Conditioning of Velocity Profiles in Pipelines

Charles M. Burt, Ph.D., P.E.
Pascal Hellmann[1]
Zachary Markow[2]

Sponsored by California Dept. of Water Resources, Division of Statewide Integrated Water Management (DSIWM)

Background

The velocity profile in a pipe with turbulent flow, after a long straight section, assumes a stable, symmetric profile. The exact profile depends upon the wall roughness and Reynolds number (Stigler, 2014). An empirical velocity profile equation for turbulent pipe flow, known as the power-law velocity profile (Cengel and Cimbala, 2006), is shown below and graphed in Figure 1. This idealized profile is symmetric and without a substantial difference in velocity throughout the cross section.

$$V/V_{max} = (1 - r/R)^{1/n} \qquad \text{(Eq. 1)}$$

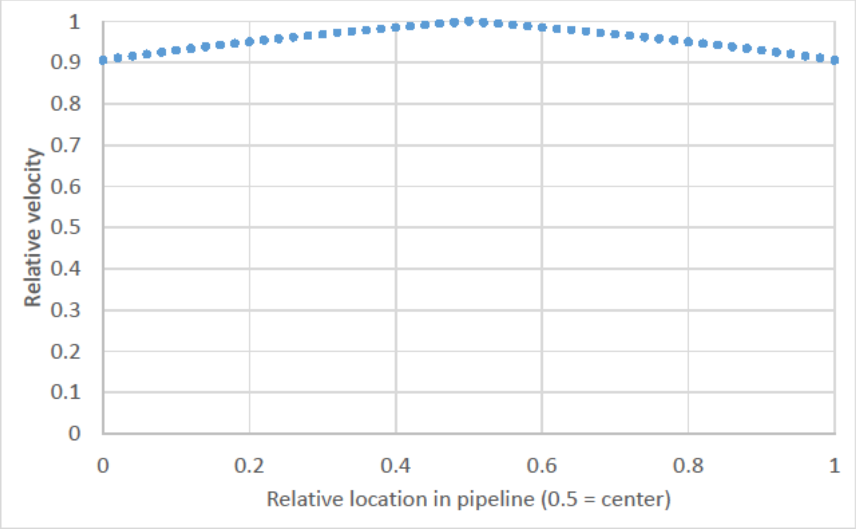

Fig. 1. Approximation of relative turbulent water velocity from the power-law

When water flows through elbows and various fittings in a pipeline, the velocity profile becomes skewed, with the maximum velocity at a point other than the center of the pipe. The ratio of max/min velocities increases. Elbows can add a rotational element to the velocity paths. Flow meter manufacturers typically provide a recommendation that flow meters be placed at least 6-10 pipe diameters downstream of obstructions or elbows. Hanson and Schwankl (1998) tested several commercial flow meters at various distances downstream of disturbances. They found that the accuracy of velocity-integrating propeller flow meters (in which the propeller

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[1] Former Irrigation Support Specialist, Cal Poly ITRC, pascal@die-hellmann.de
[2] Irrigation Support Engineer, Cal Poly ITRC. zmarkow@calpoly.edu

occupies the majority of the pipe cross section) were not affected by a check valve when installed only two pipe diameters downstream, and were not affected by 90-degree elbows. However, propeller meters were inaccurate regardless of their location, when downstream of a partially closed butterfly valve coupled with a 90-degree elbow. Swearingen (2017) notes that swirling eddies or vortices can cause problems with full-bore magnetic flow meters. Therefore, full-bore magnetic flow meter manufacturers usually recommend five diameters of straight pipe upstream, and two diameters downstream, although the senior author knows that some manufacturers are attempting to improve their products so they only require two diameters upstream. Point-velocity meters, also called "insertion meters" (those that sample the velocity at a single point or small area such as near the pipe wall), are severely affected by all forms of turbulence.

