American Gas Association

# AGA Report No. 3

## ORIFICE METERING OF NATURAL GAS AND OTHER RELATED HYDROCARBON FLUIDS

## PART 2

## Specification and Installation Requirements



**American Gas Association**
**400 North Capitol Street, N.W., 4th Floor**
**Washington, DC 20001**
**U.S.A.**

**Fourth Edition, April 2000**
**2nd Printing, June 2003**

**Catalog No. XQ0002**

# DISCLAIMERS AND COPYRIGHT

# FOREWORD

AGA Report No. 3, *Orifice Metering of Natural Gas and Other Related Hydrocarbon Fluids,* consists of four parts. **This one is Part 2 – *Specification and Installation Requirements.*** Other parts are:

Part 1 – *General Equations and Uncertainty Guidelines*

Part 3 – *Natural Gas Applications*

Part 4 – *Background, Development, Implementation Procedure, and Subroutine Documentation for Empirical Flange-Tapped Discharge Coefficient Equation*

Each of the four parts is published separately to facilitate future changes, allow immediate use, and reduce the size of the applicable part needed by most users. Although for many applications each part can be used independently, users with natural gas applications are advised to obtain Parts 1, 3 and 4.

This report applies to fluids that, for all practical purposes, are considered to be clean, single phase, homogeneous, and Newtonian, measured using concentric, square-edged, flange-tapped orifice meters; and the Part 2 of the report furnishes specifications and installation requirements, and provides specifications for the construction and installation of orifice plates, meter tubes, and associated fittings. Users of pipe tap orifice meters are referred to AGA Report No. 3, Part 3, for specifications relevant to those meters.

This report has been developed through the cooperative efforts of many individuals from industry under the sponsorship of the American Gas Association, the American Petroleum Institute, and the Gas Processors Association, with contributions from the Gas Research Institute, the Chemical Manufacturers Association, the Canadian Gas Association, and the Commission of the European Communities, Norway, Japan, and others.

The methods and criteria used to analyze data applied for April 2000 revision are described in the relevant white papers and in the Gas Research Institute research reports (see references in Appendix 2-A)

Further revisions to this report may become necessary from time to time. Whenever any revisions are deemed advisable, recommendations should be forwarded to the Operations and Engineering Section, **American Gas Association**, 400 N. Capitol Street, NW, 4th Floor, Washington, DC 20001, U.S.A. A form is included for that purpose at the end of this report.

## ACKNOWLEDGMENTS

Over the duration of the revision process, several individuals have devoted time and technical expertise, however, special acknowledgments are due to a small group of people who have played a vital role in the completion of the document. This group includes:

Mr. Ronald Beaty (Chairman), Premier Measurement Services, Houston, Texas, USA
Dr. Wojciech Studzinski, NOVA Research & Technology Centre, Calgary, Alberta, Canada
Dr. Tom Morrow, Southwest Research Institute, San Antonio, Texas, USA
Mr. Paul La Nasa, CPL & Associates, Houston, Texas, USA
Dr. Umesh Karnik, NOVA Research & Technology Centre, Calgary, Alberta, Canada
Dr. Zaki Husain, Texaco, Inc., Bellaire, Texas, USA
Mr. Klaus Zanker, Daniel Flow Products, Inc., Houston, Texas, USA
Mr. Jim Gallagher, Savant Measurement Corporation, Kingwood, Texas, USA
Mr. Dale Goodson, Daniel Flow Products, Inc., Houston, Texas, USA
Mr. Paul Johnson, Savant Measurement Corporation, Kingwood, Texas, USA
Mr. Fred Van Orsdol, Williams Energy Group, Tulsa, Oklahoma, USA and
Mr. Stephen Stark, Stark & Associates Inc., Tulsa, Oklahoma, USA

During much of the corresponding time period, a similar effort occurred in Europe. Valuable liaison between the two efforts was provided by Dr. Michael Reader-Harris, NEL, Glasgow, UK, Mr. Jan Bosio, K-Lab, Haugesund, Norway, Dr. Bob Peters, Daniel Industries, UK, Dr. Berndt Harbrink, Ruhrgas, Dorsten, Germany and Mr. Geoff Robson, British Standards Institution, London, UK.

This project was possible due to the support of the American Petroleum Institute, Gas Processors Association and American Gas Association. Special thanks to the Gas Research Institute and NOVA Gas Transmission for funding the data collection at the GRI-MRF at SwRI, Daniel Industries and the Didsbury Test Facility operated by NOVA Research and Technology Centre.

This standard has benefited from the contributions from several White Paper Writing Groups, task forces and the editing and comments of various individuals. A list (by no means complete) of the individuals who participated in the revision process is listed below.

Mr. Ron Beaty, Premier Measurement Services, Houston, Texas, USA
Mr. Manny Garcia, American Petroleum Institute, Washington, D.C., USA
Mr. Brent Berry, Applied Automation Inc., Bartlesville, Oklahoma, USA
Mr. James Bowen, Instromet, Inc., Houston, Texas, USA
Mr. R. G. Brunner, Gas Processors Association, Tulsa, Oklahoma, USA
Ms. Sharon Buffington, Minerals Management, Herndon, Virginia, USA
Mr. Stan Canfield, Dynegy Midstream Services, L.P., Tulsa, Oklahoma, USA
Mr. David Crane, Crane Manufacturing, Inc., Tulsa, Oklahoma, USA
Mr. Ronald Dunegan, Perry Equipment Corp., Mineral Wells, Texas, USA
Mr. Wayne Fling, Jr., Flow Metrology, Tulsa, Oklahoma, USA
Mr. Chuck French, Gas Research Institute, Chicago, Illinois, USA
Mr. Steve Gage, Arkansas Wester Gas Company, Ozark, Arizona, USA
Mr. Jim Gallagher, Savant Measurement Corporation, Kingwood, Texas, USA
Mr. Dale Goodson, Daniel Flow Products, Inc., Houston, Texas, USA
Mr. John Gregor, AMETEK, Largo, Florida, USA
Mr. Ed Hickl, Union Carbide Corp., Houston, Texas, USA
Mr. Jim Hollingsworth, Shell Oil Products Co., Houston, Texas, USA
Dr. Zaki Husain, Texaco, Inc., Bellaire, Texas, USA
Dr. Emrys Jones, Chevron Petroleum Tech. Co., La Habra, California, USA
Dr. Umesh Karnik, NOVA Research & Technology Centre, Calgary, Alberta, Canada
Mr. Paul LaNasa, CPL & Associates, Houston, Texas, USA
Mr. Joe Landes, SPL, Houston, Texas, USA

Dr. George Mattingly, National Institute of Standards and Technology, Gaithersburg, USA
Mr. Günter Maurer, Barton Instrument Systems, City of Industry, California, USA
Mr. Kevin Moir, Michigan Consolidated Gas Company, Detroit, Michigan, USA
Mr. Don Morley, CIG Exploration, Inc., Houston, Texas, USA
Dr. Gerald Morrison, Texas A & M University, College Station, Texas, USA
Dr. Tom Morrow, Southwest Research Institute, San Antonio, Texas, USA
Mr. Henry Poelnitz, Southern Natural Gas Co., Birmingham, Alabama, USA
Mr. King Poon, GH Flow Automation, Houston, Texas, USA
Mr. Ali Quraishi, American Gas Association, Washington, D.C., USA
Mr. Rick Rans, Trans Canada Pipelines Ltd., Calgary, Alberta, Canada
Mr. Robert Rayburn, Texas Gas, Lafayette, Louisiana, USA
Mr. Bill Ryan, El Paso Natural Gas Co., Midland, Texas, USA
Mr. Lee Smith, Micro Motion, Boulder, Colorado, USA
Mr. Steve Stark, Stark & Associates Inc., Tulsa, Oklahoma, USA
Mr. Jean Stolz, Consultant, Marly, France
Mr. John Stuart, Pacific Gas and Electric Co., Walnut Creek, California, USA
Dr. Wojciech Studzinski, NOVA research & Technology Centre, Calgary, Alberta, Canada
Late Dr. Ray Teyssandier, Texaco, Inc., Bellaire, Texas, USA
Mr. Fred Van Orsdol, Williams Energy Group, Tulsa, Oklahoma, USA
Dr. Noriyuki Watanabe, Weights and Measures Training Institute, Tokyo, Japan
Mr. Wayne Wenger, Natural Gas Pipeline Co. of America, Joliet, Illinois, USA
Ms. Jane Williams, Oryx Energy Co., Dallas, Texas, USA
Mr. Rusty Woomer, Tennessee Gas Pipeline Co., Houston, Texas, USA
Mr. Harry Bean, Consultant, El Paso, Texas, USA
Mr. Jan Bosio, STATOIL, Haugesund, Norway
Mr. Steve Caldwell, CEESI, Nunn, Colorado, USA
Mr. Richard Estabrook, Bureau of Land Management, Ukiah, California, USA
Mr. Lee Hillburn, Turnbow Engineering, Bartlesville, Oklahoma, USA
Mr. Doug Morris, American Petroleum Institute, Washington, D.C., USA
Mr. Dan Acosta, Perry Equipment Corporation, Mineral Well, Texas, USA
Mr. Randy Austerman, Phillips Petroleum Co., Bartlesville, Oklahoma, USA
Mr. Ed Bowles, Southwest Research Institute, San Antonio, Texas, USA
Mr. Michael Cushing, Honeywell IAC, Fort Washington, Pennsylvania, USA
Mr. Robert Deboom, Micro Motion, Inc., Boulder, Colorado, USA
Mr. Terry Doucet, Ing, Foxboro Canada Inc., Dollard-des-Ormeaux, Quebec, Canada
Mr. R. D. Jones, Chevron USA Production Co., Lafayette, Louisiana, USA
Mr. Jim Keating, Duke Energy, Houston, Texas, USA
Mr. Eric Kelner, Southwest Research Institute, San Antonio, Texas, USA
Mr. Gil Kraemer, Precision Combustion, Inc., New Haven, Connecticut, USA
Ms. Angie Law, Kelly Instrument Machine, Inc., Texarkana, Texas, USA
Mr. Rick Ledesma, ANR Pipeline Co., Bourbonnais, Illinois, USA
Mr. Charles McNamara, Flow Measurement Co., Inc., Tulsa, Oklahoma, US
Mr. Leonard Meaux, Mobil Oil, The Woodlands, Texas, USA
Mr. James Milling, Control-Soft Enterprises, Katy, Texas, USA
Mr. Greg Milster, Thurmond-McGlothlin Co., Inc., Owasso, Oklahoma, USA
Mr. John Naber, Daniel Industries, Inc., Houston, Texas, USA
Mr. Warren Peterson, Kenonic Controls, Calgary, Canada.
Mr. John Phipps, Institute of Petroleum, London, England
Mr. John Roussel, Texaco Natural Gas, St. Rose, Louisiana, USA
Mr. Irvin Schwartzenburg, Fisher Controls, FAS Group, Marshalltown, Iowa
Mr. Steve Scott, Scott Equipment Co., Wheatridge, Colorado, USA
Mr. Walt Seidl, CEESI, Nunn, Colorado, USA
Mr. Pat Skweres, Dow Chemical Company, Freeport Texas, USA
Mr. Jerry Paul Smith, Williams Gas Pipeline—Transco, Houston, Texas, USA

Dr. Frank Ting, Chevron Petroleum Tech. Co., La Habra, California, USA
Ms. Lori. Traweek, American Gas Association, Washington, D.C., USA
Mr. Eric Ward, BP Exploration (Alaska) Inc., Anchorage, Alaska, USA
Mr. James N. Witte, Tennessee Gas Pipeline Company, Houston, Texas, USA
Mr. Ian Wood, Halliburton (U.K.) Ltd., Dyce, Aberdeen, Scotland
Mr. James P. Avioli, Williams Gas Pipeline—Transco, Houston, Texas, USA
Mr. Frank Brown, CMS Energy Corporation, Houston, Texas, USA
Mr. Jeryl M. Mohn, CMS Energy Corporation, Houston, Texas, USA
Mr. William R. Mazotti, Pacific Gas and Electric Company, San Francisco, California, USA
Mr. Daniel G. Harris, Columbia Gas Transmission, Charleston, West Virginia, USA
Mr. Jeffrey M. Dowdell, CNG Transmission Corporation, Clarksburg, West Virginia, USA
Mr. Robert D. MacLean, ANR Pipeline Company, Detroit, Michigan, USA
Mr. Michael T. Brown, TransCanada Transmission, Calgary, Alberta, Canada
Ms. Claire L. Becker-Castle, Southern California Gas Company, Los Angeles, California, USA
Mr. Donal H. Tucker, TXU Electric and Gas, Dallas Texas, USA
Mr. John A. Vassaux, Columbia Gas of Ohio, Inc., Columbus, Ohio, USA
Mr. Dannie R. Mercer, TXU Pipeline Services, Dallas, Texas, USA

# CONTENTS

## CONTENTS

# PART 2—SPECIFICATION AND INSTALLATION REQUIREMENTS

## 2.1 Construction and Installation Requirements

This document outlines the various design parameters that must be considered when designing metering facilities using orifice meters. The mechanical tolerances found in this document encompass a wide range of orifice diameter ratios for which experimental results are available. In several sections of this document, tolerances for the mechanical specifications have been changed relative to previous editions. In particular, this revision includes a change to the installation requirements (meter tube lengths). This change reduces the uncertainty attributable to installation effects to a magnitude smaller than the uncertainty of the database supporting the Reader-Harris/Gallagher (RG) equation and, therefore, should not affect the uncertainty previously defined for that equation.

*This document does not require upgrading existing installations. If the meter installations are not upgraded to meet this current standard, however, measurement bias errors may exist due to inadequate flow conditioning and upstream straight pipe lengths. The decision to upgrade an existing installation shall be at the discretion of the parties involved.*

Use of the calculation procedures and techniques shown in the AGA Report No.3, Parts 1 and 3, with existing equipment is recommended, since these represent significant improvements over the previous methods. However, the uncertainty levels for flow measurement using existing equipment may be different from those quoted in Part 1.

Use of orifice meters at the extremes of their diameter ratio ($\beta_r$) ranges should be avoided whenever possible. Good metering design and practice tend to be somewhat conservative. This means that the use of the tightest tolerances in the mid-diameter ratio ($\beta_r$) ranges would have the highest probability of producing the best measurement. An indication of this is found in the section on uncertainty in Part 1.

This standard is based on $\beta_r$ between 0.10 and 0.75. Minimum uncertainty of the orifice plate coefficient of discharge ($C_d$) is achieved with $\beta_r$ between 0.2 and 0.6 and orifice bore diameters greater than or equal to 0.45 inch. Diameter ratios and orifice bore diameters outside of this range may be used; however, the user should consult the uncertainty section in Part 1 for limitations.

Achieving the best level of measurement uncertainty begins with, but is not limited to, proper design. Two other aspects of the measurement process must accompany the design effort; otherwise it is of little value. These aspects are the application of the metering system and the maintenance of the meters, neither of which is considered directly in this standard. These aspects cannot be governed by a single standard as they cover metering applications that can differ widely in flow rate, fluid type, and operational requirements. Therefore, the user must determine the best meter selection for the application and the level of maintenance for the measurement system under consideration.

## 2.2 Symbols/Nomenclature

This standard reflects orifice meter application to fluid flow measurement with symbols in general technical use.

| **Symbol** | **Represented Quantity** |
|---|---|
| *a* | Speed of sound |
| *Cd* | Orifice plate coefficient of discharge |
| *Cd(FT)* | Flange tap orifice plate coefficient of discharge |
| □*Cd(FT)*/*Cd* | Percent difference between baseline *Cd* and installation effect *Cd* |
| *d* | Orifice plate bore diameter calculated at flowing temperature, *Tf* |
| *dm* | Orifice plate bore diameter measured at temperature, *Tm* |
| *dr* | Orifice plate bore diameter calculated at reference temperature, *Tr* |
| *D* | Meter tube internal diameter calculated at flowing temperature, *Tf* |
| *Di* | Published meter tube internal pipe diameter |
| DL | Meter tube length downstream of orifice plate in multiples of published internal pipe diameters (see Figure 2-6) |
| *Dm* | Meter tube internal diameter measured at *Tm* |
| *Dn* | Nominal pipe diameter |

| | |
|---|---|
| $D_r$ | Meter tube internal diameter calculated at reference temperature, $T_r$ |
| $e$ | Orifice plate bore thickness |
| $E$ | Orifice plate thickness |
| $f$ | Frequency |
| °F | Temperature, in degrees Fahrenheit |
| $l$ | Recommended lengths of gauge line |
| NPS | Nominal Pipe Size |
| $\Delta P$ | Orifice plate differential pressure |
| $\Delta P_{avg}$ | Average orifice plate differential pressure |
| $\Delta P_{rms}$ | Root mean square of the fluctuating differential pressure |
| $\Delta P_t$ | Instantaneous orifice plate differential pressure |
| $P_f$ | Static pressure of the fluid at the pressure tap |
| °R | Temperature, in degrees Rankine |
| $R_a$ | Absolute roughness average |
| $Re$ | Reynolds number |
| $T_f$ | Temperature of fluid at flowing conditions |
| $T_m$ | Temperature of the orifice plate and/or meter tube at time of diameter measurements |
| $T_r$ | Reference temperature (68°F) of orifice plate bore diameter and/or meter tube internal diameter |
| UL | Meter tube length upstream of orifice plate in multiples of published internal pipe diameters (Figure 2-6) |
| UL1 | UL – UL2 |
| UL2 | Meter tube length from flow conditioner exit to orifice plate in multiples of published internal pipe diameters |
| $\alpha$ | Linear coefficient of thermal expansion |
| $\alpha_1$ | Linear coefficient of thermal expansion of the orifice plate material |
| $\alpha_2$ | Linear coefficient of thermal expansion of the meter tube material |
| $\beta$ | Ratio of orifice plate bore diameter to meter tube internal diameter ($d/D$) calculated at flowing temperature, $T_f$ |
| $\beta_m$ | Ratio of orifice plate bore diameter to meter tube internal diameter ($d_m/D_m$) calculated at temperature, $T_m$ |
| $\beta_r$ | Ratio of orifice plate bore diameter to meter tube internal diameter ($d_r/D_r$) calculated at reference temperature, $T_r$ |
| $\varepsilon$ | Orifice plate bore eccentricity |
| $\theta$ | Orifice plate bevel angle |

## 2.3 Definitions

The definitions are given to emphasize the particular meaning of the terms as used in this standard.

