Published paper
Ahmadi, A. and Beck, S.B.M. (2005) *Development of the orifice plate with a cone swirler flow conditioner.* Sensor Review, 25 (1). pp. 63-68.
http://dx.doi.org/10.1108/02602280510577861

Development of the orifice plate with a swirler flow conditioner

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Abstract

The sensitivity of orifice plate metering to poor conditioned flow and swirling flow are subjects of concerns to flow meter users and manufacturers. The distortions caused by pipefittings and pipe installations upstream of the orifice plate are major sources of poorly conditioned and swirling flow. These distortions will alter the accuracy of metering by an unacceptable degree up to 7% error in standard discharge coefficient. So the design of orifice plate meters that are independent of the initial flow conditions of the upstream is a major object of flow metering. This goal is usually conducted by using a flow conditioner. The purpose of the present paper is to describe the development of the orifice plate combined with swirler flow conditioner that is insensitive to upstream disturbances. The experimental results by using the new swirler flow conditioner shows this flow conditioner can attenuate the effect of both swirling and asymmetric flow on metering to an acceptable level.

Keywords: orifice, asymmetric, swirling flow, swirler flow conditioner

Nomenclature

β	Ratio of the orifice diameter on the pipe diameter
C	Discharge coefficient
Δ**p**	Differential pressure across the orifice
d	Diameter of the orifice
D	Diameter of the pipe
ε	Expansion factor $\varepsilon = 1-(0.41+0.35\beta^4)\dfrac{\Delta p}{\kappa \times p}$
L_1	Distance of the upstream tapping from the upstream face of the plate
L_2	Distance of the downstream tapping from the downstream face of the plate
Re	Reynolds number of the flow (related to the pipe diameter)
ρ	Density of the fluid
P	Pressure (static)
Re_D	Reynolds number of the flow
μ	Dynamics viscosity
ν	Kinematic viscosity

V Velocity

C^* New discharge coefficient with the swirler

K Correction factor for different value of β and for an orifice plate with the swirler

Introduction

The differential pressure flowmeter is the most common form of flowmeter used in industry. According to recent market studies this kind of flowmeter accounts for about half of all industrial flowmeter used in industry and the next most common flowmeter technology is used in less than 15 percent of flow measurements [1]. Many types of differential flow meters are used in industry and among them the orifice plate flowmeter is the most common form of differential pressure flowmeter. The reasons for this are that the orifice plate is simple to construct, has a low maintenance cost and wide applicability to different fluids including both liquids and gases. In addition, there is a great weight of experience to confirm its operation and installation, which is documented in both BS 1042[2] and ISO 5167 [3].

It is well known that the accuracy of this flowmeter is about 0.5 to 1 % when supplied with a well-conditioned velocity profile [1]. The most important assumption of well-conditioned flow is that the flow approaching the orifice plate must be fully developed and free of any asymmetry or swirl. In practical applications, however pipe fittings and pipe installations such as valves, bends, heat exchangers, compressors and other devices can generate a distorted and swirling flow profile. These distortions can alter the accuracy of orifice plate up to 4% error in asymmetric velocity profile [4] and from 3% up to 7% error for swirling flow generated by a double 90 degree elbows in perpendicular [5,6]. In order to produce a fully developed flow, which is free from all disturbances, a long and straight pipe must be installed before the orifice plate in upstream. British Standard or ISO recommends a minimum straight length upstream of the meter that depends on Reynolds number, pipe diameter, orifice diameter, the ratio of pipe diameter to hole diameter (β) and the pipe fitting [7]. In general, this requirement means that at least 10 pipe diameters of smooth straight pipe is required for orifice plates with small holes increasing to 36 pipe diameters for plates with large ones [7]. In many installations it is impossible to provide a sufficiently long straight pipe upstream of the meter to remove flow disturbances. In these circumstances, flow conditioners and flow straighteners can be placed upstream to remove disturbances in the flow, which reduce the number of straight upstream pipe lengths required for accurate flow measurement.

In general a flow straightener is a device that removes a swirl from the flow and has a little effect on asymmetrical velocity profile. On the other hand a flow conditioner is a device that not only removes swirl but also produces a repeatable downstream velocity irrespective of the upstream flow disturbances. Thus most flow conditioners are used to avoid unwanted shifts in the meter's calibration by reducing the effect of upstream disturbances on the meter to an insignificant level. It is desirable for a good flow conditioner to fulfil its duty within the following requirements, a low-pressure loss across the device, a short upstream length of the device from source of disturbances, a short downstream length from the orifice plate and also easy installation. However, even in the best performance of flow conditioners, they are needed to be installed at least 2 pipe diameters from the disturbances and also 4 or 5 pipe diameters from the orifice plate [8]. So, great efforts have been expended to achieve a flow conditioner that will perform with a lower number of pipe lengths and minimum pressure drop across it [9,10,11].

