Compressible bench flow adaptations to the experimental characterization of pneumatic fluid power components. Application to the determination of flow-rate characteristics of a Festo MPYE-5-3/8-010-B proportional valve

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ABSTRACT

This paper describes the operating and basic characteristics of a general purpose compressible flow bench facility developed to accomplish experimental test in fluid dynamics, as well as the required adaptations according to ISO 6358 for pneumatic fluid power components characterization such as, valves, regulators, filters, filter-regulators, cylinders,...etc, are described.

The experimental characterization of pneumatic fluid power components, especially proportional valves and servo-valves are required when their performance must be modelled. The technical characteristics from suppliers are, in general, insufficient. The sonic conductance, critical pressure ratio, coefficient of compressibility effect, and effective area, must be specified according to ISO 6358. In addition, the corrected mass flow rate as function of the absolute inlet pressure and pressure ratio must be calculated.

In this work, the experimental flow-rate characteristics of a Festo MPYE-5-3/8-010-B pneumatic fluid power proportional valve operating in open-loop circuit control, is obtained. The actual and corrected mass flow rates, sonic conductance and effective area at different absolute inlet pressures versus excitation voltage are shown. The corrected mass flow rate has been obtained in both, with upstream and downstream measuring tubes, and exhausting directly to atmosphere for different spool positions. This allows to obtain a very useful experimental correlation between effective area and excitation voltage. Also the hysteresis effects have been studied. In conclusion, a closed loop circuit control operating is recommended, since for high excitation voltage these effects are significant.

Keywords: *pneumatic proportional valve, sonic conductance, flow bench, compressible steady flow, experimental characterization*

NOMENCLATURE

A Effective area
C Sonic conductance
s Coefficient of compressibility effect
b Critical pressure ratio

1 INTRODUCTION

Fluid power is present in numerous industrial applications. Hydraulic systems are required in heavy-load applications, while pneumatic systems are utilized generally in light-load and high-speeds applications.

In many cases, the manual control systems are satisfactory, however, in other cases, the operation is more complex and an electric or electronic control is required. Moreover, the accuracy and precision of actuators must be continuously improved. In this way, manufacturer and researchers are working to improve and optimize the standard solenoids, which provide higher forces and faster operation. DeRose explain the last advances in valve technology in [1] and [2]

Proportional solenoid performance has already reached levels of control and frequency response similar to servo valves. The utilization of proportional valves in fluid power pneumatic systems provides a feasible design and simple operation, reducing the complexity when a variable velocity is needed.

A proportional valve combine the characteristics of a flow control valve, a directional valve and the rapid cycling capabilities of modern solenoids, although a proportional valve can be considered as a low-cost, low-performance-range servo valve. This is due to the much tighter clearances and tolerances during manufacturing.

Some proportional valves are only designed to provide flow control. In this case, flow rate is proportional to the command signal and it depends on the pressure drop at the valve, although it can be designed with inherent degree of pressure compensation.

In addition, proportional valves can operate like a pressure control valve, unloading valve, relief valve,...etc. providing significantly advantages due to the fact that the electrical current directed through the proportional solenoid determines the exerted force on the valve mechanism. However, the major advantage of proportional valves is the capability of providing simultaneously directional and flow control.

The experimental characterization of pneumatic fluid power components, especially proportional valves and servo-valves are required when their performance must be modelled. The sonic conductance, critical pressure ratio, coefficient of compressibility effect, and effective area, must be specified according to ISO 6358 [3]. In addition, the corrected mass flow rate as function of the absolute inlet pressure and pressure ratio must be calculated. These performance characteristics are directly applied to sizing pneumatic valves.

An alternative method to determine the sonic conductance of pneumatic component is based on the calculation of unloading characteristics time. This method is exposed by De Las Heras [4]. Thus, the influence of operating and system frequency, characterized by inlet chamber L/D ratio, about the sonic conductance is analyzed [5].

In this work a Festo MPYE-5-3/8-010-B pneumatic fluid power proportional valve operating in open loop circuit control has been experimentally characterized. Thus, the determination of flow-rate characteristics, the corrected mass flow rate, sonic conductance and effective area for different absolute inlet pressures versus excitation voltage have been accomplished.

The operating and basic characteristics of a general purpose compressible flow bench facility developed for accomplishing experimental test in fluid dynamics [6], as well as, the required adaptations according to ISO 6358 for pneumatic fluid power components characterization such as, valves, regulators, filters, filter-regulators, cylinders,...etc, are previously described.

2 EXPERIMENTAL SETUP

The tests have been accomplished in a flow bench. The flow bench consist of a 36,8 kW screw compressor, which gives 400 Kg/h of mass flow rate at 8 bar, a reservoir of 1,5 m^3, and a cleaning system for the compressed air which is composed of a dryer, filtering line and a pressure regulator.