It is also recognized that booster pump performance is negatively affected by turbulence and swirling at the inlet to the pump impeller (KSB, 2018). Whitesides (2012) states that an optimum booster pump inlet has ten diameters of straight unobstructed pipe lengths of the same diameter as the pump inlet. However, quantitative data on the impact of poor entrance conditions on pumping plant performance is not readily available.

Pumps and flow meters are often installed in confined conditions that do not offer recommended long, straight, and unobstructed pipe sections. Therefore, a variety of flow conditioning devices have been developed to create a uniform, non-swirling flow path in a short distance. The most commonly-used device consists of one or more straightening vanes. However, while straightening vanes will solve problems with swirling, they do not solve problems with non-symmetric velocity profiles. Furthermore, many designs of straightening vanes collect trash, which is a problem in agricultural applications.

The Vortab Company (2018) provides flow conditioners that consist of many small "ramps" strategically located inside the pipe cross section. These ramps direct segments of flow toward the center of the pipe, and also function as miniature straightening vanes. Flow conditioning that forces the flow to converge inward is also used in open channels upstream of flow measurement devices (Howes et al, 2012). In both cases, the center of the flow cross section is left unobstructed, which important is in high-trash water conditions.

This paper reports on the testing of a relatively simple flow conditioner for pipelines.

Methods and Materials

An experimental layout was designed to enable the following:

- Create a velocity profile that was both unsymmetrical and had rotation (swirling) in a 102 mm (4") Schedule 40 steel pipe (ID = 102.3 mm)
- Insert a flow conditioner into the pipe
- Measure point velocities at various distances downstream of a flow conditioner
- Measure the pressure drop across a flow conditioner

The distorted velocity profile was developed with a 102 mm (4") 90-degree elbow, followed by a 102 mm (4") butterfly valve. The butterfly valve was positioned at half-open to create turbulence and non-symmetric flow.

Flow Conditioners

Flow conditioners were all constructed in 102 mm-long sections of 102.3 mm ID steel pipe, with grooved Victaulic fittings for easy installation and removal. There was a 150 mm-long plain steel pipe between the butterfly valve and the inlet to the flow conditioner.

Velocity Measurement

Velocities were measured at distances of 0.5, 2, 3, 6 and 10 times the diameter, downstream of the flow conditioner, as shown in Figure 2. Four pipe transects were used, at 45 degrees from each other, for distances of 0.5 and 3 times the inside diameter. Each point of measurement represented an equal area of pipe flow.

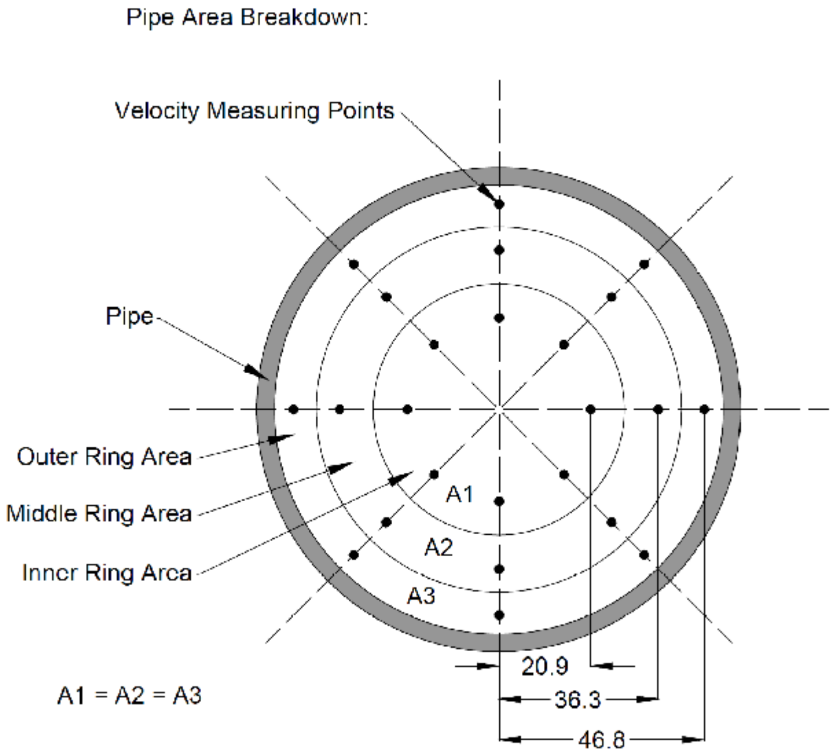

Fig. 2. Locations of velocity measurement with four transects. Units are mm.

