(An alternative method for computing the FWME that decreases the contribution of the highest flow-rate point is to use a reduced weighting factor, such as 0.4, when $q_i \geq 0.95\ q_{max}$. The designer or the operator may also use different weighting factors, depending on whether the meter is run mostly in the lower, middle or upper range of flow.)

Applying the above equation for FWME to the test data in Table A.1 (where $q_{max}$ = 87,500 acf/h) produces the results shown in Table A.2. Note that a column labeled $wf_i$ is included in Table A.2 to show the weighting factor that is applied to each $E_i$ value.

| Actual Test Rate - Reference Meter ( acf/h ) | $wf_i = qi / qmax$ | $E_i$ ( % ) | $wf_i \times E_i$ ( % ) |
|---|---|---|---|
| 3,475 | 0.0397 | +0.953 | +0.0378 |
| 6,890 | 0.0787 | +0.376 | +0.0296 |
| 21,980 | 0.2512 | -0.318 | -0.0799 |
| 37,801 | 0.4320 | -0.315 | -0.1361 |
| 60,415 | 0.6905 | -0.372 | -0.2569 |
| 86,500 | 0.9886 | -0.366 | -0.3618 |
| SUM = | 2.4807 | SUM = | -0.7672 % |

**Table A.2 FWME Calculation Summary for an 8" Diameter UM**

The FWME value for the test data in Table A.2 is calculated as follows (without any calibration-factor correction being applied to the data).

$$\text{FWME} = \text{SUM}\ (wf_i \times E_i) / \text{SUM}\ (wf_i) = -0.7672 / 2.4807 = -0.3093\%$$

A single calibration factor, F, can now be applied to the meter output to reduce the magnitude of the measurement error. The value of F is calculated using the following equation.

$$F = 100 / (100 + \text{FWME})$$

For this example, the FWME is -0.3093% and the single calibration factor , F, is calculated to be 1.0031. By multiplying the UM's output by 1.0031 (i.e., by applying the calibration factor), the calculated FWME should then equal zero. The adjusted test data are presented in Table A.3 below. In this table, each $E_i$ has been adjusted to obtain a calibration-factor-adjusted value, $E_{icf}$, using the following equation.

$$E_{icf} = ( E_i + 100 ) \times F - 100$$

| $E_i$ (%) | $wf_i$ | $E_{icf}$ (%) | $wf_i \times E_{icf}$ (%) |
|---|---|---|---|
| +0.953 | 0.0397 | +1.2662 | +0.0503 |
| +0.376 | 0.0787 | +0.6874 | +0.0541 |
| -0.318 | 0.2512 | -0.0088 | -0.0022 |
| -0.315 | 0.4320 | -0.0058 | -0.0025 |
| -0.372 | 0.6905 | -0.0629 | -0.0434 |
| -0.366 | 0.9886 | -0.0569 | -0.0563 |
| SUM = | 2.4807 | SUM = | 0.0000 % |

**Table A.3 "FWME-Corrected" Flow-Calibration Data Summary for an 8" Diameter UM**

Using the adjusted data from Table A.3 to calculate FWME produces the following result.

FWME = 0.0000 / 2.4807 = 0.0000 %

In the following plot, the FWME-corrected flow-calibration data have been added to the test data presented in Figure A.1. The triangles represent the meter's error after a single calibration factor of 1.0031 has been applied to the original flow-calibration data.