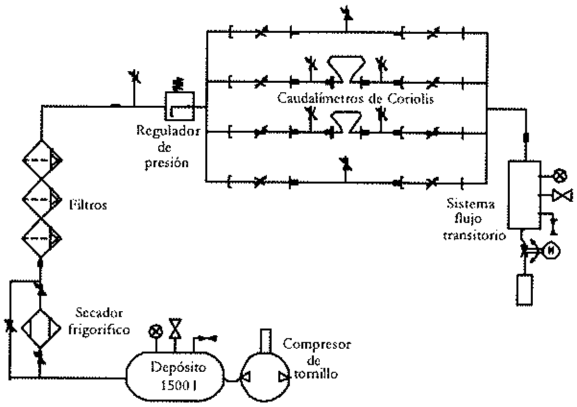

Figure 1: General bench flow layout

2.1 ADAPTATIONS ACCORDING TO REQUIREMENT ISO 6358

The standard ISO 6358 specifies the characteristics of the test circuits for components which exhausting directly to atmosphere and components with inlet and outlet ports. In the figure 2 a scheme and picture of the test circuit matched to the general bench flow is shown.

The test circuit is composed of an adjustable pressure regulator, a shut-off valve, a flow-rate measuring device, a temperature-measuring tube, a pressure-measuring tube and the component under test, in this case a 5/3 proportional valve.

When components with outlet ports are tested another pressure-measuring tube and a flow control valve are needed.

2.2 INSTRUMENTATION

2.2.1 MASS FLOW-RATE MEASURING DEVICE

In this work the mass flow rate is directly measured by a Coriolis effect mass flow rate meter, which provides a very good accuracy. In the table 1, the most important characteristics are indicated.

The upstream absolute pressure transducer is an extensiometric gage sensor and the differential pressure transducer is a configurable range diaphragm piezoresistive sensor. The static temperature was measured with a RTD Pt100, class A, four-wire connection. Finally, the output signals, are connected to a digital multimeter HP 34970A and via serial port RS-232 to PC.

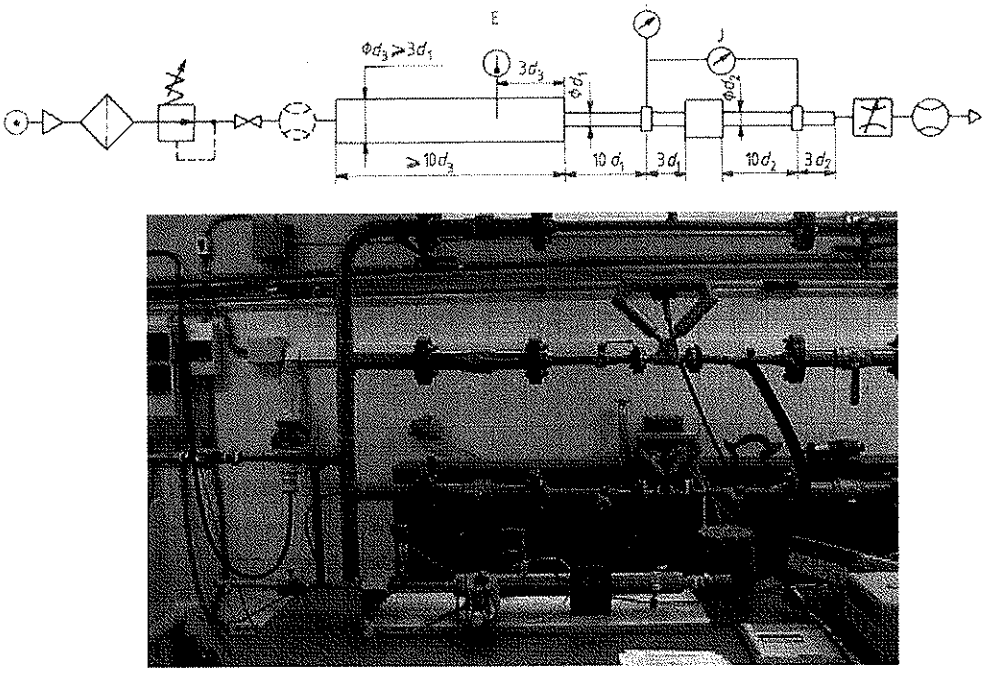

Figure 2: Test installation for pneumatic components

Manufacturer	Fischer-Rosemount MICRO MOTION	
Sensor (ELITE technology)	CMF025	CMF050
Electronically transmission (HART)	RFT9739	RFT9739
Nominal range	0-1090 Kg/h	0-3400 Kg/h
Maximum mass flow rate	2180 Kg/h	6800 Kg/h
Mass flow rate accuracy (G) (gases)	± 0.50% FS	± 0.50% FS
Repeatability (G) (gases)	± 0.25% FS	± 0.25% FS
Zero stability (G)	0.027 Kg/h	0.163 Kg/h

Table 1: Technical characteristics of Coriolis mass flow meter

The test procedure including, test conditions, test measurements, permissible variations at indicated values of upstream parameters, measuring procedure and the calculation of characteristics are established in ISO 6358.

