International Journal of Fluid Power 6 (2005) No. 2 pp. 57-64

ANALYSIS AND AUTOMATED TESTING OF A MINIATURE PNEUMATIC VALVE FOR HOSPITAL PATIENT SUPPORT EQUIPMENT

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Abstract

The steady state and dynamic performance of a miniature pneumatic valve is studied and an automated, computer-controlled test procedure is developed to determine unwanted leakage. A novel testing approach is developed using the valve dynamic leakage characteristic, and a substantially reduced test time has been achieved. A National Instruments LabVIEW hardware approach is utilised for both data acquisition and real time control and the test procedure has been put into commercial use.

Keywords: miniature pneumatic valve, automated testsystem, valve characteristics

1 Introduction

The pneumatic valve in question is a solenoid-operated valve, designed by Huntleigh Healthcare Ltd UK and manufactured by Coils UK Ltd, and is used to control air pressure in patient pressure relieving mattresses used in hospitals and nursing homes around the world. The Nimbus advanced dynamic flotation system, using the miniature pneumatic valve Fig. 1, is just one of a range of products produced by Huntleigh Healthcare Ltd UK and has been clinically proven to be one of the most effective and comfortable, yet cost efficient, mattress replacement systems.

The system effectively relieves pressures below clinically relevant thresholds close to arteriolar, capillary and venule operating pressures nominally at 30, 20 and 10 mmHg (100mm Hg = 0.132bar) for longer periods. This enables blood vessel diameters to remain as large as possible for as long as possible ensuring tissue oxygenation and nutrition are maintained and the removal of toxins is stimulated. This aids the effective prevention and treatment of pressure sores.

Technological refinements of the pneumatic valve design by the manufacturer over the past five years has resulted in an efficient, miniature, solenoid-operated valve necessary for patient care applications. The application has dictated the valve product type due to the following reasons :

This manuscript was received on 7 October 2004 and was accepted after revision for publication on 5 June 2005

- Existing equipment was considered commercially inappropriate primarily due to cost but also due the application specification.
- Very low, controllable, pressure rate operation with miniaturisation was required.
- A new dual valve assembly was required for simultaneous on/off operation using solenoid actuation, two-positions with latching at each position and with no electrical power required at each latched position.
- A new dual pneumatic power supply unit suitable for hospital and bedside use was needed

Fig. 1: *The Nimbus 3 advanced dynamic flotation system (courtesy of Huntleigh Healthcare Ltd)*

Pressures down to 100mmHg are being considered and remote from those used in conventional pneumatic valves.

The valve must be able to cycle between two connections to the appropriate mattress segment, i.e., one on while the other off, and thus both charging and discharging must be possible. This is due to the medical requirement to stimulate blood flow circulation via cyclic pressurisation of the mattress segments.

In parallel with the valve design, considerable solenoid/coil technology, miniature power supply development, and injection moulding development has been undertaken to produce the valve body design with just two plastic components. This commercial development has produced a successful unit and the authors have had no technical input to this design process. However, it became obvious that the general manufacturing and assembly approach resulted initially in some units that leaked, primarily due to seal assembly and quality issues. Therefore, in addition to continual development of the miniature valve, it was decided to consider an automated test system for both performance evaluation and manufacturing quality assessment of the valve. The brief was to determine if an individual test could be undertaken in the shortest possible time. This required development of not only the test system but also a new theory for transient pressure decay in the presence of leakage.

It is important to note that the ensuing testing procedure followed that specified by the manufacturer. The approach is not necessarily the optimum design or best selection of test components. The work was completed over a 3-month period during 2000 as a prototype design, with no consideration of circuit optimisation, and there has been no desire since to modify the approach by the company concerned.

2 The Developed Test Procedure

The pneumatic valve and test circuit are shown in Fig. 2 (a,b) and the test concept is shown in Fig.3. The main function is to allow automated detection of leakage from the Unit Under Test (UUT) and also to measure the flow characteristic of the UUT at low pressure differential. The leakage specification provided by the manufacturer was that *"the valve should so seal a 200-litre volume of air such that an initial gauge pressure of 100 mmHg should not decay below 80% of this value within 12 hours"*. The reader will note that pressures are expressed in mmHg since this is preferred in medical applications.

An equivalent test has been designed where the volume of air that is pressurised is far smaller, enabling the test to be performed in a much shorter time. This has the additional advantage of reducing the size of the equipment, making it compact enough to sit on a laboratory bench. The flow characteristic of the valve can be obtained in the range of 4 →20 litres/min of air. The apparatus was built entirely from commercial off-the-shelf products from a small number of suppliers. Assembly of the equipment required no specialist tools, beyond those usually associated with simple mechanical and electrical fitting. The time required for this task was minimised by the use of one touch pneumatic fittings. These were standardised by using 8mm external diameter tubing and 6.35mm fittings throughout the system wherever possible. The sole exceptions to this are the pilot pressure line to the 5/3 valve, the fitting on the line and the fitting on the pressure sensor.

