholtz resonant frequency of 2.2 kHz but the actual Helmholtz resonant frequency measured was 1.7 kHz. Helmholtz resonant frequencies of cavities measured are typically lower than the theoretically-derived Helmholtz resonant frequencies due to dampening effects of real materials ^[33]. For synthetic jets, the Helmholtz resonant frequency can be even lower due to extra dampening effects of the actuator. The experimental testing of the large synthetic jets indicated that the Helmholtz and actuator resonant frequency responses were partially coupled.

Increasing the cavity volume and the neck length decreases the Helmholtz resonance frequency but also lowers the exit velocity due to increased dampening. Decreasing the neck area will decrease the Helmholtz frequency and increase the synthetic jet exit velocity but may have unwanted effects in the vortex formation. For example, many studies elongate the neck area in one direction of the synthetic jets in order to simplify two dimensional analyses of the jets ^[2]. The neck depth to width ratio has been found to impact the synthetic jet exit velocity. A width to

depth ratio of less than 0.75 will create separation of the fluid from the orifice walls towards the downstream edge of the orifice resulting in a wider but slower exiting jet. Width to depth ratios greater than 0.75 results in fully attached flow through the orifice. Attachment of the fluid narrows the exit jet stream which accelerates the flow; however, shear forces from the slower moving fluid along the walls of the orifice decelerates the fast moving core of fluid. An optimum between these two phenomena occurs at a width to depth ratio of 1.25. ^{[38] [26]} The depth of the larger synthetic jets was originally designed to be 0.625 based on the optimal width to depth ratio however it was incrementally increased to 2 mm to help minimize deformation caused during the manufacturing process.

Lab Description

The experimental room used in this study was 6 meters (m) wide by 5.5 m deep and 2.5 m high or 81.5 cubic meters (m³) (2880 ft³). The supply ventilation rate measured during the experiments was 472 liters per second (lps) (1000 cfm) split between two Titus square 61cm x 61cm (24" x 24") ceiling diffusers (Figure 5) or an equivalent of approximately 21 air changes per hour. Supply flow rates were measured using a Balometer Flow Hood (ABT701, Alnor, Huntington Beach, CA).



Figure 9: Titus Square Diffuser [32]

Figure 10 shows the general room dimensions and ceiling plan. The western supply diffuser in the room was selected for these visualization experiments. The recessed lighting fixture just north of the western supply diffuser was covered with a black matte metal cover to minimize effects on the supply flow.

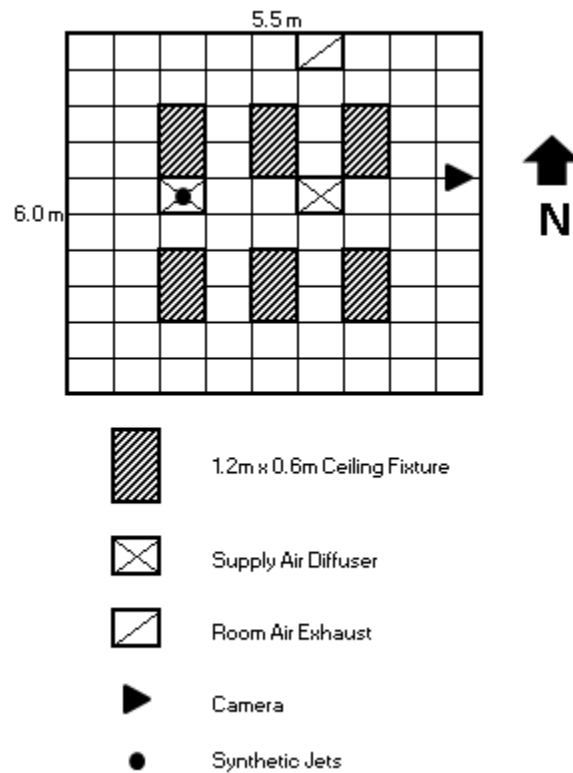


Figure 10: Lab Reflected Ceiling Plan

The supply ventilation for the room was 100% outside air provided by a central ducted air conditioning system. A 470 L/s (1000 cfm) fan coil unit provided additional heating and cooling to the space through hot and cold-water coils controlled by a local room thermostat (Figure 11).

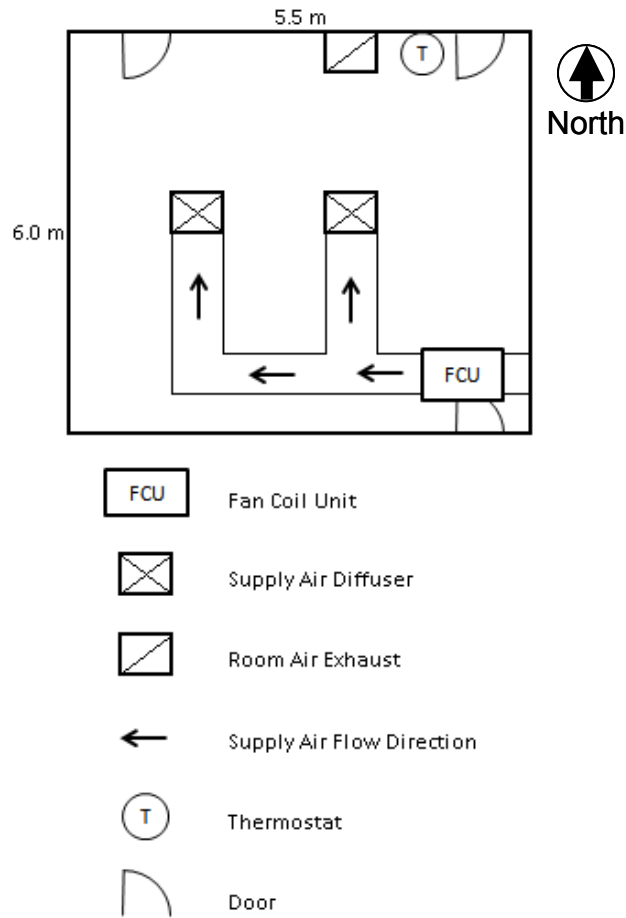


Figure 11: Lab Mechanical Plan

A single exhaust grille returned room air to the room plenum. Actual room temperature varied between 20 and 22° C. The lab was located in Boulder, Colorado at an altitude of 1615 meters (5300 feet). Typical atmospheric pressure outside the lab was 83.5 kPA during the experimental period^[39].

The synthetic jet modules were physically attached to the center of the western supply diffuser in the room. This diffuser was chosen to avoid structures that could obstruct the supply flow from the diffuser into the room.

Synthetic Jet Operation

Each pair of synthetic jets was driven using a function generator (33120A, Agilent, Santa Clara, CA). A standard sinusoidal signal was used to excite the piezoceramic actuators in the synthetic jets. Piezo Amplifiers (QPA200, MIDE, Medford, MA) were used to increase the output voltage from the function generators to a desired amount (Table 3) for each experiment. A fixed gain of 50 was used on the amplifiers while the voltage was adjusted on the function generators. The output signal was monitored using an analog Oscilloscope (OS-9020G, LG Precision, South Korea) and an universal counter (53131A, Agilent, Santa Clara, CA). The Universal Counter was also used to monitor the phase difference between the two synthetic jets. These devices were stacked and operated concurrently, as shown in Figure 12. The phase difference was adjusted between the two synthetic jets by inducing a small frequency difference (Less than 1 Hz). When the phase difference reached the desired amount (0° , 30° , 90° or 120°), the frequencies of the two driving signals were set equal again.

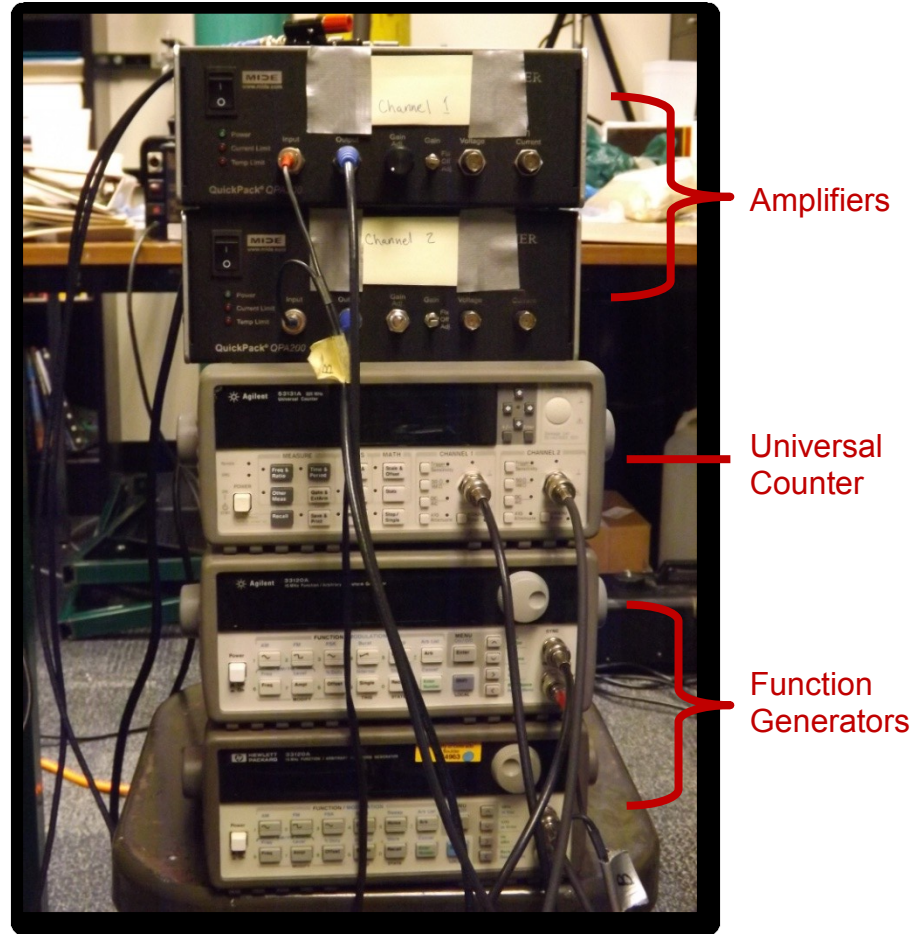


Figure 12: Synthetic Jet Control

Table 3 summarizes the operating ranges of the 3 synthetic jet modules used. Note that the large actuators had a lower acceptable voltage threshold (25 V) recommended by the manufacturer compared to the voltage required by the small actuators (50 V). The driving voltage of the actuator plays a significant role in the deflection of the actuator and ultimately the peak synthetic jet exit velocities ^[11].