There is a lot of flow conditioner, which are used in flow industry included in the British and ISO standards or given from the technical reports [2,3]. A flow conditioner is introduced by Canada pipeline called CPA 50E. This flow conditioner is a perforated plate, which can provide a repeatable swirl free and fully developed velocity profile for high-pressure natural gas application [12]. A new device, a vane perforated plate, is described as meeting the velocity profile requirement of ISO 5167, positioned six pipe diameters upstream of the orifice plate and produced pressure loss of about 1.4 dynamic heads [13].. Two kinds of new flow conditioner called In-line flow conditioning plate [14] and AS-FC flow conditioner [15] claiming they can too make a fully developed velocity profile with a low pressure lost. In other references, the efficiency of standard flow conditioner at reducing the effect of disturbed flow consists of asymmetric velocity profile and swirling flow was conducted [16].

All flow conditioners, both those are introduced in standards and ones introduced in technical reports can be categorized into two basic groups: turbulent mixing devices and vortex action devices [8]. In the turbulent mixing devices swirl and asymmetric are removed in a turbulent mixing zone 1 to 2 pipe diameters downstream of the conditioners. Examples of turbulent mixing devices include perforated plates, tube bundles and Sprinkles flow conditioner. In vortex action devices, swirl and flow distortion are removed mainly by vortex action within the passage of the conditioner. For instance etoile, AMCA, swirl-vor-tab and honeycomb flow conditioners can be laid in this category. Generally all flow conditioners are aiming either to supply a flow in a settled fully developed state same as turbulent mixing devices or to achieve a repeatable constant velocity profile independent of source of disturbances same as vortex action devices.

An approach to the flow conditioner basis of vortex action is to use a device at the short distance upstream of the orifice plate, which makes a strong swirl or disturbance that will absorb all the disturbances in a predetermined manner. This device creates a predetermined flow condition, which would be independent of the upstream conditions. Therefore the strong disturbed flow that is made by the swirler device can absorb other unknown and unwanted disturbances and achieves a repeatable velocity profile independent of disturbances [17].

The study of using a twisted piece of plastic that was positioned 1.5 pipe diameters upstream as a flow conditioner was carried out in an experimental rig using air as the working fluid [17]. This experimental work carried out for a 76 mm pipe with β=0.5 and different Reynolds number. The flow was disturbed in upstream of the orifice plate by fixing different shaped blocks in a 3.5 to 4.5 pipe diameters of the orifice plate. The results showed that this block produced up to 4% shift in measuring flow based on the equation in the British Standard [3]. The application of using a swirler flow conditioner for higher Reynolds numbers and different orifice diameters has been conducted in experimental water rig for 20 D upstream and 10 D downstream of the orifice plate with ß, 0.4 to 0.7. The measurements of flow rate were carried out for a wide variety of Reynolds number from 14000 up to 70000 for standard and non-standard velocity profile. In this rig the swirler conditioner was placed in 1.5 pipe diameter in upstream and the disturbed flow was produced by using a blocks and swirler disturbances. The effect of these disturbances on mass flow showed the effect of asymmetric velocity profile is about up 3 % shift in discharge coefficient for low Reynolds number and about 1.5 % for high Reynolds number for ß=0.4 and ß=0.7 respectively. The results of the using swirler conditioner individually also represented this device can shift the discharge coefficient up to average 5%. Also the experiment revealed the swirler flow conditioner could attenuate the distortion of different disturbances so that the shift in discharge coefficient can be kept same as the condition which swirler conditioner used in pipeline. Beside calibration of swirler conditioner represented the new discharge coefficient appropriate with different ß can be change from 1.027 to 1.04 for ß=0.7 to ß=0.4 [18]. In the pervious experiments with swirler flows conditioner, different kinds of block disturbances have been used in air rig. The result showed although this swirler can dampen the distortion due to block disturbances up to 4 to 5% shift in discharge coefficient but has a less effect on swirling flow particularly in high velocities [18]. Thus the focus of this study is to examine the effect of different shape of swirler flow conditioner in damping disturbances due to different kind of disturbances. These experiments were carried out with water and air flow in two rigs with both high Reynolds numbers and low Reynolds number.

Reference formula

The pressure drop across the orifice plate and mass flow rate are linked by equation [2]:

$$q_m = \frac{C}{\sqrt{1-\beta^4}} \varepsilon \frac{\pi}{4} d^2 \sqrt{2\Delta p \rho} \tag{1}$$

Where, here C is the discharge coefficient that depends on the type of used differential flowmeter. For instance, for a D and D/2 orifice plate flowmeter this coefficient is:

$$\begin{aligned} C &= 0.5959 + 0.0312\beta^{2.1} - 0.184\beta^{8} + 0.0029\beta^{2.5}\left[\frac{10^6}{\mathrm{Re}_D}\right]^{0.75} \\ &+ 0.09\frac{L_1}{D}\beta^4\left(1-\beta^4\right)^{-1} - 0.0337\frac{L_2}{D}\beta^3 \end{aligned} \tag{2}$$

Where, $\beta = d / D$, is of the orifice diameter to pipe diameter.

