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TESTING A SIMPLEX SWIRL INJECTOR, FOR ROCKET ENGINE APPLICATION

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Abstract. *This paper describes the test equipment used to cold test simplex swirl injectors of a certain performance, with application on liquid rocket engine. Starting with a set of well-known equations, dully modified as compared to a traditional model, it is possible to define dimensions of a test specimen capable of delivering the required mass flow at the specified spray cone angle. A simplex swirl injector was then built in accordance with that methodology, attached to a device that supplies pressurized water and equipped with sensors to collect data related to inlet pressure as well as mass flow. Actual pressure, mass flow and spray angle data were collected and compared with the values prescribed by the theoretical model and found to be within reasonable range. Finally, an equation describing the injector behavior was obtained, which exhibits the mass flows as a function of the injector inlet pressure. A significant part of the paper will be used to describe the test bench, the data collection instruments and details on the software used to summarize the data. Pictures and sketches will be used along the description to better illustrate the work.*

Keywords: *simplex, swirl, injector, rocket*

1. INTRODUCTION

The swirl injector used alone or in combination with other types of injectors, in a coaxial or axial arrangement has demonstrated to be effective in atomizing and mixing propellants in rocket engines. This type of injector has been in usefor decades, usually in a configuration that injects fuel in the inner tube and oxidant on the external part. A typical swirl injector at work can be appreciated on Fig. 1.

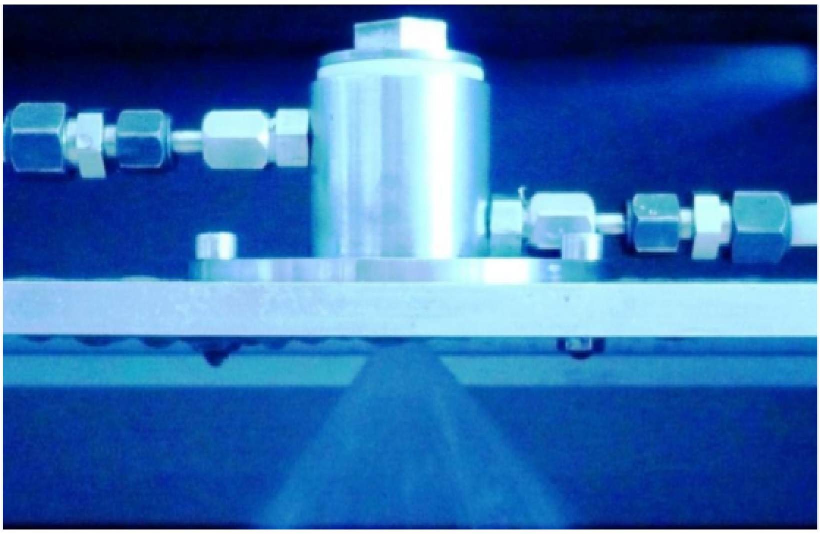


Figure 1. Typical swirl injector at work.

During operation, one of the propellants is tangentially introduced into a swirl chamber, through one or more inlet orifice, to cause a swirling vortex flow inside the device. Due to centrifugal force, the swirling film, showed in blue on Fig. 2, is attached to the chamber wall, allowing space for a hollow gas core to be created in the center region. This swirling film passes through the exit orifice in the form of a thin liquid sheet hollow cylinder, which becomes a cone in a short distance from the injector face. From this point on, wave oscillations on the liquid sheet induces the formation of holes on the surface, followed by its disintegration into ligaments and finally into droplets, as it swirls and stretches while moving away from the injector face. In case another propellant is atomized in the neighborhood, by any other means, that film exiting the injector impinges onto the surrounding propellant stream helping the atomizing process through the mechanism of sheet breakup.