### 2.3.1 PRIMARY ELEMENT

The primary element is defined as the orifice plate, the orifice plate holder with its associated differential pressure sensing taps, the meter tube, and flow conditioner, if used.

#### 2.3.1.1 Orifice Plate

The orifice plate is defined as a thin square-edged plate with a machined circular bore, concentric with the meter tube ID, when installed.

#### 2.3.1.2 Orifice Plate Bore Diameter ($d$, $d_m$, $d_r$)

The calculated orifice plate bore diameter ($d$) is the internal diameter of the orifice plate measuring aperture (bore) computed at flowing temperature ($T_f$), as specified in 1.6.2 in Part 1. The calculated orifice plate bore diameter ($d$) is used in the flow equation for the determination of flow rate.

The measured orifice plate bore diameter ($d_m$) is the measured internal diameter of the orifice plate measuring aperture at the temperature of the orifice plate ($T_m$) at the time of bore diameter measurements, determined as specified in 2.4.3.

The reference orifice plate bore diameter ($d_r$) is the internal diameter of the orifice plate measuring aperture at reference temperature ($T_r$), calculated as specified in 2.4.3. The reference orifice plate bore diameter is the certified or stamped orifice plate bore diameter.

#### 2.3.1.3 Orifice Plate Holder

The orifice plate holder is defined as a pressure containing piping element, such as a set of orifice flanges or an orifice fitting, used to contain and position the orifice plate in the piping system.

#### 2.3.1.4 Meter Tube

The meter tube is defined as the straight sections of pipe, including all segments that are integral to the orifice plate holder, upstream and downstream of the orifice plate, as specified in 2.5.1.

#### 2.3.1.5 Meter Tube Internal Diameter ($D$, $D_i$, $D_m$, $D_r$)

The calculated meter tube internal diameter ($D$) is the inside diameter of the upstream section of the meter tube computed at flowing temperature ($T_f$), as specified in 1.6.3 of Part 1. The calculated meter tube internal diameter ($D$) is used in the diameter ratio and Reynolds number equations.

The published meter tube internal diameter ($D_i$) is the inside diameter as published in standard handbooks for engineers. This internal diameter is used for determining the required meter run length in Tables 2-7 and 2-8.

The measured meter tube internal diameter ($D_m$) is the average inside diameter of the upstream section of the meter tube measured 1 inch upstream of the adjacent face of the orifice plate and at the temperature of the meter tube ($T_m$) at the time of internal diameter measurements, as specified in 2.5.1.2.

The reference meter tube internal diameter ($D_r$) is the inside diameter of the upstream section of the meter tube calculated at the reference temperature ($T_r$), as specified in 2.5.1.2. The reference meter tube internal diameter is the certified meter tube internal diameter.

#### 2.3.1.6 Diameter Ratio ($\beta$, $\beta_m$, $\beta_r$)

The diameter ratio ($\beta$) is defined as the calculated orifice plate bore diameter ($d$) divided by the calculated meter tube internal diameter ($D$).

The diameter ratio ($\beta_m$) is defined as the measured orifice plate bore diameter ($d_m$) divided by the measured meter tube internal diameter ($D_m$).

The diameter ratio ($\beta_r$) is defined as the reference orifice plate bore diameter ($d_r$) divided by the reference meter tube internal diameter ($D_r$).

#### 2.3.1.7 Flow Conditioners

Flow conditioners can be classified into two categories: straighteners or isolating flow conditioners.

Flow straighteners are devices that effectively remove or reduce the swirl component of a flowing stream, but may have limited ability to produce the flow conditions necessary to accurately replicate the orifice plate coefficient of discharge database values.

Isolating flow conditioners are devices that effectively remove the swirl component from the flowing stream while redistributing the stream to produce the flow conditions that accurately replicate the orifice plate coefficient of discharge database values.

### 2.3.2 PRESSURE MEASUREMENT

#### 2.3.2.1 Tap Hole

A tap hole is a hole drilled radially in the wall of the meter tube or through the orifice fitting and perpendicular to the centerline of the meter tube or orifice plate holder, the inside edge of which is flush and without any burrs.

#### 2.3.2.2 Flange Taps

Flange taps are a pair of tap holes positioned as follows:

a. the upstream tap center is located 1 inch upstream of the nearest plate face,
b. the downstream tap center is located 1 inch downstream of the nearest plate face,
c. the upstream and downstream taps must be in the same radial position.

#### 2.3.2.3 Differential Pressure ($\Delta P$, $\Delta P_{avg}$, $\Delta P_{rms}$, $\Delta P_t$)

The differential pressure ($\Delta P$) is the static pressure difference measured between the upstream and the downstream flange taps.

The average differential pressure ($\Delta P_{avg}$) is a time mean of the static pressure difference measured between the upstream and downstream flange taps.

The instantaneous differential pressure ($\Delta P_t$) is a single measurement of $\Delta P$ at any instance in time.

The root mean square differential pressure ($\Delta P_{rms}$)is the square root of the sum of squares of the difference between the instantaneous differential pressure ($\Delta P_t$)and time mean differential ($\Delta P_{avg}$).

### 2.3.3 TEMPERATURE MEASUREMENT ($T_f$, $T_m$, $T_r$)

The temperature ($T_f$) is the flowing fluid temperature measured at the designated location, as specified in 2.6.5.

In flow measurement, the temperature sensing device is inserted in the flowing stream to obtain the flowing temperature. However, if the fluid velocity is higher than 25% of the fluid sound speed at the point of measurement, corrections for the increase in temperature due to dynamic effects will have to be applied. Care should be taken to ensure that the temperature sensing elements are coupled to the flowing stream and not to the steel in the meter tube. This practice is recommended for all orifice meter installations. The sensed temperature is assumed to be the static temperature of the flowing fluid.

The temperature ($T_m$) is the measured temperature of the orifice plate and/or the meter tube at the time of the diameter measurements, as specified in 2.4.3 and 2.5.1.2.

The temperature ($T_r$) is the reference temperature used to determine the reference orifice plate bore diameter ($d_r$) and/or the reference internal meter tube diameter ($D_r$), as specified in 2.4.3 and 2.5.1.2.

### 2.3.4 ROUGHNESS AVERAGE ($R_a$)

The roughness average ($R_a$) used in this standard is that given in ANSI B46.1, and is "the arithmetic average of the absolute values of the measured profile height deviation taken within the sampling length and measured from the graphical centerline" of the surface profile.

## 2.4 Orifice Plate Specifications

The symbols for the orifice plate dimensions are shown in Figure 2-1.

### 2.4.1 ORIFICE PLATE FACES

The upstream and downstream faces of the orifice plate shall be flat. Deviations from flatness on the orifice plate of less than or equal to 1% of dam height (that is, 0.010 inch per inch of dam height) under nonflowing conditions are allowed. The dam height can be calculated from the formula $(D_m - d_m)/2$. This criterion for flatness applies to any two points on the orifice plate within the dimensions of the inside diameter of the pipe. The departure from flatness is illustrated in Figures 2-2a, 2-2b and 2-2c.

The surface roughness of the upstream and downstream faces of the orifice plate shall have no abrasions or scratches visible to the naked eye that exceed 50 microinches $R_a$.

The orifice plate surface roughness may be verified by using an electronic-averaging-type surface roughness instrument with a cutoff value of not less than 0.03 inch. Other surface roughness devices (for example, a visual comparator) are acceptable for determining orifice plate surface roughness if the same repeatability and reproducibility as those of the electronic-averaging-type surface roughness instrument can be demonstrated.

Due care shall be exercised to keep the plate clean and free from accumulation of dirt, ice, grit, grease, oil, free liquid and other extraneous materials, to the extent feasible, by instituting a regular inspection schedule (daily, weekly, monthly, quarterly, etc., depending on the service conditions). Damage and/or accumulation of extraneous materials on the orifice plate may result in a greater uncertainty for the orifice plate coefficient of discharge [$C_d(FT)$]. After any inspection of the plate, it shall be thoroughly cleaned (free from accumulations as stated above) prior to being placed back in service.

### 2.4.2 ORIFICE PLATE BORE EDGE

The upstream edge of the orifice plate bore shall be square and sharp. The orifice plate bore edge is considered too dull for accurate flow measurement if the upstream edge reflects a beam of light when viewed without magnification or if the upstream edge shows a beam of light when checked with an orifice edge gauge.

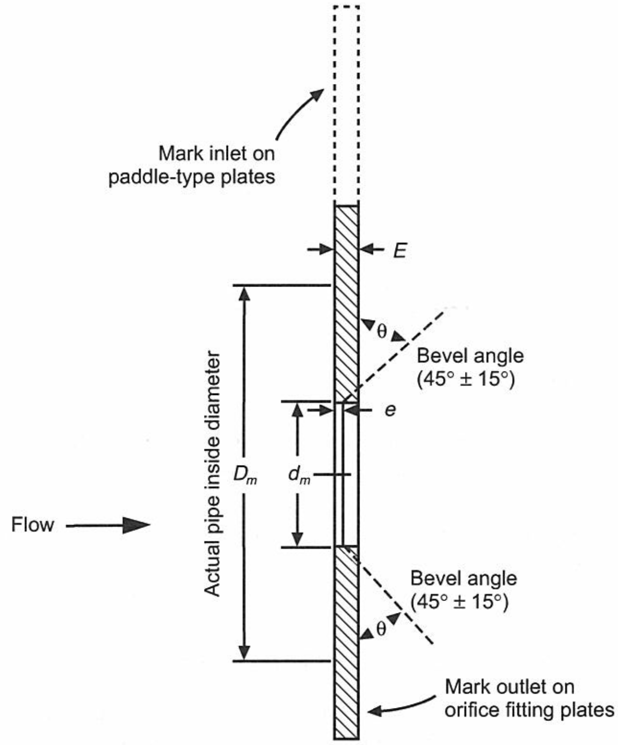



Figure 2-1—Symbols for Orifice Plate Dimensions

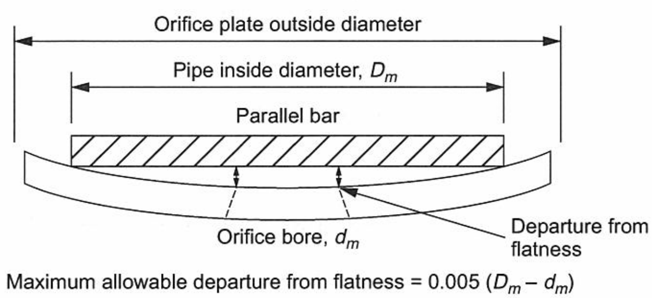



Figure 2-2a—Orifice Plate Departure from Flatness
(Measured at Edge of Orifice Bore and Within Inside Pipe Diameter)

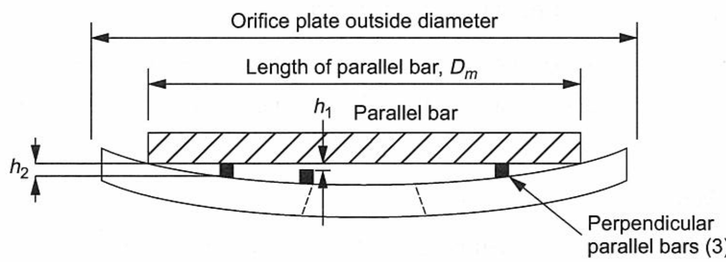
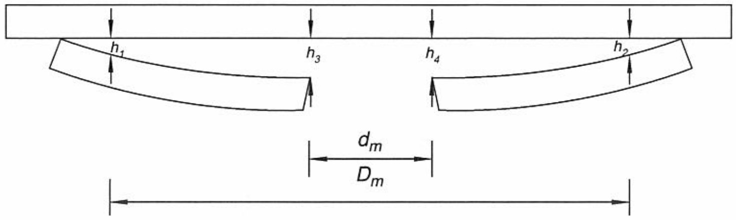



Figure 2-2b—Alternative Method for Determination of Orifice Plate Departure from Flatness
(Departure from Flatness = $h_2 - h_1$)




Maximum departure from flatness $= \dfrac{[h_3 + h_4] - [h_1 + h_2]}{2}$

Figure 2-2c—Maximum Orifice Plate Departure from Flatness

An estimation of suitable sharpness can be made by comparing the orifice plate bore edge with the bore edge of a properly sharp reference orifice plate of the same nominal diameter. The orifice plate bore edge being evaluated should feel and look the same as the edge of the reference orifice plate.

The upstream and downstream edges of the orifice plate bore shall be free from defects visible to the naked eye, such as flat spots, feathered texture, roughness, burrs, bumps, nicks, and notches.

If there is any doubt about whether the edge has sufficient quality for accurate metering, the orifice plate should be replaced.

### 2.4.3 ORIFICE PLATE BORE DIAMETER ($d_m$, $d_r$) and ROUNDNESS

The measured orifice bore diameter ($d_m$) is defined as the mean (arithmetic average) of four or more evenly spaced diameter measurements at the inlet edge. None of the four or more diameter measurements may vary from the mean value by more than the tolerances given in Table 2-1. The orifice plate temperature shall be recorded at the time the bore diameter measurements are made. These measurements shall be made under thermally stable conditions; i.e., during the measurement, the temperature should be constant within ± 1°F (± 0.5°C).

The orifice plate bore diameter ($d_r$) is defined as the calculated reference diameter at reference temperature ($T_r$) and can be determined using the following equation:

$$d_r = d_m[1 + \alpha_1(T_r - T_m)] \tag{2.1}$$

where

$\alpha_1$ = linear coefficient of thermal expansion for the orifice plate material (see Table 2-2),

$d_r$ = orifice plate bore diameter calculated at reference temperature ($T_r$),

$d_m$ = orifice plate bore diameter measured at $T_m$,

$T_m$ = temperature of the orifice plate at time of diameter measurements,

$T_r$ = reference temperature of the orifice plate bore diameter.

Note: $\alpha_1$, $T_m$, and $T_r$ must be in consistent units. For the purpose of this standard, $T_r$ is assumed to be 68°F.

The orifice plate bore diameter ($d_r$) calculated at $T_r$ is the reference diameter used to calculate the bore diameter ($d$) at flowing conditions, as specified in Part 1.

### 2.4.4 ORIFICE PLATE BORE THICKNESS ($e$)

The inside surface of the orifice plate bore shall be in the form of a constant-diameter cylinder having no defects, such as grooves, ridges, pits, or lumps, visible to the naked eye. The length of the cylinder is the orifice plate bore thickness ($e$).

The minimum allowable orifice plate bore thickness ($e$) is defined by $e \geq 0.01d_r$ or $e > 0.005$ inch, whichever is larger.

The maximum allowable value for the orifice plate bore thickness ($e$) is defined by $e \leq 0.02D_r$ or $e \leq 0.125d_r$, whichever is smaller, but $e$ shall not be greater than the maximum allowable orifice plate thickness ($E$).

Table 2-1 — Roundness Tolerance for Orifice Plate Bore Diameter, $d_m$

| Orifice Bore Diameter, $d_m$ (inches) | Tolerance (± inches) |
|---|---|
| ≤0.250[a] | 0.0003 |
| 0.251 – 0.375[a] | 0.0004 |
| 0.376 – 0.500[a] | 0.0005 |
| 0.501 – 0.625 | 0.0005 |
| 0.626 – 0.750 | 0.0005 |
| 0.751 – 0.875 | 0.0005 |
| 0.876 – 1.000 | 0.0005 |
| >1.000 | 0.0005 inch per inch of diameter |

Note: [a]Use of diameters below 0.45 inch is not prohibited, but may result in uncertainties greater than those specified in AGA Report No.3, Part 1.

Table 2-2 — Linear Coefficient of Thermal Expansion

| Material | Linear Coefficient of Thermal Expansion, α [U.S. Units (in./in. °F)] |
|---|---|
| Type 304 and 316 stainless steel[a] | 0.00000925 |
| Monel[a] | 0.00000795 |
| Carbon Steel[b] | 0.00000620 |

Note: For flowing temperature conditions other than those stated in footnotes a and b and for other materials, refer to the American Society for Metals, *Metals Handbook* .
[a]For flowing conditions between – 100°F and + 300°F, ref. ASME PTC 19.5.
[b]For flowing conditions between – 7°F and + 154°F, ref. *API MPMS* Chapter 12, Section 2.

When the orifice plate thickness (E) exceeds the orifice bore thickness (e), a bevel (see 2.4.6) is required on the downstream side of the orifice bore.

Note: Existing orifice plates, whose edge thickness meets the value defined by e < 0.33Dm, need not be rebeveled unless reconditioning is required for other reasons.

For ease in machining, the next smaller values of e, in multiples of 0.03125 (1/32 inch), may be used.

Orifice plate bores that demonstrate any convergence from inlet to outlet are unacceptable.

Bi-directional flow through an orifice meter tube requires a specially configured meter tube and the use of an unbeveled orifice plate. Use of an unbeveled orifice plate with bore thickness (e) that exceeds the limits specified in this table is outside of the scope of this standard.

### 2.4.5 ORIFICE PLATE THICKNESS (*E*)

The minimum, maximum, and recommended values of orifice plate thickness (*E*) for Types 304 and 316 stainless steel orifice plates are given in Table 2-3.