Table 3: Synthetic Jet Operating Ranges

Synthetic Jet Pair	Variable	Lower Limit	Upper Limit
S1/S3 and S2/S4	Operating Voltage	50 V	50 V
	Jet Exit Velocities	20 m/s	34 m/s
	Reynolds Number	203	346
	Strouhal Number	0.048	0.028
	Dimensionless Stroke Length	20.9	35.6
	Operating Frequency	1000 Hz	600 Hz

L1/L3	Operating Voltage	25 V	25 V
	Jet Exit Velocities	20 m/s	24 m/s
	Reynolds Number	203	244
	Strouhal Number	0.048	0.04
	Dimensionless Stroke Length	20.9	25
	Operating Frequency	1700 Hz	1700 Hz
L2/L4	Operating Voltage	25 V	25 V
	Jet Exit Velocities	20	24
	Reynolds Number	203	244
	Strouhal Number	0.048	0.04
	Dimensionless Stroke Length	20.9	25
	Operating Frequency	1100 Hz	1100 Hz

Hot Wire Calibration

Hot wire anemometers were used to measure the synthetic jet exit velocities. Before conducting the actual experiments with the synthetic jets, the hot wires were calibrated to ensure accurate measurements. Once calibrated as described below, they were used to calibrate the synthetic jets to their resonant frequency. A Mini Constant Temperature Anemometer (54T30, Dantec, Skovlunde, Denmark) was used to make velocity measurements. The anemometer was connected to two types of hot wire probes (1210-T1.5 and 1212-T1.5, TSI, Shoreview, Minnesota). The probes used a 3.2 mm long platinum plated tungsten wire of a diameter of 4 micrometers. A multimeter (61-360, Ideal Industries, Sycamore, Illinois) was used to record measurements. The constant temperature hot wire anemometer measures the voltage change across the wire. The resistance of the hot wire is sensitive to the wire's heat loss, especially when the surface area to volume ratio of the wire is large (wires of small diameter). The convective heat loss from the wire is directly proportional to the velocity of the fluid moving over it. These relationships allow for a small diameter wire to be used to measure changes in velocity. The hotwire system was calibrated on a laminar flow setup using a mass flow meter (4140, TSI, Shoreview, Minnesota) to monitor the flow rate as shown in Figure 13.

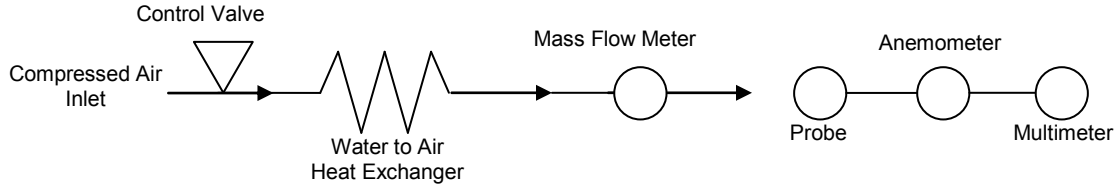


Figure 13: Hot Wire Calibration Diagram

Outdoor compressed air was controlled through a ball valve to regulate the volume. The air was then passed through a water-to-air heat exchanger to reach room temperature at 25.5 C. The volumetric flow rate of the air downstream of the heat exchanger was measured using the mass flow meter. The average air velocity was then calculated using the mass flow and the area of the 1.25 cm (1/2 in) diameter tubing the air was being channeled through using Equation 4.

$$\bar{v} = \frac{\dot{m}}{\rho A}$$

Equation 4: Velocity Prediction Calculation

The hot wire probe was placed just inside the outlet end of the laminar flow air duct to capture the average airstream velocity in the duct. The mass flow was varied over the range of the velocities expected in these experiments using the relationship in Equation 4. Velocities were expected to range between 0 and 5 m/s. Voltage readings from the anemometer at incremental mass flow rates were recorded in order to develop a calibration curve.

A quadratic correlation was used to model the relationship between predicted velocity and the anemometer readings. An example calibration curve is shown in Figure 14. All calibration curves achieved square correlation coefficients above 0.99 with a standard error of 0.12-0.14 m/s (24-28 fpm). These results suggested that the anemometer readings were accurate within a range of 0.3 m/s (60 fpm) and the calibration curves provided reasonably accurate model of the air velocity.

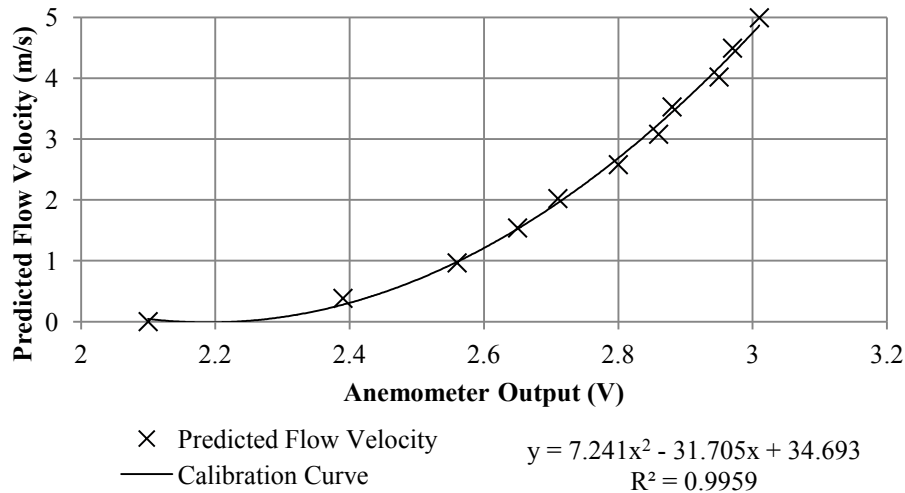


Figure 14: Representative Hotwire Calibration Curve

A residual plot is a common way to test the validity of a regression model.

Residual plots show an independent variable on the x-axis against its residuals to a regression on the y-axis. A random distribution indicates that the regression used is a good fit and the basic assumptions of the regression are met. Visual examination of the residual plot in Figure 15 shows a random distribution that suggests that the standard assumptions of independence, normal distribution, constant variance and zero mean of the random errors for the correlation are valid. Additional calibration data is included in Appendix A1.

1212 Residual Plot

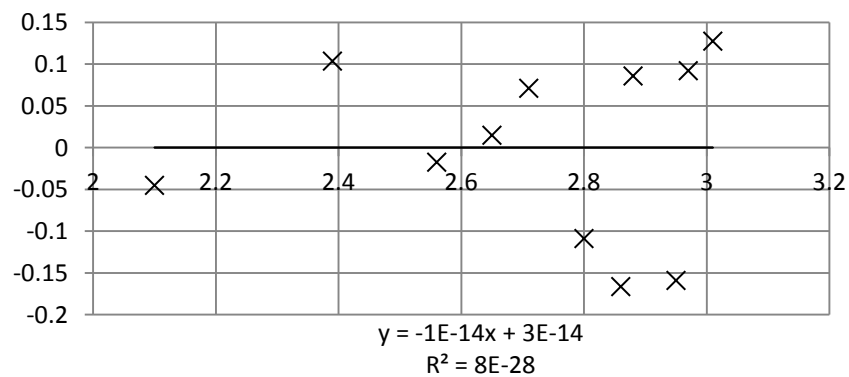


Figure 15: TSI Probe 1212 Residual Plot

Synthetic Jet Exit Velocity Measurements

The exit velocity of a synthetic jet is a primary experimentally measured variable related to synthetic jet performance. Jet exit velocity is commonly measured as peak exit velocity or as the average exit velocity ^[2]. The hot wire probe measurements correspond to the average exit velocity. The synthetic jets were oriented perpendicular to gravity to minimize the influence of gravity in the direction of the velocity measurement. The probes were positioned as close as possible to the orifice of the synthetic jets as shown in Figure 16. The measurement set up used mechanical arms to incrementally move the probe as to not make contact with the synthetic jet module or break the sensitive hot wire. The hot wire probes were extremely sensitive and could break from contact or measurements in heavily particle-laden air ^[40].

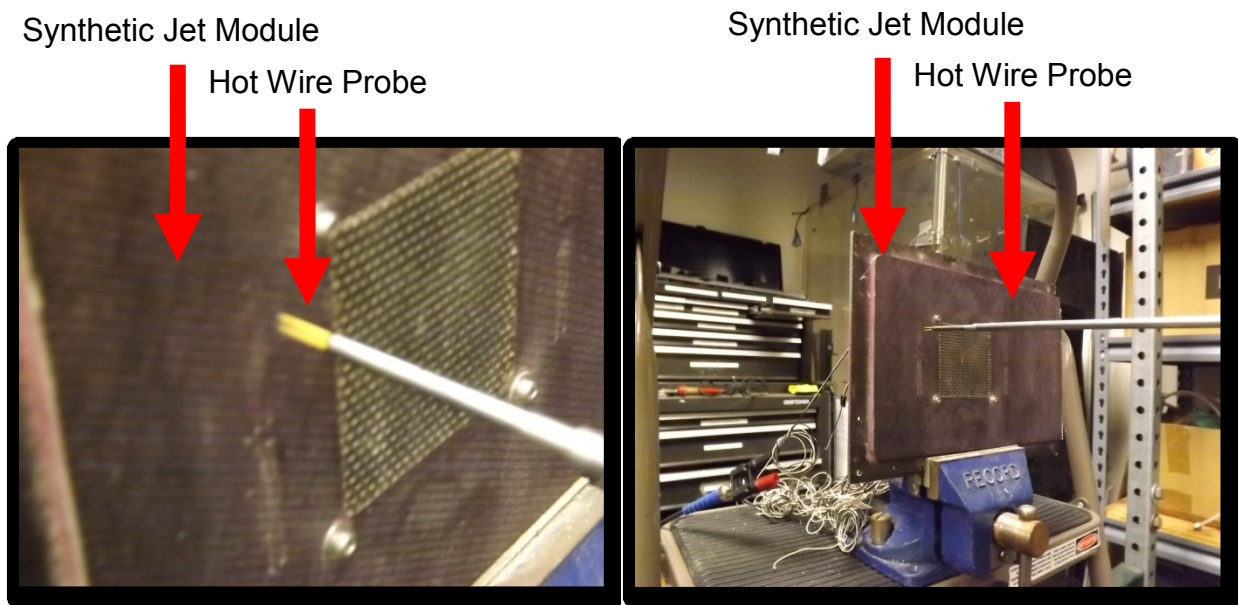


Figure 16: Synjet Exit Velocity Measurements

The synthetic jets were operated at the highest voltage recommended by the manufacturer as noted in Table 3. Previous studies ^[1] showed that increased voltage amplitude for operating the jets increased the exit velocity. Typically, the jet velocity continues to increase until the disk

becomes overloaded and is damaged, usually at a point beyond the highest operating voltage recommended by the manufacturer.