2.3 TECHNICAL CHARACTERISTICS OF PROPORTIONAL VALVE TESTED

An electro pneumatic proportional valve MPYE-5-3/8-010-B Festo has been tested. The most important technical characteristics are indicated in the table 2. The figure 3, shows a detail of proportional valve and the pneumatic symbol.

Proportional valve MPYE-5-3/8-010-B Festo	
Control type	Direct acting
Nominal size	10 mm
Flow-rate characteristic	2000 l/min ± 10%
Maximum absolute pressure inlet	10 bar
Operating voltage	0-10 Vdc (centre spool position, 5 Volts) Dither ± 5% proportional to voltage
Time response	5.2 ms
Limit Frequency	80 Hz
Hysteresis	Max. 0.3 %
Quality air compressed required	5 µm filtration

Table 2: Technical characteristics of proportional valve

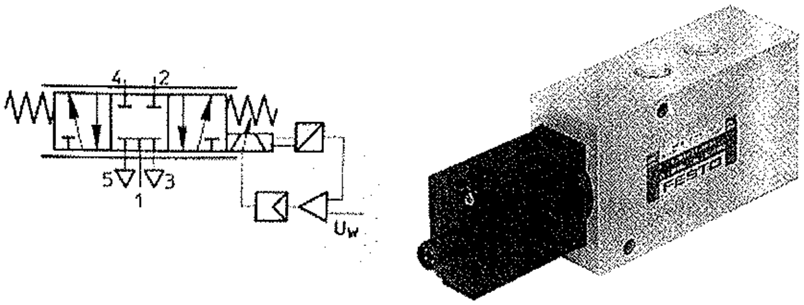

Figure 3: Pneumatic symbol and picture of proportional valve MPYE-5-3/8-010-B Festo

3 TEST PROCEDURE

The international Standard ISO 6358 specifies a method for testing pneumatic fluid power components which use compressible fluids, to enable their flow-rate characteristics under steady-state conditions to be compared.

The requirements for the test installation, test procedure, maximum uncertainty measurement allowed and presentation results are also specified.

Two test methods are described according to the type of component. When the comparison of similar components is required or when a single component is analyzed, the first method is recommended and the sonic conductance, C, and critical pressure ratio, b, relationship must be specified. The effective area, A, and the coefficient of compressibility effect, s, are utilized when the flow behaviour of several components which are connected in series must be estimated.

The test procedure consists of the following steeps:

- Fixing the inlet pressure through the pressure regulator. Test for 5, 5.5, and 6 bar$_{(gage)}$ have been accomplished

- Decreasing the downstream pressure using the flow control valve, until a further decrease no longer produces an increase in the mass flow rate. When the mass flow rate it kept constant the chocked flow condition is achieved
- Measuring static temperature, mass flow rate in sonic condition, upstream absolute pressure and pressure drop
- Close partially the flow control valve to reduce the actual mass flow rate to approximately 80% of sonic mass flow rate. Adjusting the pressure regulator as required to maintain a constant upstream pressure during the test
- Measure the mass flow rate, static temperature and pressure differential
- Repeat the steps describes before with mass flow rate equal to 60%, 40%, and 20% of sonic mass flow rate

4 UNCERTAINTY OF MEASUREMENT

Experimental determination of the sonic conductance and effective area as a function of critical pressure ratio and coefficient of compressibility effect respectively entails an uncertainty due to measurements errors and their propagation in results. In the following table, results of uncertainty calculation under ISO standard *"Guide to the Expression of Uncertainty in Measurement"* [7] are showed.

Expanded Uncertainty (Confidence interval 95%)		
Temperature	°C	%
RTD Pt100 Class A (4w)	± 0.25	± 1
Mass flow rate	Kg/h	%
CMF050 (Range 0-250 Kg/h)	± 0.9	± 0.7
Differential pressure	mbar	%
SMAR D2 (Range 0-500 mbar)	± 0.6	± 0.12
SMAR D3 (Range (0-2500 mbar)	± 2.4	± 0.1
Absolute pressure	bar	%
CERALINE (Range 0-5 bar)	± 0.03	± 0.6

Table 3: Expanded uncertainty in measured quantities

Uncertainty propagation in results	
Sonic conductance $C=\left(q_m^*/p_1\rho_0\right)\sqrt{T_1/T_0}$	± 1.64 %
Critical pressure ratio $b=1-\dfrac{\dfrac{\Delta p}{p_1}}{1-\sqrt{1-\left(\dfrac{q_m}{q_m^*}\right)^2}}$	± 1,16%
Coefficient of compressibility effect $S=1/1-b$	± 1,16%
Effective area $A=C\rho_0\sqrt{SRT_0}$	± 2,15%

Table 4: Uncertainty propagation in results

5 RESULTS

The performance characteristics related to flow-rate capacity in a standard proportional valve are stated. From these characteristics the performance of these component can be modelled and compared

5.1 FLOW-RATE CHARACTERISTICS

The mass flow rate characteristics are shaped in "V" curve. Each curve side corresponds to different port, depending of excitation voltage. In figure 4, mass flow rate for chocked flow condition is plotted for different spool positions and absolute pressure inlet. It can be observed that the maximum mass flow rate depends of pressure inlet.

