Practical Aspects of Turbine Flow Meters

Calibration and UVC principles

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Like any measurement instrument, a turbine flowmeter displays secondary sensitivity to physical parameters other than the one which is of primary interest. Although designed to measure volumetric flow, a turbine meter responds to the viscosity of a fluid as well as its density and velocity. Following is a brief discussion of the sensitivity of a turbine flowmeter to viscosity and the description of a method (UVC) which can be used to compensate it's effects.

Nature of Absolute Viscosity

Absolute viscosity (µ) is the characteristic of a fluid which causes it to resist flow. The higher the numerical value of absolute viscosity in Centipoise (cPs) of a fluid, the greater is the resistance that fluid offers to flow.

Water and gasoline are fluids with relatively low viscosity which flow very easily and which are frequently referred to as being nearly inviscid. Motor oil and honey are examples of more viscous fluids which offer far greater resistance to flow. It is the high viscosity of the honey which prevents it from running out of the bottle when cold.

Increasing viscosity in a fluid causes increasing loss in pressure as it flows. An increase in viscosity requires an increased amount of energy to pump fluid at the same rate of flow. Expressed in a different way, flow from a constant pressure source will decrease as the viscosity of the flowing fluid increases.

The absolute viscosity (µ) of a liquid is highly dependent upon it's temperature. An increase in temperature will cause a decrease in µ. For this reason, temperature changes affect the performance of turbine flowmeters.

Kinematic and Absolute Viscosity

The ratio for absolute viscosity to density appears in many engineering equations and it is called Kinematic Viscosity (v) and it is usually expressed in Centistokes (cSt):

$v = \mu/p$

It is the kinematic viscosity, v, which is of interest in turbine flowmeter applications.

Temperature and Pressure effects

The absolute viscosity of a fluid is strongly influenced by temperature. As temperature increases, the absolute viscosity of both liquids and gases decreases.

The influence of pressure on absolute viscosity is negligible at low pressures. However, pressures over about 70 bar will have a measurable effect on absolute viscosity.

Since kinematic viscosity is the ratio of absolute viscosity and density, it is affected by pressure as well as temperature. If density changes with temperature or pressure, the kinematic viscosity will also change proportionally. For gas applications, density and consequently kinematic viscosity are both strongly influenced by pressure.
It is in fact kinematic viscosity which is the key fluid parameter influencing turbine flow meter performance.

Reynolds Number - Laminar vs Turbulent Flow

Fluid flow is characterized as being either laminar or turbulent. In laminar flow the fluid moves in layers, with one sliding smoothly over the other. There is no mixing of fluid from layer to layer, since viscous shear forces damp out relative motions between layers. Since each layer of fluid is in effect flowing over the one adjacent to it, the fluid velocity increases with the distance from the pipe wall. The resulting velocity profile is approximately parabolic in shape.

In turbulent flow, there are no discrete layers of flowing liquid. The momentum of the fluid overcomes the viscous shear forces, and there is extensive and continual mixing across the flow stream. This causes the velocity profile across a pipe to be nearly flat.

A measure of the laminar or turbulent nature of flow is the Reynolds Number (Re). By definition:

$Re = DVp/\mu = DV/v$ Where D = Diameter of the flow passage
V = Velocity of the flowing fluid

The numerator in the Reynolds Number is directly related to the momentum possessed by the fluid. The denominator is the absolute viscosity of the fluid, and is therefore, directly related to the shear forces existing in the fluid. The Reynolds Number is therefore, a ratio of momentum to viscous forces.

Since a predominance of momentum is associated with turbulent flow and a predominance of viscous forces are associated with laminar flow, it is then to be expected that a large Reynold Number will be associated with turbulent flow. Conversely, a low Reynolds Number is associated with laminar flow.
The transition from laminar to turbulent flow generally occurs at a Reynolds Number between 2000 and 4000. Reynolds numbers higher than 5000 are indicative of turbulent flow.