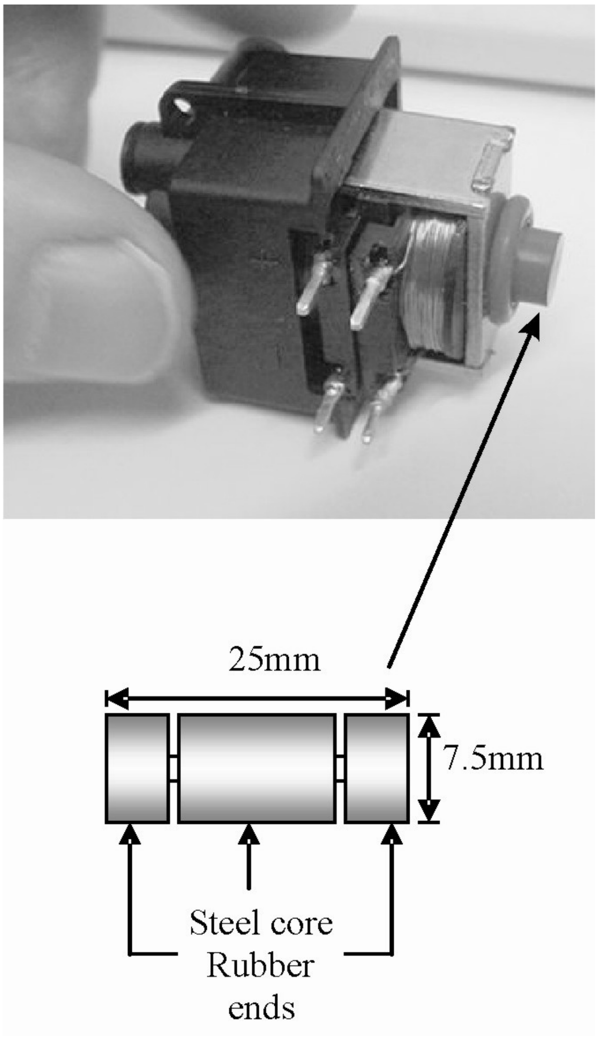


Fig. 2a: *The pneumatic unit showing the solenoid and half of the two pneumatic valve body. The plunger is latched to the right hand side*

