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Effect of bulk flow modulations on a normal jet in crossflow at a Mean Blowing ratio of 0.25

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EFFECT OF BULK FLOW MODULATIONS ON A NORMAL JET IN CROSSFLOW AT A MEAN BLOWING RATIO OF 0.25

A Thesis

Submitted to the Graduate Faculty of the Louisiana State University and Agricultural and Mechanical College in Partial Fulfillment of the Requirements for the degree of Master of Science in Mechanical Engineering

In

The Department of Mechanical Engineering

by

Jeremiah Oertling
B.S., Louisiana State University, 2004
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# TABLE OF CONTENTS

ACKNOWLEDGEMENTS ............................................................................................................ ii  

LIST OF TABLES ........................................................................................................................ iv  

LIST OF FIGURES ........................................................................................................................ v  

ABSTRACT .................................................................................................................................... viii  

CHAPTER 1: INTRODUCTION TO JETS IN CROSSFLOW ................................................................. 1  
  Engineering Applications ........................................................................................................... 1  
  Film Cooling ................................................................................................................................. 2  
  Motivation .................................................................................................................................. 5  

CHAPTER 2: EXPERIMENTAL SETUP ............................................................................................... 7  
  Hardware ..................................................................................................................................... 12  
    Wind Tunnel .............................................................................................................................. 12  
    Jet Supply System ...................................................................................................................... 14  
  Instrumentation .......................................................................................................................... 16  
    Data Acquisition and Triggering Systems ................................................................................. 16  
    Flow Meter ............................................................................................................................... 17  
    Hot Wire Anemometry and Laser Sheet Visualization .............................................................. 18  
    3-Axis Traverse ......................................................................................................................... 20  
  Data Reduction ............................................................................................................................ 20  

CHAPTER 3: DISCUSSION OF EXPERIMENTATION ........................................................................... 23  
  System Characterization ............................................................................................................. 23  
    Boundary Layer and Far Field Crossflow .............................................................................. 23  
    Jet Profiles and Associated Time Scales ................................................................................. 25  
  JICF Experimentation ................................................................................................................ 27  
    Presentation of Unforced Jet Experimentation ....................................................................... 27  
    Laser Sheet Visualization ........................................................................................................ 28  
    Spectral Analysis ..................................................................................................................... 34  
    Presentation of Pulsed JICF Data ............................................................................................... 46  

CHAPTER 4: CONCLUSION AND RECOMMENDATIONS ....................................................................... 67  

REFERENCES ............................................................................................................................... 70  

VITA ............................................................................................................................................. 71
LIST OF TABLES

Table 1 Integral Time Scale for the far field \([x/D_j = 0; y/D_j = 0; z/D_j = 11]\) ........................................24

Table 2 Location of data points and mean velocities for coarse boundary layer investigation \([f_t = 3\text{Hz or } U_\infty = 1.60\text{m/s}]\) .............................................................................................................24

Table 3 Boundary layer thickness, displacement thickness and momentum thickness at three streamwise locations for \(U_\infty = 1.60 \text{ m/s}[\text{Note: } y/D_j = 0 \text{ at three streamwise locations}]\) ...........25

Table 4 Results of pulsed tests at \(BR_m = 0.25\) obtained by the flow meter time record..........47
LIST OF FIGURES

Figure 1 Idealized Brayton Cycle........................................................................................................... 2

Figure 2 Film cooling holes as seen on a turbine blade (Garg).............................................................. 4

Figure 3 Schematic of test section showing a) coordinate system [x, y, z] with origin at jet exit; 2) jet orientation variables [θ = injection angle; α = compound angle]; 3) jet velocity and density [UJ, ρJ]; 4) freestream velocity and density [U∞, ρ∞]; 5) streamwise location of jet [LD]; 6) boundary layer thickness [δ]; 7) pressure gradient [dP/dx]; 8) jet diameter [DJ]; 9) jet length [LJ].............................................................................................................................. 8

Figure 4 Example time record, BRm = 0.25; DC = 0.25; ff = 1.0Hz....................................................... 10

Figure 5 Schematic of side view of wind tunnel..................................................................................... 12

Figure 6 Schematic of jet supply lines.................................................................................................... 15

Figure 7 Schematic of experimental setup utilizing the Hot Wire Anemometry instrumentation........... 19

Figure 8 Schematic of experimental setup utilizing laser sheet visualization instrumentation.............. 21

Figure 9 Boundary layer scan for three streamwise locations with Uθ = 1.60 m/s................................. 26

Figure 10 Jet exit profile without crossflow [Ujmax = 1.60m/s; z/DJ = 0.067]........................................... 26

Figure 11 Jet exit RMS velocity profile without crossflow (corresponding velocity profile in Figure 10) [Ujmax = 1.60m/s; z/DJ = 0.067]................................................................................................................................. 27

Figure 12 Power spectrum of jet exit without crossflow....................................................................... 29

Figure 13 Four successive images of JICF (Frame rate = 30Hz; BR = 0.425)......................................... 31

Figure 14 Evolution of a Horseshoe Vortex blow over (Frame rate = 30Hz; BR = 0.250)............... 33

Figure 15: Sample of Kelvin-Helmholtz type breakup (BR = 0.200)..................................................... 34

Figure 16 Averaged images showing jet liftoff as blowing ratio is increases...................................... 34

Figure 17 Averaged steady state BR = 0.250 overlaid with grid, colored spots indicate location at which spectral analysis is presented (4 locations, not including jet exit plane).......................... 36

Figure 18 Unforced vertical jet in cross flow at BR=0.150; Visualizations (30Hz) at jet mid-plane, x-z (1-20); Sample time records of velocity signals from chosen locations (a-d); Velocity spectra from same positions (e)........................................................................................................ 38

Figure 19 Unforced vertical jet in cross flow at BR=0.188; Visualizations (30Hz) at jet mid-plane, x-z (1-20); Sample time records of velocity signals from chosen locations (a-d); Velocity spectra from same positions (e)......................................................................................... 39
Figure 20 Unforced vertical jet in cross flow at BR=0.250; Visualizations (30Hz) at jet mid-plane, x-z (1-20); Sample time records of velocity signals from chosen locations (a-d); Velocity spectra from same positions (e). .......................................................... 40

Figure 21 Unforced vertical jet in cross flow at BR_m=0.300; Visualizations (30Hz) at jet mid-plane, x-z (1-20); Sample time records of velocity signals from chosen locations (a-d); Velocity spectra from same positions (e). .......................................................... 42

Figure 22 Unforced vertical jet in cross flow at BR=0.365; Visualizations (30Hz) at jet mid-plane, x-z (1-20); Sample time records of velocity signals from chosen locations (a-d); Velocity spectra from same positions (e). .......................................................... 43

Figure 23 Unforced vertical jet in cross flow at BR=0.465; Visualizations (30Hz) at jet mid-plane, x-z (1-20); Sample time records of velocity signals from chosen locations (a-d); Velocity spectra from same positions (e). .......................................................... 44

Figure 24 Unforced vertical jet in cross flow at BR=0.600; Visualizations (30Hz) at jet mid-plane, x-z (1-20); Sample time records of velocity signals from chosen locations (a-d); Velocity spectra from same positions (e). .......................................................... 45

Figure 25 Example of RLV amplification ........................................................................... 49

Figure 26 Forced vertical jet in cross flow at BR_m=0.25, BR_pp=0.25, DC=0.25, f_f=0.5Hz; Visualizations at jet mid-plane, x-z (1-10); Blowing ratio time-record with visualization instants marked by vertical lines (a); Velocity signals from chosen locations: phase-averaged (b), sample time records (c-f); Velocity spectra from same locations: raw (g, h), after subtracting the phase averaged signal (i, j). ........................................................................... 51

Figure 27 Forced vertical jet in cross flow at BR_m=0.25, BR_pp=0.25, DC=0.25, f_f=1.0Hz; Visualizations at jet mid-plane, x-z (1-10); Blowing ratio time-record with visualization instants marked by vertical lines (a); Velocity signals from chosen locations: phase-averaged (b), sample time records (c-f); Velocity spectra from same locations: raw (g, h), after subtracting the phase averaged signal (i, j). ........................................................................... 53

Figure 28 Forced vertical jet in cross flow at BR_m=0.25, BR_pp=0.25, DC=0.25, f_f=5.0Hz; Visualizations at jet mid-plane, x-z (1-10); Blowing ratio time-record with visualization instants marked by vertical lines (a); Velocity signals from chosen locations: phase-averaged (b), sample time records (c-f); Velocity spectra from same locations: raw (g, h), after subtracting the phase averaged signal (i, j). ........................................................................... 54

Figure 29 Forced vertical jet in cross flow at BR_m=0.25, BR_pp=0.25, DC=0.25, f_f=10.0Hz; Visualizations at jet mid-plane, x-z (1-10); Blowing ratio time-record with visualization instants marked by vertical lines (a); Velocity signals from chosen locations: phase-averaged (b), sample time records (c-f); Velocity spectra from same locations: raw (g, h), after subtracting the phase averaged signal (i, j). ........................................................................... 55
Figure 30 Forced vertical jet in cross flow at $BR_m=0.25$, $BR_{pp}=0.25$, $DC=0.50$, $f_p=0.5Hz$; Visualizations at jet mid-plane, x-z (1-10); Blowing ratio time-record with visualization instants marked by vertical lines (a); Velocity signals from chosen locations: phase-averaged (b), sample time records (c-f); Velocity spectra from same locations: raw (g, h), after subtracting the phase averaged signal (i, j)........................................................................................................................................58

Figure 31 Forced vertical jet in cross flow at $BR_m=0.25$, $BR_{pp}=0.25$, $DC=0.50$, $f_p=1.0Hz$; Visualizations at jet mid-plane, x-z (1-10); Blowing ratio time-record with visualization instants marked by vertical lines (a); Velocity signals from chosen locations: phase-averaged (b), sample time records (c-f); Velocity spectra from same locations: raw (g, h), after subtracting the phase averaged signal (i, j)........................................................................................................................................59

Figure 32 Forced vertical jet in cross flow at $BR_m=0.25$, $BR_{pp}=0.25$, $DC=0.50$, $f_p=5.0Hz$; Visualizations at jet mid-plane, x-z (1-10); Blowing ratio time-record with visualization instants marked by vertical lines (a); Velocity signals from chosen locations: phase-averaged (b), sample time records (c-f); Velocity spectra from same locations: raw (g, h), after subtracting the phase averaged signal (i, j)........................................................................................................................................60

Figure 33 Forced vertical jet in cross flow at $BR_m=0.25$, $BR_{pp}=0.25$, $DC=0.50$, $f_p=10.0Hz$; Visualizations at jet mid-plane, x-z (1-10); Blowing ratio time-record with visualization instants marked by vertical lines (a); Velocity signals from chosen locations: phase-averaged (b), sample time records (c-f); Velocity spectra from same locations: raw (g, h), after subtracting the phase averaged signal (i, j)........................................................................................................................................61

