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Abstract

The aim of this project is to study the flow dynamics and impact pressure of nozzles used in the hydraulic system of oil drilling rigs.

Development of drill bit technology has been closely related to the comprehension of the hydraulic phenomenon. Hydraulics is a main factor in the drilling process; a good understanding of these parameters could insure a successful drilling. To improve the rate of penetration it was decided to understand the main functions of this drilling fluid:

- Cutting removal from the drill bit and the well bottom
- Cooling the cutting tools
- Lubrification
- Relief of hydrostatic pressure

Two years ago, a test rig was built in Louisiana State University in order to investigate the influence of nozzles geometry on the flow dynamics and pressure distribution. Experiments had been conducted to compare the effects of four non-cylindrical nozzles versus a regular one. These tests included the measurement of the discharge coefficient and the plotting of 3-dimensional impact pressure mappings. This particular test rig was moved to the Fluids Mechanic and Propulsion Laboratory of the University of Cincinnati and modified to provide a tool capable of testing nozzles used in roller cone bits.
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1 Introduction

1.1 Project overview
The aim of this project is to study the flow dynamics and impact pressure of nozzles used in the hydraulic system of oil drilling rigs.

Since the mid 50’s, hydraulic systems are used in drilling process and particularly jets issued from nozzles placed in the drill bit body. Development of drill bit technology has been closely related to the comprehension of the hydraulic phenomenon. Thus, adding nozzles in the bit greatly increased mixing and turbulence at the bottom of the well, and thereby the drilling performance. Hydraulics is a main factor in the drilling process; a good understanding of these parameters could insure a successful drilling. To improve the rate of penetration it was decided to understand the main functions of this drilling fluid:

- Cutting removal from the drill bit and the well bottom
- Cooling the cutting tools
- Lubrification
- Relief of hydrostatic pressure

Two years ago, a test rig was built in Louisiana State University in order to investigate the influence of nozzles geometry on the flow dynamics and pressure distribution. Experiments had been conducted to compare the effects of four non-cylindrical nozzles versus a regular one. These tests included the measurement of the discharge coefficient and the plotting of 3-dimensional impact pressure mappings.
This particular test rig was moved to the Fluids Mechanic and Propulsion Laboratory of the University of Cincinnati and modified to provide a tool capable of testing nozzles used in roller cone bits. Numerous attempts have been made to increase bit performance by changing nozzle size and geometry, but the internal geometry still remained a regular surface revolution.

A proper nozzle shape can control the jet spreading rate and therefore its impact pattern and energy on the ground, the vortex dynamics, and turbulence intensity. This study will examine the fundamental flow patterns generated by different nozzles.
1.2 General background

1.2.1 Drilling process

From the first drag bit used to drill holes to the latest PDC developed, the main concern has always been to reach the oil reservoir with minimum time and cost per foot of formation drilled. A strong increase in drilling rate was achieved when the first drill bit with fluid injection was introduced. The fluid was pumped through the drill string assembly and expelled at the bit to remove cuttings and transport them back to the surface through the annulus. The fluid was injected through open-flow ports located at the center of the drill-bit. The major improvement came in 1953 with the replacement of the open flow in the center of the bit by jets issued from nozzles placed in the drill bit body.

The term "hydraulics" represents the flow of the drilling fluid through the circulation system. Hydraulics is a main factor in the drilling process and good control and understanding of the parameters affecting it will insure a successful drilling. The main purposes of injecting drilling fluid are to remove and transport the cutting out of the hole, and to cool and lubricate the bit.

An extremely large variety of bits are manufactured in order to adapt to different drilling situations, but all of them are required to work under downward thrust plus rotary motion. Drill bits are usually classified according to their design as either drag bits or roller cone bits:

- Drag bits

This designation refers to fixed cutter drill bit. The first drill bits to be manufactured for well drilling were fishtail-shaped drag bits. Actual drag bits are
generally round shaped and are provided with polycrystalline diamond cutters (PDC). There are called PDC bits. Drag bits drill by plowing cuttings from the bottom surface.

- Roller cone bits

Appearing in the early twenties, roller cone bits are now the most common bit type currently used in drilling operations. Actual roller cone bits are provided with three cones whose positions are determined by two main parameters: offset and journal. The cones are equipped with steel cutters or high hardness insert teeth. Characteristics of the bit such as offset, journal angle, tooth size and shape have to be adapted to the formation characteristic. Roller cone bits drill by chipping and crushing action.

1.2.2 Circulating system design

The hydraulic flow in the well is dictated by the circulating system on the rig. The fluid is injected by the pump through the drill string assembly, it then exits through the bit and returns through the annulus. The pump will be sized to produce a certain available pressure at the bit.

\[ P_p = P_{surf} + P_{dr} + P_b + P_{an} \]

- \( P_{surf} \) represents the pressure loss in the surface equipment
- \( P_{dr} \) is the pressure loss in the drill string
- \( P_b \) the pressure loss at the bit
- \( P_{an} \) is the pressure loss in the annulus
From Kendall and Goins [1] work a bit pressure drop of 59% to 66% of the pump pressure is required to optimise the hydraulic performance. The pressure loss at the bit can be evaluated such as:

\[
\Delta P_b = \frac{\rho Q^2}{12034 \cdot C_d \cdot A_t^2}
\]

- \( \rho \) the density of the mud
- \( Q \) the flowrate
- \( A_t \) the total nozzle area
- \( C_d \) the nozzle’s discharge coefficient

A value of 90% to 95% is usually assumed for the discharge coefficient. Then the pressure loss becomes a function only of the flowrate, the area of the nozzle and the density of the mud.

The flowrate is adjusted to make sure the cuttings are correctly removed and to overcome the slip velocity. The proper nozzle selection will greatly influence the removal of the cuttings from the bit face; making the best possible use of the available fluid energy at the bit and insuring a well is drilled at optimum performance.

### 1.2.3 Drilling fluid interest

The drilling fluid action can be summarized in three main functions:

- Annular cleaning

The fluid in the annulus needs to carry the cuttings from the bottom hole to the surface. Gravity will tend to carry the cuttings down. This phenomenon is called
slip motion. The fluid needs to travel in the annulus at an average velocity that will overcome the slip velocity of the cuttings.

Also, by keeping the pressure higher than the formation pressure, the fluid helps to prevent the well from collapsing. But this overbalance needs to be controlled, between 50 to 300 psi in order not to fracture and not to lose fluid in the formation (lost circulation).

- **Bit cleaning**

The cleaning of the bit face is a strong factor, which affects performance of drill bit and cost per foot drilled. The rate of penetration (ROP) is enhanced by the removal of cuttings from the bit face to the annulus. Cuttings generated at the face of the bit need to be removed efficiently from the bottom hole to avoid regrinding and to clean the bit. The nozzle jet influences the way cutters are cleaned. By cleaning the bit face and washing out the cuttings from the bottom hole, bit balling can be avoided. Bit balling refers to the phenomenon that occurs when the cuttings react to create a ball between the formation drilled and the drill-bit.

- **Bit cooling and lubrication**

The cutting and crushing action of the drill bit on the formation increases the temperature of the drill bit. The drilling fluid is used to cool the drill bit and especially the cutter. Adding some lubricant in the drilling fluid will also increase performances of the drill bit and reduce bit wear.
1.2.4 Drilling fluid types

Physical and chemical properties of the drilling fluid have great importance in a successful drilling program. Modifying the fluid properties could be a quick and easy way to improve drilling efficiency. Different parameters govern fluid type selection:

- Types of formation to be drilled
- Range of temperature, strength, permeability, and pore formation pressure
- Water quality available
- Environmental considerations

The formation pressure dictates the density of the mud. The pressure exerted by the fluid column should be equal to or only slightly higher than that of the formation to ensure maximum penetration rate. The rheological properties of the fluid and the annular hydraulics will interact directly with the hole stability and how the bottom hole is cleaned. Two major types of drilling fluid are used in the oil field industry:

1.2.4.1 Water-Based Mud (WBM)

The water-based mud is a solution of water mixed with chemicals, solids, and liquids. These muds can be pure water or salt water mixed with different solids. To increase lubrication and coolant capabilities, oil can be added into the mud. Inhibited components that won't react with water such as gypsum, lime, and different salts are added to the solution to retard hydration of the formation drilled. Solids also create a viscous fluid that will increase hole cleaning.
1.2.4.2 Oil-Based Mud (OBM)

The oil-based mud also contains chemicals, solids and liquids, but the main phase is oil. In oil based mud, all solids are considered as inhibited. Most oil-based muds contain additives to increase viscosity. Oil-based muds are usually more expensive than water-based muds. Thereby, they are generally used only when high lubricity is needed in order to maintain hole stability in hydratable formation.

1.2.5 Nozzle selection, optimization of drill bit hydraulics

Three different methods are used in the oil field industry to determine the size of nozzle to mount on the drill bit. These three methods are referred to as:

- **Maximum nozzle velocity**

  Pumps are sized with respect to the minimum flow rate that will lift the cuttings. Recalling that the nozzle velocity is proportional to the square root of the pressure drop at the nozzle, the velocity at the bit will be maximum when the pressure drop is maximum.

- **Maximum bit hydraulics horsepower**

  This technique has been developed by Kendal and Goins [1]. The hydraulic horsepower is the rate at which fluid works in the circulating system. It is equal to the work produced (\(W\): the pressure build up in the system) by the pump time the mass flow rate (\(\rho Q\)). The hydraulic horsepower (\(Ph\)) can be written as:

\[
Ph = \rho Q W = \Delta p Q
\]
Then knowing the pressure loss, the hydraulic horsepower at the bit can be computed. Defining the parasitic pressure (Pd) as the pressure loss between the pump and the bit and the pressure loss in the annulus, the total pressure at the pump (Pp) is then equal to:

\[ P_p = \Delta P_d + \Delta P_b \]

Kendall and Goins showed that the parasitic pressure loss in the circulating system could be evaluated such as:

\[ \Delta P_d = cQ^m \]

The theoretical value of m is 1.75 but Bourgoyne [2] determined from field data that m could actually get lower values than this. Computations need to be run during the drilling process to assure a correct value for m.

Kendall and Goins showed that bit hydraulic horsepower is maximum when the parasitic pressure loss is \(1/(m+1)\) times the pump pressure. Then the pressure drop through the nozzle can be evaluated as:

\[ \Delta P_b = (m/m+1)P_p \]

Using the maximum hydraulic horsepower method for circulation rates and nozzle size selection, it can be shown mathematically that the pressure drop across the bit is 65 % of the total pump pressure.

- Maximum jet impact force

A third way to select the correct nozzle size is to maximize the jet impact force. The jet impact is the force induced by the jet when hitting the bottom hole. When the maximum jet impact force criteria is used, it is assumed that the cleaning of
the bottom hole is maximum. The momentum of the vertical jet is transferred to the bottom hole. The rate of change of momentum is given by:

$$F_j = \frac{\Delta mv}{\Delta t} \equiv \rho Q V_n$$

Where $V_n$ is the exit velocity of the jet at the nozzle.

Recalling that:

$$V_n = C_d \sqrt{\frac{\Delta P_b}{2 \rho}}$$

Then

$$F_j = C_d Q \sqrt{2 \rho \Delta P_b}$$

Kendall and Goins showed that the impact force is maximized when the pressure drop at the bit is equal to:

$$\Delta P_b = (m/m + 2)P_p$$

In both cases, the maximum total nozzle area can be computed from the pressure loss and then the correct nozzle can be chosen. The total area $A_t$ can be written such as:

$$A_t = \frac{Q}{C_d} \sqrt{\frac{\rho}{2 \Delta P_b}}$$

The optimum nozzle size is then computed by matching the repartition of the nozzles with the total area computed.

Using the maximum jet impact force method for circulation rates and nozzle size selection, it can be shown mathematically that the pressure drop across the bit is 48% of the total pump pressure.
According to Bourgoyne, none of these three methods is considered as the perfect solution for nozzle sizing. It can be shown that when maximum jet impact occurs, the hydraulic horsepower is about 90% of its maximum value. The use of these two theories will depend on the borehole depth and the downhole conditions.