As can be noted from the measurements shown in Figure 8, the anemometer readings were recorded every 100 Hz until a peak was observed and then the frequencies were increased at a smaller increment of 10-20 Hz for greater resolution. Data points that were less than the standard error from the background room velocity are omitted from the graphics.

The set of small jets had average peak exit velocities (U_o) ranging from 20-34 m/s (3900-6700 fpm). There was a slight degradation in the measured performance from previous studies that used these jets ^[1]. Some degradation in performance is common over time among inductive ceramics such as piezoceramics ^[29]. The measured exit velocities correspond to dimensionless stroke lengths (L_o/h) between 20.9 and 35.6 and Reynolds numbers between 203 and 346. The respective Strouhal Numbers were 0.048 and 0.028.

The large jets used had average peak exit velocities between 20 and 24 m/s (3900-4700 fpm). These velocities correspond to dimensionless stroke lengths of 20.9 to 25.0 and Reynolds numbers between 203 and 244. The corresponding Strouhal Numbers for the large jets were between 0.048 and 0.040.

Two large synthetic jets test had average peak exit velocities of less than 10 m/s. Their reduced performance was likely due to production defects and therefore the jets were not used in subsequent experiments.

One previous study noted increased peak exit velocities from synthetic jets when a sawtooth or impulsed signal was used instead of a sinusoidal one ^[11]. Non-sinusoidal signals were not attempted in this study to avoid the increased turbulence and noise expected with more abrupt voltage changes.

Synthetic Jet Sound Pressure Level Measurements

Both the synthetic jet actuators and the cavities are sources of sound. The actuators are commonly used in various sound production applications including speakers and doorbells. The cavity forms a Helmholtz resonator. Any application of synthetic jets in an indoor environment must address the acoustic properties of the system. Simple measurements of the sound pressure levels produced by the synthetic jets were taken in the laboratory room where they were tested. More robust studies of synthetic jets have included testing in an anechoic chamber and muffler options for micro cooling applications ^[16].

For this study, a Sound Pressure Level Meter number (33-2050, RadioShack, Fort Worth, Texas) was used to measure the sound pressure level in decibels. The sound pressure level measurements included the noise from the synthetic jets in addition to the background noise of the lab since an anechoic chamber was not available for testing. The jets were operated at both peak frequencies corresponding with their resonant actuator frequency and their Helmholtz resonant frequency. All measurements used a C frequency weighting. The background sound pressure levels in the room were determined to be 60 db. This is a typical background level for a laboratory and the equipment that was operating in the room ^[28].

Measurements were taken as close as possible to the synthetic jet exit and then at increments of twice the distance away from the source as the previous measurement. Figure 17 shows a sample of the acoustic measurements taken for the large synthetic jet B.

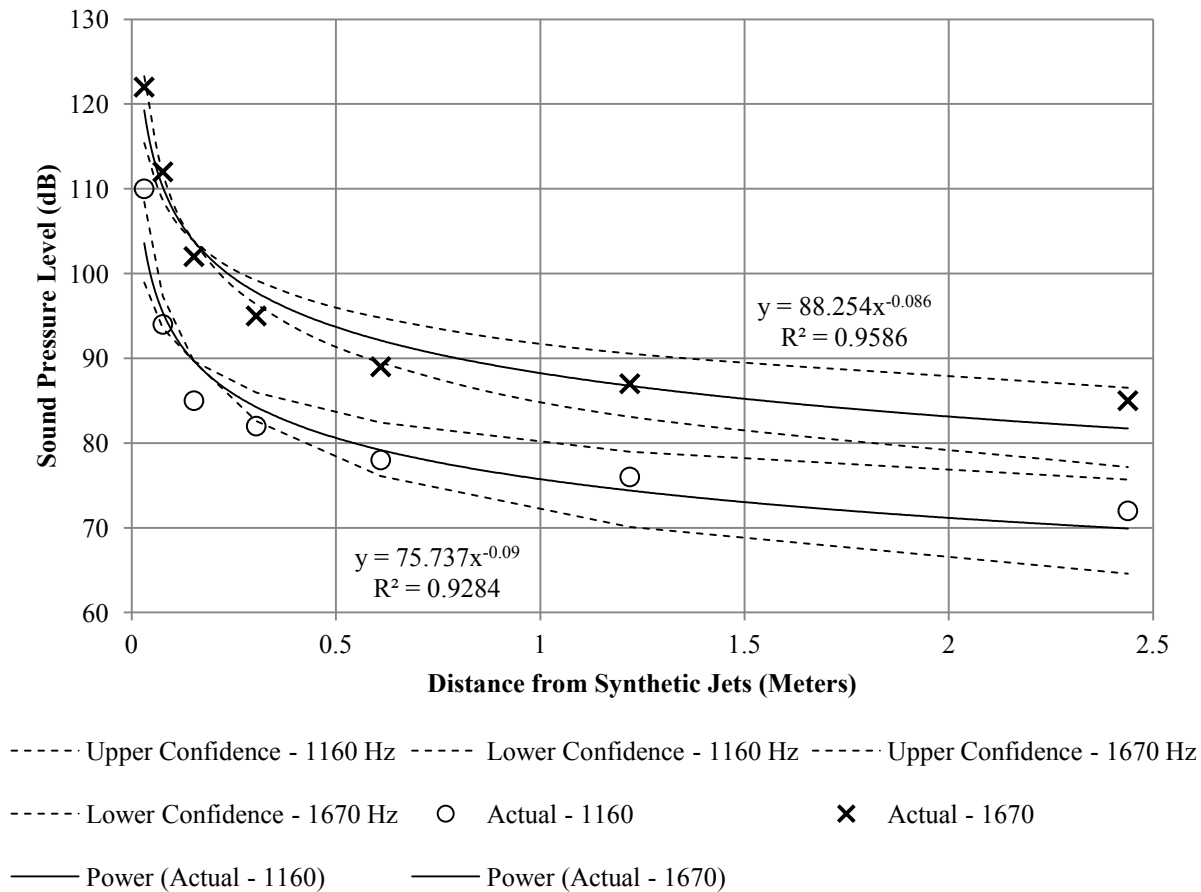


Figure 17: Synthetic Jet L2 SPL Measurements

The drop off in sound pressure level follows an expected pattern that roughly approximates the inverse square law by treating the synthetic jets as a point source. The drop off in sound pressure level was quicker in the near field and slower in the far field than would be predicted by the inverse square law. This abnormal behavior is likely due to the presence of other sources in the room (HVAC and Lab Equipment) as well as sources of reflection. A power regression was used to better model the synthetic jet noise in the laboratory setting in the presence of other sources. Both of the power regressions have correlation coefficients over 0.90 suggesting the curve fits the data well. Figure 17 shows the power regressions at both operating frequencies including the upper and lower 95% confidence intervals. The power regressions

show strong evidence that the lower operating frequency of the jets produced significantly lower noise. The format of the power regression used is described by Equation 5.

$$SPL(x) = b * x^m$$

Equation 5: Power Regression Equation

The confidence intervals shown in Figure 17 suggest that the regression “*b*” coefficient is significantly different between the two operating frequencies (1670 and 1160 Hz). The difference in the “*b*” coefficient suggests that the sound pressure level at the Helmholtz frequency is significantly higher (greater than 10 db close to the synthetic jets) than that at the actuator resonant frequency. There is not enough statistical evidence to suggest that the exponential coefficients are significantly different. The exponential coefficient should be similar because decay rate of the sound should be similar regardless of the operating frequency^[28].

Even the relatively lower sound pressure levels generated at the actuator’s resonant frequency were high for an inhabited environment. Prolonged exposure to sound pressure levels above 80 db may result in hearing damage. The Occupational Safety and Health Administration (OSHA) have set a permissible exposure limit (PEL) for sound pressure levels of 90 dB averaged over an 8 hour work day. For every 5 dB over 90 db the PEL is half of the time of the 90 db PEL. 120 db was the highest measurement taken right next to the synthetic jets. Under the OSHA PEL system a worker could only be exposed to 120 db for 7.5 minutes^[41]. The sound pressure levels close to the synthetic jets are high enough to cause hearing damage over short exposures (less than an hour) if an occupant was repeatedly exposed to it as well as discomfort. An occupant would likely be about a meter away from the synthetic jets if they were mounted on the ceiling. At one meter, an occupant would be exposed to 90 dB if the jets were operated at the Helmholtz frequency. 90 dB is equivalent to the noise of heavy traffic about 6 meters away. Due to the high

sound pressure level measurements recorded two forms of hearing protection were used at all times when operating the synthetic jets^[28].

Flow Visualization Measurements

Visualization of the supply airflow was achieved by introducing a particle seed flow into the supply airflow. The seed used was a glycol fogging solution that was atomized by two ground foggers, Models FLL-400 and FM-400, (Heshan Lide, Heshan, Guangdong China) introduced into the supply duct at the location depicted in Figure 18. This figure also shows a cross-section of the flow visualization set up and the relevant dimensions in the room. The laser sheet to illuminate the particle seed flow was positioned to reflect off a mirror such that it would cover the camera's field of view. The camera captured the near field flow of the supply jet. The interior of a fogger is included in Appendix A3.

