GAS FLOW CONDITIONING

DEVICES USED TO PRE-CONDITION THE GAS FLOW PROFILE PRIOR TO MEASUREMENT.

Klaus J Zanker

Letton-Hall Group
822 Pinesap
Houston Texas USA

Introduction

Pipe fittings such as: bends, Tees, reducers, headers, valves, filters, strainers, heat exchangers, etc, affect the velocity profile in the downstream pipe. These profile distortions are known to affect the performance of flow meters. The magnitude of the effect depends upon both the severity of the distortion and the sensitivity of the meter (Ref. 1).

One solution to these problems is to use long straight lengths of pipe upstream of the meter. Friction effects on the wall of the pipe will eventually extend to the center of the pipe to produce a fully developed velocity profile, which no longer changes with any additional pipe length. Unfortunately in certain applications this can take very long lengths (hundreds of diameters), which is often neither practical nor economic.

Other possible solutions are to design meters that are less sensitive to velocity profile distortions, or design flow conditioners that produce good velocity profiles in very much shorter lengths of straight pipe.

Fluid Mechanics

Fluids can be classed as gases or liquids with very different properties such as: density, viscosity and compressibility. However when the fluid is flowing, it is dynamic similarity, dependant on the Reynolds (Re) and Mach (M) numbers, that determine the velocity profile generated by the pipe fittings.

$$\mathrm{Re} = \frac{Vd\rho}{\mu} \ \textit{and} \ M = \frac{V}{c}$$

Where V = fluid velocity
d = pipe diameter
ρ = fluid density
μ = fluid viscosity
c = fluid speed of sound

Mach No is a measure of compressibility effects, for example a gas flow with V = 98 ft/s and c = 1400 ft/s has M = 98/1400 = 7/100. Although the gas is compressible, it will have a negligible effect on the velocity profile ($0.5*M^2$ = 0.25% change in density)

In most practical cases of gas flow Re is high and the flow is turbulent.

At low Mach number the Reynolds number (ratio of inertia to viscous forces) is the dominant similarity parameter (Ref. 2)

Flow Disturbances

Fully developed flow leads to a stable axi-symmetric velocity profile with statistically known turbulence levels, while any pipe fitting will create a disturbance.

In flow measurement it is the axial component of flow that matters; radial or circumferential flow does not contribute to the throughput, but does distort the velocity profile. Common forms of distortion are swirl, produced by bends out of plane that causes rotation about the pipe axis, secondary flow from a bend consisting of two counter rotating vortices in a plane normal to the axis, and different levels of turbulence.

Bends, Tees and valves can produce asymmetrical flow, where the maximum velocity is not on the pipe centerline, but displaced towards the pipe wall. Axi-symmetrical disturbances can also exist. A reduction in pipe area accelerates the flow making the profile more uniform and reducing the turbulence. An expansion causes a more peaked profile, leads to instability and increased turbulence. A pipe increasing in roughness with time will produce a more peaked velocity profile and more turbulence.

Combinations of fittings can produce a wide variety of flow disturbances. A few fittings can be arranged in many ways; different type of fitting, different size, different order, different orientation or plane, different straight pipe length between each fitting, different roughness, different manufacturing tolerances and different straight pipe length to the flow meter. This potential infinite variety of disturbances has led to the idea of an "isolating flow conditioner" that can protect the meter from any disturbance. It should be noted that this is an ideal that can not always be achieved in practice. However it is still a better approach than trying to individually correct every possible installation.

Good piping design can reduce disturbances. If two fittings are used it is better to separate them by at least 5D and keep them in the same plane. Close coupled fittings interact to create more severe disturbances and changing planes induces swirl. It is also good practice to avoid control valves upstream of a flow meter, as changing the valve position will change the velocity profile.

The Orifice Plate

The orifice is taken as the first example of the effect of a disturbance on a meter, and used to raise some more general points of interest. Orifice plates or the more general class of differential pressure devices (including Venturi meters, nozzles and Pitot tubes) have been around for more than 100 years. They have been thoroughly tested and standardized to such an extent that they can be used without flow calibration to within 0.5% uncertainty.