Variation of the discharge coefficient

In the examining of the effect of the disturbance on mass flow rate this effect on discharge coefficient has been tested. . According to the British Standard the flow rate was determined from differential pressure measured through the orifice plate [2]. For a fully developed velocity profile either the standard discharge coefficient (C_{d0}) can be used to calculate mass flow rate or mass flow rate can used to calculate standard discharge coefficient. Nevertheless in a disturbed flow by having a mass flow the new discharge coefficient (C_d) can be calculated from reference formula. Thus the percentage shift of the discharge coefficient ΔCd (%) can be determined as below:

$$\Delta C_d = \left[\frac{C_{d0} - C_d}{C_{d0}} \right] \times 100$$

This percentage has been used to find out how much change can occur in standard discharge coefficient due to disturbances.

Experimental Rig

In order to assess the effect of disturbed flow on the orifice plate two experimental rigs have been built for both air and water. In these rigs, the mass flow rate of the orifice plate with both standard and non-standard velocity profiles has been measured for different Reynolds number and β ratio. Through the experimental work the accuracy of the standard orifice plate with no disturbances also was compared with the British Standard [3].

For the water rig, a smooth 32 mm internal diameter pipe with 20 and 10 pipe diameters upstream and downstream respectively was used (Figure 1). For measuring the pressure difference, two pressure tapping were used D upstream and D/2 downstream of the plate. The pressure drop across the orifice plate was measured by using both a U tube water manometer and a pressure transducer, which were connected to the pressure tapping.

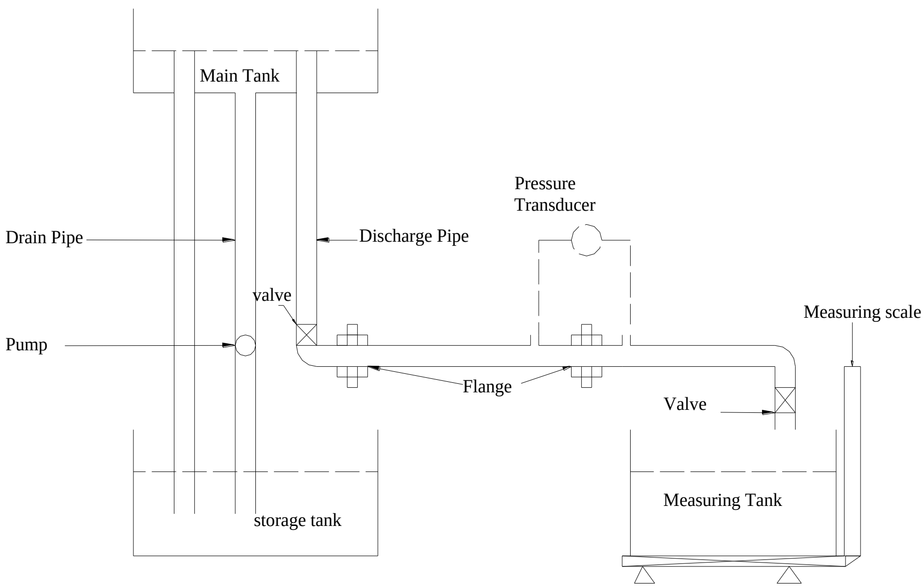

Figure 1- The sketch of the experimental rig for water flow

The orifice plates with different values of β varying from 0.4 to 0.7 were employed in this rig. The experimental mass flow rate for each case was measured by the dynamic weighting method [7]. This mass flow rate was compared to the mass flow rate calculated according to the British Standard. The difference between these two flow rates has been investigated to establish error analysis.

For the air rig, two orifice plates were positioned in series in smooth, circular pipes of 76.2 mm diameter. The first of these was used as a reference meter and the second was the one where the entry conditions were altered. They were joined together with a large air box to reserve the flow and also to allow it to settle. The experimental set up is shown in Figure 2. In air rig a diameter ratio (ß) of 0.5 was selected for both orifice meters. The pipes were 3 meters (40 diameters) long on either side of each orifice plate. This exceeded the British standard requirements of at least 20 pipe diameters.

Liquid filled differential manometers were fitted to either side of the orifice plates using British Standards D and D/2 tapping. As the flow rates were calculated using the density of the air, the atmospheric pressure was measured for each set of experiments. The air was sucked through the system using a fan controlled by a ball valve. All of the measurements were carried out simultaneously on both meters using Reynolds number of up to 40000.

