# PERFORMANCE OF ORIFICE METERS IN INSTALLATIONS WITH HEADERS

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## Abstract

Headers commonly used in multirun meter stations can generate a variety of flow profile distortions influencing the measurement error of orifice meters. The experiments conducted at the low pressure air test facility at NOVA Research & Technology Centre covered a range of header configurations used in various meter station designs. The upstream piping configuration included a straight inflow pipe, a single elbow and two elbows in perpendicular planes in two orientations. It was found that some changes in flow configuration through the header and meter runs, as well as modifications to the geometrical dimensions of the header, can result in significant flow measurement errors up to 4.3%. There are some header configurations which provide error free operation of orifice meters. The finding validates concerns that the header effect depends on a particular geometry being used and is difficult for an up front assessment at the design stage.

## Introduction

The flow range of a typical standard orifice meter does not exceed 3:1 ratio unless the flow meter extends operation to high differential pressures and special differential pressure transmitters are being applied. The practical limit of gas flows measured by a single orifice meter is dictated by the levels of acceptable pressure losses as well as available sizes of industrial orifice fittings, which seldom exceed 0.600 m (24 inches). The practicality of orifice meters larger than 0.750 m is questionable. Similar practical size limitations apply to other technologies such as multipath ultrasonic flow meters.

Therefore, multirun meter stations with headers are commonly used in large pipeline applications. Typical design consists of a header located below the ground supplied from the mainline through an expander frequently preceded by an elbow. The parallel meter runs are above the ground level and are connected to the common header through elbows preceded by vertical or 45° slanted risers. An orifice meter station with six parallel meter runs can easily measure flows as low as one eighteenth of the maximum station capacity.

Designers and users of multirun meter stations with headers are concerned about distortions of velocity profiles generated by the headers and an unequal flow distribution among all meter runs (run hogging). This concern is valid for any bare tube installations with orifice or ultrasonic flow meters.

The problem of the non-uniform velocity profile is caused by the three dimensional change in flow direction similar to those observed in the combination of two 90° elbows in perpendicular planes. The resulting velocity profile is non-symmetrical with stronger swirl component than 15 to 18 degree swirl angle observed in closely coupled two elbows in perpendicular planes [1] [2]. An additional factor, which may contribute to the generation of strong swirl, is a flow separation on one side of an expander at the entrance to the header. It was observed [3] that a combination of an elbow with a downstream expander generated "tumbling" flow in the attached meter run with swirl angles up to 10 degrees.

The magnitude of a swirl angle generated and resulting flow measurement error strongly depends on the header geometrical layout. High-pressure natural gas tests [4] of orifice meter performance downstream of a header performed by Ruhrgas indicated positive bias up to ±0.6% at $\beta$-ratio 0.57 and distance between the header and orifice meter 35 pipe diameters long.

An additional low pressure air study [5] sponsored by the same company evaluated velocity profile distortions along two different header configurations and in some of five meter runs. In the first header configuration the inlet pipe had the same diameter as the header and therefore the inlet flow was swirl free. The only source of swirl was a combination of an entrance Tee to the riser and of a 90° elbow at the entrance to the meter run. Flows with swirl angles in excess of 2 degrees were measured at 62 meter run diameters $D_{MR}$ downstream of risers 3.7 and 6 $D_{MR}$ high and no swirl was detected for the risers 8 and 10 $D_{MR}$ high.

The second tested header configuration consisted of two closely coupled 90° elbows in perpendicular planes located at the entrance to the same diameter header. The clockwise swirl entering this header propagated freely into the meter runs. The combination of inlet Tee from the header and of the 90° elbow at the top of 10 $D_{MR}$ high riser generated negligible anti-clockwise swirl (too long riser/"spacer") to reduce the swirling inlet flow. It should be noted that the inlet swirl intensity can be amplified by the reduction in the cross-sectional area between the header and meter run.

The results of Ruhrgas tests show that the inlet swirl generated e.g. by two elbows out of plane can easily propagate along the installation and influence orifice meter performance. Moreover, underground headers with risers shorter than 6 meter run diameters can generate strong swirl. A combination of a Tee on the top of the header, short riser and the 90° elbow leading to the meter run acts like two 90° elbows in perpendicular planes.

Unfortunately the study did not provide more comprehensive swirl angle measurements and associated flow rate measurement errors at shorter meter run length that 62 $D_{MR}$ as well as was limited in the investigations of interactions between the inlet swirl and swirl generated in short risers.

The complexity of the interaction between the inlet swirl and new swirl generated by the combination of header Tee, riser and the elbow was discovered at high pressure natural gas tests [6] at NOVA. Two header configurations with two-meter runs each were tested. The first configuration had a single 90° elbow followed by an expander from 0.102m to 0.15m, which was header diameter. The riser from the header to the meter run was 10 $D_{MR}$ long. The test results confirmed previous observations [5] that in the case of a long riser the last elbow determines character of velocity profile distortion (Dean vortices). The effect of the inlet elbow/expander combination was negligible contrary to other studies [3].

The second header configuration had a very short (2.8 $D_{MR}$) riser from the header to the 90° elbow preceding meter run and two closely coupled (2.6 $D_{inlet}$ spacer) 90° elbows in perpendicular planes at the entrance to the header. Both piping configurations can generate swirling flow in counter-clockwise direction. Surprisingly, measurement of the swirl angle in the meter run has shown that the swirl with 29° angle was turning clockwise. Killing the inlet swirl with a tube bundle located downstream of two elbows reinstated a counter clockwise swirl direction in the meter run as expected from the header Tee/riser/elbow configuration. The conducted CFD simulation of header flows indicates that one of the factors influencing unexpected swirl direction in the meter run is the tangential velocity component in the swirling flow in the header. It hits the trailing edge of the Tee and generates a new clockwise swirl in the riser.

Similar magnitude of swirl angles (up to 30°) was measured in headers on the air test facility at NEL. Some of the results obtained by a private consortium were made available to the public [7]. Only one of four tested header configurations generated strong swirl and orifice meter measurement errors up to 4.2% at meter run length 29$D_{MR}$. None of the tested headers contained risers and the configuration generating high swirl had inlet piping connected to the header in such a way that it resembled two elbows out of plane with 2.9$D_{header}$ spacer preceded by U-configuration of elbows ("goose neck").

Another header installation without risers [8] [9] was applied to the three run ultrasonic meter station. In order to reduce inlet swirl the header was of the same diameter as the inlet piping, which did not have any elbows. Practically the header was created from the final piece of pipeline.

Such an unusual header diameter and configuration required addressing the second concern of designers and users of meter stations namely the uneven flow distribution between the meter runs. The old rule of thumb required that the ratio of the header cross-sectional area to the sum of meter runs area should be higher than 1.5 [10]. Traditionally, there was a tendency to believe that drawing fluid from a big tank will mystically ensure not only even flow distribution but also swirl free flow in the exit piping. Experimental evidence [11] was showing extreme swirl angles over 50 degrees in flows from a big tank/header, and at least this role of big headers was questionable. It illustrated as well that in some header configurations the conservation of angular momentum plays a more important role than swirl dissipation.

A new approach to the header size design [12] have shown that quite even flow distribution between meter runs can be achieved with header/meter runs cross-sectional area much smaller than 1.5. The key to even flow distribution is to use proper layout of inlet to the upstream header and outlet from the downstream header. In this respect it was quite counterintuitive finding that so called U-type layout of a meter station headers ensures much more even flow distribution between meter runs than popular Z-type layout with the location of inlet and outlet piping on the opposite sides of the meter station.

The discussed compact header design [8] is very economical however it requires location of headers above the ground level and better mechanical tolerances of meter run lengths. Meter runs and both headers form much stiffer and less forgiving frame than more elastic configurations with risers. The pipeline has to be brought above the ground level through two elbows in plane with a spacer far enough from the header to dissipate a majority of flow distortion.

The focus of this paper is the evaluation of header installations without risers. It seems that economics will drive designers and users more toward such configurations. An additional spin off benefit is simplicity of draining any fluids collected in the headers. Although the study deals with the effect of headers on the performance of orifice meters in bare tube installations, certain conclusions will be applicable to ultrasonic or other flow meters operating in such installations.

Header installations without riser can generate swirling flow only at the inlet to the upstream header unless the inlet pipe section of the header and the meter run form installation similar to two elbows out of plane as tested by NEL. Therefore the tested inlet piping configurations will contain combinations of elbows with or without expander. The sizes of tested header configurations and meter runs will be selected to capture extremes of the designs encountered in the industrial practice. The task of choosing configuration and dimensions of header installations is not easy due to the variety of header designs used in the industry. This is one of the reasons why the orifice meter standards API/ANSI-2530 and ISO-5167 do not contain any specific recommendations for the meter run length in the bare tube installations with headers.