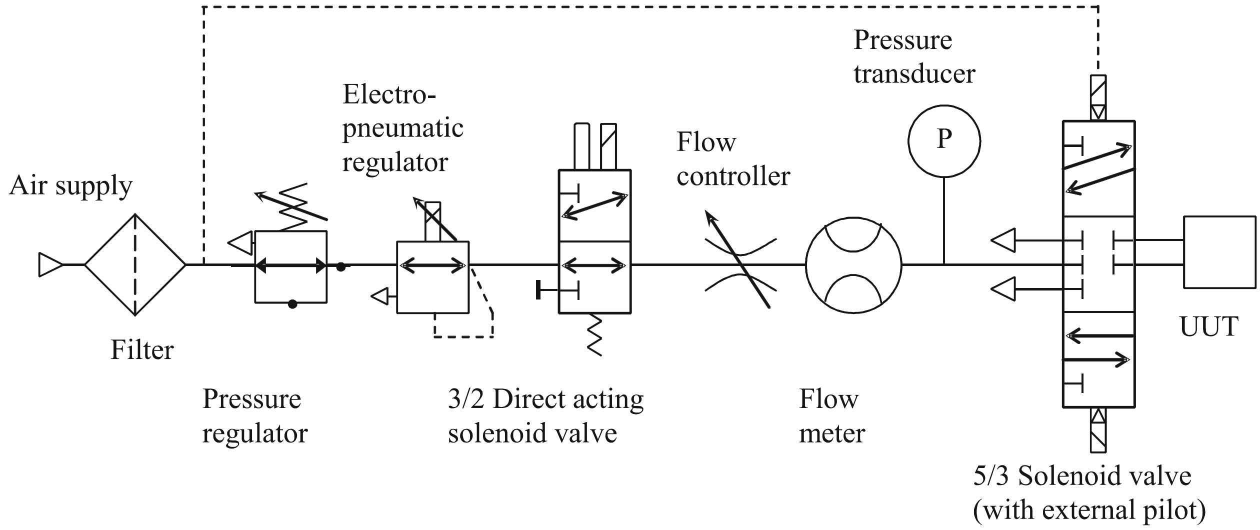


Fig. 2b: *The test circuit diagram*

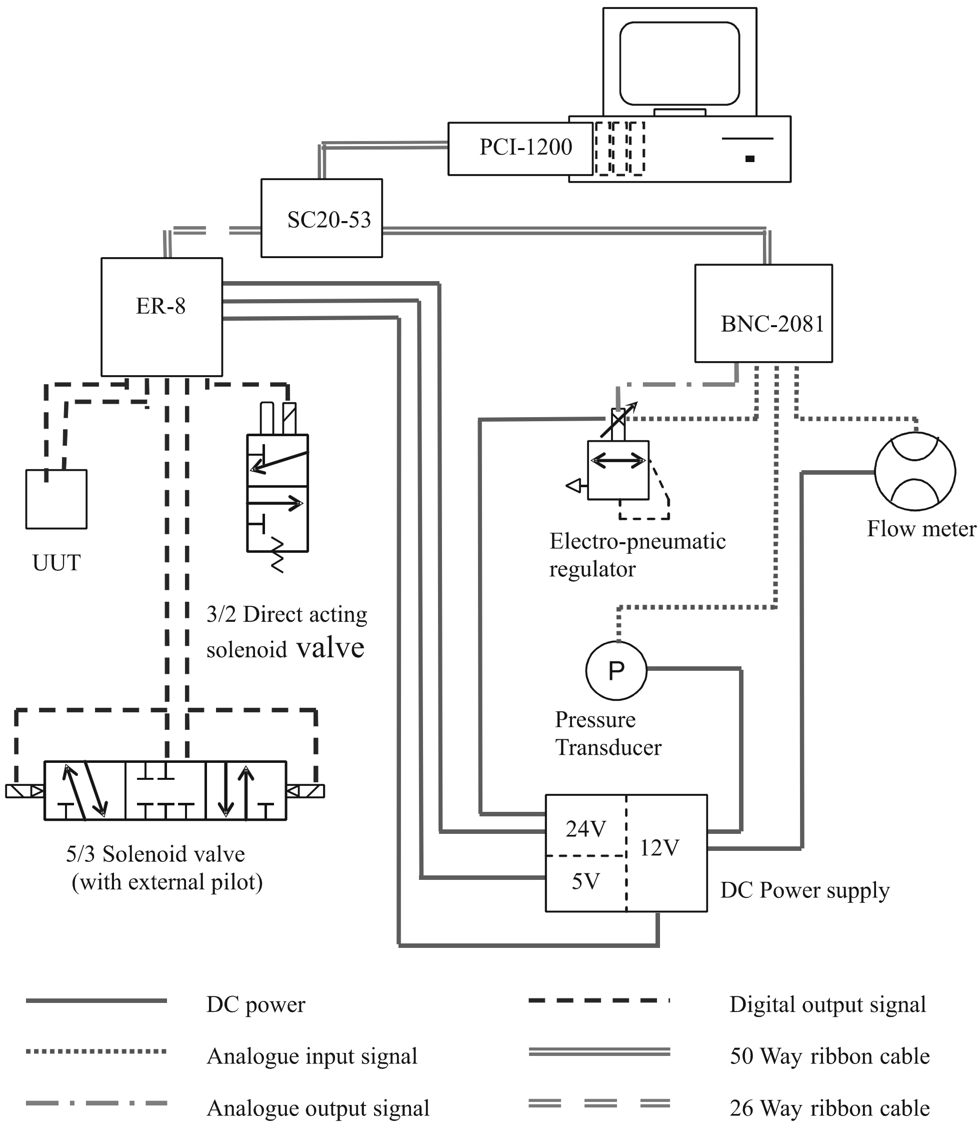


Fig. 3: *Test apparatus instrumentation connection diagram*

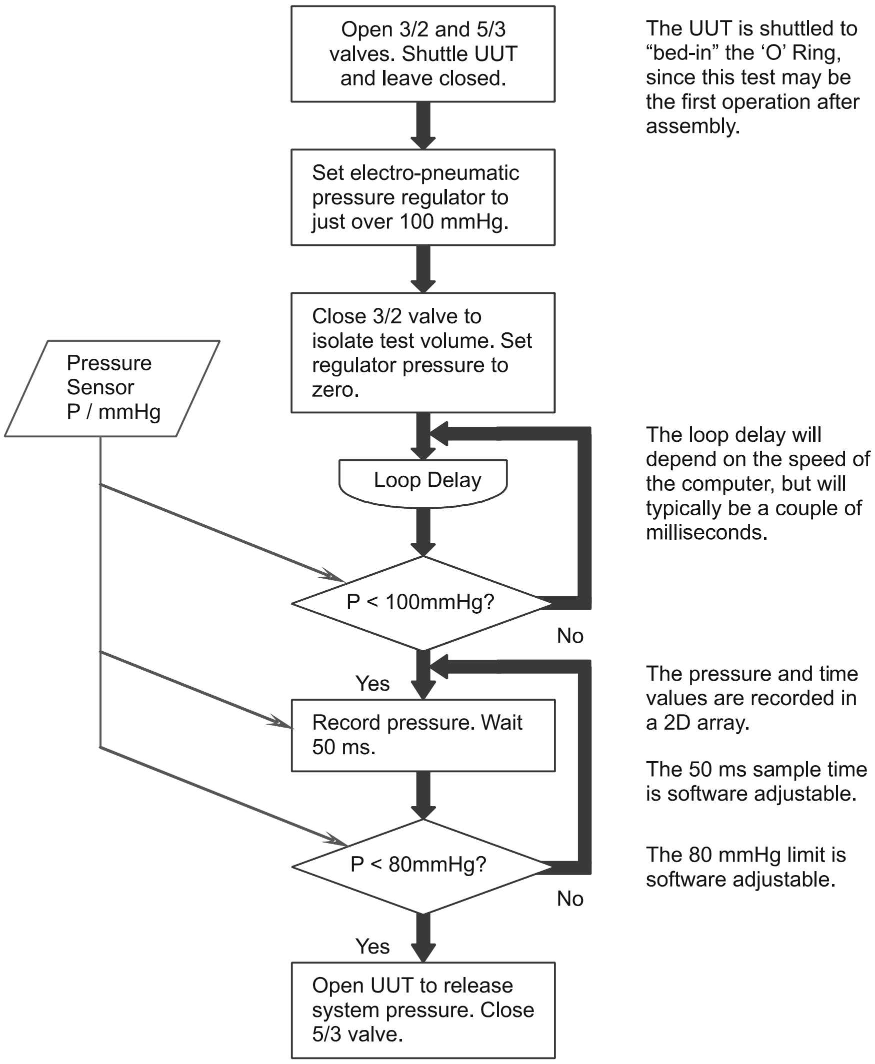


Fig. 4: *Flow chart for the pressure leakage test*

The device labelled ER-8 in Fig.3 consists of 8 electromechanical relays. These are used to allow the digital output signals from the PCI-1200 data acquisition card to automatically sequence the valve, the solenoids having normal flyback diode current protection. The software package used to control the rig and capture data from the sensors was LabVIEW from National Instruments. This is a general purpose development environment, which uses a graphical language, *G*, to produce executable programs called *virtual instruments* (VIs). In this application, these programs communicate with the test apparatus via the PCI-1200 data acquisition card (DAQ), as illustrated in the hardware description. The test procedures were developed initially as flow charts and