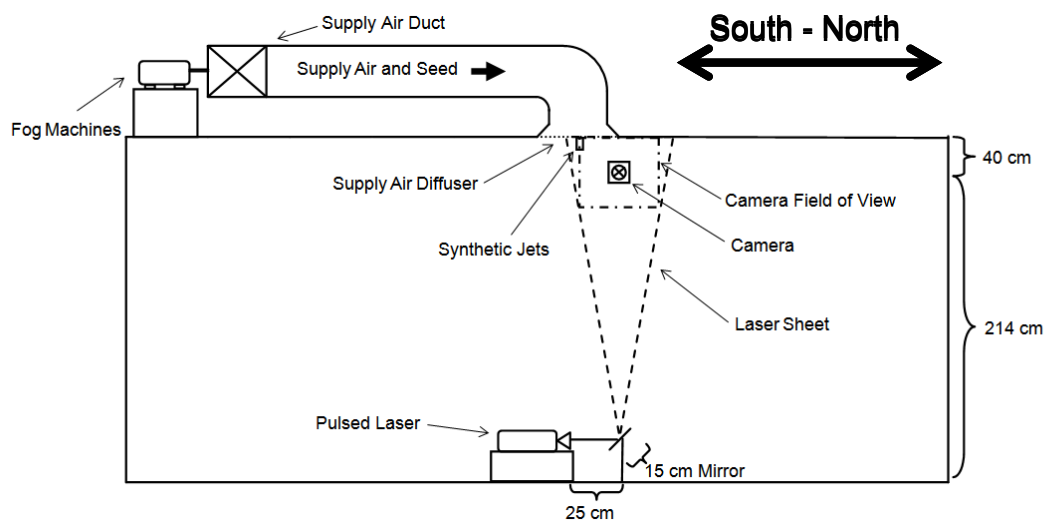


Figure 18: Lab Elevation Cross Section

The seed flow was introduced 2.5 meters upstream of the supply diffuser to allow adequate mixing of the fog with the supply air. The fog machines were capable of operating for 2 minute intervals repeatedly with some variation (+/- 30 seconds). Each experiment lasted one minute so

the fog machines were started 30 seconds before each experimental run in order to achieve a steady supply of fog throughout the experimental runs.

In order to determine whether the seed particles will be entrained in the supply jet flow and accurately represent the supply flow, the Stokes Number can be calculated^{[42] [43] [43]}.

$$S = \frac{U_f * \tau_p}{d_p} \text{ Stokes Number}$$

$$\text{Where } \tau_p = \frac{\rho_p d_a^2 C}{18\mu}$$

$$U_f = \text{Velocity of Flow Field}$$

$$d_p = \text{Seed Diameter (assuming spherical particles)}$$

$$\rho_p = \text{Particle Density}$$

$$d_a = \text{Characteristic Length of Flow}$$

$$\mu = \text{Dynamic Viscosity of the Fluid}$$

$$C = \text{Cunningham Slip Factor}$$

Equation 6: Stokes Number

The Cunningham Slip Factor is 1 assuming that the particles are spherical and the Knudsen Number is small (Knudsen $\ll 1$). The Knudsen Number is defined as 2 times the mean free path of the fluid molecule divided by the particle diameter. Particles with a Stokes number less than one are entrained in the flow field and their movement is dominated by the viscous forces of the flow. Particles with high Stokes numbers settle out quickly. The seed flow was chosen because it has a low Stokes number and serves as a good proxy for the supply ventilation flow. Typically, the seed particles generated have diameters around 1 μm and larger^[21] and have a density and viscosity similar to vegetable oil. The supply jet flow had velocities of around 0.8

m/s and below at the diffuser, as measured by the hot wire anemometer. Stokes numbers with a value less than one indicate that the seed particles will accurately represent the fluid flow ^[43].

The laser sheet optics are depicted in Figure 19. The seed particles were illuminated using a pulsed 120 mJ Nd:YAG laser. A -15 mm cylindrical lens expands the laser sheet into a plane while a second 1000 mm spherical lens compresses the plane into a thin sheet. The lenses were selected such that the laser sheet would expand to be approximately 2 meters across after travelling roughly 2.5 meters. The set-up allowed the laser sheet to be reflected off a 16 cm by 30 cm mirror after travelling 25 cm and up 2 meters onto the ceiling while being wide enough to capture the field of view of the camera.

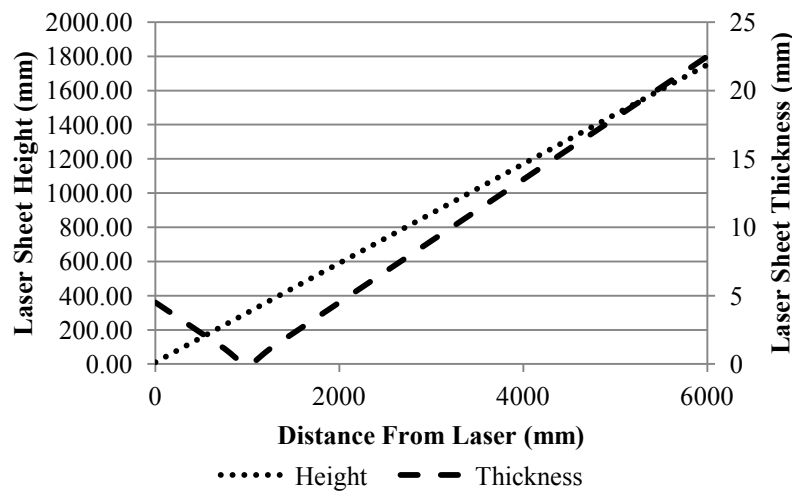


Figure 19: Laser Sheet Optics

The laser sheet was perpendicular to the ceiling and parallel to the field of view of the camera. The camera was focused as close as possible to the laser sheet at the center of the supply diffuser of interest, and at a distance of approximately 350 cm away from the camera lens.

The digital image of the flow was captured using a PIVCAM CCD (13-8, TSI, Shoreview, Minnesota) camera at a resolution of 1280x1040. The aperture setting used was f/2.8 with an exposure of 405 microseconds. The camera field of view used in these experiments was

133cm across by 113 cm down. Each image pixel represents approximately 1 mm x 1mm in the flow plane. The camera was synced to the laser using a 610034 Laser Pulse Synchronizer with a pulse rate of 3.63 Hz and pulse delay of 400 microseconds. Sixty images were captured in each experiment over 1 minute of synchronized laser pulses.

Analysis Methodology

The flow images obtained were analyzed visually and with numerical methods. The near-field flow, within 30 centimeters of the center of the supply diffuser, was numerically analyzed after completing some digital processing of the flow visualization images using the GNU Image Manipulation Program (GIMP Version 2.8) ^[44].

Visual analysis consisted of reviewing the images individually to identify differences in the supply flow angle and/or the flow structures. Transient turbulence prevented any trends from being identified visually in the individual exposure images. The averaged exposure of all the individual images allowed a better visual analysis. The average exposure was processed using the GIMP software. Differences in the angle of the supply jet were identified through visual inspection of the average images when comparing the experiments with active synthetic jets and the baseline experiments (without any synthetic jets). Slight curvature was noticed in some of the supply air jets although the effect appeared to be minor. Quantitative analysis followed visual inspection to better understand the magnitude of the effect of the synthetic jets.

To determine the long-term trend behavior of the supply flow, all the short exposure images were digitally averaged for each experiment. They were then used to simulate a long exposure over the minute of time-stepped images. This process was achieved by layering the images and reducing the opacity of each layer in a decreasing geometric sequence.

A spiked transfer function was then applied to enhance the edge of the seeded supply flow and eliminate the rest of the image. Some of the image that did not include the edge of the supply flow was retained after step E. These non-flow pixels were manually removed during step F leaving a clean image with just the pixels corresponding to the edge of the supply flow.

For each experiment, a “blank” image of non-seeded flow was first recorded. An example “blank” image is shown in Figure 20.A. Next, short exposures were taken at time steps of approximately one second for one minute synchronized with the pulsed laser as shown in Figure 20.B. These images captured transient turbulence resulting from the periodic supply flow. In order to determine the long-term trend behavior of the supply flow, all the short exposure images for a single experiment were digitally averaged together. They were then used to simulate a long exposure over the minute of time-stepped images. This process was achieved by layering the images on top of each other and reducing the opacity of each layer in a decreasing geometric sequence. A representative end image is shown in Figure 20.C. Next, the “blank” image was subtracted from the simulated long exposure image to display the difference in pixel intensity on the image generated by the seeding in the supply flow. Figure 20.D shows one of the results from this step. A spiked transfer function was then applied to the previous step to enhance the edge of the seeded supply flow and eliminate the rest of the image. Some of the image that did not include the edge of the supply flow was retained after step E. These non-flow pixels were manually removed during step F leaving a clean image with just the pixels corresponding to the edge of the supply flow. The GNU Image Manipulation Program version 2.8 was used for all digital processing of the images. Unadjusted images for analysis step F for each experimental run is included in Appendix A2. A representative supplemental flow visualization image that was used for visual inspection is included in Appendix A4.

