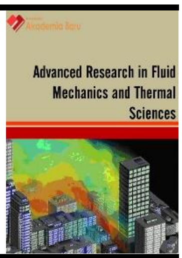
Penerbit Akademia Baru

Journal of Advanced Research in Fluid Mechanics and Thermal Sciences

Journal homepage: www.akademiabaru.com/arfmts.html
ISSN: 2289-7879



A Cost-effective Data Acquisition Instrumentation for Measurement of Base Pressure and Wall Pressure in Suddenly Expanded Flow Through Ducts

Open Access

Vigneshvaran Sethuraman[1], Parvathy Rajendran[1,*], Sher Afghan Khan[2]

[1] School of Aerospace Engineering, Universiti Sains Malaysia, 14300 Nibong Tebal, Penang, Malaysia
[2] Department of Mechanical Engineering, International Islamic University Malaysia, 53100 Kuala Lumpur, Malaysia

ARTICLE INFO

Article history:
Received 12 April 2019
Received in revised form 5 July 2019
Accepted 21 July 2019
Available online 15 August 2019

ABSTRACT

Internal flow experimental studies such as sudden expansion in ducts have been reported in literature. However, the methodology of arriving at the results is not discussed elaborately with accent on cost involved and time spent in acquiring the data. This paper explains in detail about the experimental procedure, the methodology of arriving at results and the data analysis. The experimental setup with readily available commercial data acquisition instrumentation for a typical sudden expansion internal flow is presented. It was observed that apart from the cost of hardware fabrication, the cost of instrumentation and measuring devices is also huge. This is apparent especially in fluid flow problems, where there is a need to measure pressures at multiple locations. However, commercially available DAQs have a limited number of channels. Thus, the need for an alternative cost-effective data acquisition system (DAQ) with multiple channels is crucial. Hence, an alternate arrangement of DAQ which is considerably cost-effective and is equally efficient as that of commercial instrument is proposed. The base pressure and wall pressure results obtained using fabricated DAQ had a variation of ± 1% and ± 1.5% respectively, in comparison to that of commercial DAQ. It is reported that these two arrangements give comparable results with very good accuracy and repeatability of results.

Keywords:
Base pressure; data acquisition; internal flow measurements; sudden expansion; wall pressure

1. Introduction

Suddenly expanded flows play a vital role in many important applications in the fields of automobiles, trains, aircraft, rockets, missiles and space vehicles. Base drag is a common problem that hinders the performance in the above-mentioned applications and constitutes to about 30% of the total drag [1]. Controlling of base pressure leads to reduction in base drag, which is needed in terms of operational as well as performance efficiency.

* *Corresponding author.*
E-mail address: aeparvathy@usm.my (Parvathy Rajendran)

Internal flow tests are preferred over external flow tests as the requirements for the test facility such as space required, cost involved, fabrication costs considerably less and the results obtained from either of the tests are similar with negligible variation of accuracy [2]. Sudden expansion of flow through ducts replicates external flow issues such as drag at the base of automobiles, rockets and missiles etc.

Base and wall pressure studies were also investigated through CFD simulations with Mach numbers ranging from low subsonic to high supersonic by Pathan *et al.,* [16]. They intended to understand the similarities of base pressure variation of the internal and external flows and found that the flow field at the base is similar for both cases. This reconfirms the experimental findings by Wick [2] that either of the tests are similar with negligible variation of accuracy. Other CFD work notable was on the influence of expansion level on base pressure and reattachment length [17]. While some analyzed the area ratio in a CD nozzle in a suddenly expanded duct [18].

The control of base pressure has been attempted using active and passive devices. Active controls, such as micro-jets require an external power source to perform its role as flow control mechanism while, passive controls are minor geometric modifications to the structure [3–5].

Cavities, one of the most used passive control elements were found to be effective; however, they pose some limitations [6,7]. Limited studies on ribs have shown them to be active in the parameter range studied and perform better as drag reducing devices than cavities [8,9].

In experimental work apart from the cost of hardware fabrication, the cost of instrumentation and measuring devices is also very high. Especially in fluid flow problems there is a need to measure pressures at many locations. This calls for a data acquisition system (DAQ) with multiple channels; but the commercially available instruments normally have a limited number of channels. It then becomes necessary to go in for extremely costly units to accommodate the requirements [10,11].

In the current study of suddenly expanded internal flows in ducts it was necessary to measure the base and wall pressures along with pressure loss simultaneously at 20 locations. It was found that the commercially available DAQ mostly accommodated lower number of channels and these too at a higher cost. Provisions for extra channels involved additional costs. Hence, a DAQ with 20 channels was developed specifically for this study and it proved to be extremely cost-effective and efficient. The test models, as cited in the literature, were replicated and tested using the newly developed DAQ instrumentation [1,5,9].

The subsequent sections explain the basic structure and working of the experimental test rig, fabrication of cost-effective DAQ and methodology of acquiring data, followed by analysis of data acquired and finally comparison of data from the commercial DAQ as well as proposed cost-effective DAQ. The results were repeatable with an accuracy of ±1.5%. This DAQ also has provision to increase to 40 channels for measurement at reasonably lower cost.

2. Methodology

The development of DAQ is a bit time consuming. However, the flexibility to accommodate any number of desired channels at a lower cost offsets this time delay.