Two pipe transects were used, at 90 degrees from each other, for distances of 2, 6, and 10 times the diameter, as shown in Figure 3.

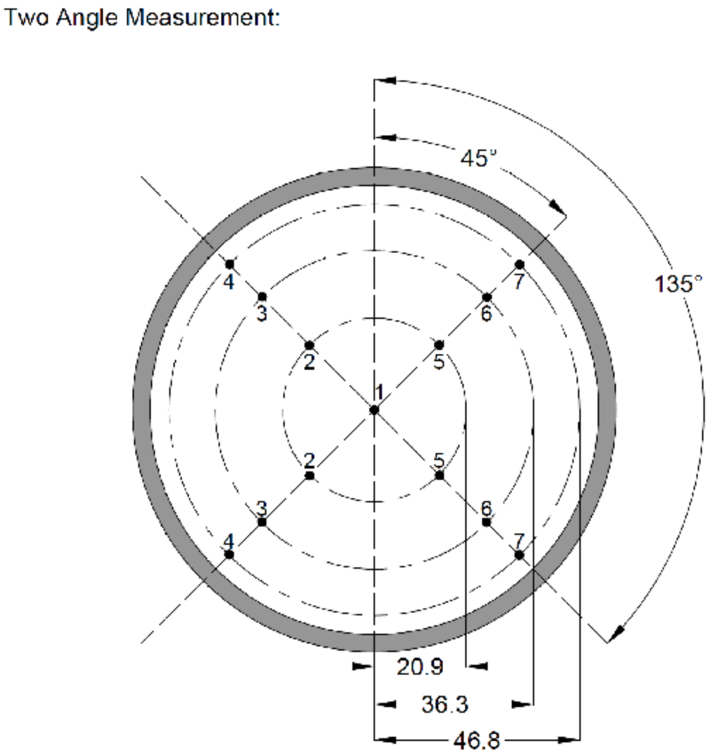

Fig. 3. Locations of velocity measurement with two transects. Units are mm.

Velocities were measured using a Collins tube (7.9 mm OD) and a water manometer. The water manometer diameter was sufficiently large to prevent bouncing of the water surface. The pipe was maintained full in all test conditions.

Flow rates were measured using a 102 mm (4”) McCrometer Ultra Mag magnetic full bore meter, which was calibrated with a large weighing tank. The weighing tank was calibrated using NIST-traceable weights.

Velocity profile tests were conducted using a flow rate of approximately 12.6 LPS (200 GPM). This provided an average velocity of 1.53 m/s (5.0 feet/s).

Head Loss Testing

For this testing, the butterfly valve was left completely open. The flow conditioner was placed in a straight pipe section located 1.3 m downstream of the 90-degree elbow, or about 12 pipe diameters downstream of the elbow. The pressures were measured using water columns, at locations of 0.305 m (1 foot) upstream and downstream of the flow conditioner. Four water columns were used at each location; measuring the head at four equidistant locations around the pipe (top, each side, and bottom). The average of the four water manometer heights provided the head at that location. Head losses were measured at 6.3, 9.5, 12.6, and 18.9 LPS (100, 150, 200, and 300 GPM).

