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UNPREDICTED BEHAVIOUR OF VENTURI FLOWMETER IN GAS AT HIGH REYNOLDS NUMBERS

by

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SUMMARY

A Venturi flowmeter is expected to produce a discharge coefficient of less than unity. Laboratory work at NEL, for Shell Expro, on a series of 150 mm (6 inch) diameter Venturi flowmeters, has resulted in discharge coefficients of several percentage points higher than predicted, according to ISO 5167-1; 1991. This work was performed in high pressure air up to 70 bar, Reynolds Numbers up to 8×10^6 and throat velocities up to 125 m/s. Calibration work previously undertaken with the same Venturi flowmeters in water, at lower Reynolds numbers, resulted in behaviour as expected with discharge coefficients near 0.9950.

The paper describes the laboratory investigation that was undertaken to determine the apparent source of error with a view to providing a straightforward solution.

The NEL high pressure recirculating loop facility was utilised, with a reference mass flowrate traceable to the UK Primary Standard Gravimetric facility. Brief details are included on integrity checks performed on the loop and its instrumentation.

Observations during testing are discussed, for example the audible whistle that occurred for certain flow conditions and the significance of throat velocity as a parameter to describe the flowmeter behaviour. The paper explains the justification for the various differential pressure tapping modifications made during the investigation.

This investigation into Venturi flowmeter behaviour has shown some surprising phenomena which, as yet, have not been fully explained. With the increased interest of the oil and gas industry in using Venturi meters in their own right and as part of multiphase flow metering systems, further work is essential to clarify these phenomena.

1 INTRODUCTION

This paper is a follow up to "High accuracy wet gas metering" presented in the 1993 North Sea Flow Metering Workshop[1]. A High accuracy metering system for wet gas was described using Venturis as the primary elements and making corrections based on the Murdock equation[2] for the relatively low quantities of liquid (less than 1 per cent by volume) that would be experienced in the application under consideration. It is worthwhile noting here that for higher liquid contents, Chisholm's equation[3,4] is better as it can cope with changes in pressure, whereas Murdock's equation is pressure independent.

The installation for which this system was designed is now installed, with start-up scheduled for the fourth quarter of 1996. The aim was to provide a metering system with overall accuracy close to that for gas fiscal metering systems. The Venturi meters will be operating at Reynolds Numbers in the range 10^6 to 10^7, above the upper range limit of 10^6 stated in ISO 5167-1[5] for machined Venturi meters. To keep things simple, Shell Expro wanted to modify the standard Venturi design as little as possible. The only modification that was introduced was to use a single tapping at upstream and throat tapping positions instead of the four tapping points, joined by a piezometer ring called for in ISO 5167-1. Shell Expro had accepted that the Venturi meters should be calibrated with liquid and gas to give baseline discharge coefficients. A test separator is installed on the facility, so there was the capability of comparing the flowline meters with the test separator meters to monitor for possible shifts in the discharge coefficients.

For various reasons the Venturi meters (6 flowline + 1 test separator gas meter) were a critical item on the fabrication plan for the facility. Calibration had to be performed quickly, and NEL was best able to carry out both sets of calibrations. The liquid calibrations, on water, went well with all discharge coefficients falling well within a ±1 per cent range centred on 0.995. However, when calibrations on high pressure air were attempted, things went drastically wrong. The first three meters to be calibrated showed high discharge coefficients between about 1.02 and 1.04, with significant variations depending on flowrate. The magnitude of these shifts came as a complete surprise to both Shell Expro and NEL. From Shell Expro's point of view, the reason for calibrating was to confirm that there would not be significant shifts and to confirm the view of other experts who had been consulted that the discharge coefficients of Venturi meters would be around 0.995 at higher Reynolds Numbers. It was evident that if the effects were indeed real and unpredictable, the whole basis on which the facility had been designed was in jeopardy.

We describe the programme of tests undertaken to quantify the problem and to establish whether a practical solution was possible. We relate this more or less as it happened, and hope to indicate the surprise, mounting concern and finally the relief that an acceptable solution was available. We have not tied up all the loose ends. There are many issues concerning the use of Venturis on high pressure gas that are not yet settled.

2 THE PROBLEM EMERGES

Calibrations of the seven Venturis were carried out in the water calibration facility at NEL. The results of these tests were in accordance with ISO 5167-1. Everything appeared to be going well. The Venturis were then transferred to the high pressure gas rig at NEL. This facility was commissioned in 1993 and uses air as the working medium. Pressure in the loop is supplied via compressors, and a high pressure blower circulates the gas between 10 and 70 bar. The flowrate reference is a gas turbine meter calibrated against the Gravimetric primary standard. The differential pressures on the Venturis were measured initially using Rosemount 1151 DP transmitters. After three Venturis had been calibrated, and all three had shown high discharge coefficients, it was clear that something was wrong. Also with the third Venturi, above a critical flowrate a loud whistle could be heard, and this was associated with a step in the discharge coefficient.

What was wrong? Was it the calibration rig? This particular rig had been troublesome since it had been built, and immediately it became a prime suspect. Was it the Venturis? All participants began asking their contacts if similar behaviour had been observed elsewhere. Where did the whistle come from? The noise pervaded the test hall and its source was not at all obvious. There was intense concern by the Shell Expro project team responsible for the facility, as there was a real possibility that the Venturi based metering system would not be viable and there was no real alternative. The only other meters that could reasonably be considered would be orifice meters, and these had been rejected early on. It was considered that the performance of orifice meters installed close to the wellhead would be poor because sand would degrade the sharp edge. Liquids can build up behind the plate, and it is difficult to guarantee that a drain hole in the orifice would remain clear.

3 TESTS PERFORMED

3.1 Confirmation of Problem

The first thing to be done was to find out whether the apparent problem lay with the Venturis or with the NEL facilities. Before calibrating the meters on water, NEL had inspected the seven Venturis carefully, and had removed burrs from the inner edges of the tappings. NEL also carried out an independent metrology of three of the Venturis. This agreed closely with that of the manufacturer. Visual inspection of the Venturis gave rise to some misgivings. The Venturis were made from three sections of Duplex Stainless steel welded together. One of the welds was at the entrance to the convergent section, the other weld was about half way along the divergent section. The surface finish across these weld areas appeared variable, but not so that the Venturis could be rejected. Apart from the single upstream and downstream tappings, the meters were manufactured in accordance with ISO 5167-1.

The Venturi flowmeters include approximately 7D of upstream straight bore. There was a further 30D upstream of this in the test loop. There was no evidence of flow disturbance, including swirl, upstream of the Venturi or reference turbine meter.

One of the Venturis was taken from the high pressure test rig to the Gravimetric rig. Similar results were obtained to those on the high pressure rig, strengthening the view that the high pressure rig was not the source of the problem.

Although all of the instrumentation used was governed by NAMAS procedures for calibration and storage, all of the other instrumentation on the rig was fully checked out. The calibration of the reference turbine meter in the high pressure rig was also checked against the secondary standard sonic nozzles, themselves calibrated against the Gravimetric rig. Its performance was within the range of its last full calibration. The Rosemount DP cells had shown significant zero drift during the first calibrations and were replaced with Mensor DPGII differential pressure gauges rated at 2 and 10 bar.

NEL looked back in their records and found an example of a Venturi nozzle calibrated on water that had shown a step change in discharge coefficient associated with a whistle. Shell Expro had discussed the matter again with metering specialists, and there were stories of Venturis that had had unexpectedly high discharge coefficients.

Thus there was good reason to believe that the problem lay in the meter and not in the NEL test facility. Shell Expro now commissioned a test programme to determine the origin of the problem and to find a solution that would involve as little modification to the Venturis as possible. The time scale demands of the overall Shell Expro project dictated the investigation objectives, and the frequency of reporting. Essentially this investigation was divided into three phases of about ten days, each culminating in a progress meeting at NEL involving NEL, Shell Expro and the metering contractor for the project.