Figure 34 Forced vertical jet in cross flow at $BR_m=0.25$, $BR_{pp}=0.25$, $DC=0.70$, $f_p=0.5Hz$; Visualizations at jet mid-plane, x-z (1-10); Blowing ratio time-record with visualization instants marked by vertical lines (a); Velocity signals from chosen locations: phase-averaged (b), sample time records (c-f); Velocity spectra from same locations: raw (g, h), after subtracting the phase averaged signal (i, j)........................................................................................................................................63

Figure 35 Forced vertical jet in cross flow at $BR_m=0.25$, $BR_{pp}=0.25$, $DC=0.70$, $f_p=1.0Hz$; Visualizations at jet mid-plane, x-z (1-10); Blowing ratio time-record with visualization instants marked by vertical lines (a); Velocity signals from chosen locations: phase-averaged (b), sample time records (c-f); Velocity spectra from same locations: raw (g, h), after subtracting the phase averaged signal (i, j)........................................................................................................................................64

Figure 36 Forced vertical jet in cross flow at $BR_m=0.25$, $BR_{pp}=0.25$, $DC=0.70$, $f_p=5.0Hz$; Visualizations at jet mid-plane, x-z (1-10); Blowing ratio time-record with visualization instants marked by vertical lines (a); Velocity signals from chosen locations: phase-averaged (b), sample time records (c-f); Velocity spectra from same locations: raw (g, h), after subtracting the phase averaged signal (i, j)........................................................................................................................................65

Figure 37 Forced vertical jet in cross flow at $BR_m=0.25$, $BR_{pp}=0.25$, $DC=0.70$, $f_p=10.0Hz$; Visualizations at jet mid-plane, x-z (1-10); Blowing ratio time-record with visualization instants marked by vertical lines (a); Velocity signals from chosen locations: phase-averaged (b), sample time records (c-f); Velocity spectra from same locations: raw (g, h), after subtracting the phase averaged signal (i, j)........................................................................................................................................66
ABSTRACT

An experimental wind tunnel is designed, built, outfitted with automated hot wire anemometry and laser sheet imagery systems. Several methods of instrumentation are tested and evaluated with the purpose of performing scientific research on the control and stabilization of a jet issuing 90 degrees into a crossflow. After the design and system characterizations were performed, the system was employed as an experimental platform to conduct an investigation of bulk flow modulation of a jet in crossflow. The Mean Blowing Ratio investigated was set at 0.25, and the effect of duty cycle, peak to peak blowing ratio and frequency of excitation are investigated.

It is shown that various vortex structures are associated with the mixing characteristics of the jet with the crossflow. These structures are identified using laser sheet visualizations and hot wire anemometry to investigate the spectra associated with these phenomena. Two vortex structures and their interactions are described in detail, specifically the Horseshoe Vortex and Ring Like Vortex.

Forcing conditions and their effects on the jet in crossflow are presented in a comprehensive table which brings together spectral analysis, processed time records and high precision imagery in an effort to characterize and understand the complex three dimensional turbulent flow associated with the jet in crossflow.
CHAPTER 1: INTRODUCTION TO JETS IN CROSSFLOW

**Engineering Applications**

Jets in crossflow are studied extensively in modern fluid mechanics and have been a subject of interest in the community for several years. Research in this area includes experimental fluid dynamics in the form of visualized and instrumented wind tunnel experiments as well as simulation studies.

Jets issuing into a crossflow are seen in many engineered systems. Some of the most visible configurations include smoke stacks. Modern chimney and industrial exhaust configurations alter the velocities at which they exhaust to affect the deposition pattern downwind of the stack. This greatly decreases the immediate temperature and pollutive effects of plant with respect to its neighbors.

Modern Vertical Short Take-Off and Landing Aircraft (VSTOL) must be designed with the flow patterns of the jet exhaust in mind. Their computer controlled flight assist systems integrate the jet in crossflow behavior into the processing algorithms to help sustain level-controlled flight.

Turbine engine combustor chambers are lined with injection holes used to mix fuel and air. Again, turbine and compressors blades make use of the JICF for flow separation near the trailing edge of the airfoil. Puffs of the working fluid are injected through holes or slots located along the surface which can advance or retard the separation point along the compressor or turbine blade. Resulting pressure distributions increase blade efficiency. In related flow geometry, turbine blades and stators use similar configurations to cool the surface of the blade. Film Cooling (FC), as the process is known, is commonly used on commercial and military aircraft engines.
Film Cooling

Turbine engines operate in a narrow envelope in terms of structural stress, thermal loads and material requirements, usually on the limits of each. Manufacturers aim to minimize weight, maximize efficiency. As seen in Equation 1, thermal efficiency of the Brayton Cycle is dictated by the Turbine Inlet Temperature ($T_{Ti}$). Figure 1 shows a diagram and thermodynamic representation of the idealized Brayton Cycle.

$$\eta_{th} = 1 - \frac{T_{Te}}{T_{Ti}}$$

Equation 1 Thermal Efficiency of Brayton Cycle

![Idealized Brayton Cycle](image)

Figure 1 Idealized Brayton Cycle

Turbine inlet temperature is limited by the material properties of the blades, stators and combustor located in this part of the engine. There have been several advances in material science that allow for increase in the thermal limits associated with these parts. Nickel and Titanium alloys, single crystal blades and ceramic thermal barrier coatings are several of the advancements used in industry.

After material advancements are exhausted, several methods of cooling the components are used. One method, Internal Cooling (IC), utilizes serpentine passages within the component.
A coolant is forced through the blade passages to remove heat transferred to the blade from the hot gas path. Extensive channel geometry and turbulence generating contours are the subject of much of the research in this field.

Another method of cooling the turbine blade, film cooling is a protective process that reduces the overall temperature of a gas turbine blade. A “film” of cool air is injected along the surface of the turbine blade. This produces a protective layer of air that shields the turbine blade from the extreme temperatures realized in the turbine.

Cool is a relative term here. The hot gas path temperatures reach on the order of 1800 K to 2000 K. The cooler air is bled off of an appropriate high pressure compressor stage. Bleeding air from another portion of the compressor results in an efficiency penalty on the engine. So, there is a trade off between high temperatures that result in better performance and better efficiency. Increasing the effectiveness will maximize performance as well as sustaining the efficiency of the turbine. The process involves expelling coolant from round holes or slots machined into the turbine blade. The holes are angled and oriented to allow for the maximum spread and distribution of the coolant along the blade. The holes are positioned all along the surface of the blade, but large concentrations of holes are located at key points where the most protection is needed. A detailed cut away of a typical arrangement of film holes can be seen in Figure 2 (Garg: 109).

Film cooling is used on most gas turbine engines. The implementation of complex arrays of holes is commonplace. The hottest portions of the blade can receive coolant from hundreds of holes in the vicinity. The limitation is one of constructing the blade; however, complex geometries can be obtained by modern manufacturing techniques while still retaining the structural integrity of the airfoil (Bunker: 774).
Film cooling presents quite a few challenges to work effectively. Various aerodynamic and heat transfer phenomena occur specifically to the engineering problem of film cooling. The process involves injecting cool jets of air from holes or slots along the turbine blade surface. The various vortex structures associated with these jets in crossflow have been the subject of many experiments. The counter-rotating vortex pair is one of these vortex structures and is one of the most noticeable flow characteristics associated with the jet in cross flow (Garg : 109).

Figure 2  Film cooling holes as seen on a turbine blade (Garg).

Film cooling is a costly method of increasing the turbine inlet temperature in terms of the operational losses associated. In addition to increasing the complexity and cost of the individual parts, the coolant must be bled from a higher pressure stage of the compressor. This coolant would normally be fed to the combustor and then to the turbine. The resulting loss of mass flow rate decreases the overall work output. With this in mind, the goal of turbine blade designers is to create a geometry which is highly efficient and maximizes the coolant being used; and if the overall amount of coolant can be reduced, there will be an associated increase in engine performance.
The flow associated with the JICF is both a turbulent and highly three dimensional. Computational efforts have seen success in predicting fluid mechanics and thermal loads associated with the JICF. Powerful, large scale computer clusters and supercomputers are typically needed to run the codes developed. Yet, utilizing impressive computational equipment, the computational process still requires extensive time to develop, input and run such programs.

With respect to the computational end of the research, there is always a need for physical experimentation for verification. In addition, the JICF geometry does not spell out the whole story. One common problem associated with computational studies arises when developing boundary and initial conditions to an experimental case study. One of the benefits of performing physical experiments is that these initial and boundary conditions can be represented to varying degrees of accuracy depending on the complexity of the test section.

**Motivation**

The motivations for this experimental process are to obtain a better understanding of the JICF mixing dynamics at a worse case scenario with an injection angle of 90° with the intention of developing a method of controlling the flow in such a way that improves the effectiveness of the film cooling process. Improvement of the film cooling process, for this experimental investigation, is defined as decreasing the vertical penetration and increasing the lateral spread of the jet while maintaining a similar or lower flow rate as the uncontrolled FC process.

These goals are accomplished via the development of experimental apparatus and experimental procedures that produce measurable conditions analogous to real world film cooling geometry. In addition, utilizing the well defined experimental conditions it is shown that desired levels of control are exacted on the film supply conditions through temporally varying the overall or global mass flow rate of coolant through the film cooling hole.
Additionally, experimental apparatus measurably describes the flow conditions via visualized representations of the flow geometry. Visualizations are corroborated by statistical measurements of the time and length scales of the flow through high speed anemometry measurements.
CHAPTER 2: EXPERIMENTAL SETUP

Having laid out some of the experimental challenges and motivations to this study, there are several variable definitions needed to describe this experiment. There is some variation within the fluid dynamics community on specific definitions of dimensionless numbers and experimental conditions. Every effort is made to relate this experiment and its conditions to previous studies and industry standards.

Figure 3 shows a diagram of the experimental setup along with several important factors in defining the working environment of the JICF. The FC jet has several important dimensions. First is the jet diameter, $D_J$, or the inner diameter of the FC hole is an important length scale and is typically used to normalize many of the flow field characteristic lengths. Another important jet dimension is the length of the jet, $L_J$. It plays an important role in defining the velocity profile at the jet-crossflow injection site.

All of the geometric variables shown in diagram are kept constant for these experiments. Their values and importance to the experimental process are described in the following sections. The only variable in Figure 3 that is changed for the experiments is the jet velocity, $U_J$.