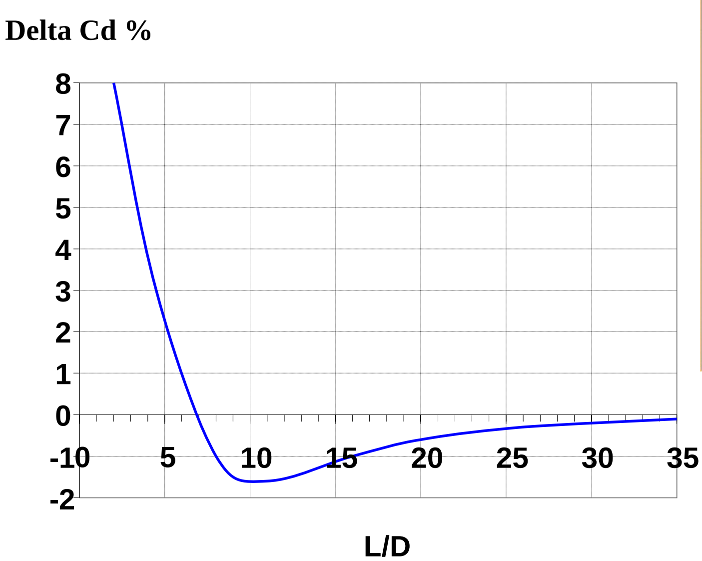
The equation for volumetric flow rate (q) is given by:

$$q = C_D \, a \, E \; Y \sqrt{2 \Delta p / \rho}$$

Where C_D = the discharge coefficient
a = the orifice area
E = velocity of approach = $(1 - \beta^4)^{-1}$
β = diameter ratio = d/D
d = orifice diameter
D = pipe diameter
Y = expansibility (Y = 1 for liquids)
Δp = differential pressure
ρ = fluid density

The performance of an orifice in disturbed flow is shown on a plot of change in C_D from fully developed flow against length (L/D) of the disturbance form the orifice. This is because all of the standard data was obtained with flow in long straight pipes with fully developed flow.

The example is for β = 0.7 orifice with a peaked velocity profile produced by a perforated cylinder on the pipe inlet.



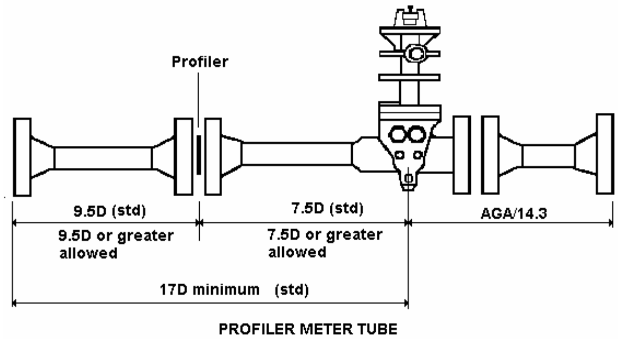
Change of Orifice Cd with Distance from Disturbance

This illustrates several interesting points:

1. The peaked profile produces a low Δp and hence a high C_D
2. There is a "sweet spot" at L/D = 7, where there is no error, but it is not a good place to work because of the steep slope. A change in L/D of ±1 changes the error by ±1%.
3. The sweet spot is probably due to a strange combination of the velocity and turbulence profile producing the correct answer
4. The velocity and turbulence development allows C_D to overshoot and slowly recover
5. The only stable flow in a pipe is fully developed flow, anything else will change towards fully developed flow
6. A flow conditioner should try to produce fully developed flow in a shorter distance

The development and testing of a suitable flow conditioner (Ref.3) allows the use of a standard 17D meter tube with the conditioner 7.5D upstream of the orifice. This arrangement covers orifice plates with β up to 0.67, with any disturbance, in any pipe size and with no upper limit on Re.