3.2 First Phase

An important detail to be resolved was the source of the audible whistle, as there was still the possibility that this was coming from the test facility. A piece of straight pipe was installed in the rig instead of the Venturi. No whistle could be heard over the whole flow range. Next, it was important to establish the influence of the impulse lines on the whistle. The Venturi which showed the loud whistle and the highest discharge coefficient was reinstalled in the test rig with blanking flanges on the pressure tappings, i.e. without the impulse lines. The whistle was thought to be related to the total volume of the tapping chamber, and removing the impulse lines should show some effect. On flowing gas, the whistle was very much present and thought to be louder for certain flow conditions. A clear plastic tubing was inserted into both upstream and downstream pressure tapping chambers to change the volume of the chamber. The whistle disappeared. The tests were repeated with the impulse lines attached to allow discharge coefficients to be determined. Although the whistle was suppressed, the discharge coefficients remained high. It was clear that the source of the whistle was the Venturi itself, but that it was not directly related to the high values of discharge coefficient observed.

The next stage of phase 1 was to install a different Venturi flowmeter in the test facility and observe the result. Shell Expro had commissioned other work on Venturi meters at NEL which required three 150 mm nominal bore Venturis manufactured in full accordance with ISO 5167-1 with β 0.4, 0.6 and 0.75. The β 0.4 Venturi (for convenience referred to as the research Venturi) was closely comparable to the seven project Venturis (β 0.41). Three of the upstream and throat tappings of the research Venturi were blanked off and a calibration chart was made. Fig 1 shows a step change of about 1 per cent midway across the Re_D range at 3.5 x 10^6, from 1.003 to 1.011. An audible whistle also started at this step. It was believed that the acoustic effects in the tapping chamber could be responsible for the step change and the whistle, so attempts were made to modify the throat tapping chamber to try to eliminate the step. Inserts were made to block up the three redundant throat tappings and were fitted as accurately as possible in the limited time available. A disc drilled with a 0.5 mm hole was fitted in the fourth tapping chamber to act as a dampener for the pressure signal. The discharge coefficient lay between 0.994 and 1.004 as shown in Fig 2. For the first time, discharge coefficients less that unity had been observed, in line with ISO 5167-1.

Buoyed up by this apparent success, the next step was to try to repeat this in the project Venturi, which had different shapes of tapping chambers to the research Venturis. The obvious way to modify the effect of the tapping chamber was to fill the volume. Accordingly inserts were made that filled both tapping chambers, paying attention that they did not protrude into the flow. Carefully cut channels were made on the inserts to allow the pressure signals through. The discharge coefficients measured with this set up were very high, about 1.09, to the disappointment of all. Completion of the tests with inserts that filled each tapping chamber produced variable results and was clearly leading nowhere. This design idea was dropped.

3.3 Second Phase

The second phase of the work started with further effort aimed at attempting to duplicate the pressure tapping arrangement of the research Venturi on the project Venturi. This entailed installation of a drilled disc within the base of the larger upper pressure tapping chamber to simulate the damping effect that had been successful with the research Venturi. The discs were located in both the upstream and throat tappings with hole diameters ranging from 0.5 - 2 mm for separate tests. Because the lengths of the lower sections of the tapping chambers were different between the project and research Venturis, efforts were made to locate a 0.5 mm diameter hole within the lower section of the tapping of the project Venturi. On testing, the discharge coefficients were essentially unchanged and remained high. However, one odd result occurred with 1 mm diameter hole discs where the discharge coefficient decreased to near unity for a small part of the Reynolds number range. The calibration chart is shown in Fig 3; the pressure tapping modification is shown in Fig 4. The abrupt step between high and low discharge coefficient was uncanny and could not be explained. With insufficient time to explore an idea that was unlikely to provide a solution, the modification design was abandoned. Next, it was thought best to decrease the diameter of the pressure tapping at the Venturi internal surface; the region in contact with the flowing gas.

Whilst new pressure tapping modification parts were fabricated, the time was spent investigating acoustic effects within the tapping chambers and impulse lines. It was thought that the acoustic study might provide an insight into the problem. An industrial silencer was fitted at various locations within the throat pressure tapping impulse line, but without changing the high discharge coefficient. Fluidborne noise was also investigated using two piezo-electric pressure transducers fitted at connections normally used for pressure measurement. One of the connections was located close to the throat of the Venturi and the other at the differential pressure sensor. Fig 5 shows pressure ratio plotted against frequency for a throat tapping test performed at 20 bar with a volume flowrate of 600 m^3/hr [pressure ratio defined as throat versus sensor pressure]. Large differences resulted between the noise seen at opposite ends of the impulse line. This was due primarily to standing wave effects in the sensing line but it showed that large variations also existed at frequencies as low as 30 Hz. The conclusion from this work was that a more thorough investigation of the underlying causes was required, which could not be performed at this time.

3.4 Third Phase

Pressure tapping inserts were installed that essentially decreased the diameter of the pressure tapping at the Venturi internal wall surface from 6 mm diameter to both 3 and 4 mm. This configuration was similar to that of the research Venturi which had a 4 mm diameter. The initial tests produced discharge coefficient values ranging from 0.97 - 0.91. This *was* less than unity but something was obviously wrong. It was thought that during the fitting of these pressure tapping inserts there was a risk that the ends of the inserts were located beyond the internal Venturi wall surface; sticking into the flowing gas stream. On inspection, it was estimated that the throat insert did extend into the Venturi area by 0.5 mm. This further illustrated the extreme sensitivity of the Venturi pressure tapping.

Further modification was made to the pressure tapping inserts in order to ensure that they did not protrude into the Venturi throat area. These new inserts were assembled and inspected prior to pressurisation. The results of these tests are shown in Fig 6, with the corresponding pressure tapping modification shown in Fig 7. It can clearly be seen that real values of low discharge coefficient, with minimal scatter resulted, similar to that obtained for the research Venturi. It was therefore, sensible to conclude that these pressure tapping inserts did not protrude into the Venturi throat area. This was the target that was set at the beginning of the investigation. The problem remained that the effect caused by the Venturi tapping insert was not fully understood and the investigation had demonstrated extreme sensitivity of Venturi pressure tapping alterations. It was concluded that the use of inserts could provide a solution, but that it was not practical to extend the idea to the full metering system.

It was known from the investigation to date that the performance of the Venturi had been repeatable. Shell instructed NEL to establish the repeatability and reproducibility for the project Venturi and the best way in which the data could be presented. Fig 8, a chart of discharge coefficient against pipe Reynolds number, depicts the data collected. A degree of scatter of the order 1.5 per cent existed when the data was represented by Reynolds number, as shown in Fig 8, with no relationship apparent. When the same data was plotted against volumetric flowrate, as shown in Fig 9, the data aligned to produce a trend proportional to volumetric flowrate (or line or throat gas velocity) and independent of line pressure, with scatter less than 0.5 per cent. This relationship could be described mathematically meaning the Venturi, despite having high values of discharge coefficient, could be used in a repeatable manner.

A large quantity of data had been collected for the project Venturi and this was plotted against volumetric flowrate on one chart and is shown in Fig 10. It can clearly be seen that the trend described above existed for the full data set. The shape of the relationship, with a cusp at a volume flowrate of approximately 400 m^3/hr [or throat velocity of 50 m/s], cannot be explained at this time. For completeness, Fig 11 shows the same full data set for the project Venturi plotted against pipe Reynolds number. No apparent relationship exists.

It was decided at this point that the Venturi flowmeter could be reliably calibrated, with a method available for describing performance, for use as intended offshore. Each Venturi was calibrated over the full range and a curve fit produced which would ultimately be used in the field. Fig 12 shows the data collected for the project Venturi with the curve fit, made up of two parts as explained later in the paper, superimposed.

3.5 CFD work

Shell Expro had commissioned NEL to carry out some computational fluid dynamics (CFD) work on Venturi meters. The main objective of this work was to investigate the sensitivity of the discharge coefficient of a Venturi to variations in its critical dimensions and surface roughness. If this sensitivity was small and predictable, then it should be possible to define the accuracy of a Venturi meter from its manufacturing tolerances, and eliminate the need to calibrate Venturi meters empirically.