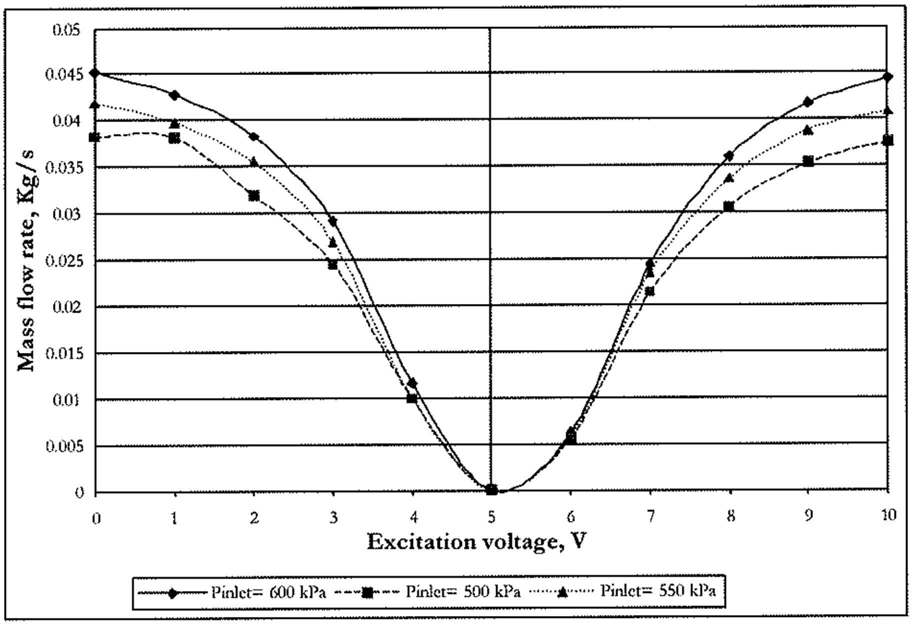

Figure 4: Maximum mass flow rate against different upstream pressures

The standard ISO 6358 establishes other characteristics to be determined to define completely the performance of a pneumatic valve. These characteristics will permit to compare it with other similar valves. Thus, sonic conductance, critical pressure ratio, coefficient of compressibility effect, and effective area must be determined. The sonic conductance is correlated with the critical pressure ratio, and the effective area must be expressed as function of the coefficient of compressibility effect.

5.2 RELATIONSHIP BETWEEN EFFECTIVE AREA AND COEFFICIENT OF COMPRESSIBILITY EFFECT. CORRELATION BETWEEN MAXIMUM EFFECTIVE AREA IN CHOCKED FLOW CONDITION AND EXCITATION VOLTAGE

In figures 5 and 6, the effective area variation versus the coefficient of compressibility effect is represented for different spool positions and upstream pressure. It can be observed that effective area is independent of inlet pressure and a low sensitivity is exhibit against the coefficient of compressibility effect. The maximum value is obtained for chocked flow conditions.

The effective area specially depends on spool position. In figure 7, is shown the effective area as function of excitation voltage. The obtained value for both extreme spool positions (exctation voltage of 0 and 10 Volts), are very similar. The average equivalent diameter obtained is 7.7 mm.

Finally, the maximum effective area for chocked flow condition versus excitation voltage is plotted. A second-order polynomial equation is used to correlate both quantities. A good agreement is achieved with experimental data. This correlation can be utilized in the modelling pneumatic systems, where these components are included.