1.2.6 Bit stability and directional jetting

Drill bit nozzles are not only used to enhance rate of penetration (ROP) and cost per foot. Nozzles can also be used in directional drilling in certain formation as an alternative to more expensive and complex tools such as turbines or mud motors. This technique is known as nozzle jetting. The well is drilled with an asymmetric nozzle selection: one of the three nozzles, called the jet nozzle, has a bigger diameter to allow a higher flow rate through it. When appropriate depth for a turn is reached, the drill bit is rotated to the proper position to run the nozzle. The rotation of the bit is stopped and drilling fluid is pumped into the system. The imbalance created by a non-symmetric nozzle repartition and the non-rotation of the tool allows the scouring action of the jet to create a "pocket". The drill bit is pushed through the pocket until adequate position is reached and then the bit is run as a regular run. A turn is typically achieved within 3 to 6 feet drilled. A second change in direction can be realized if needed to insure correct trajectory.

1.3 Non-circular jet

Non-circular jets have been studied in a wide range of applications in combustion, heat transfer, chemical reactors, lift augmentation, and noise suppression. Numerous geometries have been used: elliptic, square, rectangular,
triangular shapes with corners, lobed nozzles. Experimental and computational studies have been performed to characterize the flow introduced by these non-conventional shapes.

The geometric aspect ratio, i.e. the ratio between the major axis over the minor axis, affects the spreading of the jet. The transverse section of the flow is modified as the jet exits the nozzle. An impinging elliptic jet with an aspect ratio of 2 has been used to increase the heat transfer between the jet and a plate. The stagnation point of the jet has been moved and resulted into a shorter potential core.

Non-circular jets can be used in the drilling process to increase the turbulence at the face of the bit in order to increase the mixing with the cuttings. An increase in heat transfer between the jet and the cutter could also occur with the use of non-circular geometry. The roles of non-circular jets are also to produce side forces for cleaning, redistribute pressure, change shear stress distribution, improve discharge coefficient, split jet to multiple jets, and redirect jets.

1.4 Drill bit jet parameters

Three variables can be modified in the drill bit geometry in order to modify the jet:

- Nozzle size and geometry

The nozzle size is dictated by the pump size on the surface as mentioned earlier.

- Stand off distance

This is the axial distance measured between the nozzle exit and the bottom hole. This stand off distance varies with the type of drill bit used. A PDC bit will have a typical stand off distance of 1 to 2 in. For a roller cone bit, it will vary with the size of the bit between 2 to 10 in. The stand off distance can change the impact
power of the jet. Experimental testing showed the jet looses its potential core after a stand off distance of about 6 equivalent nozzle diameter. A stand off distance greater than 7 and up to 15 times the diameter is acceptable usually for shallow portion of the borehole where high penetration rate (higher than 30 ft/hr) occurs. The cleaning of the bottom hole is less critical than the bit balling at this stage. Large flow rate and high turbulent flow pattern are most effective. At greater depth and lower penetration rate, pressure fluctuations are more suited for a better cleaning. Here, stand off distance should less than 7.7 times the diameter (Hughes Christensen Hydraulic manuals).

- Impinging jet angle

This is dictated by geometrical considerations in drill bit design in order to locate the nozzle evenly. No real studies have been performed to determine an optimal jet angle. The impinging angle can influence the pressure distribution on the bottom hole and on the jet spreading.

1.5 Previous work

From 1999 up to now, some researches have been conducted under the guidance of Dr Gutmark at the Louisiana State University and the University of Cincinnati. Collaborating with ENSAM (french engineering school: Ecole Nationale Superieure d’Arts et Metiers), Eric Claudey began a program of research dedicated to the investigation of parameters that could enhance the drill bit efficiency. He was the first one to work on the test rig built by french undergraduate students working at the LSU. The thesis untitled “Innovative nozzles for high efficiency drill bit” [3] summerizes the work completed. It was
used at the University of Cincinnati as a starting point to produce rapidly pressure mappings for various nozzles, this test rig constitutes a rather simple tool to compare the performances of those different geometries.

In 2000 Christophe Porin and Olivier Profit [5] designed a test rig that uses not only a single nozzle but the entire drill bit in an environment closed to the real world. This project aims to design and construct a new testing facility at the Department of Aerospace Engineering and Engineering Mechanics, University of Cincinnati. Owing to this facility, several measurements have been performed on a Security-DBS roller cone bit. The acquisition of the pressure map on the well floor and the visualization of the flow field around the bit are the main targets. The goal of the current project is to test these new nozzle designs in a more realistic drilling environment. The results will show the influences of different nozzle geometries on drill bit performance. The most important ones are the cleaning of the annulus and the bottom hole, the lubrication of the bit and the removal of the cuttings. The assembly was realized by Anthony Opalski in the Gas Dynamics and Propulsion Laboratory of the University of Cincinnati. Nicolas Picard took the succession and developed the software used to run the tests and performed himself many pressure mappings and flow visualizations. The results of his work are included in his thesis report untitled "Development of novel hydraulics for oil well drilling" [4].

Those two tests rigs described latter are complementary. One is used to compare designs between themselves and extract interesting trends as exposed further. The other one gives a bigger picture of what happens down in the hole.
2 Experimental facility

2.1 Tank and pressure table

The tank and the pressure table were built in Louisiana State University. The test rig is composed of the following elements:

2.1.1 Tank

This tank is constructed with Plexiglas panels to allow flow visualization. A vertical internal panel divides the tank into two parts. The larger section provides undisturbed environment to conduct nozzle tests and includes the pressure table. The other smaller part is an overflow reservoir from which the water is sucked by the pump without disturbing the flow in the main section. The structure supporting the tank was cleaned, improved and repainted after the move to UC.

2.1.2 Pressure table

This device is used to investigate the jet pressure distribution on an impingement surface. The pressure table is a rectangular 24-in* 15-in *1-in Plexiglas panel mounted between two vertical holders. These holders are supported in position by two pairs of threaded rods that link them to a structure above the tank. The threaded rods are used to set the plate horizontal by adjusting the position of nuts. Moreover the vertical holders are drilled so that the table can be oriented at different angles. A pressure transducer tap is drilled in the center of this rectangular table.
2.1.3 Pump, piping and nozzle housings

2.1.3.1 Pump
The pump is centrifugal and driven by a 10 hp three-phase electric motor. It is the same pump and motor used at Louisiana State University. The system was dismantled to allow a restoration of its mounting.

2.1.3.2 Piping
The entire former piping was replaced. A new piping was designed and assembled, it is composed of various tubes made of PVC schedule 80. The main purpose was to create a simpler manifold system to get the smoothest flow path before the nozzle housing and move the regulation valve to a by-pass piping. In addition, a by-pass piping system prevents over heating of the water when the required flow rate is below the pump’s capacity. Each part can be remove independently if necessary due to the use of unions at the pump inlet, outlet and at the outflow reservoir outlet. This new installation can be described as four different parts:

- Downstream the pump: a 1.5-inch tube leads from the outlet to a T where the flow is divided. One branch supplies the nozzle via a flow meter and a 1-inch hose.
- The second branch constitutes the by-pass; the water passes through a valve to control the flow rate to the outflow tank.
- Upstream the pump a 2-inch tube links directly the outflow tank to the pump inlet.
• Two 2-inch drain pipes equipped with valves to empty quickly the tank for special operations.
2.1.3.3 Nozzle housings

Two nozzle-adaptors are used depending on the nozzle size. The binding that is linked to the traverse system via a vertical arm determines the nozzle orientation and provides a connection to the pump supply.

The smaller one is made of aluminum; it receives the PDC nozzles (regular, diffuser and Vortexx) and includes a pressure tap for discharge coefficient measurements, however no pressure transducer was available during the first tests. Its internal shape is a convergent nozzle, which allows the adaptation of a 1” NPT pipe thread from the piping system to the nozzle diameter. Preliminary tests were conducted using this housing during the first month.

A second housing was designed and fabricated. It is made of stainless steel for improved mechanical resistance of the threads due to the great number of nozzles changes and for increased resistance to the corrosion. It is painted with a flat-black paint to allow the use of flow visualization system such as a Particle
Image Velocimetry (PIV). A longer adaptor was chosen because the internal shape is a divergent nozzle and makes a smooth transition to prevent flow separation. For the moment this binding does not include a lateral pressure tap for the discharge coefficient measurements, this implementation will be done in the near future.

Figure 2: adaptor for roller cone bit nozzle
Figure 3: schematic illustration
Figure 4: test rig parameters
2.2 Traverse system and its structure

2.2.1 Traverse

The traverse is a 3-axis robot; it is used to automatically position the nozzle according to preprogrammed grids.

![Traverse system during assembly](image)

**Figure 5: traverse system during assembly**

Two LabView programs drive the system via a controller described in the next part. It is an assembly of Velmex BiSlide components that have the following properties:

- "I"-beam design for maximum strength
- Easily assembled for multi-axis configurations without special brackets or plates
- Fully adjustable carriage fit
- Extra guide tracks on the bottom side can be used if the tracks become damaged
• Integrated "T" slots for mounting and attachment of accessories

A certain leeway was chosen during the determination of our requirements concerning the dimension and the resistance of each component. Their characteristics are described in the next section.

Normal Load: 300 lb Dynamic and Static, 1000 lb momentary.

Thrust: 100 lb Dynamic, 200 lb Static, 300 lb momentary.

Cantilever: 500 in-lb For Cantilever loads: Equivalent Center Load = (d x L / 2) + L

d= distance load is from center (inches), L= Load (lbs.)
Deflection: \( a = 0.000011 \) degrees / in-lb (\( F \times d = \) in-lbs).

Coefficient of friction: 0.09 typical.

Coefficient range: 0.04 (Heavy Load Dynamic) to 0.15-.30 (Lubricated Heavy Load Static > 1 hour)

Repeatability: 0.0002" over short term, long-term repeatability is dependent on wear

Straight Line Accuracy: 0.003" over entire travel distance

Screw Lead Accuracy: 0.003"/10" (0.076 mm/ 25 cm)

Operating Environment: 0 to 180\(^\circ\) F (-18 to 82\(^\circ\) C)

The screws have a pitch of 0.1", associated with 400 steps/rev motor allow a precision of 0.00025" on every axis.

The arm that holds the nozzle housing is attached to the vertical traverse with a hollow metallic piece with squared section. The hose passes through this attachment and thus minimizes the distance between the jet and the vertical traverse lowering the cantilever.
2.2.2 Controller

The VP9000 is a programmable stepper motor controller, capable of running up to four motors, one-at-a-time. The controller incorporates a powerful microprocessor and support circuitry, including 64K of nonvolatile RAM for storing programs and setup parameters.

Commands and data are entered either through the RS-232 interface or selected with the front panel keyboard. A 48-character alphanumeric display shows motor position(s), setup parameters and displays menus for keyboard selections.

Commands are transmitted from a host computer.
Features

- A complete microprocessor-based controller with motors drives for the three motors.
- 400 steps per revolution (0.9° step angle) resolution.
- Linear type motor and logic power supplies result in low Electromagnetic Interference (EMI).
- A Remote Jog Controller is included, which allows motors to be jogged manually one step or slewed up to 8000 steps/sec.
- A three wire serial port, conforming to EIA standard RS-232-C, allows a host to enter commands (ASCII characters) and Data, Poll for status, and read Position information.
- A twelve-foot serial communication cable, and 25 to 9-pin adapter for PCs comes standard.
- The VP9000 can run in an interactive or stand-alone mode.
- Acceleration/Deceleration is programmable from 1,000 to 127,000 steps/sec² in 1,00 step/sec² increments.
- Speed is programmable from 1 step / 2 sec to 8000 steps/sec in 1step/sec increments. Up to six speed changes on the fly are possible in continuous Index mode.
- Incremental and Absolute Index distances are programmable from ±1 to ±16,777,215 steps.
• The VP9000 can be programmed to send a pulse or character at preset distances without stopping or slowing the motor.

• Backlash Compensation can be set to automatically finish every index approaching from the positive direction.