2.1 Pressure Distribution

The open-jet test facility at the High-Speed Aerodynamics Laboratory, Indian Institute of Technology, Kanpur, India, basically consists of three two-stage air-cooled reciprocating compressors, of which two are employed at any given time and the third kept as reserve. These compressors can deliver 10 m^3/min of air at a maximum pressure of 20 bar. Each of the compressors is driven by a three-phase induction motor. An air-drier facility is used to remove the moisture from the compressed air and dry air is passed on to the storage tanks. The compressed air is stored in four steel tanks, with a total capacity of approximately 300 m^3.

Air enters the settling chamber through a gate valve followed by a pressure regulating valve and a mixing length of 1 meter and 75 mm diameter. Past the mixing length a wide-angle diffuser is connected to the settling chamber. The settling chamber consists of closely meshed grids to minimize the turbulence in air flow. It has an inner diameter of 300 mm and a length of 600 mm. The test model is fixed at the end of the settling chamber, as shown in Figure 1. The commercial DAQ is highlighted Figure 1 and a clear image is shown in Figure 2.

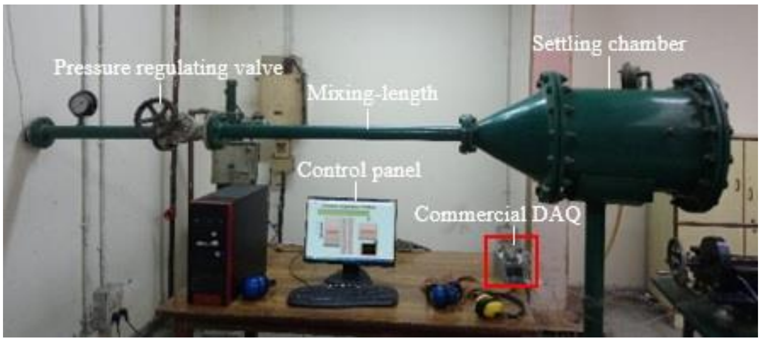


Fig. 1. 75 mm diameter pipe connected from storage tanks, followed by a pressure regulating valve, mixing length, wide-angle diffuser and settling chamber

2.2 Existing DAQ Instrumentation

Pressure Systems NetScanner™ Model 9116 pressure transducer (Figure 2), is a readily available commercial instrumentation interfaced with 802.3 ethernet to the computer [5,9]. This pressure transducer is used for measuring pressure at the base, stagnation pressure in the settling chamber and wall pressure measurements. It has 16 channels and can measure pressures up to 20 bar. The sampling rate is 250 samples per second. LabVIEW™ software is used to interface the transducer with the computer. Of the 16 channels, one channel is used for measuring stagnation pressure P_o in the settling chamber, two channels measure base pressure P_b while the remaining acquire wall pressure P_w measurements.

Fig. 2. Pressure Systems NetScanner™ Model 9116 Pressure Transducer

2.3 Experimental Procedure

The ambient temperature is noted and the pressure in cm of Hg is measured with a Fortin's Mercury Barometer. For these tests, the compressors are run until the storage tanks reach a pressure of 10 bar. A gate valve is used to control the mass flow rate of air into the settling chamber, to provide the required the stagnation pressure (or) nozzle pressure ratio (NPR). NPR is measured by connecting a measuring probe to the DAQ. There is no need for a temperature thermocouple in the settling chamber as no calculations are done using stagnation temperature.

The nozzle is connected to the exit of the settling chamber by a threaded locking mechanism that facilitates easy removal and replacement of the nozzle. The duct is connected to the nozzle using circular flanges on both ends with a groove cut in to fix the O-ring to prevent any leakage of air; the flanges are locked. A pitot probe is positioned at the duct exit to measure pressure loss, as shown in Figure 3. An x-y-z axes traverse mechanism is used to move the probe to the desired location.

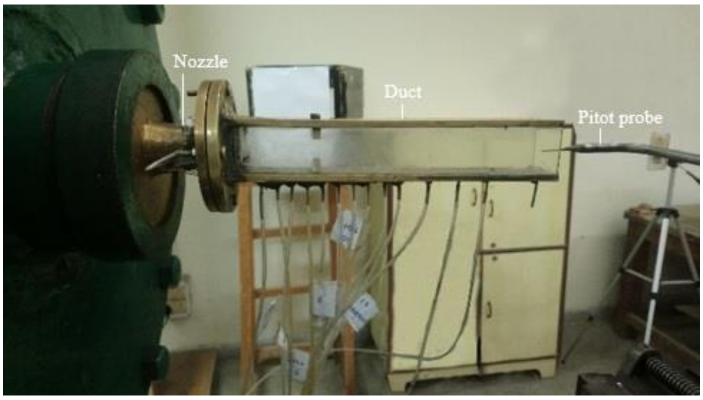


Fig. 3. Nozzle connected to the duct by flanges with a pitot probe at the duct exit, fixed to the traverse mechanism

Apart from convergent nozzles, convergent-divergent (CD) nozzles are designed for specific supersonic Mach numbers and the design calculations are based on normal shock gas tables. Nozzles can be designed as circular for axisymmetric tests while rectangular nozzles are preferred for tests on square or rectangular ducts. Nozzle calibration is to be performed for CD nozzles to obtain the actual Mach number, as compared to that of the design Mach number. Calibration is done by varying the position of pitot probe axially and tangentially, at the nozzle exit. The setup for calibration is shown in Figure 4.