Maximum allowable differential pressures for the recommended orifice plate thicknesses in Table 2-3 are for operating temperatures not exceeding 150°F. For operating conditions, orifice diameter ratios, meter tube sizes, and orifice plate thicknesses not covered in Table 2-3, see the tables found in Appendix 2-E. If a specific application is not covered by Table 2-3 or Appendix 2-E, the orifice plate and/or holding device manufacturer should be contacted for specific information on deflection (see 2.4.1 and Appendix 2-F – AGA Engineering Technical Note – High Differential Pressure Across Orifice Fittings) for a given diameter ratio, temperature, orifice plate material, orifice plate holder, and differential pressure.

The use of an orifice plate thickness other than the recommended thickness is acceptable in either new or existing orifice plate holding devices as long as the thickness is within the maximum and minimum range shown in Table 2-3; and the orifice plate eccentricity, bore thickness, differential pressure tap hole, and expansion-factor pressure-ratio tolerances and limits are satisfied.

For incompressible fluids, the maximum differential pressure across the plate is limited by the structural integrity of the fitting design. The maximum differential pressure should be limited to those shown in Table 2-3 and Appendix 2-E. If the maximum differential pressure is to exceed the limits specified, the manufacturer should be consulted for allowable maximum pressure for the fitting design. In addition, the flowing conditions downstream of the orifice plate must remain above the local vapor pressure of the flowing fluid.

Orifice fitting manufacturers should be consulted to determine the maximum allowable differential pressure during the changing of orifice plates under flowing conditions. The high forces associated with using high differential pressures may make it difficult to remove the plate, and may possibly result in damage to the orifice plate or fitting.

The use of high differential pressures ($\Delta P/P_f > 0.7$ inch of water/psia, where the $\Delta P$ is in inches of water at 68°F and $P_f$ is in psia) will result in expansion factor uncertainties in excess of 0.1% (See 1.12.4.2 of Part 1).

Operators should be aware, for a given orifice plate size, that when there is a wide swing from high to low flows, significant measurement errors will occur during the low-flow period if the orifice plate remains unchanged. Generally, operation between 10% and 90% of the calibrated differential span is considered good practice. Rangeability can also be increased using today's digital (electronic) transmitters. The effects on the accuracy of transducers and/or transmitters used for wide range should be evaluated versus savings on installation cost.

For the full range of orifice plate thicknesses, the maximum allowable orifice plate differential pressure can be obtained from Appendix 2-E.

Higher differential pressures will result in higher meter-run gas velocities and higher permanent pressure losses. It is recommended that the gas velocities be evaluated on a individual installation basis for such things as noise, erosion, and thermowell vibration. The meter run velocity is dependent on several different factors, and each individual user will have different practices and limits on velocity. Therefore, the allowable maximum differential pressures, shown in Table 2-3, do not consider meter-run gas velocity.

### 2.4.5.1 Permanent Pressure Drop

The permanent pressure drop is significant because the energy has been lost to transport the fluid through the pipeline. Several technical books list the permanent pressure loss versus β ratio for the concentric, square-edged, flange-tapped orifice meter.

$$\text{The permanent pressure loss} \approx \Delta P(1 - \beta^2)$$

Below is a table of these approximate values:

| β | Losses as a % of $\Delta P$ |
|---|---|
| 0.20 | 95 |
| 0.30 | 90 |
| 0.40 | 85 |
| 0.50 | 75 |
| 0.60 | 65 |
| 0.70 | 50 |
| 0.75 | 45 |

Examples:

a. If the user chooses to use a β of 0.30 at a $\Delta P$ of 400 inches of $H_2O$, then the permanent pressure loss would be approximately 90% of 400 inches of $H_2O$, which is about 360 inches of $H_2O$ (about 13 psi).

b. If the user chooses to use a β of 0.50 at a $\Delta P$ of 100 inches of $H_2O$, then the permanent pressure loss would be approximately 75% of 100 inches of $H_2O$, which is about 75 inches of $H_2O$ (about 3 psi).

## 2.4.6 ORIFICE PLATE BEVEL (θ)

The plate bevel angle (θ) is defined as the angle between the bevel and the downstream face of the plate. The allowable value for the plate bevel angle (θ) is 45 degrees ± 15 degrees.

The surface of the plate bevel shall have no defects visible to the naked eye, such as grooves, ridges, pits, or lumps.

If a bevel is required, its minimum dimension, ($E$-$e$), measured along the axis of the bore shall not be less than 0.0625 (1⁄16) inch.

Table 2-3—Orifice Plate Thickness and Maximum Allowable Differential Pressure Based on the Structural Limit

| Nominal Pipe Size (NPS) (inches) | Published Inside Pipe Diameter (inches) | Orifice Plate Thickness, $E$ (inches) Minimum | Maximum | Recommended | Maximum Allowable $\Delta P$("$H_20$) Orifice Fitting | Maximum Allowable $\Delta P$("$H_20$) Orifice Flanges |
|---|---|---|---|---|---|---|
| 2 | 1.687 | 0.115 | 0.130 | 0.125 | 1000 | 1000 |
| | 1.939 | 0.115 | 0.130 | 0.125 | 1000 | 1000 |
| | 2.067 | 0.115 | 0.130 | 0.125 | 1000 | 1000 |
| 3 | 2.300 | 0.115 | 0.130 | 0.125 | 1000 | 1000 |
| | 2.624 | 0.115 | 0.130 | 0.125 | 1000 | 1000 |
| | 2.900 | 0.115 | 0.130 | 0.125 | 1000 | 1000 |
| | 3.068 | 0.115 | 0.130 | 0.125 | 1000 | 1000 |
| 4 | 3.152 | 0.115 | 0.130 | 0.125 | 1000 | 1000 |
| | 3.438 | 0.115 | 0.130 | 0.125 | 1000 | 1000 |
| | 3.826 | 0.115 | 0.130 | 0.125 | 1000 | 1000 |
| | 4.026 | 0.115 | 0.130 | 0.125 | 1000 | 1000 |
| 6 | 4.897 | 0.115 | 0.163 | 0.125 | 345 | 1000 |
| | 5.187 | 0.115 | 0.163 | 0.125 | 345 | 1000 |
| | 5.761 | 0.115 | 0.192 | 0.125 | 345 | 1000 |
| | 6.065 | 0.115 | 0.192 | 0.125 | 345 | 1000 |
| 8 | 7.625 | 0.115 | 0.254 | 0.250 | 1000 | 1000 |
| | 7.981 | 0.115 | 0.319 | 0.250 | 1000 | 1000 |
| | 8.071 | 0.115 | 0.319 | 0.250 | 1000 | 1000 |
| 10 | 9.562 | 0.115 | 0.319 | 0.250 | 570 | 1000 |
| | 10.020 | 0.115 | 0.319 | 0.250 | 570 | 1000 |
| | 10.136 | 0.115 | 0.319 | 0.250 | 570 | 1000 |
| 12 | 11.374 | 0.175 | 0.379 | 0.250 | 285 | 1000 |
| | 11.938 | 0.175 | 0.398 | 0.250 | 285 | 1000 |
| | 12.090 | 0.175 | 0.398 | 0.250 | 285 | 1000 |
| 16 | 14.688 | 0.175 | 0.490 | 0.375 | 465 | 1000 |
| | 15.000 | 0.175 | 0.500 | 0.375 | 465 | 1000 |
| | 15.025 | 0.175 | 0.500 | 0.375 | 465 | 1000 |
| 20 | 18.812 | 0.240 | 0.505 | 0.375 | 235 | 1000 |
| | 19.000 | 0.240 | 0.505 | 0.375 | 235 | 1000 |
| | 19.250 | 0.240 | 0.505 | 0.375 | 235 | 1000 |
| 24 | 22.624 | 0.240 | 0.505 | 0.500 | 360 | 1000 |
| | 23.000 | 0.240 | 0.562 | 0.500 | 360 | 1000 |
| | 23.250 | 0.240 | 0.562 | 0.500 | 360 | 1000 |
| 30 | 28.750 | 0.370 | 0.562 | 0.500 | 180 | 1000 |
| | 29.000 | 0.370 | 0.578 | 0.500 | 180 | 1000 |
| | 29.250 | 0.370 | 0.578 | 0.500 | 180 | 1000 |

Notes:

1. Maximum allowable differential pressure is limited to 1,000 inches of water column, which is the limit of the coefficient of discharge database. For further details on the limit of maximum allowable differential pressure, please refer to the text in 2.4.5.
2. Maximum allowable differential pressure is calculated for worst-case diameter ratio (typically $\beta = 0.55 - 0.65$). Other diameter ratios may be able to go to higher differential pressures (see Appendix 2-E).
3. The maximum differential pressure applies to stainless steel plates at a maximum temperature of 150° F, and for the recommended plate thickness.
4. Maximum allowable differential pressure for other plate thicknesses refer to Appendix 2-E.
5. For single- or dual-chamber fittings, the orifice plate seal ring was assumed to deflect under axisymmetric conditions without plastic deformation. As such, the effect on the seal ring was not investigated.
6. Especially at very high differential pressures, the user should carefully consider the associated thermodynamic effects, such as temperature changes resulting from the Joule-Thompson effect as the stream passes through the orifice, and the limits on $\Delta P/P_f$, in particular, at low pressures. The sudden reduction of pressure will result in temperature and density changes.

## 2.5 Meter Tube Specifications

### 2.5.1 DEFINITION

The meter tube is defined as the straight upstream pipe of the same diameter length UL of the installation Tables 2-7 and 2-8, (see Figure 2-6), including the flow straightener/conditioner, if used; the orifice plate holder; and the similar downstream pipe (length DL of the installation Tables 2-7 and 2-8, see Figure 2-6) beyond the orifice plate. The upstream section of the meter tube is defined as the length of straight pipe extending from the upstream face of the orifice plate to the nearest upstream change in cross-sectional area (not including flanged fittings allowed in the standard) or change in the axis of the pipe centerline.

The length of the upstream and downstream pipe sections is addressed in 2.6.3.1. The tolerances for the diameter and the restrictions for the inside surface of the meter tube are specified in 2.5.1.1 through 2.5.1.3.

There shall be no pipe connections within the specified upstream and downstream meter tube sections other than the pressure taps specified in 2.5.4 (and pipe taps as defined in Appendix 3-D of Part 3); temperature probes specified in 2.6.5; flow conditioner attachments (either flanged or in-line); orifice plate holders (welded or flanged on the downstream or upstream end as specified in section 2.5.3.2); and in-line meter tube flanges necessary to connect sections of the meter tube. Any downstream flange connection or weld must be at least 2 inches away from the downstream face of the orifice plate. Any downstream weld within $0.5D$ or 2 inches from the downstream face of the orifice plate must be ground and/or machined to meet the downstream out-of-roundness and the inside surface roughness requirements specified in 2.5.1.3.2 and 2.5.1.1, respectively. For any downstream flange connection within $0.5D$ or 2 inches, care must be taken to avoid any protrusion of the gasket into the line. The closest an in-line meter tube flange can come to the orifice plate, in the upstream meter tube section, should be the designated flow conditioner location, or $10D_i$ for meter tubes without flow conditioner (not including flanged fittings allowed in the standard). All flanges and flange attachments within the designated meter tube lengths shall meet all meter tube requirements contained in 2.5.1.1 through 2.5.1.4.

#### 2.5.1.1 Inside Surface

The sections of the meter tube to which the orifice plate holder is attached, or the adjacent pipe sections that constitute part of the meter tube, as defined in 2.5.1, shall comply with 2.5.1.1.1 through 2.5.1.1.3. However, due to the increased upstream meter tube length requirements of Tables 2-7 and 2-8, and in keeping with the coefficient of discharge database lengths, the upstream meter tube section required to comply with 2.5.1.1.1 through 2.5.1.1.3 shall be limited to the lengths shown in Tables 2-7 and 2-8, or 17 published internal pipe diameters, whichever is less. The piping roughness $R_a$ upstream of this length should not be greater than 600 μin.

**2.5.1.1.1** The internal surface roughness of the meter tube should be measured at approximately the same internal axial locations as those used to determine and verify the meter tube internal diameter (see 2.5.1.2). The $R_a$ values specified in the items below are the arithmetic average roughness obtained using an electronic-averaging-type surface roughness instrument with a cut-off value of not less than 0.03 inch. Other surface roughness devices are acceptable for determining meter-tube surface roughness if the same repeatability and reproducibility as those of the electronic-averaging-type surface roughness instrument can be demonstrated. A minimum of four roughness measurements shall be made.

The mean (arithmetic average) of these four or more roughness measurements is defined as the meter tube internal surface roughness.

For meter runs with nominal diameters of 12 inches or smaller:

a. The maximum meter-tube roughness shall not exceed 300 microinches (μinches) $R_a$ if the diameter ratios ($\beta_r$) are equal to or less than 0.6.
b. The maximum meter-tube roughness shall not exceed 250 μinches $R_a$ if the diameter ratios ($\beta_r$) are greater than or equal to 0.6.
c. The minimum roughness shall not be less than 34 μinches for all diameter ratios.

For meter runs with nominal diameters larger than 12 inches:

a. The maximum meter-tube roughness shall not exceed 600 μinches $R_a$ if the diameter ratios ($\beta_r$) are equal to or less than 0.6.
b. The maximum meter-tube roughness shall not exceed 500 μinches $R_a$ if the diameter ratios ($\beta_r$) are greater than or equal to 0.6.
c. The minimum meter-tube roughness shall not be less than 34 μinches for all diameter ratios.

Note: The use of lower diameter ratios ($\beta_r$) reduces the effect of pipe roughness on uncertainty.

Carefully selected smooth commercial pipe may be used. To improve smoothness within the meter tube, the inside pipe walls may be machined, ground, or coated to meet the required specifications.

**2.5.1.1.2** Irregularities such as grooves, scoring, or ridges resulting from seams, welding distortion, offsets, and the like, that affect the inside diameter by more than the tolerances in 2.5.1.3, shall not be permitted. The existence of pits in the surface of the meter tube, although undesirable, is allowed provided their individual measurements do not exceed the surface roughness and/or diameter tolerance requirements of the meter tube and do not compromise the meter tube's pressure integrity. When these tolerances are exceeded, the irregularities must be corrected.

**2.5.1.1.3** Due care shall be exercised to keep the meter tube interior clean and free from accumulation of dirt, ice, grit, grease, oil, free liquid and other extraneous materials, to the extent feasible. Damage and/or accumulation of extraneous materials in the meter tube may result in a greater uncertainty for the orifice plate coefficient of discharge [$C_d(FT)$].

### 2.5.1.2 Meter Tube Diameter ($D_m$, $D_r$)

The measured internal diameter of the meter tube ($D_m$) shall be determined as specified in 2.5.1.2.1 through 2.5.1.2.5.

**2.5.1.2.1** A minimum of four equally spaced individual internal diameter measurements shall be made in a plane 1 inch upstream from the upstream face of the orifice plate. The mean (arithmetic average) of these four or more individual measurements is defined as the measured meter tube internal diameter ($D_m$).

**2.5.1.2.2** Individual check measurements of the internal diameter of the upstream section (UL in Tables 2-7 and 2-8) of the meter tube (excluding the orifice plate gasket or sealing device diameter) shall be made at a minimum of two additional cross-sections. The actual locations of the individual internal diameter check measurements, around the circumference and along the axis of the meter tube, are not specified. These individual checks should be made at points that will indicate the maximum and minimum dimensions of the internal diameter of the meter tube's upstream section.

One of these individual check measurements should be made in a region at least two pipe diameters from the face of the orifice plate, or past the orifice plate holder weld or flange, whichever is the greater distance. Other individual measurements should be made at selected points within the UL dimension.

Individual check measurements are used to verify the uniformity of the internal diameter of the upstream section of the meter tube (see 2.5.1.3), but do not become a part of the determination of the mean meter tube internal diameter.

**2.5.1.2.3** Individual check measurements of the meter tube internal diameter ($D_m$) shall be made in the downstream section of the meter tube in a plane 1-inch downstream from the downstream face of the orifice plate (see 2.5.1.3).

Additional individual check measurements of the internal diameter ($D_m$) (excluding the orifice plate gasket or sealing device diameter), shall be made at a minimum of two other cross-sections in the downstream section of the meter tube (see 2.5.1.3), similar to the measurements specified in 2.5.1.2.2.

**2.5.1.2.4** Meter tube internal diameters are not limited to published nominal inside pipe diameters. All applicable regulations and piping codes must be followed.

**2.5.1.2.5** The meter tube temperature to the nearest degree Fahrenheit (0.5 degree Centigrade) should be recorded when the internal diameter measurements are made. These measurements shall be made under thermally stable conditions; i.e., during the measurement, temperature should be constant within 5°F (2.5°C).

The reference meter tube internal diameter ($D_r$) is defined as the calculated meter tube internal diameter at reference temperature ($T_r$), and can be determined using the following equation:

$$D_r = D_m[1 + \alpha_2(T_r - T_m)] \tag{2.2}$$

where

$\alpha_2$ = linear coefficient of thermal expansion for the meter tube material (see Table 2-2),

$D_m$ = meter tube internal diameter measured at temperature ($T_m$),

$D_r$ = reference meter tube internal diameter calculated at reference temperature ($T_r$),

$T_m$ = temperature of the meter tube at the time of the diameter measurements,

$T_r$ = reference temperature of the meter tube internal diameter.

Note: $\alpha_2$, $T_m$, and $T_r$ must be in consistent units. For the purpose of this standard, $T_r$ is assumed to be 68°F (20°C).

The meter tube internal diameter ($D_r$) calculated at $T_r$ is the diameter used to calculate the meter tube internal diameter, $D$, at flowing conditions, as specified in Part 1.

#### 2.5.1.3 Tolerances and Restrictions

The tolerances for the diameter and the restrictions for the internal surface of the meter tube are specified in 2.5.1.1.1 through 2.5.1.3.3.

