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# Paper 7.3

# Venturi Tubes: Improved Shape

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# Venturi tubes: improved shape

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## 1 INTRODUCTION

There is an increasing desire to use Venturi tubes for wet gas measurement, but to ensure accuracy in wet gas it is necessary to understand their behaviour in dry gas first. It was generally assumed until about seven years ago that the discharge coefficient at high Reynolds number in high-pressure gas would be constant and approximately equal to that obtained in water at Reynolds numbers greater than $2 \times 10^5$. However, work carried out at NEL reported by Jamieson et al [1], data reported by van Weers et al [2], and the papers on subsequent work at NEL [3-7] have shown that the performance of Venturi tubes in gas is very different from that in water. Some discharge coefficients in gas were greater than would have been expected by 3 per cent or even more.

One factor which has an effect on how a Venturi tube performs is its internal shape. It is reasonable to consider the possibility that a profile with a smooth curve rather than sharp corners might be desirable. This paper therefore considers the performance of Venturi tubes of a range of profiles. Data were collected over the range of Reynolds numbers from about $10^5$ to $10^7$. The aim was to determine the best profile so that further work might provide a test of 4 Venturi tubes of the optimum profile.

## 2 DESCRIPTION OF THE VENTURI TUBES

### 2.1 Design

It has been suggested at meetings of ISO TC30/SC2 that better results would be achieved if the sharp corners in a Venturi tube with a machined convergent were rounded so that it were machined with the profile of an 'as cast' convergent. One Venturi tube of this type was lent by Atelier Pochet, of Ransart, Belgium, and is numbered AP1 and referred to subsequently as "rounded corners". Moreover, previous work [4] had shown that a convergent with an included angle of 10.5° gave particularly good results. So it was decided that the following three Venturi tubes should be manufactured:

- A Venturi tube with a machined convergent of angle 10.5° with rounded corners whose radii of curvature are those required by ISO 5167-1 [8] for a Venturi tube with an 'as cast' convergent. This Venturi tube was numbered 29478 and is referred to subsequently as "rounded corners, long".

- A Venturi tube with the distance between upstream and throat tappings equal to that for a Venturi tube of convergent angle 10.5° but with a machined convergent whose wall profile has continuous second derivatives. This Venturi tube was numbered 29479 and is referred to subsequently as "curved, long".

- A Venturi tube with the distance between upstream and throat tappings equal to that for a standard classical Venturi tube but with a machined convergent whose wall profile has continuous second derivatives. This Venturi tube was numbered 29480 and is referred to subsequently as "curved".

All four Venturi tubes are 4-inch Schedule 40 with a diameter ratio, $\beta$, of 0.6. Therefore the desired values of the diameter of the entrance cylinder, $D$, and the throat diameter, $d$, are 102.26 mm and 61.36 mm respectively.

Much literature was reviewed and many calculations undertaken to determine the detailed form of Venturi tubes 29479 and 29480. Profiles by Witoshinsky and by Spencer [9] were considered, but since wall profiles with continuous second derivatives were available it was felt that they would be desirable. The details of the wall profiles are given in Reference [10].

In the case of 29478 – 29480 the throat is parallel for *d*/3 upstream of the throat tapping and the upstream cylinder is parallel for at least *D*/3 downstream of the upstream tapping. In practice the throat is close to parallel over a longer distance. These parallel sections are significantly longer than those required by ISO 5167-1 [8]. These three Venturi tubes were manufactured by ISA Controls Ltd, Shildon, Co. Durham. Drawings of these Venturi tubes are given in Figure 1. The profiles which would have been obtained if sharp corners had been used are shown with dotted lines for comparison. In the case of the long convergent the profile with sharp corners is almost indistinguishable on the scale of the graph from that with rounded corners.

Figure 1 also shows the shape of the Venturi tube AP1 manufactured by Atelier Pochet.

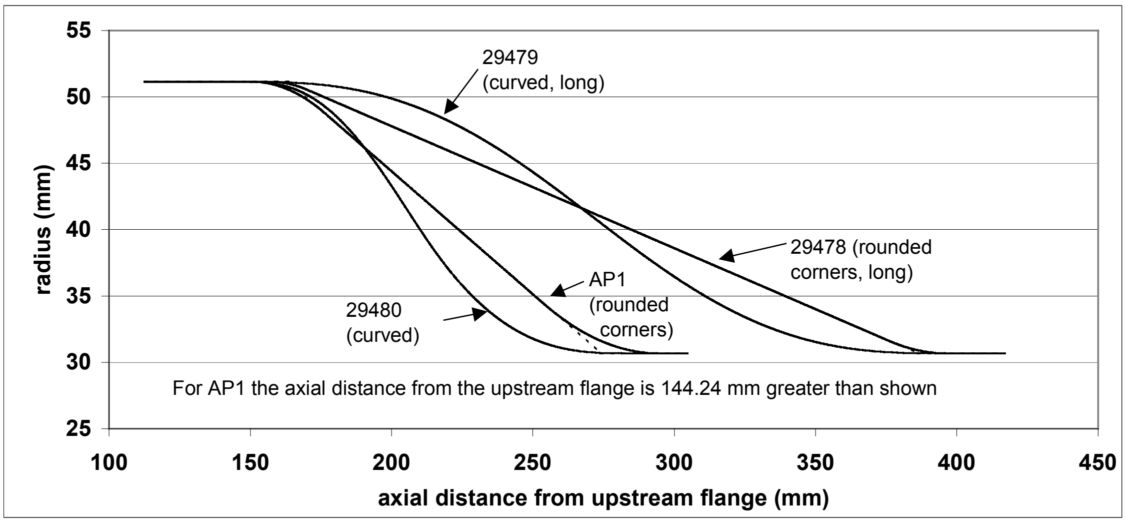


**Fig. 1 Profile from the upstream tapping to the throat tapping for each Venturi tube**

The Venturi tubes were manufactured to drawings with tight tolerances designed to ensure that where possible the results were not affected by uncontrolled variables. They were made of stainless steel and were suitable for use at pressures up to 60 bar with ANSI Class 600 flanges. They were designed not only to meet the requirements of ISO 5167-1 but to follow its recommendations. The Standard recommends the use of a divergent angle between 7° and 8°: 7½° was specified for 29478 - 29480. AP1 has a divergent angle of 7°; it also has a divergent truncated by 26 per cent of its length.

So that the results would not be corrupted by the introduction of steps at joins in the pipework, an upstream length of 8*D* and a downstream length of 4*D*, where *D* is the diameter of the entrance cylinder, had previously been manufactured by boring out Schedule 80 pipe to the bore of a Schedule 40 pipe. The lengths of pipe and the Venturi tubes were dowelled to ensure concentricity; O rings were used to ensure that there would not be recesses or protruding gaskets. The distance from the upstream pressure tappings to the first upstream flange was 1.1*D*.

In addition to the shorter lengths of pipework already described, an additional 21*D* length had been manufactured by welding a 19*D* length of Schedule 40 pipe to a 2*D* length of pipe machined to the bore of the other pipes, smoothing off any step at the weld. This length of pipe was installed with the machined length adjacent to the machined pipe already described, so that there was 10*D* of machined pipework, whose bore matched that of the Venturi tube very accurately, immediately upstream of the Venturi tube. In total there was 29*D* of pipe of the same schedule with no recesses, protruding gaskets or significant steps upstream of the Venturi tube. Upstream of this assembly, there was generally further pipe of the same nominal diameter preceded by a flow conditioner.