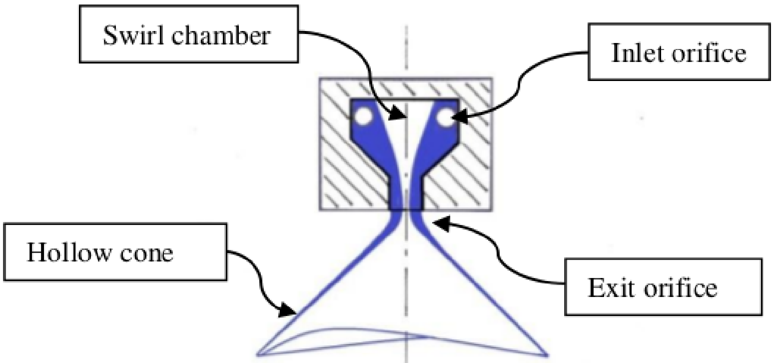


Figure 2. Internal elements of a typical swirl injector.

2. INJECTION MECHANISM

For the flow of an incompressible fluid through a hydraulic orifice (Ref. 6), we have:

$$m = C_d \cdot A \cdot \sqrt{2\rho\Delta P} \quad (1)$$

Where "m" (kg/s) is the mass flow of the propellant, "C_d" is a dimensionless discharge coefficient, "A" (m^2) is the area of the metering orifices the propellants go through, "ρ" (Kg/m^3) is the fluid density and "P" (Pa) is the pressure difference between the injector inlet pressure and the external pressure.

At this point, we find ourselves with a set of information that has to be provided by the user, at the beginning of the design process, basically the desired mass flow, fluid density and pressure drop. The two remaining items, area and discharge coefficient, are the focus of this work and as such will be defined using the proper methodology. Considering our initial objective of finding the orifices dimensions, both inlet and outlet, it makes sense to rearranging Eq. (1) in the format of Eq. (2), which defines the orifice area in function of the same parameters shown on the previous paragraph.

$$A = \frac{m}{C_d \cdot \sqrt{2\rho\Delta P}} \quad (2)$$

During our experiments we found out that it is recommended the separation of the exit orifice dimensioning from the inlet orifices. Eq. (2) will be used to define the orifice area, both inlet and outlet, however, the discharge coefficients will be found following different procedures. They will be treated as if they were working two independent missions, or having two different responsibilities. The exit orifice will be used as a mean to define the spray cone angle, while, the responsibility to control the mass flow through the injector will be transferred to the inlet orifices.

Another consequence of giving the inlet orifices the responsibility for flow control is that manufacturing errors can be divided between two, or even more elements, as opposed of using the only one exit hole. It also allows small adjustments on the inlet diameters, in case we are building injectors on small quantities.

3. CASE STUDY

The hydraulic injector main dimensions, as shown on Fig. 3, can be evaluated with reasonable precision by a parametric model based on a set of information provided by the customer in the form of High Level Requirements that includes mass flow, fluid density, pressure drop and the desired spray cone angle at the injector exit. In order to check the validity of the model presented, a swirl injector for a $200N$ liquid rocket engine was designed, in such way that it could deliver a mass flow of $0,050kg/s$ of water that should leave the injector at a spray angle of $90°$ under a pressure of $3Bar$. Once the equations are placed into action, they allowed the definition of the final product, as per Fig. 4. All dimensions are in millimeters.

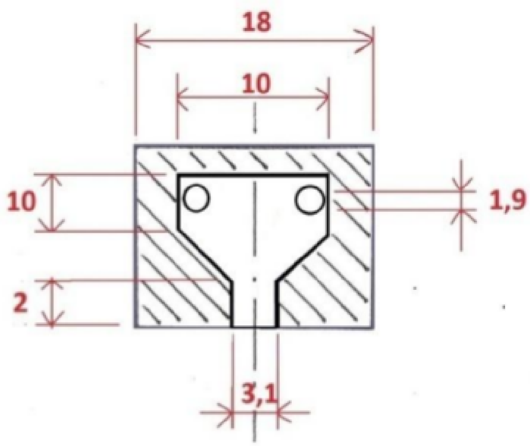


Figure 3. Main dimensions.

4. TEST HARDWARE

That test specimen shown on Fig. 3, was attached to a test bench and data related to the swirl cone angle and the mass flow was collected in order to compare the actual versus forecasted values. In order to do so, we had to use the test bench defined as per the diagram shown on Fig. 4. It consists of a pressure vessel, dubbed as water reservoir, connected to the test specimen through a flow meter and a pressure transducer, both of them linked through a data acquisition system to a laptop. In order to register the tests a digital camera was made available, and was also connected to the laptop.