then implemented in the software following a modular approach. Initially, low-level VIs were built to carry out basic functions (such as operating the solenoids and setting the pressure output of the electro-pneumatic regulator). These were then combined with data acquisition VIs to form individual test VIs, which were finally brought together in a top-level VI to allow user interaction. The conceptual flow chart for the test is reproduced in Fig. 4 along with a brief description of the test philosophy.

3 Theoretical Analysis

This test can be modelled as a flow of air from a pressurised container of constant volume, as illustrated in Fig. 5.

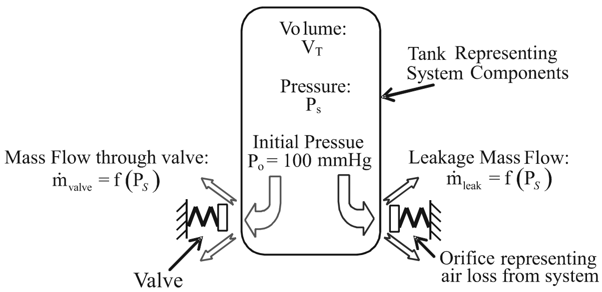


Fig. 5: *Modelling conceptual diagram*

Considering the pneumatic flow theory (Perry 1949, Stenning 1955, Tsai and Cassidy 1961, Jebar et al 1978, McCloy and Martin 1980, Miyata and Hanafusa 1989, Han et al 1999, Esposito 2000, de las Heras 2001) leads to the following mass flow Eq. :

$$\dot{m} = \frac{c_d c_m a P_s}{\sqrt{T}} \tag{1}$$

where:

$\dot{m}$ = mass flow rate [kg/s]

c_{d} = discharge coefficient

c_{m} = mass flow parameter, $\left[\mathrm{kg}\sqrt{\mathrm{K}}/\mathrm{sPa}\right]$

a = orifice area [m^2]

P_{s} = upstream absolute pressure [Pa]

T = absolute upstream temperature [K]

The upstream temperature is assumed to remain constant and the mass flow parameter varies with the ratio of the absolute pressures upstream and at the vena contracta. However, since the valve exhausts to the atmosphere, no pressure recovery occurs downstream and the pressure at the vena contracta remains constant at atmospheric pressure. This enables the mass flow coefficient to be determined purely as a function of upstream pressure. For upstream gauge pressures of about one atmosphere and above, the flow becomes choked and c_{m} attains a constant value. For lower upstream pressures, the value of c_{m} reduces to zero, in accordance with the following Eq. assuming the gas constant R=287J/kg$\cdot$K and the ratio of specific heats γ =1.4 (McClog and Martin 1980):

$$c_{\mathrm{m}} = \sqrt{\frac{2\gamma}{\mathrm{R}(\gamma\text{-}1)}\left[\left(\frac{P_{\mathrm{st}}}{P_{\mathrm{s}}}\right)^{2/\gamma} - \left(\frac{P_{\mathrm{st}}}{P_{\mathrm{s}}}\right)^{(\gamma+1)/\gamma}\right]}$$
$$c_{\mathrm{m}} = \sqrt{0.024\left[\left(\frac{760}{P_{\mathrm{s}}}\right)^{1.43} - \left(\frac{760}{P_{\mathrm{s}}}\right)^{1.71}\right]} \qquad (2)$$

where P_{s} = upstream system absolute pressure (mmHg), P_{st} = static pressure at the vena contracta. Figure 6 shows this relationship for absolute pressures of 700→1600 mmHg and demonstrates the limiting effect of choked flow on the mass flow parameter.

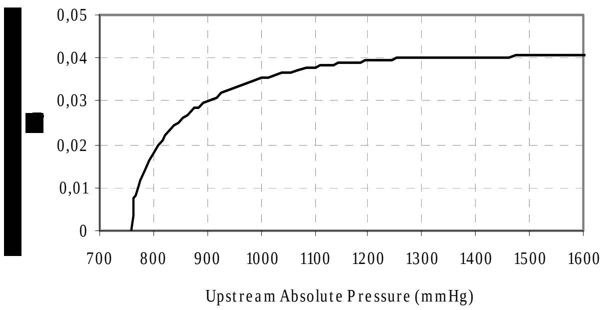
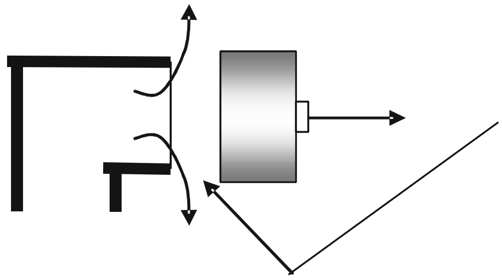


Fig. 6: *Variation in c_m with gauge pressure*

The discharge coefficient can be a complex function of orifice geometry and fluid flow characteristics. Without extensive experimentation or Computational Fluid Dynamics work, this factor is difficult to quantify. From previous experimental work [Tsai and Cassidy 1961, Jebar et al 1978 and McCloy and Martin 1980] two contradictory trends in c_{d} can be identified, a decrease with falling pressure and an increase as a result of the consequential narrowing of the orifice. There is also the possibility of a sharp decline at very small pressure drops as the flow becomes laminar. Tests carried out on the valve assembly by the manufacturer showed that the plunger is displaced as port pressure is increased, thus increasing the orifice area. This test programme used a laser sensor to measure the rubber plunger movement with applied pressure and revealed a position change of 0.01mm/100mmHg applied pressure. This implies that the orifice peripheral area will increase in direct proportion to the applied pressure, although it is difficult to say what the exact flow area and the flow coefficient is without a more detailed analysis beyond this study. In reality, imperfections at the seal interface will exist and subsequently at zero gauge pressure, a non-zero orifice area will exist. It is therefore proposed through discussions with the manufacturer that the pressure-area relationship can be described as follows:



$$a = g(P_{\mathrm{s}} - 760) + a_0 \qquad (3)$$

a_{o}= orifice area at zero gauge pressure, g = area gradient

A fuller consideration of this area relationship is considered later when the model is fitted to the experimental pressure decay characteristic. A similar relationship was also seen to exist in the system leakage model. This may be due to components showing pressure-dependant orifice characteristics, or it may be due to discharge coefficient variation. If Eq. 2 and 3 are now substituted into Eq. 1, then for any given duration of time, D, the mass of air that has escaped from the system is given by integrating with respect to time over the limits t = 0 to D. This is shown for the valve in Eq. 4.