• RS-232 baud rate is settable to 9600, 4800, 1200, or 300.

• Limit Switches for CW and CCW directions are provided with plug-in connection to BiSlide limit switch assemblies. Limits can be used for "homing"; unused limit switch inputs can be software disabled.

• The VP9000 can be set to signal the host when a limit switch has been encountered.

• Single Step mode is provided for debugging a program or as a controlled interrupt.

• Self-testing with error messages displayed on front panel minimize troubleshooting.

• Compact Enclosure, rack mountable, with no fans or vent openings.

• Motor position can be read while motor is in motion.

2.2.3 Structure
The structure was designed to support the traverse independently above the tank. It is a simple parallelepiped constructed with Unistrut but reinforced eight struts to prevent any motion of any kind during operation. Its main characteristic is its rigidity. This sturdy design proved itself since the vibrations are hardly detectable during operation.
Figure 7: Unistrut structure

The frame is fixed to the floor by six anchors. The upper part of this frame is fixed to a concrete sidewall.

Figure 8: corner struts and sidewall fixation
The vertical 1-in pipe connecting to the pump outlet is fastened securely to the frame to prevent vibrations during the test rig operation.

Figure 9: vertical piping fastened to the green Unistrut structure

2.2.4 Traverse set-up

Three “tools” were used to set the position of the tank relatively to the nozzle motion:

- A plumb line materializes a vertical line coming from the center of the nozzle down to the pressure measuring plate.
- A cross, composed of two perpendicular lines, has been drawn on the pressure tap plate. The longest axis (500mm) corresponds to the traverse X-axis, whereas the other one is the Y-axis (300mm).
• The traverse controller. It indicates the position of each motor in steps relative to the (0,0,0) position.

Figure 10: operation #1
The following procedure was used to position properly the tank and the traverse:

1. Center approximately the flow tank inside the green structure by keeping the tank sides parallel to the frame sides.

2. Move the plumb line above the pressure tap using the weight tip as a pointer. Reset the values of X, Y and Z in the controller memory. The triplet (0,0,0) corresponds now to the center of the grid.

3. Move the traverse with respect to the X-axis, 250 mm to the left (negative value of X) at a constant value of Y (Y=0). Check if the tip of the weight points towards the line drawn on the plate. If not, move the traverse along the Y-axis until it is the case and note the corresponding Y-deviation in steps. By repeating the previous operation, one can calculate the angle that exist between the grid and the traverse motion and apply the proper correction.

4. Operation 3 is repeated for the Y-axis. A shorter distance is used to accommodate the rectangular shape of the pressure table.

5. Apply the brakes on the tank wheels.

6. Check the final setting by moving the plumb line along the X and Y-axis.

Some spacers composed of threaded rods were added to secure the position of the tank and allow finer settings by tightening or loosening nuts.
Figure 11: picture of the right spacer

Figure 12: test rig before the last stage of completion
2.2.5 Pressure table setup

Assuming that the Plexiglas rectangle is sufficiently flat, a level was used to adjust the pressure table in a plane parallel to the traverse motion. Corrections were applied by adjusting the threaded rods lengths.

The controller can be used to confirm the parallelism between the traverse and the plate by executing the process explained in this paragraph. The following procedure assumes that the geometrical characteristics of the plate are satisfactory. The adjustment is similar to the one performed for positioning the pressure table relative to the traverse. As the controller displays the position in steps for each axis, the user sets the tip of the plumber line flush with one tip of the drawn cross, notes the position, and moves to the opposite branch of the cross and repeats the operation. The angle can be calculated using simple trigonometric calculus.

2.3 LabView software and programs

LabView is a graphical programming development environment based on the G programming language for data acquisition and control, data analysis, and data presentation. LabView gives the flexibility of a powerful programming language with minimal difficulty and complexity because of its graphical programming methodology, which is intuitive to scientists and engineers. LabView includes libraries of functions and development tools designed specifically for instrument control and data acquisition. LabView programs are called virtual instruments (VIs) because their appearance and operation mimic actual instrumentation.

Various VIs have been developed for the purpose of the present research.
2.3.1 The basic virtual instruments

These VIs are used in order to build the main program. The main VI is described in detail, while the others are listed in alphabetical order.

VP9000Cmd.vi

This VI allows sending of an arbitrary string of characters to the controller, over a serial port. It is the basic VI used by most of the more complex VI's described later. It can also be used to send any string to the controller, in order to implement functions not included in this driver set.

INPUTS

- **Serial Port No.**
  
  This input allows the user to specify the host’s serial port that is connected to the Velmex Controller. The default is COM2 (many PC’s use COM1 for the Mouse). This is an Unsigned Long Integer Control with the following definition:

  0 = COM1, 1 = COM2, 2 = COM3, 3 = COM4

- **Command Line**
  
  This input is used to specify the character string to be sent to the Velmex Controller
Absolute Index.vi
This VI lets the user move the motion stage to an absolute (destination) location.
The distance to move (index) is calculated based on the current position and the
destination. Note that sending this command implements the motion only.

INPUTS
- Serial Port No.
- Motor Number
- Absolute Index

Get Motor Position.vi
This VI queries the Controller for the position (in steps) of the selected motor.
The purpose of this VI is to determine the rest position of a stage after the Index
Motor.vi.

INPUTS
- Serial Port No
- Motor Number

OUTPUTS
- Position (steps)
  The response to this query gives the selected motor's current position in steps.

Get Status.vi
This VI queries the Controller for its Status, by sending it the single character “V.
This is a good VI to use after placing the Controller On-Line, to verify the Serial
Port Link with the Controller.
INPUTS

- Serial Port No.

OUTPUTS

- Status Response

  If the Controller is On-Line, a single string character will be returned: an “R” if the Controller is idle (waiting for a Command), a “B” if it is busy running a program, and a “J” if it is in the Jog/slew mode.
Index Motor to Zero.vi
This VI lets the user move the motion stage to the defined Zero location. The distance to move (index) is calculated based on the current position and the Zero location. Note that sending this command implements the motion only. Use the Wait for Prompt.vi VI immediately after to have the Controller signal when motion has stopped.

INPUTS
  - Serial Port No.
  - Motor Number

Index Motor.vi
This VI lets the user move the motion stage a specified number of steps. Note that sending this command implements the motion only

INPUTS
  - Serial Port No
  - Motor Number
  - Steps to Index

InitSerP.vi
This VI initializes the host PC’s Serial Port to the parameters required by the VP9000, specifically 9600 Baud, 7 data bits, 2 stop bits and even parity. This command is generally be used at the very beginning of any automation program, to ensure the host and the Controller’s ports are synchronized.

INPUTS
  - Serial Port No.
- **Baud Rate**
  
  Specifies the Baud rate that the selected serial port (on the host PC) will be set to. The default is 9600.

**Offline.vi**

This VI takes the Velmex Controller off-line, by sending the “Q” character to the Controller. The Controller is returned to the Jog/slew mode, and host/controller interaction is disabled.

**INPUTS**

- **Serial Port No.**

**OUTPUTS**

- **Error Code**
- **Warning String**

**Online.vi**

This VI places the Velmex Controller On-Line, by sending the “F” character to the Controller. This command is necessary prior to any host/controller interaction. This VI should be used immediately after the “InitVP9000.vi” in any automation program.

**INPUTS**

- **Serial Port No.**

**Run.vi**

This VI sends “R” character to the Controller, which Runs any previously entered program. Note that the drivers described herein all include the “R” character
when necessary; that is, if for instance the “Index Motor” VI is called, it will run without the need to send an additional “Run” command

**INPUTS**

- **Serial Port No.**

**Wait For Prompt.vi**

This VI waits for a character to appear at the host PC’s Serial Port Input Buffer. It is used after one of the Index commands, to note the termination of motion. Because the Controller moves only one stage at a time, it is prudent to use this VI to indicate that motion is done, prior to selecting and indexing another motor.

**INPUTS**

- **Serial Port No.**
2.3.2 The programs

The aim of these programs is to make the nozzle follow a predefined grid. It uses sequences and loops.

2.3.2.1 Program “EssaiCycle”

The first program was written to obtained only one grid, the experimenter needs to run the program as many times as the number of required grids.

The procedure is the following:

- The first step is to put the nozzle housing manually above the pressure tap to center the grid. One can use the jog when the controller is off-line. Once the nozzle is properly set, the operator can reset the position to zero on the three axes (each time the program is run, whatever the current position the robot will go first to this position before executing the pressure measurements). A subfolder must be created in the main folder dedicated to store the pressure mappings. The name of this subfolder is usually the name of the nozzle preceded with its diameter in 1/32 of an inch. Example: 1432modular

The test number can be specified in a window dedicated to this purpose. Any additional information can be added. The goal is to allow the experimenter to recognize the files latter.

- The second step is the grid choice, many grids can be chosen:
  - Coarse
  - Fine
  - Coarse with a 21-degre angle
- Fine with a 21-degree angle
- Customized, each parameters can be separately chosen (number of points, distance between points)
- Demonstration, this grid is a simple mesh designed in order to check the traverse motion and the measurements
  - The last step is to defined:
    - The time delay during which the traverse waits before moving to the next point
    - The nozzle diameter
    - The L/D ratio (non-dimensional stand-off distance between the plate and the jet exit)
    - Specify the offset along the X-axis in case of Vortexx nozzle trial.
  - Run the program
A nozzle is mounted in a housing, the traverset moves the nozzle in a plane parallel to the plate. The pressure transducer reads the pressure on the surface of the plate through a small hole in the middle. The program drives the traverse following a virtual grid. At each point of the grid, the traverse stops and the pressure is read after a flow stabilization delay. When the program is started the computer will first ask for the positions of the traverse for each axes, if the answer to the query is different from \((x=0,y=0,z=0)\) the traverse moves the nozzle to the position \((0,0,0)\) which is the center of the grid. Following that, the nozzle goes to the lower left corner to the grid, now the following sequence is made:

- Wait the time prescribed in the front panel
- Acquire the pressure
- Move to the next point

The grid is scanned at constant X, as soon a line is finished the nozzle comes back, the position on the Y and Z-axe are modified and so on.

When the grid is completed, the nozzle returns to point \((0,0)\), the arrays in which the data points are stored, are modified and bundled as one array in order to be send for example to Tecplot to be analyzed. Simultaneously a 3-dimension mapping is plot in the LabView front panel to verify the data completeness.

The structure of the program is sufficiently flexible to include the acquisitions of different parameters (temperature, flow rate...) and their processing with statistical tools.
2.3.2.2  Program “Test A”

This program is a modification of the previous one. After the size of the grid’s unitary cell and the other parameters were determined (number of samples, sampling rate, settling time...) as a compromise between the surfaces covered, the precision and the time consumption, this program was written. It allows the experimenter to run series of coarse grid and fine grid for chosen L/D ratios in a single sequence. L and D stand for:

- L= stand-off distance
- D= nozzle’s diameter

The procedure is similar to the previous one. Some parameters are added to describe the series of grid. These parameters are:

- The increments between two successive grids
- The total number of grids
- The number of points along a grid side for the coarse and fine one

The program is based on a loop sequence and starts at L/D=1, the selector switch “constant for grid number” permits to begin the test from a different L/D ratio.
2.3.2.3 The grids

Two types of grids are used during the tests: a coarse grid and a fine grid. The purpose of the first one is to cover the maximum area while the second one must capture the details near the center. These grids are squares composed themselves of unitary finite elements. The number of points is odd in order to center the grid on the point (0,0) and have a symmetric structure. As explained before the coarse grid is obtained and then the fine grid. A typical coarse grid consists of 29 x 29 points whose spacing is 0.09 in (area 6.35 in$^2$). The fine grid contains 19 x 19 points with a distance of 0.03 in (area 0.29 in$^2$). The distance between two points being three times lower, the fine grid is 9 times denser than
the coarse one. In order to have a fine grid that matches the coarse one the number of points must be equal to $6n+1$, $n$ being an integer.
<table>
<thead>
<tr>
<th>$N$, integer</th>
<th>Number of points</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>13</td>
</tr>
<tr>
<td>3</td>
<td>19</td>
</tr>
<tr>
<td>4</td>
<td>25</td>
</tr>
<tr>
<td>5</td>
<td>31</td>
</tr>
<tr>
<td>6</td>
<td>37</td>
</tr>
<tr>
<td>7</td>
<td>43</td>
</tr>
</tbody>
</table>

Table 1: Number of points required to constitute a fine grid

Both of them can be merged as a unique grid using the program “merge” presented in the next part.