Fig. 4. Nozzle calibration setup

The stagnation pressure P_{01} from settling chamber and nozzle exit pressure P_{02} are measured. P_{01} and P_{02} are divided by atmospheric pressure P_a and P_{02}/P_{01} value is checked with the normal shock gas table ($\gamma = 1.4$) to find the corresponding Mach number for that P_{02}/P_{01} ratio. The data from the DAQ software, which measures gauge pressure, is converted to absolute pressure by adding the ambient pressure of the day. DAQ system is calibrated to zero before starting the runs. Atmospheric pressure and temperature for the day are input to the system for zero calibration. The system considers 1 atm or ambient pressure for the day as zero and the other pressures measured as gauge pressures. For example, to achieve NPR 2 the stagnation pressure P_1 is set at 1 atm instead of 2 atm, as the measured pressure is gauge pressure.

First, the DAQ system is initialized. Next, zero calibration is done followed by creation of two data files to store the data acquired. The DAQ instrumentation can acquire up to 250 samples per second and an average of the values provides the final output. A layout of the DAQ control panel is shown in Figure 5.

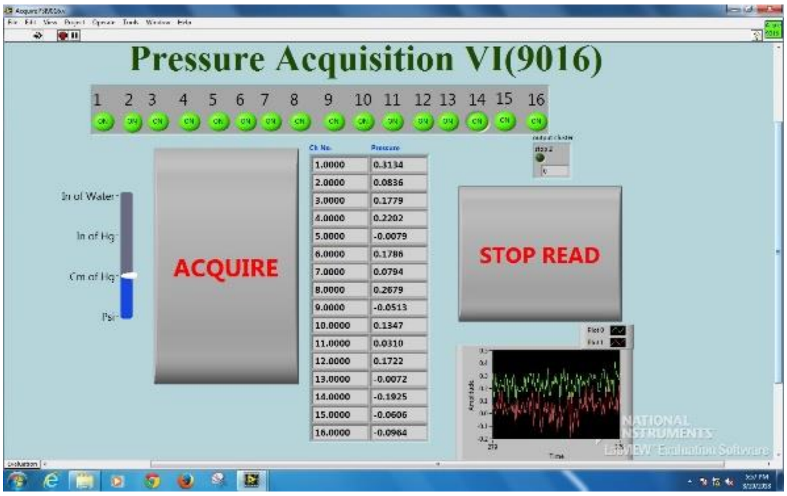


Fig. 5. DAQ control panel

Any channel can be switched on or off depending upon the requirements. All values measured are in gauge pressure. Channel 1 measures stagnation pressure or NPR, channels 2 and 3 measure base pressure P_b while channels 4 to 16 measure wall pressure P_w. The output is obtained in the form of a notepad file, which is converted into an Excel file for easy calculation.

The values obtained are in cm of Hg. The ambient pressure P_a that normally ranges from 74.1 cm of Hg to 74.5 cm of Hg (range obtained during the days of testing), and the values can be divided by P_a to convert the unit to bar for easier understanding of data. A reference table with pressure values in cm of Hg and its equivalent in bar, absolute as well as gauge, is used while performing the runs.

The pressure profile recorded as base pressure and wall pressure are non-dimensionalized by dividing with P_a. The results are plotted as base pressure versus NPR, showing detailed analysis of flow distribution along the base region at varied NPRs. Similarly, wall pressure is plotted versus the axial positions of pressure tapping to understand the fluctuations in wall pressure along the duct for a specific NPR.

3. Proposed Cost-effective DAQ

The cost of a Pressure Systems NetScanner™ Model 9116 pressure transducer is quite high but is a preferred choice due to its high sampling rates of 250 samples per second per channel [5,9]. However, the number of channels is restricted to only 16, which is a limiting factor when it comes to

acquiring data for cases where measurements must be carried out for higher number of locations simultaneously. It is in this context that a different strategy was adopted to counter the cost issue and acquire data from a higher number of channels without compromising data accuracy.
Low-cost, dry-air pressure sensors were chosen as alternates. From the literature it is learnt that the base pressure and wall pressure readings do not exceed 1 bar in most cases [1,5,9], though for a few exceptional cases wall pressure could go up to 1.8 bar [5].

It is with these factors as reference, Honeywell TruStability™ High Accuracy Silicon Ceramic (HSC) Series, Low Pressure Sensors - HSCDANN015PAAA5, HSCDANN030PAAA5 (absolute) and HSCDANN010BGAA5 (gauge) were chosen. HSC Series TruStability® Pressure Sensor, shown in Figure 6 is a piezoresistive silicon pressure sensor offering a ratiometric analog or digital output for reading pressure over the specified full-scale pressure span and temperature range [12]. The sensors have a dual in-line (DIP) package enabling mounting of the sensor on the breadboard.