$$M_{\mathrm{valve}} = \int_{t=0}^{D} \left(\frac{\dfrac{c_{\mathrm{d}}\sqrt{0.024\left[\left(\dfrac{760}{P_{\mathrm{s}}(\mathrm{t})}\right)^{1.43} - \left(\dfrac{760}{P_{\mathrm{s}}(\mathrm{t})}\right)^{1.71}\right]}}{\sqrt{T}}}{\dfrac{\left[g(P_{\mathrm{s}}(\mathrm{t}) - 760) + a_0\right]P_{\mathrm{s}}(\mathrm{t})}{\sqrt{T}}} \right) \mathrm{dt} \qquad (4)$$

The volume of the test system remains constant and so the system pressure, P_{s}, will decrease as air escapes. This process can be modelled using the ideal gas law :

$$P_{\mathrm{s}}V_{\mathrm{T}} = M\mathrm{R}T \qquad (5)$$

V_{T} = total volume of the system, R = gas constant, M = mass of air remaining in the system T = absolute temperature

If the system volume and the initial pressure, P_0, are known, the mass of air contained in the system initially can be calculated. Since pressure changes occur very slowly and at standard pressures and temperatures, the ideal gas law may be assumed by using mass continuity. From Eq. 4 and 5, an expression for the state of the system after D seconds can be written :

$$\frac{V_{\mathrm{T}}}{\mathrm{R}T}P_{\mathrm{s}}(D)=\frac{V_{\mathrm{T}}}{\mathrm{R}T}P_0-M_{\mathrm{leak}}-M_{\mathrm{valve}} \tag{6}$$

This equation cannot be solved explicitly. However, it is possible to generate numerical solutions for specific values of $a_{\mathrm{o}}c_{\mathrm{d}}$, c_{d} g and a by using a spreadsheet and repeating the following steps:

- calculate the initial mass flow, multiply by a finite time interval to give the mass leakage,
- subtract this from the remaining system mass,
- calculate the new pressure

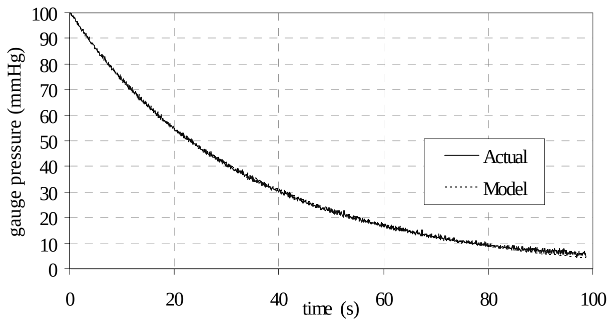


Fig. 7: *A comparison of the pressure decay model with actual results*

Using the test rig developed for this project, real pressure decay waveforms were then recorded in a spreadsheet form and compared with those produced using the method based on Eq. 6. It was found that an excellent degree of agreement between the two existed, as shown in Fig. 7.

The result illustrated in Fig. 7 show that the model is a good approximation to reality over the entire range of the pressure decay. The model was deduced by varying the area gradient and initial area, Eq. 3, to achieve the best result via an Excel spreadsheet. This was not particularly time consuming since it became quickly evident that the linear area assumption was appropriate. In order to test the valve for pressure leakage, it is only intended to examine the decay over a portion of this curve. In fact, the specification for the valve leakage is that, given a volume of 200 litres at a gauge pressure of 100 mmHg, the pressure must not fall by greater than 20% in 12 hours. If the model is now re-examined over this pressure range, it can be seen that a number of simplifications can now be made. Figure 8 illustrates that within the regime in which the test is specified; c_{m} deviates less than 5% from a value of 0.0255.