On arrival at NEL the entrance cylinder and throat diameters of the Venturi tubes were measured at several recorded stations. Diameters were measured in three planes and at four positions taken round the circumference. Mean values from three planes have been used to determine $D$ and the throat diameter, $d$, for the calibrations. In the case of AP1 the Venturi tube is to be used elsewhere and the values supplied by the manufacturer were used. If the NEL measurements were used the discharge coefficients for AP1 would increase by 0.12 per cent.

The Standard requires that the surface finish of the entrance cylinder, the convergent section and the throat be such that $R_a/d$ shall always be less than $10^{-5}$, where $R_a$ is the arithmetical mean deviation of the roughness profile. The measured values generally exceed the permitted values by a factor of approximately 2.4; the typical surface finish was $R_a \approx 1.5$ μm. All the Venturi tubes had $10^{-5} < R_a/d < 10^{-4}$. The project wished to use Venturi tubes with surface roughnesses typical of those used in the field. If the Final Draft International Standard proposed to replace ISO 5167-1 is accepted the maximum permissible roughness will be increased so that $R_a/d < 10^{-4}$.

It was decided that 29478 – 29480 should have four 4 mm tappings so that data collected with a triple-T should be comparable with all the data described in [3 – 7]. It had been observed that the data obtained in gas with 8 mm tappings in previous work had larger humps than the data obtained with 4 mm tappings. So 29478 – 29480 each were designed to have 1 mm, 2 mm, 6 mm and 8 mm single tappings in addition to the 4 mm tappings. 29480 did not have a pair of 1 mm tappings. For the 4 mm, 6 mm and 8 mm tappings, the throat pressure tappings were of constant diameter for a length of 94 mm and the upstream tappings for a length of 53 mm. As actually manufactured the 1 mm and 2 mm tappings were much shorter; over the distance between the interior of the Venturi tube and the ¼" BSP fitting there could be up to two changes in tapping diameter. AP1 had four 4 mm tappings upstream and four 2 mm tappings in the throat. In both cases the tappings were connected by annular chambers. The 4 mm tappings were of length 10 mm and the 2 mm tappings were described on the drawing as being of minimum length 8 mm.

## 3 CALIBRATION IN WATER

The Venturi tubes were calibrated first in water at NEL. In order to investigate whether the performance of tappings connected in a triple-T differed from that of single tappings, data were collected with a single pair of 4 mm tappings as well as with triple-T tappings in the case of 29478 and 29479; the tappings used were those of the highest quality as determined by visual inspection. The pairs of single tappings were given a single letter, e.g. 'A' or 'B'. For each Venturi tube the data in water lay on a straight line as a function of pipe Reynolds number, $Re_D$, and with a small scatter, provided that $Re_D$ was above a critical value. The pipe Reynolds number below which $C$ was not on the straight line, varied, but was typically about $3 \times 10^5$. In the case of 29480 there was a significant hump in the data at $Re_D \approx 2.5 \times 10^5$.

The differences between data taken with single tappings and those with triple-T tappings are surprisingly large. They imply that much of the scatter in discharge coefficient from one apparently similar Venturi tube to another is due to the pressure tappings, and therefore if a Venturi tube is used uncalibrated the use of single tappings instead of triple-T tappings (or other multiple pressure tappings) will result in increased uncertainty.

## 4 CALIBRATION IN GAS

The Venturi tubes were calibrated in nitrogen at NEL at two static pressures, 20 bar and 60 bar. Although this paper deals with discharge coefficients largely in terms of Reynolds number there is an effect of throat velocity in many of the sets of data, where peaks and troughs of discharge coefficient occur for both static pressures at the same throat velocity.

## 5 ANALYSIS

Much work had been undertaken previously [3-7] to determine the best fit for the discharge coefficient for standard Venturi tubes and for those of different convergent angles. It was observed that some of the variation in $C$ can be removed by examining $C - C_{water}$ where $C_{water}$ is the mean value for the water data for that Venturi tube. One cause for the change in discharge coefficient is static hole error, which is the effect that pressure tappings of finite size do not measure the pressure which would have been measured using an infinitely small hole. The effect of static hole error is that the measured pressure using a pressure tapping is higher than the static pressure would have been if the tapping had not been present. Since the effect at the upstream tapping is much smaller than the effect at the throat tapping it is possible simply to correlate the data with the throat tapping Reynolds number; the simplest presentation of this is to define the Venturi throat tapping Reynolds number

$$Re^* = \frac{d_{tap}}{d} Re_d \ , \qquad (1)$$

where $d_{tap}$ is the diameter of the throat tapping and $Re_d$ is the throat Reynolds number, which is equal to $Re_D/\beta$.

Then for each set of data it is found that

$$C - C_{water} = a - b\,e^{-0.4(Re^*/10^5)} \ , \qquad (2)$$

where $a$ and $b$ are coefficients to be determined. For sets of data collected both in this project and previously it is possible to determine both the coefficients in Equation (2) and the scatter about the resulting equation. Going beyond the work in [3 – 7], it was desirable both to examine the water and gas data together since the objective is to obtain an equation which fits all the data and to plot all the data against the exponential function of $Re^*$ in Equation (2) rather than against $Re^*$ itself. In Figures 2 - 10 some of the new data from this project are presented: all the data for Venturi tube 29478 are presented. For other Venturi tubes only the data taken with triple-T 4 mm tappings are presented. In each case data for $Re_D < 2 \times 10^5$ have been excluded as the discharge coefficient tends to decrease as the Reynolds number decreases below this point. Data for $Re^* < 20000$ have also been excluded as the static hole error decreases rapidly as $Re^*$ decreases below this point. Where data in water start to depart from a linear fit to the data as the Reynolds number decreases, for instance to form a hump, all the data below an appropriate Reynolds number have been excluded.

