Slotted Orifice Flowmeter

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A new type of obstruction flowmeter has been developed as a "drop-in" replacement for the standard plate in an orifice flowmeter. The replacement consists of radial arrays of slots arranged over the entire surface of the plate. Generalizing the definition of the beta ratio for any obstruction flowmeter as:

$$\beta=\sqrt{\frac{A_{\text{open}}}{A_{\text{total}}}},$$

comparisons between various designs can be made. The value of β for the standard orifice flowmeter using this generalized definition is still the ratio of the orifice diameter to the pipe diameter. Performance for a slotted orifice to a standard orifice have been compared with the plates installed in the same orifice run where various inlet velocity profiles were introduced to simulate poor upstream flow conditioning. The slotted orifice has less overall headloss and less sensitivity to upstream flow conditioning than the standard orifice plate. This results in a flowmeter which is more accurate than the standard orifice flowmeter over a much broader range of operating parameters.

A standard orifice plate is one of a variety of obstruction-type flowmeters that can be used to measure the flow rate of a fluid in a pipe. By measuring the pressure drop across such a device, the pressure and temperature upstream of the device, the mass flow rate of the fluid can be determined. In its simplest form, the orifice flowmeter consists of a thin plate, with a hole in the center, that is clamped between pipe flanges. Because geometry is simple, it is low in cost and easy to install or replace. This device is used extensively to measure flows in processing plants, pipelines, water distribution systems, and at well heads. The main disadvantage of the standard orifice plate is its sensitivity to upstream flow conditions. Currently, efforts are under way to better quantify upstream flow conditioning effects on standard orifice flowmeters with the goal of increasing the installed accuracy by an order of magnitude.

This work has taken another approach to obtaining the increased accuracy: replacing the standard orifice plate with a "slotted orifice" plate which exhibits significantly better operating characteristics. It is less sensitive to upstream flow conditions and has less overall head loss. The ultimate goal is to develop a "drop-in" replacement for standard orifice plates which results in a significantly more accurate meter for minimal investment.

Background

Recent investigations by Karnik et al. (1991), Mattingly and Yeh (1991), Brennan et al. (1991), Morrow et al. (1991), Gajan et al. (1991), and Morrison et al. (1992) have shown the effects of varying the upstream velocity profile on the accuracy of standard orifice flowmeters. Karnik et al., Mattingly and Yeh, Brennan et al., and Morrow et al. varied the placement of standard tube bundles upstream of various β ratio orifice plates and observed how the coefficients of discharge were affected. Karnik et al. and Morrow et al. added to the database by using hot-film anemometry to measure the velocity profile just upstream of the orifice plate. From these data, they observed that for a given mass-flow rate, an increase in the velocity near the pipe wall (with a corresponding decrease along the pipe centerline) resulted in an increased pressure differential which corresponds to a decreased coefficient of discharge. The opposite occurs if the velocity along the pipe wall decreases. Morrison et al. investigated this effect more closely by manufacturing a concentric tube flow conditioner, which can vary the upstream velocity profile while maintaining a constant mass-flow rate. The mean velocity profile was measured 1.75 pipe radii upstream of the orifice plate using a Pitot probe. They determined that the change in discharge coefficient was related to the second-order moment of momentum:

$$mvrr=\int\int_A r^2\rho U^2 dA=2\pi\int_0^R \rho r^3 U^2 dr$$

All of the studies show that the discharge coefficient for larger β ratio orifice plates are more sensitive to changes in the upstream flow condition.