Flow Conditioner Designs

Four designs were used, all with configurations that forced outside flow toward the center. Two also had straightening vanes. The four configurations, which are shown in Figure 4, were:

1. Cone pointed downstream, with 82 mm (3.22") inside diameter. This resulted in a 20% reduction in diameter
2. Cone pointed downstream, with 87 mm (3.43") inside diameter, plus six vanes
3. Orifice plus four ramps and sills
4. 82 mm (3.22") cone with vanes

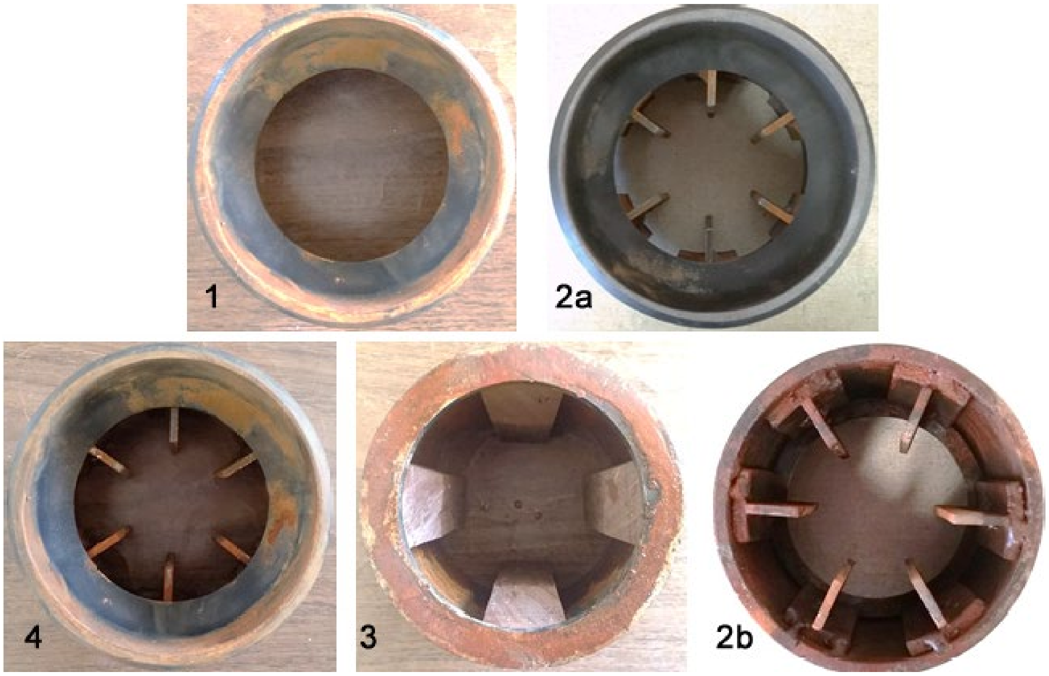

Fig. 4. Four conditioner designs. Clockwise from top left, viewed from upstream unless noted: (1) 82 mm (3.22") cone; (2) 87 mm (3.44") cone viewed (a) from upstream and (b) from downstream; (3) orifice plus ramps, and (4) 82 mm (3.22") cone plus six vanes

Results

Figure 5 shows the velocity profiles at various distances downstream of the blank section, and with different cross sections. This can be considered as the "control".