Figure 15: coarse grid (29*29 pts) and fine grid (19*19 pts) centered
2.3.2.4 Program “Merge”
This program also written with LabView extracts the coordinates of each point and the value of the pressure and distributes them in a new array with respect to their position. It compares simultaneously X and Y starting from the lower left hand corner and order them. If two points from the two grids are common an averaging of the pressure is done. In this particular case the relative difference between the pressure from the coarse grid and the pressure for the fine grid is stored in a second array.

2.3.2.5 Program “Complex Grid”
It was decided in order to obtain a better continuity between two neighboring points of the coarse and fine grids to acquire the pressure following directly the merged grid. This leads unfortunately to a less flexible tool. The heterogeneousness of the grid implies to use Tecplot in a mode different from the one use to plot the simpler grids. This mode is called “finite elements”, each quadrilateral cell must be declared by the order of its four corners in the main array. Due to the complexity involved by the type of plotting required by Tecplot, the program was written to deal with only the merged grid shown in the figure 12.

2.4 Instrumentation and data acquisition

2.4.1 Pressure transducers
Two PDCR 130 Druck pressure transducers are used to measure the values of the pressure on the table and inside the nozzle housing. . The transduction
principle lies in an integrated silicon strain gauge bridge. These PDCR 130/W/C are particularly suitable for industrial and aerospace applications where vibrations and relatively hostile environment could be present. The maximum pressure for both of them can go up to 200 psig but for the present application the pressure transducers have been calibrated between 0 and 100 psig

2.4.2 Pressure manometer
A mechanical liquid filled pressure gauge TREICE Model #800LFB featuring a 3.5” dial, which ranges from 0 to 200 psi, allows setting a constant pressure of 90 psi for each test. This manometer was installed at the pump outlet.

2.4.3 Flow meter
The 1” Great Plains Industries electronic digital meter translates pulse data from a turbine into calibrated flow units shown on the meter’s readout.

2.4.4 Computer and data acquisition board
Host computer
A Pentium PC is used to perform several tasks:

- Drive the 3-axe traverse controller
- Acquire the value of parameters such as pressure with respect to a predefined grid. One data acquisition board is installed to fulfill this task.

2.4.4.1 Data board acquisition DAS-1801HC
The DAS-1801HC is a high-gain board. Major features of these boards are as follow:
• The board makes 16-bit data transfers on the AT bus.
• The boards are software-configurable for 64 single-ended or 32 differential analog input channels.
• Channels are individually software-configurable for gain.
• The board measures inputs at up to 333ksamples/s with 12-bit resolution.
• A 1024-location FIFO data buffer ensures data integrity at all sampling rates.
• A 64-location channel/gain queue supports high-speed sampling at the same or different gains and in sequential or non-sequential channel order.
• Interrupt levels are software-configurable.
• Dual 12-bit digital to analog converter outputs have simultaneous updates.
• The board has four digital inputs.

2.5 Flow visualization
As previously discuss the tank being made of transparent Plexiglas permits photography and video recording if needed. The digital camera is an Olympus D600L mega-pixel.

3 Experimental testing - horizontal plate

3.1 Operating conditions
The design of the facility allowed the experimenter to set either the pump outlet pressure or the flow rate (in a given range). Setting both parameters independently is impossible. During the tests the temperature of the water
increased from 30°C to 50°C. These temperature variations did not have a significant effect on the pressure measurements.

Data was acquired using computer control. Before any acquisition, the settling time of one second was chosen to allow the pressure at the transducer to reach steady state. At each point, 1000 data samples were acquired for the pressure at a sampling rate of 1000 Hz.

Two series of tests were performed: a preliminary one with the small nozzles and the main one with the roller cone bit nozzles.

3.1.1 Time required to perform a test

The time required to perform a test depends on the number of points for each grid, the settling time, the number of samples and the sampling frequency.

In the next table is stored an example for a settling time of one second, 1000 samples at 1000Hz. This calculus is based on the time recorded for both the coarse and the fine grid.

By dividing the time by the number of points one gets the average time required for one point. This calculus is stored in the second line of the following array; the test rig in this particular case performs the acquisition for one point in 0.072 minute. By multiplying this constant by the number of points for a given grid one can establish the following table:
<table>
<thead>
<tr>
<th>Num of pts on one side</th>
<th>Total num of pts</th>
<th>Time to scan a pt (min)</th>
<th>Total time (min)</th>
<th>Total time hour</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>81</td>
<td>0.07</td>
<td>5.8</td>
<td>0.10</td>
</tr>
<tr>
<td>11</td>
<td>121</td>
<td>0.07</td>
<td>8.7</td>
<td>0.15</td>
</tr>
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<td>13</td>
<td>169</td>
<td>0.07</td>
<td>12.2</td>
<td>0.20</td>
</tr>
<tr>
<td>15</td>
<td>225</td>
<td>0.07</td>
<td>16.2</td>
<td>0.27</td>
</tr>
<tr>
<td>17</td>
<td>289</td>
<td>0.07</td>
<td>20.8</td>
<td>0.35</td>
</tr>
<tr>
<td>19</td>
<td>361</td>
<td>0.07</td>
<td>26.0</td>
<td>0.43</td>
</tr>
<tr>
<td>21</td>
<td>441</td>
<td>0.07</td>
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<td>38.1</td>
<td>0.64</td>
</tr>
<tr>
<td>25</td>
<td>625</td>
<td>0.07</td>
<td>45.0</td>
<td>0.75</td>
</tr>
<tr>
<td>29</td>
<td>841</td>
<td>0.07</td>
<td>60.6</td>
<td>1.01</td>
</tr>
</tbody>
</table>

Table 2: time required to perform a grid with respect to its size
3.1.2 Particle Image Velocimetry

3.1.2.1 Introduction

Particle Image Velocimetry or PIV is the most advanced system for measuring fluid velocity available today. PIV is an optical technique that can perform three dimensional velocity measurements over an entire plane. This technique has the enormous advantages over LDA and other point-by-point measuring systems in that instantaneous velocity vector fields can be obtained, quantitative flow visualizations may be obtained, and data acquisition is much quicker.

The principle behind stereo PIV is simple. The flow is seeded with particles and is illuminated by a laser sheet. Two images are recorded by a pair of CCD cameras with a short time delay, t, between the two exposures. By calculating the average displacements, \( .x \) and \( .y \), of a given set of neighboring particles over the time delay, the average velocity components of the set of particles, \( u_x \) and \( u_y \) can be found. The third velocity component is resolved by comparing the apparent motion of a set of particles from the perspective of one camera to their apparent motion from the perspective of the other camera.

![Figure 16: Stereo PIV layout](image-url)
The system used at the University of Cincinnati was manufactured by TSI. The hardware was controlled by a PC and consisted of a synchronizer, two pulsed YAG lasers, and optics to focus the laser, two CCD cameras, and data processing software.

A pair of 120 mJ YAG lasers was used to illuminate the flow. The laser beams were transmitted to the test section through an articulated arm, and were split into sheets of variable thickness depending on the lenses used. Two 2048 x 2048 pixel CCD cameras were used for image acquisition. The synchronizer controlled the triggering for the cameras and lasers.

The synchronizer was responsible for accepting commands from the PC, sending accurately timed signals to the cameras and lasers and receiving pulse information from the cameras. Upon receiving a command from the PC to begin acquiring data, the synchronizer sends a TTL trigger signal to the two cameras. The cameras respond with similar pulses to the synchronizer to verify that they are ready to acquire data. The cameras simultaneously activate their CCD arrays for an exposure time of 255 µs. The synchronizer waits 250 µs after the exposures have begun and then fires the first laser whose pulse duration is 6 ns. After the exposure is complete, the cameras pass the information received by their CCD arrays into their memory and begin transferring the information to RAM or directly to the hard drive. The cameras reactivate their CCD arrays while information is still being transferred to the PC and the laser fires a second time. There is a 200 ns delay between the cameras completing the first exposure and starting the second exposure. The cameras wait until the first image is
transferred from their memory to the PC and then begin transferring the second image to the PC. The amount of time required for the cameras to transfer both exposures to the computer determines the minimum amount of time between captures.

Saving data directly to the hard drive requires approximately 1 s per capture while saving to RAM requires approximately 0.5 s per capture. The exposure times and pulse delay time may be modified in the software but are usually not adjusted. The user must adjust the delay time between laser pulses in order to ensure that the seeding particles move an appropriate distance between the two frames. Too small or too great delays result in erroneous data. In this setup, both cameras are focused on the center of the test section. Scheimpflug adapters are mounted on the cameras to tilt the CCD chips relative to the lens to maintain focus over the entire field of view. The entire field of view will be in focus when the planes of the field of view, the lens and the CCD array intersect on the same line. There should be an angle of at least 30 between the two cameras in order to accurately resolve the velocity component perpendicular to the laser sheet. The laser sheet is normally focused to have a thickness of approximately 1 mm.

Each camera observes the particle moving through a different displacement: the left camera observes a displacement shown by the red vector and the right camera observes a displacement shown by the purple vector. By comparing the apparent displacements between the two sets of images, the software is able to compute all three-velocity components of the particle.
It is important in PIV measurements to carefully control the amount of seeding in the flow. If there are too few particles in the flow the data processing software does not have sufficient information to accurately compute a velocity value. On the other hand, if too much seeding is used the image becomes saturated and the software is unable to distinguish individual particles.

Calibrating the stereo PIV system requires placing a calibration target in the test section along the plane of the laser sheet. The laser is deactivated and each camera acquires an image of the target. The target is a flat panel with a series of grooves machined on its surface. A matrix of evenly spaced white dots is marked on its surfaces in such a way that every other dot is located in one of the grooves. At the center of the target there is a cross (fiducial mark) that is recognized by the software. During the calibration process, the software first locates the fiducial mark in each image and then locates each calibration dot.

The software then identifies each dot as being on either the front surface of the target or in one of the grooves. The user enters the spacing of the dots in the software and the depth of the grooves. This allows the software to calibrate displacement of the seeding particles between the sets of images to actual distance in the test section and also to account for the distortion caused by glass surfaces between the laser sheet and the cameras. The first step in three-dimensional data processing is for the computer to perform a cross correlation on each set of images (left and right) separately, as though they were two-dimensional vector maps. The software uses an interrogation grid that is rectangular in the plane of each camera’s CCD chip for this step. These results in
two two-dimensional vector maps, each representing the instantaneous flow field as recorded from the perspective of each camera. Using data stored in the calibration images, the software maps points from a rectangular interrogation grid in the plane of the light sheet onto the left and right vector maps. The two-dimensional vector maps are individually resampled over the new interrogation points using an interpolation scheme to estimate the two-dimensional vectors based on their nearest neighbors. This gives the two-dimensional displacement as seen by each camera at each point on a common interrogation grid, and the true three-dimensional displacement can be estimated by solving four equations with three unknowns through a least-squares scheme.

While there are many great advantages to PIV, there are also several drawbacks. A velocity vector calculated in an interrogation region is an average of the velocities of the seeding particles in that region. Additionally, data processing is slow for PIV systems. Each capture, which resulted in a single instantaneous three-dimensional velocity vector plot, required acquisition of four images using 8 Mb of hard drive space each. Each capture took approximately 100 seconds to process. While tens or hundreds of thousands of samples are easily possible with LDA and hotwire measurements, limited hard drive space and excessive processing time limit the current system to 100 samples at each data point. This results in a poorer average of the mean velocity data, and less smooth velocity contours and profiles.
3.1.2.2 Application to the test rig

For our particular application with a water jet on a plate in a water medium the amount of air bubbles being important one has to take care a very important issue: the scattering of light. The interface between the air inside the bubbles and the water outside changes the direction of the laser. If the deviated light from the laser hits the CCD from the cameras some pixels can be burnt. The fragility and the very expensive price of this apparatus require a protection. Using fluorescent particles does this protection. The fluorescent dye utilized to manufacture the beads is exited by the laser color -green- (532 nm in wavelength) and emit a reddish color (612 nm), a high-pass filter mounted on the cameras’ lenses transmit 85% of the light above 600 nm and cut 100% of the light under 560 nm. The pictures can thus be taken and processed by the software. This is in theory; the actual tests and issues will be discussed later in one of the following chapter dedicated to this topic.