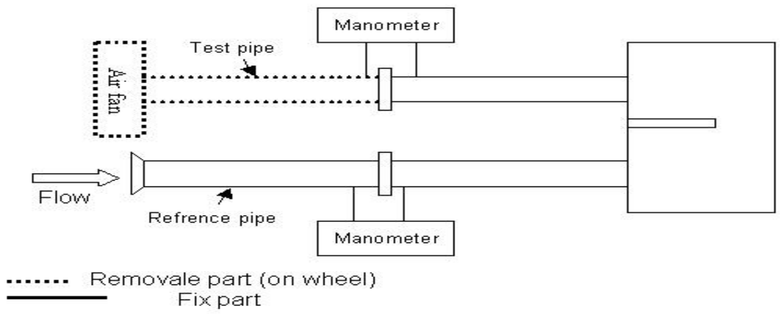

Figure 2- The sketch of air experimental rig

Swirler flow conditioner

The initial shape for the swirler was a piece of twisted plastic with a 90 degree twist in its length. The length of swirler was about 1.5 of the pipe diameter that this was similar to that in initial experiments [17, 18]. In the new series of experiments the development of swirler conditioner on disturbed flow was a main task. The main reason was that the previous results showed the original swirler conditioner could attenuate the effect of asymmetric flow very well but for swirling flow it was defeated. So, four kinds of swirler shape were designed for the experiments. The length of these was kept same as its original, 1.5 pipe diameters, and in same position in upstream. These four shapes of swirler can be categorized into the following division:

- Joint two-piece of swirler
- Two-piece of swirler with a gap between these two parts
- Four piece of swirler with a gap between each part
- Cone swirler

These shapes and original shape of swirler, one piece, are shown in Figure 3.

Figure 3- The picture of swirler shapes

Disturbances

Velocity profiles different from those formed in fully developed flow can produce by using disturbances upstream of the orifice plate. These disturbances can provide either asymmetric velocity profile or swirling flow. However, in some cases the combination of asymmetric flow and swirling flow could occur. In order to assess the effect of the swirler flow conditioner on disturbed flow, both types disturbances have been examined in the experimental rigs. To achieve an asymmetric velocity profile, block disturbances were used. These bocks were cut from a circular piece of metal and were placed on the bottom of the pipe. One block, which is called 1/4 disturbance, had a cross-section of ¼ of the area of the pipe and causes a significant distribution. The second one, which was called 1/8 disturbance, had a cross section 1/8 of the area of the pipe and made a weaker disturbance (Figure 4).

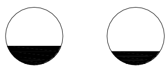

Figure 4- Block disturbances

A swirling flow was produced in the pipe using a similar device to the one piece swirler. Its length was one D and had an angel of 90 and 180 degree. Also, a two out of plane elbows were employed in water rig. So that, the following disturbances were evaluated in experimental rigs two elbows in same plane and out of plane, swirler disturbance with different twist angles and block disturbance. All of the disturbances also were 1.5 D in length and were positioned about 3 D from the orifice plate. The configuration of swirler, disturbances, orifice plate and their position from the upstream face of orifice plate has shown in Figure 5. As it was already mentioned the one D upstream and D/2 downstream pressure tapping used for metering a pressure drop that they do not represent in the sketch.

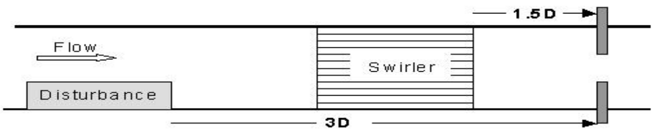

Figure 5-The positions of disturbances and swirler from orifice plate

In the experiments the measurement of the mass flow rate was carried out four times. The first time, it was done for a standard and settled velocity profile to obtain the accuracy of rig in comparison with the British Standards. Then the effect of disturbances was examined on the flow metering. The effects of each swirler flow conditioners were investigated on the mass flow rate in presence of disturbances. Finally the effect of each individual swirler flow conditioner was examined on mass flow rate. In conclusion these mass flow rates used to calculate new discharge coefficient and in comparison with its standard one the shift of C were calculate. All of these results were with a β of 0.5

Results and discussion

Performance of swirler conditioner on standard orifice metering

In order to assess the effect of different kinds of swirler on flow measurement the water experimental rig was run with individual swirlers and the shift of discharge coefficient results are shown in Figure 6. The graph shows that the behaviour of cone swirler on standard discharge coefficient is similar to the single piece swirler. It means the shift of standard discharge coefficient with employing a cone swirler can be changed from 4% in low Reynolds number to about 6% for high Reynolds number for water rig. Figure 6 also represents the mass flow rate with standard orifice plate and without any disturbances, fully developed velocity profile, can perform about 1% error in discharge coefficient similar to accuracy of orifice metering mentioned in most references [7]. This figure clearly shows the behavior of other kinds of swirler is far from our pervious results [17,18]. However it can be found that the effect of four piece of swirler individually is similar to cone swirler but in presence of disturbances the appropriate its discharge coefficient would alert dramatically.

Therefore in the next stage the effect of different shape of swirler on non-standard velocity profile were examined on metering by using block and swirler disturbances.