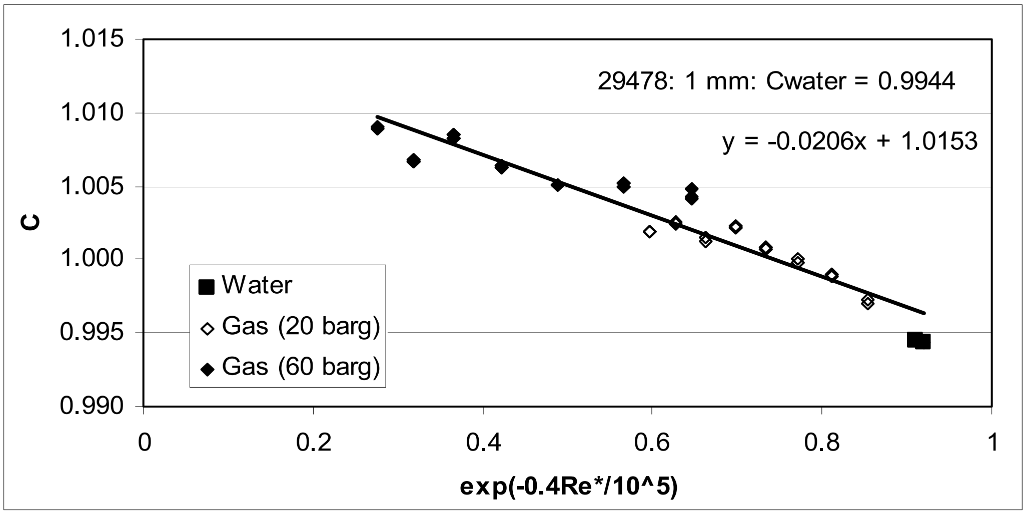


**Fig. 2 All data for Venturi tube 29478 (rounded corners, long) (1 mm tappings)**

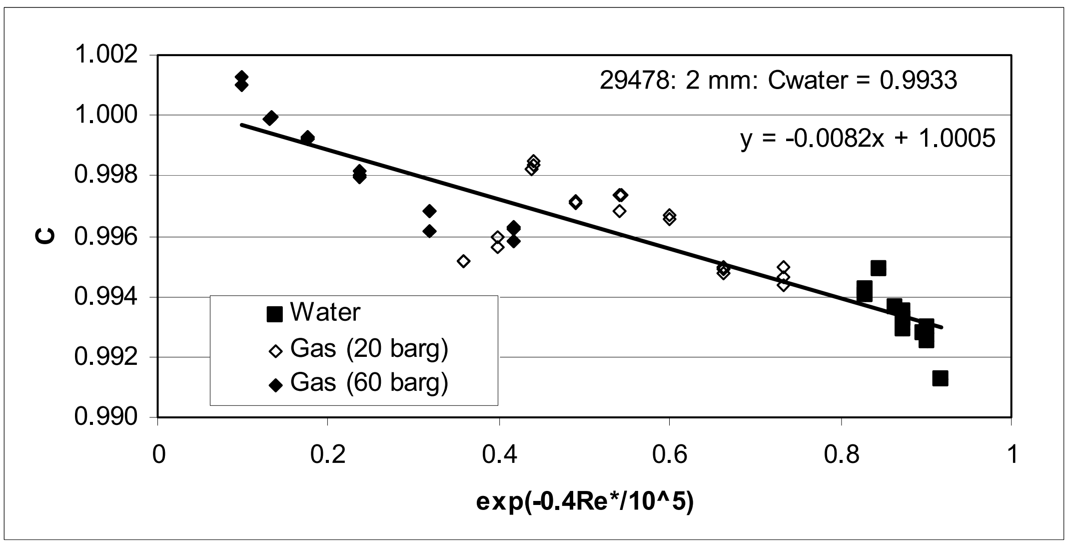


**Fig. 3 All data for Venturi tube 29478 (rounded corners, long) (2 mm tappings)**

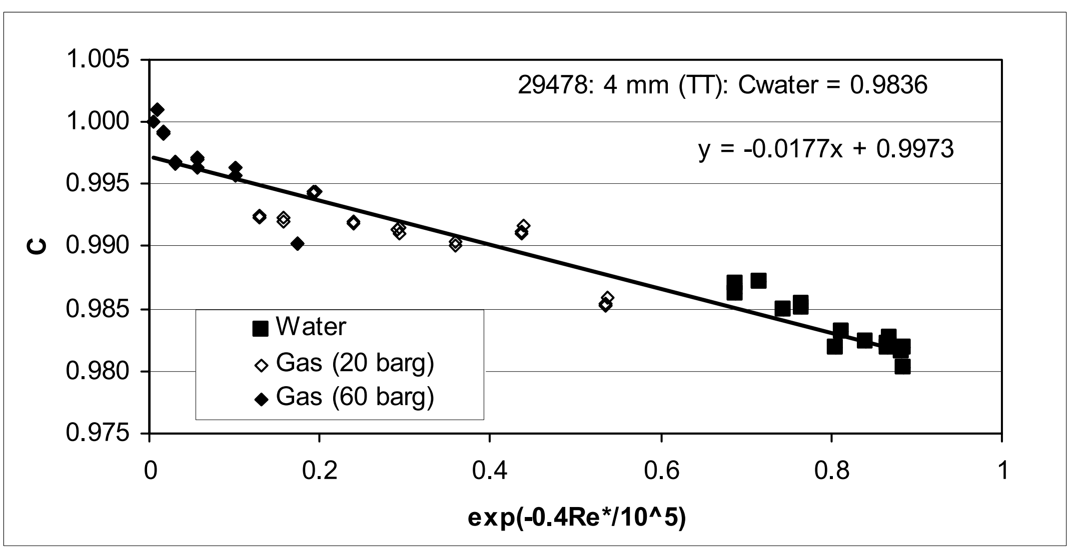


**Fig. 4 All data for Venturi tube 29478 (rounded corners, long) (4 mm (triple-T) tappings)**

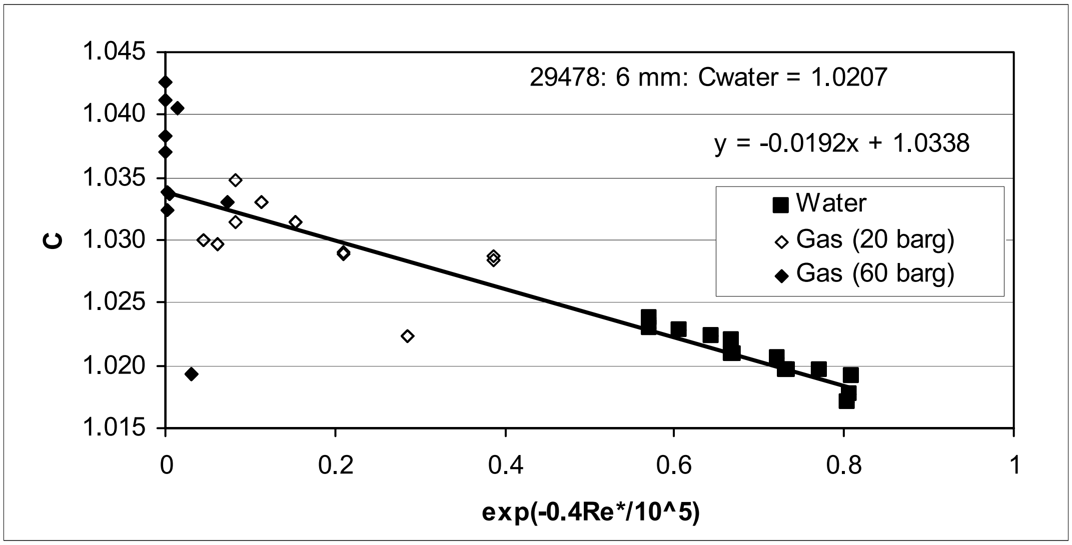


**Fig. 5 All data for Venturi tube 29478 (rounded corners, long) (6 mm tappings)**

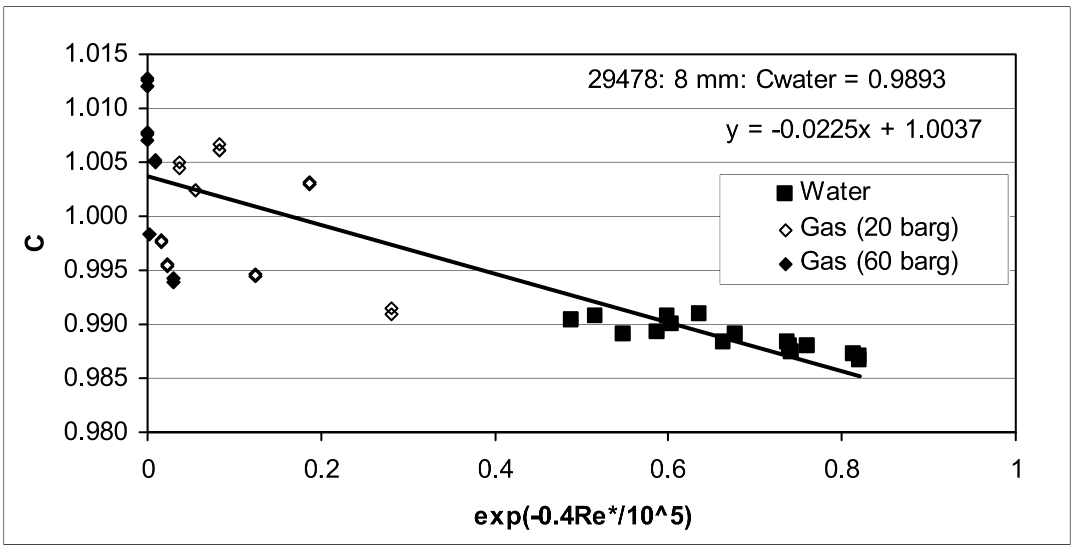


**Fig. 6 All data for Venturi tube 29478 (rounded corners, long) (8 mm tappings)**

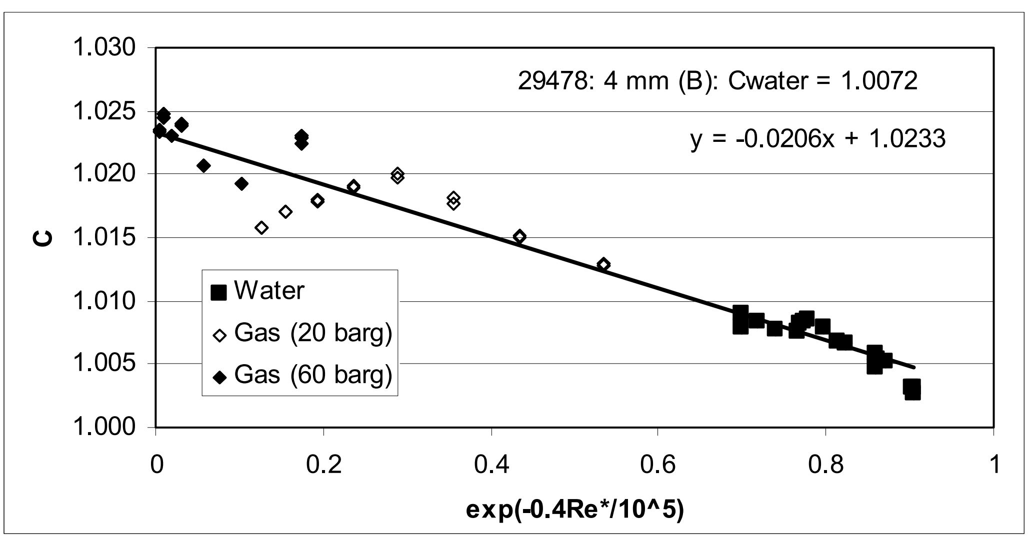


**Fig. 7 All data for Venturi tube 29478 (rounded corners, long) (4 mm ('B') tappings)**

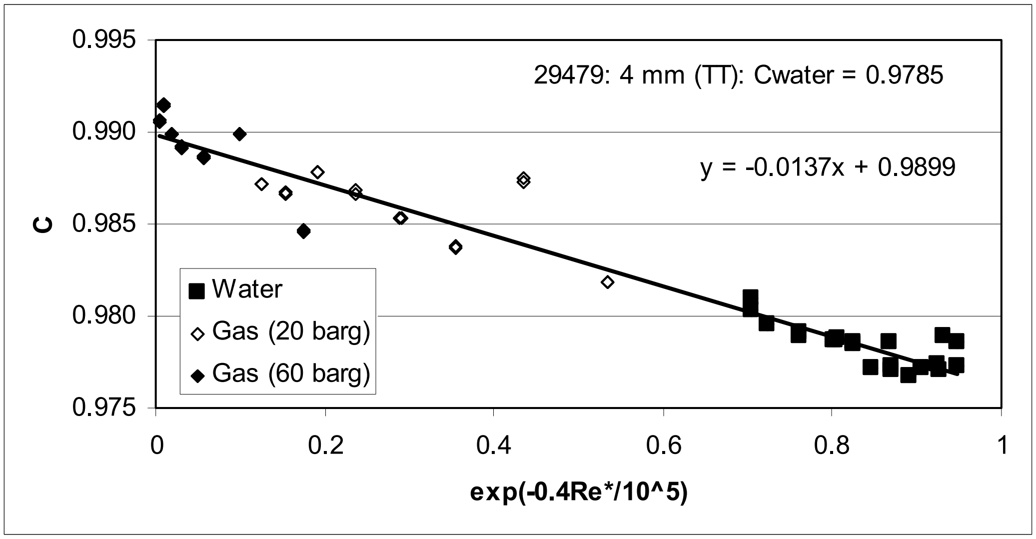


**Fig. 8 All data for Venturi tube 29479 (curved, long) (4 mm (triple-T) tappings)**

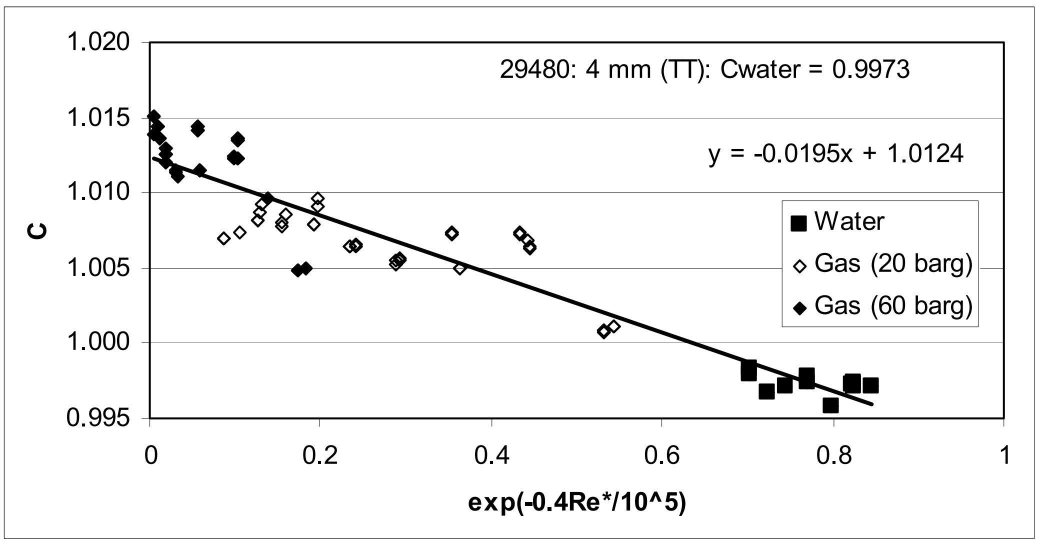


**Fig. 9 All data for Venturi tube 29480 (curved) (4 mm (triple-T) tappings)**

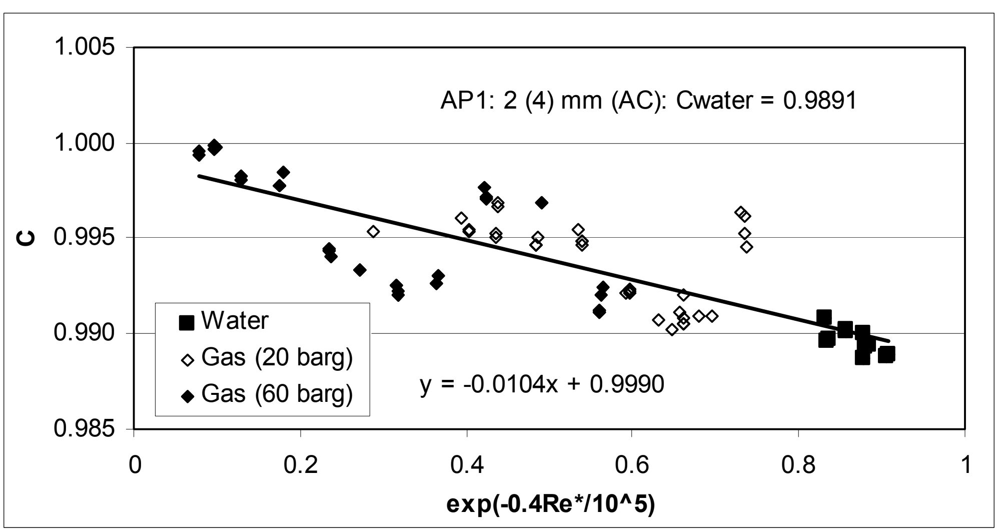


**Fig. 10 All data for Venturi tube AP1 (rounded corners)**

From this work the good agreement between water and gas data is clear. The line fits from Figures 2 – 10 and the other data collected but not presented here are presented in Table 1, which shows the line fits in terms both of $C$ and of $C - C_{water}$ and the standard deviation of the data about the line fits.