The physical phenomena, which cause the pressure drop across the orifice plate, are the inward radial acceleration re-

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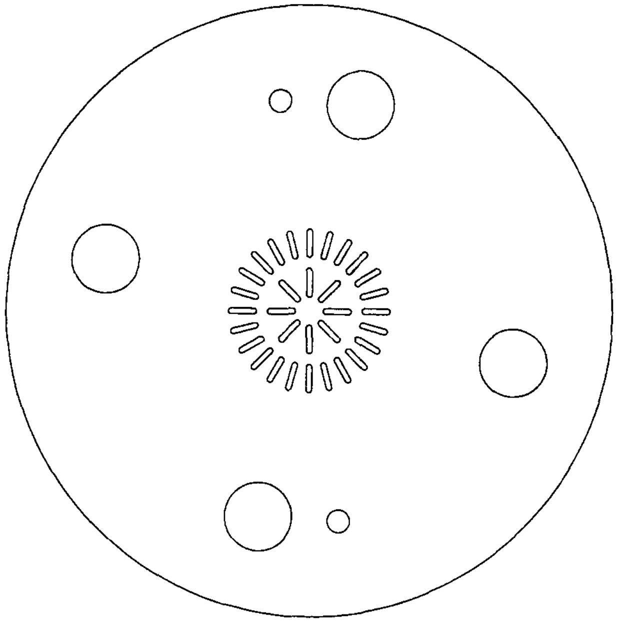

Figure 1. Slotted orifice plate, $\beta_{eff} = 0.43$.

quired for the flow to enter the orifice. The force needed to cause the acceleration is provided by the local pressure gradient. Larger accelerations require larger forces, hence, an increase in the pressure gradient. When more fluid flows near the wall, additional radial acceleration is required to move the fluid into the orifice resulting in a larger pressure drop across the orifice plate. The slotted orifice plate (Figure 1) alleviates this effect by distributing the open area more uniformly across the pipe cross section. In this manner, radial movement of the fluid particles is greatly reduced resulting in a decreased sensitivity on the upstream velocity profile. Slots are preferred to a distribution of circular holes because a slot with an aspect ratio larger than 4:1 will result in a lower headloss. In addition, the increased wetted perimeter/area ratio provides significantly more shear layer area in the downstream "orifice/slot" jets, which results in faster spreading of the jets and, hence, a faster pressure recovery. Finally, the slots are placed in a radial pattern so that they effectively act as a flow straightening device. This would not occur if the slots were arranged in circumferential arcs. The slotted orifice in Figure 1 was designed for a 50.8-mm (2-in.) pipe and has two rings of slots. The outer ring has a diameter of 45.97 mm. This particular plate has a much larger flange area for the purpose of assuring alignment in the flanges. For larger diameter pipes, additional rings of slots would be used. The goal is to obtain the same ratio of open area to total area in each ring. The plate shown has an effective β ratio, $\beta_{eff} = [A_{open}/A_{total}]^{1/2}$, of 0.43.

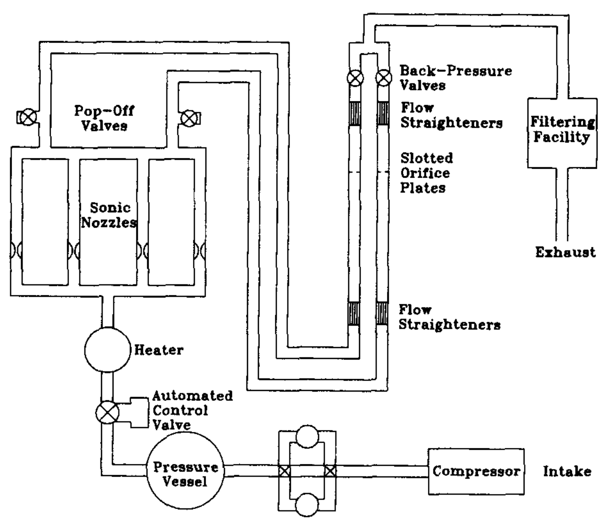

Figure 2. Flowmeter test facility.

Pressure and temperature are carefully controlled at a dew point of −40°C or lower, providing a constant mass-flow rate through the sonic nozzles.

Objective

The objective of this work is to demonstrate that the slotted orifice flowmeter is less sensitive to upstream flow conditions than a standard orifice flowmeter. This can be accomplished by measuring the wall pressure distributions upstream and downstream of both a standard orifice plate and a slotted orifice plate for varying upstream flow conditions. The effective beta ratio is the same for both orifice plates. The overall headloss and flange tap pressure differential can be measured and compared between the two orifice plates.