##### 2.5.1.3.1 Meter Tube Internal Diameter Roundness Tolerance

###### 2.5.1.3.1.1 Within the First Mean Meter Tube Diameter ($D_m$) Upstream of the Orifice Plate

The absolute value of the percentage difference between the measured meter tube internal diameter ($D_m$) and any individual diameter measurement within a distance of one meter tube diameter ($D_m$) on the upstream side of the orifice plate shall not exceed 0.25% of $D_m$. The measurement resolution shall be to the nearest thousandth of an inch (0.001 inch) or better.

$$\left| \frac{\langle \text{Any diameter within one } D_m \rangle - D_m}{D_m} \times 100 \right| \leq 0.25\% \qquad (2.3)$$

An example of this situation is provided in Table 2-4. All measurements within one meter tube diameter upstream of the orifice plate face are within 0.25% of the 2.0695 mean.

Table 2-4—Example Meter Tube Internal Diameter—Roundness Tolerances Within First Mean Meter Tube Diameter Upstream of Orifice Plate

| | Meter Tube Internal Diameter Measurements (inches) | | | | |
|---|---|---|---|---|---|
| Position | A | B | C | D | Mean, $D_m$ |
| 1-inch upstream plate | 2.0696 | 2.0694 | 2.0694 | 2.0696 | 2.0695 |
| Within one $D_m$ | 2.0700 | 2.0676 | 2.0671 | 2.0655 | N/A |
| % deviation from mean $D_m$ | 0.024% | 0.092% | 0.116% | 0.193% | N/A |

###### 2.5.1.3.1.2 For All Upstream Meter Tube Individual Internal Diameter Measurements, Including Those Within One Meter Tube Diameter Upstream of the Orifice Plate

The percentage difference between the maximum measured individual internal diameter measurement and the minimum measured individual internal diameter measurement of all upstream meter tube individual internal diameter measurements, including those within the first meter tube diameter upstream of the orifice plate, shall not exceed 0.5% of $D_m$:

$$\frac{\text{Maximum diameter} - \text{Minimum diameter}}{D_m} \times 100 \leq 0.5\% \qquad (2.4)$$

An example of this situation is provided in Table 2-5.

Table 2-5—Example Meter Tube Internal Diameter Roundness Tolerances—All Upstream Meter Tube Individual Internal Diameter Measurements

| | Meter Tube Internal Diameter Measurements (inches) | | | | |
|---|---|---|---|---|---|
| Position | A | B | C | D | Mean, $D_m$ |
| 1-inch upstream plate | 2.0696 | 2.0694 | 2.0694 | 2.0696 | 2.0695 |
| Within one $D_m$ | 2.0700 | 2.0676 | 2.0671 | 2.0655 | N/A |
| Upstream check measurement | 2.0621 | 2.0620 | 2.0613 | 2.0601 | N/A |

The calculation to verify that the measurements meet the tolerance criterion is as follows:

$$\frac{2.0700 - 2.0655}{2.0695} \times 100 = 0.22\%$$

All upstream meter tube individual internal diameter measurements, including those within one meter tube diameter ($D_m$) upstream of the orifice plate are within 0.5% of $D_m$.

#### 2.5.1.3.2 Internal Roundness Tolerance for the Downstream Section of Meter Tube

The absolute value of the percentage difference between the measured meter tube diameter ($D_m$) and any individual internal diameter on the downstream side shall not exceed 0.5% of $D_m$:

$$\left| \frac{(\text{Any downstream diameter}) - D_m}{D_m} \times 100 \right| \leq 0.5\% \tag{2.5}$$

#### 2.5.1.3.3 General Meter Tube Restrictions

Abrupt changes of the inside meter tube surface (shoulders, offsets, ridges, welding seams, and the like) shall not exist in meter tubes, with the exception of those allowed in 2.5.1 and 2.5.5.

### 2.5.1.4 Orifice Plate Gasket or Sealing Device Recesses and Protrusions

The orifice plate gasket or sealing device tolerances and restrictions specified in 2.5.1.4.1 through 2.5.1.4.5 shall apply at locations immediately upstream and downstream of the orifice plate face.

**2.5.1.4.1** Protrusions resulting from an orifice plate gasket or sealing device that extend into the pipe bore are not permitted.

**2.5.1.4.2** A recess resulting from an orifice plate gasket or sealing device, of 0.25 inch or less in length, as measured parallel to the pipe axis, does not require recess depth restriction, diameter ratio ($\beta_r$) limitation, or additional uncertainty.

**2.5.1.4.3** A recess resulting from an orifice plate gasket or sealing device, of more than 0.25 inch but less than or equal to 0.5 inch in axial length, does not require diameter ratio ($\beta_r$) limitation or additional uncertainty if the depth of the recess is within the limitations of 2.5.1.3 ($0.005D_m$).

**2.5.1.4.4** All orifice plate sealing devices shall be of the same nominal inside pipe diameter (within the limits specified in 2.5.1.4.1 through 2.5.1.4.3) as the orifice plate holder in which they are used.

**2.5.1.4.5** For recesses larger than those described in 2.5.1.4.2 and 2.5.1.4.3, additional uncertainty may be required.

## 2.5.2 ORIFICE FLANGES

Orifice flanges for orifice meter tube installations should be constructed and attached to the pipe so that all of the mechanical specifications in 2.5.1.1 and 2.5.1.4 are met.

Any distortion of the pipe resulting from welding the flange to the pipe shall be removed by machining or grinding to meet the limitations specified in 2.5.1.3.

## 2.5.3 ORIFICE FITTINGS

### 2.5.3.1 General

Orifice fittings represent a class of orifice holders that is widely used throughout the industry. With these devices, it is possible to reproduce the orifice coefficients defined by the equation in Part 1 within the same uncertainty limits as would be found for an orifice plate held between two flanges (the original test devices). To do this, these devices must be manufactured to the tolerances specified in this standard. With orifice fittings, however, some practical considerations should be recognized; some critical inspections that are unique to these devices should be performed. The following information is based on devices that were commonly known to exist at the time this standard was developed and may not cover innovations that have become commonly known since its publication. Such innovations may be deemed to be in accordance with this standard as long as they meet all tolerances contained herein.

#### 2.5.3.2 Attachment to Pipe

When an upstream flanged orifice fitting is used, the mean inside diameter of the meter tube connected to the inlet side shall agree with the mean inside diameter of the fitting within the tolerance given in 2.5.1.3. When the fitting is installed, the inlet side should be connected to the upstream section of the meter tube first, and carefully centered; no sharp edges at this junction are allowed.

To prevent misalignment at this joint when a flanged connection has been used, two diametrically opposed bolt holes may be reamed and snug-fitting bolts installed, or dowel pins may be used. Other alignment methods may be used as long as the same result is obtained.

When the upstream section of the meter tube is attached to the orifice-fitting body by welding (preferred method), any distortion of the pipe resulting from the welding shall be removed by machining or grinding to meet the requirements of 2.5.1.3.

#### 2.5.3.3 Inspection Considerations

In some instances, the inspection of an orifice fitting may not be as easy as the inspection of a conventional flanged orifice meter. This is true when the fitting in question is of the weld neck design and has already been connected to the meter tube. Unless the meter tube is of a large size, it may be difficult to make measurements in the vicinity of the orifice plate. To make this inspection easier, the fitting should have at least one flanged side (preferably the downstream side). The user should refer to the relevant pressure vessel and pipeline codes to determine whether this particular design may be used in a given system. All measurements of mechanical tolerances should be made after the fitting has been pressure-tested at the maximum required test pressure.

#### 2.5.3.4 Bypass Checks

In orifice fittings, there is the possibility that some fluid may bypass the orifice plate. Tests shall be conducted after the meter run has been pressure-tested in accordance with the relevant code to ensure the following:

a. No differential pressure tap communication or leakage exists.
b. No holding or sealing device fluid bypass exists.

### 2.5.4 PRESSURE TAPS

#### 2.5.4.1 Flange Taps

Meter tubes using flange taps shall have the center of the upstream pressure tap hole placed 1 inch from the upstream face of the orifice plate. The center of the downstream pressure tap hole shall be 1 inch from the downstream face of the orifice plate. Each tap hole shall be located at the 1-inch dimension within the tolerances shown in Figure 2-3. It is recommended that the maximum diameter ratio ($\beta$) of 0.75 allowable pressure tap hole location variation be used in the design of installations.

Orifice fittings may require different methods of confirming pressure tap hole location than orifice flanges.

Under no circumstances should there be any flow through or out of the flange tap or taps for purposes other than measuring static and/or differential pressure. This includes flows resulting from manufacturing defects that allow for tap communication or the use of the flange taps as a source of fluid for other instruments. For the latter, other taps located outside of the designated meter tube dimensions should be used.

The sharing of metering taps by multiple differential pressure devices may cause increased uncertainty and/or operational problems. If possible, such a practice should be avoided.

##### 2.5.4.1.1 Orifice Fittings

When an orifice fitting is used, pressure tap hole measurements may be taken prior to final fabrication of the meter tube, especially when a fitting is to be welded to one end of the piping that will become an integral part of the completed meter tube. These measurements may be accomplished by using commercially available micrometers and gauges. Other technically valid techniques for verifying the pressure tap hole location are acceptable.

In orifice fittings, the orifice plate is held in place by a carrier mechanism that is intended to correctly position the orifice plate relative to the pressure tap holes. The plate/carrier combination used during pressure tap hole location testing should be of the

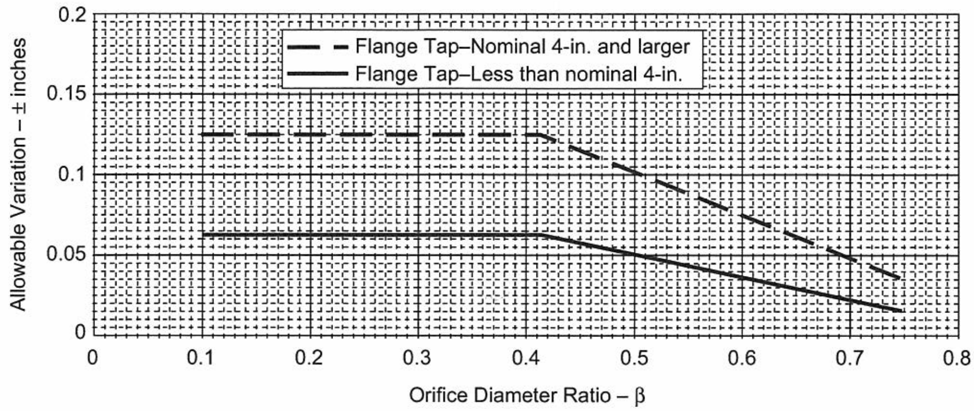



Figure 2-3—Allowable Variations in Pressure Tap Hole Location

same type (design) as will be employed in practice. If the internal mechanism of an orifice fitting is replaced, the inspection should be repeated.

For flange-tapped orifice fittings, the location of the flange tap relative to the faces of the orifice plate must be maintained. This precludes the use of either thicker or thinner plates than are specified by the original design, unless the thickness is within the maximum and minimum range shown in Table 2-3, and differential pressure tap hole tolerances and limits as specified in Figure 2.3 are satisfied, or the fitting has been redrilled. Likewise, the seals or other orifice holding devices should not affect the location of the plate relative to the taps. Seal/plate combinations should be checked to ensure that the tolerance on the location of the flange taps is not exceeded.

### 2.5.4.1.2 Orifice Flanges

When orifice flanges are used, the pressure tap hole placement may be determined by measuring from the face of the flange to the pressure tap hole center. Allowance must be made for the thickness and compression of gaskets, o-rings, or other plate-sealing mechanisms when the orifice plate is pressed between the two flanges.

### 2.5.4.2 Pressure Tap Drilling

Pressure tap holes shall be drilled radially to the meter tube; i.e., the centerline of the tap hole shall intersect and form a right angle with the axis of the meter tube.

### 2.5.4.3 Pressure Tap Diameter

The diameter of the pressure tap holes at the inner surface of the meter tube and along the drilled length of the holes shall be 3/8 (0.375) inch ± 1/64 (0.016) inch, providing for a maximum diameter of 0.391 inch and a minimum of 0.359 inch for pipe with a nominal diameter of 2 or 3 inches; and shall be 1/2 (0.5) inch ± 1/64 (0.016) inch, providing for a maximum diameter of 0.516 inch and a minimum of 0.484 inch for pipe with a nominal diameter of 4 inches or more.

The pressure tap holes in the orifice plate holder may be drilled out and prepared to receive the desired size of pressure-sensing line connection.

The diameter of the tap hole shall not be reduced within a length equal to 2.5 times the tap hole diameter, as measured from the inside surface of the meter tube. Reduction of the tap hole diameter while in service, due to the collection of liquids and/or particulate contamination, is unacceptable.

All pressure tap holes must be round to a tolerance of ± 0.004 inch throughout their length.

Similarly, the inside diameter of the gauge line should remain constant up to the differential pressure sensor and/or manifold.

To avoid any resonance in the gauge line, the length of the gauge line should be as short as possible or should have lengths (*l*) specified according to the highest frequency (*f*) of concern from one of the following formulas:

$$0 \le l_1 \le 2.5a/(2\pi f) \quad (2.6)$$

$$l_2 = 2.5a/(2\pi f) \quad (2.7)$$

$$l_3 = 5.5a/(2\pi f) \quad (2.8)$$

$$l_4 = 8.5a/(2\pi f) \quad (2.9)$$

$$l_5 = 11.5a/(2\pi f) \quad (2.10)$$

where

$a$ = speed of sound in the flowing fluid at operating conditions,

$f$ = frequency of pulsation levels,

$\pi$ = mathematical constant = 3.14159.

The length of the gauge line determined from any of these formulas will ensure that no resonance and/or amplification of pressure pulsation exist in the gauge line. Both gauge lines should be of equal length and have no sudden changes in the internal diameter, especially for low-pressure applications. In some cases, direct-mount manifolds may reduce the effects of pulsation.

See 2.6.4 for acceptable pulsation environment.

#### 2.5.4.4 Pressure Tap Edges

The edges of the pressure tap holes on the inner surface of the meter tube shall be free from burrs and may be slightly rounded.

### 2.5.5 FLOW CONDITIONERS

Flow conditioners can be classified into two categories: straighteners or isolating flow conditioners.

Flow straighteners are devices that effectively remove or reduce the swirl component of a flowing stream, but may have limited ability to produce the flow conditions necessary to accurately replicate the orifice plate coefficient of discharge database values.

Isolating flow conditioners are devices that effectively remove the swirl component from the flowing stream while redistributing the stream to produce the flow conditions that accurately replicate the orifice plate coefficient of discharge database values.

It is not the intent of this standard to recommend any particular type of flow conditioner. However, in an effort to eliminate or reduce the potential for flow measurement bias in existing installations and to provide guidance for improved measurement accuracy in new installations, this standard provides installation recommendation for the 19-tube uniform concentric tube bundle flow straighteners cited in the installation effects research. Due to the significant (outside the designated uncertainty band) coefficient of discharge differences experienced from variations in straightening vane tube bundle construction, only those tube bundle flow straighteners meeting the following criteria are specified to produce "no additional uncertainty" when installed as recommended. All other tube bundles should be considered as "other" flow conditioners.

#### 2.5.5.1 Description of the 1998 Uniform Concentric 19-Tube Bundle Flow Straightener

It is necessary for all the tubes, or thin wall pipe, to be of uniform smoothness, outer diameter, and wall thickness and to be arranged in a cylindrical pattern as in Figure 2-4. The individual tube outer walls must come in direct contact with each other; they may not be spaced or gapped. To reduce the swirl that can occur between the exterior tubes of the tube bundle flow straightener and the wall of the meter tube, tube outer-diameter sizing shall be based on the resulting tube bundle flow-straightener outside diameter (OD) being at maximum equal to $D_i$ and at minimum equal to $0.95D_i$. The length ($LTB$) of the vanes shall be 3 x NPS for NPS of 2 inches; 2.5 x NPS for 2 inches < NPS ≤ 4 inches; and 2 x NPS for NPS greater than 4 inches.

#### 2.5.5.2 Tubing of the 1998 Uniform Concentric 19-Tube Bundle Flow Straightener

The individual tube wall thickness of the 1998 Uniform Concentric 19-Tube Bundle Straightener shall be less than or equal to 2.5% of the $D_i$. All tubes shall be parallel, with an internal chamfer on both ends not less than 50% of wall thickness by 45 degrees, and shall be mounted axially with the pipe.

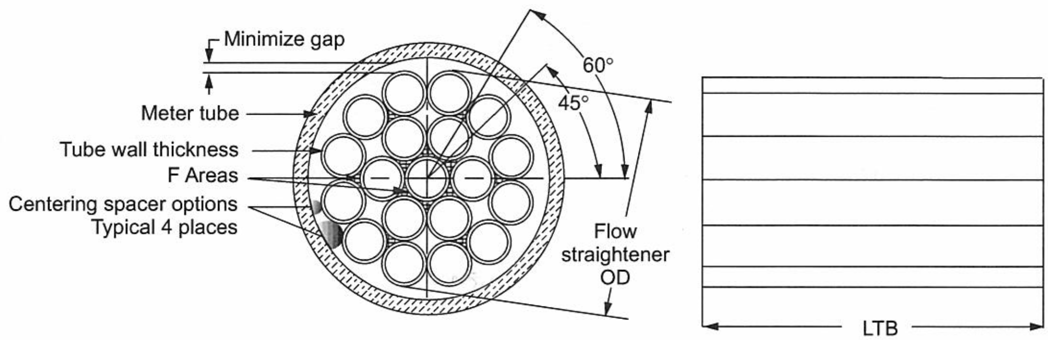



Figure 2-4—1998 Uniform Concentric 19-Tube Bundle Flow Straightener

### 2.5.5.3 Fabrication of the 1998 Uniform Concentric 19-Tube Bundle Flow Straightener

The 1998 Uniform Concentric 19-Tube Bundle Straighteners must be sturdily fabricated. Individual tubes should be welded together at the points of tangency at both ends of the tube bundle with welds at each point not exceeding more than 20 degrees around the tube circumference. For tube bundles of 4 inches NPS or less, the *F* areas (see Figure 2-4) may be filled with weld. Centering spacers may be provided on the outside of the assembly to assist the installer in centering the device in the meter tube. After being inserted in the meter tube, the tube bundle shall be securely fastened in place, with either a mounting flange or a pinning arrangement, to prevent the device from vibrating or from being dislodged and pushed downstream against the orifice plate. Secure fastening, however, should not distort the tube bundle assembly with respect to symmetry within the meter tube.