| N.B. (inch) | $\beta$ | Venturi shape | Serial No | Type of Tappings | $C$ | $C - C_{water}$ | Standard deviation |
|---|---|---|---|---|---|---|---|
| 4 | 0.6 | Rounded corners, long | 29478 | 1 mm | 1.0153 – 0.0206*x* | 0.0209 – 0.0206*x* | 0.00129 |
| 4 | 0.6 | Rounded corners, long | 29478 | 2 mm | 1.0005 – 0.0082*x* | 0.0072 – 0.0082*x* | 0.00105 |
| 4 | 0.6 | Rounded corners, long | 29478 | 4 mm (triple-T) | 0.9973 – 0.0177*x* | 0.0137 – 0.0177*x* | 0.00191 |
| 4 | 0.6 | Rounded corners, long | 29478 | 6 mm | 1.0338 – 0.0192*x* | 0.0131 – 0.0192*x* | 0.00416 |
| 4 | 0.6 | Rounded corners, long | 29478 | 8 mm | 1.0037 – 0.0225*x* | 0.0144 – 0.0225*x* | 0.00478 |
| 4 | 0.6 | Rounded corners, long | 29478 | 4 mm ('B') | 1.0233 – 0.0206*x* | 0.0161 – 0.0206*x* | 0.00183 |
| 4 | 0.6 | Curved, long | 29479 | 1 mm | 0.9893 – 0.0062*x* | 0.0051 – 0.0062*x* | 0.00056 |
| 4 | 0.6 | Curved, long | 29479 | 2 mm | 0.9923 – 0.0109*x* | 0.0101 – 0.0109*x* | 0.00112 |
| 4 | 0.6 | Curved, long | 29479 | 4 mm (triple-T) | 0.9899 – 0.0137*x* | 0.0114 – 0.0137*x* | 0.00123 |
| 4 | 0.6 | Curved, long | 29479 | 6 mm | 1.0102 – 0.0243*x* | 0.0179 – 0.0243*x* | 0.00215 |