## Selection of Header Installations for Testing

Selection of header dimensions and configuration builds on the practically encountered proportions between the diameters of inlet piping, header and meter runs as well as common spacing between meter runs. It was decided to go beyond the established range of diameter ratios used and to test more extreme cases to make sure that any unknown practical cases will be covered.

The analysis of ten multi-run meter station designs established that the ratio of header diameter to meter run diameter varies from 1.6 to 2.3 and header diameter to inlet pipe diameter from 1.0 to 1.65. The spacing between meter runs is dictated by a practical access of operators and is approximately 1.5m to 2.5m (center to center) regardless of the meter station size. Usually the spacing is 2m or less.

Two sizes of headers were selected for the testing with two 0.102m internal diameter (4 inches) orifice meter runs. The first header denoted "A" (Fig 1) had an internal diameter 0.102m and two sizes of inlet piping namely 0.041m (1.5 inch ID) and 0.102m (4 inch ID). The nominal spacing (center to center) between meter runs was 0.267m and was adjusted in some of the tests. The length of header sections upstream and downstream of meter runs was adjusted as well in selected tests. Only one meter run was operated at a time therefore the ratio of header cross-sectional area to the meter run area was equal 1.

The second header denoted "B" (Fig 2) had a diameter of 0.259m (10 inch ID) and one size of inlet piping 0.102m (4 inch). The header "B" was feeding two 0.102m orifice meter runs spaced 0.392m center to center. The ratio of header cross-sectional area to the single meter run area was equal 6.25.

The tested ratio of header diameter to meter run diameter was therefore varied from 1.0 to 2.5 and header diameter to inlet pipe diameter was from 1.0 to 2.7. Selection of the header diameter equal to the meter run diameter minimized any swirl amplification effect just due to the contraction between header and meter run cross-sectional areas. Large ratio of header diameter to inlet pipe diameter maximized effects of flow separation in the expander on the intensity of swirl (if any) generated by that fitting. Moreover it reduces the intensity of swirl generated upstream by two elbows out of plane just due to large increase in cross-sectional area.

A few most common inlet piping configurations tested with each header to asses the impact of the inlet swirl (or lack of it) can be summarized as follows:

a) straight pipe (with or without upstream flow conditioner) co-axial with the header with or without a connecting expander

b) single 90° elbow R/D = 1.5 preceded by a straight pipe (in one plane with meter runs) and connected to the header directly or through the expander

c) two 90° elbows R/D = 1.5 closely coupled (zero spacer) in perpendicular planes preceded by a straight pipe (with or without upstream flow conditioner) and connected to the header directly or through the expander

It should be noted that the expander connecting 0.041m ID (1.5 inch) piping or elbows to the small header "A" was bell shaped with a half angle approximately 31 degrees and the expander connecting 0.102m ID piping or fittings to the larger header "B" was conical with a half angle 12 degrees.

## Test Facility

All tests were conducted in the low-pressure air facility at the NOVA Research & Technology Centre (NRTC). The 0.102m (4-inch ID) meter run and the upstream header were located on the suction side of 30 HP air blower (Fig. 3). Six different orifice plates ($b$ = 0.2, 0.4, 0.5, 0.6, 0.67 & 0.75) were mounted in a special high precision orifice fitting with flange taps at 45° angle from the plane of header being studied (45° from the 9 or 12 o'clock position, when looking in the flow direction). For each $b$ ratio, the reference standard consisted of an ASME profile sonic nozzle (throat diameters ranged from 6.8mm to 28.8mm). The nozzles were originally calibrated at the CEESI air facility in Nunn, CO in 1988. One of the nozzles used in this study was sent to CEESI again in July 1999 for re-calibration and the discharge coefficient had only changed 0.1% over a period of more than ten years. The quoted uncertainty of the latest CEESI calibrations was ±0.1% and the calibration was traceable to a gravimetric standard. Using the newly calibrated nozzle, all other nozzles were re-calibrated using a calibrated orifice meter; the discharge coefficients determined in this manner were within 0.1% for all nozzles except the smallest one which differed by 0.4%. Therefore, all data in this study were processed using the original nozzle calibration data.

The test section for the baseline tests consisted of a $96D_{MR}$ to $112D_{MR}$ long honed meter run tube. In some cases a NOVA-50 flow conditioner was located $7.5D_{MR}$ from the inlet. Air was drawn from the laboratory and the $96D_{MR}$ distance between the flow conditioner and the orifice plate ensured full development of the velocity profile for the baseline tests of the orifice meter used.

It is important to ensure a fully developed velocity profile at the entrance to tested fittings. Such an approach eliminates any impact of a distorted velocity profile on the new flow distortion generated by the fitting. In the case of the headers connected to 0.102m pipe, air was drawn through a $20.5D_{MR}$ long inlet pipe with a NOVA-50 flow conditioner located $15D_{MR}$ upstream of the fitting (see Fig. 3). The orifice meter standard ISO 5167-2 indicates that the orifice meters will perform properly with this type of flow conditioner located even as close as $8.5D_{MR}$ for $b \leq 0.67$. It is an indirect indication that the velocity profile $15D_{MR}$ downstream of NOVA50 flow conditioner is close to the fully developed velocity profile. The reference choked nozzle was always located downstream of the orifice meter to isolate the meter from any flow pulsation and noise generated by the blower.

The ratio of differential to static pressure for the orifice meter was kept low in all tests and never exceeded 1%. This low range was chosen in order to make use of a high quality differential pressure transmitter that was calibrated over the 0-1000 Pa range with an uncertainty of ±0.05%.

The tested headers were built of plastic piping in a segmented fashion. Tee-components of the headers were glued to ensure relatively sharp edges. Quick connecting metal sheet couplings with a rubber seal (Lorenz standard coupling) were used to align different length spacers between both Tees, connect Tees to metal pipe meter runs or to the inlet piping. All the tests were conducted with just one of the meter runs open. The second unused meter run was closed with a cap at an approximate distance $2.5D_{MR}$ and formed a cylindrical cavity. The tests described in the literature [5][6] with the flow through more than one meter run did not indicate any significant change in

the header and orifice meter performance due to the opening or closing of another meter run.  It should, however, be noted that the study was dealing with the headers followed by risers.

Due to the large number of possible changes in the header and inlet piping geometry it was not possible to conduct comprehensive testing at all β-ratio and several meter run lengths for every case.  The tactic used was to measure at first an impact of various header configurations on the orifice meter located $11D_{MR}$ downstream at β=0.4.  Once an effect of swirl was detected by measuring positive $\Delta C_D$ that header configuration was tested more extensively at different meter run lengths or β-ratios.  Therefore some of the presented results will be just summarized in the text or a simple table whereas other more comprehensive and more interesting results will be presented in several graphs.

In the past, there was a perception that low-pressure test facilities do not generate very reliable data and data scatter was one of the concerns.  However, the location of the test rig on the suction side of the blower, a long meter run, a very accurate differential pressure transducer for the orifice meter, and the isolating effect of the choked nozzle contributed to very good repeatability and long term stability (±0.15%) of the NRTC facility.  The meter run Reynolds number for this facility ranged from 5,100 at $b$=0.2 up to 92,000 at $b$=0.75.  Therefore, any conclusions related to flows with swirl have to take into account higher level of swirl decay at those relatively low Re numbers.

## Baseline Tests

The first step in any test of installation effects is a check of the orifice meter baseline.  According to the acceptance criteria developed in the White Paper on the Orifice Meter Installation Configurations with and without Flow Conditioners [7], and adopted in the revised API/ANSI-2530 orifice standard [13], the facility should be able to reproduce the orifice discharge coefficients within ±2$s$ of the stated uncertainty of the R-G equation.  The deviations $\Delta C_D$ between the baseline orifice meter and the reference nozzles obtained in June 1999, August 1999 and in February 2000 are presented in Fig. 4.  The recent data from fall 2002 are shown in Fig. 5.   All baseline results are within the uncertainty limits  ±2σ of the R-G equation even at the infinite Re number.

The effect of installations such as headers was defined as a difference $DC_D$ between the discharge coefficients of the orifice meter influenced by the header and the orifice meter from the conducted baseline tests as defined by eq(1).

$$DC_D = (C_{D\ install} - C_{D\ baseline}) / C_{D\ baseline} \times 100\% \qquad (1)$$

Typically, five data points were taken for each distance between the fitting and the orifice.  A single data point was an average of 1024 measurements taken over a 20-second period of time.  The pressure transducer was able to measure differential pressure fluctuations, caused by flow instabilities, in the range of 0-50Hz.

For a particular piping configuration, the deviation of the orifice discharge coefficient $DC_D$ was considered negligible when it was smaller than one standard deviation σ of the R-G equation.  This acceptance condition is consistent with that used for the development of installation recommendations in the API and ISO standards [7].

## Test Results – Straight Inlet Pipe Co-Axial With the Header With or Without a Connection Expander

The tests with a straight co-axial inflow to the header were performed on the small 0.102m ID header "A" and on the 0.26m ID header "B".