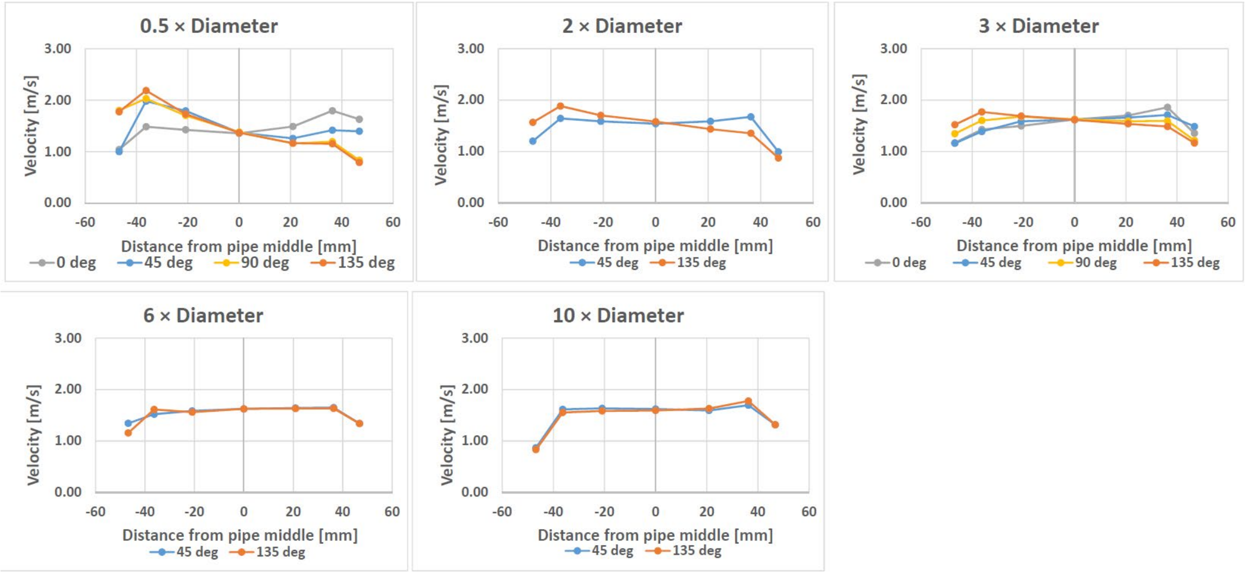

Fig. 5. Velocity profiles with a blank conditioning section

Figure 6 shows the best velocity profiles measured. The best results occurred with the 82 mm (3.22”) cone. The authors had anticipated that the best results would occur with a combination of cone/orifice plus vanes, with vanes required to minimize swirling. However, swirling problems appeared to be minimal except at the 0.5 × diameter location.

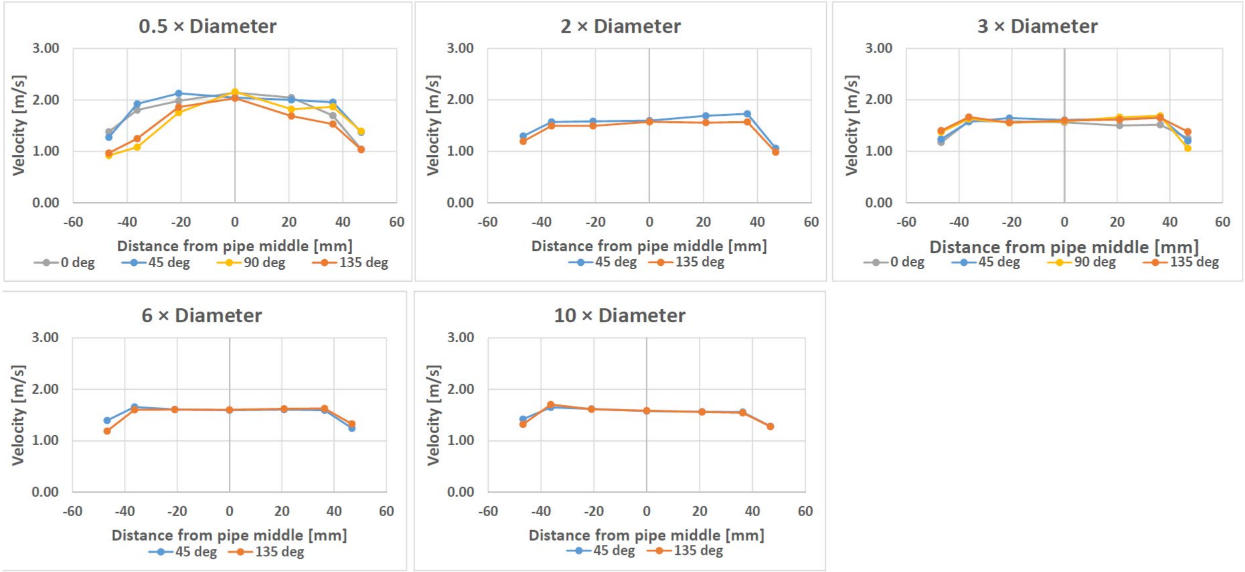

Fig. 6. Velocity profiles with 82 mm (3.22”) cone, no vanes.