Facilities

This study was performed in the facility shown in Figure 2. Compressed air was supplied by a screw-type air compressor via a desiccant air dryer, an electro-pneumatic pressure regulator and an electric heater to a sonic nozzle bank. By maintaining a constant humidity (−40°C, −40°F dew point), pressure (618 kPa, 90 psig), and temperature (43°C, 110°F) the mass-flow rate through each of the four sonic nozzles remained the same every time the facility was operated. Each of the four sonic nozzles had a different size so that various combinations produced a wide range of Reynolds numbers. A Reynolds number of 54,700 was used for this study in a 5.08-cm (2 in.) pipe.

The air metered by the sonic nozzle bank comes into one of two different orifice runs. Each orifice run has a nine-tube flow conditioner both upstream and downstream of the orifice plate when well conditioned flows are desired. For this study, a concentric tube flow conditioner, which consists of a 25.4-mm pipe concentrically mounted inside a 50.8-mm pipe, is placed between the upstream flow conditioner and the orifice plate. The flow is split between the inner pipe and the annulus to generate various axisymmetric velocity profiles. A tee followed by a gate valve is located between the tube bundle and the upstream flow conditioner. The flow through the gate valve enters the inner pipe of the concentric tube flow conditioner. The remainder of the flow is diverted through the tee to the outer annulus of the concentric tube flow conditioner. This flow is metered using three rotameters. The system allows any value from no flow to the entire flow to pass through the inner tube. The exit of the concentric tube flow conditioner is located 4.4 pipe radii upstream of the orifice plate. Downstream of the orifice plate, a gate valve throttles the flow and maintains a pressure of 34 kPa gage upstream of the orifice plate.

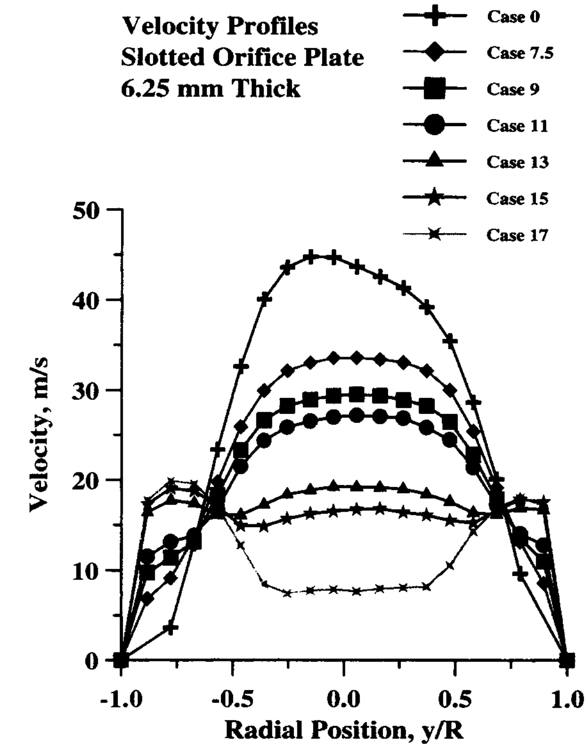

Figure 3. Mean velocity profiles 1.75R upstream of a 6.25-mm-thick, $\beta=0.43$ slotted orifice plate, *Re* = 54,700.