### Small Header "A"

The results obtained on smaller header "A" with 0.102m ID inlet pipe $20.5D_{MR}$ long are shown in Figure 6.  All data for β=0.4, 0.5 and 0.6 were collected at the distance $11D_{MR}$ between the outlet from the header and the orifice plate.  The trend of negative values of  $\Delta C_D$ resembles closely measurements taken for a rounded edge Tee junction with an extension $10D_{MR}$ long [14].  Observed effects were the same for each meter run operating independently.

Application of a smaller 0.041m ID (1.5 inch) inlet piping $74D_{inlet}$ long and of an expander at the header "A" inlet reduced measurement error  $\Delta C_D$ at $11D_{MR}$ practically to zero at all three β-ratios (Fig 7) regardless of the meter run tested.

### *Large Header "B"*

The large header "B" was evaluated with a co-axial straight inflow from 0.1 mm ID pipe. No tests were performed with 0.26m ID inlet piping. The inlet pipe was $22.3D_{MR}$ long with NOVA50 flow conditioner located $17D_{MR}$ from the expander inlet. The length of 0.102m ID meter run from header outlet to the orifice plate was $11D_{MR}$. The effect of a straight co-axial inflow on the large header "B" and metering error $\Delta C_D$ at $\beta = 0.4$ was practically zero ($\pm 0.03\%$) regardless if meter run #1 or #2 was in use. An increase of spacing between meter runs to 0.54 m (center to center) did not change the bias $\Delta C_D$ in the meter run 1 which remained close to zero (-0.1%). The focus of those tests was to detect any traces of swirl due to non-symmetrical flow separation at the expander. Lack of any positive bias $\Delta C_D$ at $\beta = 0.4$ where swirl effect should be most pronounced did not justify further testing at other $\beta$-ratios.

It is to some degree surprising that the presence of a strong flow disturbance associated with expanders does not lead to larger $\Delta C_D$ errors even in the small header "A". That can be explained by good flow mixing and transverse transport of momentum (resulting from flow separation) downstream of the expander. Ultimately it leads to faster formation of a fully developed velocity profile in the meter run than from a relatively "smooth" however distorted Tee-junction type of flow.

In practical terms designers or users of orifice bare tube installations do not need to be concerned about the impact of the inlet expander to the header on swirl generation so long as the inlet piping is co-axial with the header.

## Test Results – Single 90° Elbow R/D =1.5 at the Header Inlet With or Without a Connecting Expander

The tests conducted with an elbow at the inlet to headers were driven by a concern that the elbow combined with the expander can generate swirl [3] in the header, which subsequently may propagate even to the meter run.

### *Small Header "A"*

A long radius R/D=1.5 elbow ID=0.102m (4 inch) was connected to the header "A" without an expander. The 0.102m ID piping preceding the elbow was $20.5D_{MR}$ long and NOVA flow conditioner was located $5.5D_{MR}$ from the inlet to ensure a fully developed flow at the elbow inlet.

The effect of an inlet elbow on the header of the same diameter and the same size orifice meter run $11D_{MR}$ long (Fig 8) resembles the already discussed effect of a co-axial inflow (Fig 6). The small header with the same size inlet piping and meter run becomes a part of a new complex piping configuration. The observed bias $\Delta C_D$ was more negative at higher $\beta$-ratio, however, the effect was not as strong as in the case of co-axial inflow and "Tee type" flow. The orifice meter error was approximately 0.2% higher (at $\beta = 0.5$) when flow was directed only to the meter run 2, which was closer to the inlet elbow. An increase of the header length upstream of the meter run 2 by $2D_{MR}$ (0.2m) did not have any impact on the orifice meter performance.

An addition of a 0.041m to 0.102m expander at the header inlet preceded by $74D_{inlet}$ of 0.041m (1.5″ ID) piping has changed significantly the effect of an elbow/header installation on the orifice meter performance. The measured bias $\Delta C_D$ (Fig 9) was practically reduced to zero for $\beta = 0.4$, 0.5 and 0.6 at meter run length $11D_{MR}$. There was no trace of swirl effect. An increase of the header length between the meter run 2 and the expander by $2D_{MR}$ (0.2m) did not have any impact on the orifice meter bias.

Again that surprising result may be explainable in terms of strong transverse momentum transportation in flows downstream of separation. An analogy can be seen with the shorter length needed to get fully developed flow downstream of a partially open gate valve than downstream of a single 90° elbow [13].

### *Large Header "B"*

Similar results were observed in the tests of the 0.259m ID header "B". The tests were conducted with a 0.102m ID (4 inch) long radius single elbow R/D=1.5 connected to the header by an expander. The elbow was preceded by 0.102m ID pipe $15D_{MR}$ long, NOVA50 flow conditioner and $5.5D_{MR}$ long section of an inlet pipe. The measured bias at $\beta = 0.5$ was −0.19% when meter run #1

was open and –0.11% for meter run 2.  Both meter runs were 11$D_{MR}$ long.  Lack of any swirl effect did not justify testing of that case at different meter run lengths or β-ratios.

Similarly as in the case of a co-axial inlet flow the addition of an expander does not lead to the generation of swirling flow and even reduces orifice meter bias due to the fast dissipation of flow distortion (low Re number in the large header).  It should be noted that the discussed [3] effect of elbow/expander combination and associated swirl were observed in the meter run directly downstream of the expander (no header) and at a high Reynolds number.

## Test Results – Two 90° Elbows Out of Plane at the Header Inlet With or Without Connecting Expander

Meter stations with headers are commonly supplied with gas through two 90° elbows with R/D=1.5 installed in perpendicular planes.  Such a combination of elbows is used to bring piping above ground level and keep meter runs customarily aligned with the pipeline.  Typically two elbows out of plane have a spacer which for large diameter pipeline can be as short as two pipe diameters..  The tests presented here were performed with elbows connected tightly to achieve zero spacer length and asses maximal impact on the orifice meter performance.  It should be noted that the tested headers "A" and "B" did not have any risers connecting to meter runs to avoid complex interactions with an apparent second set of two elbows out of plane formed by the header, riser and elbow leading to the meter run [6].

### *Large Header "B"*
The tests of two closely coupled 90° elbows (0.102m ID only) in perpendicular plane and preceded by 20.5$D_{MR}$ long inlet pipe with NOVA50 flow conditioner were performed on 0.26m ID (10 inch) header "B".  The connecting expander in that case had 12 degree angle, smaller than the expander used in header "A".  The 0.102m ID meter runs were 11$D_{MR}$ long.  The tests performed at β=0.4 resulted in $\Delta C_D$ =+0.1% for the meter run 1 and $\Delta C_D$ = +0.08% for the meter run 2.  Similar bias $\Delta C_D$ = +0.12% was measured in the meter run 1 at β=0.5.  Low level of bias associated with swirl generated by the two elbows out of plane and the expander connected to the large header "B" did not justify tests at other β-ratios and meter run length and shifted research focus to the small header "A".

The conclusion from these limited tests should be carefully assessed when compared to the following results from the small header test.  At the same flow rate the Reynolds number in the large header was 2.5 times lower than in the small header and the swirl decay rate is 33% higher [16].

### *Small Header "A"*
Initial tests were conducted with the 0.102m ID (4 inch) meter run 11$D_{MR}$ long.  Two 0.102m ID elbows with zero spacer were preceded by 20.5$D_{MR}$ inlet pipe with NOVA50 flow conditioner located at 5.5$D_{MR}$ from the inlet.  The positive bias $\Delta C_D$  ranging from +0.5% to 1.1% (Fig 10) was measured in the meter run 2 (closer to the header inlet) at  β=0.4, 0.5 and 0.6.  The highest positive bias indicating presence of swirl at the orifice meter location was observed at β=0.6.  Surprisingly the sign of bias was changed to the negative when measured at the orifice meter in run 1.  The same level of negative bias was observed in the orifice meter run 2 when the distance between the meter run 2 and expander outlet was increased by 2$D_{MR}$ (0.2m).  This negative bias trend resembles the effect of header with a single 90° elbow at the inlet (Fig 8).

Much stronger positive bias  $\Delta C_D$ was measured when two closely coupled 0.041m elbows in perpendicular planes were connected to the small header "A" through an expander.  The inlet piping 0.041m ID (1.5 inch) leading to the elbows was 74$D_{inlet}$ long and did not have a flow conditioner.  The measurement results shown in Figure 11 indicate the presence of strong swirl at the orifice meter located 11$D_{MR}$ in the meter runs 1 and 2.   The bias is positive (up to 4.3%) at all β-ratios except for 0.75.  Again, an introduction of 0.2m long insert to increase header length between meter run 2 and expander outlet reduces positive bias in both meter runs, however only in the meter run 1 it becomes negative in particular at higher β-ratios.  The change of the inlet elbow configuration to the opposite of that shown in Fig 1b (mirror image) reduced the positive bias at β=0.5 by 0.18%, which is close to the test rigs repeatability.