Figure 2 showed where point velocities were measured for a 4-transect sampling. Each velocity measurement point is in the middle of a ring. Every ring has the same area. Velocities in each ring were used to characterize the impact of each flow conditioner on the water velocity uniformity. The two characteristics used to describe uniformity are:

- Average (minimum/maximum) velocities within each of the three equal-area rings inside the pipe (see Figure 7). The computation was:

$$\text{Average velocity ratio} = \frac{\sum_{1}^{3} \frac{Minimum\ velocity\ in\ a\ ring}{Maximum\ velocity\ in\ a\ ring}}{3} \qquad \text{(Eq. 2)}$$

- Coefficient of variation (cv) of all velocities at each downstream distance (see Figure 8):
  cv = (standard deviation)/mean (Eq. 3)

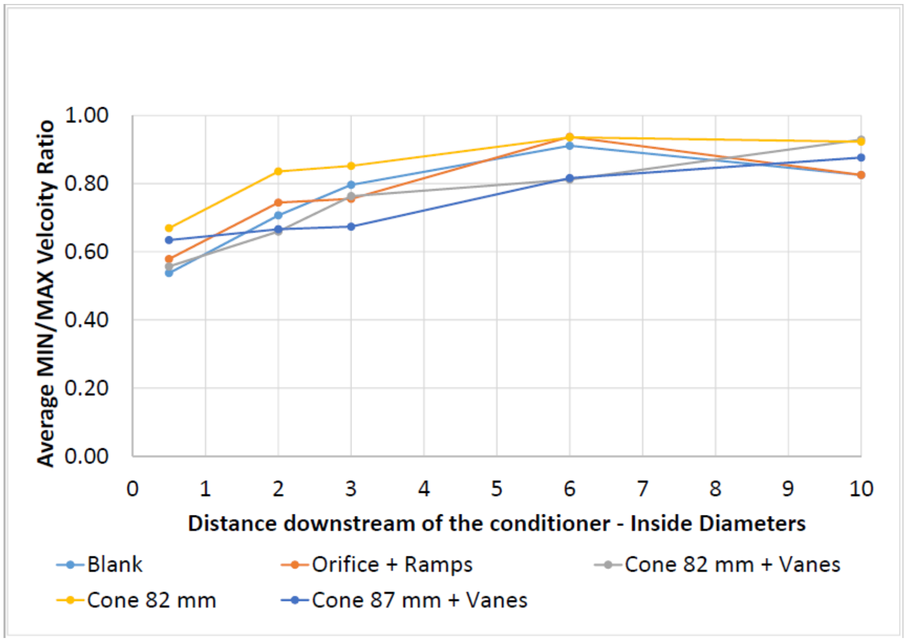

Fig. 7. Average (minimum/maximum) velocity ratios in three concentric area rings

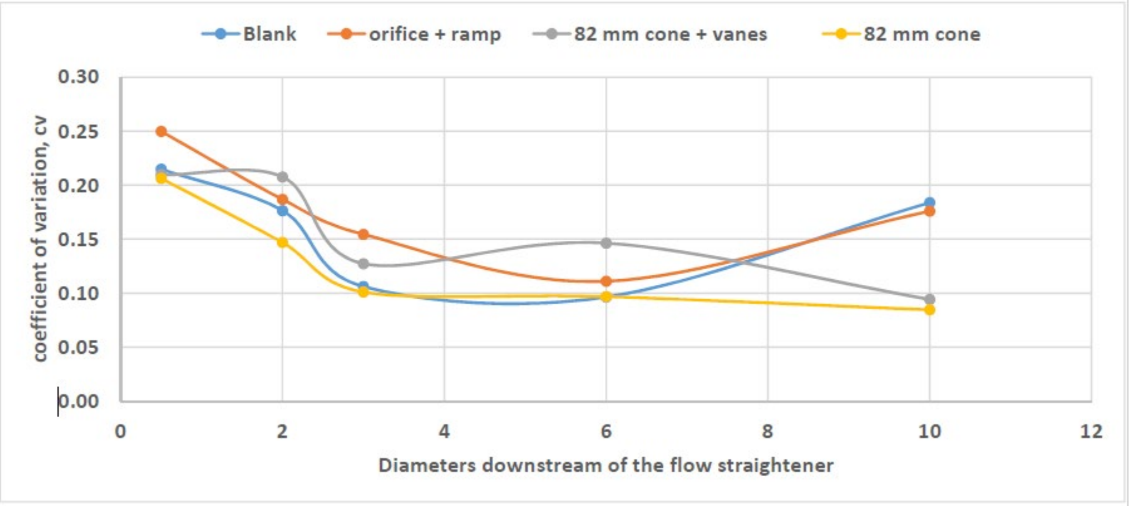

Fig. 8. Coefficient of variation (cv) of all velocities

Friction Loss