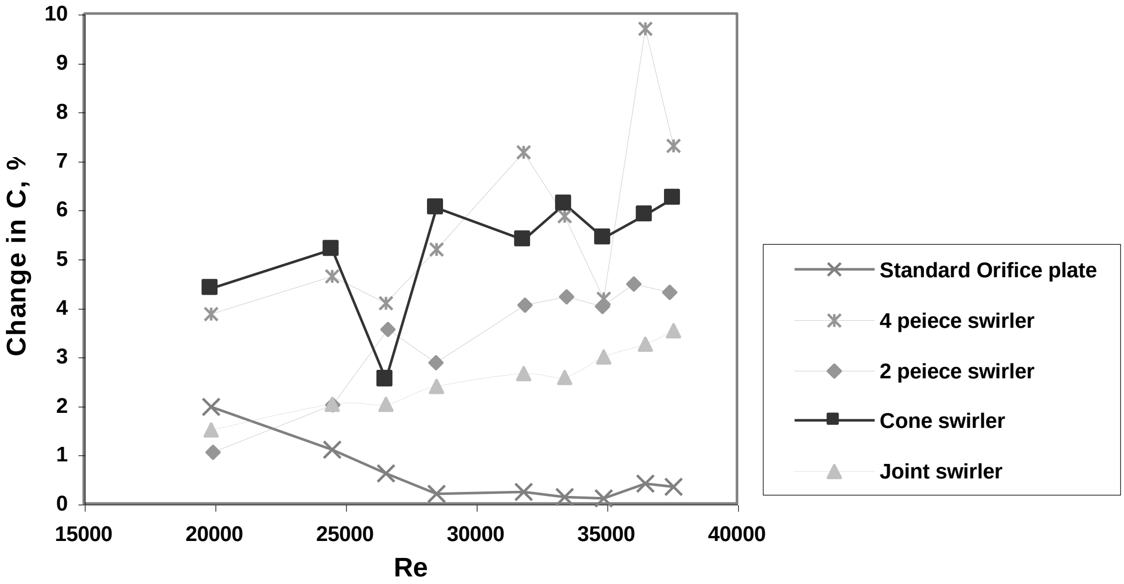

Figure 6- Change in discharge coefficient for different swirler flow conditioner

Employment of block disturbance on metering

It is well known that the orifice plate flowmeter is a symmetrical device thus the velocity profile approaching to orifice plate should be symmetrical for accuracy. Thus any asymmetrical velocity profile can causes a major error in metering. In order to understand how much change could be acquired by using the asymmetrical velocity profile, the water experimental rig was run with employment of block disturbance in upstream. In this case the effect of the combination of swirler flow conditioners on asymmetrical velocity profile also has been investigated. The results are shown in Figure 7.

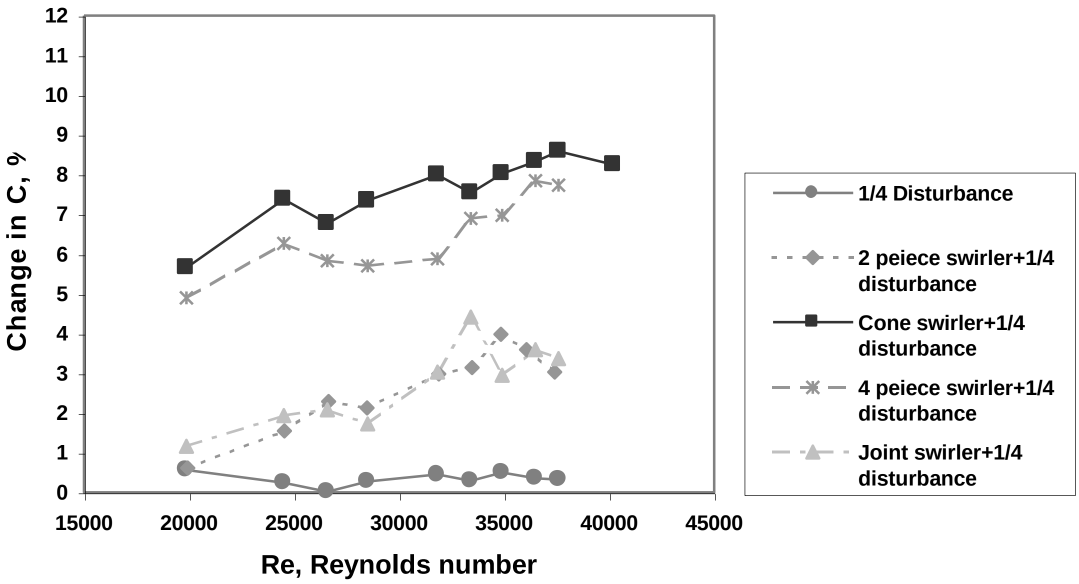

Figure 7- The effect of swirler conditioners on block disturbance (1/4 disturbance)

It can be seen from figure that the block disturbance can cause about 1 to 2 % change on standard discharge coefficient. The effect of asymmetric velocity profile can reduce by a cone swirler conditioner by changing C to about 5 to 7%. However, the other kinds of swirler flow conditioner in presence of block disturbance behave very different relative to using each of them invidiously. In other words, new discharge coefficient C for package of cone swirler and disturbance is the same and independent of inlet condition. In comparison with other kinds of swirler the figure shows that the shift of C for two-piece of swirler with block disturbance is similar with cone swirler opposite of four- piece of swirler in former case.