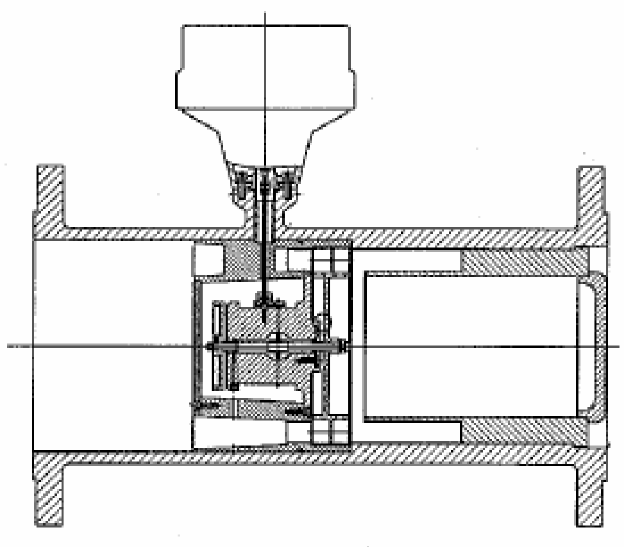
The Flow Conditioner



17D Orifice Meter Tube

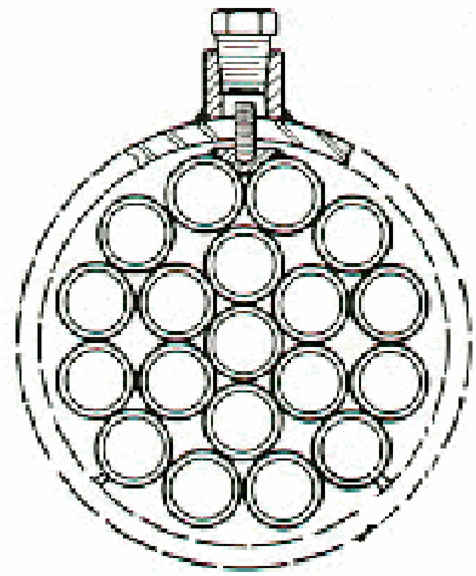
Turbine Meters

Gas turbine meters were developed to overcome the square root limitations of the orifice. The turbine meter is linear and has a larger turn down, but at the expense of moving parts and bearings.



The flow through the meter impinges on the turbine rotor blades, which are free to rotate about a shaft held on the centerline of the meter by stators and bearings. The bearing and fluid friction are minimal such that the angular (rotational) velocity of the turbine rotor is directly proportional to the axial velocity through the turbine. An electric pickup on the meter body gives an output frequency proportional to the flow rate. A further advantage of the turbine meter is that each electric pulse represents a small incremental volume of flow.

The basic principal of converting axial velocity into angular velocity dictates that there should be no angular velocity, or swirl, present in the upstream flow. The meter design can use the stator bearing supports as guide vanes to reduce swirl, but it has become standard practice to use the 19 tube bundle straightening vanes with turbine meters.



The 19 tube bundle

The current standard (Ref.4) recommends a 5D meter tube with a tube bundle 2.5D long, placed 2.5D upstream of the turbine meter.

Positive Displacement Meters

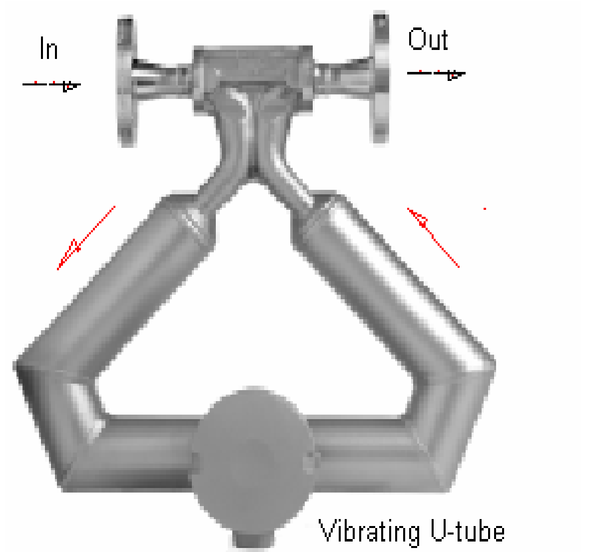
The positive displacement principal is probably the oldest form of flow measurement, going back to the ancient practice of counting buckets of water. Modern positive displacement meters are ingenious mechanical devices to continuously count discrete fixed volumes of gas. Because of clearances between moving parts there is the possibility of leakage, making true positive displacement difficult to achieve in practice. However in principal it does not matter how the fixed volumes are filled, as long as they are full. This suggests that the velocity profile is irrelevant and that the meter would work in disturbed flow.