The tests conducted with meter runs 11$D_{MR}$ long have shown that the small header "A" with 0.041m ID inlet and two elbows out of plane followed by the expander has the strongest impact on

the orifice meter performance. Therefore the following tests were focused on that installation configuration and tried to assess $\Delta C_D$ bias for various meter run lengths and $\beta$-ratios.

The results of comprehensive testing performed on this installation and the orifice meter operating in the meter run 1 (farther from header inlet) are shown in Fig. 12. The presence of strong swirl is illustrated by a positive bias $\Delta C_D$ observed at $\beta=0.4$, 0.5, 0.6 and even 0.67 at meter run lengths ranging from $11D_{MR}$ to $55D_{MR}$. The negative bias was consistently observed at $\beta=0.75$ only. The recommended meter run length for this particular bare tube installation (meeting ANSI-2530 and ISO-5167 criteria) should be at $55D_{MR}$ mainly due to swirl effects at $\beta=0.6$. Maximum swirl effect at $\beta=0.6$ confirms the experiments and theoretical justification observed before [15].

There is similarity to the trend observed at the same test facility in the measurements of the effects of two close coupled elbows out of plane (no header) on the orifice meter [15]. The main difference is larger magnitude of bias $\Delta C_D$ in tests with headers at meter run length $18D_{MR}$. This can be explained by stronger swirl generated by two elbows/expander/header installation than two elbows out of plane. It seems that the rate of swirl decay is higher for the header than two elbows out of plane. Maybe it is due to the effect of difference in the initial velocity distribution [16] generated by each installation. Moreover the measurements discussed were taken at Reynolds numbers not exceeding $10^5$ at which swirl decay rate is relatively high. As it was found from the tests of two elbows out of plane at high pressure test facility [15] at Reynolds numbers approaching $10^7$ the minimum bare tube length exceeded tested length $81D_{MR}$ and was established by API/ANSI-2530 at $95D_{MR}$. Similar length can be expected in header installations.

An addition of $2D_{MR}$ long (0.2m) insert between expander outlet and meter run 2 inlet significantly changed orifice meter bias in the meter run 1 (Fig 13). All measurement errors $\Delta C_D$ became negative similar to the effect of a non-symmetrical velocity profile. The recommended meter run length for the bare tube installation can be reduced in that case from $55D_{MR}$ to $44D_{MR}$.

Selected tests performed with the orifice meter at run 2 (closer to the header inlet) are shown in Figs 14 and 15. The observed bias $\Delta C_D$ at $L/D_{MR} = 11$ and 18 was positive and higher than at meter run 1. An addition of $2D_{MR}$ (0.2m) long insert to increase the inlet header length reduced the bias, however, it did not change to negative values as in the case of the orifice located in the meter run 1.

The performed tests indicate that the design of a header installations (without risers to the meter runs) should be carefully optimized in terms of potential generation of strong swirl by a combination of two closely coupled 90° elbows in perpendicular planes followed by an expander. Larger size of the header in comparison to the meter runs cross-sectional area reduces Reynolds number and intensifies swirl decay.

Table 1 summarizes the tested effects of headers just at one $\beta$-ratio ($\beta=0.4$), at the selected meter run length $11D_{MR}$ and with meter run 2 open.

| | Averaged change of the orifice meter discharge coefficient $\Delta C_D$ at $\beta=0.4$ and $11D_{MR}$ run length | | |
|---|---|---|---|
| Inlet piping configuration | **Small header "A"** | | **Large header "B"** |
| | without inlet expander $D_{inlet} = 0.102m$ ID | with inlet expander $D_{inlet} = 0.041m$ ID | with inlet expander $D_{inlet} = 0.102m$ ID |
| a) Co-axial inlet piping | -0.2% (Fig 6) | 0% (Fig 7) | 0% |
| b) Single 90° elbow (R/D=1.5) | -0.1% (Fig 8) | -0.1% (Fig 9) | -0.1% ($\beta=0.5$) |
| c) Two 90° elbows in perpendicular planes (R/D=1.5) | +0.5% (Fig 10) | +4.3% (Fig 11) | +0.1% |
| d) Two 90° elbows out of plane and extended header | -0.1% (Fig 10) | +2.7% (Fig 11) | — |

Table 1: Comparison of the effect of various header configurations on the orifice meter performance at $\beta=0.4$ and $11D_{MR}$ long meter run 2

## Conclusions

Design of header installations for flow metering purposes has to take into account risk of generating strong swirling flows in meter runs, which may have detrimental impact on measurement uncertainty in particular in bare tube installations.

Headers with the meter runs in the same plane (no risers) do not generate strong swirling flows when the inflow piping is aligned with the inlet header axis or there is a single 90° elbow at the header inlet. This was tested and proven for headers of larger diameter than the inlet piping, which contained an expander, as well as for headers of the same diameter as supply pipeline without expanders.

Utilization of two close coupled 90° elbows in perpendicular planes to bring buried piping above ground level and supply gas to the header can result in the propagation of strong swirl to the meter runs when the ratio of header to all meter runs cross-sectional areas is smaller than 1.0. Associated orifice measurement errors in bare tube installations can be up to 4.3%. However, this problem was observed only when the elbows were of smaller diameter than the header. An extension of the header length between the expander and the first meter run reduced swirl intensity. Increased spacing between meter runs has negligible effect on swirl intensity and measurement errors.

The bare tube length needed to dissipate such swirl is comparable if not longer than recommended in the orifice standards for the orifice meter tube downstream of two elbows out of plane.

## Acknowledgements

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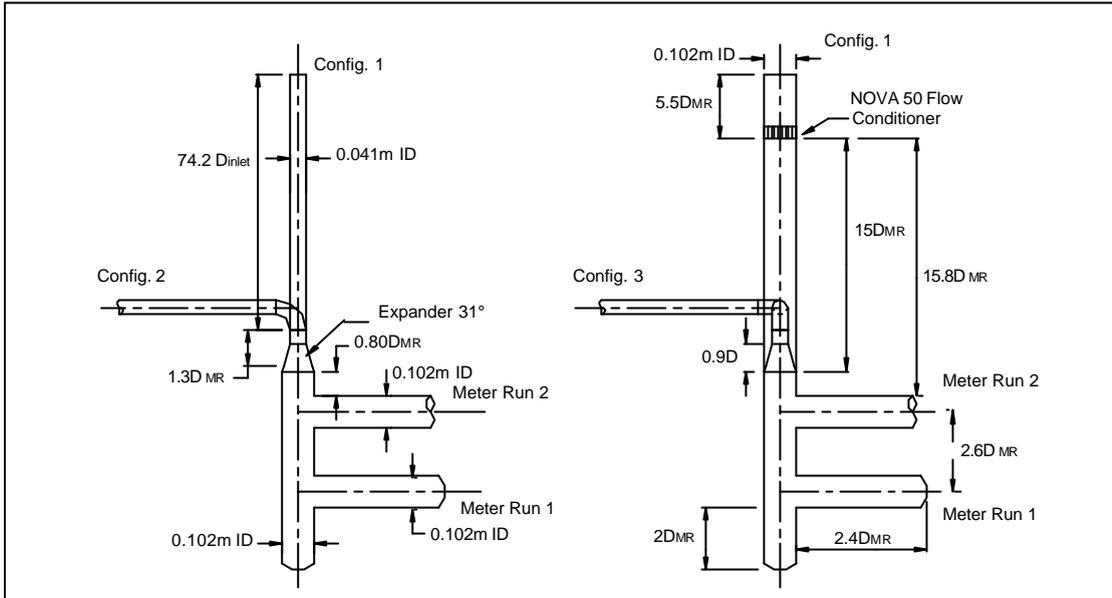
Fig 1a. Schematic of small header "A" with examples of inlet piping configurations 1) co-axial in flow, 2) single 90° elbow, 3) two elbows close coupled out of plane.
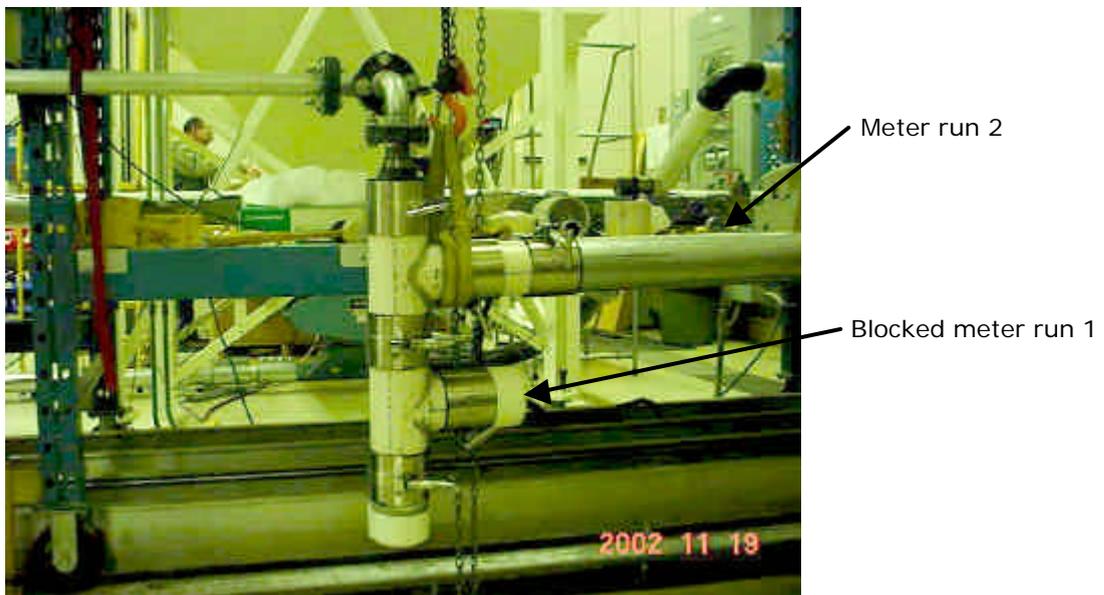