Fig. 6. HSC Series TruStability® Pressure Sensor, DIP package, AN single-axial, barbed-port, analog output type, 10% to 90% of V_{supply} transfer function, 5V DC supply voltage [12]

The pressure sensors (HSCDANN015PAAA5, HSCDANN030PAAA5 and HSCDANN010BGAA5) are basically eight-pin, single-axial, barbed-port, fixed on the breadboard. The circuit of the sensor is shown in Figure 7. As for the layout of the sensors, pin 2 is for input voltage V_{supply} which is 5V constant, pin 3 is output voltage V_{out} with values ranging from 0.5V to 4.5V, depending upon the output values during the tests, and pin 4 is grounded (GND).

HSCDANN015PAAA5 pressure sensor is capable of measuring up to 1 bar absolute pressure [12], which is sufficient for measuring base pressure as the value does not exceed 1 bar [1,5,9]. In order to measure wall pressure for subsonic and sonic flow conditions pressure sensor HSCDANN015PAAA5 can be used. For supersonic flow conditions, HSCDANN030PAAA5 [12] is preferred as the values might exceed 1 bar [5] and this pressure sensor is capable of measuring pressures up to 2 bar [12]. For measuring NPR, pressure sensor HSCDANN010BGAA5, capable of measuring up to 10 bar [12], is employed.

The output values of all the sensors are in the form of volts V and the transfer function is from 10% to 90% of the total output range (i.e. 0.5V (min) to 4.5V (max)) (Figure 8) [12] and the output voltage is calculated using Eq. (1). For HSCDANN015PAAA5, 0.5V implies 0 bar while 4.5V implies 1 bar. This conversion factor is applied to the pressure values obtained from the tests.

$$Output\ Voltage\ (V) = \frac{0.8\ x\ V_{supply}}{P_{max} - P_{min}}\ x\ \left(P_{applied} - P_{min}\right) + 0.10\ x\ V_{supply} \tag{1}$$

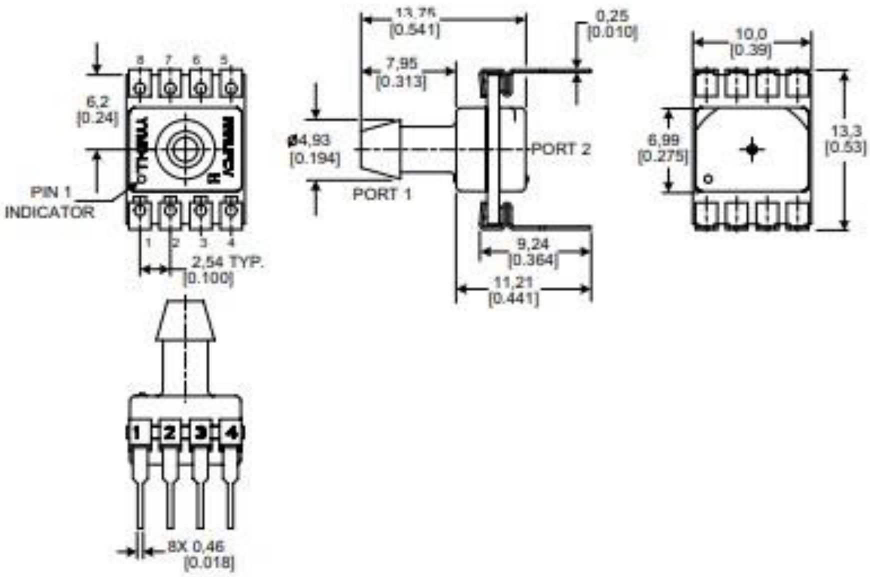


Fig. 7. Circuit diagram [12]

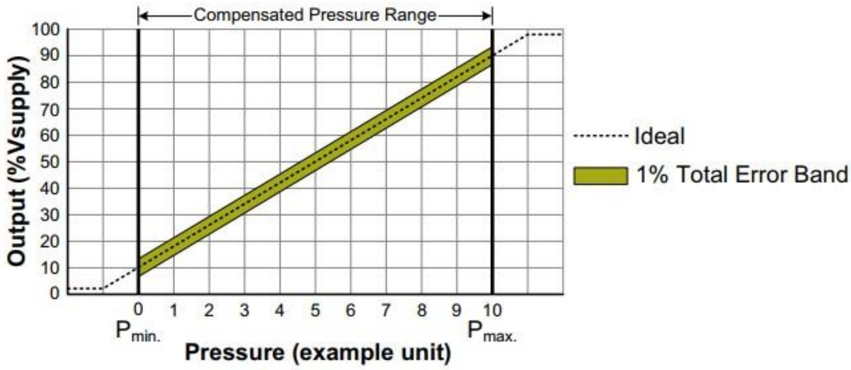


Fig. 8. Output transfer function [12]

Graphtec MIDI GL220, a 20-channel data logger, is used for data acquisition. A layout of pressure sensors fixed on the basic breadboard circuit, with a bus circuit to power the sensors, is shown in Figure 9.