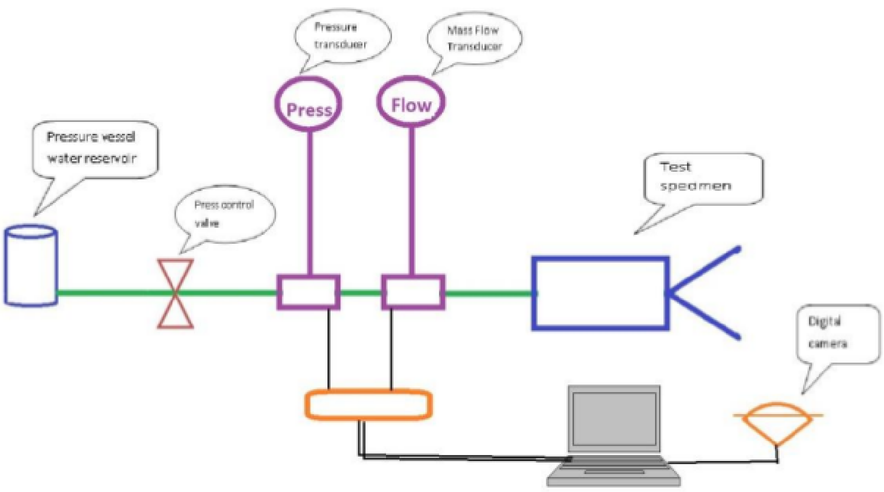


Figure 4. Test equipment diagram.

Figure 5, on the left, shows the actual test equipment existing at ITA test laboratory, with the pressurized water reservoir (silver cylinders), pressure control valves, analog manometers and flow meters. The blue hoses are the conduit for the pressurized water, connecting the water reservoir to digital data collection system shown on the left side, designed as part of this exercise. You will notice the analog manometer on the right side picture, which was used on the test bench initial calibration efforts.

For this particular application, it was defined that a flowmeter capable of measuring from 1 to 5 liters/min would be satisfactory. From the possibilities available commercially it was decided for a turbine type sensor, that could sustain pressures of up to $17Bar$, with error in the range of $\pm$ 2%, working with power requirement in the 3.5 to 24 VDC and 10 mA maximum current. The pressure transducer selected was able to measure up to $10Bar$, with $\pm$ 2% error, requiring a

Figure 5. Test hardware.

power supply of 10 to 30 VDC connected to it. Both, the pressure transducer and the flowmeter were linked to a NI 6008 USB electronic data unit that provides a 12-bit analog input, with sampling in the 12 kS /s. The selected positioning of the electronic test hardware can be seen on Fig. 7.