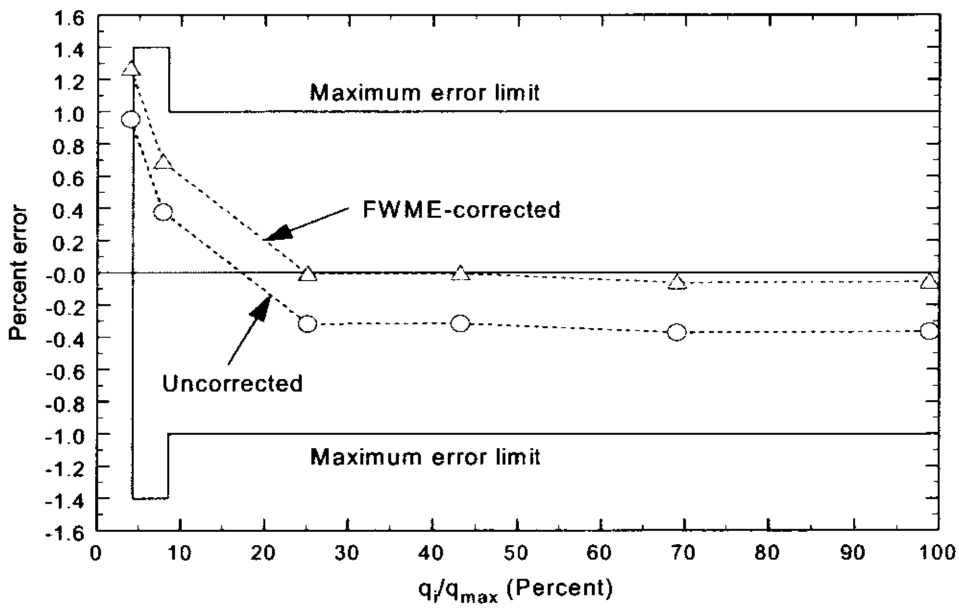


**Figure A.2: Uncorrected and FWME-Corrected Flow-Calibration Data for an 8" Diameter UM**

Figure A.2 shows that for gas flow rates above about 25% of the capacity of the meter, the measurement error has been virtually eliminated by applying a single FWME calibration-factor adjustment to all of the test flow data. However, for flow rates below about 25% of the meter's capacity, the single FWME calibration-factor adjustment does not completely eliminate the measurement error because the UM has a nonlinear characteristic over this portion of its operating range. Therefore, the operator must either accept the higher measurement error on the low end of the meter's operational range or apply a more sophisticated correction scheme to reduce or eliminate the measurement error on the low end of the meter's range.

**Note:** The laboratory test data used in this example calculation of FWME were provided courtesy of Southwest Research Institute, San Antonio, Texas.

## APPENDIX B: Electronics Design Testing

The design of the UM's electronics should be tested to demonstrate that the UM will continue to meet the performance requirements of Section 5, while operating under the influences and disturbances specified in the current revisions of OIML R 6, *General Provisions of Gas Volume Meters*, and OIML D 11, *General Requirements for Electronic Measuring Instruments*. OIML is the Organization Internationale de Metrolocie Legale (i.e., the International Organization of Legal Metrology). OIML publishes these documents for the expressed purpose of harmonizing national performance requirements and testing procedures for gas meters.

For the climatic conditions, the requirements shall be for class 4K3, "open locations with average climatic conditions, thus excluding polar and desert environments." For the mechanical conditions, the requirements shall be for class 3/4M5, "locations with significant or high levels of vibration and shock"; e.g., transmitted from adjacent compressors. The combination of these two conditions leads to OIML class F for determining the severity level for each test.

These test requirements shall apply to the design of all circuit boards, ultrasonic transducers, interconnecting wiring and customer wiring terminals. The electronics shall be in operation, measuring zero flow, and remain 100% functional during the tests. In the case of high-voltage transient and electrostatic discharge tests, the meter may temporarily stop functioning but shall automatically recover within 30 seconds.

During these tests, the ultrasonic transducers may be operated in a smaller and lighter test cell (or test cells) instead of a full meter body. However, the transducers shall actually be measuring zero flow and be exposed to the same test conditions as other parts of the electronic system.

The following sections provide a brief description of the required tests and severity levels. Note that the severity levels are listed here for information only and may change in future revisions of the OIML documents. For detailed testing procedures, the manufacturer may refer to the referenced OIML documents, which, in turn, refer to applicable International Electrotechnical Commission (IEC) publications.