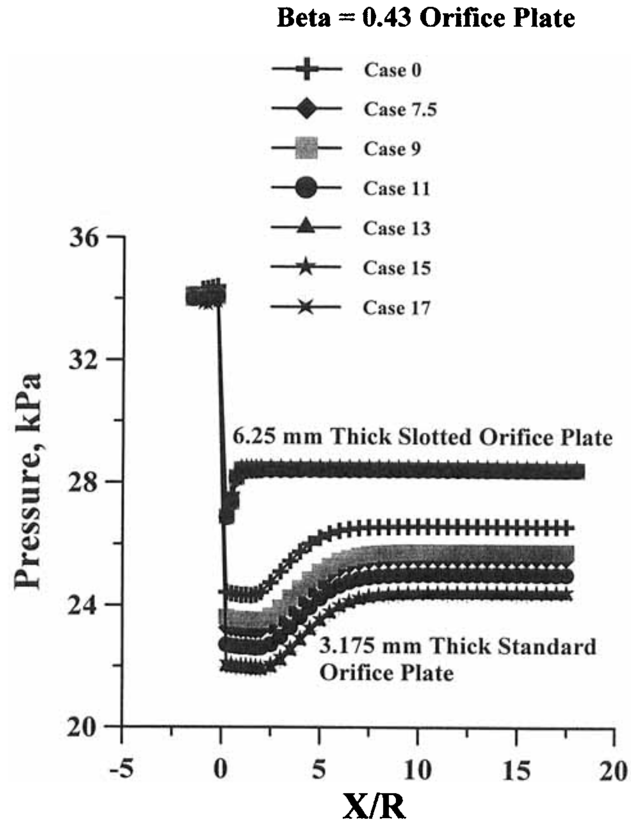

Figure 4. Wall pressure distribution for the 3.175-mm-thick standard orifice plate and the 6.25-mm-thick slotted orifice plate, $\beta=0.43$, *Re* = 54,700.

Results

The concentric tube flow conditioner has been used previously by Morrison et al. (1992). For this study, a Pitot tube was used to measure the velocity profiles present 1.75 pipe radii upstream of $\beta=0.43$ standard and slotted orifice plates operating at a Reynolds number of 54,700. Figure 3 illustrates the range of velocity profiles possible with this system for the slotted orifice plate. The standard orifice plate upstream velocity profiles were similar. The case number represents the amount of fluid passing through the annulus of the flow conditioner. For the study shown, the flow in the annulus varies from its lowest velocity in case 0 to the highest in case 17.

The wall pressure distributions for the $\beta=0.43$ standard orifice plate are shown in Figure 4. The orifice plate is a 3.175-mm (1/8-in.)-thick plate with a 45° bevel on the downstream side. The smallest pressure drop occurs for flow case 0, where all of the flow exited the 25.4-mm-dia. center tube 4.4 pipe radii upstream of the 21.8-mm-dia. orifice. This condition should be expected to produce the lowest pressure drop, since the flow exiting the flow conditioner has only a slightly larger flow area than that of the orifice plate. As more flow is diverted to the annulus the pressure drop increases to a maximum for case 17. For all cases, the pressure recovers to its maximum downstream value approximately seven pipe radii downstream of the orifice plate. The deceleration of the fluid and accompanying pressure recovery downstream of the orifice plate is the same for all upstream cases as shown by the downstream wall pressure distributions being parallel. This was previously observed by Gajan et al. (1991). Thus, the variations of the pressure drop with upstream velocity profile are due to variations in the upstream flow as it enters the orifice and the pressure drop across the orifice plate.

The exact ratio of slot width to plate thickness for optimum slotted orifice plate performance is not known. Therefore, two slotted orifice plates were manufactured: one with the same thickness as the standard orifice plate (3.175 mm) and the other twice as thick (6.25 mm). Figure 4 shows the wall pressure distribution for the 6.25-mm-thick slotted orifice plate. The slotted orifice plate exhibits a significantly different wall pressure distribution. The pressure recovery is very quick occurring in the first pipe diameter downstream of the plate. For this thicker plate, the pressure distributions show almost no dependence on the upstream flow conditioning for the fairly wide variation in velocity profile studied in these experiments. The goal of designing an orifice plate which is insensitive to upstream flow conditioning has been achieved.