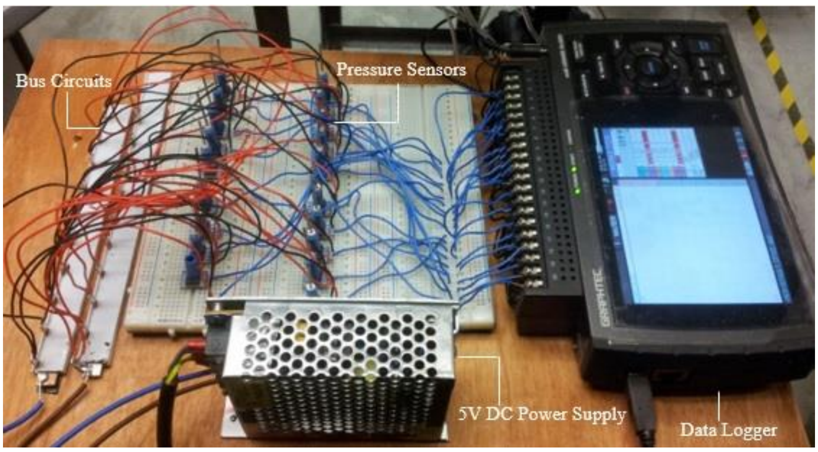


Fig. 9. Cost-effective DAQ instrumentation

The power source is connected to pin 2 of the sensor. Pin 3 is connected to the voltmeter to measure output voltage, while pin 4 is grounded to the power source. An adapter is fixed to the air inlet port of the pressure sensor for measurement of pressure. The sensors are then fixed one by one, evenly, on a breadboard circuit and a bus circuit is employed to supply power uniformly to the sensors. The power supply is denoted by the red colored wires connected to the supply terminal, while the black colored wires denote grounding (Figure 9). A voltmeter is used to check the output power supply of the 5 V DC supply equipment. A similar procedure is followed to check if the value of atmospheric pressure is accurately being captured by the pressure sensors. Atmospheric pressure for the day, initially measured using a Fortin's Barometer, is cross-checked with the data from the pressure sensor.

The data logger can acquire data from 20-channels simultaneously and has a provision to add 20-more channels (if required) which makes it 40 channels in total to acquire data. A storage capacity of up to 2 GB can be added which makes it convenient to conduct multiple runs eliminating the need for an individual to be at the computer to manually monitor and acquire data. Channel 1 of the data logger is connected to the settling chamber to measure gauge pressure, while channels 2, 3 and 4 are used to acquire base pressure P_b measurements. The average of these three channels is used to obtain the actual base pressure value for a given NPR. Channels 5 to 20 are utilized for wall pressure P_w measurements. The rate of data acquisition is enough for simple cases such as suddenly expanded flow through ducts as the flow is stabilized upon exiting the settling chamber and the base pressure and wall pressure values are constant for a fixed NPR, for a given configuration. The output from the data logger is in the form of volts V and can be converted to psi or bar depending upon the convenience for calculations.

Since base pressure and stagnation pressure data are very critical for analysis the accuracy of that data proves to be of vital importance. A device with a higher sampling rate could be considered for the measurement of the above, while a simple data logger like Graphtec MIDI GL220 could be used for wall pressure measurements. The National Instruments NI 9215 (Figure 10) is an analog input module which includes four simultaneously sampled analog input channels, a successive approximation register (SAR) and 16-bit analog-to-digital converters (ADCs). NI 9215 has built-in signal conditioning and can acquire up to ±10V, with an over voltage protection of ±30V available with screw-terminal, spring-terminal or BNC connection types [13].

Fig. 10. NI 9215 DAQ [13]

LabVIEW™ software is configured to act as the DAQ interface to the computer, like the pressure transducer. The output obtained is in the form of voltage in an Excel sheet, like that of Graphtec MIDI GL220 data logger. The DAQ flowchart (Figure 11) and the control panel (Figure 12) are shown below. The process is automated and only a click to start and stop is required to record the data. Control panel shows the pressure variation as voltage V with respect to time and input pressure.