### B.1 Static Temperature, Dry Heat

Exposure to a static temperature of 131° F (55° C) during a period of two hours. The change of temperature shall not exceed 1.8° F/min (1° C/min) during heating up and cooling down. The humidity of the air shall be such that condensation is avoided at all times.

### B.2 Static Temperature, Cold

Exposure to a static temperature of -13° F (-25° C) during a period of two hours. The change of temperature shall not exceed 1.8° F/min (1° C/min) during heating up and cooling down. The humidity of the air shall be such that condensation is avoided at all times.

### B.3 Damp Heat, Steady State

Exposure to a constant temperature of 86° F (30° C) and a constant relative humidity of 93% for a period of four days. The handling of the electronics shall be such that no condensation of water occurs on this unit.

## B.4 Damp Heat, Cyclic

Exposure to cyclic temperature variations between 77° F and 131° F (25° C and 55° C), maintaining the relative humidity above 95% during the temperature change and low temperature phases, and at 93% at the upper temperature phases. Condensation should occur on the electronics during the temperature rise. The test consists of two cycles of 24 hours each following the specified procedure per cycle.

## B.5 Random Vibration

Exposure to a random vibration level specified below.

| | |
|---|---|
| Frequency range: | 10-150 Hz |
| Total RMS level: | 5.25 $ft/s^2$ (1.6 $m/s^2$) |
| ASD level 10-20 Hz: | (0.048 $m/s^2$) |
| ASD level 20-150 Hz: | -3 dB/octave |
| Number of axes: | 3 |
| Duration: | 2 minutes or longer if necessary to check the various functions. |

## B.6 Sinusoidal Vibration

Exposure to a sinusoidal vibration by sweeping the frequency in a range of 10-150 Hz at 1 octave per minute at an acceleration level of 6.56 $ft/s^2$ (2 $m/s^2$). The electronics shall be tested in three perpendicular axes. The duration of the test is 20 cycles per axis.

## B.7 Mechanical Shock

The electronic unit, standing in its normal position of use on a rigid surface, is tilted at one bottom edge to a height of 1" (25 mm) and then is allowed to fall freely onto the test surface — twice for each bottom edge.

## B.8 Power Voltage Variation

Exposure to the specified power supply conditions for a period long enough to achieve temperature stability and to perform checks on the performance of the meter.

| | |
|---|---|
| Mains voltage: | Nominal mains voltage ± 10% |
| Mains frequency: | (50 Hz or 60 Hz) ± 2% |

## B.9 Short Time Power Reduction

Exposure to mains voltage interruptions and reductions specified below. The reductions shall be repeated 10 times with an interval of at least 10 seconds.

| | |
|---|---|
| Reduction: | 100% during 10 ms (milliseconds) |
| | 50% during 20 ms |

## B.10 Bursts (Transients)

Exposure to bursts of voltage spikes having a double exponential wave form. Each spike shall have a rise time of 5 ns (nanoseconds) and a half amplitude duration of 50 ns. The burst length shall be 15 ms; the burst period (repetition time interval) shall be 300 ms. The peak value shall be 0.5 kV.

## B.11 Electrostatic Discharge

Exposure to 10 electrostatic discharges with a time interval between each discharge of 10 seconds. If the electrode giving the discharge is in contact with the electronics, the test voltage shall be 6 kV. If the electrode is approaching the electronics and the discharge occurs by spark, the test voltage shall be 8 kV.

## B.12 Electromagnetic Susceptibility

Exposure to a radiated electromagnetic field. The frequency range shall be 0.1 to 500 MHz, with a field strength of 10 Volts/meter (V/m).

# APPENDIX C: Ultrasonic Flow Measurement for Natural Gas Applications

**A.G.A. Operating Section Transmission Measurement Committee**

**Engineering Technical Note M-96-2-3**

This technical note contains reference information for measuring high-pressure natural gas using large-capacity ultrasonic flow meters, including principles of operation, technical issues, evaluation of measurement performance, error analysis, calibration and reference literature.