3.1.2.3 Stokes number

The Stokes number is a parameter of paramount importance in PIV application. This non-dimensional number characterizes the fact that a particle of given dimension and density is going to follow the surrounding flow. Knowing that the cameras acquire pictures of the seeding particles, those must mimic the characteristics of the flow in order to obtain significant results. The Stokes number is the ratio of the particle time scale and the flow time scale, the Stokes number should be smaller than 1.
Using the fluorescent particle’s properties provided by its manufacturer, the flowrate and the nozzle geometry. One can estimate the Stokes number to be:

$$St = 9441 \cdot \text{Diameter}_{\text{Particle}}^2$$

$St < 1$ when the particle has the critical size smaller than 0.01 m.
3.1.3 Preliminary tests

Since the beginning of August 2001, many tests were run involving different nozzles. The nozzles mounted in the test rig were the following:

- 16/32 pdc
- 16/32 diffuser
- 9/32 diffuser
- 13/32 pdc
- 13/32 diffuser
- 13/32 vortext

Because the 16/32s and the 9/32 respectively have the biggest and the smallest nozzle diameter, they were initially chosen to determine the test rig’s characteristics, i.e. pump outlet pressure and flow rate for full-open and full-closed by-pass valve. The values are given in the following table.

<table>
<thead>
<tr>
<th>Nozzle</th>
<th>Pressure psi</th>
<th>Flow rate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Max</td>
<td>Min</td>
</tr>
<tr>
<td>9/32 diffuser</td>
<td>106</td>
<td>29.0</td>
</tr>
<tr>
<td>16/32 pdc</td>
<td>97</td>
<td>21.0</td>
</tr>
<tr>
<td>16/32 diffuser</td>
<td>96</td>
<td>21.0</td>
</tr>
<tr>
<td>13/32</td>
<td>102</td>
<td>24.0</td>
</tr>
</tbody>
</table>

Table 3: pump outlet pressure and flow rate for full-open and full-closed by-pass valve

In a preliminary study, for these same nozzles, the tests were done at full flow rate for constant stand-off distance and/or constant L/D ratio where:
- \( L \): stand-off distance
- \( D \): nozzle's diameter

Usually, the L/D values are 1, 5, 9, 13, 17 and 21 because they cover a wide range of distances.

Multiple grid have been tried to determine which number of points and resolution would be the best regarding to:

- Size
- Definition
- Time consumption

### 3.1.4 3-dimensional pressure mappings

![Figure 17: Modular PDC nozzle L/D of 1 5 9 13 17 21](image1)

![Figure 18: Vortexx PDC nozzle L/D 1 5 9 13 17 21](image2)
3.1.5 2-dimensional pressure mappings

Figure 19: Modular PDC nozzle L/D of 1 5 9 13 17 21

Figure 20: Vortexx PDC nozzle L/D 1 5 9 13 17 21

pressure: 4 5 5 6 7 8 10 11 13 15 17 20 23 27 31 36 42 49 56 65
3.1.6 Test Matrix

<table>
<thead>
<tr>
<th>Nozzle</th>
<th>L/D ratio for pressure mappings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modular 20/32</td>
<td>1, 3, 5, 7, 9, 13, 17 and 20**</td>
</tr>
<tr>
<td>Modular 18/32</td>
<td>1, 3, 5, 7, 9, 13, 17 and 21</td>
</tr>
<tr>
<td>Modular 16/32</td>
<td>1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20 and 21</td>
</tr>
<tr>
<td>Modular 14/32</td>
<td>1, 3, 5, 7, 9, 13, 17 and 21</td>
</tr>
<tr>
<td>Modular 12/32</td>
<td>1, 3, 5, 7, 9, 13, 17 and 21</td>
</tr>
</tbody>
</table>

** Table 4: test matrix for modular nozzles, pressure mappings **

** L/D=21 cannot be performed because the distance is not compatible with the Z-axis length.**
4 Results – horizontal plate

4.1 Numerical results for the modular nozzles

<table>
<thead>
<tr>
<th>L/D</th>
<th>Pressure PSIG</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>80.63</td>
</tr>
<tr>
<td>3</td>
<td>80.55</td>
</tr>
<tr>
<td>5</td>
<td>79.4</td>
</tr>
<tr>
<td>7</td>
<td>68</td>
</tr>
<tr>
<td>9</td>
<td>50.35</td>
</tr>
<tr>
<td>13</td>
<td>27.46</td>
</tr>
<tr>
<td>17</td>
<td>17.22</td>
</tr>
<tr>
<td>21</td>
<td>11.65</td>
</tr>
</tbody>
</table>

Table 6: 12/32 modular – pressure

<table>
<thead>
<tr>
<th>L/D</th>
<th>Pressure PSIG</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>76.56</td>
</tr>
<tr>
<td>3</td>
<td>76.32</td>
</tr>
<tr>
<td>5</td>
<td>75</td>
</tr>
<tr>
<td>7</td>
<td>63.78</td>
</tr>
<tr>
<td>9</td>
<td>46.76</td>
</tr>
<tr>
<td>13</td>
<td>26.69</td>
</tr>
<tr>
<td>17</td>
<td>16.23</td>
</tr>
<tr>
<td>21</td>
<td>11.2</td>
</tr>
</tbody>
</table>

Table 7: 14/32 modular – pressure
<table>
<thead>
<tr>
<th>L/D</th>
<th>Pressure PSIG</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>67.69</td>
</tr>
<tr>
<td>2</td>
<td>66</td>
</tr>
<tr>
<td>3</td>
<td>67.57</td>
</tr>
<tr>
<td>4</td>
<td>65.85</td>
</tr>
<tr>
<td>5</td>
<td>66.06</td>
</tr>
<tr>
<td>6</td>
<td>62.43</td>
</tr>
<tr>
<td>7</td>
<td>57.52</td>
</tr>
<tr>
<td>8</td>
<td>49.81</td>
</tr>
<tr>
<td>9</td>
<td>43.3</td>
</tr>
<tr>
<td>10</td>
<td>36.51</td>
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<tr>
<td>11</td>
<td>Not exploitable</td>
</tr>
<tr>
<td>12</td>
<td>27.24</td>
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<tr>
<td>13</td>
<td>22.89</td>
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<tr>
<td>14</td>
<td>20.69</td>
</tr>
<tr>
<td>15</td>
<td>Not exploitable</td>
</tr>
<tr>
<td>16</td>
<td>Not exploitable</td>
</tr>
<tr>
<td>17</td>
<td>13.88</td>
</tr>
<tr>
<td>18</td>
<td>13.17</td>
</tr>
<tr>
<td>19</td>
<td>Not exploitable</td>
</tr>
<tr>
<td>20</td>
<td>11</td>
</tr>
<tr>
<td>21</td>
<td>9.34</td>
</tr>
</tbody>
</table>

Table 8: 16/32 modular – pressure

The missing values are the origin of the discontinuous graphs in the following pages.
### Table 9: 18/32 modular - pressure

<table>
<thead>
<tr>
<th>L/D</th>
<th>Pressure (PSIG)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>57.9</td>
</tr>
<tr>
<td>3</td>
<td>60.17</td>
</tr>
<tr>
<td>5</td>
<td>58.84</td>
</tr>
<tr>
<td>7</td>
<td>49.5</td>
</tr>
<tr>
<td>9</td>
<td>36.56</td>
</tr>
<tr>
<td>13</td>
<td>19.72</td>
</tr>
<tr>
<td>17</td>
<td>12.69</td>
</tr>
<tr>
<td>21</td>
<td>7.5</td>
</tr>
</tbody>
</table>

### Table 10: 20/32 modular - pressure

<table>
<thead>
<tr>
<th>L/D</th>
<th>Pressure (PSIG)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>47.95</td>
</tr>
<tr>
<td>3</td>
<td>47.2</td>
</tr>
<tr>
<td>5</td>
<td>45.72</td>
</tr>
<tr>
<td>7</td>
<td>38.2</td>
</tr>
<tr>
<td>9</td>
<td>28.57</td>
</tr>
<tr>
<td>13</td>
<td>15.51</td>
</tr>
<tr>
<td>17</td>
<td>9.67</td>
</tr>
<tr>
<td>20</td>
<td>7.98</td>
</tr>
</tbody>
</table>
4.2 Pressure vs. L/D

Figure 21: Pressure Vs. Non Dimensional Stand-off Distance
4.3 3-dimensional and 2-dimensional graphs for the modular nozzles

4.3.1 12/32 modular

4.3.1.1 12/32 modular with L/D=1

Figure 22: 12/32 modular – L/D=1
Figure 23: 12/32 modular – L/D=1
4.3.1.2 12/32 modular with L/D=3

Figure 24: 12/32 modular – L/D=3
Figure 25: 12/32 modular – L/D=3
4.3.1.3  12/32 modular with L/D=5

Figure 26: 12/32 modular – L/D=5
Figure 27: 12/32 modular – L/D=5
4.3.1.4  12/32 modular with L/D=7

Figure 28: 12/32 modular – L/D=7
Figure 29: 12/32 modular – L/D=7
4.3.1.5 12/32 modular with L/D=9

Figure 30: 12/32 modular – L/D=9
Figure 31: 12/32 modular – L/D=9
4.3.1.6 12/32 modular with L/D=13

Figure 32: 12/32 modular - L/D=13
Figure 33: 12/32 modular - L/D=13
4.3.1.7 12/32 modular with L/D=17

Figure 34: 12/32 modular – L/D=17
Figure 35: 12/32 modular - L/D=17
4.3.1.8  12/32 modular with L/D=21

Figure 36: 12/32 modular – L/D=21
Figure 37: 12/32 modular - L/D=21
4.3.2 14/32 modular

4.3.2.1 14/32 modular for L/D=1

Figure 38: 14/32 modular – L/D=1
Figure 39: 14/32 modular – L/D=1
4.3.2.2  14/32 modular for L/D=3

Figure 40: 14/32 modular – L/D=3
Figure 41: 14/32 modular – L/D=3
4.3.2.3 14/32 modular for L/D=5

Figure 42: 14/32 modular – L/D=5
Figure 43: 14/32 modular – L/D=5
4.3.2.4 14/32 modular for L/D=7

Figure 44: 14/32 modular – L/D=7
Figure 45: 14/32 modular – L/D=7
4.3.2.5 14/32 modular for L/D=9

Figure 46: 14/32 modular – L/D=9
Figure 47: 14/32 modular – L/D=9
4.3.2.6  14/32 modular for L/D=13

Figure 48: 14/32 modular – L/D=13
Figure 49: 14/32 modular – L/D=13
4.3.2.7  14/32 modular for L/D=17

Figure 50: 14/32 modular – L/D=17
Figure 51: 14/32 modular – L/D=17
Figure 52: 14/32 modular – L/D=21
Figure 53: 14/32 modular – L/D=21
4.3.3 16/32 modular

4.3.3.1 16/32 modular for L/D=1

Figure 54: 16/32 modular – L/D=1
Figure 55: 16/32 modular – L/D=1
4.3.3.2 16/32 modular for L/D=3

Figure 56: 16/32 modular – L/D=3
Figure 57: 16/32 modular – L/D=3
4.3.3.3 16/32 modular for L/D=5

Figure 58: 16/32 modular – L/D=5
Figure 59: 16/32 modular – L/D=5
4.3.3.4 16/32 modular for L/D=7

Figure 60: 16/32 modular – L/D=7
Figure 61: 16/32 modular – L/D=7
4.3.3.5  16/32 modular for L/D=9