It is not good to have very disturbed flow entering the meter as it can produce extraneous forces that the meter was not designed for, and could lead to premature ware. However, in general the mechanical meter does not require flow conditioning.

Coriolis Meter

Coriolis meters make use of Newton's law: Force = Mass * Acceleration. In this case it is the Coriolis acceleration ($2\Omega*V$) associated with a particle moving with a radial velocity (V) on a body rotating with angular velocity (Ω). It is difficult to apply this to fluid motion with continuous rotation, but becomes feasible if the rotation is replaced by vibration.

A typical meter has two U-tubes vibrating as a balanced tuning fork, with the flow through both U-tubes. As the



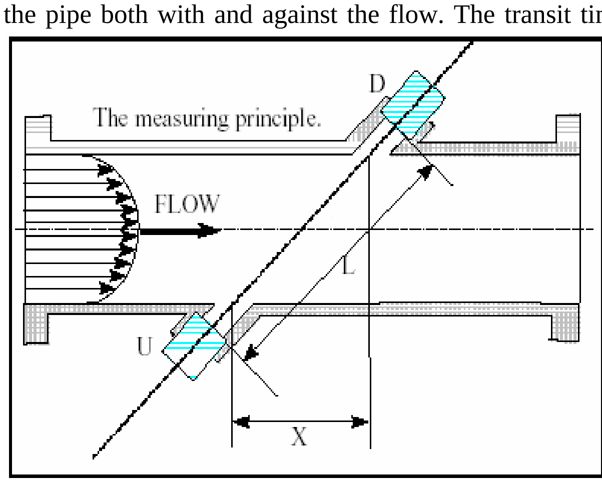
flow direction changes in the U-tube so does the Coriolis force, the combined effect being to twist the U-tube in proportion to the mass flow.

The inlet pipe flow accelerates (as the U-tube is of smaller diameter than the pipe) and has to turn through 135^0 to enter the U-tube. This is like having a built in disturbance that dominates over any other upstream disturbance, and tends to make the meter insensitive to profile effects.

Newer Coriolis meters are of a straight tube design and have been shown to be sensitive to upstream profile effects, thus requiring flow conditioning, preferably to produce fully developed flow.

Ultrasonic Meters

The principle of the transit time difference ultrasonic meter is to transmit ultrasonic signals diagonally across the pipe both with and against the flow. The transit time



with the flow t_{UD} is shorter than the transit time against the flow t_{DU} and the axial velocity (V) is given by:

$$V = \frac{L^2}{2X} \frac{(t_{DU} - t_{UD})}{t_{DU}\, t_{UD}}$$

Where L and X are defined in the figure
t_{DU} = transit time from Downstream to Upstream
t_{UD} = transit time from Upstream to Downstream

The main advantage comes with multi-path meters, offering the freedom to choose the number, location and orientation of the paths. There is also a wide choice of integration techniques to obtain the flow rate from the measured path velocities. This gives the opportunity to design meters that are less sensitive to velocity profile distortions (Ref. 5).

There are many different meter designs on the market, so it is difficult to make any simple universally true statements, however a reasonable guide would be:

1. With 20D or more upstream straight pipe conditioning is probably unnecessary
2. If less space is available consider flow conditioning
3. An isolating conditioner is probably best
4. Calibrate the complete meter/flow conditioner combination

Practically an ultrasonic pulse has no inertia and responds to the turbulence in the flow, affecting the short time repeatability of the meter.