Experimentation is conducted in a 3ft x 2ft cross section wind tunnel with a useful test section length of 10ft. The wind tunnel is capable of sustained velocities in excess of 30 m/s; however, all testing is conducted at a $U_\infty = 1.6$ m/s. This value was chosen for its stability, resulting boundary layer thickness and associated turbulence intensity. All experimentation for this study was conducted under cold conditions with a density ratio of unity. The TI of the freestream outside of the boundary layer was found to be less than 0.7% at this velocity. All mean velocities and turbulence intensities were calculated from time records sampled for statistical independence.
Experimental conditions for this investigation rely heavily upon the definition of the Blowing Ratio (BR). The definition of the BR is given in Equation 2. This definition simplifies to a velocity ratio for our conditions, density ratio of unity. With this definition of BR, the jet velocity, $U_J$, still needs to be defined.

$$BR = \frac{\rho_J U_J}{\rho_\infty U_\infty}$$

Equation 2 Definition of Blowing Ratio

$$U_J = \frac{Q_J}{A_J}$$

Equation 3 Definition of Jet Velocity

Equation 3 gives the definition of the jet velocity, $U_J$. Later, the BR and jet velocity are presented as cyclic in nature. All BR values reported are obtained from a flow rate based definition as seen in combining Equation 3 and Equation 2. All other velocity ratios are defined
as a pointwise velocity measurement scaled with the freestream velocity, $U_{\infty}$. This approach of defining the BR is taken in order to be consistent with the literature as well as error resulting from taking pointwise measurement of a velocity profile resulting from pipe flow. Any pointwise measurement used to define a blowing ratio is subject to flow entrainment experienced during a jet issuing into a large volume. In our case the fluid entrainment and distortion are important in defining the structure and behavior of the JICF, but pointwise definitions of jet velocity are not used in the definition of the Blowing Ratio.

The current discussion is aimed at describing the method by which control is achieved and the important factors to be considered in describing the supply flow. The resulting dynamics of the BR are discussed in Chapter 3. Combined with the ability to alter the geometry, three independent variables are important for these experiments, frequency, duty cycle and flow rate. Figure 4 shows an example of a typical cyclic BR achieved and the forcing function, the plot of “Valve Signal,” used to achieve the flow rate. Conditions of the example case are presented as follows and are subsequently explained.

First, the frequency of excitation needs to be controlled. The ability of the system to achieve higher frequencies is dictated by the response time of the solenoid valve. The current solenoid valve was shown to operate at a maximum frequency of 20Hz, but the resulting flow rate cycle becomes increasingly distorted due to the slow response time of the solenoid valve. Thus, the solenoid valve had a maximum operating frequency of 10Hz. Figure 4 shows an example of how the valve signal results in a delayed response in the flow rate.

Second, the duty cycle is defined by the time the BR is at its “high” point over the total time of the period. The associated BR at the “high” and “low” portions of the cycle is dubbed $BR_h$ and $BR_l$ respectively. $BR_h$ and $BR_l$ are the final variables that were controlled.
Figure 4 Example time record, BRm = 0.25; DC = 0.25; ff = 1.0Hz

As can be seen, the resulting flow rate is distorted from the ideal “square” wave represented by the Valve Signal. As a point of clarification, the Valve Signal represents the direct current voltage signal sent to the Solenoid Valve. The valve has two positions, on and off. The valve is normally open; therefore, when the Valve Signal is at 0 potential, the valve is open and we get BRm. When the valve is sent voltage, the valve closes and we get BRl. The Valve Signal is scaled for ease of presentation on a graph, but the signal is either at 0V or 12V.

The resulting distortion seen in Figure 4 is a result of the mechanical-fluid system’s slow response time relative to the electronic control system. The example given is at the low end of the spectrum in terms of forcing frequency. At higher forcing frequencies such as 5Hz and 10Hz, the forcing signal is compensated to produce a BR that is desired. The DC is used as the control variable to compensate for the distortion. The frequency is quite accurately represented.
for the frequencies investigated. The distortion manifests itself in a delay or phase shift, and is accurately represented to within 10% of the desired forcing frequency, duty cycle and BR. Only in the high frequencies such as 10Hz is there significant distortion to alter the behavior of the desired blowing ratio, and at this frequency other system dynamics come into play, such as acoustic frequencies; but, particular system frequencies are discussed in Chapter 3.

As stated earlier the definition of BR becomes a function of the forcing function during forced conditions. One specific definition was found to be of particular interest is the time averaged BR or $BR_m$, standing for Mean Blowing Ratio. Under forced conditions it becomes necessary to designate specific blowing ratios to specific portions of the cycle. Interestingly enough, $BR_m$ is not a function of the frequency, only the DC, $BR_h$ and $BR_l$. The relation is shown in Equation 4. The relation is shown in this way because $BR_h$ and $BR_l$ are directly controlled by the experimental setup, and the mean blowing ratio is a pertinent value because it represents an overall usage of coolant in a film cooling application. Additionally the Peak to Peak Blowing Ratio, $BR_{pp}$ is defined. This is another intuitive relation between the high and low blowing ration.

$$BR_m = BR_h[DC] + BR_l[1 - DC]$$

or

$$BR_m = BR_{pp}[DC] + BR_l$$

Equation 4 Definition of the Mean Blowing Ratio [$BR_m$]

$$BR_{pp} = BR_h - BR_l$$

Equation 5 Definition of peak to peak blowing ratio [$BR_{pp}$]

Note that all experimental conditions utilize a jet diameter of 25.4mm. Jet length was held constant at 14in for all tests. The JICF behavior has been shown to rely heavily upon the ratio between the boundary layer thickness and the jet diameter. As stated earlier, the crossflow conditions for the experiment are held constant, allowing for a constant boundary layer height.
and Reynolds Number. The ratio between the boundary layer and jet diameter is maintained at 0.59 for all tests. Boundary layer thicknesses were measured and are reported and discussed in Chapter 3 in order to properly describe the experimental conditions and establish spatial uniformity.

Figure 5 Schematic of side view of wind tunnel

**Hardware**

**Wind Tunnel**

Figure 5 shows a side view of the wind tunnel with some of the important features. As shown the test section is immediately preceded by the wind tunnel contraction. This configuration gives control over the properties of the wind tunnel flow. Turbulence intensity can be adjusted thru a series of screens located at the inlet of the wind tunnel contraction. The wind tunnel is an open channel design with a contraction at the inlet. The 2D reduction of the entrance region from 100ft$^2$ to 6ft$^2$ evolves over a length of 9ft. Uniformity of the crossflow entering the
test section is maintained under this configuration. Spatial uniformity of the crossflow conditions is discussed in greater detail in Chapter 3.

The test section of the wind tunnel is fitted with movable walls to control the stream wise pressure gradient. For all tests the walls were situated in a configuration which gave a negligible pressure gradient, and all measurements were taken within 50D of the ending contraction.

Instrumentation and personnel access is achieved through several hatches located on the walls of the wind tunnel. The roof of the wind tunnel’s test section is fully removable and is replaced with several configurations to utilize the particular measurement system needed. Two main roof systems were used for the current experimentation. First, the probe access roof utilizes several uninterrupted channels that run along the x-direction. The channels are fitted with a gasket system that allows a probe to passed through and slide along the channel. Subsequent probe designs utilize appropriate strain relief required to resist the sliding action during probe movement.

Probe movement is achieved via a computer controlled three-axis traverse system and is discussed in greater detail in the following sections. Second, a transparent roof is utilized for all visualization experiments. The entire roof section is replaced with an acrylic sheet. In conjunction the side wall of the wind tunnel is made of the same material. This optical access allows for laser sheet illumination and appropriate camera access.

Personnel access can also be achieved via an access door located on the wall opposing the fixed acrylic wall. This port is utilized to perform periodic maintenance on the instrumentation and experimental setup. It provides convenient access after the roof is set in place.
Jet Supply System

All experiments performed were conducted with a 14in length of stainless steel pipe attached to the wind tunnel floor via a support frame and positioning plate. Stainless steel was chosen as the material for the jet for its resistance to the Titanium Tetrachloride (TiCl₄) used for visualization. The seeding system used for visualizations is described in the next section. The support frame and positioning plate were designed to be modular to accept a plethora of injection angles and compound angles, \( \theta \) and \( \alpha \) respectively as referenced in Figure 3.

Figure 6 shows a schematic of the piping system common to the supply jet. Control of the jet is achieved via computer actuated solenoid valve. Computer control of the forcing of the jet was necessary for proper instrumentation for the experiment. The details of the system integration with instrumentation are discussed in the following section. The jet was supplied by two separate branches, the Main Flow (MF) and Seed Flow (SF). The majority of the fluid injected into the crossflow is composed of the Main Flow. Main Flow was supplied by an Atlas Capco Air Compressor with a large volume reservoir. The supply line is also equipped with multiple shutoff valves and pressure regulators. The pressure supplied to the pulsation system was regulated at 20psig for all testing. The regulator was positioned upstream of the solenoid valve. Upstream of the regulator the air compressor was set to supply a pressure of 150psig to 170psig to the reservoir.

The Atlas Capco air compressor supplied compressed ambient air to a descant dryer inline to the compressor and reservoir, which supplied dry air to the experiment. The pressure range set on the compressor resulted in compressor cycling at approximately 30min intervals to adequately supply air for a continuously running experiment at nominal Blowing Ratio. Compressor operation was monitored during experimental activities and did not result in supply fluctuation.
The second branch of the supply system, the Seed Flow, is supplied by a 250gallon bottle of Nitrogen. The flow rate is metered using a low flow rotameter and pressure transducer. The Seed Flow is broken into two flows. One branch flows through a TiCl$_4$ atomizer, and the other branch flows through a humidification system. The individual flow rates in each branch are manually controlled with needle valves during experimentation.

Each of the Seed Flow branches is combined with the Main Flow at separate locations as seen in Figure 6. The TiCl$_4$ reacts with moisture, and the supply nitrogen is dry. This allows the continuous delivery of TiCl$_4$ to the Main Flow, allowing all chemical reaction to occur within the jet. This is necessary because the resulting TiO$_2$ particles would quickly clog the Seed Flow supply lines. The relatively large diameter jet required periodic cleaning, due to seed use, but the jet is easily cleaned. And, the cleaning process was integrated into the experimental procedure.
Therefore, by adding the volumetric flow rates of the Main Flow and Seed Flow, a combined flow rate is obtained to determine the jet flow rate and subsequent BR. Seed Flow is maintained as a constant for all experiments, and comprised approximately 20%-40% of the flow rate depending on the conditions investigated.

Actuation of the jet is controlled via two needle valves in concert with a computer controlled solenoid valve. The purpose of this portion of the supply system is to control the flow rate as described.

**Instrumentation**

**Data Acquisition and Triggering Systems**

Control of the solenoid valve is achieved using a National Instruments multifunction I/O PCI card. This hardware is controlled via LabVIEW. LabVIEW is utilized to integrate all of the instrumentation and control systems. The purpose of the Digital Control system is to simultaneously produce two signals. These two signals are sent to a National Instruments break out box where they are output via BNC type connector to two separate systems.