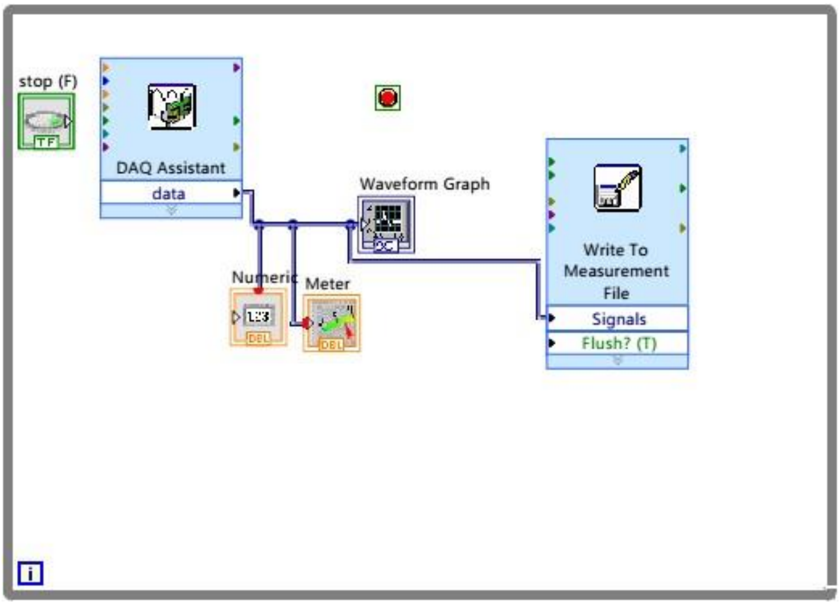


Fig. 11. LabVIEW™ DAQ – Process flowchart

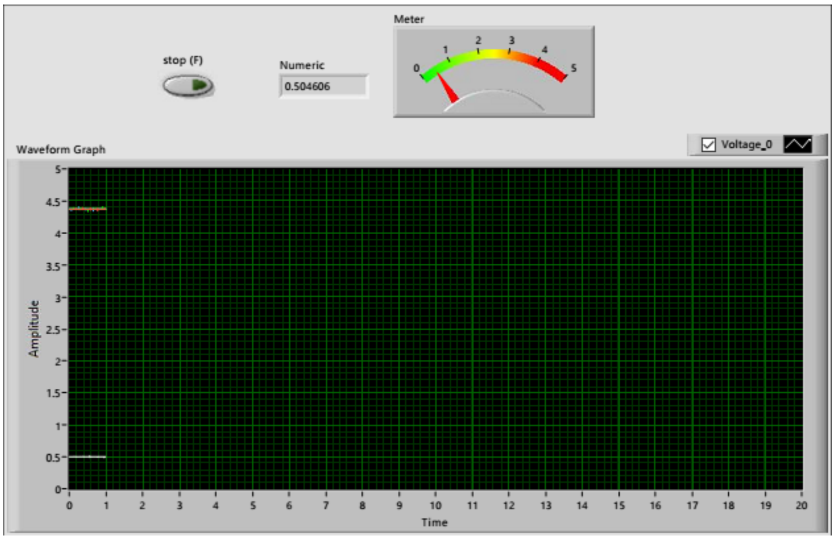


Fig. 12. LabVIEW™ – Control panel for DAQ

4. Comparison of Data from the Two Different DAQs

Base pressure (P_b/P_a) versus nozzle pressure ratio (P_o/P_a) and wall pressure (P_w/P_a) versus pressure tapping location along the length of the duct (x/D) plots have been considered for evaluating the two different DAQs. Repeatability of the results from tests and their accuracy are the assessing factors. The base pressure values against NPR for L/D = 6 obtained from the low-cost DAQ as well as commercially available DAQ is presented in Figure 13 and the numerical data is shown in Table 1. Base pressure decreases with increase in nozzle pressure ratio (P_o/P_a). With decrease in base pressure, turbulence increases paving way for better flow mixing in combustion chambers.

In the case of wall pressure measurements plotted against x/D for a fixed nozzle pressure ratio in Figure 14, continuous increase along the length of the duct is noticed for a given NPR and reaches atmospheric pressure by the time the flow exits the duct. This implies that the length of the duct L/D = 6, is enough for the flow to reattach and stabilize. The numerical data obtained from both the cases are shown in Table 3.

The base pressure and wall pressure values were found to be repeatable upon testing at different times. The trendlines are similar with both the cases, with an average variation of ± 1% for base pressure and ± 1.5% for wall pressure. The error percentage for individual NPRs in the case of base pressure and individual pressure tapping locations for wall pressure are presented in Table 2 and Table 4 respectively.

Table 1
Base pressure data obtained from validation using low-cost DAQ

	1	1.25	1.5	1.75	2	2.26	2.51	2.76	3
P_b/P_a (Commercial DAQ)	0.969	0.887	0.826	0.755	0.713	0.657	0.599	0.549	0.501
P_b/P_a (Fabricated DAQ)	0.963	0.895	0.823	0.762	0.706	0.654	0.604	0.553	0.504

Table 2
Base pressure error percentage (%) – Fabricated DAQ

NPR	1	1.25	1.5	1.75	2	2.26	2.51	2.76	3
P_b/P_a	-0.619	0.902	-0.363	0.927	-0.982	-0.457	0.835	0.729	0.599

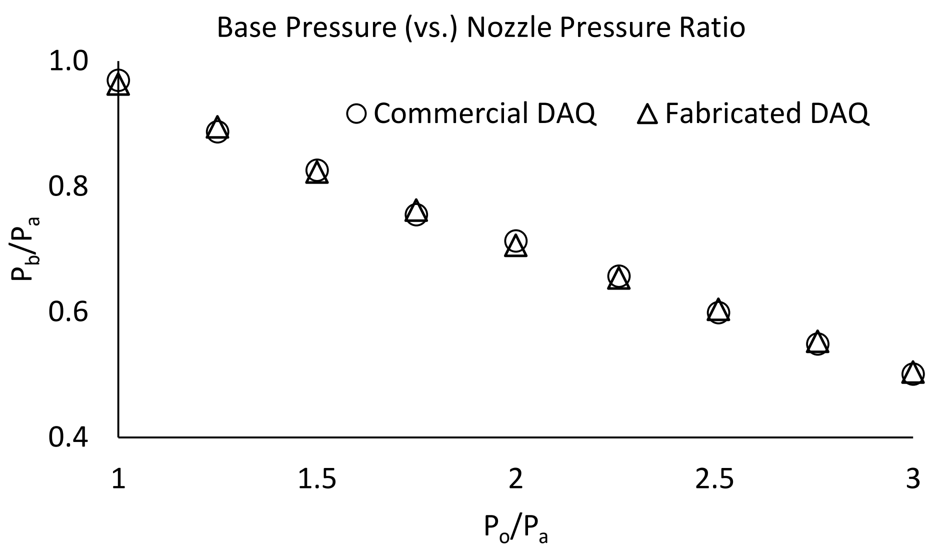


Fig. 13. Base pressure data validation for L/D = 6

Table 3
Wall pressure data obtained from validation using commercial pressure transducer.