The valve orifice area varies slightly more significantly than the mass flow parameter, but the error caused by assuming a constant value is still less than 10%. By making these two assumptions, it is possible to re-write Eq. 4 as Eq. 7.

$$M_{\mathrm{valve}}=\frac{c_{\mathrm{d}}c_{\mathrm{m}}a}{\sqrt{T}}\int_{t=0}^{D}P_{\mathrm{s}}(t)\mathrm{d}t \tag{7}$$

This allows a simplified version of Eq. 6 to be generated, one which it is possible to solve explicitly as follows :

$$\frac{V_{\mathrm{T}}}{\mathrm{R}T}P_{\mathrm{s}}(D)=\frac{V_{\mathrm{T}}}{\mathrm{R}T}P_0-\frac{a_{\mathrm{valve}}c_{\mathrm{d\,valve}}c_{\mathrm{m}}}{\sqrt{T}}\int_{t=0}^{D}P_{\mathrm{S}}(t)\mathrm{d}t-\frac{a_{\mathrm{leak}}c_{\mathrm{d_{leak}}}c_{\mathrm{m}}}{\sqrt{T}}\int_{t=0}^{D}P_{\mathrm{s}}(t)\mathrm{d}t \tag{8}$$

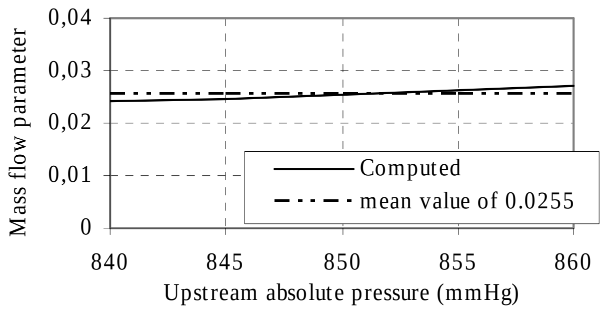


Fig. 8: *Variation in the mass flow parameter c_m with abso lute pressure over the test operating range*

Taking Laplace transforms of Eq. 8 and assuming the input to the system to be a step input of pressure P_{o}, gives the s-domain relationship shown in Eq. 9.

$$P_{\mathrm{s}}(s)=\frac{P_{\mathrm{o}}}{s+K}$$
$$K=\frac{(a_{\mathrm{valve}}c_{\mathrm{d_{valve}}}+a_{\mathrm{leak}}c_{\mathrm{d_{leak}}})c_{\mathrm{m}}\mathrm{R}\sqrt{T}}{V_{\mathrm{T}}} \tag{9}$$

The pressure-time decay is then the simple exponential form as follows :

$$P_{\mathrm{s}}(t)=P_{\mathrm{o}}e^{-\mathrm{Kt}} \tag{10}$$

The value of the time constant, K, related to the test specification can be calculated by substituting the values of P_{s} = 840 mmHg, P_{o} =860 mmHg and t = 12 hours into Eq. 10. For an ideal test rig ($\dot{m}_{\mathrm{leak}}=0$), this is found to be 3.27x10^{-5} min^{-1}. If this value is back-substituted into Eq. 10, the drop in pressure over the first second can be found. By considering mass continuity, Eq. 11 gives the volume of air that escapes in 1 second, which is effectively the initial leakage rate :

$$P_{\mathrm{o}}V_{\mathrm{T}}=P_{\mathrm{s}}(t)V_{\mathrm{T}}+P_{\mathrm{atm}}V_{\mathrm{esc}}(t) \tag{11}$$

where:

P_{atm} = absolute atmospheric pressure,

V_{esc} = volume of air escaped as a function of time

V_{esc} was found to be approximately 123mm^3 after 1 second, equivalent to an initial flow rate of about 7.4litres/min. Using the simplified model, a value of 7.3litres/min is deduced. If the composition of the time constant, K, is considered it can be seen that it is the sum of two elements, one representing the test system leakage and the other representing the valve leakage. However, the total volume of the test system, V_{T}, is common to both elements. This enables the 200litre volume specified in the test requirement to be scaled down to a size better suited to the laboratory, with a predictable effect on the pressure decay. As the test volume decreases, the time constant increases in inverse proportion. Once the volume of the test equipment is known, a new value for the time constant can then be determined. The volume of the test system can be found experimentally by adding lengths of pipe with a known internal diameter (and hence volume) to the existing apparatus. Note however that there are other inherent unknown volumes within the sensors and control valve, hence the need to consider a range of added volumes. If the natural logarithm of the pressure decay signal is plotted against time, the resultant graph will be a straight line with a gradient equal to the overall time constant, K. The total volume, V_T, is now a function of the test equipment volume, V_e, and the added volume, V_{add}. This relationship is illustrated by Eq. 12.

$$V_{\mathrm{add}} = b\frac{1}{K} - V_{\mathrm{e}} \tag{12}$$

K = time constant of pressure decay

$$\mathrm{b} = \left(a_{\mathrm{valve}} c_{\mathrm{d_{valve}}} + a_{\mathrm{leak}} c_{\mathrm{d_{leak}}}\right) c_{\mathrm{m}} \mathrm{R}\sqrt{T}$$

The value of b will be constant for any given orifice, since the addition of a length of pipe will have no effect on the system leakage characteristic. Therefore, if the volume added is plotted against the reciprocal of the time constant, it is possible to extrapolate the data to find V_e, the intercept on the Y axis. This was done using the development test rig and replacing the valve with a variable orifice in the form of a restrictor. The experiment was repeated four times, each time with a different size of orifice and the results are shown in Fig. 8.