The two signals are identical in shape but differ in amplitude. The shape of the signals is digital in nature in that they are either on or off. The first signal, 0 to 12V, is sent directly to the solenoid valve to control the position of the valve. The second signal, 0 to 5V, is used as a timing reference for all of the instrumentation systems. It was necessary to produce two signals because the solenoid valve requires such a large voltage to operate compared to the 5V imposed by the manufacturer of the image capturing system and a limit of 10V imposed by the Data Acquisition system. The time resolution reported by National Instruments for the Digital I/O card is reported to have a dedicated 24-bit resolution clock. This gives a time resolution several orders of magnitude greater than the response time of the solenoid valve as well as the time constant associated with the Hot Wire Anemometry system implemented. Accurate control
and representation of the forcing function is needed to assure proper actuation of the solenoid valve. Both the Data Acquisition and hot Wire Anemometry systems are discussed in the following sections.

All data acquired during experimentation is recorded via digital computer storage of data files and images. The Data Acquisition (DAQ) system utilizes another multifunction PCI card, but with that additional features of both Analog and Digital I/O. This system is integrated with each of the instrumentation systems in all of the configurations used for experimentation.

The time resolution for the DAQ system gives the capability of simultaneously acquiring a multitude of signals, voltage signals in our case, at rates exceeding one million samples per second; however, the maximum frequency used for data acquisition did not exceed 5 kHz. Such high frequencies are needed to determine the power spectrum. During the system identification, it was determined that at all flow conditions the power dissipation associated with viscous flow relegated the power to frequencies at or above 1 kHz. The number of independent voltage signals recorded during any one experimental data set did not exceed six, while the system is more than capable of adding additional channels of acquisition, up to a total of eight independent channels.

Flow Meter

For all experimentation, with the exception of the boundary layer and jet profile testing, the DAQ system is utilized to obtain a time record of the flow rate of the jet and the forcing function sent to the jet. In all other cases the flow rate and subsequently the Blowing Ratio was monitored and recorded utilizing the DAQ system. The flow rate was measured using a TSI thermal mass flow meter. The response time of this flow meter is reported at 4ms and had a working range of 0 to 200L/min. Response time and operating limits were found to be quite adequate to record and regulate the experimental conditions. The maximum forcing frequency
imposed on the jet had a maximum value of 10Hz that gives adequate representation of the resulting jet flow rate; additionally there is an acoustic frequency that was detected by the flow meter. This system characteristic is discussed in Chapter 3. No spectral analysis was performed on the flow meter time records due to the relevant time scales being much smaller that that of the flow meter.

As stated earlier, the jet flow rate is comprised of two separate flows, a Main Flow and a Seed Flow. The Main Flow is monitored using the TSI digital flow meter and the Seed Flow was monitored using a ceramic Low Flow Rotameter with sapphire float and is produced by Omega. The materials chosen for the flow meter are resistant to the corrosive gases found in the seeding system. The flow rate of the SF was kept constant for all of the testing, and was found to be very stable even under forced conditions, i.e. the system dynamics associated with the forcing system did not affect the Seed Flow rate.

**Hot Wire Anemometry and Laser Sheet Visualization**

The experimental data describing the flow phenomena associated with the JICF take two forms, velocity data obtained through Hot Wire Anemometry and flow visualizations obtained from laser sheet illuminated images. First, the Hot Wire Anemometry system is discussed. Figure 7 is a diagram of the instrumentation system in the HWA configuration. This configuration is utilized for all experimentation involving point wise velocity measurement.

The system is actually made of two independent systems. One system, the triggering and solenoid valve system integrate with the experimental setup to control the experimental process. The second system is used to monitor and record the results of the experimentation. Integration of this system with the Laser Sheet Visualization system is accomplished by allowing the control system computer to act independently of the other systems. This ensures that the presence of the monitoring equipment is not changed when altering the system
Figure 7 Schematic of experimental setup utilizing the Hot Wire Anemometry instrumentation

Figure 8 shows a schematic of the Laser Sheet Visualization system. As stated earlier, the control system remains unchanged from the setup of the HWA system. The only difference is the way in which the system utilize the triggering signals emanating from the control system The HWA system actually records the valve signal as it is being sent to the solenoid valves, while the Laser Sheet Visualization system utilizes the logic structure of the same solenoid valve signal to time the pictures being taken of the experimental process.

The Laser sheet Visualization system utilized a New Wave Research Nd:YAG laser with an operating frequency of 30Hz. The laser timing was controlled by digital synchronizer used in concert with a software program designed to capture high speed images used in particle image velocimetry. The system was manufactured by TSI Incorporated.
3-Axis Traverse

Several instrumentation setups are utilized to acquire experimental data for this investigation. One investigative tool utilized extensively in this study was a Hot Wire Anemometry (HWA) system. The HWA system takes pointwise measurements of flow velocity. The spatial area of importance for the experimental setup encompasses a large volume, and many pointwise measurements were taken, especially in the boundary layer and jet profile scans. In order to properly characterize this system, an automated 3-axis traverse system was utilized. The three axis positioning system is used to place the probe in a repeatable and automated way. The spatial accuracy of the system is reported to be ±0.003in. Integrating the three axis system with the HWA was accomplished via the DAQ system as shown Figure 7.

The same computer used to record all of the data coming form the flow meter, HWA and solenoid also controls an ISA-type digital computer card responsible for sending signals to a controller for a 3-axis traverse system. The traverse is manufactured by Compumotor. The system consists of three individual linear stages arranged to supply positioning in a 3 dimensional Cartesian system. The Compumotor system has and integrated control system capable of receiving command line instructions or to be controlled by LabVIEW. All of the instrumentation equipment was either monitored or controlled by automated instructions controlled by LabVIEW.

Data Reduction

All data reduction was performed using Matlab. Raw data was stored in the form of ASCII text files and read into Matlab. Hot Wire Anemometry data was the focus of much of the data processing. After the data collection process, raw text files containing voltages were converted using various transfer functions to data files containing properly scaled values. These
data files were then imported into Tecplot. Tecplot is powerful graphing software, capable of organizing large data files. All plots presented were produced using the Tecplot software.

Experimental procedure dictates that BR₁ is set using the straight valve, and then BR₃ is set using the solenoid bypass. This gives us control over the high and low blowing ratio. BR₃ then becomes a function of the duty cycle, DC. Upon determining the experimental condition of interest, utilize control over the BR₁, BR₃, and DC to set the conditions needed.

Figure 8 Schematic of experimental setup utilizing laser sheet visualization instrumentation

Equation 4 can be manipulated to determine the high and low blowing ratios. All experimentation under forced conditions utilized this relationship between the blowing ratios.

Please note the following:

1. Three variables must be set before the mean blowing ratio conditions can be met. This is just one way of interpreting the experimental conditions. For example, it may be of
interest to maintain BR\textsubscript{l}. In this case the experimental conditions would be manipulated in such a way as to maintain BR\textsubscript{l}. For this study and experimental configuration it made sense to keep it as a function of BR\textsubscript{l}, BR\textsubscript{h} and DC because they are the variables that are directly controlled.

2. Additionally, Equation 4 gives a fourth variable BR\textsubscript{pp}. The peak to peak blowing ratio was found to be an intuitive parameter to look at. It simply relates the high and low blowing ratios.

3. Simply setting these three conditions statically and then forcing the system does not result in perfectly represented square wave. The resulting wave and steps taken to remedy the flow rate distortion are discussed further.

The locations, other than the record at the jet exit, of the HWA velocity records were chosen on the basis of forced and unforced visualization studies. The focus of the phase averaged data is the relation of the blowing ratio measured by the flow meter and the velocity measurements made at the jet exit. The flow meter is located approximately 24 jet diameters before the jet exit. This spatial difference between the flow meter and the hot wire probe results in very little phase lag within the cycle, they are in actuality superimposed on top of each other for the low frequencies and the lag is estimated to be less than 5ms.

Distortion of the flow meter signal from the ideal square wave seen in the Valve function comes from two distinct characteristics of the system. Solenoid valve response time is approximately 10ms and the close time is approximately 25ms. These response times are not very important at low frequencies. But, as the frequency approaches period times along similar orders of magnitude, the delay time becomes more important. At \( f \) = 5.0Hz and 10.0Hz the duty cycle forcing functions were changed to alter the flow pattern to resemble the duty cycles desired.
CHAPTER 3: DISCUSSION OF EXPERIMENTATION

System Characterization

Before JICF experiments are carried out, the experimental operating conditions are investigated to assure that the wind tunnel, air jet supply, seeding system and instrumentation are performing to specs. The systems are integrated for use with each other and subsequently characterized to assure their operational modes. System interaction conditions are the overall experimental conditions sought for this experiment; therefore, it was necessary to characterize the individual components of the system to properly gauge their interaction.

Proper definition of the operating conditions of the experiment is necessary in order to discuss the possible interactions of system dynamics with the phenomena being investigated.

Boundary Layer and Far Field Crossflow

Measurements are taken to describe mean and spectral qualities of the crossflow. In order to obtain statistically independent values for the mean values of the flow in this turbulent region it was necessary to determine the Lagrangian Integral Time Scale from the autocorrelation of discrete time records.

Utilizing the automated flying hot wire system developed, coarse vertical scans of the boundary layer and far field of the crossflow are taken to determine the proper sampling conditions needed to accurately measure the flow. Table 1 shows the sampling conditions and a brief table of results for the far field. Integral time scales shown are from a block averaged autocorrelation integrated over the fundamental time. The number of blocks and subsequent time of integration was varied. The integral time scale varied by less 10%; however, as the fundamental time approached the integral time scale, the autocorrelation function no longer captures the correlated events.
The measured integral time scales given are used to obtain statistically independent measurements of the mean values of the crossflow. Mean values for the crossflow were needed to obtain a calibration curve for the wind tunnel. Measurements obtained for this calibration were compared to a similar calibration completed using a pitot probe.

Table 1 Integral Time Scale for the far field \(x/D_j = 0; y/D_j = 0; z/D_j = 11\)

<table>
<thead>
<tr>
<th>Fan Speed [Hz]</th>
<th>(U_\infty) [m/s]</th>
<th>(f_s) [kHz]</th>
<th>(t_s) [sec]</th>
<th>Time Scale [sec]</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>1.60</td>
<td>5</td>
<td>210</td>
<td>3.2</td>
</tr>
<tr>
<td>5</td>
<td>2.57</td>
<td>5</td>
<td>210</td>
<td>3.0</td>
</tr>
<tr>
<td>8</td>
<td>4.10</td>
<td>5</td>
<td>210</td>
<td>1.9</td>
</tr>
</tbody>
</table>

Additionally, the crossflow near the wall was investigated in the coarse scan. The scan at 3Hz is discussed because it was the crossflow velocity used for all JICF experiments.

Boundary layer data begins with the coarse investigation of the region to determine the integral time scale, just as the crossflow far from the wall. Table 2 shows the locations of the points taken for the coarse boundary layer examination as well as the mean velocities resulting from those tests. After plotting the mean velocities from this test, it was determined that a grid with increased resolution was needed to capture the velocity gradient within the boundary layer.