| 4 | 0.6 | Curved, long | 29479 | 8 mm | 0.9674 – 0.0172*x* | 0.0096 – 0.0172*x* | 0.00362 |
| 4 | 0.6 | Curved, long | 29479 | 4 mm ('A') | 1.0004 – 0.0189*x* | 0.0154 – 0.0189*x* | 0.00169 |
| 4 | 0.6 | Curved | 29480 | 2 mm | 1.0096 – 0.0144*x* | 0.0135 – 0.0144*x* | 0.00172 |
| 4 | 0.6 | Curved | 29480 | 4 mm (triple-T) | 1.0124 – 0.0195*x* | 0.0151 – 0.0195*x* | 0.00196 |
| 4 | 0.6 | Curved | 29480 | 6 mm | 1.0167 – 0.0225*x* | 0.0165 – 0.0225*x* | 0.00262 |
| 4 | 0.6 | Curved | 29480 | 8 mm | 1.0130 – 0.0280*x* | 0.0170 – 0.0280*x* | 0.00373 |
| 4 | 0.6 | Rounded corners | AP1 | 2 mm throat, 4 mm upstream: annular chambers | 0.9990 – 0.0104*x* | 0.0099 – 0.0104*x* | 0.00193 |

**Table 1 Equations fitted to water and gas data collected in this project: $x$ represents $\exp(-0.4Re^*/10^5)$**

Given that the standard deviation depends on the tapping size it is desirable also to see how for 4-inch $\beta = 0.6$ Venturi tubes with 4 mm triple-T tappings the standard deviation depends on the shape of the Venturi tube. To do this the data in [3, 4 and 7] for two standard Venturi tubes 28909 and 28909C and for two Venturi tubes 98488 and 98491 which were standard except for convergent angles 10.5° and 31.5° respectively have been analysed. The water and gas data are shown in Figures 11 - 14.