In the next movement to establish a comprehensive assessment of using the swirling flow conditioner the effect of swirling flow were examined. As it already mentioned, two sorts of device can achieve a swirling flow either double elbows in a same plane and perpendicular plane or using a swirler similar to the conditioner as a swirling disturbance in upstream. Thus, the results of using a swirler disturbance with different kinds of swirler flow conditioner are plotted in figure 8.

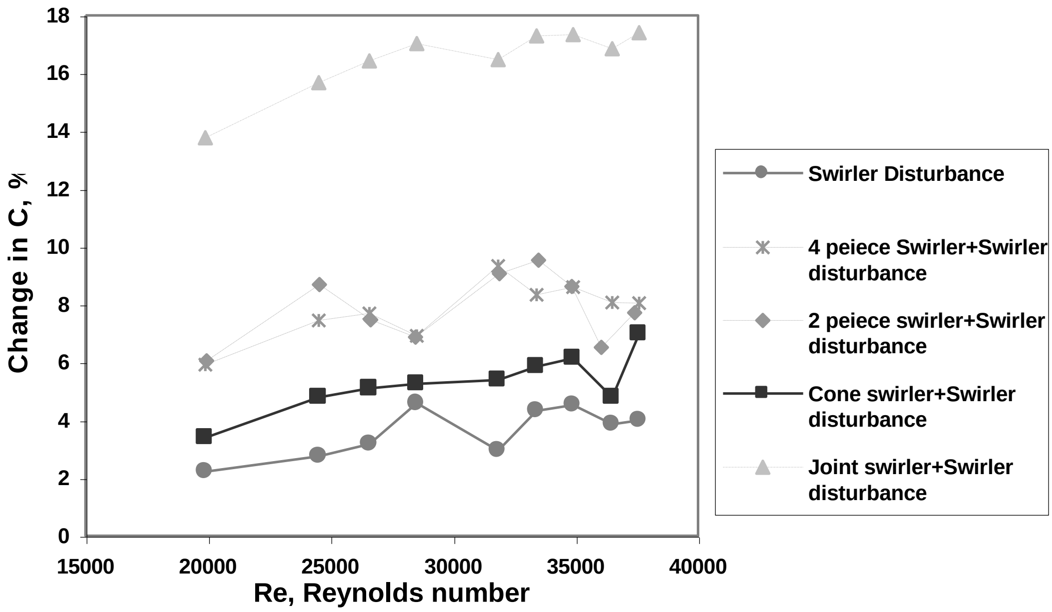

Figure 8-The effect of swirler conditioner on swirler disturbance

This figure clearly shows the effectiveness of the swirling flow conditioner with the cone swirler particularly good at reducing the effect of swirling flow on the meter. It can be seen that although the swirler disturbance still makes the shift up to 4% in the standard discharge coefficient this shift with a cone swirler flow conditioner would keep same as amount of individual cone swirler. It implies that the employment of the cone swirler upstream of the orifice plate is especially effective when used with swirling flow. In combination of the cone swirler and disturbance it is sufficient to change the standard discharge coefficient to 4% in low Reynolds number up to 6% for its high values. By having a new discharge coefficient for the cone swirler it provides a flow meter that is broadly independent of inlet disturbances. Also it can be concluded from the graph that other sorts of swirling flow conditioner could not damp out the effect of swirling flow.

In the final stage of using a swirler flow conditioner in a swirling flow the effect of cone swirler has been investigated with the other sources of swirling flow. As it already mentioned two elbows in a same plane and out of plate are the main sources of swirling flow in most references [7, 2]. So, double elbow disturbances were set in water rig and the effect of these configurations on standard orifice plate and alongside with cone swirler conditioner was obtained. These results for are plotted in below figure.