Viscous Drag effects on a Turbine Flowmeter

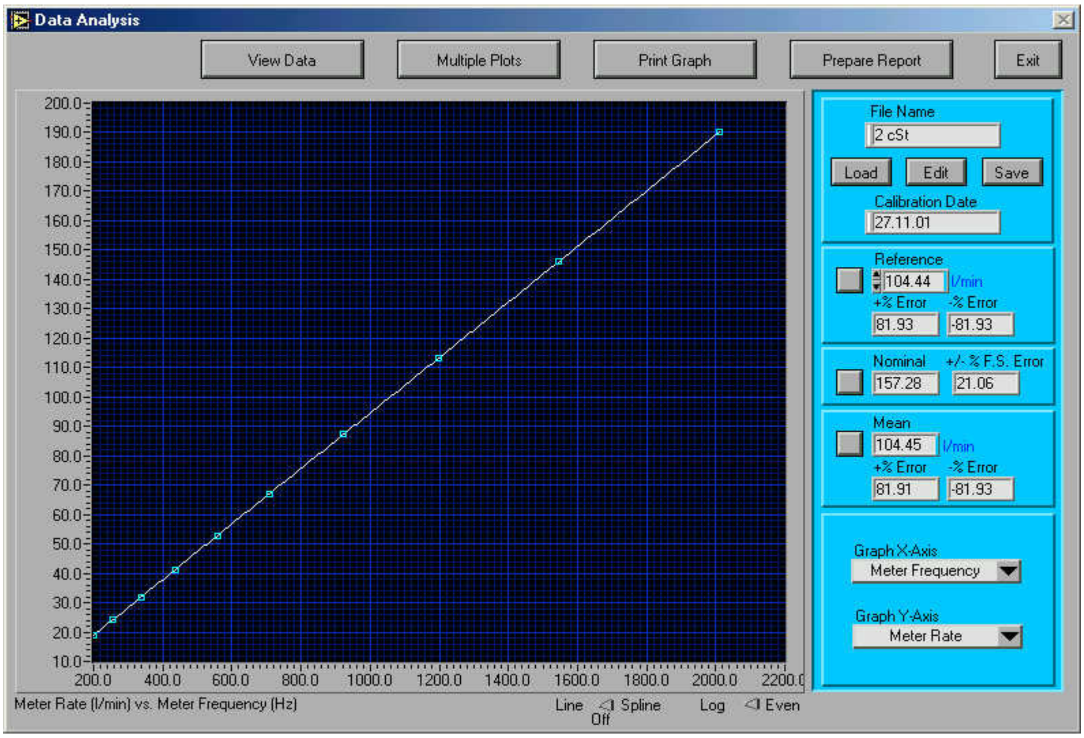
The viscous drag exerted by the metered fluid acts on all of the moving surfaces of a turbine flowmeter. This drag acts within the bearing and in the space between the rotor blade tips and the housing. The viscous drag exerted on the surfaces of the rotor blades produces both a downstream thrust and a retarding torque on the rotor.

Because of the viscous retarding forces, the rotor does not spin as fast as it would in an inviscid (low viscosity) fluid. The rotor actually slips in the stream of flowing fluid, so that the surface of the blades slightly deflects the fluid. As a result of the slippage, the rotational motion is retarded. The amount of slip of the rotor will depend upon both the kinematic viscosity and the velocity of the fluid. It follows then that the performance of a turbine flow meter is therefore a function of the Reynolds number which in itself is a characteristic of the existing flow conditions.

Viscous drag also contributes to the pressure drop across the turbine meter. Increasing viscosities will limit the maximum attainable flow rate.