Table 2 Location of data points and mean velocities for coarse boundary layer investigation \(f_r = 3\text{Hz} \text{ or } U_\infty = 1.60\text{m/s}\)

<table>
<thead>
<tr>
<th>(x/D_j) Position</th>
<th>(y/D_j) Position</th>
<th>(z/D_j) Position</th>
<th>Mean Velocity [m/s]</th>
<th>Turbulence Intensity [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.33</td>
<td>4.74</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0.2</td>
<td>1.20</td>
<td>3.47</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0.4</td>
<td>1.53</td>
<td>1.40</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0.6</td>
<td>1.60</td>
<td>0.49</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0.8</td>
<td>1.60</td>
<td>0.43</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1.61</td>
<td>0.39</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>1.2</td>
<td>1.61</td>
<td>0.39</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>1.4</td>
<td>1.60</td>
<td>0.46</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>11</td>
<td>1.60</td>
<td>0.39</td>
</tr>
</tbody>
</table>

A total of nine boundary layer scans are made to show spatial uniformity. Figure 9 shows three of the nine positions investigated for the fine grid boundary layer testes. The plots shown
correspond to the three scans taken at three streamwise locations. The spanwise direction is held constant for these tests.

Boundary layer tests show spanwise uniformity and indicate a laminar boundary layer at the jet exit location. Table 3 gives corresponding shape factors for the three boundary layer locations. Shape factors fall below the theoretical limit for separation in a laminar boundary layer with zero pressure gradient given by solution of the Falkner-Skan equation. \( (H = 2.59) \) (Schlichting, H. and K. Gersten) This gives us a laminar boundary layer at the jet exit. Note: Similar conditions were set in the study conducted by Ekkad, S. and R. Rivir.

Utilizing such low velocity, dominated by viscous effects, associated flow frequencies drop to levels at which our forcing system is able to achieve accurate flow pulsations, i.e. we do not become limited by the frequency response of the solenoid valve used. Specific frequencies associated with the JICF and its associated modes are discussed further in the discussion of the forced JICF section.

Table 3  Boundary layer thickness, displacement thickness and momentum thickness at three streamwise locations for \( U_\infty = 1.60 \text{ m/s} \) [Note: \( y/D_J = 0 \) at three streamwise locations]

<table>
<thead>
<tr>
<th>( x/D_J )</th>
<th>(-\delta/\delta_J)</th>
<th>(-*\delta/\delta_J)</th>
<th>(-\theta/\theta_J)</th>
<th>Shape Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>-4.75</td>
<td>0.528</td>
<td>0.169</td>
<td>0.069</td>
<td>2.45</td>
</tr>
<tr>
<td>0.00</td>
<td>0.587</td>
<td>0.182</td>
<td>0.076</td>
<td>2.40</td>
</tr>
<tr>
<td>4.75</td>
<td>0.626</td>
<td>0.185</td>
<td>0.082</td>
<td>2.27</td>
</tr>
</tbody>
</table>

Jet Profiles and Associated Time Scales

Similar mean value and spectral tests were conducted on the jet used for the experimental process. It was necessary to perform spanwise and streamwise profiles of the jet without crossflow to establish symmetry and confirm the spatial characteristics of the jet. Figure 10 shows the velocity profile at the exit at two orthogonal planes of view. This view exemplifies the symmetry achieved by the jet. Figure 11 shows the RMS velocity at the jet for the same velocity conditions. The Reynolds number based on max jet velocity is 3400. This falls in the
laminar transitional regime and represents the upper limit of jet velocities investigated during these experiments.

Figure 9 Boundary layer scan for three streamwise locations with $U_\infty = 1.60$ m/s

Figure 10 Jet exit profile without crossflow [$U_{\text{max}} = 1.60$ m/s; $z/D_j = 0.067$]

Figure 11 shows increased turbulence in the region of the jet perimeter. This is to be expected as there is a large velocity gradient in this region. Stationary surrounding fluid meets
with the high momentum jet and shear ensues. This region is of great interest during tests with crossflow. The region is directly distorted by the ensuing boundary layer and further skewed by the bent over condition of the jet interacting with the crossflow. Subsequent jet shear layer rollup forms asymmetrically and evolves in such a way that the asymmetry is amplified in the near field region. These subjects are discussed further in the visualization study where specific vortex structures are illuminated.

Figure 11 Jet exit RMS velocity profile without crossflow (corresponding velocity profile in Figure 10) \( [U_{J\max} = 1.60\text{m/s}; z/D_J = 0.067] \)

**JICF Experimentation**

**Presentation of Unforced Jet Experimentation**

Figure 12 shows the power spectrum of the jet at three theoretical blowing ratios. They are theoretical because they were conducted without the crossflow present. As stated earlier the crossflow velocity is kept constant for all tests, so it was a natural course to scale the velocity with the presumed crossflow velocity.

Increasing jet velocity results in a delayed drop-off in power, i.e. there is more power at higher frequencies. Two important points can be made with reference to the spectrum of the
unforced jet. First, there is a smooth power drop-off as the frequency increases. This indicates that there are no prevalent “low” frequencies induced by the supply system. Note that jet flow rate is comprised of the main flow from the compressor and the TiCl₄ injection system.

Secondly, the frequency spikes seen at 100 to 2000Hz are prevalent in each of the blowing ratios. This could indicate these frequencies are naturally present in the system are not flow related. Additionally, these spikes are several orders of magnitude, at the lowest blowing ratio, from the forcing conditions that will be investigated for this series of experiments.

From these investigations we can state that the design of the supply system minimizes the frequency overlap of natural frequencies present in the flow relative to the forcing imposed on the jet. Under forced conditions there is measurable acoustic interaction of the wavelike pressure oscillations within the jet. Efforts are taken to design the jet to minimize the acoustic interaction with the forcing that is imposed on the jet; however, the acoustic frequency within the flow is pervasive in the forced cases. In addition to these tests conducted at the exit plane of the jet, several spectral analyses are presented for the far field. They explore the natural frequencies seen in the shear layer and viscous breakup region seen as the blowing ratio increases. These conditions are related to the pulsed cases to exemplify the resulting amplification or attenuation of these frequencies.

**Laser Sheet Visualization**

Utilizing the computer controlled actuation of the laser-camera-solenoid system, phase locked images are taken within the cycle of the pulsed jet in crossflow. The term phase locked imagery refers to the time reference at which the images were taken. For the forced cases this reference indicates the position within the forcing cycle. Averaging the phase locked images shows features of the flow that are periodic and has the effect of filtering out fluctuations not
related to the jet periodic flow. Therefore, it is necessary to examine both the averaged phase
locked images and the constituent images.

![Power Spectrum of Jet Exit Without Crossflow](image)

Figure 12 Power spectrum of jet exit without crossflow

In addition to the phase locked images acquired during the pulsed tests, images are
acquired for the steady state cases at a maximum frame rate of 30Hz. This allows the viewing of
an evolution of flow structure seen during a steady state case. Both cases examine how the
supply conditions interact and bring about the specific vortex patterns that emerge. With the
knowledge of the frequency and position of these various flow structures, proper instrument
placement and sampling conditions were able to be implemented. Without the visualization
studies, large spatial scans would be necessary, resulting in a daunting exploration. The
maximum frame rate the system was capable of was 30Hz. This low frequency yields only three
images of the cycle with respect to a forcing condition of 10Hz. Therefore a phase locked
system was utilized for forcing conditions.
Figure 13 shows a time lapse of four pictures of an unforced JICF at BR = 0.425. At steady blowing ratios above 0.3, there were consistently formed rollup vortex structures resembling the so called Ring Like Vortex (RLV). The RLV formation is prevalent in jets with higher blowing ratios where the jet is fully detached, and the leading and trailing sides of the structure do not interact with the wall, as it does in this case. It should be noted that the sites shown with the arrow are assumed evolution sites of the vortex rollup.

The final frame shows another formation of a RLV structure. Immediately trailing the leading edge of the RLV, another circulation in the opposite direction is seen. It is possible that this formation is the trailing edge of the next RLV structure forming. Orthogonal plane examination should illuminate this possibility.

These are instantaneous shots at rather large successive times for some of the frequencies seen in the flow; however, the visual length scale of the vortex shown and the calculated upper limit of the distance a particle would move are such that indicate the evolution indicated are the same vortex structure. Later examination of the power spectrum discusses these occurrences in greater detail. But, coupling the images with statistical data taken from HWA reinforces the evidence that the structure shown is correct.

Figure 14 shows a different type of vortex structure and its evolution, the Horseshoe Vortex (HV). HV formation is prevalent for a wide range of blowing ratios according to literature and is seen at every blowing ratio investigated for this series of tests. However, at low blowing ratios, below BR = 0.300 and above 0.250, the HV is sometimes ingested into the jet and ejected with the main bulk of the jet. The evolution showed begins with the moment the HV is ejected. The stable HV normally sits just in front of the jet. It is noteworthy that the direction of circulation is different than that of the leading edge side of the RLV.
Figure 13 Four successive images of JICF (Frame rate = 30Hz; BR = 0.425)
The leading edge RLV and HV form in the same vicinity near the leading edge of the jet exit. At BR = 0.300 there is interaction between the two structures. When they interact, the RLV precedes the HV shedding, but when either formation is seen in this range of blowing rations they interact and both are shed in quick succession. Another interpretation or consequence of the shedding is that there is massive breakup of the jet in these instances. What could be perceived as interaction may be the magnification of another type of vortex structure. Another reason it is not clear is that the shedding of the HV is not a consistent process unlike the RLV at higher blowing ratios.

At low blowing ratios, below BR = 0.250, there is no large scale vortex apparent within the vicinity of the jet exit. Unsteadiness in this region is discussed in the frequency analysis section. But, the visual inspection of this region shows the exit profile of the jet remains intact for 2 to 3 jet diameters. Figure 15 shows and instantaneous shot of the low blowing ratio breakup region. Unsteadiness insuring is related to the Kelvin-Helmholtz instability and initially perturbed by vertical momentum injected by the jet as well as jet-wall interactions. It is not clear where exactly the instability originates, but the spectral analysis illuminates some possibilities.

The tendency of the jet to liftoff from the immediate downstream surface is a well known phenomena. Figure 16 shows a series of images captured for the two blowing ratios that capture a change in jet attachment. It can not be said that the jet is fully detached at this point, but there is a definite change in seed density close to the wall immediately behind the jet when comparing BR = 0.300 to BR = 0.350. The flow directly behind the jet shows signs of a separation or circulation point at which unseeded crossflow in entrained with the jet. This condition could be confirmed if the crossflow were seeded and the jet was to remain free of the seeding particles.
Figure 14 Evolution of a Horseshoe Vortex blow over (Frame rate = 30Hz; BR = 0.250)
The unforced cases shed a great deal of light on the flow regimes of importance to the JICF. Much of the literature is focused on higher blowing ratios and does not provide specifics for the cases of interest here. This series of tests illuminated many of the flow structures and provided a metric by which to choose sites to investigate the spectral qualities of the flow.