Interesting results that were difficult to interpret were being obtained from this project just before the high discharge coefficients were discovered. From the computations of flow through a Venturi, profiles (e.g. velocity, pressure, turbulence etc.) were obtained. Spikes were observed in all the profiles close to the pipe wall along the length of the Venturi. These spikes occurred at the intersections of the Venturi sections; in particular at the intersection of the conical convergent and the throat and at the intersection of the throat and the conical divergent sections. These spiky profiles do not just occur along the pipe wall but persist into the flow and decay with distance from the pipe wall; at the centreline all profiles are smooth and there are no spikes. Even when the radius of curvature at these intersections was increased to 15 mm, the maximum permitted by ISO 5167-1, the spikes were still present. The most interesting of these profiles is the static pressure profile at the wall (Fig 13) where, for a Venturi with diameter ratio 0.4, the static pressure at the intersection of the convergent and the throat sections is 41% lower than that at the throat tapping position (centre of the throat section). At 0.25d upstream of the throat tapping position the static pressure has decreased by only 1.2%; this indicates that the positioning of the throat tapping is not critical.

Fig 14 shows the results of a computation for a Venturi of diameter ratio 0.4. It gives turbulent kinetic energy which relates to the fluctuation velocity in the flow. As the flow enters the throat section the turbulence in the centre of the pipe increases to forty times that which would be expected in fully developed flow; the turbulence at the throat tapping is also at a similar level. It indicates that the throat region is one of intense disturbance; it may not be the best place to try to make sensitive measurements.

Rough pipe computations were performed for Venturi meters with a pipe diameter of 0.154 m, Reynolds number of 2×10^7 and a diameter ratio of 0.75. The surface finish of the Venturi in some cases has a significant influence on the discharge coefficient. Certainly a very rough Venturi (roughness criterion, $R_a = 25\ \mu m$) can cause a negative shift in discharge coefficient of the order of 1% compared to that of a smooth Venturi. For a surface finish close to the maximum permissible in ISO 5167-1 ($R_a = 0.8\ \mu m$ for the entrance, the convergent and the throat sections and 3.2 μm elsewhere) the computed change in discharge coefficient from that computed for a smooth Venturi was -0.2%. It is clear from these results that pipe roughness effects cannot account for the high discharge coefficients observed in the experimental tests.

4 THE SOLUTION

From the foregoing, once it was clear that the discharge coefficient was a repeatable function of line or throat velocity, and was independent of line pressure, a solution to Shell Expro's immediate problem was available that would not involve modifying the Venturis. Although it is possible to consider tuning the discharge coefficient by inserting inserts into the tapping chambers, Shell Expro considered that this was not practical, as accurate positioning of such inserts would be critical.

The solution chosen was to calibrate the Venturis on high pressure gas at a number of flowrates and find best fit relations between discharge coefficient and flowrate for each Venturi meter. In practice, this was not simple. For some of the meters it was not possible to find a single equation to fit the data. This is best illustrated by the meter on which most of the test data was gathered, shown in Fig 12. At about the flowrate at which the Venturi began to whistle, there appears to be a cusp in the relation between discharge coefficient and flowrate. We decided to fit two curves, one covering the low flowrates and the other the high flowrates. This was also done for some of the other meters.

To enter the data into the stream flow computers, a selection of points from the fitted curves was made and their co-ordinates entered. The flow computer then made an iterative straight line interpolation between the entered points to determine the discharge coefficient and corresponding flowrate from the measured differential pressure.

Recall that the flowline meters could be checked against the test separator meters. In the original scheme of things, Shell Expro did not want to compare the flowline meters with a meter working on a different principle, so a Venturi meter was also installed on the test separator outlet. When the Venturis were shown to be meters whose performance depended on an empirical calibration, it was considered prudent to install a different type of meter on the test separator. The choice was between a multipath ultrasonic meter and an orifice meter. The ultrasonic meter was chosen. It was only slightly more expensive, as an orifice meter would have meant increasing the line diameter. The ultrasonic meter offered greater tolerance to liquid carry over, better diagnostic capability and expected lower maintenance.

5 DISCUSSION

As can be seen from the foregoing, the image that has been building up of a Venturi meter as a simple, robust and highly accurate device is somewhat tarnished. Venturis have became attractive as metering devices because it is reasonable to install them with minimal straight length requirements close to wellheads where they will encounter multiphase fluids, sand, and debris. They are being used as an essential component of some multiphase flowmeters. We can reasonably expect them not to be damaged by these in the way an orifice plate would be. The availability of high precision DP sensors mean that a turndown in flow of close to 10 to 1 is realistic with good accuracy. We had hoped that over a few years experience would show that we could predict the discharge coefficient of a Venturi quite accurately from its dimensions and the manufacturing tolerances. It is evident that this is no longer possible: out of seven nominally identical Venturis we have had a range of discharge coefficients up to 4 per cent high and with a spread of about 3 per cent.

We also showed that by modifying the tapping chambers we could shift the discharge coefficient by ± 10 per cent. Although the modifications that resulted in these shifts were fairly extreme (i.e. tapping chambers almost completely filled leading to + 10 per cent, and protrusions into the throat leading to -10 per cent) it is not unrealistic to expect build up of deposits in the tapping chamber, or round the tapping point into the throat, leading to shifts of 1 per cent or so.

The whole issue of acoustics in the tapping chamber and impulse lines has not been investigated in any detail. We were thankful enough that for our application we had an empirical solution that allowed us to achieve our accuracy requirements without too much modification of the system.

In practice, Venturis for applications such as ours will be sized with low values of β, essentially to give good metering capability over as long a period as possible without changing out the Venturis. This means that with line velocities of 15 m/s, throat velocity is about 90 m/s or 300 km/hr! We have also shown that the throat is an area of extreme turbulence and not the best conditions in which to try to make sensitive and accurate measurements.

Notwithstanding the above, the Venturi is still a very practical device if its limitations are borne in mind. It is not the highly accurate dream solution we had been looking for, but it does offer reasonable accuracy. Indeed if one simply looks at the spread of our data per Venturi, they fall within a 2 per cent range, which is what ISO 5167-1 permits. However, it cannot be used on high pressure gas without calibration.

As Venturis are of interest to several operators, it is worthwhile investigating Venturi performance further on a Joint Industry basis. However the first steps should be to carry out a thorough literature study to find out what really was known about Venturis before they slipped into obscurity.

6 CONCLUSIONS

Venturi meters designed and manufactured to ISO 5167-1 and calibrated on high pressure gas at high Reynolds Numbers show discharge coefficients several percentage points higher than predicted. The project Venturi, the one on which the majority of tests were performed, was shown to produce repeatable and reproducible results independent of line pressure, which could be described mathematically. The other Venturis followed the same pattern. The discharge coefficient is best represented as a function of throat or line velocity (or volumetric flowrate). The relationship between discharge coefficient and throat velocity resulted in a cusp at about 50 m/s which could not be explained.

Both research and project Venturis were sensitive to modification to the pressure tappings. The discharge coefficient is particularly sensitive to changes in the tapping chamber volume (+ 10 per cent) and on small tapping protrusions into the flowing gas stream (- 10 per cent).

When attempting to duplicate the pressure tapping configuration of the research Venturi on the project Venturi, it was possible to reduce the discharge coefficient to near unity. Although this was the investigation aim, the problem remained that the effects caused by Venturi tapping inserts were not fully understood. It was concluded that it was not practical to extend the idea to the offshore metering system.

Preliminary investigations demonstrated that there were intense acoustic effects in the pressure tapping chambers. Evidently, further study is required to quantify this effect.

Venturi meters are not simple, predictable devices with inherent high accuracy when used on high pressure gas. Further research will be required to establish clearly their limitations and applicability for the future. It is likely that the optimum way forward is with a Joint Industry programme, as Venturi flowmeters are of interest to several operators.