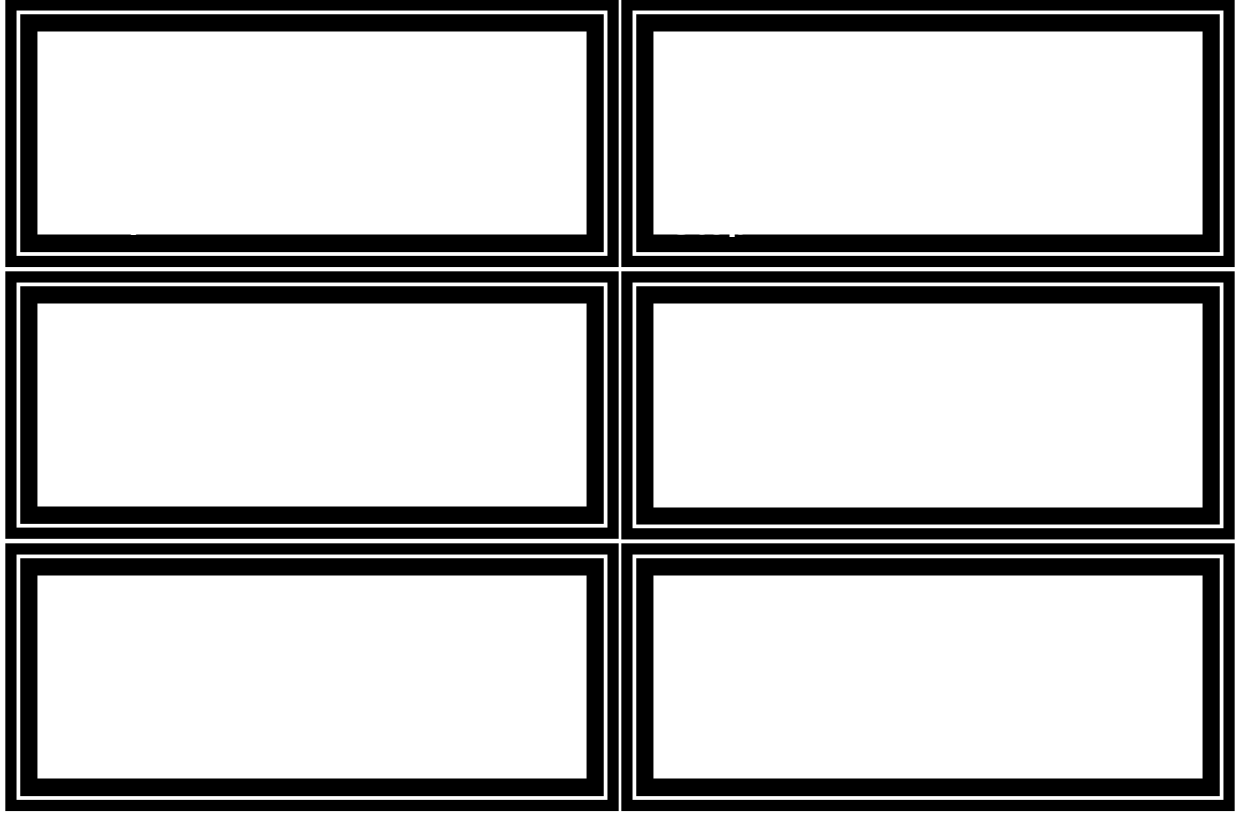


Figure 20: Digital Processing Steps

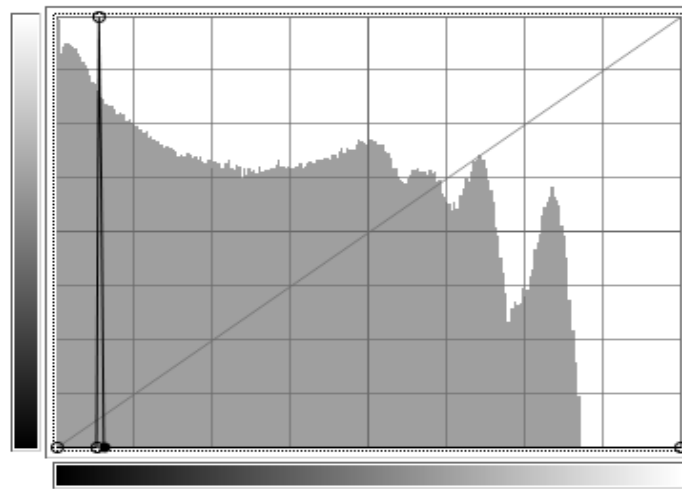


Figure 21: Edge Detection (Threshold) Transfer Function

After visual inspection, the final processed long exposure images were exported for statistical analysis as a text file. A linear regression was performed on the locations of the edge pixels to determine the line of best fit to represent the edge of the flow. The inverse tangent of

the slope results in the best fit angle of the supply flow. This method provided a standard numerical method that was used to compare the experiments. An example of this analysis for supply ventilation flow with synthetic jets is shown in Figure 22 and Table 4.

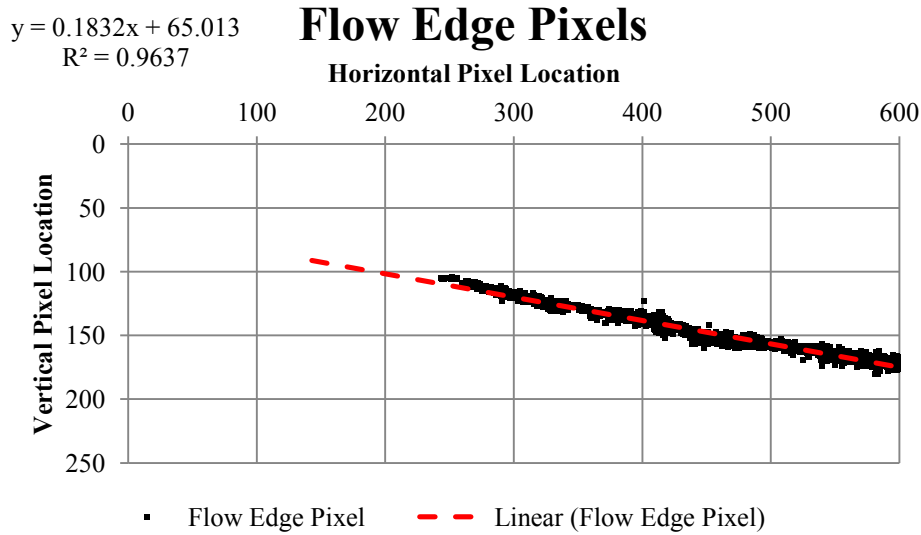


Figure 22: Sample Flow Edge Linear Regression

Table 4: Sample Flow Edge Linear Regression

	<i>Coefficients</i>	<i>Standard Error</i>	<i>t Stat</i>	<i>Lower 95%</i>	<i>Upper 95%</i>
Intercept	65.01	0.43	151.10	64.17	65.87
X	0.18	0.00094	194.93	0.18	0.19

<i>Regression Statistics</i>	
Multiple R	0.98
R Square	0.96
Adjusted R Square	0.96
Standard Error	3.40
Observations	1432

This analysis enabled comparisons between experiments using the slope of best fit and R squared value. Low R-Square values correspond with non-linear supply flows while high R-squared values, close to one, indicate that the visualized flow-capture is linear in the near-field.

Analysis Results and Discussion

Statistical hypothesis testing was used to compare the mean supply flow angle out of the diffuser during synthetic jets activation to the angle of the baseline case (no flow control). The null hypothesis set the difference in the mean angles between the baseline flow and any flow with a synthetic jet active equal to zero. A two-sample t-test was used to assess the difference between the two plume slopes. The summary results for the set of small synthetic jets are shown in Figure 23. In this figure, the plume angle (in degrees) determined using the numerical analysis for each phase difference (between the leading and lagging jets) tested is included. The null hypothesis was rejected at an level of significance (α) level of 5%. This was true for all the operating modes except when the two jets were operated at a zero phase difference.

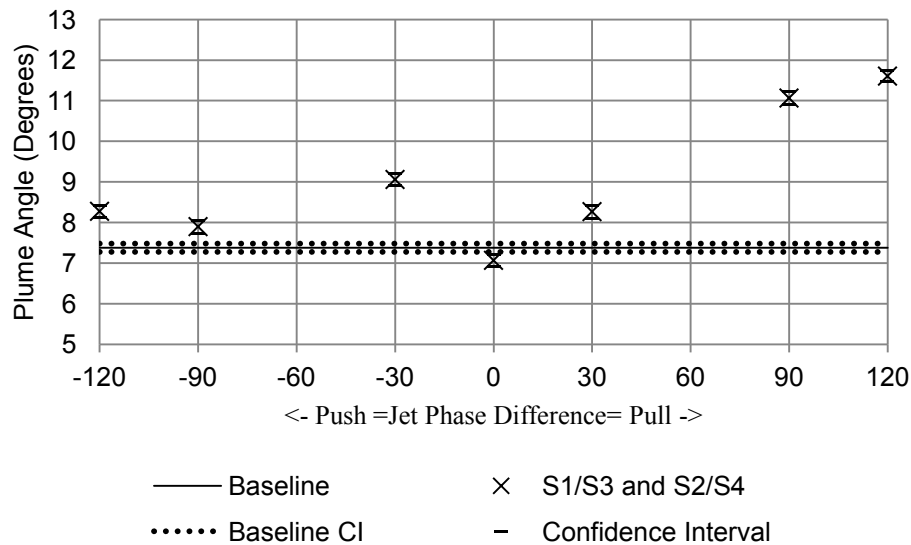


Figure 23: Flow Visualization Summary Results – Small Synjets

The large jets showed mixed results compared to the small jets. Figure 24 shows that the null hypothesis would fail to be rejected for the L2/L4 synthetic jet pair at operating phase differences of -30, 90 and 120 degrees. For the large L1/L3 jets, the null hypothesis appears that it would fail to be rejected at a phase difference of -90 degrees.

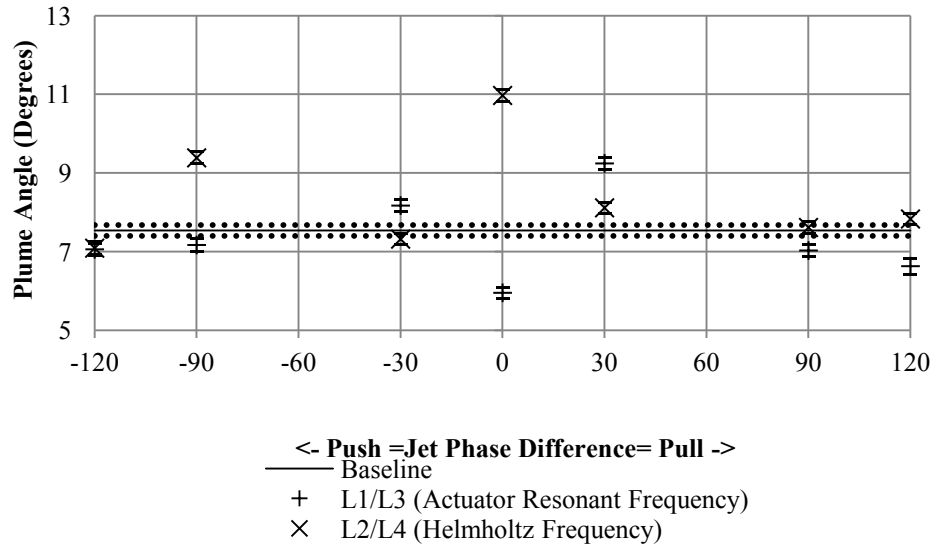


Figure 24: Flow Visualization Summary Results - Large Jets

A rejection of the null hypothesis in this case indicated that the synthetic jets had a visually detectable impact on the angle of the supply flow entering the room. By manipulating this effect, the supply flow jet attachment and detachment to nearby surfaces can be controlled to some extent. As summarized in Room Air Diffusion background section, the attachment/detachment of the supply jet flow has meaningful impacts on the room air diffusion including the control of drafts and the efficiency at which the air in the room is exchanged. Increasing the slope of the supply air jet with detach the jet from nearby surfaces increasing drafts in the room. A decrease in the supply jet angle produced by the L1/L3 synthetic jets operating at a phase difference of zero as seen in Figure 24 would result in an increased attachment and acceleration of the supply air jet along the attached surface. A decrease in slope may result in better mixing in the room and increased thermal comfort for the occupants.