In addition to the unforced JICF, pulsed tests were also conducted. Visual inspection of the flow field was revealing with respect to attenuation or amplification of certain vortex structures, but combination of the spectral analysis and the visualization is necessary to better describe what effect the pulsation has on the flow.

Spectral Analysis

A total of four locations within the flow were probed for spectral analysis. The locations of the probe placement were chosen using the images taken during the visualization portion of
the experimental process. Three major locations, in addition to the immediate exit of the jet were investigated. These locations correspond to phenomena associated with the images taken earlier.

In addition to the pulsed tests, the steady state tests discussed in the system identification portion of this report were repeated to determine the effect of the crossflow on the jet core. At these jet velocities the crossflow has the effect of increasing the energy dissipation rate at higher frequencies. This implies the turbulence of the jet has increased in the presence of the crossflow. The is somewhat intuitive considering the dramatic effect the crossflow has on the geometry of the jet issuing into a crossflow compared to a jet exiting into a relatively quiescent flow.

Figure 17 shows the specific locations for all cases investigated, and for any data presented the specific location of the data point is given. The grid overlaid in Figure 17 is approximate, but the location of the data points was achieved utilizing the computerized linear traverse system, and the specific locations of data are reported on a case by case basis. Figure 17 should be used as a reference for all velocity data reported. The colored tabs correspond to the colors of the plots given at these locations. The flow conditions shown in the grid overlay was for BR = 0.250, and the locations in the far field were chosen for their interaction with the higher blowing ratios, but these regions still see the effects of the pulsation. All positions investigated were aligned with the streamwise center line.

Spectral data was taken at a sample rate of 5 kHz for a duration of 20 seconds. Filtering was accomplished via the HWA system and chosen on the Nyquist criteria for dealiasing. The specific low-pass cutoff frequency set for the filter was 2kHz. Under these conditions a frequency resolution of 0.05Hz is achieved. Pictorial and pointwise velocity data is presented for Blowing Ratios in the range of 0.150 to 0.465. The steady state blowing ratio data is presented on Figure 18 to Figure 24.
Each position labeled on Figure 17 represents a HWA measurement. The data taken at these points are presented in two separate ways. First, and example time record is presented to impart a sense of the level of turbulence during any one part of the cycle. Position 1 corresponds to the red marker on Figure 17. This location is located right at the jet exit region. Secondly, the time record is presenting utilizing Fourier analysis. The time records and visualizations indicate the structure of the jet is quite stable at low blowing ratios, below 0.250, accompanies by relatively long distance before jet breakup. As the BR increases up to BR=0.250, the HV begin to destabilize and becomes ingested into the jet. Figure 20 frame 13, 14 and 15 show this process taking place.

With the BR increasing still further, at BR=0.300, the HV begins to interact with the leading edge of the jet in a different way. Figure 21 frame 9 corresponds to the beginning of the HV ingestion, but unlike the earlier case, the ingestion acts in a way to feed the leading edge of the jet, frame 10, until the leading edge is pinched, frame 11, and finally the roll up is forced out of the jet in frame 12. Along with the visualized flow phenomena in this region, increased
periodicity is seen in the time records, and the curvature of the Power Spectrum starts to show an increase in the frequency at which the Power Level begins to drop. Note that for all cases at this location, and others, high frequency spikes are seen beginning around 200Hz. The continued presence of these spikes at these high frequencies indicates that those spikes are not flow related and do not effect the experiment.

The time record for this position increases in its erratic nature. This is to be expected because the erratic nature of the type of measurement increases with increases Reynolds number associated with pipe flow. Unless the ingestion is large enough that the interface comes into contact with the probe, the erratic nature will continue but not exhibit the signs of detached turbulent flow, as is seen in the progression of data at the second, green data point.

The second region of interest is an interesting position in that it is a region located in a unique position to see the jet flow fluctuation and ensuing crossflow fluctuations, and interaction between the two. This region is highly dynamic, in that its interface is a recirculation region associated with both the HV and RLV. BR=0.25 shows a case with flow reversal not common to any other conditions. The flow is assumed to reverse direction due to the abrupt descent and sequential ascent right at the minimum detectable velocity.

As the Blowing Ratio increases there is an associative increase into turbulent conditions; however, the flow reversal seen in Figure 20 is not repeated with the exception of those in Figure 24. Turbulence decreases temporarily at BR=0.465 due to the orientation of the jet angle with the probe, which is now injecting fluid at an angle and more directly at the probe. The reading given by the probe is more directly in the core of the jet, shielding the probe in the relative calm of the jet. At BR=6 in Figure 24 the flow becomes highly detached and the probe is once again in the vicinity of the interacting crossflow and jet velocity streams. It is for this reason that the 3-axis traverse system was important.
Figure 18 Unforced vertical jet in cross flow at BR=0.150; Visualizations (30Hz) at jet mid-plane, x-z (1-20); Sample time records of velocity signals from chosen locations (a-d); Velocity spectra from same positions (e).
Figure 19 Unforced vertical jet in cross flow at BR=0.188; Visualizations (30Hz) at jet mid-plane, x-z (1-20); Sample time records of velocity signals from chosen locations (a-d); Velocity spectra from same positions (e).

$D_J=25.4 \text{mm}, U_\infty=1.6 \text{m/s}, \delta/D_J=0.59$
Figure 20 Unforced vertical jet in cross flow at BR=0.250; Visualizations (30Hz) at jet mid-plane, x-z (1-20); Sample time records of velocity signals from chosen locations (a-d); Velocity spectra from same positions (e).

$D_j=25.4\text{mm, } U_\infty=1.6\text{m/s, } \delta/D_j=0.59$
Now we move to position 3. This location is downstream of the hole and gets the majority of the wash swept back from the jet exit. This region is expected to be and is a highly turbulent region of flow due to the crossflow and jet interacting with the wall. Spectrum analysis at these locations indicates a predominant frequency within the flow. The corresponding positions 1 and 2 do not exhibit preferential frequencies at these low BR; however at position 3 under a BR of 0.150 to 0.188 we have a frequency spike at approximately 20Hz. This frequency dissipates as the BR increases, and slowly all of the velocity signals begin to spike at the same location.

Interestingly, positions 3 and 4 share the same frequency spike at low blowing ratios, where jet breakup follows a different method that that of a higher blowing ratio, where RLV structures are the prevalent flow structure. Position 3 was chosen for it breakup characteristics. In all cases the region selected here, falls within the turbulent breakup region of the JICF. These two points sharing a frequency could indicate the initiation of jet breakup has origins closer to the jet exit, i.e. the prevalent frequency in the breakup region is also found in a region farther upstream.

These steady state tests show important flow structures associated with the JICF. The graphical representation of frequencies, time records and pictures are easily used to paint a picture of the phenomena associated with this flow structure. Instantaneous images capture specific flow phenomena associated with the flow, and staggered images allow for the visualization of the evolving flow structure. They layout of example time records also give the perspective of an instantaneous measurement to associate with the individual images.
Figure 21 Unforced vertical jet in cross flow at BR$_m$=0.300; Visualizations (30Hz) at jet mid-plane, x-z (1-20); Sample time records of velocity signals from chosen locations (a-d); Velocity spectra from same positions (e).

$D_J=25.4\text{mm}$, $U_\infty=1.6\text{m/s}$, $\delta/D_J=0.59$
Figure 22 Unforced vertical jet in cross flow at BR=0.365; Visualizations (30Hz) at jet mid-plane, x-z (1-20); Sample time records of velocity signals from chosen locations (a-d); Velocity spectra from same positions (e).
Figure 23 Unforced vertical jet in cross flow at BR=0.465; Visualizations (30Hz) at jet mid-plane, x-z (1-20); Sample time records of velocity signals from chosen locations (a-d); Velocity spectra from same positions (e).

D_J=25.4mm, U_∞=1.6m/s, δ/D_J=0.59
Figure 24 Unforced vertical jet in cross flow at BR=0.600; Visualizations (30Hz) at jet mid-plane, x-z (1-20); Sample time records of velocity signals from chosen locations (a-d); Velocity spectra from same positions (e).

\[ D_J = 25.4 \text{mm}, \quad U_\infty = 1.6 \text{m/s}, \quad \delta/D_J = 0.59 \]
The picture painted by the graphical representation of these flow conditions is quite helpful in gaining an understanding of the JICF flow geometry. Three flow régimes are put forth for a steady jet in crossflow issuing normally into a flow. The order or presentation follows a progression of low blowing ratios around 0.150 to an upper limit of 0.600. The specific régimes exhibit specific flow phenomena.

First, at the low end of the Blowing Ratio jet formation is quite steady, while unsteadiness ensues via a Kelvin-Helmholtz type instability several jet diameters downstream of the jet exit, a steady continuous coverage is seen behind the jet exit until the unsteadiness is met and massive breakup of the jet ensues.

Second, at moderate blowing ratios at or above 0.25, the Horseshoe Vortex structure found at the leading edge of the jet begins to interact with the jet column at the injection point. Initially, when the two vortex structures interact, the HV may be ingested and maintain its cohesion so as to be blown over the oncoming jet. If the HV is ingested enough to cause a pinch point in the newly emerging jet, the resulting structure resembles the Ring Like Vortex structure.

Finally, for the range of Blowing Ratios investigated, the JICF is dominated by a steady production of RLV structures. The structures have enough cohesion to remain organized well throughout the field of view shown. The vortex patterns recognized in this study all seem to interact with each other. Their formation and subsequent shedding seem to overlap, thereby inferring a relationship between them. The origin of these vortex structures can be linked to the shear and turbulence induced by the JICF geometry.

Presentation of Pulsed JICF Data

A low response time flow meter designed by TSI was implemented to both record the conditions of the test and to set the conditions in a real-time fashion. Integrating the flow meter into the existing DAQ system gives a great deal of control over the experimentation. The flow
meter signal has the benefit of allowing for the comparison of the flow visualizations with the hot wire data. Because of the system setup, it is possible to separately acquire images and obtain how wire data. During the post-processing operations, the data is brought together for the presentation. The two sets of data are integrated with each other by recording the timing signals sent to the solenoid valve and the flow meter signals simultaneously. Under these conditions we can overlay the information received from the HWA with the images acquired during visualizations.