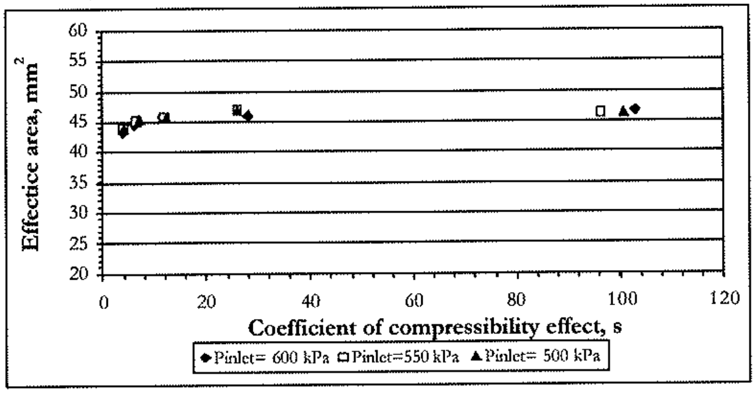

Figure 5: Influence of inlet pressure in effective area. V=10 Volts

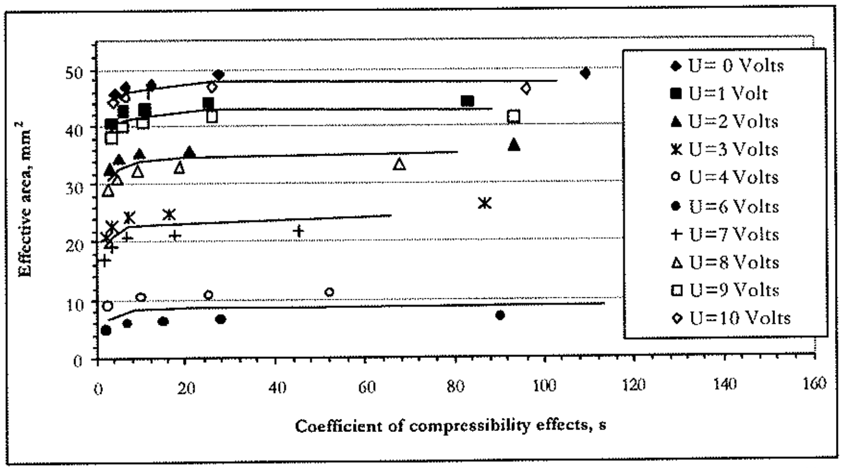

Figure 6: Effective area variation versus coefficient of compressibility effect for different spool valve positions. Pressure inlet 550 kPa

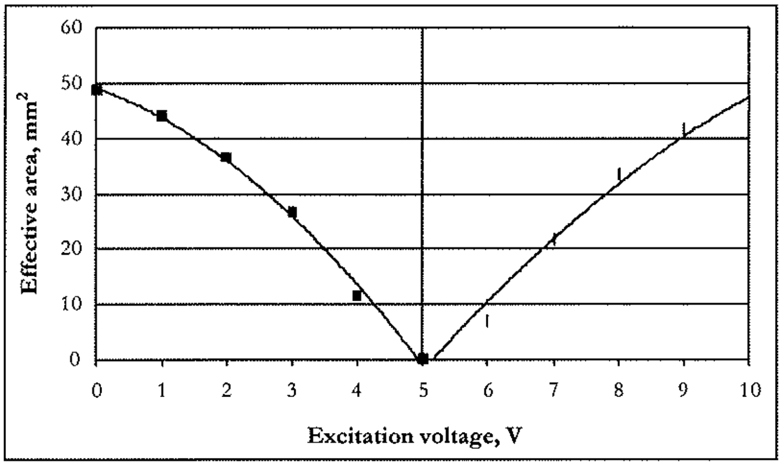

Figure 7: Correlation for maximum effective area as function of excitation voltage

$$A_{eff} = -0.9177(V-5)^2 + 14.5725(V-5)$$

5.3 RELATIONSHIP BETWEEN SONIC CONDUCTANCE AND CRITICAL PRESSURE RATIO

The sonic conductance is defined in [3]. In steady flow, when the upstream pressure is maintained in a constant value, the sonic conductance only depends on effective area of the pneumatic valve. This is the same that considering an infinite capacity pneumatic system. This hypothesis it is not totally certain in actual pneumatic systems. In the most of cases, the upstream chamber of a pneumatic component is characterized by a L/D geometric ratio. This ratio affects the sonic conductance value [5].

The sonic conductance is utilized in modelling discharge curve of pneumatic fluid power components. In this work, the relationship between sonic conductance and critical pressure ratio has been obtained for different spool positions and upstream pressures. The discharge curves of the proportional valve MPYE-5-3/8-010-B have been obtained for all ports.

The figure 8 shows the discharge curve for several upstream pressures and excitation voltages of 0 and 10 volts. It is corresponds with the extreme spool positions, when the effective area is maximum.

It can be observed that the corrected mass flow rate in a proportional valve varies with the pressure ratio describing a typical discharge curve. In addition, it can be seen that the mass flow rate is the same in both ports and it depends on upstream pressure.