The well known 4-chord Westinghouse design (Ref. 6), with chords located at ± 0.309R and ±0.809R with weighting factors (W) of 0.3618 and 0.1382 respectively, works well in turbulent flow. The average flow velocity (V) is given by numerical integration with $V = \Sigma V_i * W_i$ where V_i = chord velocity and W_i = chord weight, and it is almost independent (< 0.1%) of the Reynolds number and the pipe roughness.

Flow Conditioners

Tube bundles and straightening vanes (Etoile and AMCA) have existed since the 1930's. They basically divide the pipe cross section into many parallel channels to remove swirl. However these channels prevent mixing and tend to preserve the velocity profile, especially if placed close to a disturbance.

In the 50's Sprenkle used three perforated plates in series as a conditioner (Ref. 7). The high resistance substantially destroyed any swirl and profile distortion, producing a highly turbulent flow, which allowed a new flow profile to develop.

In the 60's Zanker produced the first conditioner designed to create fully developed flow in a short length (Ref. 8). It consisted of a graded resistance plate followed by a

honeycomb (square tube bundle) to remove swirl, and effectively making many orifice meter tubes in parallel. With the same pressure drop across each tube, the orifice area ratio determines the velocity, and can thus be tuned to reproduce a fully developed velocity profile.

The next innovation was made by Mitsubishi in the 70's (Ref. 9), who showed that a thick (D/8) plate, with some resistance, substantially removed swirl.

The 80's and 90's were very productive with work from Laws in England, K-Lab in Norway, Nova in Canada, NEL in Scotland, Gallagher & Zanker in America, leading to the availability of several high performance isolating flow conditioners on the market.

Conditioners obstruct the flow and cause pressure loss. Pressure loss provides the energy to re-distribute the velocity profile. More severe disturbances might require more pressure loss, but most fiscal metering systems try to avoid severe disturbances.

Conditioning Orifice Plate

It is possible to combine the function of the orifice and conditioner into one unit, and use the conditioner as a meter (Ref.10). Examples of two other similar devices that have come to market recently, with the idea of making the meter less sensitive to velocity profile distortions are the Rosemount 1595 and Texas A & M slotted orifice. They basically have a distributed resistance instead of a single central hole. A jet could pass through the central orifice with little pressure loss (high C_D) while an annular flow would have a high loss (low C_D).

The Rosemount plate with 4 holes seems more practical than the Texas A & M plate with 48 slots.

In a metering system that includes a flow conditioner it is possible to use the conditioner as a check meter (Ref. 11)

The Rosemount 1595

The Texas A & M Slotted Orifice

Conclusions

Profile distortions are known to affect the performance of flow meters to a certain degree.

The magnitude of the effect depends upon both the severity of the distortion and the sensitivity of the meter

These effects can be mitigated by:
- Long straight lengths of upstream pipe
- Designing meters that are less sensitive to velocity profile distortions
- Designing flow conditioners that produce good velocity profiles in much shorter pipe lengths

Long lengths of pipe are often neither practical nor economic. The meter design is not under the control of the user. Then flow conditioners offer the only available solution.

Flow conditioners were first developed for orifice plates, where it was quickly realized that fully developed flow was the ideal condition. This led to high performance isolating conditioners.

There is a virtually infinite variety of flow disturbances situations that can occur in practice and the isolating conditioner tries to offer a universal solution.

Turbine meters are sensitive to swirl, and tube bundles were found to offer an effective solution.

Positive displacement and Coriolis meters have been found to be almost immune to profile effects.

Ultrasonic meters offer the opportunity of designing systems that are less sensitive to profile effects.

Flow conditioners can be used as differential pressure flow meters, but have not been standardized

Flow conditioners used with other meters can double as check meters.

The latest development with differential pressure devices is the design of combined orifice/conditioning, which is much less sensitive to distorted profile effects.

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Klaus Zanker