Table 4 Results of pulsed tests at BR_{m} = 0.25 obtained by the flow meter time record

<table>
<thead>
<tr>
<th>f_{r} [Hz]</th>
<th>BR_{m}</th>
<th>BR_{l}</th>
<th>BR_{n}</th>
<th>BR_{pp}</th>
<th>DC to get</th>
<th>DC to set</th>
</tr>
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<tbody>
<tr>
<td>Actual</td>
<td>0.5</td>
<td>0.255</td>
<td>0.188</td>
<td>0.444</td>
<td>0.256</td>
<td>0.263</td>
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<td>Actual</td>
<td>1.0</td>
<td>0.254</td>
<td>0.185</td>
<td>0.429</td>
<td>0.244</td>
<td>0.284</td>
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<td>Actual</td>
<td>5.0</td>
<td>0.251</td>
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<td>0.421</td>
<td>0.234</td>
<td>0.276</td>
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<td>Actual</td>
<td>10.0</td>
<td>0.252</td>
<td>0.188</td>
<td>0.401</td>
<td>0.213</td>
<td>0.301</td>
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<td>0.3</td>
<td>1.5</td>
<td>2.4</td>
<td>5.2</td>
</tr>
<tr>
<td>Deviation</td>
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<td>-1.3</td>
<td>-1.9</td>
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</tr>
<tr>
<td>Deviation</td>
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<td>-0.3</td>
<td>-3.8</td>
<td>-6.4</td>
<td>10.4</td>
</tr>
<tr>
<td>Deviation</td>
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<td>0.3</td>
<td>-8.3</td>
<td>-14.8</td>
<td>20.4</td>
</tr>
<tr>
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<td>0.1250</td>
<td>0.375</td>
<td>0.250</td>
<td>0.516</td>
<td>0.50</td>
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<tr>
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<td>0.252</td>
<td>0.123</td>
<td>0.374</td>
<td>0.252</td>
<td>0.516</td>
</tr>
<tr>
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<td>0.122</td>
<td>0.372</td>
<td>0.249</td>
<td>0.520</td>
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<tr>
<td>Actual</td>
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<td>0.127</td>
<td>0.362</td>
<td>0.236</td>
<td>0.499</td>
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<tr>
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<td>0.500</td>
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<td>-1.6</td>
<td>-0.3</td>
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<tr>
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<td>-0.8</td>
<td>-0.4</td>
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<tr>
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<td>-0.2</td>
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<td>0.250</td>
<td>0.708</td>
<td>0.70</td>
</tr>
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<td>0.088</td>
<td>0.325</td>
<td>0.238</td>
<td>0.708</td>
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<td>0.091</td>
<td>0.325</td>
<td>0.234</td>
<td>0.715</td>
</tr>
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<td>0.114</td>
<td>0.320</td>
<td>0.206</td>
<td>0.685</td>
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<td>0.147</td>
<td>0.321</td>
<td>0.174</td>
<td>0.710</td>
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<td>0.0</td>
<td>-4.8</td>
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<tr>
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<td>21.3</td>
<td>0.0</td>
<td>-6.4</td>
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<tr>
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<td>-1.5</td>
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<tr>
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<td>8.4</td>
<td>96.0</td>
<td>-1.2</td>
<td>-30.4</td>
<td>1.4</td>
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</table>

The simultaneous acquisition of solenoid valve and flow meter gives an added dimension of clarity to the system characterization. We are able to pick out response times of the solenoid valve and acoustic interaction within the supply jet. This gives a great deal of information to
track the evolution of specific flow spectra. Data taken by the HWA system and Laser Sheet Visualization system are presented in a condensed form in order to organize the information in such a way that all data relating to a specific flow régime can be compared.

JICF experiments which utilized the HWA system are presented in order to show several aspects of the flow. The first HWA data given in the presentation of the experimental results, part b in all of the combined data formats, are Phase Averaged time records. The phase averaged time records are obtained by breaking up the continuous time record into single cycles based on the forcing function sent to the solenoid valve and overlaying individual cycles and taking the average at each time instant relative to a fixed point within the cycle. The resulting time record displays the contribution of the time record directly correlated to the cyclic excitation of the jet. All frequency components within the flow that are produced as a result of the forcing are preserved. While non-linear interaction and any other spectral or turbulence related qualities resent in the flow are attenuated. All time records of flow conditions are given to show the stability of the data taken as a basis of comparison with the Phase Averaged data.

Table 4 shows the results of the phase averaged flow meter records. Mean values are obtained from the phase averaged time record and reflect the inaccuracies seen from system distortion of the flow signal. The system suffers signal degradation at 10Hz. Errors greater than ten percent from the desired value are in excess of 10% for cases in which the solenoid was not able to accurately produce the flow desired.

The most difficult case for the system to achieve is DC = 70%, seen in the purple shades area of Table 4. The error for this case originates from the inability of the system to obtain the low flow rate. The systems inability to get this low flow rate comes from two sources. First, the system must always retain a small amount of flow required for seeding flow normally used for the visualizations portion of the study. Secondly there is a zero offset present in the flow
meter which results in an error of approximately 5% at the lowest low blowing ratio tested. With this in mind, the 70% duty cycle case resulted in far worse achieved values for the conditions set, and the conditions that were most deviated from the set were at this duty cycle at $f_r = 10$Hz.

Figure 25 Example of RLV amplification

Table 4 also shows the compensation taken to adjust the solenoid function. The compensation was used to achieve the duty cycles desired for the investigation. This correction was made to compensate for the low response time of the solenoid valve relative to the forcing frequency.
Figure 26 to Figure 37 contain the forced test data. This data is organized in a similar fashion to the data of the unforced cases. They show phase locked images in frames 1 through 10 with a sample cycle of the flow meter record and valve signal in frame (a). Also contained in frame (a) are a series of ten vertical black bars. These bars represent the temporal position within the cycle that each of the images was taken. The phase averaged data shows several important features regarding the time response of the solenoid valve and acoustic frequencies present. Because of the high forcing frequency, cases in which \( f_f \geq 5 \text{Hz} \) show the acoustic frequency in greater detail. Utilizing phase averaged data and oscilloscope measurements taken throughout the experimental process, the acoustic frequency of the present jet setup was measured to be approximately 47Hz. It is important to note that this frequency is dependant upon the jet geometry as opposed to the operating conditions. The acoustic frequency was present in all forced tests and did not vary with the blowing ratios investigated.

As in the unforced cases, pointwise measurements of the flow conditions are presented. The benefits of the instrumentation setup are evident in the compilation of the data. The purple lines in the phase averaged time records and unprocessed time records represent a time signal at a location 3.5D\(_j\) downstream of the jet. Reference Figure 17 for a pictorial representation of the data points collected. As the frequency increases we see the flow disturbance moving within the cycle. This is a result of the period of the cycle decreasing with the increasing forcing frequency. The disturbance actually takes a similar amount of time to be realized from the signal of the valve opening to the measurement, approximately 300ms. This means the disturbance seen in the plots of \( f_f = 5.0 \text{ Hz} \) is from the previous cycle, and the disturbance in \( f_f = 10.0 \text{ Hz} \) is from three cycles in advance. This representation allows for phase tracking of events. Frequency tracking of events can be much better represented by spectral analysis of the jet exit characteristics.
Figure 26 Forced vertical jet in cross flow at BR_m=0.25, BR_pp=0.25, DC=0.25, f_r=0.5Hz; Visualizations at jet mid-plane, x-z (1-10); Blowing ratio time-record with visualization instants marked by vertical lines (a); Velocity signals from chosen locations: phase-averaged (b), sample time records (c-f); Velocity spectra from same locations: raw (g, h), after subtracting the phase averaged signal (i, j).
Figure 25 indicates a case in which the RLV structure is amplified. Increasing the Blowing Ratio to a high enough value at any point in the cycle results in similar amplification. One such case shown includes a theoretical high blowing ratio of 0.625. Actual blowing rates achieved are found via the flow meter signal located on the figure. In a steady state blowing ratio at this magnitude, RLV structures are very prevalent. The phase locked image shown indicates a consistently well formed RLV structure. Specifically the image shows the rollup resulting from the initial burst of increased flow. The first RLV is the small structure immediately trailing the large circulation. The next ensuing RLV structure is seen forming at the jet exit.

The formations seen throughout the cycle are similar, with the exception of the initial rollup, to the structures seen in steady the steady state case, but the pulsed case shown exhibits greater vortex spacing and vortex uniformity during the initial high part of the cycle.

In contrast to the RLV amplification seen in Figure 25, Figure 30 through Figure 33 show images of a case with theoretical BR_h = 0.375. This case, albeit a less severe compared to the previous conditions, readily displays the formation of the RLV in the steady state, see Figure 22. But, the images taken during the high part of the cycle do not exhibit these formations. Upon examination of the instantaneous, non-averaged, images it is apparent that there are isolated cases of the formation of the RLV; however, they are much smaller in size and less frequent compared to the steady state case.

The visualization studies were important to gain a better understanding of specific mechanisms present in the flow. They also emphasized the need for frequency analysis of the flow and gave insight on where to examine the spectra. It is also shown that the forcing of the flow can both attenuate and amplify flow phenomena seen in an unforced condition.
Figure 27 Forced vertical jet in cross flow at BR$_m$=0.25, BR$_{pp}$=0.25, DC=0.25, f$_t$=1.0Hz; Visualizations at jet mid-plane, x-z (1-10); Blowing ratio time-record with visualization instants marked by vertical lines (a); Velocity signals from chosen locations: phase-averaged (b), sample time records (c-f); Velocity spectra from same locations: raw (g, h), after subtracting the phase averaged signal (i, j).
Figure 28 Forced vertical jet in cross flow at BR<sub>m</sub>=0.25, BR<sub>pp</sub>=0.25, DC=0.25, f<sub>j</sub>=5.0Hz; Visualizations at jet mid-plane, x-z (1-10); Blowing ratio time-record with visualization instants marked by vertical lines (a); Velocity signals from chosen locations: phase-averaged (b), sample time records (c-f); Velocity spectra from same locations: raw (g, h), after subtracting the phase averaged signal (i, j).
Figure 29 Forced vertical jet in cross flow at $BR_m=0.25$, $BR_{pp}=0.25$, $DC=0.25$, $f_c=10.0\text{Hz}$; Visualizations at jet mid-plane, x-z (1-10); Blowing ratio time-record with visualization instants marked by vertical lines (a); Velocity signals from chosen locations: phase-averaged (b), sample time records (c-f); Velocity spectra from same locations: raw (g, h), after subtracting the phase averaged signal (i, j). 

$D_J=25.4\text{mm}; U_\infty=1.6\text{m/s}; \delta/D_J=0.59$
Upon examination of the steady state images, the formation frequency of the RLV was seen to be on the order of 10Hz. This is also reinforced by the spectral analysis done on this case. While forcing at 5Hz, there is only 100ms of time at which the high blowing ratio is present. This leaves time for one RLV to form, if it conforms to the steady state case. Upon viewing the entire cycle, only one possible RLV exists, but it is highly disorganized and lopsided. A more accurate description would be the initial burst tries to form a RLV but becomes to distorted to form the RLV structure and a single initial rollup is formed and separated from the bulk of the flow coming from the jet.

The forced cases show a different spectral signature with respect to the unforced case, and they change more with respect to frequency then with duty cycle. First, there is a prevalent spike for each of the forced cases at the forcing frequency. This is to be expected. In addition to the spike at the forcing frequency, there are harmonics of this same frequency. The types of harmonics manifested depend on the duty cycle.