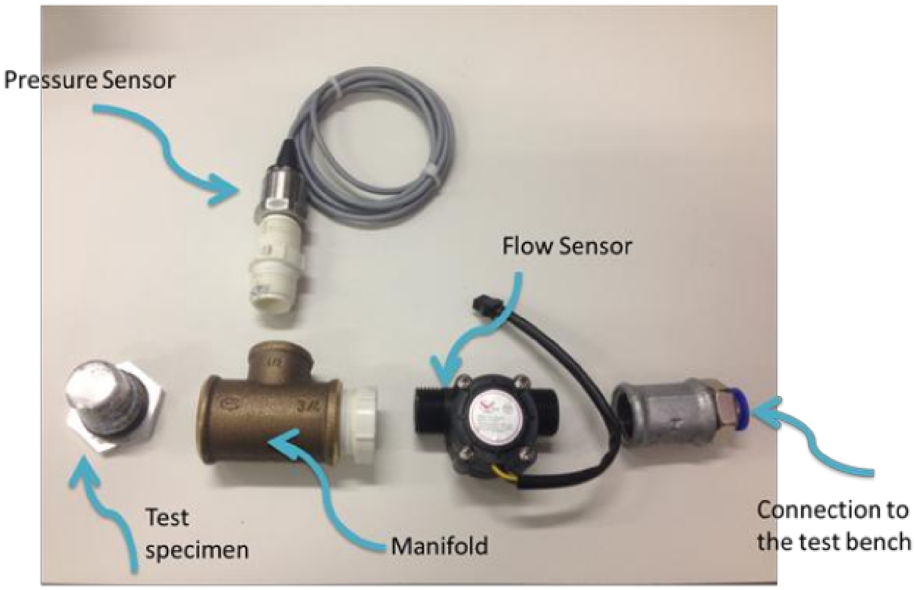


Figure 6. Test hardware, details.

5. SOFTWARE

Among the many options available in the market, LabView was selected, for a number of reasons, including availability and costs. The logical sequence basically takes the information coming from the pressure transducer as a reference, followed by the flow meter reading, and generates a table with the data collected. Data collected at the transducers flow through the conditioning board and is loaded into a laptop through a USB port. Refer to Fig. 7, for more details about the operation designed to keep the test bench hardware in constant communication with the laptop.

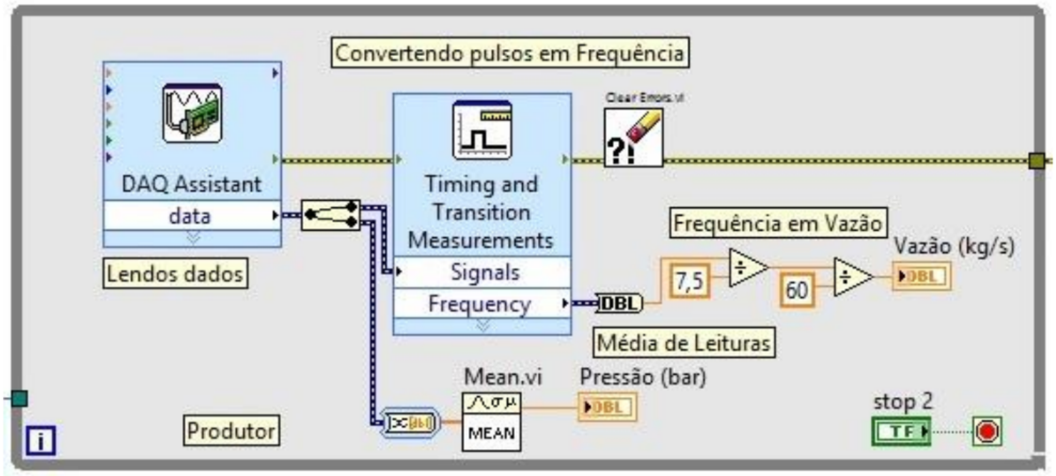


Figure 7. Data acquisition.

The software documentation was generated on TDMS, an extension provided by NI which is compatible with MS Excel. While working with this extension, it is possible to add specific fields to the spreadsheet in such way that data is registered on its selected location (lines and columns), available for editing on an Excel spreadsheet. This sequence is shown in details on Fig. 8.

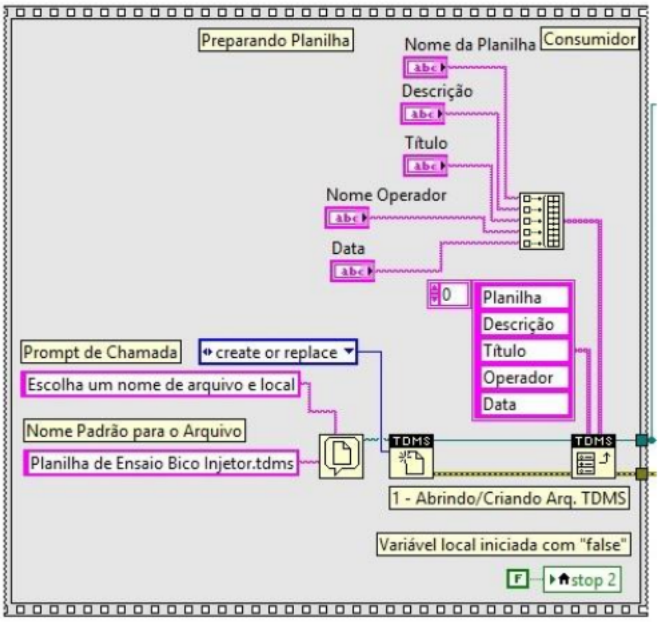


Figure 8. Data formatting.