Fig 1b. Small header "A" with 74D of 0.041m ID inlet pipe followed by two elbows out of plane and 31° expander.
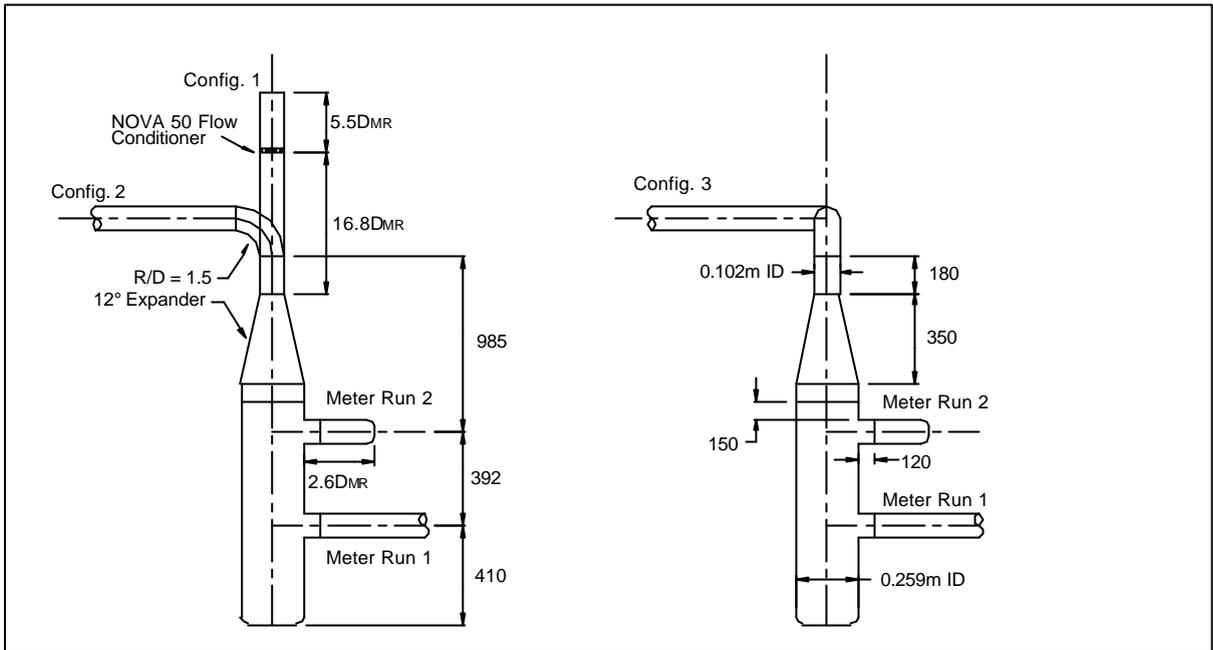
Fig 2a. Schematic of large header "B" with examples of inlet piping configurations: 1) co-axial in flow 2) single 90° elbow 3) two close coupled 90° elbows in perpendicular planes.
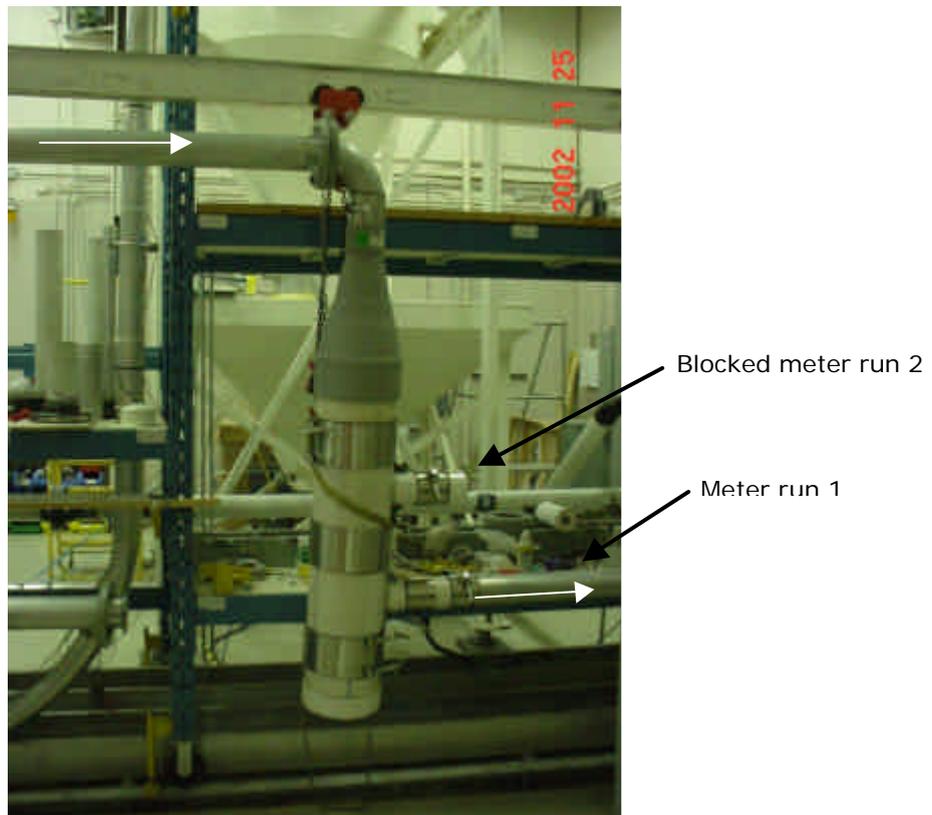