The large scale inertial range is seen in the lower forcing frequencies of 0.5Hz and 1.0 Hz. The transition frequency at which the dissipation rate changes is also more dramatic and is pushed to a higher frequency. A similar change in spectral signal is seen for the higher forcing frequencies, but there is more energy at the higher frequencies for these cases.

The second position chosen for the pulsed case, red graphs, corresponded to 0.5 Dj above the jet exit. There is speculation about the possibility that this vertical position does not capture the shear layer. Additional data is required for this region. Addition of a spatial point corresponding the steady state case at z/Dj = 0.25 would definitely shed some light as to the existence of frequencies around the forcing frequency. There is and indication that the frequency of excitation is being read and imposing an effect on the flow, but the level seen at the higher forcing frequencies compared to those of the lower forcing frequency leads one to believe the
high frequency excitation exhibits more of an effect because the overshoot seen in time records and images show measurably greater overshoots for the high forcing frequency case. Reference any high frequency acquisition, 5 to 10 Hz, to get an idea of the relative value of the overshoots seen in all the cases. Overshoots caused increased high blowing ratios on the order of 10 to 15% greater than that desired for the forcing frequency of 10Hz. The case being referenced is at a mean blowing ratio of 0.25 and a duty cycle of 0.50. While overshoots are recorded, average values show that the desired values are obtained to within 8%.

With the possibility that the probe placement is not in the best location stated, the effect of the pulsation is seen via a different frequency signature compared to the steady state case. The steady state case does show a prevalent frequency, as opposed to the spectrum at the jet exit plane. A frequency around 10Hz is present in the unforced case in the shear layer region.

As seen in the shear layer region, there is still a prevalent frequency in the unforced case, and as before forcing around this natural mode of 10Hz results in large amplitudes at 10Hz and its harmonics. Also, as before the lower forcing frequencies see an associated attenuation at these frequencies, and the forcing frequency harmonics are quickly dampened out at only slightly higher frequencies. It is not possible to distinguish harmonic placement over the noise past 10Hz for a forcing frequency of 1.0Hz. All of the power signatures have a typical turbulent dissipation curve.

The far field region at $x/D_j=3.5$ was chosen because of the apparent large scale breakup seen during visualization. This region typical large scale breakup made choice for the vertical interrogation point a topic of controversy. It was desired to pick a location that would actually see the disturbances associated with the jet breakup as well as capture specific phenomena associated with different blowing ration. The larger the blowing ratio, the deeper penetration
Figure 30 Forced vertical jet in cross flow at BR$_m$=0.25, BR$_pp$=0.25, DC=0.50, f$_r$=0.5Hz; Visualizations at jet mid-plane, x-z (1-10); Blowing ratio time-record with visualization instants marked by vertical lines (a); Velocity signals from chosen locations: phase-averaged (b), sample time records (c-f); Velocity spectra from same locations: raw (g, h), after subtracting the phase averaged signal (i, j).
Figure 31 Forced vertical jet in cross flow at $BR_m=0.25$, $BR_p=0.25$, $DC=0.50$, $f_r=1.0\text{Hz}$; Visualizations at jet mid-plane, x-z (1-10); Blowing ratio time-record with visualization instants marked by vertical lines (a); Velocity signals from chosen locations: phase-averaged (b), sample time records (c-f); Velocity spectra from same locations: raw (g, h), after subtracting the phase averaged signal (i, j).
Figure 32 Forced vertical jet in cross flow at $BR_m=0.25$, $BR_{pp}=0.25$, $DC=0.50$, $f_z=5.0$Hz; Visualizations at jet mid-plane, $x$-$z$ (1-10); Blowing ratio time-record with visualization instants marked by vertical lines (a); Velocity signals from chosen locations: phase-averaged (b), sample time records (c-f); Velocity spectra from same locations: raw (g, h), after subtracting the phase averaged signal (i, j).
Figure 33 Forced vertical jet in cross flow at $BR_m=0.25$, $BR_{pp}=0.25$, $DC=0.50$, $f_c=10.0\,\text{Hz}$; Visualizations at jet mid-plane, x-z (1-10); Blowing ratio time-record with visualization instants marked by vertical lines (a); Velocity signals from chosen locations: phase-averaged (b), sample time records (c-f); Velocity spectra from same locations: raw (g, h), after subtracting the phase averaged signal (i, j).
was seen at this location downstream of the jet. All choices taken for the vertical placement of the probe saw some seed flow. Even the maximum point of $1.25D_j$ saw seeding at a blowing ratio of 0.150.

The natural frequency of the jet for the unforced case is still present in the power signature for this location. A similar shape is seen from the interaction of the forcing frequency for 10Hz excitation and natural jet frequency. The forcing frequency of 10Hz and its harmonics are prevalent even into the high frequencies. A difference is seen in the signature of the lower forcing frequency of 1.0Hz. The 10 Hz signature is still present for this forcing frequency, as opposed to the other locations investigated. This region may be spatially far enough away from the initial disturbance of the pulsation to allow for normal jet modes to occur.

This last case makes sense in that the farther away the flow is from the jet, the more homogenized the flow will become in terms of turbulence distribution. Meaning the flow evolution is such that, close to the jet the forcing causes mixing characteristics to be spatially aligned to either inhibit or enhance mixing. The jet eventually returns to a mode in which the natural frequencies present from wall and crossflow interactions come to fruition again.
Figure 34 Forced vertical jet in cross flow at $BR_m=0.25$, $BR_{pp}=0.25$, $DC=0.70$, $f_f=0.5$Hz; Visualizations at jet mid-plane, x-z (1-10); Blowing ratio time-record with visualization instants marked by vertical lines (a); Velocity signals from chosen locations: phase-averaged (b), sample time records (c-f); Velocity spectra from same locations: raw (g, h), after subtracting the phase averaged signal (i, j).
Figure 35 Forced vertical jet in cross flow at $\text{BR}_m=0.25$, $\text{BR}_p=0.25$, $\text{DC}=0.70$, $f_r=1.0$Hz; Visualizations at jet mid-plane, $x$-$z$ (1-10); Blowing ratio time-record with visualization instants marked by vertical lines (a); Velocity signals from chosen locations: phase-averaged (b), sample time records (c-f); Velocity spectra from same locations: raw (g, h), after subtracting the phase averaged signal (i, j).
Figure 36 Forced vertical jet in cross flow at $BR_m = 0.25$, $BR_{pp} = 0.25$, $DC = 0.70$, $f_t = 5.0\, \text{Hz}$; Visualizations at jet mid-plane, $x-z$ (1-10); Blowing ratio time-record with visualization instants marked by vertical lines (a); Velocity signals from chosen locations: phase-averaged (b), sample time records (c-f); Velocity spectra from same locations: raw (g, h), after subtracting the phase averaged signal (i, j).

$D_j = 25.4\, \text{mm}; U_\infty = 1.6\, \text{m/s}; \delta/D_j = 0.59$
Figure 37 Forced vertical jet in cross flow at $BR_m=0.25$, $BR_{pp}=0.25$, $DC=0.70$, $f_t=10.0\,\text{Hz}$; Visualizations at jet mid-plane, x-z (1-10); Blowing ratio time-record with visualization instants marked by vertical lines (a); Velocity signals from chosen locations: phase-averaged (b), sample time records (c-f); Velocity spectra from same locations: raw (g, h), after subtracting the phase averaged signal (i, j).
CHAPTER 4: CONCLUSION AND RECOMMENDATIONS

Design and implementation of an experimental apparatus investigating the effect of bulk pulsation of a Jet In Crossflow with measurable and controllable conditions is accomplished. The experimental data produced is a direct result of this particular goal being accomplished. An experimental wind tunnel fitted with a modular jet design is equipped with a normal jet issuing 90° into a crossflow. This tunnel, instrumented with an automated high spatial precision placement system integrated with Hot Wire Anemometry, high speed data acquisition, computer controlled valve actuation and high speed image capturing capabilities is now in service at Louisiana State University.

The mean and spectral characteristics of the jet and crossflow are designed and found to exhibit the conditions set forth by the experimenters. These conditions are defined in such a way that industrial and research standards are directly applicable. Specific conditions include:

1. Frequencies present in the undisturbed flow are such that they will not interact with the excitation conceived for these experiments
2. A laminar boundary layer with a thickness approximately 0.5 \( D_j \) is found at the jet entrance region.
3. A laminar-turbulent jet issues into the wind tunnel crossflow.

The cases studied here were chosen with respect to a mean blowing ratio of 0.25 for all instances, forced and unforced. The low blowing ratio is of particular interest to the film cooling community. Increasing the effectiveness of the film cooling jet at such low blowing ratios allows for the decrease in flow rate taken from the engine.

At this blowing ratio, it is clear that both mixing dynamics with the crossflow and wall interactions play vital roles in maintaining the film cooling jet coverage and overall continuity. The dynamics associated with both wall and freestream flow regimes are not separable events in
this case, and individual system dynamics and flow phenomena interact with each other causing non-linear interactions.

Bulk flow pulsations are shown to both amplify and attenuate naturally occurring flow structures depending on frequency of excitation. Forcing frequencies imposed at or near the natural jet frequencies are shown to either amplify frequencies present or cause harmonics to pervade throughout the spectrum; while, forcing frequencies imposed at lower values show attenuation of such natural frequencies in spatial regions within the shear layer and immediately downstream of the jet.

The role of the duty cycle is shown to be an important factor needed to accurately describe the flow conditions. The inclusion of the duty cycle allows for a more detailed discussion of the forcing conditions, especially at the low frequencies of interest for this study. The natural dissipation of energy or dynamic nature of the fluid mechanics inhibits the formation of a perfectly modulated or controlled bulk flow pulsation.

With the definition of the duty cycle an experimentation protocol is easily designed and modified to describe a myriad of flow conditions. Measurements made for these conditions can be compiled in such a way that allows for comparison between the same test and cases where a parametric study is called for.

The increase in effectiveness as defined by this experiment includes the lateral spread of the film cooling jet. While initial investigation indicated lateral spread under similar conditions, the conditions can not be confirmed to the accuracies seen in all data presented. Therefore with the present system capabilities, orthogonal planes of view need to be taken to compare the lateral spread of the jet in crossflow.

The additional spatial locations described in the spectral analysis section of this paper indicated several reasons for additional points of measurement.
This experimental setup is already capable of implementing particle image velocimetry studies, but current image resolution would make any such investigation impractical. The feasibility of acquiring an imaging system with greater resolution may greatly decrease the time needed to carry out such experiments and increase the quality of the images produced.
REFERENCES


VITA

Jeremiah Oertling was born in New Orleans, Louisiana to Marie Louise and Robert Michael Oertling. He grew up in southern Louisiana attending High School at Jesuit High School in New Orleans. He graduated in 1999. After Jesuit, he attended Louisiana State University and graduated in 2004 with a Bachelor of Science Degree from the Mechanical Engineering Department. Since then, he has fulfilled all of his class requirements for completing the Master of Science Degree. This thesis is the last step in the completion of that degree.