x/D	0	0.5	0.6	0.8	1.2	1.6	1.8	2.2	2.5	3
P_w/P_a (Commercial DAQ)	0.706	0.742	0.764	0.757	0.749	0.785	0.795	0.841	0.867	0.913
P_w/P_a (Fabricated DAQ)	0.699	0.748	0.753	0.747	0.754	0.781	0.804	0.843	0.866	0.908

Table 4
Wall pressure error percentage (%) – Fabricated DAQ.

x/D	0	0.5	0.6	0.8	1.2	1.6	1.8	2.2	2.5	3
P_w/P_a	-0.992	0.809	-1.440	-1.321	0.668	-0.510	1.132	0.238	-0.115	-0.548

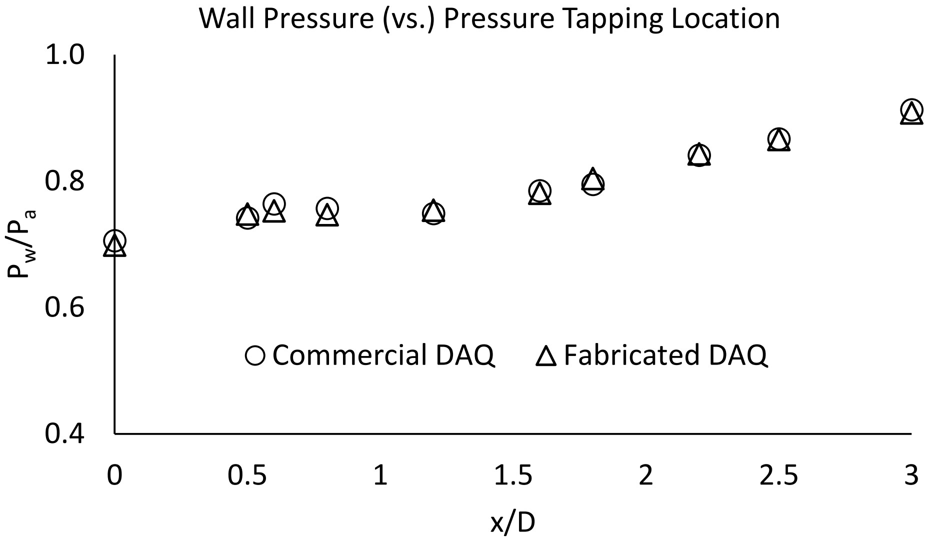


Fig. 14. Wall pressure data validation for L/D = 6

It is hence proven that the proposed DAQ can cater to the requirements of the tests with a variation of ±1% for base pressure and ±1.5% for wall pressure, as compared to that of commercially available DAQ. The cost of a commercially available 16-channel DAQ is approximately RM 90,000, while the 20-channel assembled sensors along with power supply, circuiting, basic data logger would cost approximately RM 8,000. Adding the high sensitivity 4-channel data logger for higher accuracy in the case of base pressure measurements, will incur an addition of up to RM 2,000 per unit. Multiple high sensitivity 4-channel units could also be used instead of basic data logger for acquiring data and in such a case for 20-channel the price would rise to RM 18,000 – 20,000. It should be noted the costing mentioned does not include the cost of LabVIEW™ license and computer.

5. Conclusions

In the case of sudden expansion flow into a duct of larger cross-sectional area, the base pressure variation gradually reduces with increase in NPR. The wall pressure on the other hand shows continuous increase along the length of the duct for a given NPR and reaches atmospheric pressure by the time the flow reaches the duct exit. It has been established in the current work that the two types of DAQ employed in measuring the base and wall pressure variations have very little to choose between them by way of variation in accuracy which is negligible except the cost factor and time involved in fabrication of the fabricated DAQ.

The cost of individually assembled unit along with interface for 20 channels works out to approximately one-fourth of the commercially available pressure transducer and has provision to increase the number of channels at reasonably low additional cost. It is reported that both the instruments viz. readily available commercial pressure transducer and individual pressure sensor units for data acquisition give excellent accuracy and repeatability and could be used at the researcher's discretion depending upon the funds and time available.

Acknowledgements
The authors express their gratitude to Mr. Suresh Mishra, Mr. Shivanshu Shukla, Mr. Mohd. Aqib and Mr. Rohit Panthi for providing support during the experimental runs. Special thanks are due to Mr. Suren Bharadwaj and Dr. Ramgopal Sampath for assisting with the plots and images. We also thank

Prof. Rakesh Kumar for all his valuable help in the execution of this work and Prof. K. Padmanaban for his critical review and feedback on this paper. The authors acknowledge the support provided by RU Grant Universiti Sains Malaysia PAERO/1001/814276 in carrying out this work.

References

[1] Sethuraman, Vigneshvaran, and Sher Afghan Khan. "Effect of sudden expansion for varied area ratios at subsonic and sonic flow regimes." *International Journal of Energy, Environment and Economics* 24, no. 1 (2016): 99-111.

[2] Robert S. Wick. "The effect of boundary layer on sonic flow through an abrupt cross-sectional area change." *Journal of the Aeronautical Sciences* 20, no. 10 (1953): 675-682.