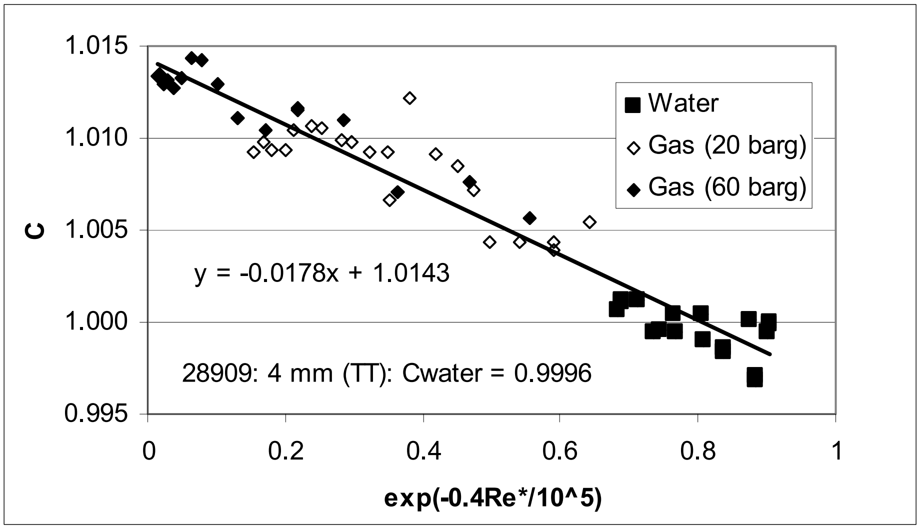


**Fig. 11 All data for Venturi tube 28909 (standard) (4 mm (triple-T) tappings)**

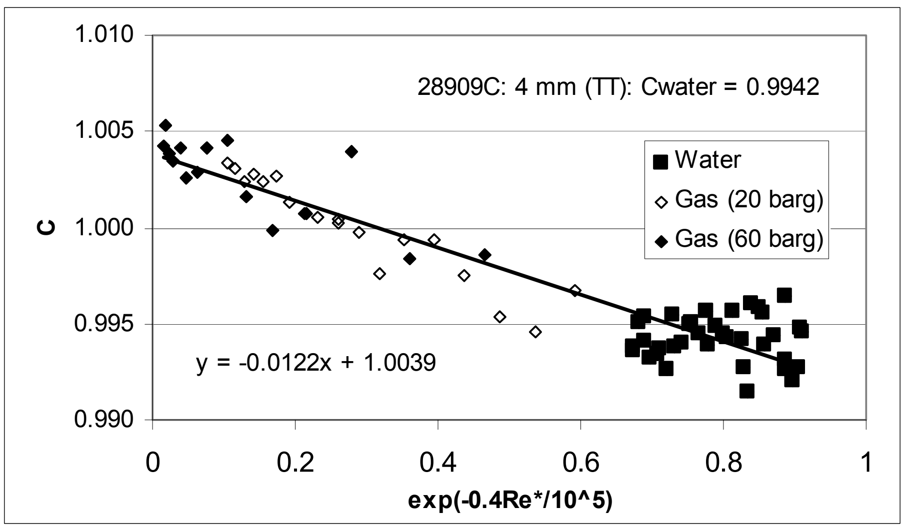


**Fig. 12 All data for Venturi tube 28909C (standard) (4 mm (triple-T) tappings)**

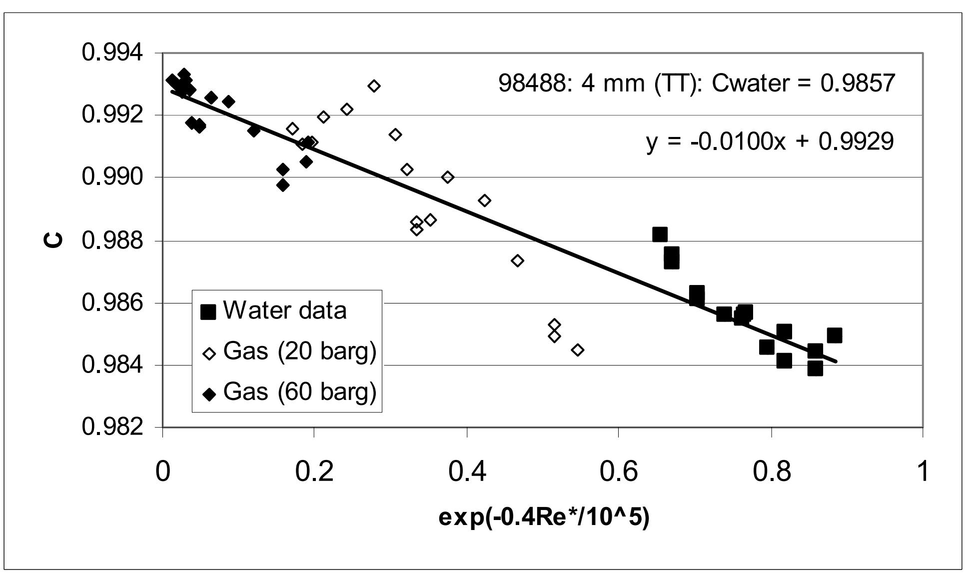


**Fig. 13 All data for Venturi tube 98488 (10.5° convergent angle) (4 mm (triple-T) tappings)**

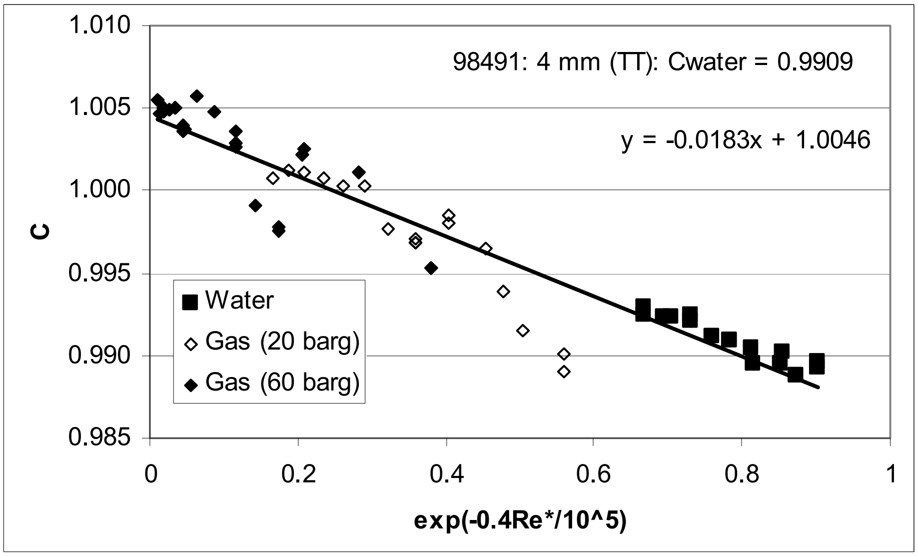


**Fig. 14 All data for Venturi tube 98491 (31.5° convergent angle) (4 mm (triple-T) tappings)**

The equations for 4-inch $\beta$ = 0.6 Venturi tubes with 4 mm triple-T tappings (and the data from AP1 with annular chambers) are then presented in Table 2.

| N.B. (inch) | $\beta$ | Venturi shape | Serial No | Type of Tappings | $C$ | $C - C_{water}$ | Standard deviation |
|---|---|---|---|---|---|---|---|
| 4 | 0.6 | Rounded corners, Long | 29478 | 4 mm (triple-T) | 0.9973 – 0.0177$x$ | 0.0137 – 0.0177$x$ | 0.00191 |
| 4 | 0.6 | Curved, Long | 29479 | 4 mm (triple-T) | 0.9899 – 0.0137$x$ | 0.0114 – 0.0137$x$ | 0.00123 |
| 4 | 0.6 | Curved | 29480 | 4 mm (triple-T) | 1.0124 – 0.0195$x$ | 0.0151 – 0.0195$x$ | 0.00196 |
| 4 | 0.6 | Rounded corners | AP1 | 2 mm throat, 4 mm upstream annular chambers | 0.9990 – 0.0104$x$ | 0.0099 – 0.0104$x$ | 0.00193 |
| 4 | 0.6 | Standard | 28909 | 4 mm (triple-T) | 1.0143 – 0.0178$x$ | 0.0147 – 0.0178$x$ | 0.00140 |
| 4 | 0.6 | Standard | 28909C | 4 mm (triple-T) | 1.0039 – 0.0122$x$ | 0.0097 – 0.0122$x$ | 0.00138 |
| 4 | 0.6 | 10.5° Convergent | 98488 | 4 mm (triple-T) | 0.9929 – 0.0100$x$ | 0.0072 – 0.0100$x$ | 0.00111 |
| 4 | 0.6 | 31.5° Convergent | 98491 | 4 mm (triple-T) | 1.0046 – 0.0183$x$ | 0.0137 – 0.0183$x$ | 0.00167 |

**Table 2 Equations fitted to water and gas data for 4-inch $\beta$ = 0.6 Venturi tubes with triple-T tappings or annular chambers**

On the basis of Table 2 it appears that the best choice for subsequent work is the Venturi tube with sharp corners which is standard except for a convergent angle of 10.5°. Since two Venturi tubes of this shape have already been manufactured and tested, numbers 98487 and 98489 of diameter ratio 0.4 and 0.75 respectively, their water and gas data are shown in Figures 15 and 16 for comparison. The equations for 4-inch Venturi tubes with 10.5° convergent angles and 4 mm triple-T tappings are presented in Table 3.