UVC (Universal Viscosity Calibration) principles

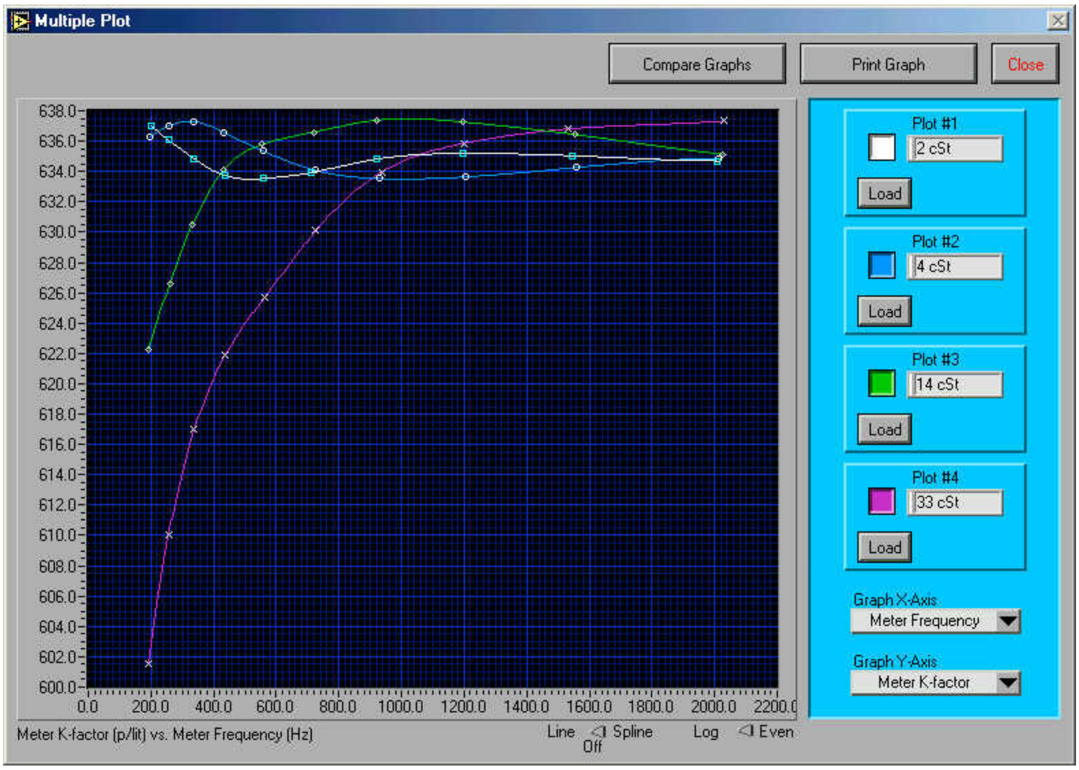
Calibration of a turbine flowmeter consists primarily of recording the output frequency (Fr in Hz) of the meter at specific rates of flow (Q in lit/min) generated by a calibration system.



File Name 2 cSt
Calibration Date 27.11.01
Reference 104.44 l/min
+% Error 81.93
-% Error -81.93
Nominal 157.28
+/- % F.S. Error 21.06
Mean 104.45 l/min
+% Error 81.91
-% Error -81.93
Graph X-Axis Meter Frequency
Graph Y-Axis Meter Rate

Figure 1 - Q (lit/min) vs. Frequency Presentation

When the calibration data are plotted in a simple Q vs Fr form, the result is a straight line as illustrated in Figure 1. However, this representation is coarse and does not readily show deviations from linear behavior that are usually present at the lower part of the flowmeter's range.



Plot #1 2 cSt
Plot #2 4 cSt
Plot #3 14 cSt
Plot #4 33 cSt
Graph X-Axis Meter Frequency
Graph Y-Axis Meter K-factor

Figure 2 - K Factor (pul/lit) vs. Frequency Presentation

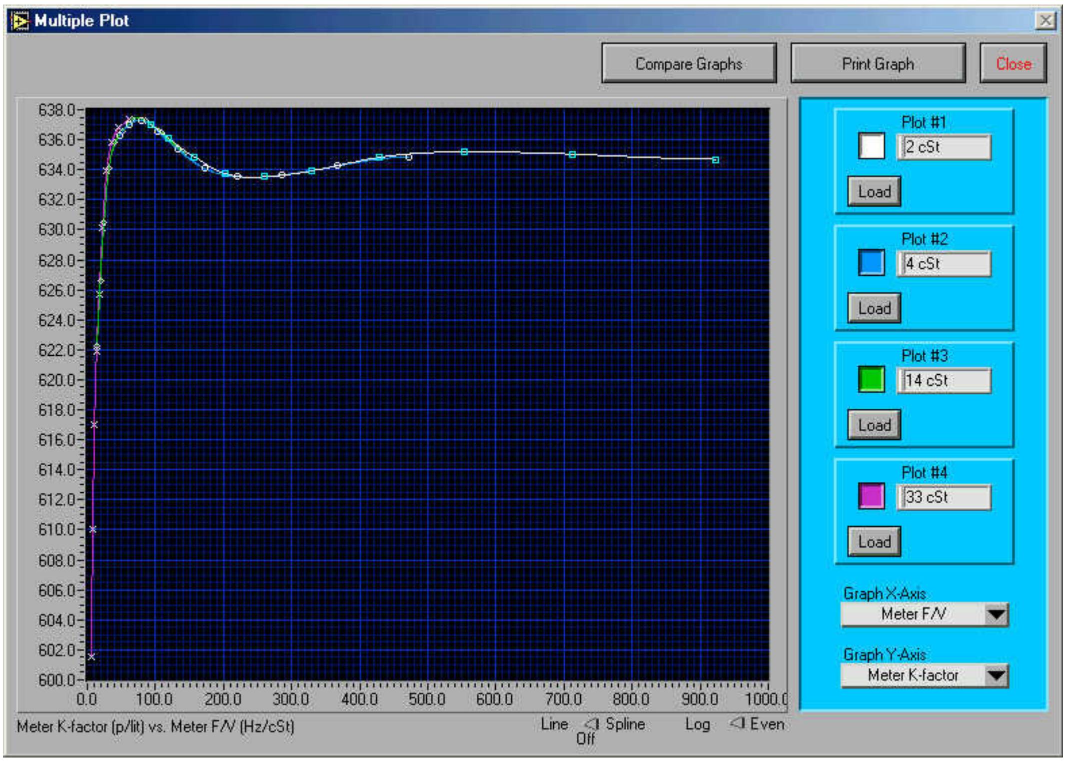
A more usable presentation of a turbine flowmeter's calibration data is in terms of K Factor:
K = Fr*60/Q pulses/lit