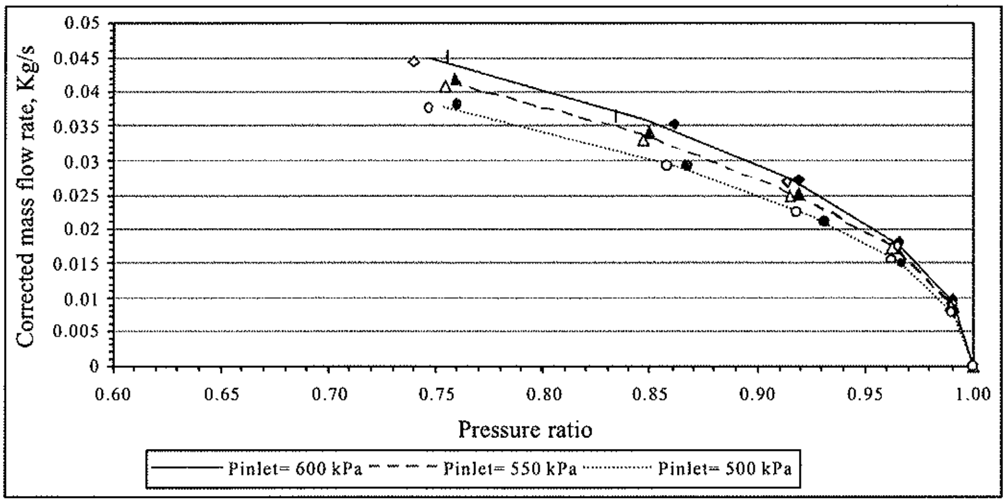

Figure 8: Discharge curve for different upstream pressures. Excitation voltage 0-10 V

When the experimental discharge curve is compared with the presented in Annex B of ISO 6358, it is concluded that the chocked flow condition it is not reached. It is due to the experimental setup utilized. In this work a downstream measuring tube is arranged. By consequent, and additional pressure drop exists between the proportional valve throat and downstream pressure measurement location. In this setup, the discharge curve is modified and the critical pressure ratio decrease down to b'(according to ISO 6358). The discharge curve seems a truncated ellipse.

The figure 9 shows the discharge curve for 600 kPa absolute inlet pressure and different spool positions or excitation voltages.

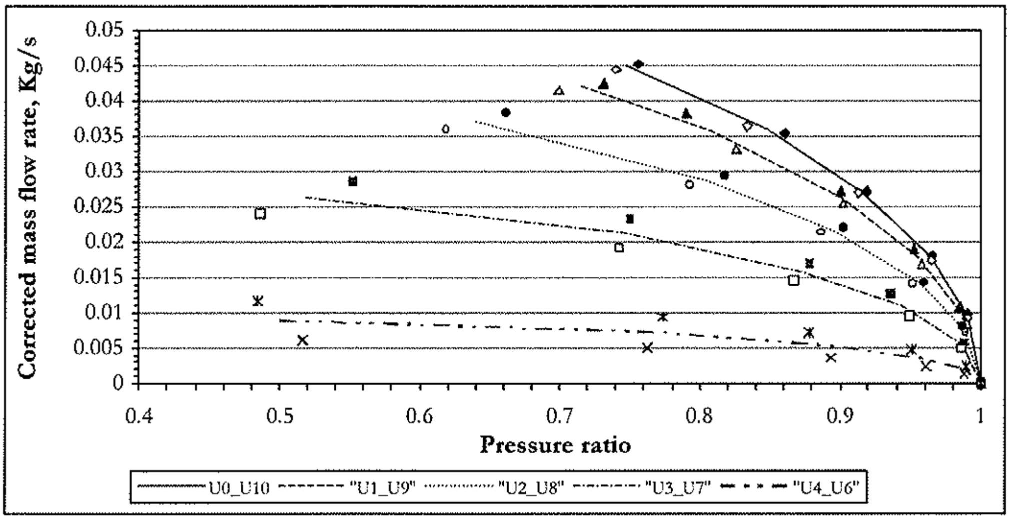

Figure 9: Discharge curve for different spool positions. Absolute pressure inlet, 600 kPa

5.4 SONIC CONDUCTANCE

In the subsonic range, the discharge curve of a pneumatic component can be correlated in two possible forms through non-dimensional parameter. The sonic conductance and the critical pressure ratio or the effective area and the coefficient of compressibility effects can be utilized. When the chocked flow condition is reached the discharge curve is correlated only with the sonic conductance.

The figure 10 shows the sonic conductance in chocked flow condition for different spool positions and upstream pressures. It can be observed that the sonic conductance is not influenced by inlet pressure.

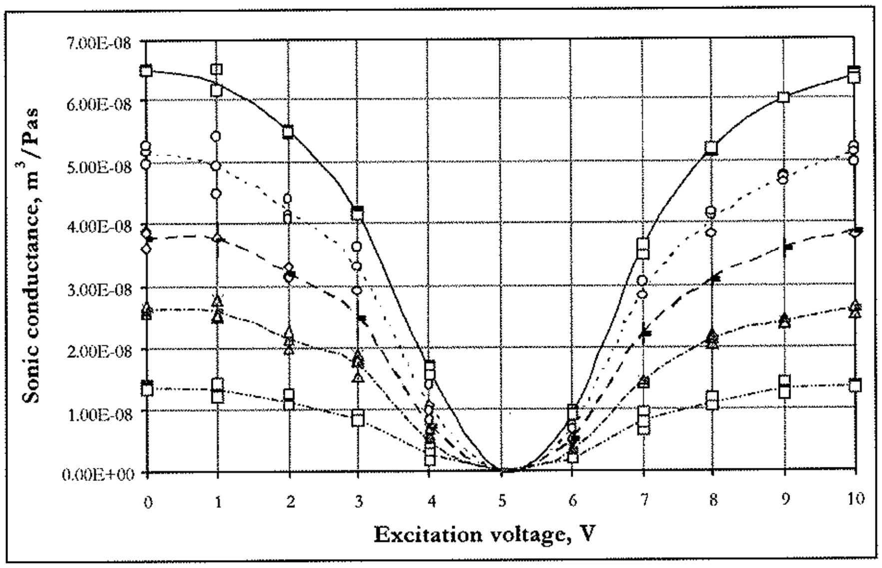

Figure 10: Sonic conductance for different spool positions and upstream pressures

In the figure 11, the variation of sonic conductance with the pressure ratio is shown. It can be concluded that the upstream pressure influence is insignificant.