Fig 2b. Large header "B" with 0.102m ID inlet pipe followed by a single 90° elbow and 12° expander
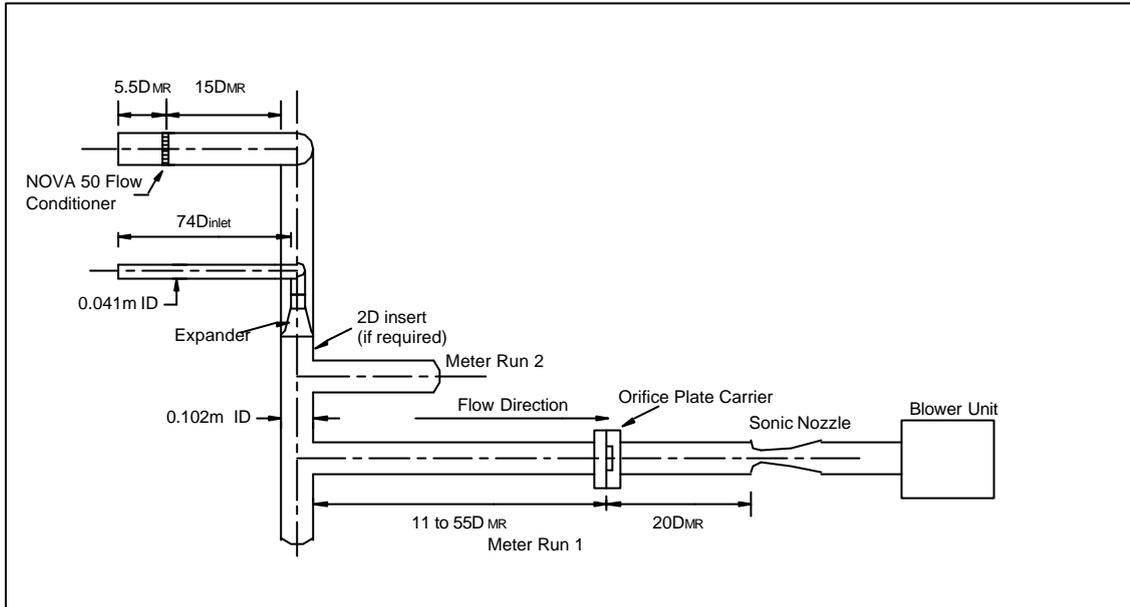
Fig 3.   Low pressure air test facility setup, test of small header "A" effects on the performance of the orifice meter.
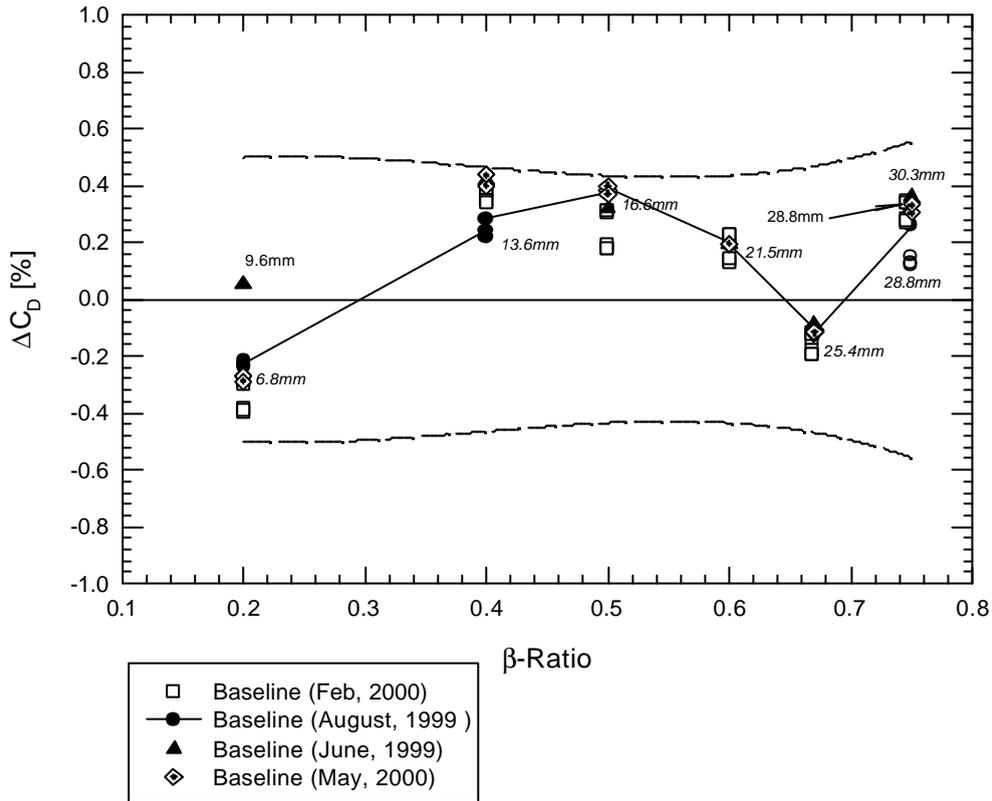
Fig. 4. Historical orifice meter baseline tests of air facility. Dash line denotes uncertainty limit of R-G discharge coefficient equation at infinite Reynolds number. (Nozzle throat diameter is denoted at each set of data points.)
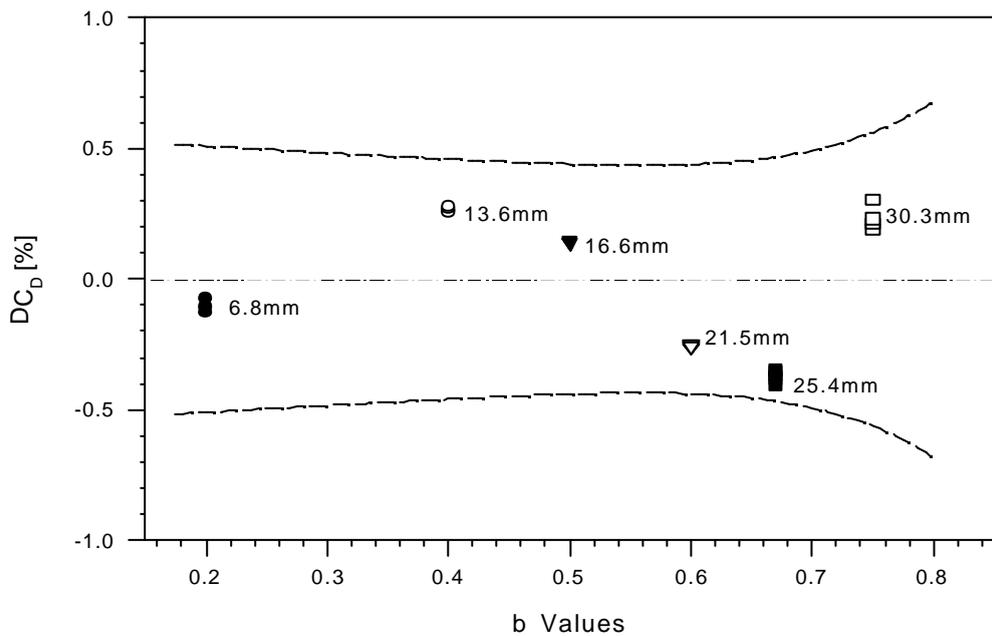


Fig. 5. New orifice meter baselines obtained for header tests in November and December 2002. (Nozzle throat diameter is denoted at each set of data points.)
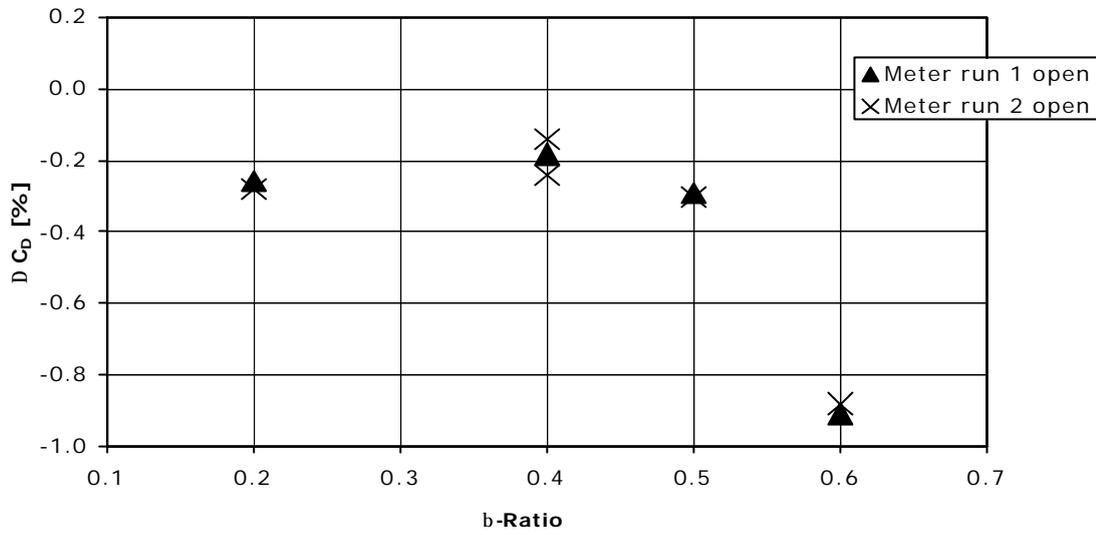
Fig. 6. Test results of small header "A" with **co-axial 0.102m ID inlet pipe** 21.3 diameters long and $11D_{MR}$ long meter run.
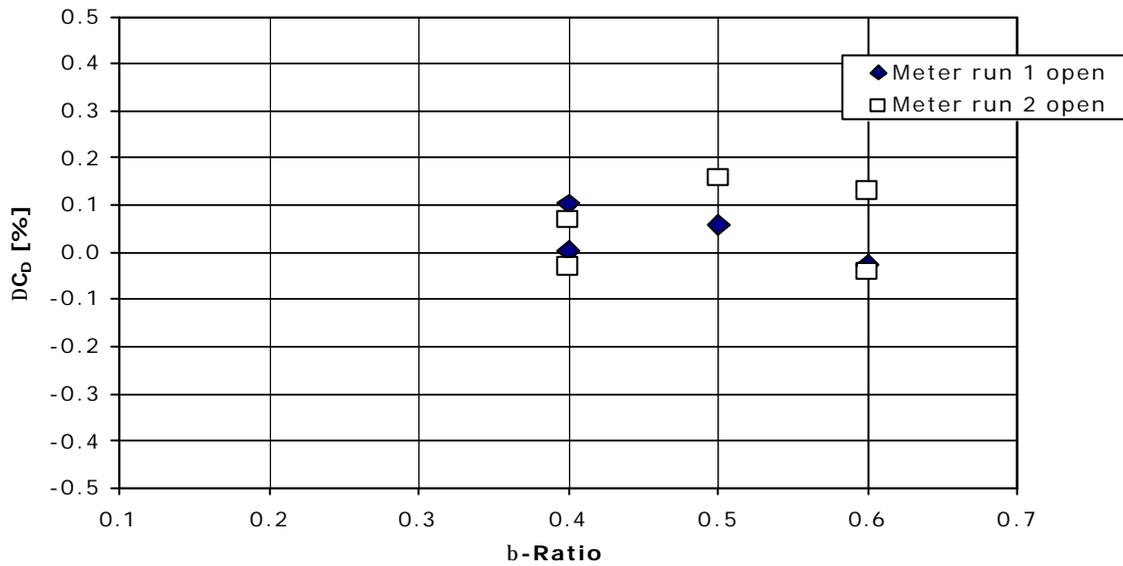