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FIGURES

Fig. 1 Calibration of research Venturi with single pressure tappings

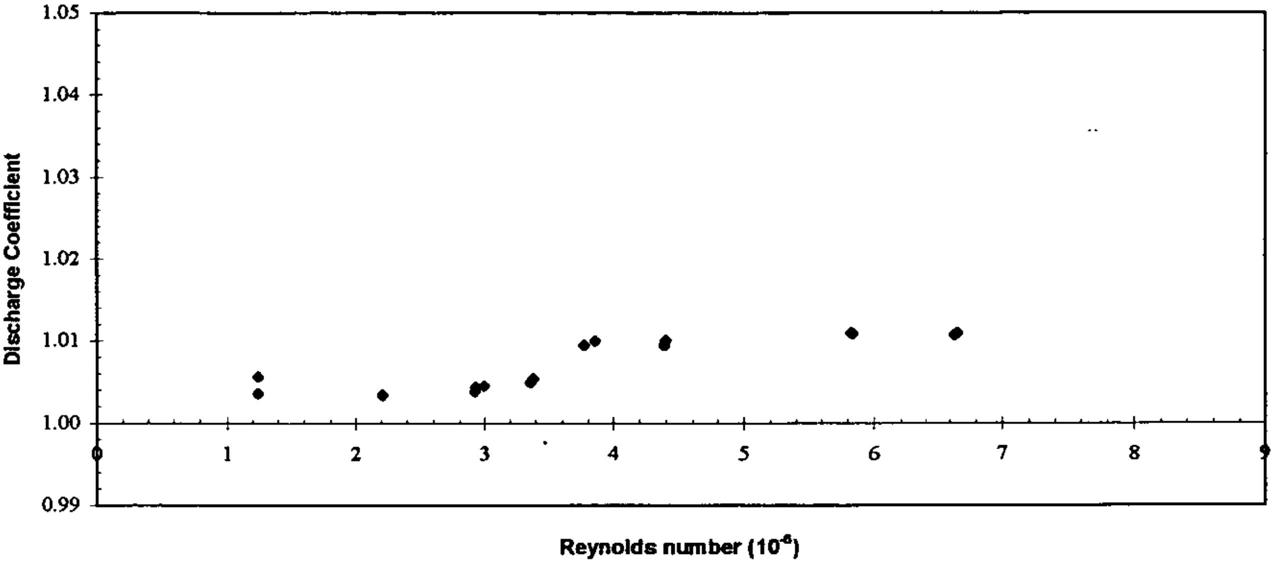


Fig. 2 Calibration of research Venturi with plugs in redundant throat tappings and discs in used tappings