[3] Khan, Sher Afghan, and E. Rathakrishnan. "Control of suddenly expanded flow." *Aircraft Engineering and Aerospace Technology* 78, no. 4 (2006): 293-309.

[4] Khan, Sher Afghan, and Ethirajan Rathakrishnan. "Control of suddenly expanded flows from correctly expanded nozzles." *International Journal of Turbo and Jet Engines* 21, no. 4 (2004): 255-278.

[5] Sethuraman, Vigneshvaran, and Sher Afghan Khan. "Base pressure control using micro-jets in supersonic flow regimes." *International Journal of Aviation, Aeronautics, and Aerospace*5, no. 1 (2018): 1-24

[6] Rathakrishnan, E., O. V. Ramanaraju, and K. Padmanaban. "Influence of cavities on suddenly expanded flow field." *Mechanics research communications* 16, no. 3 (1989): 139-146.

[7] Pandey, Krishna Murari, and E. Rathakrishnan. "Influence of cavities on flow development in sudden expansion." *International Journal of Turbo and Jet Engines* 23, no. 2 (2006): 97-112.

[8] Rathakrishnan, E. "Effect of ribs on suddenly expanded flows." *AIAA journal* 39, no. 7 (2001): 1402-1404.

[9] Vijayaraja, K., C. Senthilkumar, S. Elangovan, and E. Rathakrishnan. "Base Pressure Control with Annular Ribs." *International Journal of Turbo & Jet-Engines* 31, no. 2 (2014): 111-118.

[10] Chen, Lin, Keisuke Asai, Taku Nonomura, Guannan Xi, and Tianshu Liu. "A review of Backward-Facing Step (BFS) flow mechanisms, heat transfer and control." *Thermal Science and Engineering Progress* 6 (2018): 194-216.

[11] Montazer, Elham, Hooman Yarmand, Erfan Salami, Mohd Ridha Muhamad, S. N. Kazi, and A. Badarudin. "A brief review study of flow phenomena over a backward-facing step and its optimization." *Renewable and Sustainable Energy Reviews* 82 (2018): 994-1005.

[12] Honeywell. "TruStability® Board Mount Pressure Sensors." (2014) https://sensing.honeywell.com/honeywell-sensing-trustability-hsc-series-high-accuracy-board-mount-pressure-sensors-50099148-a-en.pdf.

[13] Instruments, National. "NI 9215 Datasheet." (2016) http://www.ni.com/pdf/manuals/373779a_02.pdf.

[14] Sethuraman, Vigneshvaran, and Sher Afghan Khan. "Effect of sudden expansion for varied area ratios at subsonic and sonic flow regimes." *International Journal of Energy, Environment and Economics* 24, no. 1 (2016): 99.

[15] Vijayaraja, K. "Effect of rib on suddenly expanded supersonic flow." (2009).

[16] Pathan, Khizar Ahmed, Prakash S. Dabeer, and Sher Afghan Khan. "Investigation of Base Pressure Variations in Internal and External Suddenly Expanded Flows using CFD analysis." *CFD Letters* 11, no.4 (2019): 32-40.

[17] Pathan, Khizar Ahmed, Prakash S. Dabeer, and Sher Afghan Khan. " Influence of Expansion Level on Base Pressure and Reattachment Length. " *CFD Letters* 11, no.5 (2019): 22-36.

[18] Khan, Sher Afghan, Abdul Aabid, Fharukh Ahmed Mehaboobali Ghasi, Abdulrahman Abdullah, Al-Robaian, and Ali Sulaiman Alsagri. "Analysis of Area Ratio In a CD Nozzle with Suddenly Expanded Duct Using CFD Method. " *CFD Letters* 11, no.5 (2019): 61–71.

[19] Isa, N Mat, A F Ab Rahman, and A Sadikin. "Numerical Simulation of Splitting Devices in Horizontal Pipeline Akademia Baru." *Journal of Advanced Research in Applied Mechanics* 5, no. 1 (2015): 8–14.

[20] Jehad, D G, G A Hashim, A K Zarzoor, and C S Nor Azwadi. "Numerical Study of Turbulent Flow over Backward-Facing Step with Different Turbulence Models." *Advanced Research Design* 4, no. 1 (2015): 20–27.

[21] Ny, G Y, N H Barom, S M Noraziman, and S T Yeow. "Numerical Study on Turbulent-Forced Convective Heat Transfer of Ag/Heg Water Nanofluid in Pipe." *Journal of Advanced Research in Materials Science* 22, no. 1 (2016): 11–27.

[22] Razali, A A, and A Sadikin. "A CFD Simulation Study on Pressure Drop and Velocity across Single Flow Microchannel Heat Sink." *Journal of Advanced Research Design* 8, no. 1 (2015): 12–21.

[23] Yamin, E S Abdull, and C S Nor Azwadi. "Prediction of Fluid Flow in Artificial Cancellous." *Journal of Advanced Research in Materials Science* 3, no. 1 (2014): 8–14.

[24] Zainal, S, C Tan, C J Sian, and T J Siang. "ANSYS Simulation for Ag/HEG Hybrid Nanofluid in Turbulent Circular Pipe." *Journal of Advanced Research in Applied Mechanics* 23, no. 1 (2016): 20–35.