Prepared by the

Ultrasonic Metering Task Group



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Phil Barg, Chair

Ultrasonic Task Group

March 1996

## C.1 Introduction

The Transmission Measurement Committee of the American Gas Association submits the following reference information for measuring natural gas with ultrasonic flow meters.

Ultrasonic meters measure flow by measuring velocity in the gas stream using pulses of high-frequency sound. By measuring the transit time, the average velocity of the gas is calculated. Volume and mass flow rates are then calculated using standard equations of state (such as A.G.A. Report No. 8, *Compressibility Factors of Natural Gas and Other Related Hydrocarbon Gases*).

These meters have a number of important attributes for measuring large volumes of natural gas. For instance, ultrasonic meters have a high turndown ratio and incur a small pressure loss. The uncertainty of these meters is in line with other types of meters. However, care must be taken by the user in order to ensure a proper understanding of the characteristics and limitations of these meters, so that the expected results can be achieved.

Single-path and multipath meters are addressed. Where there is no reference to the number of paths, the particular section can be assumed to apply to both. Multipath meters are used to reduce uncertainties, especially when dealing with non-uniform gas velocity profiles and other disturbances such as swirl.

This is a compilation of information by experts in the field at the time of publication. It is not intended for use as a reference in contracts.

### *C.1.1 Task Group Scope*

a) Develop an A.G.A. Engineering Technical Note to address the following:
   - Review the current state of ultrasonic metering technology.
   - Share and disseminate operating experience with ultrasonic meters. Leverage off of the experience of the European Community.
   - Develop an understanding of the potential applications and related business parameters.

b) Identify technical issues or limitations and related research needs.

c) Review current industry standards with a view to developing an A.G.A. report for the installation and operation of ultrasonic meters.

### *C.1.2 Engineering Technical Note Scope*

This Technical Note is limited to ultrasonic meters in high-pressure natural gas transmission. Although references are made to ultrasonic meters for liquid flow applications, the general theme and the recommendations relate specifically to high-pressure natural gas applications.

## C.2 Principle of Operation

### *C.2.1 Introduction*

An ultrasonic flow meter is a measurement device that consists of ultrasonic transducers, which are typically located along a pipe's wall. The transducers are in direct contact with the gas stream and, therefore, the pressure at the location of the transducer is contained by gas-tight seals. Ultrasonic acoustic pulses transmitted by one transducer are received by the other one, and vice versa. Figure 1 shows a simple geometry of two transducers, *Tx1* and *Tx2*, at an angle $\varphi$ with respect to the axis of a straight cylindrical pipe with diameter *D*. In some instruments a reflection path is employed, where the acoustic pulses reflect one or more times off the pipe wall.

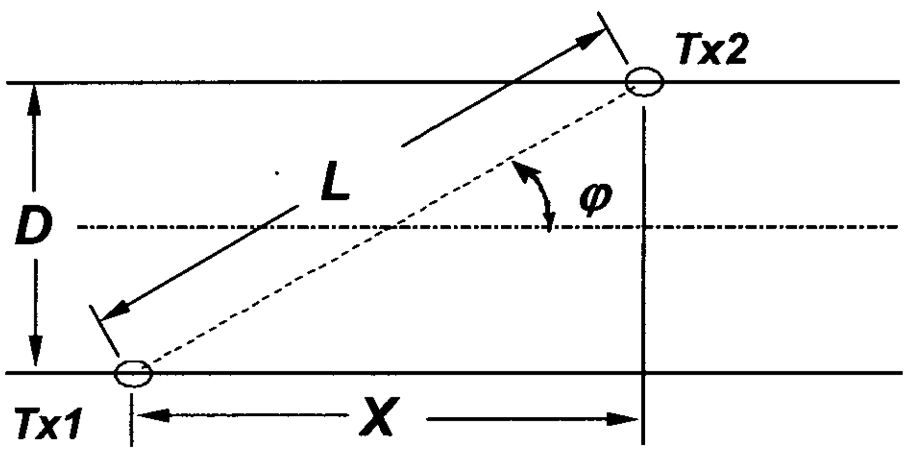


**Figure 1 - Simple geometry of ultrasonic flow measurement**

The acoustic pulses are crossing the pipe, like a ferryman crossing a river. Without flow, they propagate with the same speed in both directions. If the gas in the pipe has a flow velocity other than zero, pulses traveling downstream with the flow will move faster, while those traveling upstream against the flow will move slower. Thus, the downward travel times $t_D$ will be shorter and the upward ones $t_U$ will be longer, as opposed to when the gas is not moving. The travel times are measured electronically. From the transit times, the measured velocity $\bar{v}$ is calculated by