Controlling the supply air jets using synthetic jets may also be used to direct contaminants entrained in the flow toward the ventilation system. The size of particles entrained in the flow is theoretically dictated by the Stokes Number. Stokes numbers over 1 suggest that

the given particles will follow the fluid flow well while Stokes numbers under 1 suggest particles will settled out of the flow field due to gravity. At a macro scale, such as a room, the synthetic jets may provide a means to control the dispersion of contaminants from sources within that room.

Controlling the supply air jets using synthetic jets may also be used to direct contaminants entrained in the flow toward the ventilation system. The size of particles entrained in the flow is theoretically dictated by the particle Stokes Number. Stokes numbers over 1 suggest that the given particles will follow the fluid flow well while Stokes numbers under 1 suggest particles will settled out of the flow field due to gravity. At a room scale, the synthetic jets may provide a means to control the dispersion of contaminants from sources within that space.

For the large jets, the greatest impact on the supply flow appears to occur at an operating phase difference of zero. The small synthetic jets had the least effect on the supply jet flow at an operating phase difference of zero and the greatest impact at a highest phase difference tested (120 degrees) in the pull mode. The strong pulling ability of the small synthetic jets was observed previously in small scale studies ^[1]. The small jets had the greatest impact at -120 degrees creating a change in the supply air jet angle of over 4 degrees. The greatest impact on the supply jet that the large synthetic jets were able accomplish was pulling it away from the ceiling 3 degrees at a phase difference of zero. The effect of the synthetic jets both large and small was mostly a pulling effect leading to an increase in the supply jet angle. The greatest pushing effect of the jets was less than half of the magnitude of the pulling effect. The greatest push effect was observed at a phase difference of zero for the L1/L3 jets and created a change in supply jet angle of less than 1.5 degrees.

Synthetic jets are small and can be installed at the terminal of an air distribution system; therefore, they can be retrofitted into present buildings or integrated into new constructions. Retrofitting would allow synthetic jets to potentially address issues such as drafts in current construction that may not be addressed cost-effectively using passive methods.

The main obstacle to the application of synthetic jets indoors is the acoustic properties of the jets. The synthetic jets are very loud under the current designs. One promising solution to this obstacle is to use a driving actuator that operates at a different resonant frequency. Custom actuators are available at a wide range of resonant frequencies but the cost can be high. The actuators used in this study were readily available and cost-effective but had a resonant frequency near the frequencies at which the human ear is most sensitive (1 kHz) ^[28]. Operation at the Helmholtz resonant frequency also had a significantly higher sound output. Synthetic jets operating at a frequency below 20 Hz or above 20,000 Hz would likely be imperceptible to human occupants. It is not suggested to attempt to address the issue through the Helmholtz frequency since it would require a very small or very large cavities or orifices to obtain the desired frequencies. The exit velocity of synthetic jets using extremely small cavities become sensitive to manufacturing defects and viscous losses while very large cavities are susceptible to energy losses due to an increased mass of air inside the cavity relative to the magnitude of the force of the actuator.

Conclusion

Results of this flow visualization study suggest that synthetic jets may be used for indoor flow control; however, more research is still needed. These results showed a noticeable vectoring of the supply jet away from the ceiling of up to 4° or 50% of the original supply angle. The reduction of the supply jet angle was expectedly smaller due to the constraining influence of the

ceiling.. The greatest reduction in the supply flow angle achieved by any of the synthetic jets was less than 1.5° . The small pairs of synthetic jets showed performance consistent with previous studies ^[1] with the strongest effect of the jets measured in the “pull” mode of operation. The large jets had much less consistent performance exemplified by The L1/L3 pair having a 1° “push” effect towards the ceiling and the L2/L4 pair having a 3° “pull” effect away from the ceiling on the supply jet at an operating phase difference of 0° . Both the pull and push effects of the large jets had less impact on the supply jet angle compared to the small jets.

Several factors may have influenced these results. As reported by previous studies ^{[2] [1]} ^[33], synthetic jet performance is highly dependent on the parameters of the cavity. Firstly, imperfections in the manufacturing process can dramatically alter the performance of the synthetic jets. Some deformation or damage to the synthetic jets may have been introduced during the initial printing of the cavities, the cleaning of excess residue from the cavities after the printing process, during the attachment of the actuators or by handling the synthetic jets. Secondly, many of the design parameters for the large synthetic jets were not optimized for this application. The limited availability of commercial actuators greater than 50 mm in diameter led to the use of actuators with less than desired characteristics. The orifice depth used in these experiments was made longer than optimum in order to minimize structural deformation of the orifice during the manufacturing process. Greater control over the manufacturing process and the actuator properties will decrease the uncertainty of the results and enable a clearer understanding of how large synthetic jets interact with supply flow jets.

Greater control of the manufacturing process and selection of the actuator properties is required to decrease the uncertainty of the results and develop a clearer understanding of how larger synthetic jets interact with supply flow jets.

Future Work

These results suggest various directions for research to further develop synthetic jets for improving indoor environmental quality. Indoor environments are subject to a wide variety of heating, cooling and ventilating parameters that impact the performance of the synthetic jets. Variations in room conditions including heat loads, ventilation rate, supply air diffuser type, supply air temperature and room pressurization may influence synthetic performance. Particle Image Velocimetry studies can provide more detail for how the synthetic jets interact with the supply jet flow including potential increases or decreases in supply air velocity and how the supply jet mixes with room air. Contaminant concentration studies following ASHRAE Standard 129 could show whether or not the use of synthetic jets can influence air change effectiveness in a room. Room air distribution theory suggests that the synthetic jets ability to vector the supply jet and influence its attachment to the ceiling would impact the mixing of room air and possibility increase the air change effectiveness of the system^[21].

Additional ventilation experiments could examine using the jets to facilitate the mixing or air in a room in “dead regions” where air circulation is poor or in absence of other mechanical ventilation. Synthetic jets could even potentially provide an alternative to fans for air movement particularly in circumstances that require low pressures drops due to the zero-net mass flux characteristics of the jets.

Optimization of synthetic jet parameters including actuator resonant frequency, actuator deflection, cavity size and orientation of the cavity orifice has been shown to affect synthetic jet performance^{[2] [26] [27]}. Variation of these parameters may give insights to the ability of synthetic jets to operate in the indoor environment. These studies could be performed experimentally^[26] by adapting derived models^[33] or building on past CFD studies^[44].

Acoustic research is needed to properly assess the implementation of synthetic jets in indoor environments. Optimization between the flow control and acoustic performance of synthetic jets may prove useful for various applications^[16]. Several acoustic abatement strategies may improve their effectiveness indoors including coupling/decoupling of synthetic jet resonant peaks, selection of operating frequencies outside of the audible range, mufflers, selection of different materials or even active noise cancellation^[28].

Sound from the synthetic jets may be useful in certain applications. In particular, for flow control use in emergency situations, the synthetic jets may provide an audible alarm in addition to their flow control functions. Operation of flow hoods or other laboratory exhaust systems may benefit from acoustic and flow control characteristics of synthetic jets. Fire suppression is another potential avenue that could take advantage of both of these traits. Both environments often require audible alarms and may use active systems contain hazards.

With acoustic abatement, synthetic jets could be used as a personal cooling or ventilation strategy due to their improved cooling capability^[15], compact size and low energy consumption. Personal cooling application would require much lower noise generation (30 db+) to avoid acoustic discomfort.

Finally, the particle sorting attributes of synthetic jets could be implemented as part of indoor filtration strategies. The compact size, low energy consumption and low pressure drop are all major advantages for using synthetic jets for indoor air filtration. Careful selection of the driving parameters of the actuators (specifically frequency and voltage) could be used to manipulate the vortex formation of the synthetic jets in order to entrain particles of different sizes in the jet flow. By adjusting the phase difference between two adjacent jets the entrained

particles could be vectored into a scupper or some sort of collection device and removing them from an air stream.

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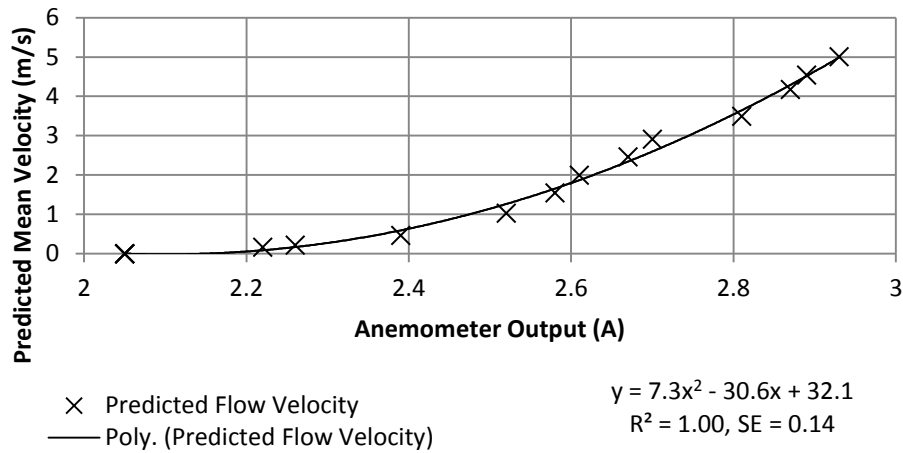
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Appendix

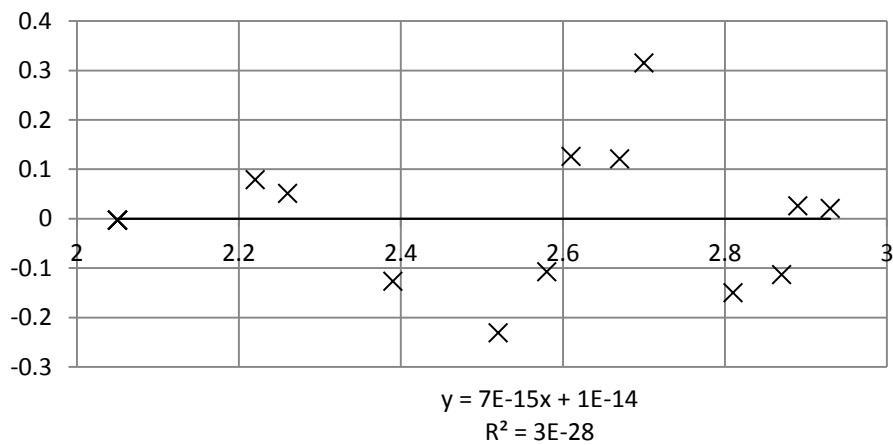
A1.