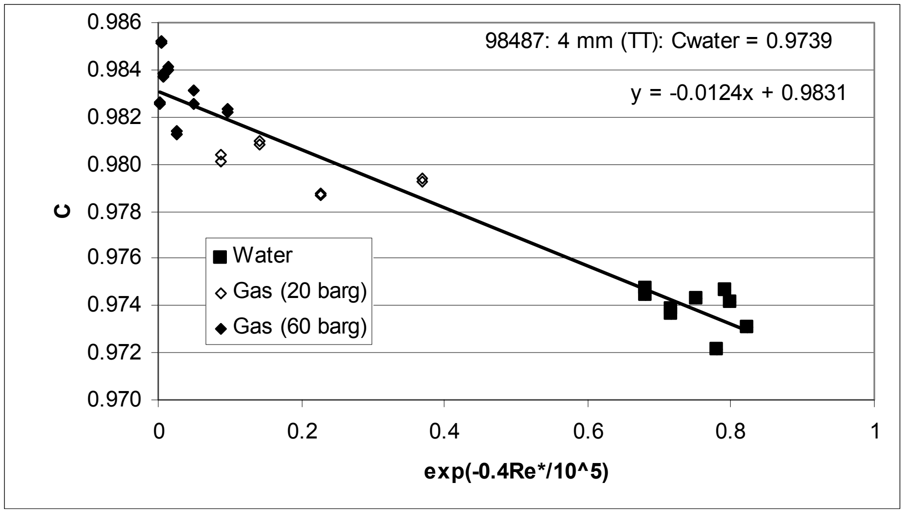


**Fig. 15 All data for Venturi tube 98487 (4 mm (triple-T) tappings, 10.5° convergent angle, $\beta$ = 0.4)**

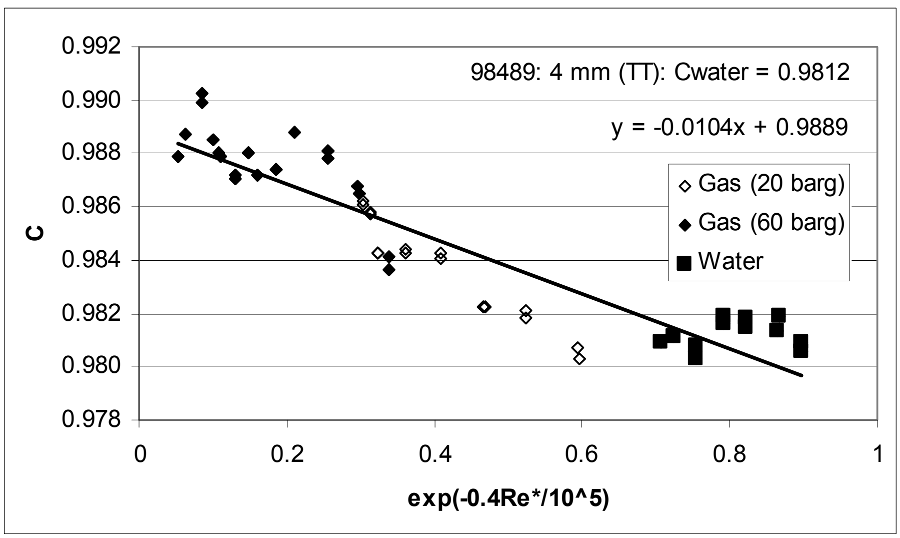


**Fig. 16 All data for Venturi tube 98489 (4 mm (triple-T) tappings, 10.5° convergent angle, $\beta$ = 0.75)**

| N.B. (inch) | $\beta$ | Venturi shape | Serial No | Type of Tappings | $C$ | $C - C_{water}$ | Standard deviation |
|---|---|---|---|---|---|---|---|
| 4 | 0.4 | 10.5° Convergent | 98487 | 4 mm (triple-T) | $0.9831 - 0.0124x$ | $0.0092 - 0.0124x$ | 0.00111 |
| 4 | 0.6 | 10.5° Convergent | 98488 | 4 mm (triple-T) | $0.9929 - 0.0100x$ | $0.0072 - 0.0100x$ | 0.00111 |
| 4 | 0.75 | 10.5° Convergent | 98489 | 4 mm (triple-T) | $0.9889 - 0.0104x$ | $0.0077 - 0.0104x$ | 0.00124 |

**Table 3 Equations fitted to water and gas data for 4-inch Venturi tubes with 10.5° convergent angles and 4 mm triple-T tappings**

On the basis of Table 3 it is clear that the relationship between water and gas data as expressed by the equations for $C - C_{water}$ is remarkably similar for the three Venturi tubes. This is obviously very advantageous if it is repeated for a larger population of such Venturi tubes. The standard deviation is very low. Moreover, the fact that the slope is small and corresponds well to the effect of static hole error as computed by CFD [7, 11] is encouraging.

One other area which is of great interest is the effect of tapping size on Venturi tube discharge coefficients. It is clear from Table 1 that for these three Venturi tubes manufactured the standard deviation increases for tapping sizes greater than 4 mm. It is obviously important to establish whether the same is true for standard Venturi tubes. Within the previous work [5] two Venturi tubes, 28908 and 28911, of diameter ratio 0.5 and 0.7 respectively, had tapping sizes modified. Given that the tappings for smaller tapping sizes were achieved using inserts those data have not been reanalysed here. However, the 8 mm tappings were obtained by drilling, and those data together with the 4 mm tapping data have been reanalysed here, although they are not plotted here.

| N.B. (inch) | $\beta$ | Venturi shape | Serial No | Type of Tappings | $C$ | $C - C_{water}$ | Standard deviation |
|---|---|---|---|---|---|---|---|
| 4 | 0.5 | Standard | 28908 | 4 mm (triple-T) | $1.0130 - 0.0195x$ | $0.0156 - 0.0195x$ | 0.00116 |
| 4 | 0.5 | Standard | 28908 | 8 mm | $1.0098 - 0.0326x$ | $0.0195 - 0.0326x$ | 0.00409 |
| 4 | 0.5 | Standard | 28908 | 4 mm ('A') | $1.0181 - 0.0264x$ | $0.0203 - 0.0264x$ | 0.00242 |
| 4 | 0.7 | Standard | 28911 | 4 mm (triple-T) | $1.0207 - 0.0206x$ | $0.0173 - 0.0206x$ | 0.00200 |
| 4 | 0.7 | Standard | 28911 | 8 mm | $1.0089 - 0.0176x$ | $0.0111 - 0.0176x$ | 0.00376 |
| 4 | 0.7 | Standard | 28911 | 4 mm ('A') | 1.0202 – 0.0199x | 0.0155 – 0.0199x | 0.00194 |

**Table 4 Equations fitted to water and gas data for 4-inch Venturi tubes with $\beta$ = 0.5 and 0.7**

On the basis of Table 1 and Table 4 it is possible to see the effect of the size of pressure tappings on the standard deviation. Data from Venturi tubes with more than one size of pressure tapping are given in Figure 17. The 4 mm single tapping and triple-T tapping data are slightly offset from 4 mm so that they can be distinguished. It is interesting to note that the standard deviation increases rapidly as the tapping size increases from 4 mm to 6 mm. This may be a significant part of the reason why commercial Venturi tubes, whose pressure tappings are often of diameter 6 mm, perform significantly worse when calibrated in gas at NEL than Venturi tubes manufactured for the Flow Programme, whose pressure tappings are normally of diameter 4 mm. Whether 4 mm triple-T tappings actually perform significantly better as regards standard deviation than 4 mm single tappings is not clear. The main advantage of triple-T tappings is that when a Venturi tube is used uncalibrated the discharge coefficient is likely to be closer to the expected value for that type of Venturi tube than if a single tapping were used. They must also require shorter upstream lengths downstream of some fittings.