Figure 62: 16/32 modular – L/D=9
Figure 63: 16/32 modular – L/D=7
4.3.3.6  16/32 modular for L/D=13

Figure 64: 16/32 modular – L/D=13
Figure 65: 16/32 modular – L/D=9
4.3.3.7 16/32 modular for L/D=13

Figure 66: 16/32 modular - L/D=13
Figure 67: 16/32 modular - L/D=13
4.3.3.8 16/32 modular for L/D=17

Figure 68: 16/32 modular – L/D=17
Figure 69: 16/32 modular - L/D=17
4.3.3.9 16/32 modular for L/D=21

Figure 70: 16/32 modular – L/D=21
Figure 71: 16/32 modular - L/D=21
4.3.4 18/32 modular

4.3.4.1 18/32 modular for L/D=1

Figure 72: 18/32 modular – L/D=1
Figure 73: 18/32 modular – L/D=1
4.3.4.2 18/32 modular for L/D=3

Figure 74: 18/32 modular – L/D=3
Figure 75: 18/32 modular – L/D=3
4.3.4.3 18/32 modular for L/D=5

Figure 76: 18/32 modular – L/D=5
Figure 77: 18/32 modular – L/D=5
4.3.4.4 18/32 modular for L/D=7

Figure 78: 18/32 modular – L/D=7
Figure 79: 18/32 modular – L/D=7
4.3.4.5 18/32 modular for L/D=9

Figure 80: 18/32 modular – L/D=9
Figure 81: 18/32 modular – L/D=9
4.3.4.6  18/32 modular for L/D=13

Figure 82: 18/32 modular – L/D=13
Figure 83: 18/32 modular – L/D=13
4.3.4.7  18/32 modular for L/D=17

Figure 84: 18/32 modular – L/D=17
Figure 85: 18/32 modular – L/D=17
18/32 modular for L/D=21

Figure 86: 18/32 modular – L/D=21
Figure 87: 18/32 modular – L/D=21
4.3.5 20/32 modular

4.3.5.1 20/32 modular for L/D=1

Figure 88: 20/32 modular – L/D=1
Figure 89: 20/32 modular – L/D=1
4.3.5.2 20/32 modular for L/D=3

Figure 90: 20/32 modular – L/D=3
Figure 91: 20/32 modular – L/D=3
20/32 modular for L/D=5

Figure 92: 20/32 modular – L/D=5
Figure 93: 20/32 modular – L/D=5
20/32 modular for L/D=7

Figure 94: 20/32 modular – L/D=7
Figure 95: 20/32 modular – L/D=7
Figure 96: 20/32 modular – L/D=9
Figure 97: 20/32 modular – L/D=9
4.3.5.4 20/32 modular for L/D=13

Figure 98: 20/32 modular – L/D=13
Figure 99: 20/32 modular – L/D=13
4.3.5.5 20/32 modular for L/D=17

Figure 100: 20/32 modular – L/D=17
Figure 101: 20/32 modular – L/D=17
Figure 102: 20/32 modular – L/D=20
Figure 103: 20/32 modular – L/D=20
### 4.4 Results for the Coanda nozzle

<table>
<thead>
<tr>
<th>Stand-off distance [inch]</th>
<th>Pressure [PSIG]</th>
<th>Nozzle diameter</th>
<th>L/D</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>45.46</td>
<td>0.5</td>
<td>8</td>
</tr>
<tr>
<td>5</td>
<td>33.35</td>
<td>0.5</td>
<td>10</td>
</tr>
<tr>
<td>6</td>
<td>25.42</td>
<td>0.5</td>
<td>12</td>
</tr>
<tr>
<td>7</td>
<td>19.28</td>
<td>0.5</td>
<td>14</td>
</tr>
</tbody>
</table>

### 4.5 Results for the Vortexx nozzle

<table>
<thead>
<tr>
<th>Stand-off distance [inch]</th>
<th>Pressure [PSIG]</th>
<th>Nozzle diameter</th>
<th>L/D</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>29.50</td>
<td>0.5</td>
<td>8</td>
</tr>
<tr>
<td>5</td>
<td>19.09</td>
<td>0.5</td>
<td>10</td>
</tr>
<tr>
<td>6</td>
<td>14.39</td>
<td>0.5</td>
<td>12</td>
</tr>
<tr>
<td>7</td>
<td>11.11</td>
<td>0.5</td>
<td>14</td>
</tr>
</tbody>
</table>

A set of tests has been recently done for this Vortexx nozzle:

<table>
<thead>
<tr>
<th>L/D</th>
<th>P (psig)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>76.40</td>
</tr>
<tr>
<td>3</td>
<td>74.20</td>
</tr>
<tr>
<td>5</td>
<td>55.80</td>
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<tr>
<td>7</td>
<td>34.40</td>
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<td>9</td>
<td>22.25</td>
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<tr>
<td>17</td>
<td>7.90</td>
</tr>
<tr>
<td>21</td>
<td>5.25</td>
</tr>
</tbody>
</table>
It is important to recall that:

The X and Y coordinates featuring on the plotting are the coordinates of the geometrical point that is in the center of the nozzle (not the jet) at the exit plan. This explains the symmetry with respect to the center of the plot when one switches to the 2D or 3D color pressure mappings.
### 4.6 Results for the Side-Port nozzle

<table>
<thead>
<tr>
<th>Stand-off distance [inch]</th>
<th>Pressure [PSIG]</th>
<th>Nozzle diameter</th>
<th>L/D</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>35.47</td>
<td>0.5</td>
<td>8</td>
</tr>
<tr>
<td>5</td>
<td>24.85</td>
<td>0.5</td>
<td>10</td>
</tr>
<tr>
<td>6</td>
<td>18.36</td>
<td>0.5</td>
<td>12</td>
</tr>
<tr>
<td>7</td>
<td>13.75</td>
<td>0.5</td>
<td>14</td>
</tr>
</tbody>
</table>
5 Discussion

5.1 Modular nozzles

The dimensional pressure measured for the various L/D ratios (Fig 14) was normalized by the maximum pressure obtained for each nozzle. The results are plotted in Fig. 98. This graph represents non-dimensional pressure delivered by the five modular nozzles with respect to the L/D ratio.

![Non-dimensional pressure vs L/D ratio](image)

**Figure 106: Non-dimensional pressure vs. L/D ratio for the modular nozzles**

A very interesting trend was obtained in Fig 98; the curves corresponding to all five nozzles collapsed on a single line. Few points are slightly shifted, notably L/D=1 for the 1832 and L/D=2 and 4 for the 1632. The exception of the 1832...
nozzle is possibly due to a “vena contracta” effect that causes the flow to accelerate downstream of the nozzle exit. A possible reason for the deviation of the 1632 data points is that the even L/D data was taken as a different set than the odd L/D values because of the program sampling structure.

The behavior of the graph can be divided into two sections:

- From L/D=1 to 5 the curve is flat and the parameter P/Pmax is approximately equal to 1. Pmax is the maximum pressure of each nozzle. The constant level for L/D<5 is a result of the potential core of the jet. Its typical length is 5 diameters and within this distance the mean velocity on the jet axis is not changing resulting in an invariant impact pressure.

- From L/D=5 to 21 the curve drops down with the P/Pmax ratio inversely proportional to L/D.

As stated above, the behavior of the impact pressure is related to the velocity field via Bernoulli’s equation. Since the velocity is constant along the jet potential core, whose length is typically 5 diameters, the impact pressure will stay constant for stand-off distance smaller than 5D. Downstream of the tip of the potential core, the velocity decays at a rate inversely proportional to the distance from the nozzle due to mixing with the ambient stationary flow. Therefore, the impact pressure will drop in a similar manner. By plotting the square root of the ratio of the maximum pressure and the actual pressure for a given set of measurements for a particular nozzle, we can relate the variation of the impact pressure to the behavior of the rate of decay of the mean jet velocity using Bernoulli’s equation
along a streamline. Once this realized one obtains the following graphical representation that shows a nearly linear variation of this variable with L/D.

\[ \text{Sqrt}(P_{\text{max}}/P) \text{ vs. L/D ratio} \]

This plot could be related to the graph representing the variation of the mean velocity along a circular air jet provided on the page 581 of I. Wygnanski and H. Fiedler's article entitled “Some measurements in the self-preserving jet” (“Some measurements in the self-preserving jet”, J. Fluid Mechanics (1969), volume 38, part 3, pp 577-612). However, in this particular case one is limited to the very left part of the curve (L/D less than 21), which is not yet considered as the self-preserving region by the previously cited authors. Velocity measurements of the various jets flow field will be performed using PIV technology and will be compared with the present results.
5.2 Spreading rates

For this particular graph it was decided to use the value of the radius corresponding to a pressure of 50% of the maximum pressure for a given nozzle (r0.5); this parameter is usually called jet half width when it deals with the speed. In this case one conducted a similar approach but with the pressure. Once divided by the diameter in order to make the parameter dimensionless the spreading rates were plotted against L/D ratio. The coefficient of linearity between r0.5/d and l/d represents the jet’s angle tangent value (recalling that the jet’s angle is the angle be formed between the axis and the line representing r0.5). Unfortunately the number of points is probably too small to show an interesting trend.
5.3 **Vortexx nozzle Vs. 1632 Modular nozzle**

The number of experimentations done with those two nozzles featuring the same outside diameter allows plotting these next graphs:

![Vortexx Vs. Modular (1632)](image)

*Figure 109: Vortexx Vs. Modular (1632) – Pressure Vs. L/D*
Figure 110: Vortexx Vs. Modular

Figure 111: Vortexx Vs. Modular
The Vortexx nozzle shows somewhat higher maximum pressure relative to the modular nozzle for L/D<3. However, its velocity decay is so rapid that by L/D=7 the maximum pressure drops to less than 50% of the modular nozzle. Fig. 102 shows that both nozzles exhibit the same linear variation of the square root of $P_{\text{max}}/P$ but the slope of the Vortexx nozzle is much higher due to its faster decay rate. Velocity measurements using PIV will be used to obtain detailed velocity field measurements of the various nozzles to allow better understanding of this behavior.
5.4 **16/32 nozzles of different types**

This graph shows the superposition of the pressures performed by four different 16/32 nozzles of different designs. One can see that the Coanda nozzle is close to the regular modular 16/32. One should be also canny concerning the signification of the points showing the Sideport pressure values because this type of nozzle includes two jets in its design that implies different diameters.
6 Conclusions

6.1 Modular nozzles

The modular nozzles follow the same trend if the outlet pressure is constant and the results and variables are non-dimensional. The initial first 5 diameters exhibit a constant value due to the potential core length. Downstream of this location we can determine a trend line of impact pressure decrease by using a polynomial approximation for the relevant range of L/D ratios.

\[ y = 2 \times 10^{-5}x^4 - 0.0011x^3 + 0.0306x^2 - 0.4201x + 2.6162 \]

\[ R^2 = 1 \]

Figure 113: Modular nozzles, approximation of P/Pmax for L/D ranging from 7 to 21

The plot can be divided into two parts comparable to straight segments:
• From L/D=1 to L/D=5: the horizontal plateau is related to the constant velocity profile inside the jet potential core.