### 2.5.5.4 Other Flow Conditioners

Specifications for the description, installation, or uncertainty of other flow conditioners are not presented in this standard.

Flow straighteners not conforming with the description given in 2.5.5.1 through 2.5.5.3 are to be considered as "Other Flow Conditioners" and the installation requirements of Tables 2-8a and 2-8b may not be applicable.

The use of other types of flow conditioners should be based on technical performance data obtained from the performance test(s). This standard provides a uniform criterion for evaluation of installation and/or flow conditioner performance (perturbation) test or tests. This test(s) is required by the standard to confirm the performance level that can be achieved by an orifice meter installation using a flow conditioner. (See Appendices 2-C and 2-D for details.) The performance test(s) will confirm the orifice meter diameter ratio ($\beta$) meter tube length, and flow conditioner location for which acceptable performance is obtainable.

#### 2.5.5.4.1 Performance Criteria

The performance criteria selected [$\Delta C_d\,(FT)$] are the same ones used to measure the installation influences in meter tubes without flow conditioners and with the 19-tube uniform cylindrical tube bundle flow straightener. The deviation [$\Delta C_d\,(FT)$] of the values of the discharge coefficient from reference values determined from separate "baseline" calibrations with the same orifice plates should be used as the measure of the flow conditioner's performance.

Acceptable performance levels constituting no need for additional measurement uncertainty are defined as $\Delta C_d$ variation equal to or less than 50% of the stated $2\sigma$ uncertainty in the Reader-Harris/Gallagher orifice equation at infinite Reynolds number (see Part 1, 1.12.4).

#### 2.5.5.4.2 Required Elements of the Installation Performance Test

The types of flow conditions and installation disturbances that form the basis for the installation performance test(s) are as follows:

a. *Good flow conditions.* If a meter tube, with or without a flow conditioner, is installed in a piping configuration in which the axial velocity profile is close to ideal (as produced by 75 or more published inside pipe diameters [$D_i$] of straight pipe), and the amount of swirl is low (less than 2 degree of swirl angle), then the flow conditioner should not introduce a perturbation that causes a significant deviation from the baseline calibration.

b. *Two adjoining (close coupled) out-of-plane 90-degree elbows installed directly upstream of the meter tube.* This configuration is known to produce a swirl velocity component, as well as alter the shape of the axial velocity profile. Swirl angles of up to ± 15 degrees have been measured directly downstream of the second elbow.
c. *A 50% closed valve installed upstream of, and in line with, the meter tube.* When the valve is a gate or ball valve, this configuration can produce a strongly asymmetric axial velocity profile downstream of the valve.
d. *High swirl.* This test generates a high swirl flow condition that is representative of the flow field downstream of installations such as headers. Research on the effect of a header upstream of a meter tube has shown that swirl angles of up to ± 30 degrees can be measured in the meter tube; and that a header may also cause the axial velocity profile to be asymmetric.

The detailed conditions of the performance test can be found in Appendix 2-D.

## 2.6 Installation Requirements

### 2.6.1 GENERAL

The orifice plate coefficients of discharge [$C_d$ $(FT)$] given in this standard are based on the results of many experiments conducted in the United States and Europe. In all cases, normal flow conditions were obtained by the use of long straight lengths of meter tube, both upstream and downstream from the orifice, or by the use of flow conditioners upstream from the orifice meter (see Part 1, 1.12.4.3). To obtain the uncertainty specified on the coefficient of discharge presented in Part 1, similar fluid dynamic conditions must be attained in practice.

### 2.6.2 ORIFICE PLATE

#### 2.6.2.1 Eccentricity (ε)

The orifice plate bore must be concentric with both the upstream and the downstream inside bore of the orifice plate holder. Any eccentricity shall be within the following tolerances:

a. *Eccentricity parallel to the axis of the differential pressure taps* ($\varepsilon_x$). For any eccentricity in the *x-y* plane shown in Figure 2-5, the component of orifice plate bore eccentricity parallel to the axis of the differential pressure taps, shall be less than or equal to the tolerance defined by the following equation:

$$\varepsilon_x \leq \frac{0.0025 D_m}{0.1 + 2.3\beta_m^4} \tag{2.11}$$

where

$\varepsilon_x$ = measurement $(X - X')/2$ as shown in Figure 2-5.

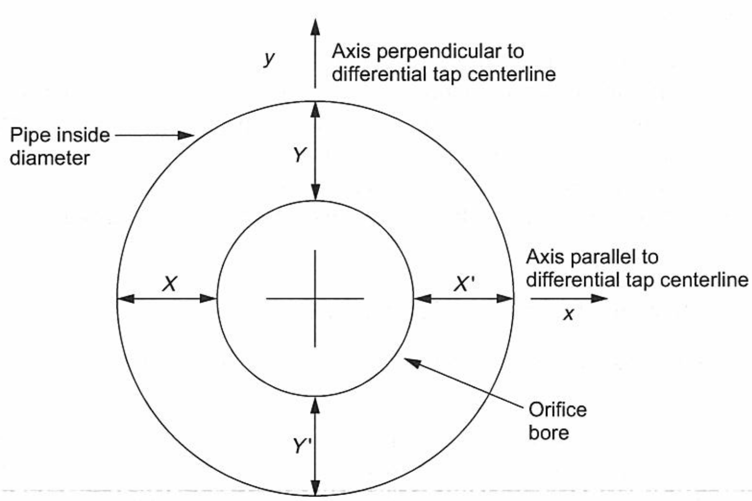



Figure 2-5—Eccentricity Measurements (Sample Method)

Table 2-6—Maximum Tolerance of Orifice Plate Bore Eccentricity ($\varepsilon_x$) in Inches

| | Meter Tube Inside Diameter (inches) | | | | | |
|---|---|---|---|---|---|---|
| $\beta_m$ | 2.067 | 3.068 | 4.026 | 6.065 | 7.981 | 10.020 |
| 0.20 | 0.050 | 0.074 | 0.097 | 0.146 | 0.192 | 0.242 |
| 0.25 | 0.047 | 0.070 | 0.092 | 0.139 | 0.183 | 0.230 |
| 0.30 | 0.044 | 0.065 | 0.085 | 0.128 | 0.168 | 0.211 |
| 0.35 | 0.038 | 0.057 | 0.075 | 0.113 | 0.148 | 0.186 |
| 0.40 | 0.033 | 0.048 | 0.063 | 0.095 | 0.126 | 0.158 |
| 0.45 | 0.027 | 0.039 | 0.052 | 0.078 | 0.103 | 0.129 |
| 0.50 | 0.021 | 0.032 | 0.041 | 0.062 | 0.082 | 0.103 |
| 0.55 | 0.017 | 0.025 | 0.032 | 0.049 | 0.064 | 0.081 |
| 0.60 | 0.013 | 0.019 | 0.025 | 0.038 | 0.050 | 0.063 |
| 0.65 | 0.010 | 0.015 | 0.020 | 0.030 | 0.039 | 0.049 |
| 0.70 | 0.008 | 0.012 | 0.015 | 0.023 | 0.030 | 0.038 |
| 0.75 | 0.006 | 0.009 | 0.012 | 0.018 | 0.024 | 0.030 |

Table 2-6 shows some maximum allowable values of the eccentricity, $\varepsilon_x$.

b. *Eccentricity perpendicular to the axis of the differential pressure taps* ($\varepsilon_y$). For any eccentricity in the $x$-$y$ plane shown in Figure 2-5, the component of orifice plate bore eccentricity perpendicular to the axis of the differential pressure taps—measurement $(Y–Y')/2$ in Figure 2-5—may be four times the amount calculated using Equation 2.11.

The maximum allowable orifice plate bore eccentricity calculated using Equation 2.11 can be doubled if flange taps 180 degrees apart are connected together to obtain an average pressure. Care should be taken to ensure that equal lengths of tubing of equal diameter (with the nominal diameter being greater than or equal to the tap diameter) are used to connect the taps, and that the connection to the differential pressure ($\Delta P$) device is located midway between the taps. This approach is not recommended if there are concerns about pulsating or fluctuating flow.

When measurement of the eccentricity of an orifice plate installed in orifice flanges is not possible, two accurately located alignment pins should be used to support and center the orifice plate while the bolts are tightened. The eccentricity relative to the upstream side is considered the most critical.

Therefore, it is recommended that any alignment pins or other devices used to position the orifice plate be mounted so that the plate is centered relative to the upstream section of the meter tube and pressure tap.

Plate-centering techniques are a function of the design and are only constrained by the maximum allowable eccentricity described above. In most orifice fittings, the orifice plate is held in the flowing stream by a carrier mechanism. Such mechanisms theoretically produce a repeatable eccentricity for the orifice plate; this should be checked for several operations of installing the plate in, and removing it from, the orifice fitting. The carrier used to perform this test shall be the carrier used in the field. If any of the fitting's internal mechanisms are replaced, this inspection should be repeated.

#### 2.6.2.2 Perpendicularity

The orifice plate holder should maintain the plane of the orifice plate at an angle of 90 degrees to the meter tube axis.

### 2.6.3 METER TUBE

#### 2.6.3.1 Length

To ensure accurate flow measurement, the fluid should enter the orifice plate with a fully developed, swirl-free flow profile. Such a condition is best achieved through the use of flow conditioners and associated pipe lengths or adequate lengths of straight pipe upstream and downstream from the orifice plate. Any serious distortion of the average (time mean) flow profile or significantly increased flow pulsation level will produce flow measurement errors. Obviously, the best means of eliminating uncertainty or bias due to pulsation is to eliminate it at the source. For further discussion, see Part 1, 1.12.4.3, pulsation reduction measures (see Part 1, 1.7.5) and operation of the orifice meter within flow pulsation limits (see 2.6.4).

In many piping configurations, the orifice meter may not produce results within the uncertainty of this standard. However, some of the more common types of piping installations have been studied with regard to their effect on metering accuracy. Tables 2-7 and 2-8 provide the required lengths of meter tube and the 1998 Uniform Concentric 19-Tube Bundle Flow Straightener locations for the installations studied.

For applications that are not explicitly addressed in the installation Tables 2-7 and 2-8, the required lengths and the 1998 Uniform Concentric 19-Tube Bundle Straightener locations of the "any other configuration" classification from Tables 2-7 and 2-8 should be followed. This includes multiple fittings upstream of the orifice plate where the distance between the fittings is $22D_i$ or less. The majority of the installations were tested so that the upstream piping resulted in a fully developed flow at the inlet to the installation by using a combination of flow conditioners and straight pipe. In some tests, it was found that the interaction between two fittings was negligible if the spacing between the two was greater than $22D_i$, thus suggesting that the flow profile is similar to a fully developed flow. If the characteristics of the inlet profile deviates from that specified above, the specified meter run lengths may be inadequate for optimal orifice-meter performance.

Generally, meter run lengths for installations with or without flow straighteners are not sensitive to variations of Reynolds numbers and roughness within the specified limits in the standard. Exceptions for the case without flow conditioners are two 90 degree elbows in perpendicular planes, separated by a spacer less than or equal to $5D_i$, or any other installation generating swirl such as headers, eccentric expanders, and expanders in combination with elbows. The latter installations fall under the category of "any other configuration" in Table 2-7.

### 2.6.3.2 Installation Tables

Installation Table 2-7 provides the required minimum installation lengths for meter tubes without flow conditioners.

Installation Table 2-7 indicates that, for meter tubes without flow conditioners, the recommended upstream meter-tube length varies with the diameter ratio ($\beta_r$); and that longer lengths of upstream meter tube are required for the higher diameter ratios ($\beta_r$). When the diameter of the orifice bore requires changing to meet different flowing conditions, the recommended length of the installed meter tube should be determined for the maximum diameter ratio ($\beta_r$) that may be used. The design criteria for new installations should be the lengths quoted for diameter ratios ($\beta_r$) equal to 0.75. Upstream meter tubes longer than those shown in Table 2-7 are desirable.

Installation Table 2-8 provides the 1998 Uniform Concentric 19-Tube Bundle Flow Straightener allowable location range and the recommended location for two upstream meter-tube length categories, $17D_i \leq \text{UL} < 29D_i$, and $\text{UL} \geq 29D_i$. The standard does not address upstream meter-tube lengths of less than $17D_i$.

Those installations and/or flow conditioners not explicitly addressed in Tables 2-7 and 2-8 may be flow-tested either in situ or by a flow-testing laboratory with an established base line within the RG coefficient of discharge uncertainty (see Appendix 2-C). The flow testing should be performed with calibration devices and methods conforming to nationally and/or internationally approved standard(s). All instruments used to monitor the flow parameters, and/or to calculate the flow rate, shall be traceable to the local, state, or national certifying organization of weights and measures. The primary flow system may be portable or permanently installed. A master meter that has been calibrated with a primary flow standard can also be used for the flow testing. Both the master meter and the proving system must meet appropriate nationally recognized standards.

Note: If the flow testing is to be conducted in a flow-testing laboratory, the installation tested should consist of the meter tube or meter station with manifold and appropriate upstream piping configuration, as is necessary to define the flow signature (velocity profile and swirl) entering the meter tube or meter station.

The flow testing should be performed over the normal range of Reynolds numbers experienced during every-day operation. Acceptable performance levels constituting no need for additional measurement uncertainty are defined as $\Delta C_d$ variation equal to or less than 50% of the stated $2\sigma$ uncertainty in the Reader-Harris/Gallagher orifice equation at infinite Reynolds number (see Part 1, Section 1.12.4; and Part 2, Appendix 2-C).

### 2.6.3.3 Requirements for Flow Conditioners

To provide the most comprehensive installation options possible, this standard does not propose to recommend any particular flow conditioner. Rather, the standard provides sufficient installation information to reduce or eliminate any systematic biases resulting from installation considerations. This standard provides minimum required meter tube lengths for meter tubes without flow conditioners. It also provides location ranges and recommended locations for two meter tube length categories ($17D_i \leq \text{UL} < 29D_i$ and $\text{UL} \geq 29D_i$ ) for 1998 Uniform Concentric 19-Tube Bundle Flow Straighteners, which meet the construction criteria stipulated in 2.5.5.1 through 2.5.5.3. In addition, the standard provides a performance test by which isolating flow conditioners, other flow straighteners, meter tubes without flow conditioners, and meter tube installations can be evaluated against the "no additional" uncertainty requirement. For further information, refer to Appendices 2-C and 2-D.

In determining whether or not flow conditioners are required, the governing factor may not always be the nearest piping fitting at the inlet end of the meter tube. For example, the last piping fitting or fittings may give no indication of the presence of swirling flow or degree of velocity profile asymmetry. Each individual station design may have a different set of conditions. Therefore, it

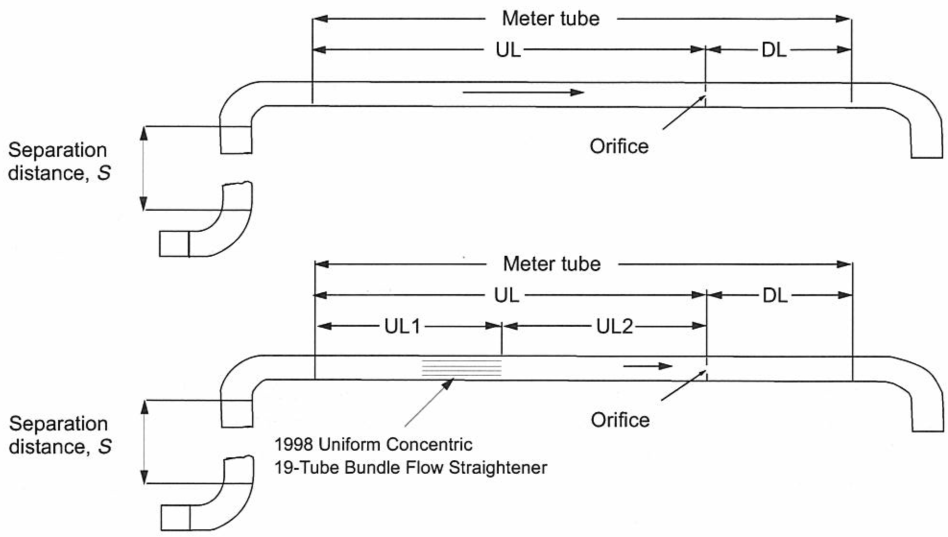



Figure 2-6—Orifice Meter Tube Layout for Flanged or Welded Inlet

would be impractical to set up specifications that would suit all conditions. The main consideration should be to minimize flow disturbance at the orifice plate from any upstream piping fittings.

The proper installation of flow conditioners may considerably reduce the amount of straight pipe required upstream of an orifice plate. The purpose of the flow conditioner is to reduce or eliminate the effect on the flow measurement of velocity profile asymmetry and/or swirl resulting from the pipe fittings and valves upstream of the meter tube. When flow conditioners are installed, they should be kept clean and free from debris, which may collect against the upstream end.

No flow conditioner can eliminate all possible profile effects unless properly installed and used. Care should be taken to minimize flow disturbances and swirl-generating configurations in the metering system, particularly upstream of the orifice. Thus, when properly located, in well designed installations, the 1998 Uniform Concentric 19-Tube Bundle Flow Straightener can eliminate bias in orifice measurement. For further information on proper installation of this flow straightener, refer to Tables 2-8a and 2-8b.