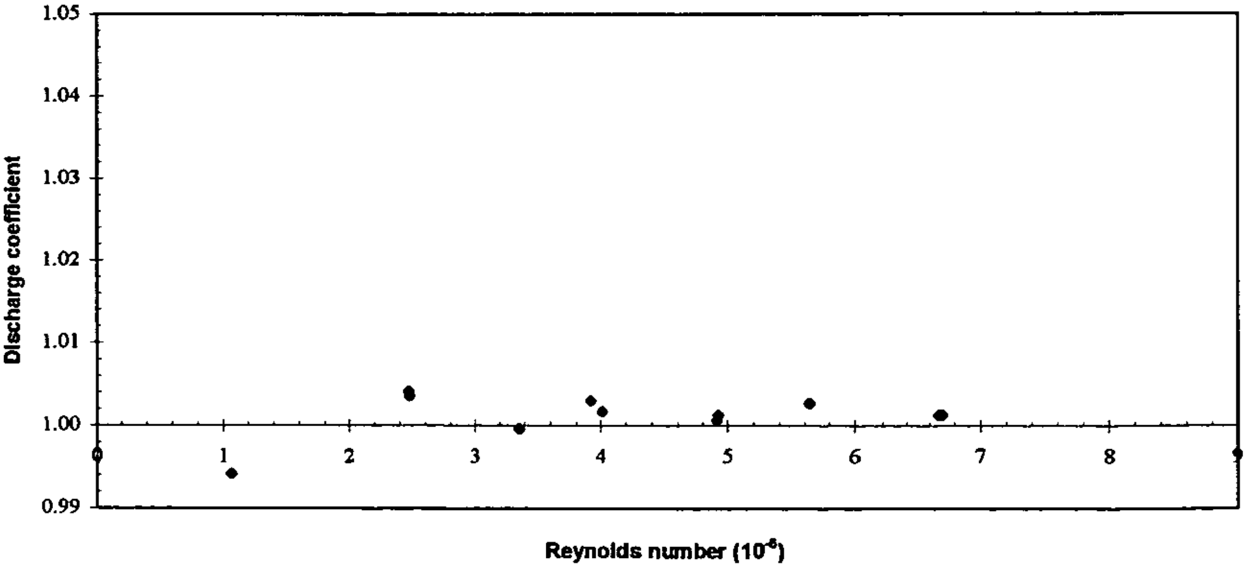


Fig. 3 Calibration of project Venturi with 1mm hole discs and metal tube

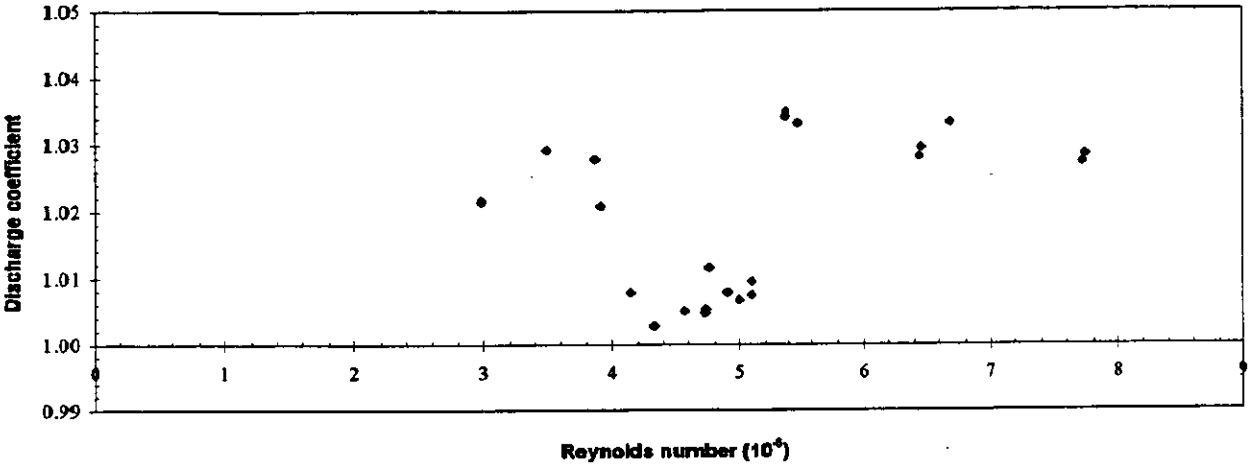


Fig. 4 Drilled disc located in major pressure tapping chamber of project Venturi