To evaluate the friction loss of each flow conditioner, the friction loss in kPa got calculated with the pressure measurements before and after the flow conditioner. Figure 9 shows the friction loss in kPa for each flow conditioner. The "K" value of the 82 mm (3.22") cone is 1.0, for the formula:

Friction = K × (Velocity Head) (Eq. 4)

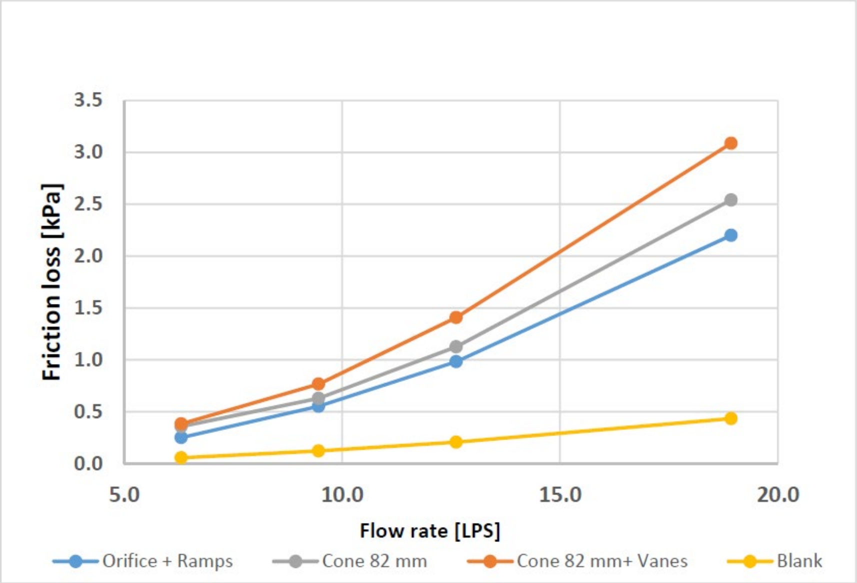

Fig. 9. Friction loss for three flow conditioners

Conclusions

A pipeline velocity flow conditioner that is constructed with an internal cone, having an inside diameter of 80 percent of the pipeline ID, provided the best results. It provided good velocity conditioning at a distance of two diameters downstream of an obstruction. The minor loss is equal to the velocity head of the flow in the original pipeline diameter.

Notation

The following symbols are used in this paper:
cv = coefficient of variation;
GPM = gallons per minute;
ID = inside diameter;
K = local friction loss coefficient;
kPa = kilopascal;
LPS = liters per second;
m = meters;
n = typically assigned a value of 7;
R = radius of the flow path;
r = point along the radius, r=0 in the center; r=1 at edge of pipe;
s = seconds; and
V = velocity.

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