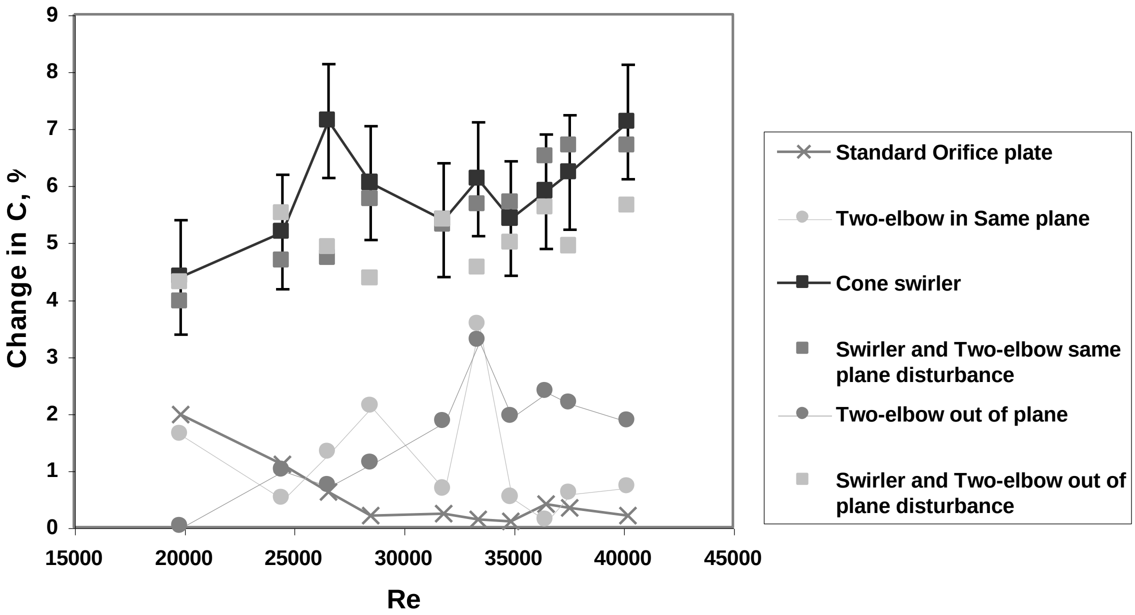

Figure 9- The effect of two-elbow and cone swirler conditioner

The figure-9 shows the two-elbow disturbances can make a 2 to 3% shifts in standard discharge coefficient [5]. However, by combination of a cone swirler with two-elbow disturbance the change of new discharge coefficient can be kept up as much as to 4 to 6% of individual cone swirler. As the figure also represents that all of the result with cone swirler conditioner falls within the 1% error bars.

By knowing the interaction of the cone swirler on a disturbed flow at high Reynolds number, which was achievable for water rig this procedure was examined on air rig with low Reynolds number. The obtained results for air rig in different combinations of disturbances and cone swirler are shown in Figure 10.

In the air rig low Reynolds number up to 20000 was obtained. The graph represents putting cone swirler in pipe changes the standard discharge coefficient up to 1.5%. This trend can repeat when a combination of block disturbance and cone swirler put in upstream. It means the cone swirler can attenuate the effect of asymmetric flow in low Reynolds number. On the other hand, however employment of swirler disturbance makes up to 1.5 % error on metering this error with putting a swirler conditioner reach up under the 0.5% error.

It means the cone swirler cannot compensate the effect of swirling flow as much as asymmetric flow. In brief, the air results reveal that the cone swirler has a less effect on swirling flow in low Reynolds number; however it has a good effect on asymmetric flow in low Reynolds number.