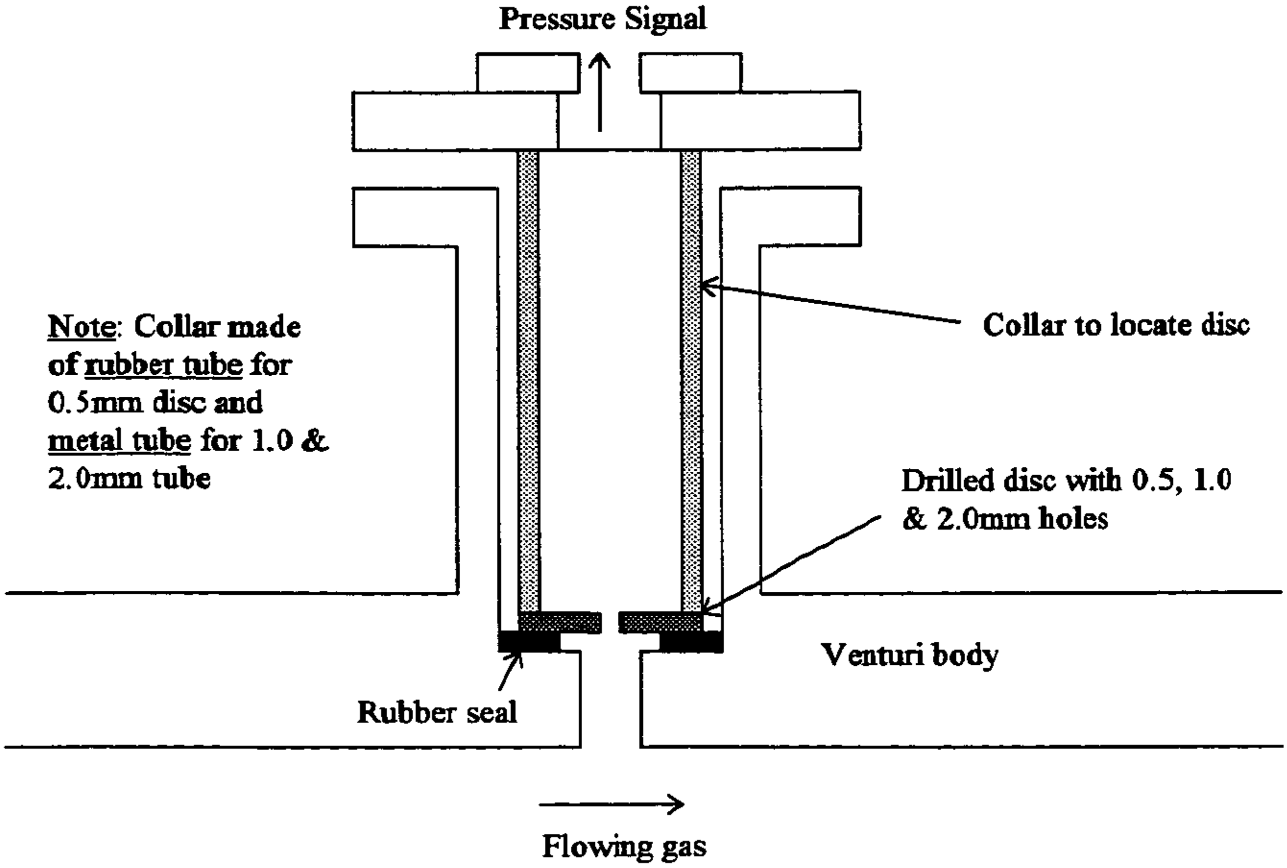


Fig. 5 Pressure ratio between throat and sensor ($600m^3/hr$, 20 bar)

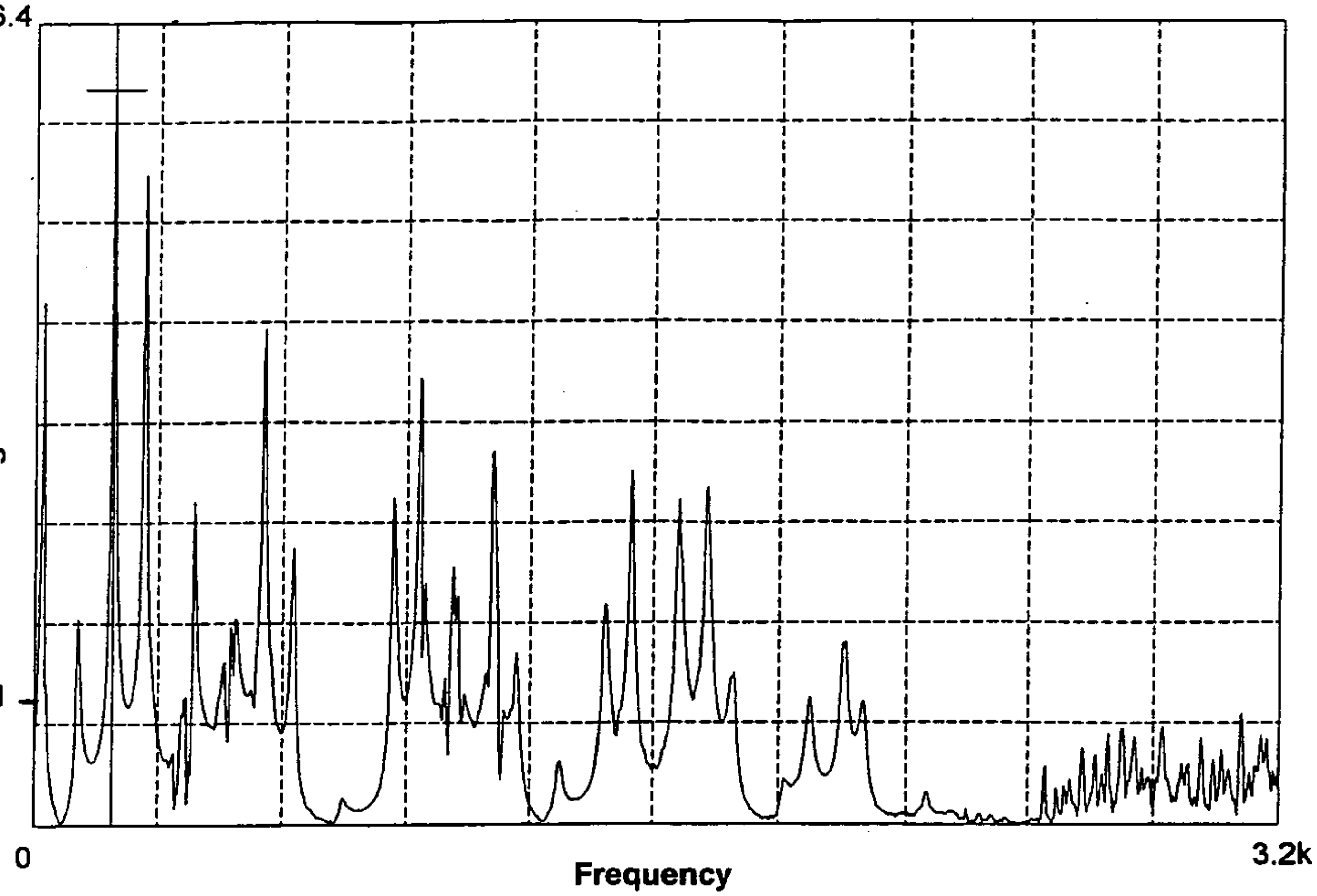
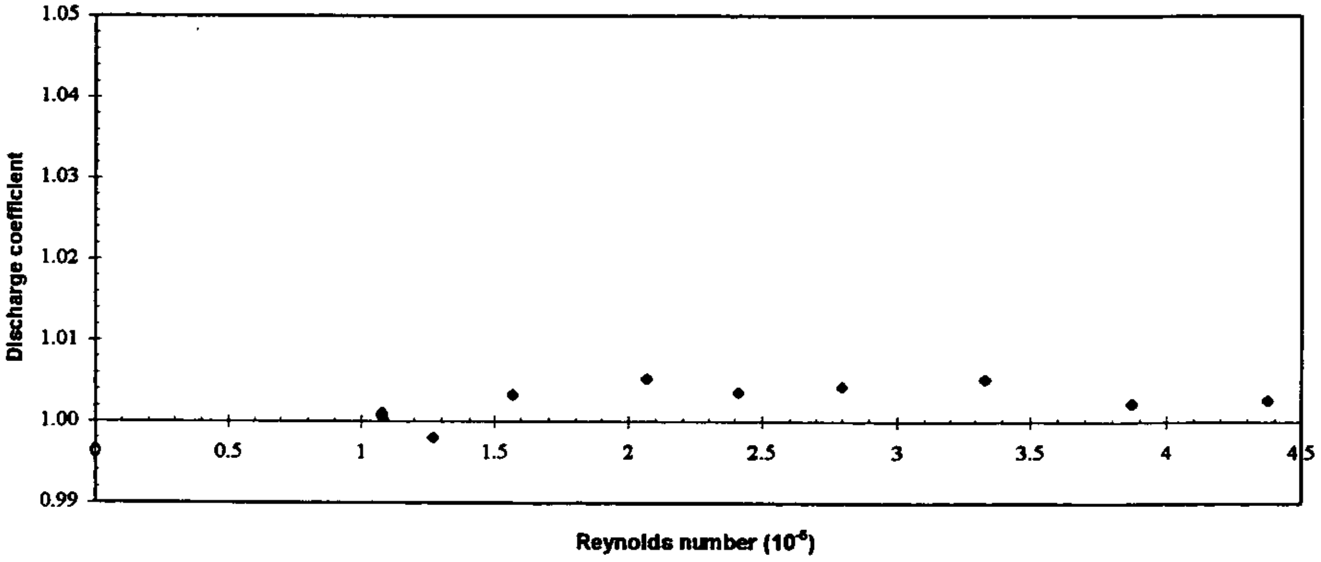
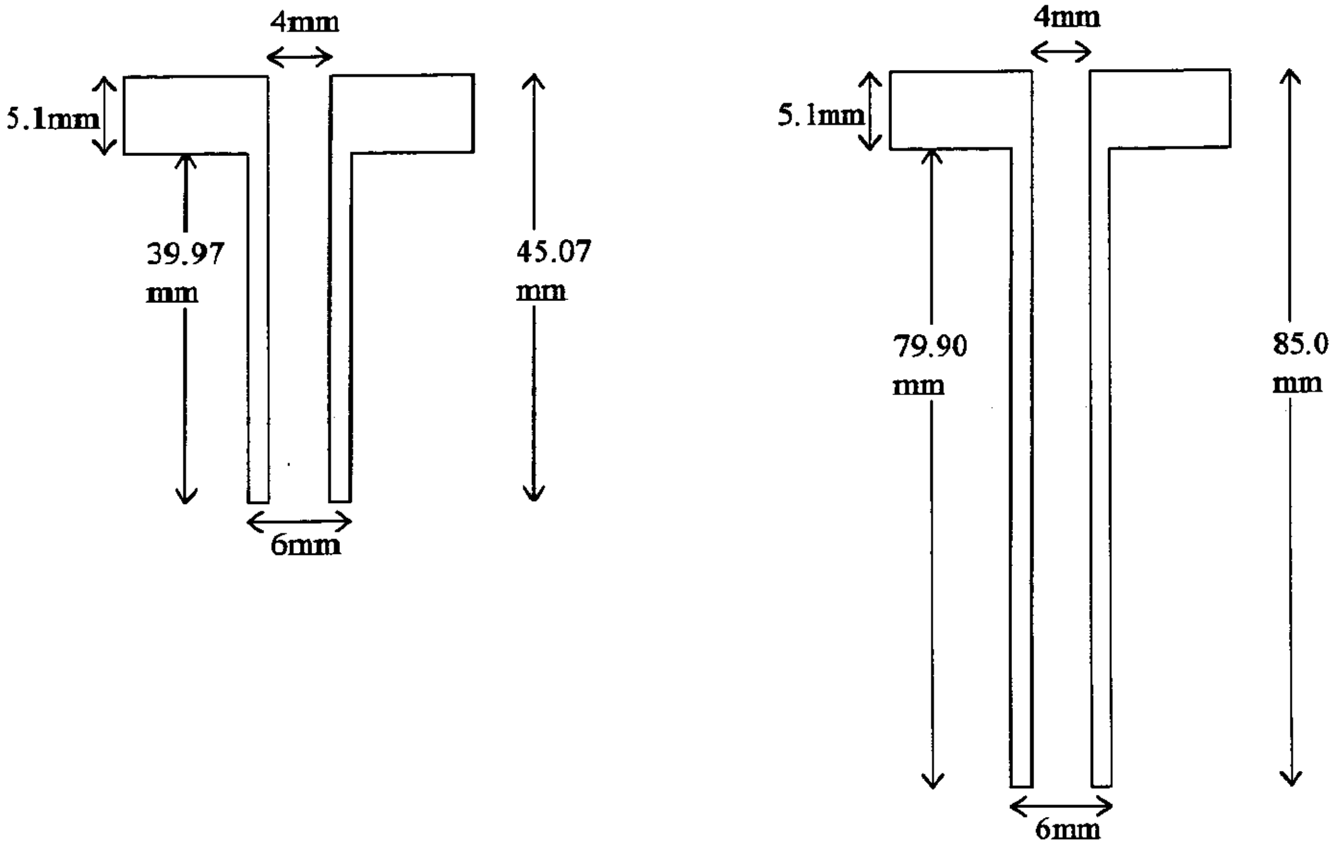