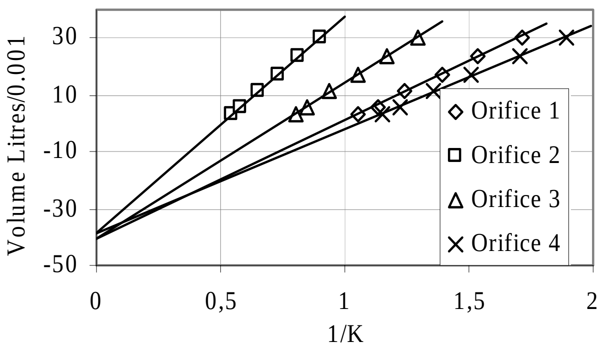


Fig. 9: *Results of experiment to find V_T*

From this work, V_e was found to be 0.04 litres. Using this value for V_T, if the test conditions remain otherwise unchanged, the time constant for the pressure decay specification will increase to 0.163 min^{-1}. If the apparatus is changed (for example, to include a manifold connector for the UUT), it will be necessary to repeat the experiment to find the new value of V_e. In order that a practical test can be specified, the system leakage must first be characterised. This is done by replacing the UUT in the apparatus with air stops and performing a pressure decay test. In this case, since there is no valve flow, the pressure decay time constant is simply a measure of system leakage. Figure 10 shows the results of one such test where the pressure decays from 660 mmHg to 850 mmHg absolute.

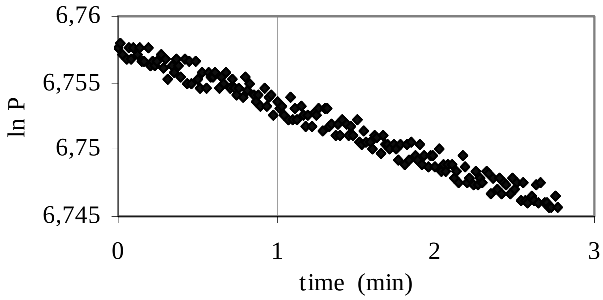


Fig. 10: *Pressure decay test showing system leakage (UUT blocked off)*

Figure 10 shows the very low level of control valve leakage, the gradient of the line of best fit being $4.3\text{x}10^{3}$ min^{-1}. The test criterion should therefore be adjusted such that the total time constant should be equal to the sum of the valve test criterion (K = 0.163 min^{-1}) and the system inherent leakage (K = 0.004 min^{-1}). If this overall time constant of 0.167 min^{-1} is now substituted into Eq. 10, the time for which the pressure must not drop below 80% of its initial value can be calculated as 8.5 seconds. A linear interpolation of the decay characteristic over the very short time interval also gives the same result. It is now a simple matter to connect a valve into the test circuit, initiate the test procedure from the computer and observe the pass/fail outcome from the analysed pressure decay data. The fully-functional test facility has also been extended to measure the flow characteristic of the UUT, but results are not presented here.

4 Conclusions

- The presented flow theory was shown to give a very good prediction of the pressure dynamic decay and was aided by realistic approximations to the valve restriction flow characteristic.
- Correcting factors are usually necessary to allow calculation of flow rates under different pressure conditions. However, the nature of the rapid test procedure proposed means that the effect of pressure on the mass flow parameter is of secondary importance.
- A linear first-order pressure decay characteristic has been clearly identified allowing a much simplified technique of performance assessment to be used.
- The developed theory and experimental validation allows testing to be done under much smaller volume conditions. The experimental approach developed now allows much quicker valve testing to be done than originally anticipated.
- A novel theory has been presented that allows system calibration to be done under different test conditions, and also allows a relatively straightforward estimate of test volume.
- A fully integrated working system has been developed using standard components allowing automated steady state and dynamic tests to be carried out.

- All aspects of the LabVIEW software routine may be stored on disc, running within the LabVIEW environment. The appropriate data when graphically presented allows rapid assessment of the valve leakage characteristic and this has been put into practice for batch testing and has been operating satisfactorily over the past 5 years.

5 Acknowledgements

The authors wish to thank Coils UK Ltd for originating the project thus providing both financial and technical support. Thanks are also extended to Huntleigh Healthcare Ltd for technical support. In addition the authors also thank both companies for permission to publish the work described.

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