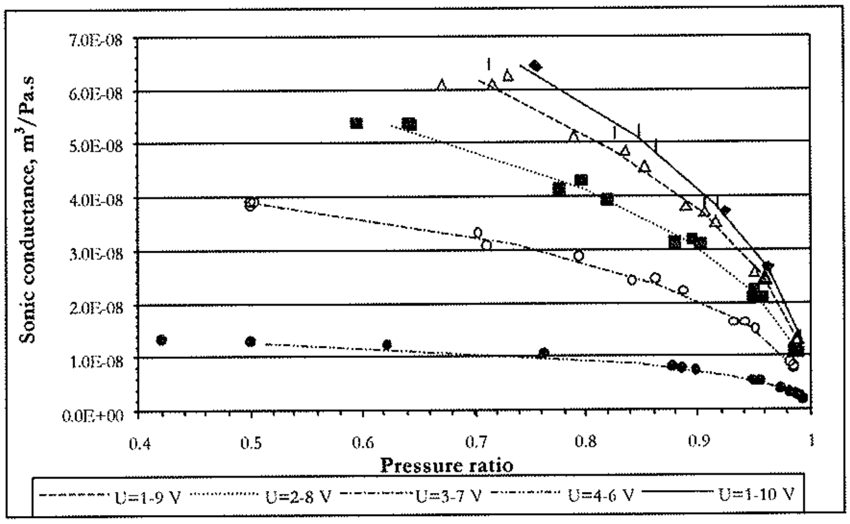

Figure 11: Sonic conductance variation with pressure ratio and different inlet pressures

5.5 TEST OF COMPONENTS EXHAUSTING DIRECTLY TO ATMOSPHERE

These types of tests are required to the valve ports that exhausting directly to atmosphere. In this work, the proportional valve has been tested for both extreme spool positions varying the upstream pressure between 100 and 600 kPa.

The figure 12 shows that the corrected mass flow rate is proportional to the inlet pressure when the choked flow condition is reached. Through this test the critical pressure ratio can be determined.

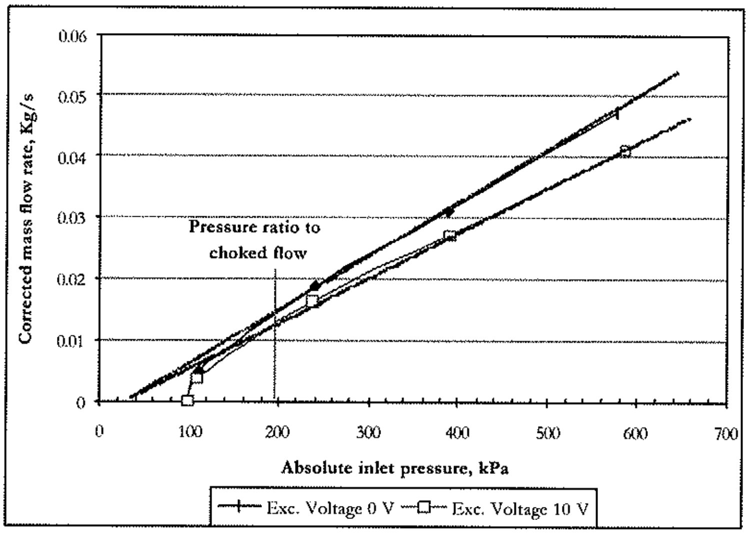

Figure 12: Discharge curve for valve ports exhausting directly to atmosphere

5.6 CHECKING HYSTERESIS EFFECT AT PROPORTIONAL VALVE

The accuracy and repetitiveness in operation of proportional valve depends on the positioning of the spool. Errors can be produced by hysteresis effect in coil, spring elasticity and friction. The hysteresis effect has been checked increasing and reducing the exciting voltage between 0 to 10 Volts. In both series the mass flow rate of chocked flow condition has been determined. The upstream pressure is maintained constant at 600 kPa

In figure 13 the corrected mass flow rate versus pressure ratio increasing and reducing the excitation voltage are shown. When the proportional valve operates in open loop, the hysteresis error increases at the excitation voltage is increasing.