When K Factor is plotted against Fr or Q, the linear region of the flowmeter approximates a horizontal straight line. This is shown in figure 2 where calibration data for a flowmeter at different viscosities are shown. It can be seen that above a threshold frequency (which varies with the viscosity), the K factor remains constant within +/- 0.5%. In fact, many users of turbine flowmeters assume a constant K-factor for their flowmeters and use the following equation to calculate flow rate regardless of frequency:

Q = Fr*60/K

This is a reasonable approximation when flowmeters are used over their linear (usually 10:1) range. However, even this more sophisticated presentation of calibration data does not readily allow compensation for the effects of viscosity, as can be seen in figure 2. In effect, a different line will result for every viscosity, making this presentation of flowmeter performance very unwieldy except in cases where single and constant viscosity operation is expected. The user would have to graphically interpolate to obtain accurate results.

In order to address these shortcomings, the Universal Viscosity Curve (UVC) has been developed and deployed. In this presentation, the flowmeter calibration data are plotted in terms of K Factor versus Fr/v as shown in figure 3.



Plot #1 2 cSt
Plot #2 4 cSt
Plot #3 14 cSt
Plot #4 33 cSt
Graph X-Axis Meter F/V
Graph Y-Axis Meter K-factor
Meter K-factor (p/lit) vs. Meter F/V (Hz/cSt)

Figure 3 - K Factor (pul/lit) vs. Fr/v (Hz/cSt) Presentation

The rationale for using the ratio Fr/v is that it is directly proportional to the Reynolds Number for any given set of flow conditions. Hence the UVC is essentially a plot of meter sensitivity (pulses per unit volume) vs. Reynolds Number. As such, it reflects the combined effects of velocity, density and absolute viscosity acting on the meter. The latter two are combined into a single parameter by using kinematic viscosity (v).

The Universal Viscosity Curve is formed by plotting K vs. Fr/v for multiple viscosities within the operating viscosity range of the flowmeter. Typically, ten points are used per viscosity. The number of viscosities

varies required varies depending on the application but a rule of thumb is that any two consecutive viscosities should not differ by more than a factor of 10.
For example, if the operating viscosity is expected to vary from 1 to 100 cSt, a three-viscosity calibration at 1, 10 and 100 cSt is recommenced.
If the range to be covered is 3-40 cSt, calibrations at 3, 10 and 40 cSt should be performed. In this case however it may also be possible to use only 3 and 40 cSt and still obtain reasonable results.

The calibration points from all the different viscosities of a UVC are plotted on a common graph to form a smooth curve as shown in figure 4. This single Universal Viscosity Curve (UVC) can then be used to predict the performance of the flowmeter with high degree of accuracy under all conditions within the calibration viscosity range.

When using UVC principles, volumetric flow rate can be determined from measured output frequencies and viscosities following the steps shown below and illustrated in figures 4 and 5 for liquid and gas applications respectively:

•Measure flowmeter output frequency in Hz.