When the thinner slotted orifice plate is evaluated, there is some wall pressure variation with upstream flow conditions. However, these variations are significantly less than those for the standard orifice plate. Interestingly, the dependence of the pressure drop magnitude on the velocity profile is exactly opposite that for the standard orifice plate. The cases with more flow at the outer edges of the pipe resulted in smaller pressure drops. The range of pressure drops is smaller than that for the standard orifice, indicating that a slotted orifice plate with the same thickness as a standard orifice plate is less sensitive to upstream flow conditioning.

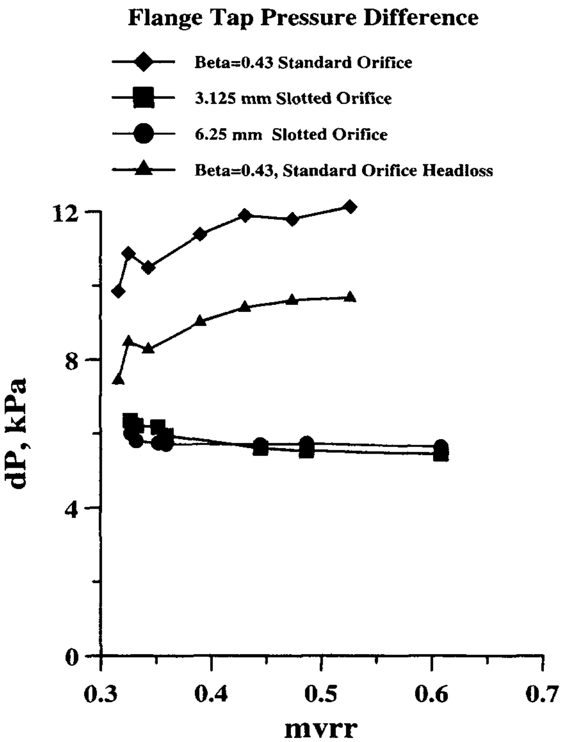

Figure 5. Flange tap pressure difference and standard orifice plate head loss.

Figure 5 shows the flange tap location pressure drops for both types of orifice plates for the various upstream flow conditions plotted as a function of the second-order moment of momentum (*mvrr*). The flange tap pressure drop is larger for the standard orifice plate and tends to increase with increasing *mvrr* (increasing velocity near the wall). The 3.175-mm-thick slotted orifice plate for all cases has less differential pressure and significantly less variation with *mvrr*. There is even a slight decrease in pressure drop for the flow cases with more flow near the pipe wall (higher *mvrr*). Almost no variance is seen for the 6.25-mm-thick slotted orifice plate. Figure 5 also shows the overall head loss for the standard orifice plate. It varies from 16 to 50% more than the pressure differences measured for the slotted orifice plate. Because the pressure recovery is so quick for the slotted orifice, the flange tap pressure differences are essentially the headloss for this 50.4-mm pipe. Thus, the slotted orifice plate produces a smaller head loss than a standard orifice plate with the same effective beta ratio.

Conclusions

The slotted orifice plate has been shown to be less sensitive to upstream flow conditions and to produce a significantly smaller head loss than a standard orifice plate with the same effective beta ratio. More work is required to optimize the design of slotted orifice plates with respect to slot width, slot length, plate thickness, and slot placement. This study considered the first two designs we manufactured and demonstrated that the slotted orifice plate can be made insensitive to upstream flow conditioning. Further study is required to investigate the effects of upstream swirl and modified plate design. The goal is to develop a "drop-in" replacement which can easily be installed in existing orifice meter facilities.

Acknowledgments

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Notation

A_{open} = open area in orifice plate
A_{total} = pipe cross-sectional area
D = pipe diameter
$mvrr$ = $\int\int_A r^2 \rho U^2 \, dA$
P = pressure
r = radial distance from pipe centerline
R = pipe radius
Re = Reynolds number, $U_{ave}D/\nu$
U = local axial velocity
U_{ave} = bulk averaged axial velocity
X = distance downstream of the orifice plate
β = beta ratio, $\sqrt{A_{open}/A_{total}}$
ν = kinematic viscosity
ρ = density

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