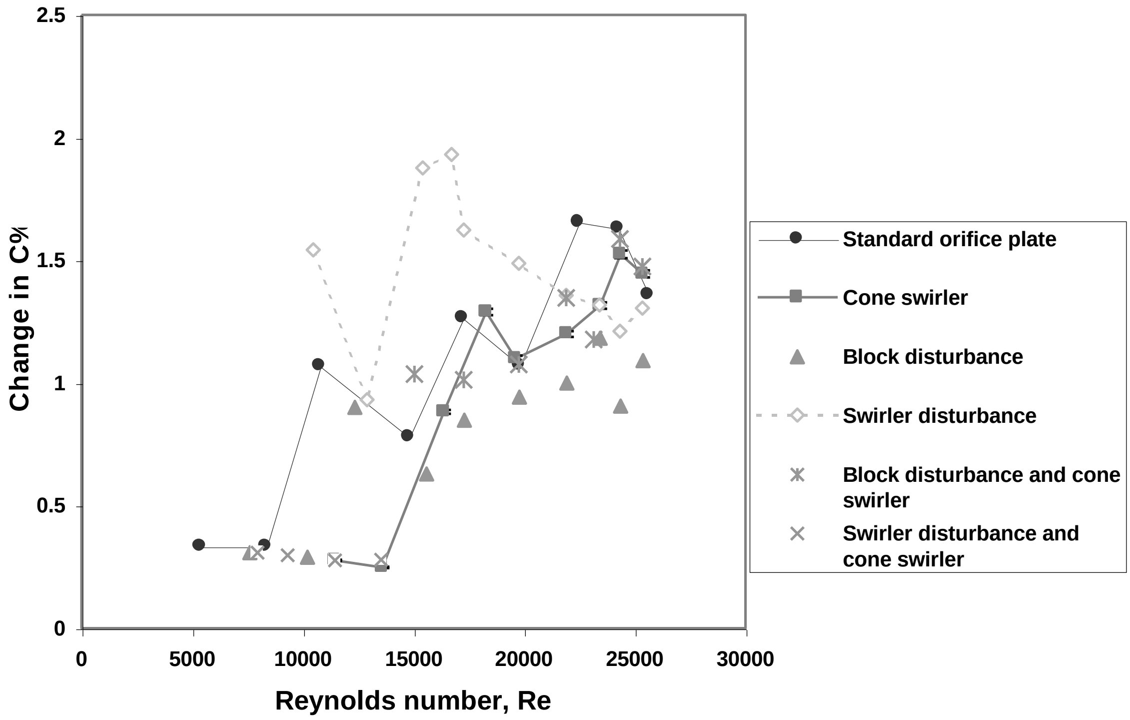

Figure 10-The effect of cone swirler on disturbed flow for air rig

Calibration of The cone swirler

Basically, when the swirler is used in front of an orifice plate the standard discharge coefficient cannot be used to calculate a mass flow rate. Unless the appropriate discharge coefficient for combination of the swirler and an orifice plate was determined.

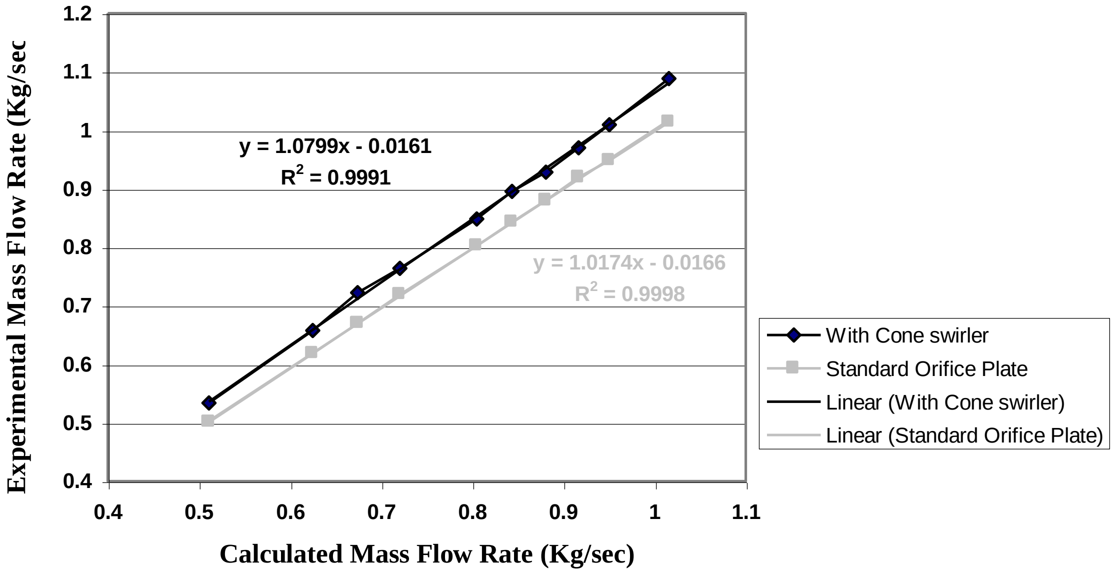

Figure 11- Calibration of the cone swirler

Figure 11 shows the calibration curve for combination of cone swirler and orifice plate. The experimental mass flow rate in presence of cone swirler is plotted versus the calculated mass flow rate basis of the standard discharge coefficient. It can be seen that the orifice plate and cone swirler combination appears to give about 7% more flow rate than the orifice plate on its own. Besides calibration of the new design provides a very good fit line that means the new discharge coefficient (C^*) can be calculated by multiplying the standard discharge coefficient by the correction factor (K). The graph represents that this correction factor (K) for a cone swirler is 1.0799. So it means the new discharge coefficient can be calculated: $C^* = 1.079C$

Source of errors

By considering the data acquisition, a review on error sources associated with reading of the different parameters should be considered in this section. The accuracy of weighting scale was 0.1% and stop watch 0.01%. Also as already mentioned the pressure drop was measured by two kinds of pressure meters, a pressure transducer and U-tube manometer. The pressure difference between these two meters always compared and the difference was about 1.8 cm $H2O$ or 176 Pascal which seems negligible in metering. On the other hand same procedure was used for measuring the mass flow rate so inaccuracy was same for the mass flow rate. Thus it can be concluded there were not major errors in metering and inaccuracy in calculation was negligible.

Conclusion

The present study has shown that the novel idea of the using a swirler flow conditioner in disturbed flow can reduce the error of metering caused by disturbances. To find out the best design of the swirler flow conditioner a variety of different shapes were considered. So far the results show a cone swirler can reduce the distortion due to asymmetric velocity profile on metering in high and low Reynolds numbers. On the other hand, this kind of swirler conditioner has a very good effect on swirling flow in high Reynolds number but has a less effect in swirling flow for low Reynolds number. The new discharge coefficient appropriate of cone swirler flow conditioner can vary from 0.5 % in low Reynolds number up to 6 to 7% of standard discharge coefficient for high Reynolds number. In order to find out what characteristics exist in swirler flow conditioner that it can reduce the error of disturbed flow, a CFD numerical analysis of swirler flow conditioner is under a way.

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