•Measure kinematic viscosity v or estimate v by using a temperature vs. viscosity table.

•Calculate Hz/v

•Read up from known Hz/v to K vs. Fr/v curve

•Read over from curve to determine K factor

•Calculate: lit/min = Hz*60/K

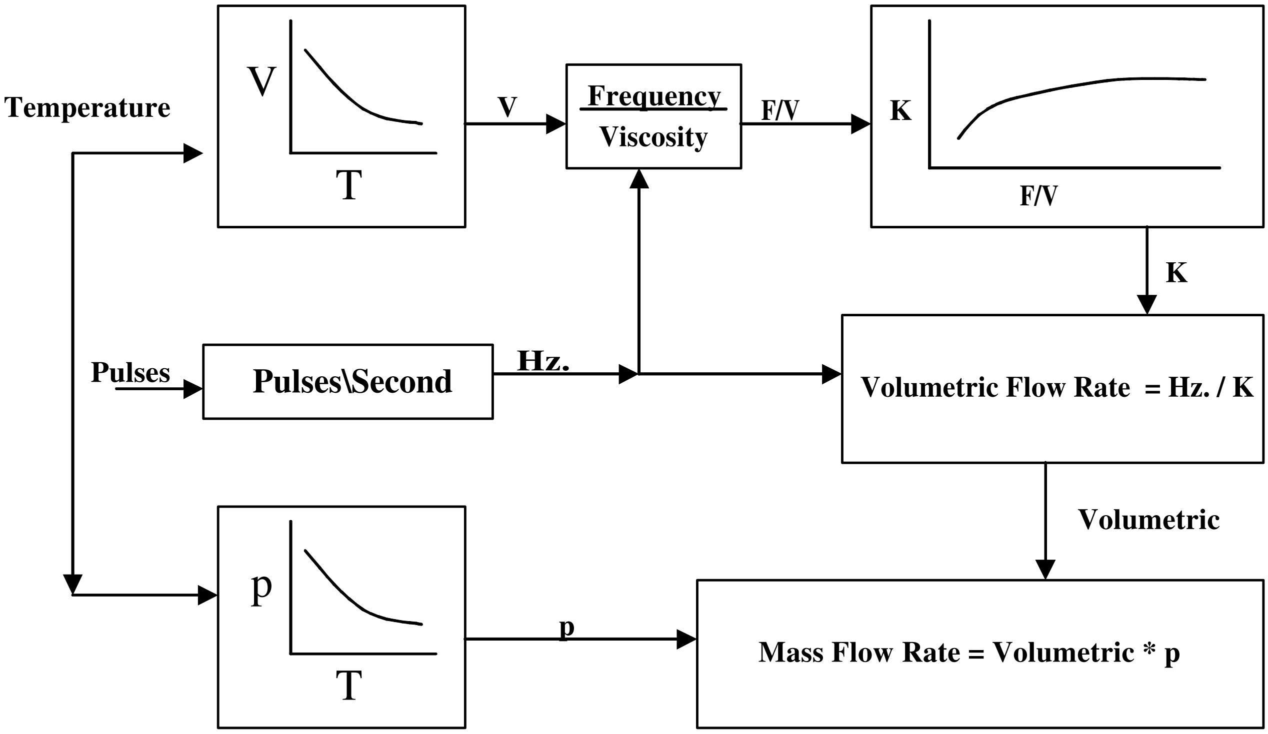


Figure 4 - Liquid Flow Rate Calculation using UVC

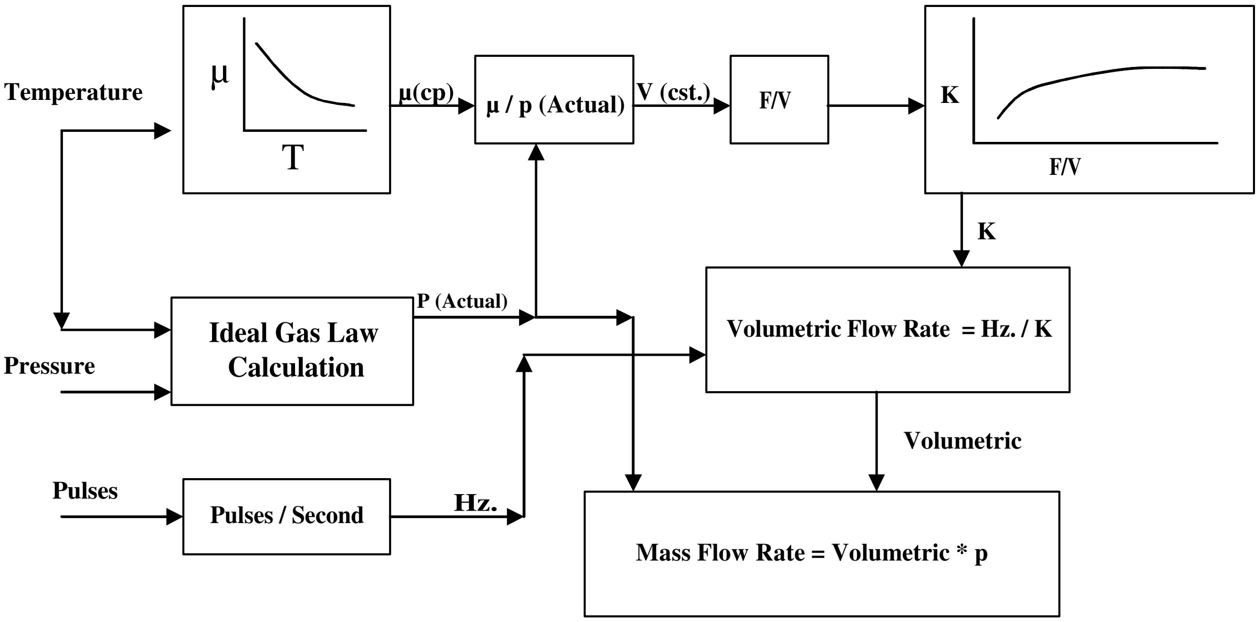


Figure 5 - Gas Flow Rate Calculation using UVC

Limitations of UVC Method

The UVC method is a very powerful tool in accurately determining flow using turbine flowmeters. It does however have limitations which should be kept in mind.

The main limitation is that it is applicable mainly over the linear range of turbine flowmeters. This means that within a 10:1 and perhaps as high as 30:1 of the upper range of turbine flowmeters, depending on type and manufacture, +/- 0.5% accuracy can be maintained. Outside this range, separation of the curves begins to occur and the user must be diligent in order to insure reliable measurement. Usually an analysis of calibration data will help determine the range of flow and viscosities over which the UVC will produce results within expectations.

There are tools available in the market place (such as the UVC Editor utility offered by TrigasFI GmbH, www.trigasfi.com) which can be used to effectively implement the UVC concepts in day-to-day flow measurement applications.