### 2.6.4 ACCEPTABLE PULSATION ENVIRONMENT

Accurate measurement of flow with an orifice meter operating under pulsating flow conditions can be ensured only when the root mean square (rms) of the fluctuating differential pressure amplitude normalized over differential pressure time mean does not exceed 10%.

$$\Delta P_{rms} / \Delta P_{avg} \leq 0.10 \qquad (2.12)$$

This limit applies to single frequency flow pulsations with or without several harmonics (e.g., generated by reciprocating compressor or closed relief/blowdown valves) and to broad-band flow pulsations/noise (e.g., generated by throttling valves). Random turbulent pulsations generated by orifice plates in normal pipe flow do not cause additional measurement errors because these effects have been accounted for in the coefficient of discharge regression database (see Part 1, 1.7.1).

The specification for allowable flow pulsation level does not mean that a higher level of normalized pulsations will lead to flow measurement error. However, there is no assurance that it will not happen.

Currently, no satisfactory theoretical or empirical adjustment for orifice measurement in pulsating flow applications exists that, when applied to custody transfer measurement, will maintain the measurement accuracy predicted by this standard. Arbitrary application of any correcting formula may even increase the flow measurement error under pulsating flow conditions. The user should make every practical effort to eliminate pulsations at the source to avoid increased uncertainty in measurements.

### 2.6.5 THERMOMETER WELLS

Thermometer wells should be located to sense the average temperature of the fluid at the orifice plate. The wells may be placed on the downstream side of the orifice and neither closer to the plate than dimension *DL* nor farther than 4*DL*, as shown in Tables 2-7 and 2-8.

If a flow conditioner is used, the thermometer well may be located no closer than 36 inches upstream from the flow conditioner inlet.

Thermometer wells exposed to the influences of the ambient environment may result in biased measurement.

Care should be taken to ensure that the temperature sensor indicates the flowing gas temperature and is not thermally coupled to the meter run pipe.

### 2.6.6 INSULATION

Insulation of the meter tube may be required in the case of extreme temperature differences between the ambient temperature and the temperature of the flowing fluid, and/or for fluids being metered near their critical point, where small temperature changes result in major density changes. This can be critical at low flow rates, where heat transfer effects may cause not only distorted temperature profiles, but also a change in the mixed mean temperature values from the upstream to the downstream side of the meter run, and changes to the mean velocity profile.

### Table 2-7—Orifice Meter Installation Requirements Without a Flow Conditioner

| Diameter ratio $\beta$ | Minimum Straight Unobstructed Meter Tube Length from the Upstream Side of the Orifice Plate (in multiples of published internal pipe diameter, $D_i$) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | a. Single 90° elbow. b. Two 90° elbows in the same plane with $S > 30D_i$. c. Two 90° elbows in perpendicular planes with $S > 15D_i$. | Two 90° elbows in the same plane "S" configuration spacer $S \le 10D_i$ | Two 90° elbows in the same plane, "S" configuration $10D_i < S \le 30D_i$ | Two 90° elbows in perpendicular planes, $S < 5D_i$* | Two 90° elbows in perpendicular planes, $5D_i \le S \le 15D_i$ | Single 90° Tee used as an elbow but not as a header element | a. Single 45° elbow. b. Two 45° elbows in the same plane "S" configuration $S \ge 22D_i$ | Gate valve at least 50% open | Concentric reducer | Any other configuration (catch all category)* | Downstream meter tube length |
| | UL | UL | UL | UL | UL | UL | UL | UL | UL | UL | DL |
| ≤ 0.20 | 6 | 10 | 10 | 50 | 19 | 9 | 30 | 17 | 6 | 70 | 2.8 |
| 0.30 | 11 | 10 | 12 | 50 | 32 | 9 | 30 | 19 | 6 | 108 | 3.0 |
| 0.40 | 16 | 10 | 13 | 50 | 44 | 9 | 30 | 21 | 6 | 145 | 3.2 |
| 0.50 | 30 | 30 | 18 | 95 | 44 | 19 | 30 | 25 | 7 | 145 | 3.5 |
| 0.60 | 44 | 44 | 30 | 95 | 44 | 29 | 30 | 30 | 9 | 145 | 3.9 |
| 0.67 | 44 | 44 | 44 | 95 | 44 | 36 | 44 | 35 | 11 | 145 | 4.2 |
| 0.75 | 44 | 44 | 44 | 95 | 44 | 44 | 44 | 44 | 13 | 145 | 4.5 |
| Recommended length for maximum range $\beta \le 0.75$ | 44 | 44 | 44 | 95 | 44 | 44 | 44 | 44 | 13 | 145 | 4.5 |

UL = Minimum meter tube length upstream of the orifice plate in internal pipe diameter ($D_i$)(see Figure 2-6). Straight length shall be measured from the downstream end of the curved portion of the nearest (or only) elbow or of the tee or the downstream end of the conical portion of reducer or expander.
DL = Minimum downstream meter tube length in internal pipe diameters ($D_i$)(see Figure 2-6).
S = Separation distance between piping elements in internal pipe diameter ($D_i$) measured from the downstream end of the curved portion of the upstream elbow to the upstream end of the curved portion of the downstream elbow.
* These installations exhibit the strong effect of Reynolds number and pipe roughness on the recommended length due to the rate of swirl decay. The present recommendations have been developed for high Reynolds numbers and smooth pipes to capture the worst case.

Note: The tolerance on specified lengths for UL and DL is $\pm\ 0.25D_i$.

Table 2-8a—Orifice Meter Installation Requirements With 1998 Uniform Concentric 19-Tube Bundle Flow Straightener for Meter Tube Upstream Length of $17D_i \leq UL < 29D_i$.

| | Single 90° elbow $R/D_i = 1.5$ | Two 90° elbows out of plane S ≤ 2Di $R/D_i = 1.5$ | Single 90° tee used as an elbow but not as a header element | Partially closed valves (at least 50% open) | High swirl combined with single 90° Tee | Any fitting (catch-all category) | Downstream meter tube length |
|---|---|---|---|---|---|---|---|
| Diameter Ratio, β | UL2 | UL2 | UL2 | UL2 | UL2 | UL2 | DL |
| 0.10 | 5 – 14.5 | 5 – 14.5 | 5 – 14.5 | 5 – 11 | 5 – 13 | 5 – 11.5 | 2.8 |
| 0.20 | 5 – 14.5 | 5 – 14.5 | 5 – 14.5 | 5 – 11 | 5 – 13 | 5 – 11.5 | 2.8 |
| 0.30 | 5 – 14.5 | 5 – 14.5 | 5 – 14.5 | 5 – 11 | 5 – 13 | 5 – 11.5 | 3.0 |
| 0.40 | 5 – 14.5 | 5 – 14.5 | 5 – 14.5 | 5 – 11 | 5 – 13 | 5 – 11.5 | 3.2 |
| 0.50 | 11.5 – 14.5 | 9.5 – 14.5 | 11 – 13 | b | 11 – 13 | c | 3.5 |
| 0.60 | 12 – 13 | 13.5 – 14.5 | a | *Not allowed* | a | *Not allowed* | 3.9 |
| 0.67 | 13 | 13 – 14.5 | *Not allowed* | *Not allowed* | *Not allowed* | *Not allowed* | 4.2 |
| 0.75 | 14 | *Not allowed* | *Not allowed* | *Not allowed* | *Not allowed* | *Not allowed* | 4.5 |
| Recommended tube bundle location for maximum range of β | 13 β ≤ 0.67 | 13.5 – 14.5 β ≤ 0.67 | 13 β ≤ 0.54 | 9.5 β ≤ 0.47 | 13 β ≤ 0.54 | 9.5 β ≤ 0.46 | 4.5 |

[a] $13D_i$ allowed for up to β = 0.54.
[b] $9.5D_i$ allowed for up to β = 0.47.
[c] $9.5D_i$ allowed for up to β = 0.46.
S = Separation distance between elbows, measured as defined in Table 2-7.
UL1 = UL – UL 2 (see Figure 2-6).
Note 1: Lengths shown under the UL2 column are the dimensions shown in Figure 2-6, expressed as the number of published internal pipe diameters ($D_i$) between the downstream end of the 1998 Uniform Concentric 19-Tube Bundle Flow Straightener and the upstream surface of the orifice plate.
Note 2: The tolerance on specified lengths for UL, UL2, and DL is $\pm 0.25D_i$.
Note 3: *Not allowed* means that it is not possible to find an acceptable location for the 1998 Uniform Concentric 19-Tube Bundle Flow Straightener downstream of the particular fitting for all values of UL.

Table 2-8b—Orifice Meter Installation Requirements With 1998 Uniform Concentric 19-Tube Bundle Flow Straightener for Meter Tube Upstream Length of UL ≥ 29$D_i$.

| | Single 90° elbow $R/D_i = 1.5$ | Two 90° elbows out of plane $S \le 2D_i$ $R/D_i = 1.5$ | Single 90° Tee used as an elbow but not as a header element | Partially closed valves (at least 50% open) | High swirl combined with single 90° Tee | Any fitting (catch-all category) | Downstream meter tube length |
|---|---|---|---|---|---|---|---|
| Diameter Ratio, β | UL2 | UL2 | UL2 | UL2 | UL2 | UL2 | DL |
| 0.10 | 5 – 25 | 5 – 25 | 5 – 25 | 5 – 13 | 5 – 23 | 5 – 13 | 2.8 |
| 0.20 | 5 – 25 | 5 – 25 | 5 – 25 | 5 – 13 | 5 – 23 | 5 – 13 | 2.8 |
| 0.30 | 5 – 25 | 5 – 25 | 5 – 25 | 5 – 13 | 5 – 23 | 5 – 13 | 3.0 |
| 0.40 | 5 – 25 | 5 – 25 | 5 – 25 | 5 – 13 | 5 – 23 | 5 – 13 | 3.2 |
| 0.50 | 11.5 – 25 | 9 – 25 | 9 – 23 | 7.5 – 15 | 9 – 19.5 | 11.5 – 14.5 | 3.5 |
| 0.60 | 12 – 25 | 9 – 25 | 11 – 16 | 10 – 17 | 11 – 16 | 12 – 16 | 3.9 |
| 0.67 | 13 – 16,5 | 10 – 16 | 11 – 13 | 10 – 13 | 11 – 13 | 13 | 4.2 |
| 0.75 | 14 – 16,5 | 12 – 12.5 | 12 – 14 | 11 – 12.5 | 14 | *Not allowed* | 4.5 |
| Recommended tube bundle location for maximum range of β | 13 β ≤ 0.75 | 12 – 12.5 β ≤ 0.75 | 12 – 13 β ≤ 0,75 | 11 – 12.5 β ≤ 0.75 | 13 β ≤ 0.75 | 13 β ≤ 0.67 | 4.5 |

$S$ = Separation distance between elbows, measured as defined in Table 2-7.
UL1 = UL – UL2 (see Figure 2-6).

Note 1: Lengths shown under the UL2 column are the dimensions shown in Figure 2.6 and as defined in Table 2-8a.
Note 2: The tolerance on specified lengths for UL, UL2, and DL is ± 0.25$D_i$.
Note 3: *Not allowed* means that it is not possible to find an acceptable location for the 1998 Uniform Concentric 19-Tube Bundle Flow Straightener downstream of the particular fitting for all values of UL.

# APPENDIX 2-A—RESEARCH PROJECTS AND TESTS CONDUCTED BETWEEN 1922 AND 1999

Note: This appendix is not a part of this standard and is included for informational purposes only. Further, the standard is revised solely on the information in the White Papers (maintained by API), which use selected references from those listed in this Appendix.

## 2-A.1 Introduction

During the preparation of AGA Report No.3, the committee analyzed the data from research projects and tests conducted between 1922 and 1998. Some of the projects were conducted directly under the supervision of API, Gas Processors Association (GPA), and American Gas Association (AGA) personnel. Other tests were conducted by the Commission of the European Communities. Still other tests, by independent investigators worldwide, made significant contributions to the data base. The references described in 2-A.2 through 2-A.12 are from the original document known as AGA Report No. 2. The references described in 2-A.13 through 2-A.19 were incorporated in the reference list of the document known as AGA Report No. 3. The more recent references listed in 2-A.20 through 2-A.25 were part of an intense review and subsequent white paper developed by the API Chapter 14, Section 3, Part 2, (AGA Report No.3, Part 2) working group.

## 2-A.2 Cleveland Holder Tests (1925)

The Cleveland holder tests were conducted by the Gas Measurement Committee using a gas holder owned by the East Ohio Gas Company in Cleveland. These tests were made under the chairmanship of H. C. Cooper and the direct supervision of Professor R. S. Danforth of the Case School of Applied Science. Representatives of the National Bureau of Standards and the U.S. Bureau of Mines were present as observers. The test line consisted of orifice meter runs of 8-, 10-, and 16-inch pipe; 4-inch orifice plates were installed in each of these runs.

## 2-A.3 Buffalo Disturbance Tests (1926)

The Buffalo disturbance tests were conducted by the Gas Measurement Committee at the Daly Station of the Iroquois Gas Corporation, Buffalo, New York. The object of these tests was to determine the effects of disturbances produced in a gas stream by various kinds of pipeline fittings located near an orifice plate on the indications of an orifice meter.

## 2-A.4 Disturbance and Rate-of-Flow Tests (1927)

Disturbance and rate-of-flow tests were conducted by the Gas Measurement Committee at Daly Station of the Iroquois Gas Corporation, Buffalo, New York, under the personal supervision of Howard S. Bean. The first part of these tests was a continuation of the 1926 series described in 2-A.3. The rate-of-flow tests had two objectives:

a. To build up, by means of a series of intercomparisons, a series of relative orifice coefficient values for orifices in an 8-inch pipe that ranged in diameter from 1 inch to 61.2 inches.

b. To study the effect on orifice coefficients of increasing value of the ratio of differential pressure to static pressure ($h/p$), that is, the ratio of the differential pressure, in inches of water, to the absolute static pressure, in pounds per square inch.

## 2-A.5 Rate-of-Flow, Flange Form, and Supercompressibility Tests (1928)

Rate-of-flow, flange form, and supercompressibility tests were conducted at the Daly Station of the Iroquois Gas Corporation, Buffalo, New York, by the Gas Measurement Committee under the direction of Howard S. Bean. The objects of these tests were as follows:

a. To extend the study of effects on orifice coefficients resulting from changes in the h/p ratio to orifices in 4-inch pipes.
b. To compare the relative indications obtained with recessed and unrecessed orifice ranges.
c. To determine the deviation from Boyle's Law and its effect on measuring gas by orifice meters.
d. To investigate the effect on orifice coefficients for an equal diameter ratio changing from an 8-inch to a 4-inch line.

## 2-A.6 Shop Tests on Effects of Orifice Installation Conditions (1929–1930)

Shop tests on effects of orifice installation conditions were performed by the Bailey Meter Company, the Foxboro Company, the Metric Metal Works, and the Pittsburgh Equitable Meter Company for the Gas Measurement Committee in accordance with an outline prepared by Howard S. Bean. The object of these tests was to determine the effects on orifice meter indications that result from some installation conditions not covered by the disturbance tests described in 2-A.3 and 2-A.4. Additional information was desired about the following conditions:

a. Position and size of straightening vanes.
b. Position and design of thermometer wells, particularly on the upstream side of the orifice.
c. Roughness of pipe adjacent to the orifice.
d. Form of flange in which the orifice plate is held.
e. Inaccuracy in centering the orifice in the pipe.
f. The condition of the upstream edge of the orifice.
g. The ratio of the width of the orifice edge to the diameter of the orifice.

The results of these tests were reported in the article "Effect of Some Installation and Construction Conditions Upon the Indications of an Orifice Meter," *American Gas Association Monthly*, July – August 1947, Volume 29, pp. 7 and 8.

## 2-A.7 Edgewood Tests (1922–1925)

The Edgewood tests were conducted at Edgewood Arsenal, Maryland, by the National Bureau of Standards with the cooperation of the Chemical Warfare Service, U.S. War Department, under the immediate supervision of Howard S. Bean, with the advice of Edgar Buckingham, and the assistance of Paul S. Murphy. The object of these tests was to obtain original information on the orifice discharge coefficients over as wide a range of pipe sizes, diameter ratios, pressures, and pressure ratios as was permitted by the facilities available. The setup included orifices in 4-, 6-, and 8-inch pipes. Forty-eight orifice plates were used, with orifice-to-pipe diameter ratios ranging from 0.108 to 0.858.

## 2-A.8 Chicago Holder Tests (1923–1924)

The Chicago holder tests were conducted in Chicago by the American Gas Association Committee on the Measurement of Large Volumes of Gas, under the chairmanship of M. E. Benesh. On invitation from Mr. Benesh, the National Bureau of Standards cooperated in these tests, the main object of which was to study the accuracy of several types of meters, including orifice meters used to measure large quantities of gas at pressures near atmospheric.

## 2-A.9 Ohio State University Steam and Water Tests (1929–1931)

Steam and water tests were conducted by the Ohio State University Engineering Experiment Station and the Bailey Meter Company at the Mechanical Engineering Laboratory of Ohio State University, under the supervision of Professors Paul Bucher and Samuel Beitler. The object of the tests was to determine the expansion factor and the coefficients of orifices measuring both steam and water. Both 3- and 6-inch lines were used and a series of orifices were tested, first using water and then steam.

## 2-A.10 Intercomparison of Meter Runs (1932)

An intercomparison of meter runs was conducted by the Peoples Gas Light and Coke Company at its Joliet Measuring Station, Joliet, Illinois, under the supervision of M. E. Benesh.

## 2-A.11 Columbus Tests (1932–1933)

The Columbus tests were conducted by the Joint Orifice Meter Committee at the Hydraulic Laboratory of Ohio State University, Columbus, Ohio, under the immediate supervision of Professor Samuel R. Beitler. Nearly 80 separate orifice plates were used in tests with 1-, 1½-, 2-, 3-, 6-, 10-, and 15-inch pipes; and in many cases, the same orifice was used in two or more different pipe sizes. The orifice pipe diameter ratio ranged from 0.04 to 0.84.