Fig. 7. Test results of small header "A" with **co-axial 0.041m ID inlet pipe** 74 diameters long and $11D_{MR}$ meter run.
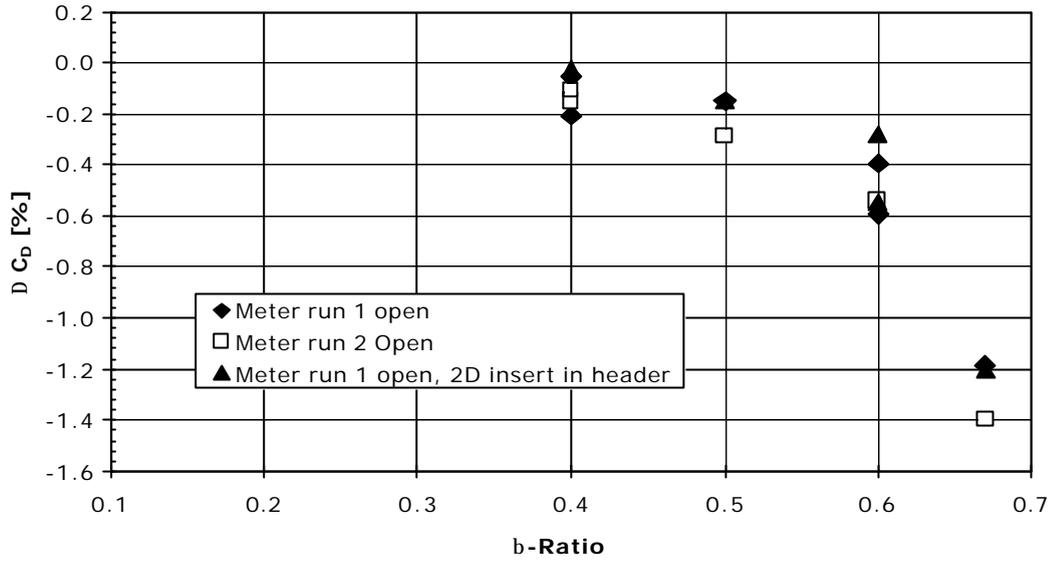
Fig. 8.  Test results of header "A" with a **0.102m ID single elbow** at the inlet and $11D_{MR}$ long meter run
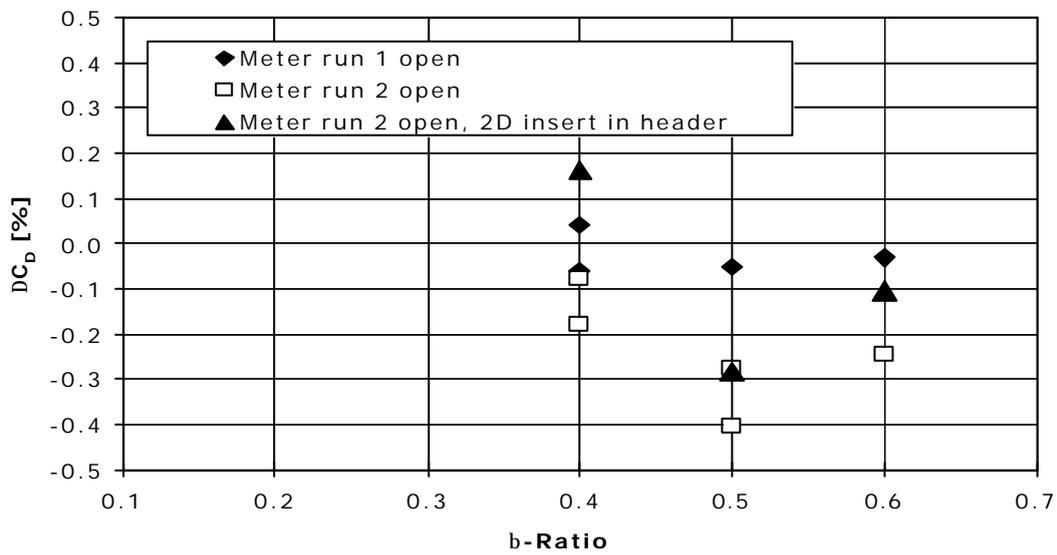


Fig. 9.  Test results of header "A" with a **0.041m single elbow** and $31°$ expander at the inlet and $11D_{MR}$ long meter run.
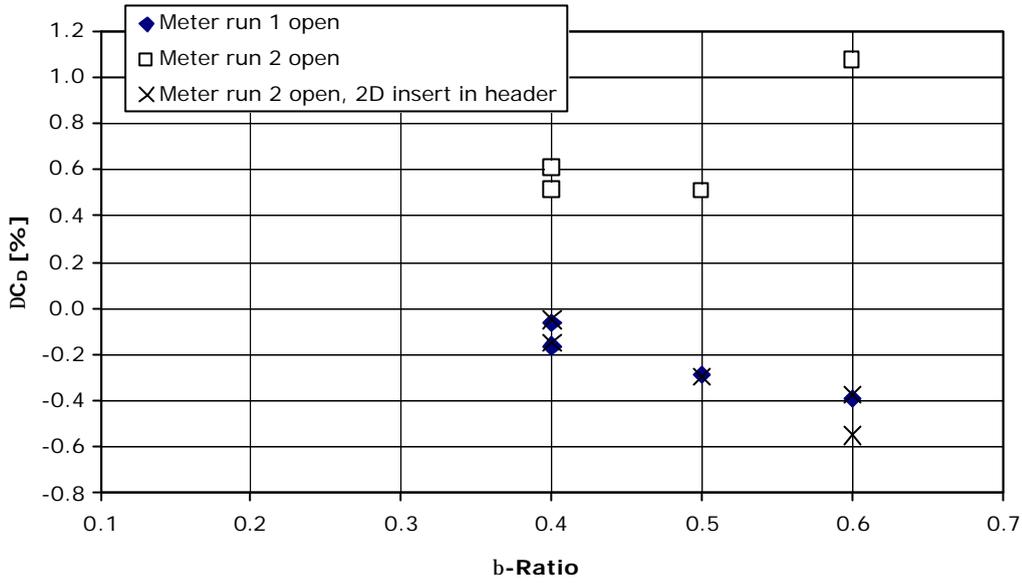
Fig. 10. Test results of header "A" with **two 0.102m ID close coupled 90° elbows** in perpendicular planes of the inlet and $11D_{MR}$ long meter run.
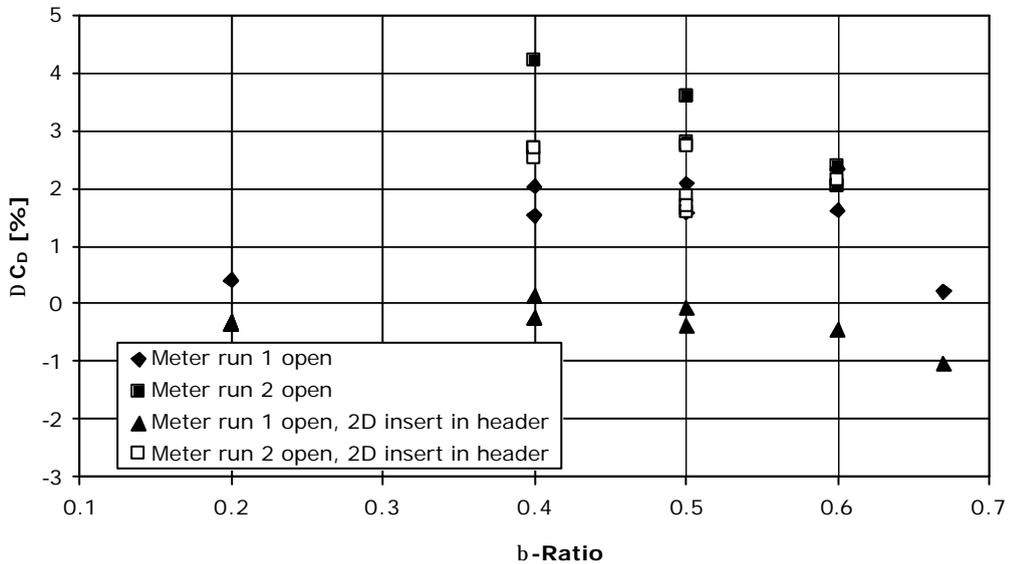