Another important factor in developing this software was the interface with the operator. One of the objectives behind the control panel was to keep it as simple as possible, which was done by keeping on the front panel only information relevant to the operator. It consists of two main dials with analog and digital readings, one dial for pressure, with indication in Bar, and the other for mass flow, with indication in kg/s. A key button is used to Record data at the specified pressure and another button is used to stop the operation. Refer to Fig. 9, where the control panel is presented, in details.

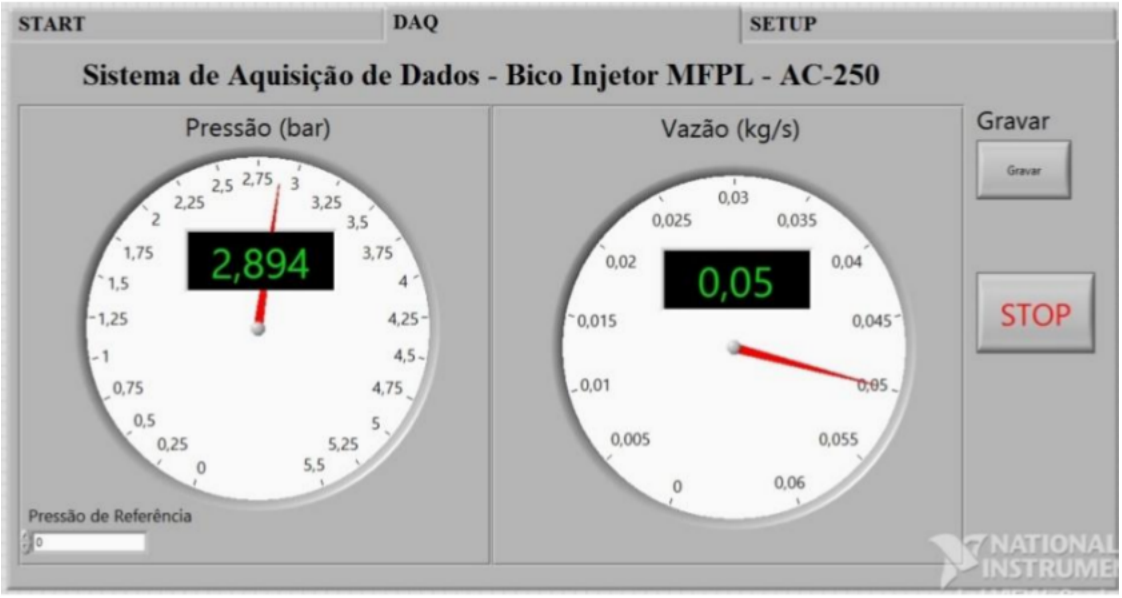
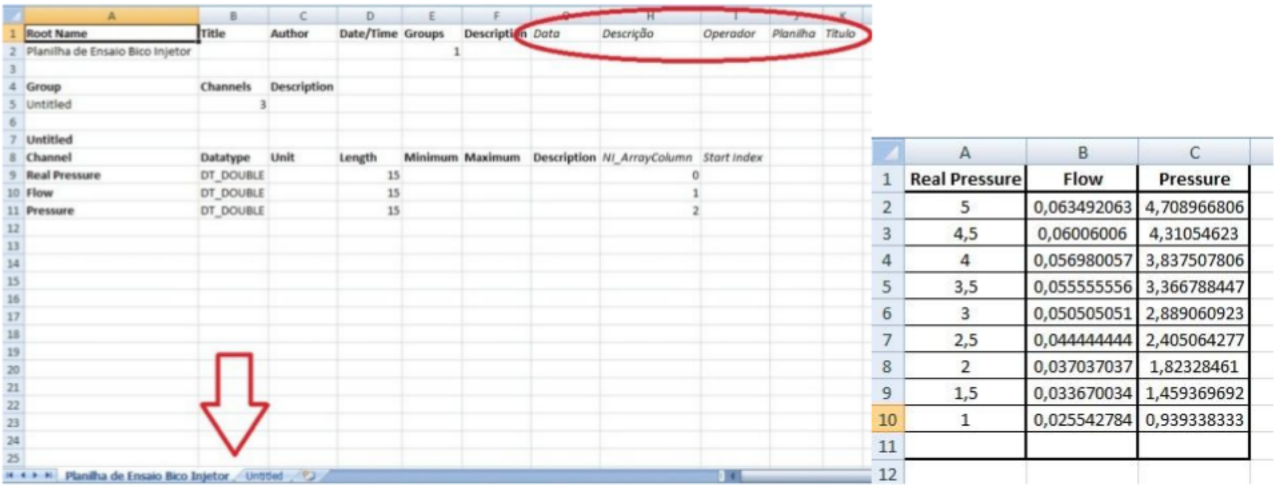