## 2-A.12 South Columbus Flange Form and Pressure Hole Tests (1932)

Flange form and pressure hole tests were conducted by the Joint American Gas Association-American Society of Mechanical Engineers Committee on Orifice Meters at the South Columbus Measuring Station of the Ohio Fuel Gas Company, under the immediate supervision of J. E. Overbeck, with the advice of Professor Samuel R. Beitler. The object of these tests, which were made with natural gas, was to determine more completely than had been done either at Buffalo (2-A.3 and 2-A.4) or by the shop tests (2-A.6) the effects of various sizes of internal flange recesses adjacent to the orifice plate. Both the width and the depth of the recesses were varied in the 2-, 4-, and 8-inch pipe sizes that were used in these tests. The orifice-to-pipe diameter ratio ranged from 0.125 to 0.75. In combination with these recesses, various diameters of pressure holes were used.

## 2-A.13 Rockville Tests (1949–1951)

The Rockville tests were conducted by the Joint American Gas Association-American Society of Mechanical Engineers Committee under the direction of Howard S. Bean. Tests with natural gas were performed at the Rockville, Maryland, Measuring Station of the Atlantic Seaboard Corporation to study the following:

a. The effect of plug, globe, and gate valve disturbances on measurement.
b. The effect of elbow placement disturbances (comparison with Buffalo tests).
c. The effect of orifice meter fittings, compared with conventional orifice flanges.
d. The effect of orifice tube roughness.
e. Installations of 2- and 8-inch piping.

The results of these tests were published by the American Gas Association in two interim reports, each entitled "Investigation of Orifice Meter Installation Requirements," and dated March 1951, and January 1954.

## 2-A.14 National Bureau of Standards Hydraulics Laboratory Tests (1950–1951)

The National Bureau of Standards Hydraulics Laboratory tests were conducted by the Joint American Gas Association-American Society of Mechanical Engineers Committee on Orifice Meters at the Hydraulics Laboratory, National Bureau of Standards, Washington, D.C., under the immediate supervision of Howard S. Bean. The object of this project was, in part, to make comparative tests with water for the roughness and orifice fitting installations used in the Rockville tests (2-A.13) and, in part, to examine the effect of pressure tap location and tap hole size. The results were reported in conjunction with those from the Rockville tests.

## 2-A.15 U.S. Naval Boiler and Turbine Laboratory Tests (1948–1954)

The U.S. Naval Boiler and Turbine Laboratory tests were conducted by the Bureau of Ships, U.S. Department of the Navy, in conjunction with the Joint American Gas Association-American Society of Mechanical Engineers Committee on Orifice Meters, at the U.S. Naval Boiler and Turbine Laboratory in Philadelphia.

This work was conducted under the direction of James W. Murdock. The object of these tests, which were made with steam, was to determine the effect of globe valves and expansion bends on orifice meter indications. Additional tests were performed to check the values of expansion factors to be used in the measurement of steam. The results of these tests were reported in a series of four interim reports published by the U.S. Naval Boiler and Turbine Laboratory. These reports were entitled "Determination of the Minimum Length of Straight Pipe Required Between Various Pipe Fittings," and "The Orifice Plate for Acceptable Orifice Meter Accuracy," and were dated January 1950, March 1950, May 1950, and November 1951.

## 2-A.16 Refugio Large-Diameter Orifice Tube Tests (1952–1953)

The Refugio large-diameter orifice tube tests, a PAR Project, were conducted by the Project NX-4 Supervising Committee, under the chairmanship of E. E. Stovall. The primary objective was to determine experimentally whether the basic orifice coefficient data contained in the AGA Gas Measurement Report No. 2 could be extrapolated for use in measuring gas accurately through large-diameter tubes. The test installation was located near Refugio, Texas, on a transmission line of the Tennessee Gas Transmission Company. The results of these tests were published by the American Gas Association in a report, "Large Diameter Orifice Tube Tests," dated June 1954.

## 2-A.17 Eccentric and Segmental Orifice Tests (1948–1954)

Eccentric and segmental orifice tests were conducted under the supervision of a Subcommittee of the American Society of Mechanical Engineers (ASME) Research Committee on Fluid Meters with the cooperation of the AGA Gas Measurement Committee. The chairman of the ASME subcommittee was L. E. Gess of the Minneapolis Honeywell Company. The objective of the tests was to determine the coefficients of discharge of round orifices mounted with one edge tangent to the pipe wall and of plates with segmental orifices in them. The tests were run at Ohio State University under the supervision of Professor Samuel R. Beitler and were analyzed by Professor E. J. Lindahl of the University of Wyoming. The results of these tests were reported in two ASME papers: "Calibration of Eccentric and Segmental Orifices in 4- and 6-Inch Pipelines," *Transactions of the ASME*, 1949, Volume 71, and "Coefficients of Discharge for Eccentric and Segmental Orifices in 4-inch, 6-inch, 10-inch, and 14-inch Pipes," presented at the Annual Meeting of the American Society of Mechanical Engineers, New York, November 1954.

## 2-A.18 Pipe Roughness Study (1957–1960)

A pipe roughness study, a PAR Project, was conducted by the Project NW-20 Supervising Committee under the chairmanship of J. W. Murdock. W. B. Ruff, Jr., of the Southern Natural Gas Company, served as the Gas Measurement Committee representative coordinating and supervising the project. The primary purpose of this program was to determine, qualitatively and quantitatively, the effect of the character of the interior surface of orifice tubes on fluid flow measurements by orifice meters. A secondary objective was to correlate any effect on flow measurement with some physical measurement of the tube roughness (such as microinches) to the end that a recommendation could be made about the relative roughness range for satisfactory metering service. The preliminary tests were conducted at the U.S. Naval Boiler and Turbine Laboratory in Philadelphia. The full-scale tests were conducted in Birmingham, Alabama, at Southern Natural Gas Company facilities. Four-inch meter tubes were used in these tests. The results of these tests were published by the American Gas Association in the report, "The Effect of Pipe Roughness on Orifice Meter Accuracy (Catalog No. 33/PR)," dated February 1960.

## 2-A.19 Ohio State University Flow Distortion Tests (1960–1962)

The Ohio State University flow distortion tests constituted PAR Project NY-34. The supervising committee chairman was C. W. Brown, Texas Gas Transmission Corporation. These tests were carried out at Ohio State University to determine the amount of error caused by distortion of the approach velocity profile on the coefficient of orifices. An attempt was made to eliminate swirl, so the report describes the effect of changes in the axial profile only. Six-inch orifice pipes with honed walls (roughness of about 15 microinches) were used, and the inlet profile was distorted by use of special flow disturbances and piping configurations. It was concluded that ordinary disturbances caused by piping configurations, which did not produce swirl, resulted in errors of less than 2% if there were at least six diameters of straight uniform pipe ahead of the orifice.

## 2-A.20 API Experimental Program

American Petroleum Institute, Washington, D.C., "Coefficients of Discharge for Concentric, Square-Edged, Flange-Tapped Orifice Meters: Equation Data Set-Supporting Documentation for Floppy Diskettes," 1988.

Britton, C.L., Caldwell, S., and Seidl, W. "Measurements of Coefficients of Discharge for Concentric, Flange-Tapped, Square-Edged Orifice Meters in White Mineral Oil Over a Reynolds Number Range of 70 to 90,000," American Petroleum Institute, Washington, D.C., 1988.

Whetstone, J.R., Cleveland, W.G., Bateman, R.B., and Sindt, C.F., "Measurements of Coefficients of Discharge for Concentric, Flange-Tapped, Square-Edged Orifice Meters in Natural Gas Over a Reynolds Number Range of 25,000 to 11,600,000," American Petroleum Institute, Washington, D.C., 1988.

Whetstone, J.R., Cleveland, W.G., Baumgarten, G.P., Woo, S., and Croarkin, M.C.,"Measurements of Coefficients of Discharge for Concentric Flange-Tapped Square-Edged Orifice Meters in Water Over the Reynolds Number Range 600–2,700,000" (Technical Note 1264), National Institute of Standards and Technology, Washington, D.C., June 1989.

## 2-A.21 EEC Experimental Program

Hobbs, J.M., "Experimental Data for the Determination of Basic 100 mm Orifice Meter Discharge Coefficients," (Report EUR 10027), Commission of the European Communities, Brussels, 1985.

Hobbs, J.M., "The EEC Orifice Plate Project: Part I. Traceabilities of Facilities Used and Calculation Methods Employed," (Report PR5:EUEC/17), Commission of the European Communities, Brussels, 1987.

Hobbs, J.M., "The EEC Orifice Plate Project: Part II. Critical Evaluation of Data Obtained During EEC Orifice Plate Tests" (Report PR5:EUEC/17), Commission of the European Communities, Brussels, 1987.

Hobbs, J.M., "The EEC Orifice Plate Project: Tables of Valid Data for EEC Orifice Analysis" (Report EUEC/17), Commission of the European Communities, Brussels, 1987.

Hobbs, J.M., Sattary, J.A., and Maxwell, A.D., "Experimental Data for the Determination of Basic 250 mm Orifice Meter Discharge Coefficients" (Report EUR 10979), Commission of the European Communities, Brussels, 1987.

Hobbs, J.M., Sattary, J.A., and Maxwell, A.D., "Experimental Data for the Determination of Basic 600 mm Orifice Meter Discharge Coefficients," Commission of the European Communities, Brussels, in press.

Spencer, E.A., "Study of Edge Sharpness Effects Measured During the EEC Orifice Plate Coefficient Programme" (Report EUR 11131 EN), Commission of the European Communities, Glasgow, 1987.

## 2-A.22 Orifice Eccentricity and Deformation

Austerman, R., Teyssandier, R., Husain, Z., Goodson, D., and Brown, M., "White Paper: Orifice Plate Thickness, API Chapter 14.3, Part 2, Working Group", March 3, 1998.

Belomos, D., "Tests Shed Light on Orifice-Plate Bending," *Oil & Gas Journal*, Jan. 1959.

Gorter, J., "Deformation of Orifice Plate: Theory and Practice," FLOMEKO 1978, IMEKO Conference on Flow Measurement of Fluids, Groningen, North-Holland Publishing, Amsterdam, Holland, 1978.

Husain, Z.D., and. Teyssandier, R.G., "Orifice Eccentricity Effects for Flange, Pipe and Radius (D – D/2) Taps" (ASME Paper 66-WA/FM-1), American Society of Mechanical Engineers, New York, 1966.

Husain, Z.D., and Roussel, J., "Measurement Accuracy of 1/4" Thick Orifice Plate Installed in 8" Orifice Fitting Designed for 1/8" Thick Plate," Gas Measurement Research Council, San Antonio, Texas, August 1997.

Husain, Z.D., and Goodson, F.,D., "Effects of Thickness and Bevel Angle on Discharge Coefficients of a 50 mm (2 inch) Orifice Meter," ASME/Winter Annual Meeting, FM-4 Symposium on Flow Meters, Anaheim, California, December 1986.

Husain, Z.D., Roussel, J.B. and Goodson, F.D., "Measurement Accuracy of 1/4" (6.35 mm) Thick Orifice Plate Installed in an 8" (200 mm) Orifice Fitting Designed for 1/8" (3.175 mm) Thick Plate," Fourth International Symposium on Fluid Flow Measurement, Denver, Colorado, June 1999.

Husain, Z.D., and Teyssandier, R.G., "Orifice Eccentricity Effects for Flange, Pipe and Radius (D – D/2) Taps," ASME Paper 86-WA/FM-1, American Society of Mechanical Engineers, New York, 1986.

Husain, Z.D., and Teyssandier, R.G., "The Effect of Orifice Eccentricity in a Small Line Size," Paper presented at the International Conference on the Metering of Natural Gas and Liquefied Hydrocarbon Gases, London, February 1984.

Jepson, P., and Chipchase, R., "Effect of Plate Buckling on Orifice Meter Accuracy," *Journal of Mechanical Engineering Science*, Vol. 17, No. 6, 1975, pp. 330–337.

Karnik, U., "Effect of Increasing Plate Thickness on the Metering Accuracy of an 8-Inch Orifice Meter Run," American Gas Association 1996 Operations Conference, Montreal, May 19-22, 1996.

Mason, D., Wilson, M.P., and Birkhead, W. G., "Measurement Error Due to the Bending of Orifice Plates," ASME Paper 75-WA/FM-6, American Society of Mechanical Engineers, New York, 1975.

Miller, R.W., and Kneisel, U., "Experimental Study of the Effects of Orifice Plate Eccentricity on Flow Coefficients," ASME Paper 68-WA/FM-1, American Society of Mechanical Engineers, New York, 1968.

Norman, R., Rawat, M.S., and Jepson, P., "An Experimental Investigation into the Effects of Plate Eccentricity and Elastic Deformation on Orifice Metering Accuracy," Paper presented at the International Conference on the Metering of Natural Gas and Liquefied Hydrocarbon Gases, London, February 1984.

Trumpler, W.E., "Design Data for Flat Circular Plates with Central Holes," ASME Journal of Applied Mechanics, American Society of Mechanical Engineers, New York, September 1943.

Wahl, A.M., and Way, S., "Stress and Deflection of Circular Plates," American Society of Mechanical Engineers, New York.

## 2-A.23 Orifice Edge/Surface Condition

Benedict, R.P., Wyler, J.S., and Brandt, G.B., "The Effect of Edge Sharpness on the Discharge Coefficient of an Orifice Plate," ASME Paper No. 74–WA/FM-4, American Society of Mechanical Engineers, New York, 1974.

Crockett, K.A., and Upp, E.L., "Measurement and Effects of Edge Sharpness on the Flow Coefficients of Standard Orifices," *ASME Journal of Fluids Engineering*, American Society of Mechanical Engineers, New York, NY, USA, June 1973, pp. 271-275.

Fr. von Herning, "Experiments on the Problem of the Edge Sharpness of Standard and Segmental Orifice Plates," *Brenns-Warme-Kraft*, Vol. 14, No. 3, Germany, 1962, pp. 119–126.

Fr. von Herning, and Wolowski, E., "The Edge Sharpness of Standard and Segmental Orifices and the Laws of Similarity," *Brenns-Warme-Kraft*, Vol. 15, No. 1, Germany, 1963, pp. 26–30.

Hobbs, J.M., and Humphreys, J.S., "The Effect of Orifice Plate Geometry Upon Discharge Coefficient," *Journal of Flow Measurement and Instrumentation*, Vol. 1, No. 3, April 1990, pp. 133–140.

McVeigh, J.C., "Further Investigations into the Effect of Roughness of the Orifice Plate on the Discharge Coefficient," *Instrument Engineer*, April 1962.

Newcombe, J., "Orifice Plate Edge Thickness," AGA Report No. 3, Letter to Harry P. Bean from Manager, Control & Instruments, United Kingdom.

Ruppel, G., "The Discharge Coefficient of Standard Orifices and Their Dependence on the Length of the Edge," VDI, Berlin-Siemensstadt, Germany.

Spencer, E.A., "Study of Sharpness Effects Measured During the EEC Plate Coefficient Programme," (Report EUR 11131 EN), Commission of the European Communities, Brussels, 1987.

Spencer, E.A., Calame, H., and Singer, J., "The Influence of Edge Sharpness and Pipe Roughness on Orifice Plate Coefficients," NEL Report No. 427, National Engineering Laboratory, East Kilbride, Glasgow, 1969.

Studzinski, W., "Effects of Abnormal Conditions on Accuracy of Orifice Measurements," *Proceedings of the 66th International School of Hydrocarbon Measurement*, 1988, pp. 70–74.

Studzinski, W., Bell, D.G., and McConaghy, B.J., "Primary Device Research," AGA Transmission and Distribution Conference, Toronto, 1988, pp. 536–547.

Studzinski, W., Berg, D., Bell, D., and Richards, D., "Effects of Orifice Conditions on Accuracy of Flow Rate Measurements," 2nd International Conference on Flow Measurement, London, May 11–13, 1988.

Studzinski, W., Szabo, J., Eastwood, J., Rans, R., and Bell, D., "Performance of Orifice Meters in Field Conditions," International Symposium on Measurements, Properties and Utilization of Natural Gas, Montreal, Quebec, Canada, Nov. 25–27, 1987.

Thrasher, L.W., and Binder, R.C., "Effect of Edge Thickness on Small Orifice Meters," *Instruments & Automation*, November 1954.

Two-Inch Orifice Plate Investigation, "A Report for the Commission of the European Communities Directorate General for Science Research and Development Community Bureau of Reference," October 1991.

## 2-A.24 Pipe Roughness

Bean, H.S., and Murdock, J.W., "Effect of Pipe Roughness on Orifice Meter Accuracy," Research Project NW-20, American Gas Association, Arlington, Virginia, February 1960.

Brennan, J.A., McFaddin, S.E., Sindt, C.F., and R.R. Wilson, "Effect of Pipe Roughness on Orifice Flow Measurement," (Technical Note 1329), National Institute of Standards and Technology, Washington, D.C., July 1989 (Also GRI-89/0228).

Clark, W.J., and Stephens, R.C., "Flow Measurement by Square-Edged Orifice Plates: Pipe Roughness Effects," *Proceedings of the Institution of Mechanical Engineers*, Vol. 171, No. 33, London, 1957.

Reader-Harris, M.J., "Computation of Flow Through Orifice Plates Downstream of Rough Pipework," International Conference on Flow Measurement in the Mid 80s, Paper 7.3, June 9–12, 1986.

Reader-Harris, M.J., "Pipe Roughness and Reynolds Number Limits for the Orifice Plate Discharge Coefficient Equation," Second International Symposium on Fluid Flow Measurement, June 6–8, 1990.

Reader-Harris, M.J., "The Revision of ISO 5167—An Update," 16th North Sea Flow Measurement Workshop 1998.