$$\bar{v} = \frac{L^2}{2X}\frac{(t_U - t_D)}{t_U t_D} \qquad (1)$$

where *L* denotes the straight line length of the acoustic path between the two transducers, and *X* denotes the axial distance exposed to the flow. The speed of sound can be calculated from

$$c = \frac{L}{2}\frac{(t_U + t_D)}{t_U t_D} \qquad (2)$$

## *C.2.2 Theory of Ultrasonic Flow Measurement*

### C.2.2.1 Pipe Flow Velocity

Flow velocity may be described by a three-dimensional velocity vector $v$, which in general depends on space $x$ and time $t$: $v = v(x,t)$. In steady, swirl-free flow through long straight cylindrical tubes with radius $R$, the only non-zero time-averaged velocity component will be in the axial direction, and it will be a function of radial position $r$ only. The function for a fully developed velocity profile can be approximated by a semi-empirical power law

$$v(r) = v_{\max}\left(1 - \frac{r}{R}\right)^{\frac{1}{n}} \qquad \textbf{(3)}$$

where $n$ is a function of the pipe Reynolds number $Re$ and pipe roughness. For smooth pipes, Prandtl's equation applies (Schlichting, 1968)

$$n = 2\log_{10}\left(\frac{Re}{n}\right) - 0.8 \qquad \textbf{(4)}$$

In smooth pipes, if the Reynolds number is known, $n$ can be calculated. Using this value of $n$, the velocity profile $v(r)$ can be computed, which essentially is a steady-state description of the flow. Figure 2 shows the velocity profiles, normalized by the maximal velocity $v_{max}$ at the center of the pipe, as computed by the formulas mentioned above, for three Reynolds number values of $Re=10^5$ (n=7.455), $Re=10^6$ (n=9.266) and $Re=10^7$ (n=11.109).

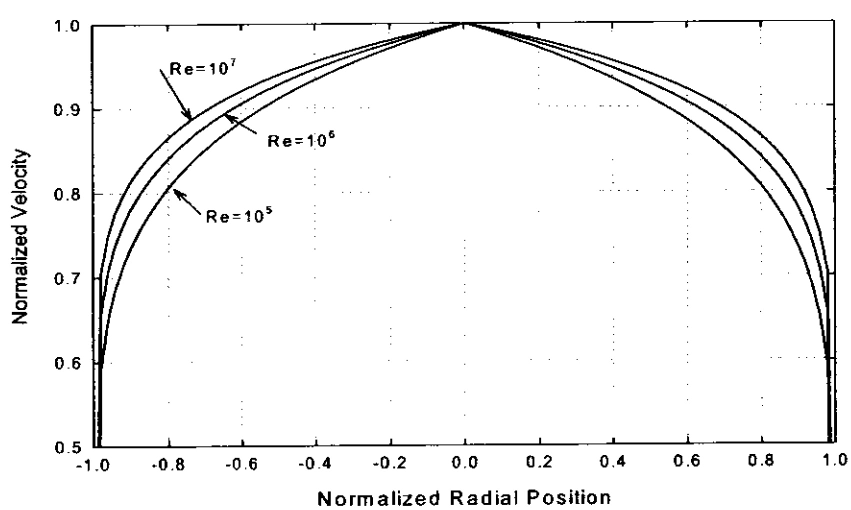


**Figure 2 - Smooth pipe turbulent velocity profiles for $Re = 10^5$, $10^6$ and $10^7$**