Hot Wire Calibration

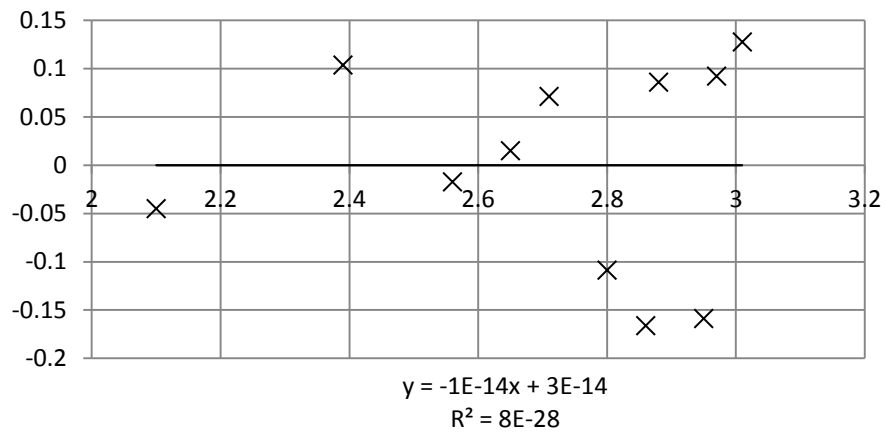
Predicted Flow Velocity - 1210



1210 Residual Plot



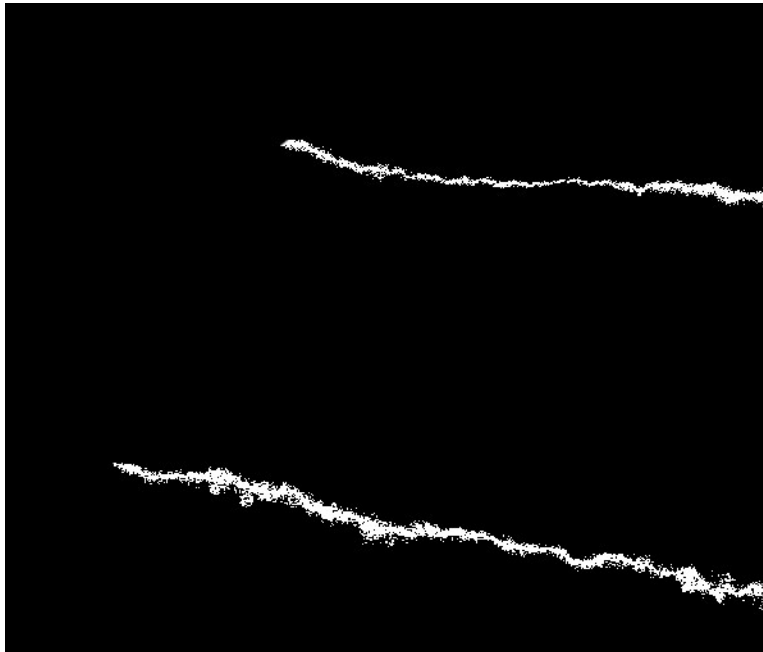
1212 Residual Plot



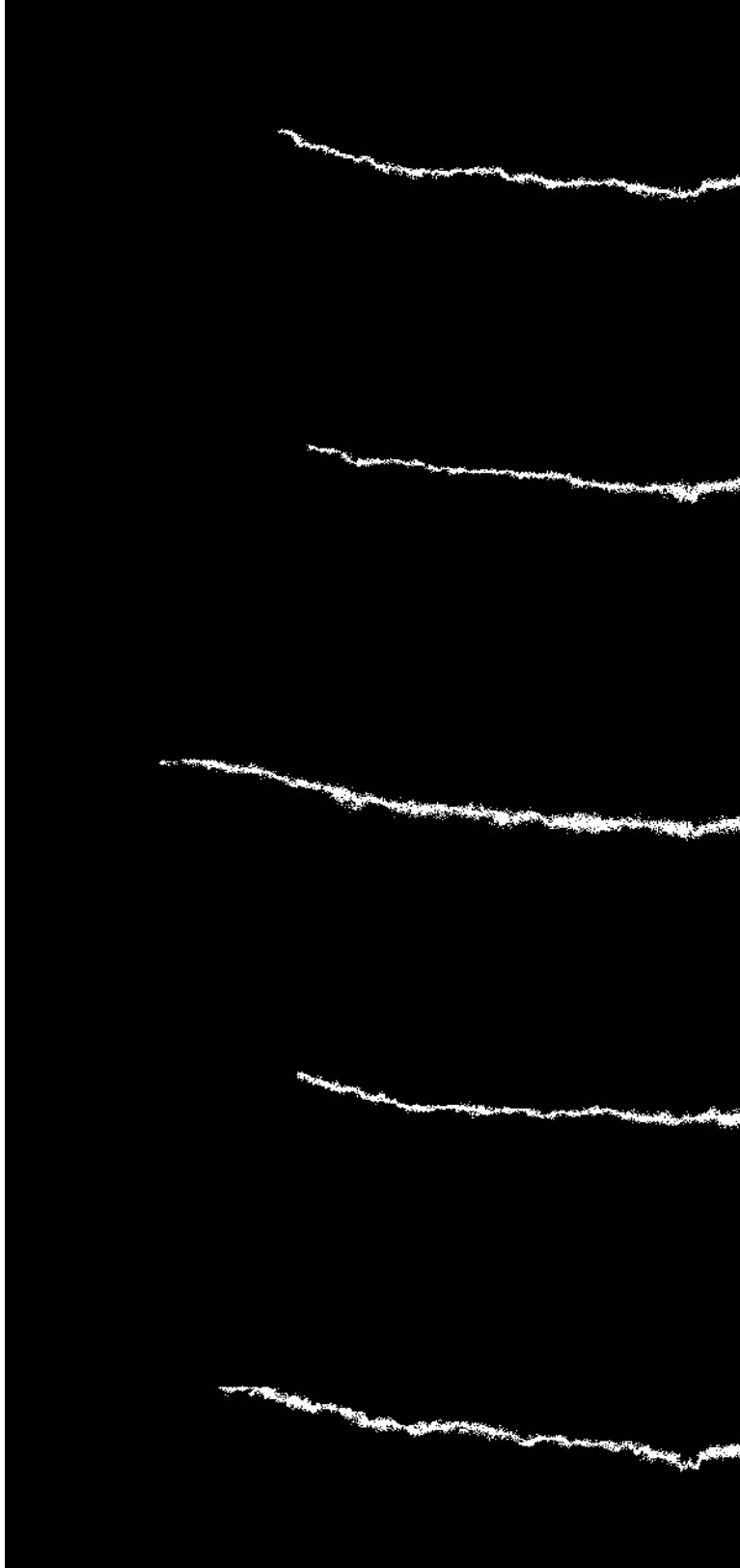
A.2

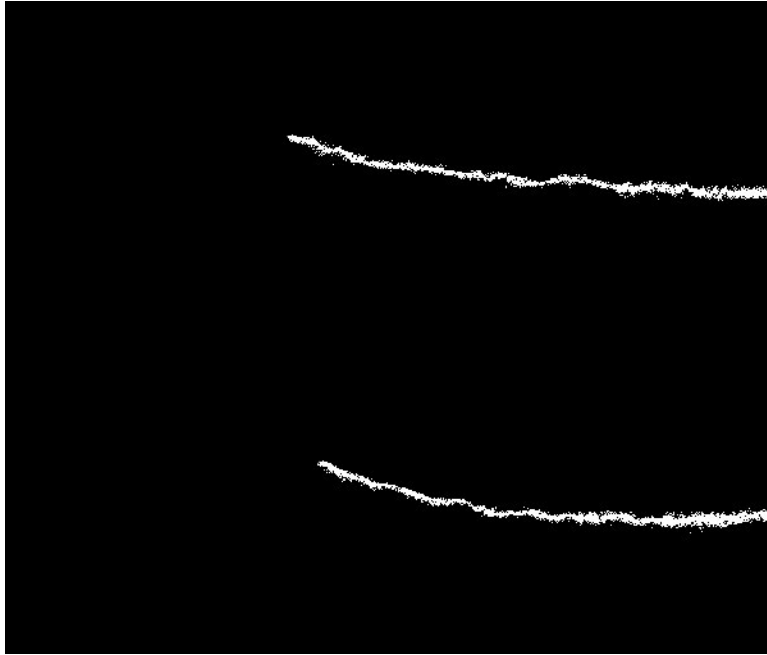
Uncorrected Averaged Experimental Run Images (Step F In Analysis)

- Baselines (No Jets)