Fig. 11. Test results of header "A" with **two 0.041m ID close coupled 90° elbows** in perpendicular planes followed by the 31° expander at the header inlet; orifice plate located $11D_{MR}$ from the header outlet to the meter run.
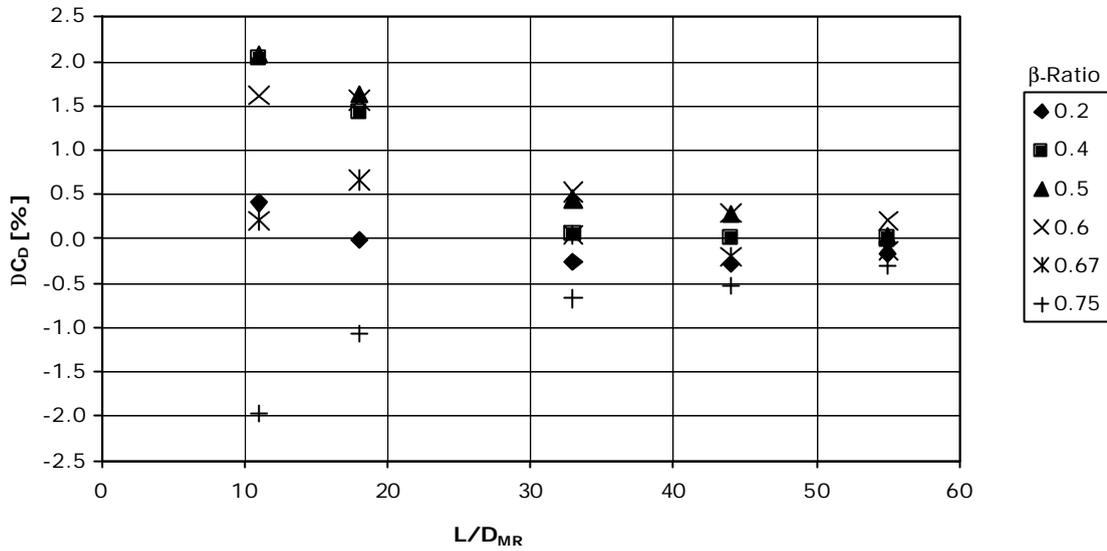
Fig. 12. Test results of header "A" with **two 0.041m ID close coupled 90° elbows** in perpendicular planes followed by the 31° expander. Meter run 1 open, meter run 2 closed
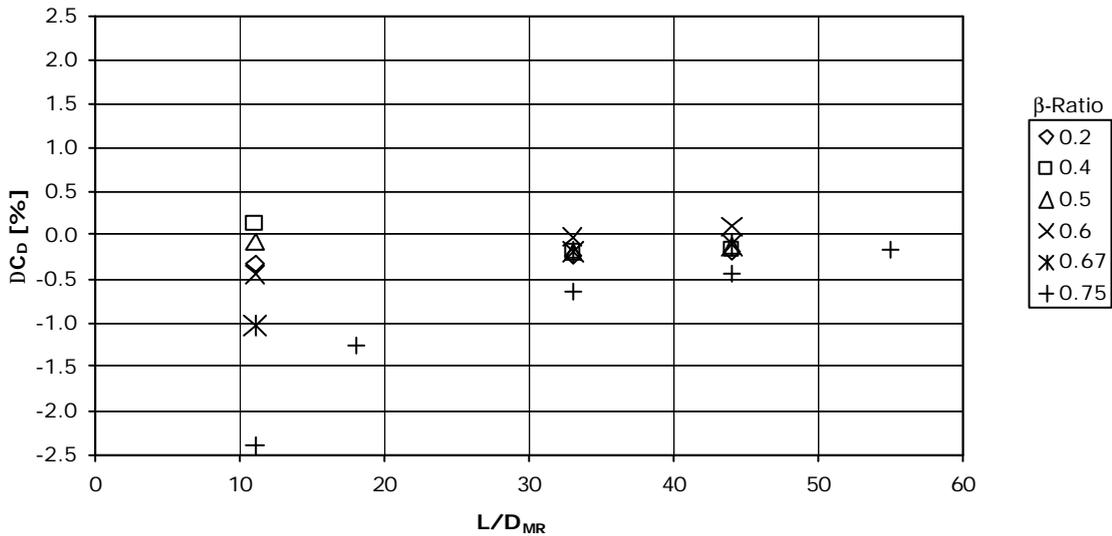


Fig. 13. Test results of header "A" with **two 0.041m ID close coupled 90° elbows** in perpendicular planes followed by the 31° expander and **$2D_{MR}$ long insert** extending the header length. Meter run 1 open, meter run 2 closed.
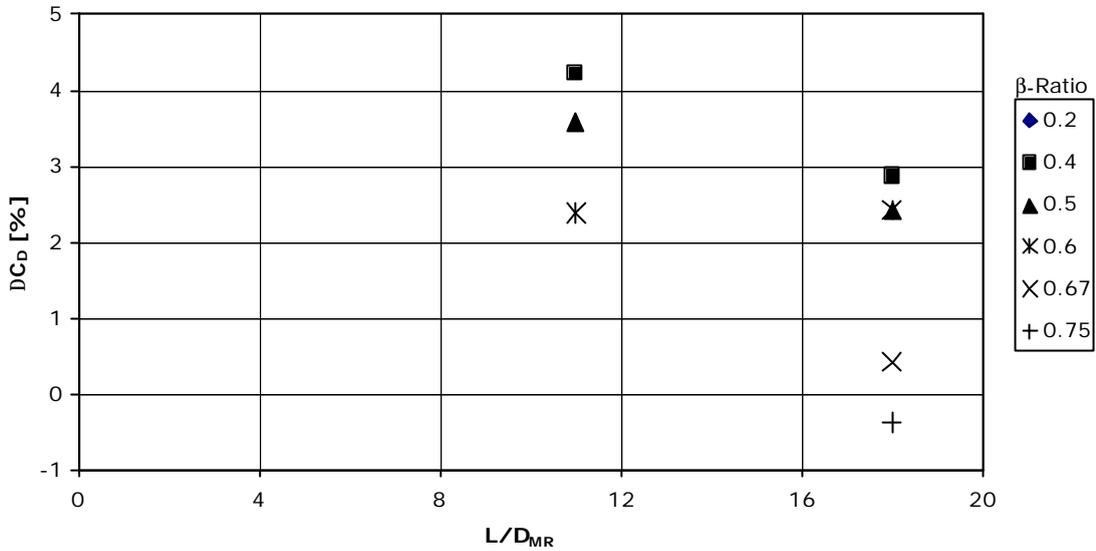
Fig. 14. Test results of header "A" with two 0.041m ID close coupled 90° elbows in perpendicular planes followed by the 31° expander. **Meter run 2 open**, meter run 1 closed.
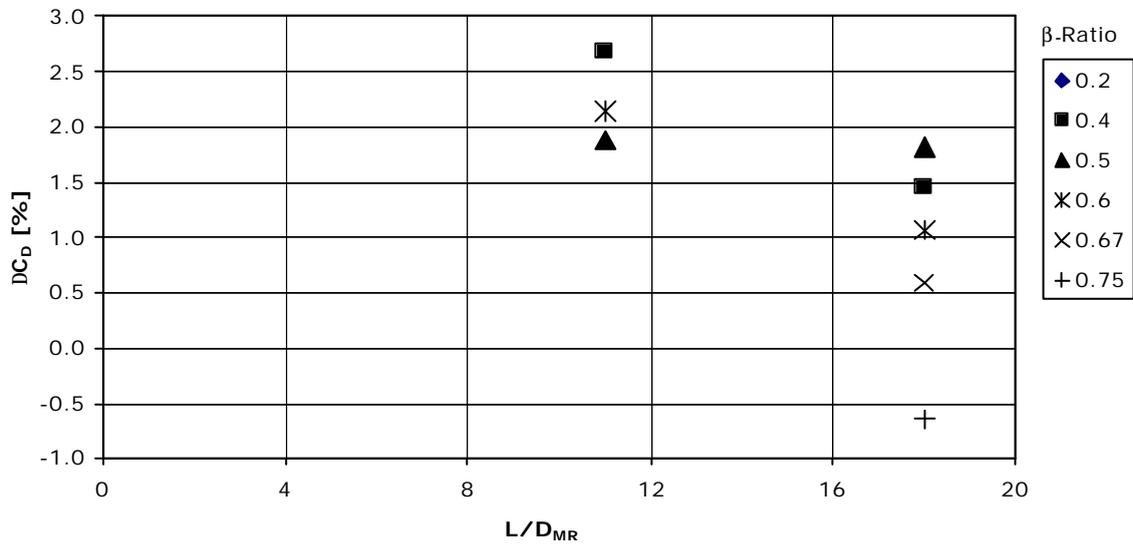


Fig. 15. Test results of header "A" with two 0.041m ID close couple 90° elbows in perpendicular planes followed by the 31° expander and **2D$_{MR}$ long insert** extending the header length. **Meter run 2 open,** meter run 1 closed.