Fig. 6 Calibration of project Venturi with modified 4mm neck inserts





UPSTREAM DOWNSTREAM

GENERAL INFORMATION

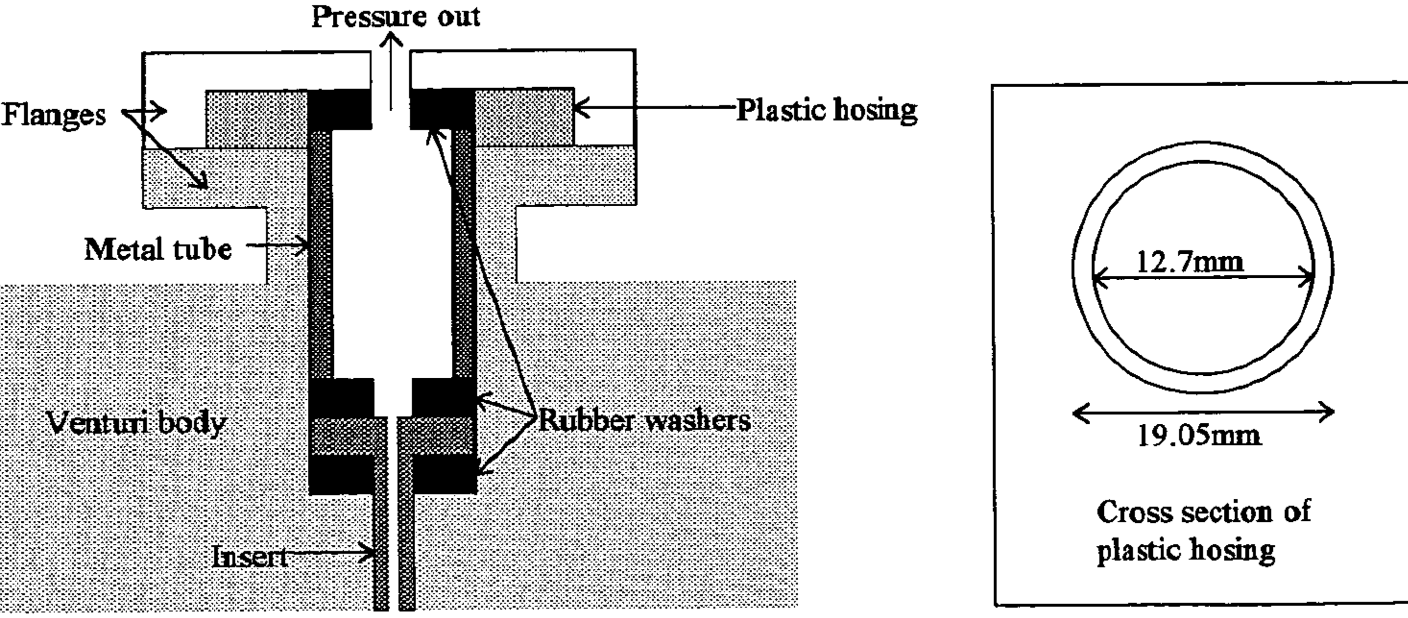


Fig. 7 Inserts reducing the 6mm pressure tapping bore to 4mm

Fig. 8 Calibration of project Venturi to assess repeatability and reproducibility