Another limitation of the UVC method is that although it compensates of viscosity (which may be induced by changes in temperature and/or pressure) it does not compensate for other temperature and pressure effects such as flowmeter body expansion. There are ways to take this effect into account as well, notable the Roshko/Strouhal method which is subject of several publications and has been found to be effective in providing an additional measure of accuracy in the use of turbine flowmeters (see references below).

References

1. Mattingly, G. E., Journal of Research os the National Institute of Standards and Technology, Vol. 97, Number 5, Sept.-Oct. 1992, The Characterization of a Piston Displacement-Type Flowmeter Calibration Facility and the Calibration and Use of Pulsed Output Type Flowmeters.
2. Streeter, Vistor, L. Fluid Mechanics, Fourth Edition, McGraw-Hill, 1966.
3. Sargent, L.B., Jr. Significance of Viscosity Studies of Fluid Lubricants at High Pressure. Lubrication Engineering. July-August 1955, pp. 249-254
4. Hoerner, Sighard F. Fluid Dynamic Drag. Published by Hoerner Fluid Dynamics, 2 King Lane, Brick Town, N.J. 98723.
5. Rubin, M., Miller, R.W., and Fox, W.G. Driving Torques in a Theoretical Model of a Turbine Meter, Transactions of the ASME. Journal of Basic Engineering, Paper Number 64 - WA/FM-2, 1965
6. Marks, Lionel, S., and Baumeister, T. Mechanical Engineers Handbook, McGraw-Hill Book Co., Eighth Edition, 1978
7. Miller, Richard W., Flow Measurement Engineering Handbook, McGraw-Hill Book Co., Second Edition, 1989
8. FTI Flow Technology, EB-88251