• For L/D>5, Fig. 103 demonstrates the inverse proportionality with L/D that is described by a single 4\textsuperscript{th} order polynomial equation. When the square root of P\textsubscript{max}/P is plotted as in Fig. 104, the linear relationship with L/D is shown to follow a slope of 0.1121 which is within the range of decay rate obtained previously for circular jets. This universal behavior provides the drilling engineer with a simple tool of choosing between nozzles of different diameters when a certain impact pressure is desired at a given stand-off distance.

\[ y = 0.1121x + 0.2588 \]
\[ R^2 = 0.9993 \]

\[ Sqrt(P_{\text{max}}/P) \text{ vs. } L/D \text{ ratio} \]

\[ L/D \text{ ratio} \]

\[ Sqrt(P_{\text{max}}/P) \]

\[ y = 0.1121x + 0.2588 \]

\[ R^2 = 0.9993 \]

Figure 114: Square root of P\textsubscript{max}/P Vs. L/D Ratio for L/D between 9 and 21
Non-Dimensionalized Pressure Vs. Diameter (inch) for L/D Ratio ranging from 1 to 17

Figure 115: Non-Dimensionalized Pressure Vs. Diameter (inch) for L/D Ratio ranging from 1 to 17
Extending the results obtained for the tested nozzle with second order polynomial trend lines one can predict pressures for smaller or greater diameter nozzle. For example: using a 10/32 for a L/D ratio of 9;

\[ 10 \div 32 = 0.3125 \text{ inch}, \text{ subbing this value in the equation corresponding to the L/D 9 trend line:} \]

\[-220.89 \times 0.3125^2 + 134.88 \times 0.3125 + 30.619 = 51.2 \text{ psig} \]
7 Experimental testing - tilted plate

7.1 Operating conditions
The operating conditions are the same as in the previous tests performed with the flat horizontal plate. The pressure at the pump outlet is maintained at 90 psi. The size of each grid is optimized so that the largest footprint is integrally included on the pressure mapping. However in those following tests each cell has the same size, it is a .12" * .12" square. This latter is slightly bigger than the one used for the horizontal plate test for a time consumption issue.

Utilizing the universal behavior of modular nozzles shown in the previous chapter conclusion one decided to perform the test for modular nozzles with a 16/32. Furthermore this choice gives the opportunity to compare directly the pressure mappings induced by the modular with the ones created by the 16/32 Vortexx nozzle currently available in the laboratory.

7.2 Test Matrix
The angles chosen for the tests are the following: 15, 21, 30 and 45 degrees. The value of 21 degrees may seem odd but the pressure table already included a hole determining this position. The current configuration and geometry of this device prevents any modification. The other values come from a compromise of different issues:

- Restrain the number of tests to a minimum number for time consumption
- Preserve the pressure table integrity
Since one performs tests using large 16/32 modular and vortexx nozzles, it is important to concentrate these for l/d ratios both representative of actual dimensions found on the drill bits and compatible with the traverse displacements. Due to the last remark the l/d ratios are: 10, 12, 14, 16, 18 and 20.
8 Results – tilted plate

8.1 Numerical results

Table 11: Pressure in psig for the 16/32 modular nozzle

<table>
<thead>
<tr>
<th>Modular</th>
<th>15</th>
<th>21</th>
<th>30</th>
<th>45</th>
</tr>
</thead>
<tbody>
<tr>
<td>16/32</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>28.76</td>
<td>27.04</td>
<td>23.02</td>
<td>17.73</td>
</tr>
<tr>
<td>12</td>
<td>20.86</td>
<td>20.55</td>
<td>16.8</td>
<td>13.16</td>
</tr>
<tr>
<td>14</td>
<td>16.28</td>
<td>15.45</td>
<td>12.95</td>
<td>10.7</td>
</tr>
<tr>
<td>16</td>
<td>13.23</td>
<td>12.6</td>
<td>10.65</td>
<td>8.45</td>
</tr>
<tr>
<td>18</td>
<td>10.9</td>
<td>10.03</td>
<td>8.38</td>
<td>7.37</td>
</tr>
<tr>
<td>20</td>
<td>9.24</td>
<td>8.75</td>
<td>7.04</td>
<td>6.12</td>
</tr>
</tbody>
</table>

Furthermore, the maximum pressures obtained at l/d ratio of 1 have been recorded to compute non-dimensional pressures for the following values of the angle: 15, 21 and 30 degrees. 45 degrees cannot be acquired because the too pronounced tilt perturbs the nozzle displacement. Hence non-dimensional pressure cannot be plotted for the last increment.

Table 12: Pressure in psig for the 16/32 vortexx nozzle

<table>
<thead>
<tr>
<th>Vortexx</th>
<th>15</th>
<th>21</th>
<th>30</th>
<th>45</th>
</tr>
</thead>
<tbody>
<tr>
<td>16/32</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>18.23</td>
<td>17.58</td>
<td>15.63</td>
<td>11.83</td>
</tr>
<tr>
<td>12</td>
<td>13.41</td>
<td>12.63</td>
<td>11.51</td>
<td>8.95</td>
</tr>
<tr>
<td>14</td>
<td>10.78</td>
<td>10.42</td>
<td>8.87</td>
<td>7.3</td>
</tr>
<tr>
<td>16</td>
<td>8.97</td>
<td>8.61</td>
<td>7.39</td>
<td>6.03</td>
</tr>
<tr>
<td>18</td>
<td>7.81</td>
<td>6.91</td>
<td>6.42</td>
<td>5.22</td>
</tr>
<tr>
<td>20</td>
<td>6.66</td>
<td>6.22</td>
<td>5.58</td>
<td>4.59</td>
</tr>
</tbody>
</table>
8.2 Pressure vs. L/D

Figure 117: Pressure vs. l/d ratio for the modular nozzle

Figure 118: Pressure vs. l/d ratio for the modular nozzle
8.3 2-dimensional graphs

8.3.1 16/32 Modular 15 degree

8.3.1.1 16/32 Modular L/D=10 15 degree

Figure 119: 16/32 Modular L/D=10 15 degree
8.3.1.2 16/32 Modular L/D=12 15 degree

Figure 120: 16/32 Modular L/D=12 15 degree
8.3.1.3 16/32 Modular L/D=14 15 degree

Figure 121: 16/32 Modular L/D=14 15 degree
8.3.1.4  16/32 Modular L/D=16 15 degree

Figure 122: 16/32 Modular L/D=16 15 degree
Figure 123: 16/32 Modular L/D=18 15 degree
Figure 124: 16/32 Modular L/D=20 15 degree
8.3.2 16/32 Modular 21 degree

8.3.2.1 16/32 Modular L/D=10 21 degree

Figure 125: 16/32 Modular L/D=10 21 degree
Figure 126: 16/32 Modular L/D=12 21 degree
8.3.2.3 16/32 Modular L/D=14 21 degree

Figure 127: 16/32 Modular L/D=14 21 degree
8.3.2.4  16/32 Modular L/D=16 21 degree

Figure 128: 16/32 Modular L/D=16 21 degree
8.3.2.5 16/32 Modular L/D=18 21 degree

Figure 129: 16/32 Modular L/D=18 21 degree
8.3.2.6 16/32 Modular L/D=20 21 degree

Figure 130: 16/32 Modular L/D=20 21 degree
8.3.3 16/32 Modular 30 degree

8.3.3.1 16/32 Modular L/D=10 30 degree

Figure 131: 16/32 Modular L/D=10 30 degree
8.3.3.2 16/32 Modular L/D=12 30 degree

Figure 132: 16/32 Modular L/D=12 30 degree
Figure 133: 16/32 Modular L/D=14 30 degree
8.3.3.4 16/32 Modular L/D=16 30 degree

Figure 134: 16/32 Modular L/D=16 30 degree
8.3.3.5  16/32 Modular L/D=18 30 degree

Figure 135: 16/32 Modular L/D=18 30 degree

---

pressure

8.38
8.04
7.70
7.36
7.02
6.67
6.33
5.98
5.65
5.31
4.97
4.63
4.29
3.85
3.61
3.26
2.82
2.58
2.24
8.3.3.6 16/32 Modular L/D=20 30 degree

Figure 136: 16/32 Modular L/D=20 30 degree
8.3.4 16/32 Modular 45 degree

8.3.4.1 16/32 Modular L/D=10 45 degree

Figure 137: 16/32 Modular L/D=10 45 degree
8.3.4.2  16/32 Modular L/D=12 45 degree

Figure 138: 16/32 Modular L/D=12 45 degree
8.3.4.3  16/32 Modular L/D=14 45 degree

Figure 139: 16/32 Modular L/D=14 45 degree
8.3.4.4 16/32 Modular L/D=16 45 degree

Figure 140: 16/32 Modular L/D=16 45 degree
8.3.4.5  16/32 Modular L/D=18 45 degree

Figure 141: 16/32 Modular L/D=18 45 degree
8.3.4.6  16/32 Modular L/D=20 45 degree

Figure 142: 16/32 Modular L/D=20 45 degree
8.3.5 16/32 Vortexx 15 degree

8.3.5.1 16/32 Vortexx L/D=10 15 degree

Figure 143: 16/32 Vortexx L/D=10 15 degree
8.3.5.2  16/32 Vortexx L/D=12 15 degree

Figure 144: 16/32 Vortexx L/D=12 15 degree
8.3.5.3  16/32 Vortexx L/D=12 15 degree

Figure 145: 16/32 Vortexx L/D=14 15 degree
8.3.5.4 16/32 Vortexx L/D=16 15 degree

Figure 146: 16/32 Vortexx L/D=16 15 degree
8.3.5.5 16/32 Vortexx L/D=18 15 degree

Figure 147: 16/32 Vortexx L/D=18 15 degree
8.3.5.6  16/32 Vortexx L/D=20 15 degree

Figure 148: 16/32 Vortexx L/D=20 15 degree
8.3.6 16/32 Vortexx 21 degree

8.3.6.1 16/32 Vortexx L/D=10 21 degree

Figure 149: 16/32 Vortexx L/D=10 21 degree
8.3.6.2  16/32 Vortexx L/D=12 21 degree

Figure 150: 16/32 Vortexx L/D=12 21 degree
8.3.6.3  16/32 Vortexx L/D=14 21 degree

Figure 151: 16/32 Vortexx L/D=14 21 degree
8.3.6.4  16/32 Vortexx L/D=16 21 degree

Figure 152: 16/32 Vortexx L/D=16 21 degree
8.3.6.5  16/32 Vortexx L/D=18 21 degree

Figure 153: 16/32 Vortexx L/D=18 21 degree
Figure 154: 16/32 Vortexx L/D=20 21 degree
8.3.7 16/32 Vortexx 30 degree

8.3.7.1 16/32 Vortexx L/D=10 30 degree

Figure 155: 16/32 Vortexx L/D=10 30 degree
8.3.7.2 16/32 Vortexx L/D=12 30 degree

Figure 156: 16/32 Vortexx L/D=12 30 degree
8.3.7.3  16/32 Vortexx L/D=14 30 degree

Figure 157: 16/32 Vortexx L/D=14 30 degree
8.3.7.4 16/32 Vortexx L/D=16 30 degree

Figure 158: 16/32 Vortexx L/D=16 30 degree
8.3.7.5 16/32 Vortexx L/D=18 30 degree

Figure 159: 16/32 Vortexx L/D=18 30 degree
8.3.7.6  16/32 Vortexx L/D=20 30 degree

Figure 160: 16/32 Vortexx L/D=20 30 degree
8.3.8 16/32 Vortexx 45 degree

8.3.8.1 16/32 Vortexx L/D=10 45 degree

Figure 161: 16/32 Vortexx L/D=10 45 degree
8.3.8.2 16/32 Vortexx L/D=12 45 degree

Figure 162: 16/32 Vortexx L/D=12 45 degree
Figure 163: 16/32 Vortexx L/D=14 45 degree
8.3.8.4 16/32 Vortexx L/D=16 45 degree

Figure 164: 16/32 Vortexx L/D=16 45 degree
8.3.8.5 16/32 Vortexx L/D=18 45 degree

Figure 165: 16/32 Vortexx L/D=18 45 degree
8.3.8.6  16/32 Vortexx L/D=20 45 degree

Figure 166: 16/32 Vortexx L/D=20 45 degree
8.4 Discussion

The first point to consider is the absolute value of the impact pressure for each and every tests: the modular nozzle produces higher pressure than the vortex nozzle. These results are consistent with previous tests run with a horizontal plate.