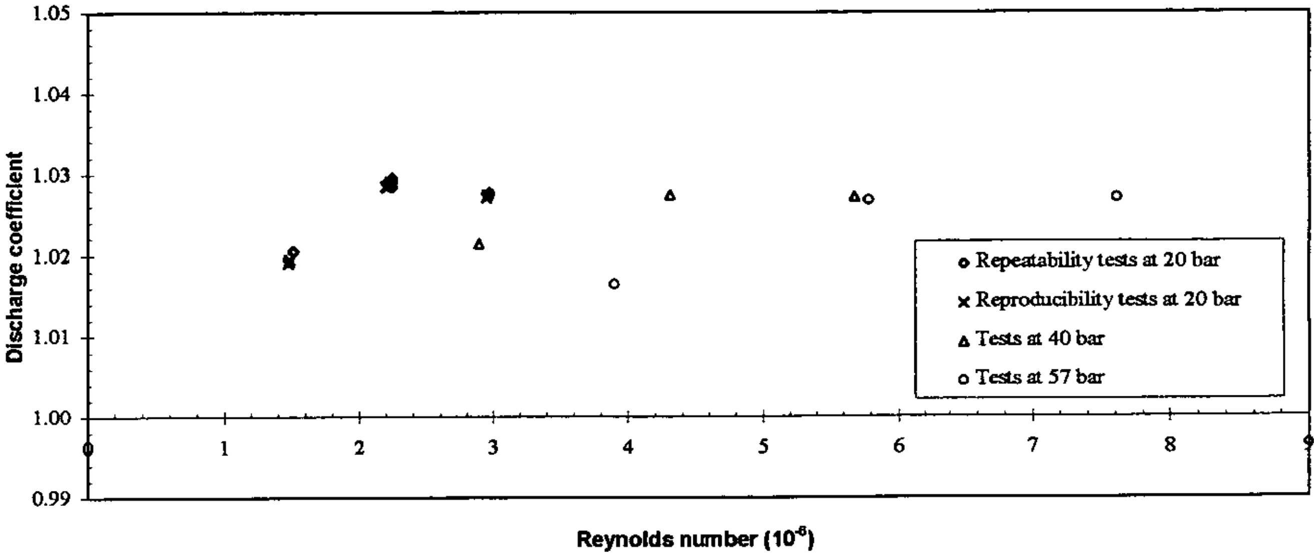


Fig. 9 Calibration of project Venturi with volumetric flowrate

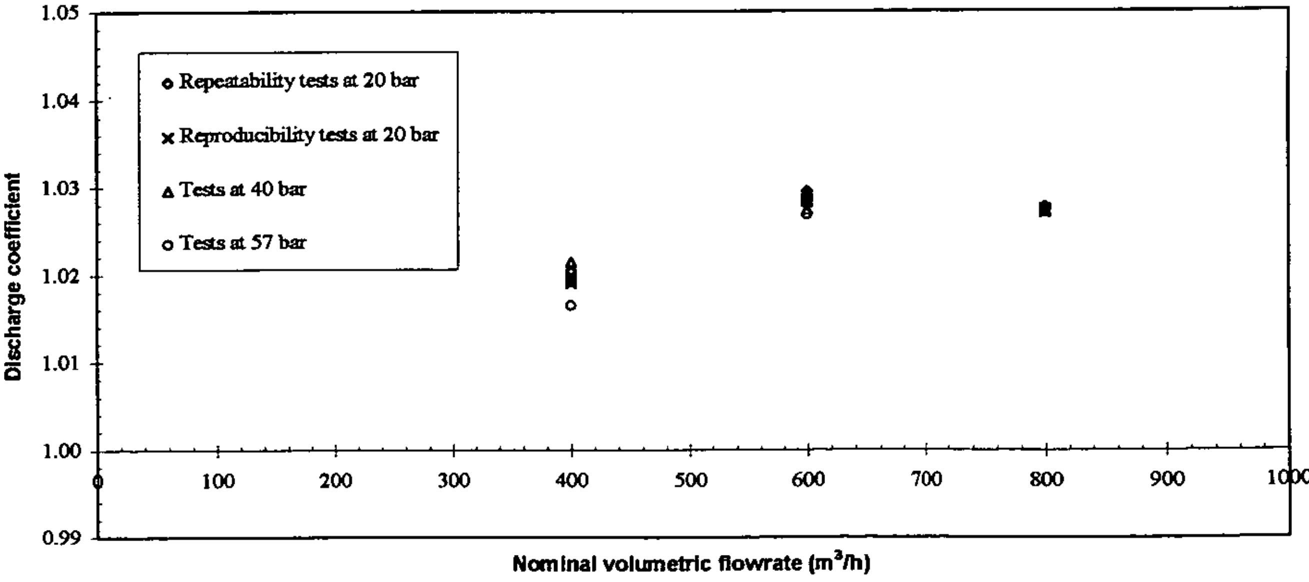


Fig. 10 Calibration of project Venturi with volumetric flowrate

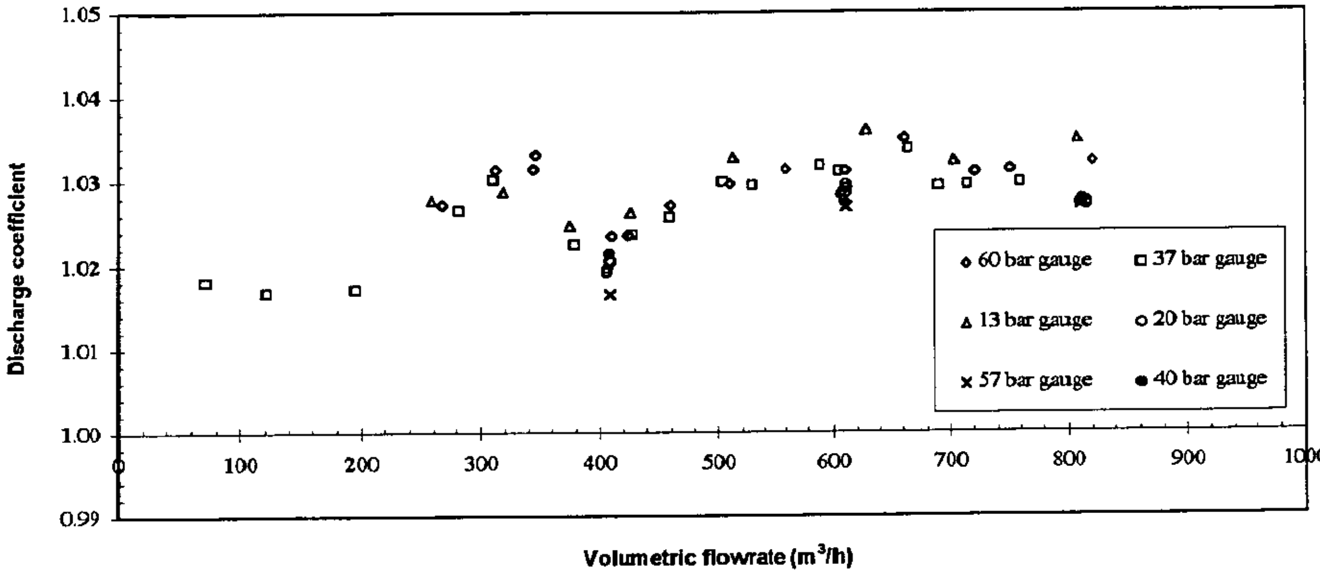


Fig. 11 Calibration of project Venturi with pipe Reynolds number

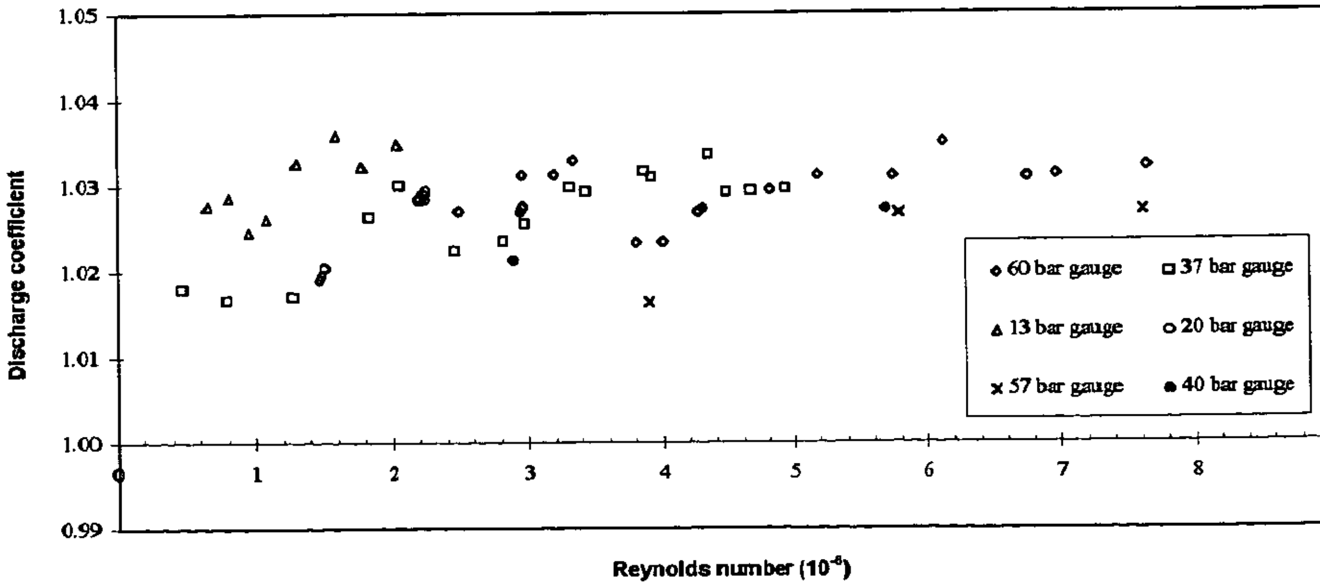


Fig.12 Calibration of project Venturi with curve fits

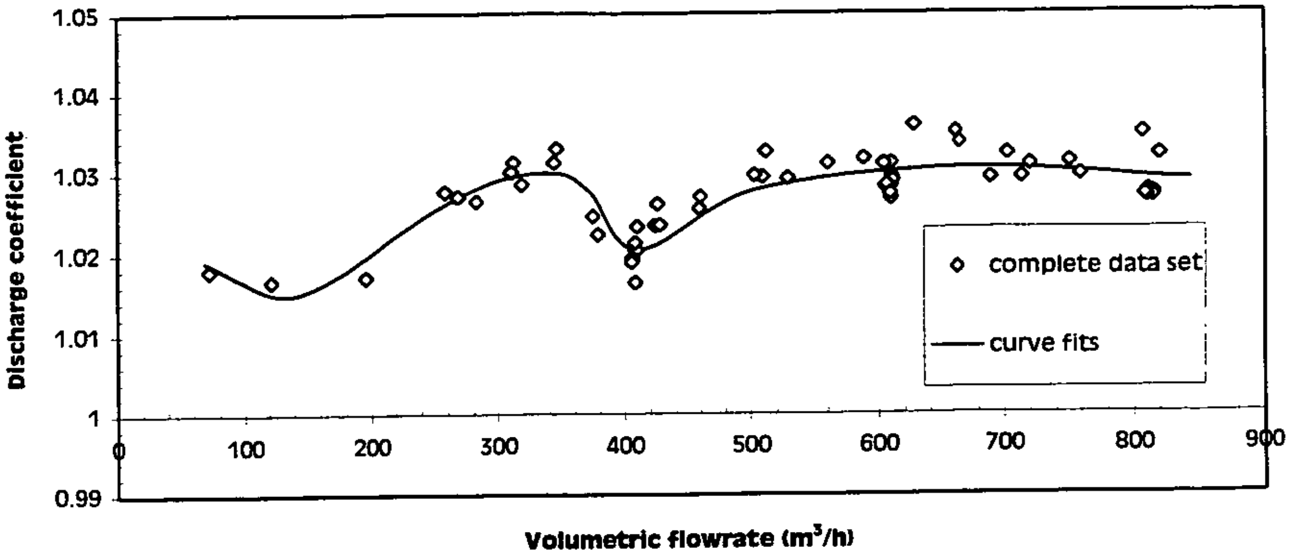
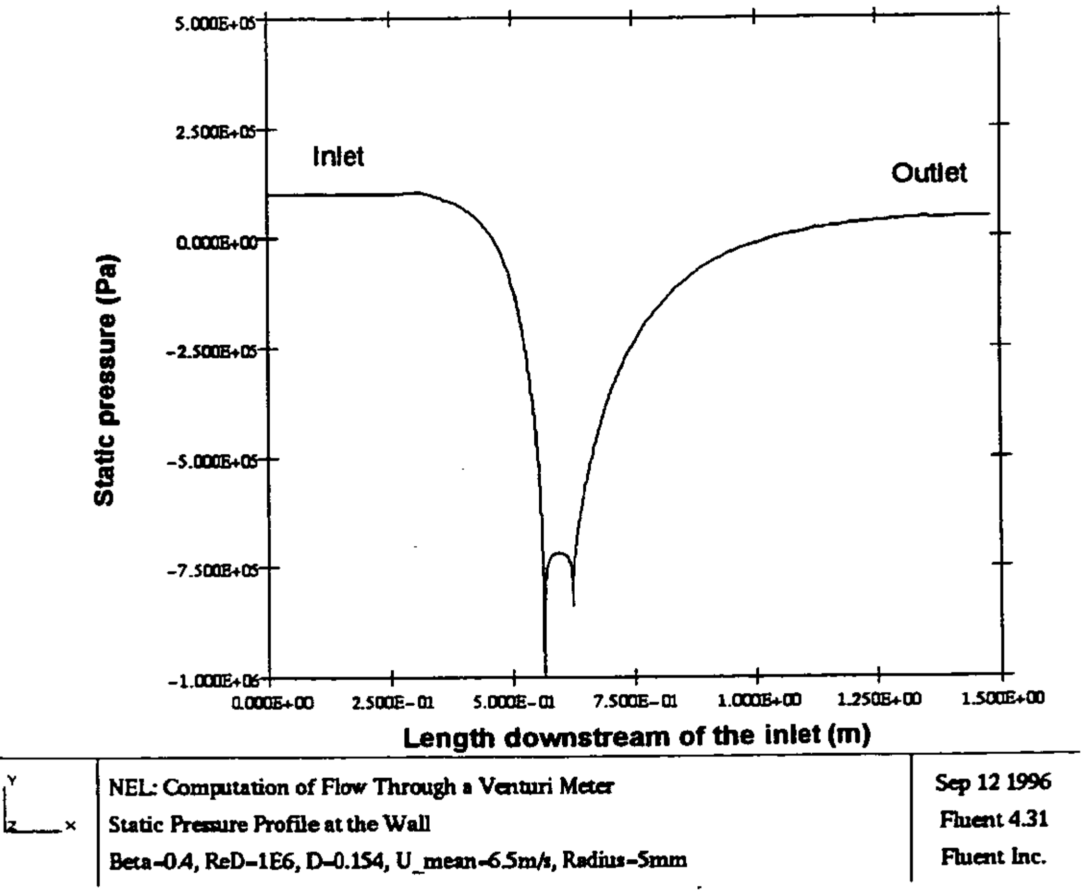


Fig. 13 Profile of static pressure along the length of the Venturi



NEL: Computation of Flow Through a Venturi Meter
Static Pressure Profile at the Wall
Beta=0.4, ReD=1E6, D=0.154, U_mean=6.5m/s, Radius=5mm

Sep 12 1996
Fluent 4.31
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Fig. 14 Contours of turbulence in the throat region of the Venturi