Figure 9. Control Panel.

The last operation performed by the software is the production of a spreadsheet containing the data collected during the tests. This output contains information on test name, data and time as well as the pressure and mass flow observed during the tests. Due to a peculiar flow characteristics of the pressurized water tanks, it was necessary to make extensive use of the analog manometer, used as a reference for the pressure we intent to test the injector. This information was added to a column called ”Real Pressure”. Figure 10 shows the main spreadsheet, on the left, and a more detailed insert, on the right corner, where the numbers coming from the transducers are provided.



Real Pressure	Flow	Pressure
5	0,063492063	4,708966806
4,5	0,06006006	4,31054623
4	0,056980057	3,837507806
3,5	0,055555556	3,366788447
3	0,050505051	2,889060923
2,5	0,044444444	2,405064277
2	0,037037037	1,82328461
1,5	0,033670034	1,459369692
1	0,025542784	0,939338333

Figure 10. Spreadsheet - sample.

6. TESTING

Once hardware and software were in place, test specimen described on Section 3 – Case Study, was connected to the test bench, and data was collected as planned.

The first task was related to the spray angle measurement. With the test specimen attached to the test bench, pressure was adjusted to certain level and pictures were taken with a digital camera. The results can be appreciated on the pictures below. Figure 11 shows the test specimen doing what it was designed for, delivering the 90 degrees spray angle cone.

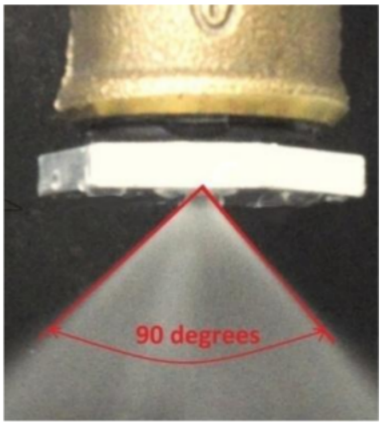


Figure 11. Spray cone angle (Inlet Pressure @ $3Bar$).

It is important to mention that the spray angle does not change much, even when submitted to a wide range of variation on the inlet pressure. Figure 13 shows how the spray cone forms, starting with a blob when the pressure is low enough, in the neigh borough of $0,1Bar$, but stabilizing at angles near 90 degrees as soon as the pressure gets above $0,5Bar$. At pressures as low as $1Bar$, the spray angle reaches 90 degrees and stays there, with almost no variation as the inlet pressure increases.