![Graph: Comparison Pressure]

**Figure 167: modular and vortex nozzle impingement pressures vs. l/d**

If one applies the same method utilized for the previous series of tests, dividing the pressure at each point by the maximum impact pressure (obtained at the lower l/d ratio of 1) give the graphs plotted in the next two figures. It is obvious to remark that the larger the value of the angle is the lower the pressure is. Using a 4th order polynomial trendline and the fact that non-dimensional pressure curves superpose for different diameter, one can get information for various nozzle size from one set of values.
Modular 16/32 non-dimensional pressure

\[ y = 3 \times 10^{-5}x^4 - 0.0023x^3 + 0.0598x^2 - 0.7173x + 3.59 \]

\[ R^2 = 1 \]

Figure 168: modular non-dimensional pressure

Vortexx 16/32 non-dimensional pressure

\[ y = 1 \times 10^{-5}x^4 - 0.001x^3 + 0.0283x^2 - 0.3618x + 1.9272 \]

\[ R^2 = 0.9999 \]

Figure 169: vortexx non-dimensional pressure
9 Particle Image Velocimetry experimental testing

9.1 Presentation
The impingement table has been modified so that various tilt angles can be selected and the plate disposed two different ways. The left structure in the tank holding the plate has been cut to allow the cameras to see the water jet and the plate. It was initially planned to test the Modular nozzle that is symmetric and after the non-symmetric Vortexx nozzle. Willing to fully investigate the non-symmetric jet geometry requires rotating the plate from an angle of 90 degree with respect to the vertical axis. This permits to get the necessary second set of frames without moving the PIV system. The set of lenses with which the cameras are equipped are 28 mm, this focal length is barely compatible with the test-rig dimensions. In order to cope with that the nozzle housing has to be offset and brought closer to the tank wall and the table edge.

Figure 170: laser arm and water tank
9.2 Seeding particles
As previously discussed in a former chapter the particles are fluorescent polymer microspheres. Regular seeding particles such as silver coated hollow spheres were ruled out to prevent CCD pixel to accidentally burn due to laser reflection.
The previous figure is a picture of a laser sheet, the bubbles generated by the jet are clearly visible. In this peculiar case the flowrate is lower than usual and the laser is at the lowest power.

After consulting TSI, one opted for 1 micrometer in diameter fluorescent spheres. Few unsuccessful attempts showed that the light emitted by the seeding was not powerful enough to allow good quality pictures from the flow field. Knowing that the quantity of fluorescent light produced by the sphere is proportional to its volume, a significant improvement should be achieved easily. However one has to keep in mind that the seeding particles should follow the flow in order to get relevant values, this is synonymous of keeping the Stokes number as small as possible (below one). Switching from 1 micrometer to 30 micrometer allowed increasing theoretically 27000 times the amount of light emitted, in fact multiplying the diameter by 30 multiplied the volume by $30^3$ (hence 27000).

Unfortunately the largest particles proposed by our supplier did not match our requirements in light quantity even with the maximum laser power output. In order to be sure that the light was effectively the problem the lenses and the filter have been checked. Putting actually those filters between someone’s eyes and the test rig permits to see clearly the particles in red without any reflected green color, from this experience it was shown that the filter should not be under examination but rather the CCD sensibility. Switching to an even bigger size of particles should be the most effective modification to bring.

Another way has been explored by using the dirt and the rust present in the water as seeding particles. Being unable to control the size or the weight of those
elements a proper calculation of the Stokes number cannot be computed but estimated. However choosing the lowest laser output sufficient enough to illuminate the flow one gets sometimes interesting results. When by chance large bubbles do not reflect a large proportion of the laser it is likely to observe the structure of the jet when the table is in a horizontal position. This type of test has been conducted for the next increments of angle but without any success.

9.3 Tests, partial results and conclusion

In each test the parameters are the same as those selected for the pressure mappings.

U represents the velocity component relative to the X axis and V the velocity component relative to the Y axis.

For the following two figures we have captures of an average set of 100 acquisitions. In this case the impingement table is horizontal.

The jet’s structure seems correct:

- The velocity is negative in the core for the V component and zero everywhere else;
- The velocity values are in the order of magnitude of what the flowrate should deliver (about 27 m/s for a 16/32 nozzle with a flowrate of 54 gpm);
- The values of U show that the flow follows the plate in a direction that goes from the center towards the exterior of the jet.
Figure 173: modular nozzle l/d=10 horizontal velocity component

Figure 174: modular nozzle l/d=10 vertical velocity component
For the following two figures, we still have captures of an average set of 100 acquisitions. In this case the impingement table is at an angle of 15 degrees.

**Figure 175:** modular nozzle l/d=10 horizontal velocity component

**Figure 176:** modular nozzle l/d=10 vertical velocity component
It is unfortunate that the time needed to solve step by step each and every acquisition and seeding problems kept stopping the progress of this part of the research. However several conclusions can be drawn from the multiple attempts to produce relevant information that could back up the pressure mappings:

- Bigger fluorescent spheres must be considered.
- A pair of 60 mm macro lenses should be used to improve the pictures quality on which rely the software.
10 Annexe

This annexe has for final goal to explain to someone how to use the test rig. As previously explained in the first chapters this test rig can be divided into several parts or sub systems. Those are mainly hardware but can also be software. Let us enumerate and then describe them.

- Tank and pressure table
- Data acquisition
- Hydraulic circuit
- Traverse system and the frame
- Computer

10.1 Tank

This tank is constructed with Plexiglas panels to allow flow visualization. A vertical internal panel divides the tank into two parts. The larger section provides undisturbed environment to conduct nozzle tests and includes the pressure table. The other smaller part is an overflow reservoir from which the water is sucked by the pump without disturbing the flow in the main section. These parts should be cleaned regularly if the tank is used in a closed loop mode or if the water is not drained after a long time. If the test rig is used to perform many tests in a row the overflow hose should be use to drain excessively hot water and cold water should be continuously poured in the overflow reservoir. Some modifications should be done to this part of the test rig. Since some air bubbles prevent a continuous flow in this overflow hose, an air vent should be installed.
Furthermore if one wants to adjust the flow rate, a valve can also be installed downstream or upstream the air vent. Their relative positions should be discussed.

Once the walls and the components are cleaned few elements should be checked prior to start filling the tank. In the current configuration (no valve on the overflow hose) the overflow hose should be securely installed in the drain located in the middle of the experiment area. It is also wise to bring the two drain hoses coming from under both tank’s parts to this very same drain. It is important to understand that these hoses are very flexible and that their shapes change a lot when the water circulates through them. If they are not properly placed water spillage will occur!

The two bottom valves should be closed, the filter should be cleaned and pressure table settings checked; then the water can be poured. Depending on the flow rate it takes about 25 minutes to fill the tank. The hose should be securely fastened if left unattended or water spillage will occur!

10.2 Pressure table

This device is used to investigate the jet pressure distribution on an impingement surface. The pressure table is a rectangular Plexiglas panel mounted between two vertical holders. These holders are supported in position by two pairs of threaded rods that link them to a structure above the tank. The threaded rods are used to set the plate horizontal by adjusting the position of nuts. Moreover the vertical holders are drilled so that the table can be oriented at different angles. A pressure transducer tap is drilled in the centre of this rectangular table. The
setting is straightforward and does not required anything but some time. The front edges of the vertical holders should be installed so that they are in contact with the tank’s Plexiglas wall to prevent vibrations. Assuming that the Plexiglas rectangle is sufficiently flat, a level is used to adjust the pressure table in a plane parallel to the traverse motion. Corrections are applied by adjusting the threaded rods lengths.

The controller can be used to confirm the parallelism between the traverse and the plate. The following procedure assumes that the geometrical characteristics of the plate are satisfactory. The adjustment is similar to the one performed for positioning the pressure table relative to the traverse. As the controller displays the position in steps for each axis, the user sets the tip of the plumber line flushed with one tip of the drawn cross, notes the position, and moves to the opposite branch of the cross and repeats the operation. The angle can be calculated using simple trigonometric calculus.

If numerous tests have to be performed, a newer, stronger pressure table adapted to the inside dimensions of the test region should improve the quality of the test rig and its ease of utilization.

### 10.3 Data acquisition

Two pressure transducers are used to measure the values of the pressure on the table and inside the nozzle housing. These PDCR 130/W/C are particularly suitable for industrial and aerospace applications where vibrations and relatively hostile environment could be present. For the present application the pressure transducers should be calibrated between 0 and 100 psig. The coefficients have
to be replaced in the dedicated fields that can be found in the data acquisition structure of the program. For this program only the value of the pressure read by the transducer on the table is stored.

10.4 **Hydraulic circuit**

10.4.1 **Pump**

If the pump is not used for a long time the inner parts rust. This rust circulates through the piping as soon as the electric motor is started; particles will visually pollute the flow.

10.4.2 **Piping**

Check that the following items are correctly attached or fastened together:

- Downstream the pump: a 1.5-inch tube leads from the outlet to a T where the flow is divided. One branch supplies the nozzle via a flow meter and a 1-inch hose.
- The second branch constitutes the by-pass; the water passes through a valve to control the flow rate to the outflow tank.
- Upstream the pump a 2-inch tube links directly the outflow tank to the pump inlet.
- Two 2-inch drain pipes equipped with valves to empty quickly the tank for special operations.
10.5 Nozzle housings
Two nozzle-adaptors are used depending on the nozzle size. The binding that is linked to the traverse system via a vertical arm determines the nozzle orientation and provides a connection to the pump supply.

The smaller one is made of aluminium; it receives the PDC nozzles and includes a pressure tap for discharge coefficient measurements.

A second housing made of stainless steel for improved mechanical resistance of the threads. A longer adaptor was chosen because the internal shape is a divergent nozzle and makes a smooth transition to prevent flow separation.

10.6 Structure
The structure was designed to support the traverse independently above the tank. Its main characteristic is its rigidity. The vertical 1-in pipe connecting to the pump outlet is fastened securely to the frame to prevent vibrations during the test rig operation. This part should be checked once in a while.

10.7 Traverse
The traverse is a 3-axis robot; it is used to automatically position the nozzle according to grids. Velmex, the manufacturer, provided the traverse with an user guide which is very useful to set up the axis. It is very important to follow attentively the procedure to set properly the parallelism between the two X axis.

Small tolerances make this operation the most difficult one. Once the traverse is assembled it is placed on top of the green cage. Fasteners and bolts link the traverse to the structure. Depending on the nozzle size, the nozzle housing is chosen and attached to the vertical arm; this assembly is bolted to the hollow
spacer through which the hose goes. Some pictures in the first chapters show those parts.

10.8 Controller
The VP9000 is a programmable stepper motor controller that runs motors one-at-a-time. Commands and data are entered through the RS-232 interface. A 48-character alphanumeric display shows motor position(s), set-up parameters and displays menus for keyboard selections. Commands are transmitted from the host computer. Initially the centre of the nozzle housing must be brought flushed just above the pressure tap and the controller must be zeroed by pushing the button 0 on the controller’s front panel. The traverse motion is describe with respect to this point.

10.9 LabView program
The first program, “EssaiCycle”, was written to obtained only one grid, the experimenter needs to run the program as many times as the number of required grids.

The procedure is the following:

- The first step is to check that the previously described items are prepared. Then a subfolder must be created in the main folder dedicated to store the pressure mappings. The name of this subfolder is usually the name of the nozzle preceded with its diameter in 1/32 of an inch. A yellow sign located on the upper left corner of the screen reminds the user to do so.
The test number can be specified in a window dedicated to this purpose. Any additional information can be added. The goal is to allow the experimenter to recognize the files latter.

- The second step is the grid choice, many grids can be chosen from the menu. Those grids are self explanatory.

- The last step is to defined the remaining parameters:
  - In case of the use of a custom grid, the experimenter must tailor this latter by choosing the number of points and the distance between two consecutive points.
  - The nozzle diameter
  - The L/D ratio (non-dimensional stand-off distance between the plate and the jet exit)
  - Set the impingement plate angle corresponding to the geometrical value of the angle existing between the horizontal and the flat plate
  - Specify the offset along the X-axis and the Y-axis if required
  - Choose the number of samples and the sampling frequency
  - Select the time delay during which the traverse waits before moving to the next point

Then the electric motor driving the pump should be started and the by pass valve closed until the pressure chosen is red on the manometer; at this moment the program should be run from Labview.
11 References


[19] Drilling and Drilling Fluids, BdF 622-338 CHIL. “Factors Affecting the Rate of Penetration, Functions of Drilling Fluids, Rotary Drilling Bits”