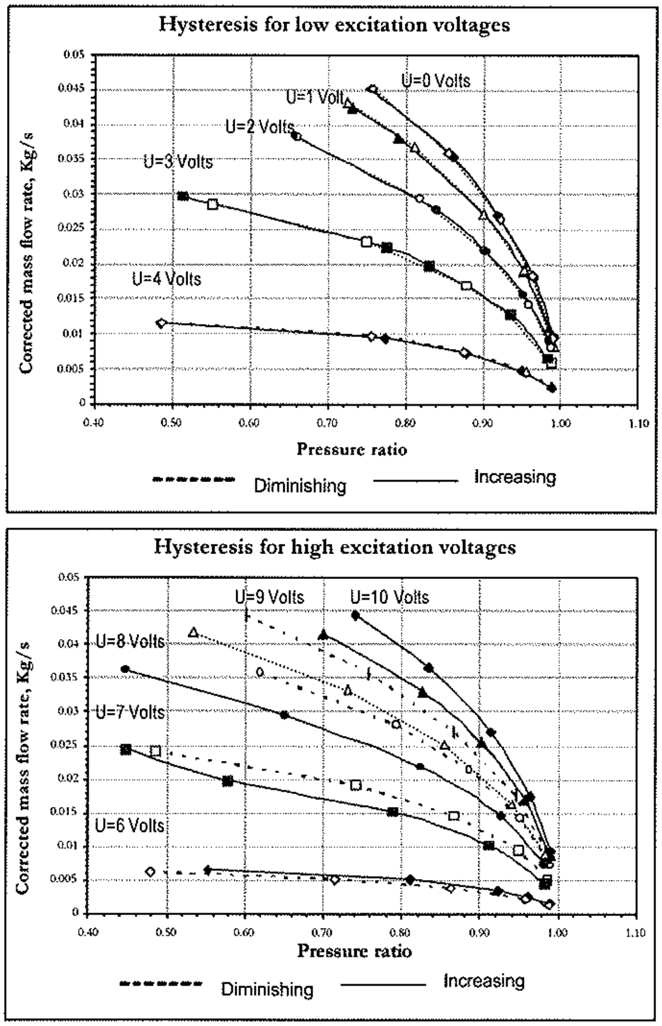

Figure 13: Checking hysteresis effect

The hysteresis effects are reduced in actual pneumatic fluid power proportional valves operating in closed loop and a superimposed high frequency signal called "dither". This control system is more expensive. However, the high hysteresis errors obtained justifies the closed loop control system when high accuracy is required.

In the figure 14, the hysteresis error is represented versus the excitation voltage.

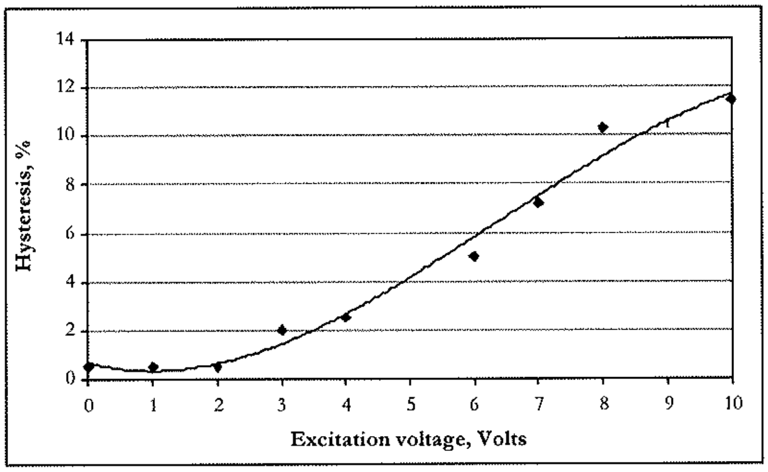

Figure 14: Hysteresis effect in open-loop operation

CONCLUSIONS

The required adaptations of a general purpose flow bench to test pneumatic fluid power components have been accomplished. These adaptations are according to standard ISO 6358. Although, the uncertainty measurements achieved and their propagation in results are below of limits established in ISO 6358.

The proportional valve Festo MPYE-5-3/8-010-B has been tested with pressure measuring tubes fitted to upstream and downstream and with ports exhausting directly to atmosphere.

A complete characterization of a pneumatic proportional valve has been performed. The mass flow rate characteristics, sonic conductance and effective area have been obtained for different excitation voltages or spool positions and upstream pressures. The dimensional maximum mass flow rate is closely to performance provided by manufacturer.

The discharge curve of this type of pneumatic component it is well correlated by sonic conductance and critical pressure ratio in both, subsonic range and in chocked flow condition. Also, the effective area has been correlated with the excitation voltage. A maximum equivalent diameter of 7.7 mm, lower than nominal size of 10 mm has been obtained for choked flow conditions. This information can be used in pneumatic fluid power systems modelling.

The hysteresis effect has been checked when the proportional valve is operated in open-loop. The disagreements at corrected mass flow rate when the excitation voltage is increasing and diminishing are substantial at higher voltages. So, when high accuracy is required a closed-loop system control must be used.

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