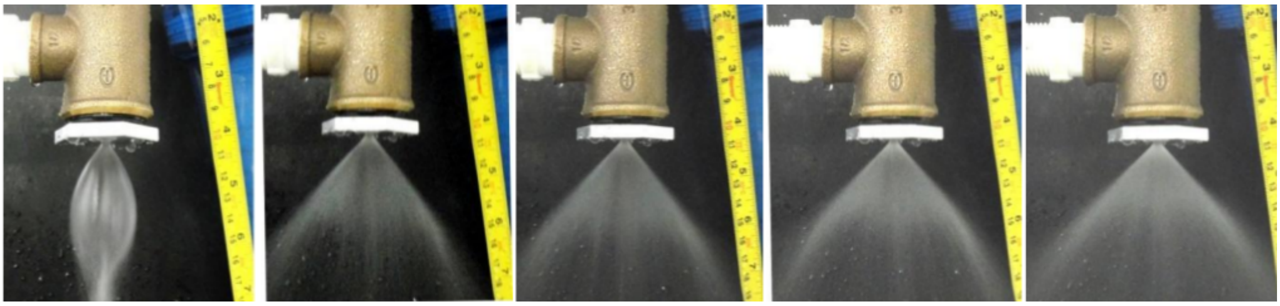


Figure 12. Spray angle at $0,1Bar$, $0,2Bar$, $0,5Bar$, $1Bar$ and $2Bar$.

With all the equipment in place, the next part of the work is collecting data about the performance of the swirl injector. Five sets of data were collected, ranging from $1Bar$ to a maximum of $5Bar$, while changing pressure at $0,5Bar$ steps. Three sets of samples were taken, starting from $1Bar$ up to $5Bar$, and two sets of data were collected starting the other way around, i.e., starting with $5Bar$ and going down to $1Bar$. In total, 22 samples were collected, loaded into an Excel spreadsheet and sorted by pressure. The result was consolidated in a chart, as shown on Fig.13.

With this information available, we are able to use the injector equation, to infer that the mass flow, obtained with a pressure drop of 3 Bar across the injector, is 0,050 kg/sec, which is in line with the expected value.

7. CONCLUSIONS

An existing test bench that used analog devices, requiring manual data collection, was upgraded with the incorporation of more sophisticated digital instruments and automatic data collection capabilities. New hardware was incorporated into the test bench and specific software was designed to take care of the data collection. Significant improvement on data precision was possible.

In order to validate the new approach, a test specimen was designed, and built, using certain procedures. It was attached to the test bench and submitted to a series of test, where data related to mass flow, inlet pressure and spray angle was collected. Actual data was compared with the forecasted data and found to be within reasonable limits. As a final comment, we would like to recommend further tests, where injectors of different sizes would be built and tested, in order to verify the validity of the test equipment over a wider range of performance.

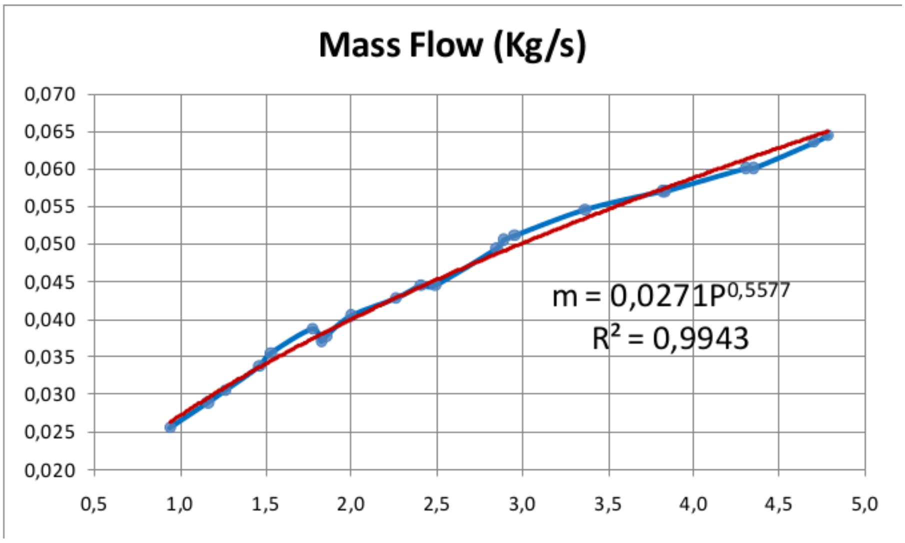


Figure 13. Mass Flow as a function of the Inlet Pressure.

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