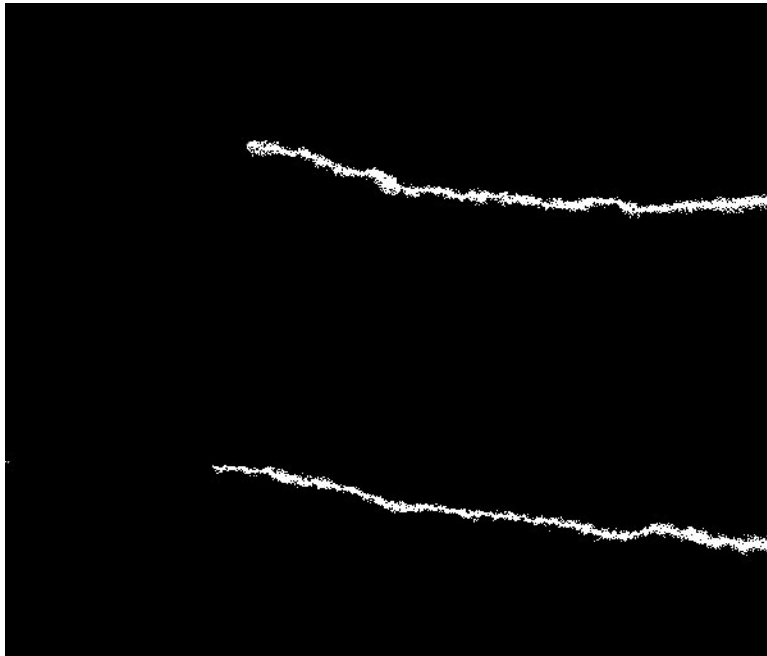


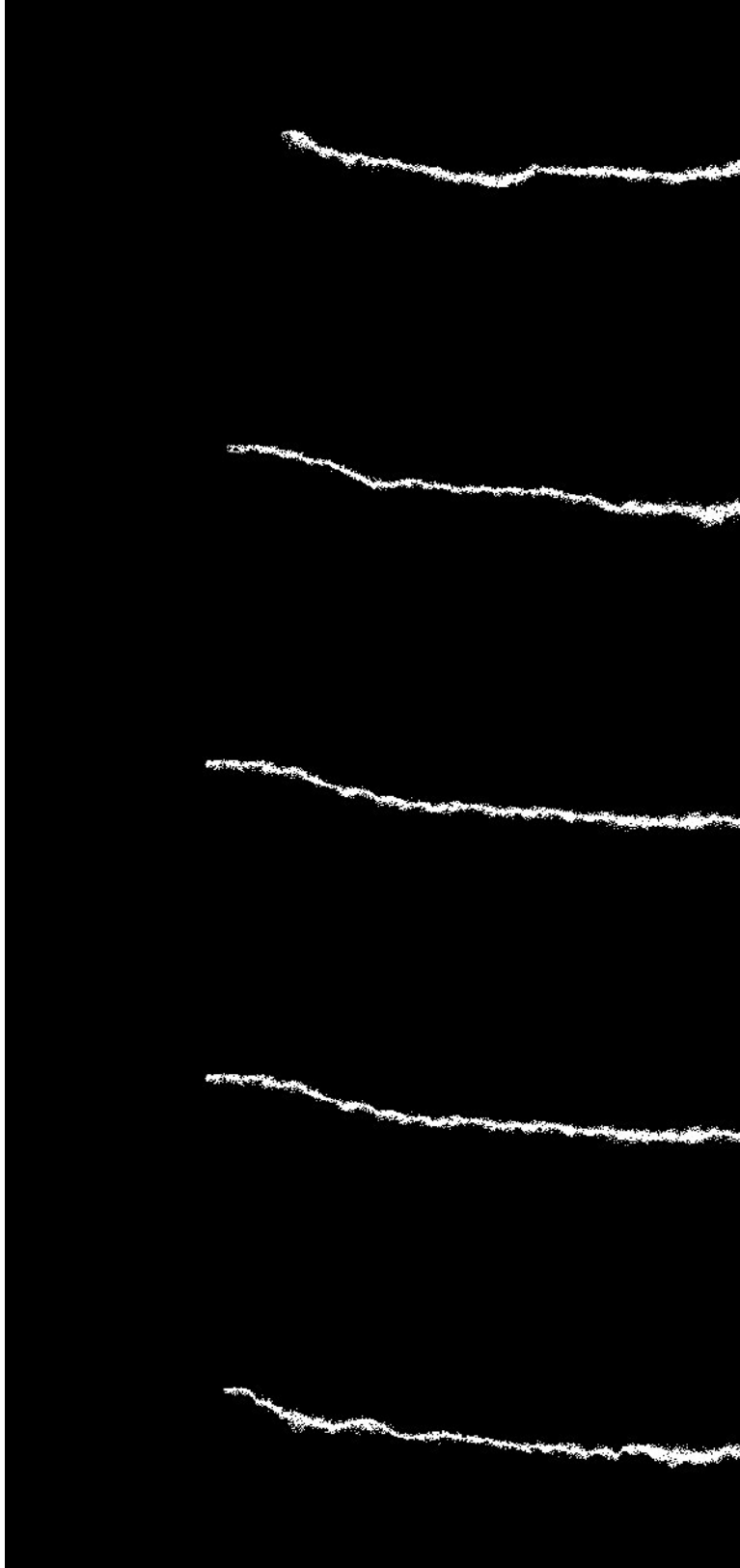
- L1/L3 Jets (From -120 to +120)



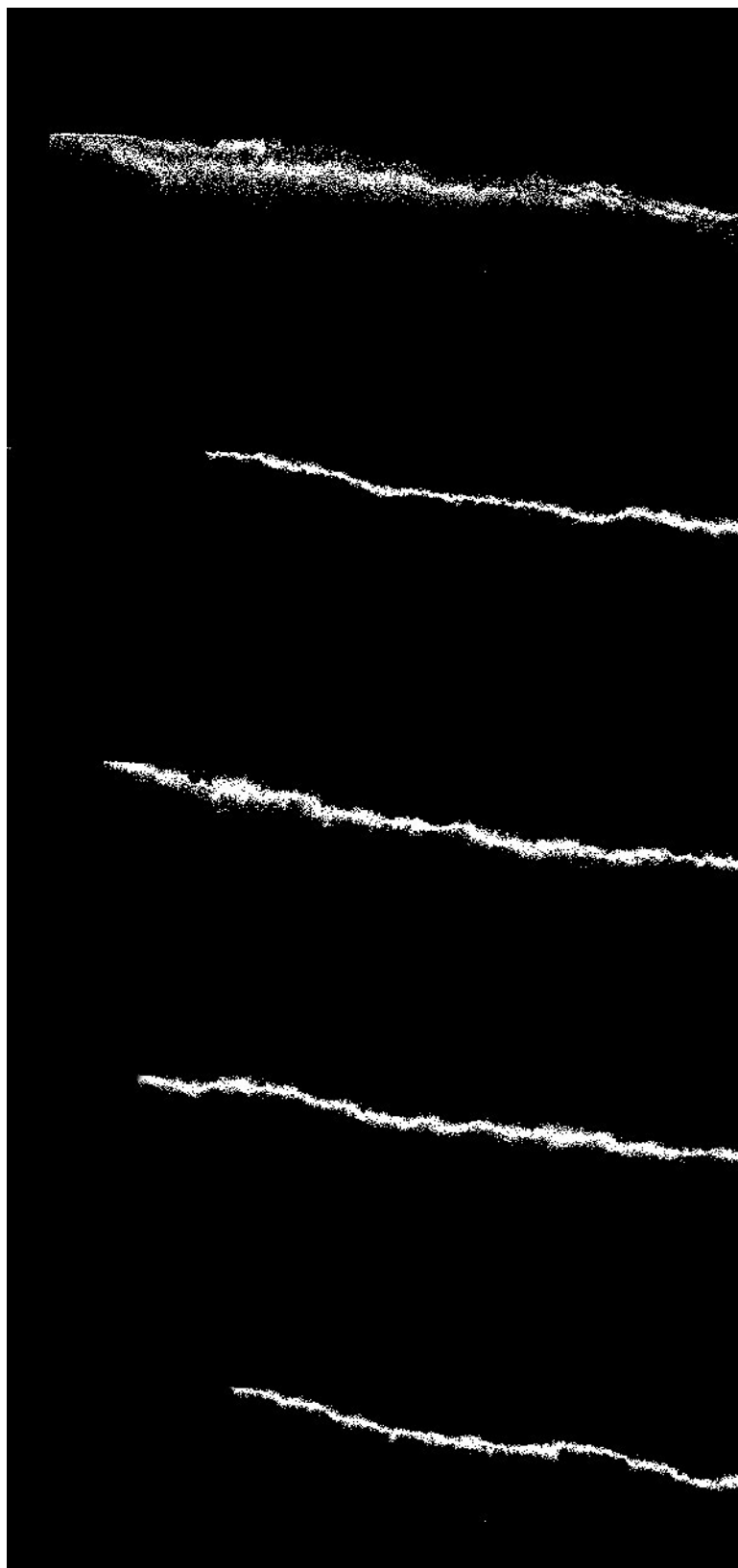


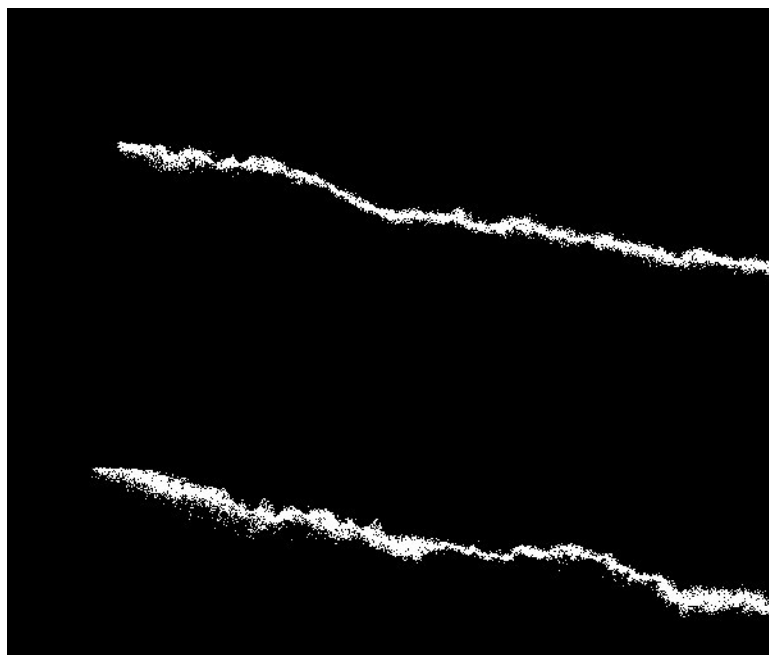
- L2/L4 Jets





- S1/S3 and S2/S4 Jets





A.3

Industrial fogger interior



A.4

Flow Visualization of Ventilation without Synthetic Jets