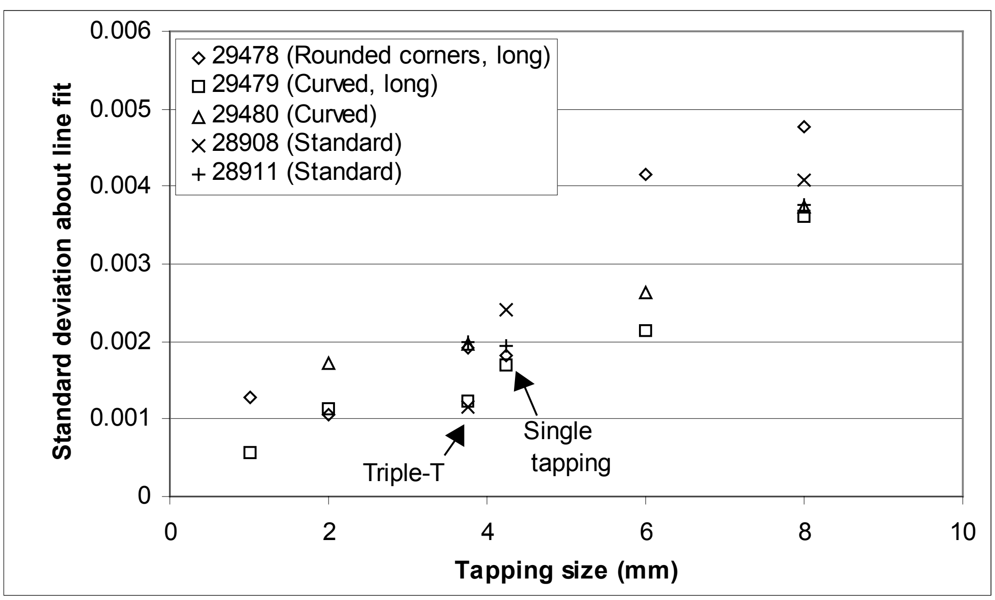


**Fig. 17 The standard deviation of the water and gas data about the line fit as a function of tapping size**

The slopes of the different fits versus $\exp(-0.4Re^*/10^5)$ are plotted in Figure 18 as a function of the tapping size for those Venturi tubes with more than one size of pressure tapping. It is noticeable that the slopes increase in absolute value with tapping size and that the spread of slope values is smaller for tapping sizes in the range from 2 mm to 6 mm than it is for tapping sizes of 1 mm or 8 mm.

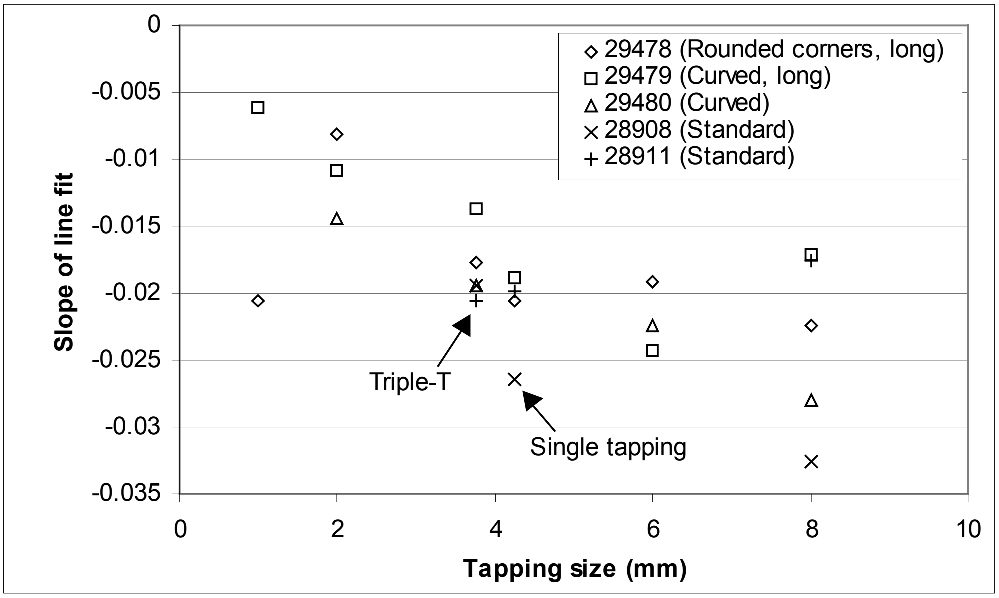


**Fig. 18 The slope of the water and gas data about the line fit versus exp(-0.4*Re**/10$^5$) as a function of tapping size**

## 6 CONCLUSIONS

Three Venturi tubes have been manufactured, and four Venturi tubes calibrated in water and high-pressure gas. All were of diameter 100 mm and had diameter ratio 0.6, but they had different profiles for the convergent. The data have been presented against a function of throat-tapping-hole Reynolds number. The agreement between water and gas data is very good.

The standard deviation of the data about the best-fit line has been determined for each set of the new data and for each set of data from previous projects with the same diameter and diameter ratio but different convergent profiles. The best convergent profile has been determined to be one with a 10.5° included angle with sharp corners on the basis that it gives the lowest standard deviation of the data about the fitted line. Two other Venturi tubes with this particular profile have already been calibrated in water and gas; when they were evaluated in the same way the standard deviations of the data about best-fit lines were low. Moreover, for all three the slope of the line fit was very similar. It has therefore been decided that additional Venturi tubes of diameter 50 mm and 150 mm should be manufactured with a 10.5° included angle and sharp corners where the convergent meets the throat and the upstream cylinder.

The three Venturi tubes manufactured within this project had single pairs of tappings of diameter 1 mm (except for one Venturi tube), 2 mm, 6 mm, and 8 mm and four pairs of tappings of diameter 4 mm. Data could be collected with a single pair of 4 mm tappings or using all four pairs connected in triple-Ts. All the work to determine the best profile used 4 mm tappings in triple-Ts. The same process of evaluation used to determine the best profile showed that 8 mm tappings and, to a lesser extent, 6 mm tappings gave worse performance than smaller sizes. Moreover, the data collected with different tapping hole sizes helped to confirm that an equation based on a static-hole-error model is appropriate. The additional Venturi tubes to be manufactured will therefore have a single pair of tappings of diameter 2 mm and four pairs of tappings of diameter 4 mm.

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## NOTATION

| | | |
|---|---|---|
| $C$ | Discharge coefficient | - |
| $C_{water}$ | Mean discharge coefficient in water | - |
| $D$ | Diameter of entrance cylinder | m |
| $d$ | Throat diameter | m |
| $d_{tap}$ | Tapping hole diameter | m |
| $R_a$ | Arithmetic mean deviation of the roughness profile | m |
| $Re_D$ | Pipe Reynolds number | - |
| $Re_d$ | Throat Reynolds number | - |
| $Re^*$ | Venturi throat tapping Reynolds number (= $Re_d d_{tap}/d$) | - |
| $x$ | Function of $Re^*$ (=exp(-0.4$Re^*/10^5$)) | - |
| $\beta$ | Diameter ratio (= $d/D$) | - |

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