Reader-Harris, M.J., and Keegan, W., "Comparison of Computation and LDV Measurements of Flow Through Orifice and Perforated Plates, and Computation of the Effect of Rough Pipework on Orifice Plates," *Proceedings of International Symposium on Fluid Flow Measurement*, American Gas Association, Arlington, Virginia, November 1986.

Sindt, C.F., Brennan, J.A., and McFaddin, S.E., "NBS Research on the Effects of Pipe Roughness and Flow Conditioners on the Orifice Discharge Coefficients," AGA Distribution/Transmission Conference, May 4–6,1987.

Sindt, C.F., Brennan, J.A., McFaddin, S.E., and Kothari, K.M., "Effect of Pipe Surface Finish on Gas Flow Measurement with an Orifice Meter," 1989 International Gas Research Conference, April 1990, pp. 550–557.

Spencer, E.A., Calame, H., and Singer, J., "The Influence of Edge Sharpness and Pipe Roughness on Orifice Plate Coefficients," NEL Report No. 427, National Engineering Laboratory, East Kilbride, Glasgow, 1969.

Studzinski, W., Berg, D.H., Bell, D.J., and Karwacki, L., "Effects Of Meter Run Roughness On Orifice Meter Accuracy," Second International Symposium on Fluid Flow Measurement, Calgary, Alberta, June 6–8, 1990.

Studzinski, W., Berg, D.H., Bell, D.J., and Gagnon, D.J., "Primary Device Research Meter Tube Roughness Effects On Orifice Metering," *Proceedings of the Canadian Gas Association (CGA) 28th Annual Gas Measurement School*, London, Ontario, June 13–15, 1989.

Upp, E.L., and Durapau, S., "Pipe Roughness Study Proposal," Daniel Memorandum re: subject, Daniel Flow Products, Inc., Houston, Texas, 1983.

## 2-A.25 Installation Effects

Brennan, J.A., McFaddin, S.E., and Sindt, C.F., "Effect of the Location of an In-Line Tube Bundle on Orifice Flowmeter Performance," *Journal of Flow Measurement and Instrumentation*, Vol. 1, No. 1, pp. 9–14, October 1989.

Brennan, J. A., Sindt, C.F., Lewis, M.A., and Scott, J.L., "Choosing Flow Conditioners and Their Location for Orifice Flow Measurement," *Journal of Flow Measurement and Instrumentation*, Vol. 2, No. 1, January 1991, pp. 40–44.

Brennan, J.A., and Stuart, J.W., "Sliding Vane Flow Conditioner Tests in a 100 Diameter Long 10" Natural Gas Orifice Meter at Pacific Gas and Electric," National Institute of Standards and Technology, Gaithersburg, Maryland, and Pacific Gas & Electric Co., San Francisco, October 1992. (Also: GRI-92/0576.)

Delanny, B., and Verstraete, Chr., "The Effectiveness of Perforated Plates Used as Flow Straighteners in Non-Symmetrical Flows," Applied Sciences Faculty, Department of Thermodynamics and Turbine Machines, Catholic University of Louvain, Belgium, 1977.

Gregor, J.G., and Kothari, K.M., "Effects of Flow Conditioner Location on Orifice Meter Performance," 1992 International Gas Research Conference, pp. 668–679, April 1993.

Humphreys, J.S., and Hobbs, J.M., "An Investigation of the Effectiveness of Flow Conditioners," *Proceedings of International Symposium on Fluid Flow Measurement*, American Gas Association, Arlington, Virginia, November 1986.

Harbrink, B., "Header Effects on Gas Flow Profiles," *Journal of Flow Measurement and Instrumentation*, Vol. 2, No. 1, pp. 34–39, January 1991.

Humphreys, J.S., and Hobbs, J.M., "The NEL Installation Tolerant Orifice Plate Package," The 5th International IMEKO-Conference on Flow Measurement, FLOMEKO 1989, VDI Berichte Nr. 768, Germany, pp. 99–106.

Irving, S.J., "Effect of System Layout on the Discharge Coefficients of Orifice Plates—Part 2: Experimental Investigation Into the Effect of Isolated Fittings," BHRA Report RR1424, British Hydromechanics Research Association, Bedford, England, August 1977.

Irving, S.J., "Effect of System Layout on the Discharge Coefficient of Orifice Plates: Summary of Results," January 1978.

Irving, S.J., "Effect of System Layout on the Discharge Coefficients of Orifice Plates—Part 3: Experimental Investigation into the Effects of Bend Combinations," BHRA Report RR1462, British Hydromechanics Research Association, Bedford, England, April 1978.

Irving, S.J., "The Effect of Disturbed Flow Conditions on the Discharge Coefficient of Orifice Plates," *International Journal of Heat and Fluid Flow*, Vol. 1, No. 1, 1979, pp. 5–11.

Jaumotte, A.J., and Nagel, P.P., "Predetermination of the Relative Error on Flow Coefficient of Orifice Meter In Non-Standard Approach Conditions," *Transactions of the ASME*, Vol. 100, American Society of Mechanical Engineers, New York, March 1978.

Jepson, P., and Chipchase, R., "The Performance of a Zanker Type Flow Straightener in Swirling Flow," British Gas Engineering Research Station Report R406, February 1973.

Karnik, U., Jones, B., and Studzinski, W., "Orifice Meter Installation Effects: Four-inch Orifice Meter Tests: No Flow Conditioner, " 1996. (Also: GRI-96/0384.)

Karnik, U., Jungowski, W. M., and Botros, K.K., "Effect of Turbulence on Orifice Meter Performance," *ASME Journal of Offshore Mechanics and Arctic Engineering*, Vol. 116, No. 2, 1994, pp. 77–85.

Karnik, U., "A Compact Orifice Meter/Flow Conditioner Package," Third International Symposium on Fluid Flow Measurement, San Antonio, Texas, March 20–22 1995.

Karnik, U., and Williamson, I., "Effect of Expanders on Orifice Meter Accuracy," Third International Symposium on Fluid Flow Measurement, San Antonio, Texas, March 20–22, 1995.

Karnik, U., Jungowski, W.M., and Botros, K.K., "Effects of Flow Characteristics Downstream of Elbow/Flow Conditioner on Orifice Meter," 9th North Sea Flow Measurement Workshop, Bergen, Norway, October 24, 1991.

Kinghorn, F.C., "The Use of Etoile Flow Straighteners with Orifice Plates in Swirling Flow," ASME 79-WA/FM-7, American Society of Mechanical Engineers, New York.

Kinghorn, F.C., "Flow Measurement in Swirling or Asymmetric Flow—A Review," *Flow-Con 77 Proceeding*, Institute of Measurement and Control, Gatton & Kent, England, United Kingdom, 1977, pp. 45–71.

Kinghorn, F.C., McHugh, A., and Dyet, W.D., "The Use of Etoile Flow Straighteners with Orifice Plates in Swirling Flow," *Journal of Flow Measurement and Instrumentation*, Vol. 2, No. 3, July 1991, pp. 162–168.

Kothari, K.M., Brennan, J.A., and Gorter, J., "Effect of Tube Bundle Flow Conditioners on Orifice Meter Discharge Coefficients," 1989 International Gas Research Conference, pp. 541–549, April 1990.

Laws, E.M., and Ouazzane, A.K., "Compact Installations for Differential Flowmeters," *Journal of Flow Measurement and Instrumentation*, Vol. 5, No. 2, April 1994, pp. 87–92.

Martin, C.N.B., "Effects of Upstream Bends and Valves on Orifice Plate Pressure Distributions and Discharge Coefficients," *International Journal of Heat and Fluid Flow*, Vol. 3, No. 3, September 1982, pp. 135–141.

Mattingly, G.E., and Yeh, T.T., "Summary Report of NIST's Industry-Government Consortium Research Program on Flowmeter Installation Effects with Emphasis on the Research Period November 1988 – May 1989," NISTIR 4310, National Institute of Standards and Technology, Gaithersburg, Maryland, April 1990. (Also: GRI-90/0197.)

Mattingly, G.E., and Yeh, T.T., "Effects of Pipe Elbows and Tube Bundles on Selected Types of Flowmeters," *Journal of Flow Measurement and Instrumentation*, Vol. 2, No. 1, January 1991, pp. 4–13.

Mattingly, G.E., and Yeh, T.T., "Summary Report of NIST's Industry-Government Consortium Research Program on Flow Meter Installation Effects with Emphasis on the Research Period May 1989 – February 1990: Tube Bundle Effects," NISTIR

4751, U.S. Department of Commerce, National Institute of Standards and Technology, Gaithersburg, Maryland, December 1991. (Also: GRI-91/0429.)

Mattingly, G.E., and Yeh, T.T., "Summary Report of NIST's Industry-Government Consortium Research Program on Flow Meter Installation Effects with Emphasis on the Research Period February – December 1990: TEE, Used as an Elbow Configuration," NISTIR 4753, U.S. Department of Commerce, National Institute of Standards and Technology, Gaithersburg, Maryland, January 1992. (Also: GRI-92/0231.)

Mattingly, G.E., and Yeh, T.T., "Summary Report of NIST's Industry-Government Consortium Research Program on Flow Meter Installation Effects with Emphasis on the Research Period January – September 1991: The Reducer," NISTIR 4779, U.S. Department of Commerce, National Institute of Standards and Technology, Gaithersburg, Maryland, February 1992. (Also: GRI-92/0443.)

Mattingly, G.E., and Yeh, T.T., "Summary Report of NIST's Industry-Government Consortium Research Program on Flow Meter Installation Effects: The 45 Degree Elbow," NIST TN 1408, U.S. Department of Commerce, National Institute of Standards and Technology, Gaithersburg, Maryland, September 1994. (Also: GRI-94/0497.)

McFaddin, S.E., Sindt, C.F., and Brennan, J.A., "Optimum Location of Flow Conditioners in a 4-inch Orifice Meter," NIST Technical Note 1330, U.S. Department of Commerce, National Institute of Standards and Technology, Gaithersburg, Maryland, July 1989. (Also: GRI-89/0229.)

McManus, S.E., Bateman, B.R., Brennan, J.A., Vasquez, I., and Mann, D., "The Decay of Swirling Gas Flow in Long Pipes," Paper 85-DT-S4, *Proceedings of the AGA Operating Section*, American Gas Association, Arlington, Virginia, 1985.

Mercenier, Preat, and Wauters, "Flowrate Measurement Using Orifice Plates In Non-Standardized Conditions," Internal Note No. 77251, Catholic University of Louvain, Belgium, 1977.

Morrow, T.B., and Park, J.T., "Installation Effects on Orifice Meter Performance," Topical Report to Gas Research Institute, Report No. GRI-93/0054.1, September 1993.

Morrow, T.B., "Orifice Meter Installation Effects: Sliding Vane Test With a 17 D Meter Tube and Alternative Flow Conditioner Designs Downstream of Tee," Technical Memorandum to Gas Research Institute, Report No. MRF-UE-13, May 1994.

Morrow, T.B., "Orifice Meter Installation Effects: Alternative Flow Conditioner Designs Tested in 45 D Meter Tube Downstream of a Tee, and 17 D Meter Tube Downstream of Double Out-Of-Plane Elbows," Technical Memorandum to Gas Research Institute, Report No. MRF-UE-14, August 1994.

Morrow, T.B., "GRI-97-0207, Technical Memorandum, Orifice Meter Installation Effects: Development of a Flow Conditioner Performance Test," December 1997.

Morrow, T.B., "GRI-97-0293, Technical Memorandum, "Orifice Meter Installation Effects: Effect of a Variable Spacer Length Between Two 90° Ells Out-of-Plane", February 1998.

Morrow, T.B., Park, J.T., and McKee, R.J., "Determination of Installation Effects for a 100 mm Orifice Meter Using a Sliding Vane Technique," *Journal of Flow Measurement and Instrumentation*, Vol. 2, No. 1, January 1991, pp. 14–20.

Morrison, G.L., Panak, D.L., and DeOtte, Jr., R.E., "Numerical Study of the Effects of Upstream Flow Condition upon Orifice Flow Meter Performance," 11th International Conference on Offshore Mechanics and Arctic Engineering, Calgary, Alberta, June 7–11, 1992, pp. 47–52.

Morrison, G.L., DeOtte, Jr., R.E., and Beam, E.J., "Installation Effects Upon Orifice Flowmeters," *Journal of Flow Measurement and Instrumentation*, Vol. 3, No. 2, 1992, pp. 89–93.

Morrison, G.L., Hall, K., Holst, J., Macek, M., Ihfe, L., and DeOtte, Jr., R.E., "Upstream Velocity Profile Effects Upon Orifice Flowmeters," *Journal of Flow Measurement and Instrumentation*, Vol. 5, No. 2, April 1994, pp. 87–92.

Murdock, J.W., Foltz, C.J., and Gregory, Jr., C., "Effect of a Globe Valve on Approach Piping on Orifice-Meter Accuracy," *ASME Transactions*, February 1956, p. 369.

Nagel, P.P., and Jaumotte, A.J., "Effect of Disturbances on the Flow Coefficient of a Standardized Orifice Plate: Experimental Study," *Thermiques et Aerauliques*, Vol. 7E, No. 1, March 1976.

Oshima, M., and Koyama, N., "Effect of Upstream Pressure Tapping on Flow Coefficients of Differential Head Type Flow-Meters," ISA, 1981.

Reader-Harris, M.J., Sattary, J.A., and Woodhead, E., "The Use of Flow Conditioners to Improve Flow Measurement Accuracy Downstream of Headers," Gas Research Institute Third International Symposium on Fluid Flow Measurement, San Antonio, Texas, March 20–22, 1995.

Reader-Harris, M. J., Woodhead, E. , Sattary, J. A., and McEwen, D., "Report on Flow Conditions Downstream of Headers," NEL Report to The Header Consortium, Report HCP001 (223/94), National Engineering Laboratory, Glasgow, Scotland, September 1995.

Sattary, J. A., "EEC Orifice Plate Programme—Installation Effects," *Journal of Flow Measurement and Instrumentation*, Vol. 2, No. 1, January 1991, pp. 14–20.

Sattary, J.A., "The Effects of Installations and Straighteners on the Discharge Coefficient of Orifice Plate Flowmeters," NEL Progress Report No. 10, National Engineering Laboratory, Glasgow, Scotland, March 1991.

Scott, J.L., Sindt, C.F., and Lewis, M.A., "Flow Conditioner Location Effects in Orifice Flowmeters," NIST Technical Note 1356, U.S. Department of Commerce, National Institute of Standards and Technology, Gaithersburg, Maryland, January 1993. (Also: GRI-92/0363.)

Shen, J.J.S., and Ting, V.C., "Velocity Profile Measurement in an Orifice Meter Calibration System for Natural Gas," *Proceedings of International Symposium on Fluid Flow Measurement*, American Gas Association, Arlington, Virginia, November 1986.

Sindt, C.F., Brennan, J. A., and McFaddin, S.E., "NBS Research on the Effects of Pipe Roughness and Flow Conditioners on the Orifice Discharge Coefficient," National Bureau of Standards, Boulder, Colorado, 1988.

Sindt, C.F., Lewis, M.A., and Brennan, J.A., "Orifice Meter Performance Downstream of a Tube Bundle Flow Conditioner, Elbows, and a Tee," NIST Technical Note 1344, U.S. Department of Commerce, National Institute of Standards and Technology, Gaithersburg, Maryland, December 1990. (Also: GRI-90/0343.)

Spearman, E.P., Sattary, J.A., Reader-Harris, M.J., and Rhodes, F.S., "The Effect of Upstream Installations on Orifice Meter Discharge Coefficients," NEL Flow Measurement Memo: FL/445, National Engineering Laboratory, Glasgow, Scotland, July 1995.

Sprenkle, R.E., "Piping Arrangements for Acceptable Flowmeter Accuracy," ASME Transactions, American Society of Mechanical Engineers, New York, July 1945.

Studzinski, W., Karnik, U., LaNasa, P., Morrow, T., Goodson, D., Husain, Z., and Gallagher, J., "White Paper on Orifice Meter Installation Configurations With and Without Flow Conditioners (also "Upstream Effects" paper)," API Chapter 14.3, Part 2, (AGA Report No. 3, Part 2) Working Group, December 5, 1997.

Studzinski, W., "Annex 1.0 to White Paper on Orifice Meter Installation Configurations With and Without Flow Conditioners, API Chapter 14.3, Part 2, (AGA Report No.3, Part2) Working Group," March 8, 1998.

Studzinski, W. , Karnik, U., LaNasa, P, Morrow, T., Goodson, D., Husain, Z., and Gallagher, J., "Revision of ANSI-2530 Orifice Standard—Basis of Recommended Meter Run Length," 4th International Symposium of Fluid Flow Measurements, Denver, Colorado, June 28–29, 1999.

Williamson, I.D., Botros, K.K., and. Price, G.R., "Flow Characteristics and Orifice Meter Error Caused by Upstream Headers in Multi-Run Meter Stations," Forum on Fluid Measurement and Instrumentation, ASME FED-Vol. 161, American Society of Mechanical Engineers, New York, 1993, pp. 1–11.

## 2-A.26 Sensing Taps

Allen, C.M., and Hooper, L.J., "Piezometer Investigation," *Transactions of ASME*, Vol. 54, Paper HYD 51-1, American Society of Mechanical Engineers, New York, 1932.

Beitler, S.R., "The Flow of Water Through Orifices," Bulletin 89, The Engineering Experiment Station, The Ohio State University, Columbus, Ohio, 1935.

Karnik, U., "Effects of Tap Size and Quality On Orifice Meter Performance," North Sea Flow Measurement Workshop, National Engineering Laboratory, Glasgow, Scotland, June 13–18, 1994.

Oshima, M., and Koyama, N., "Effect of Upstream Pressure Tapping on Flow Coefficients of Differential Head Type Flowmeters," ISA, 1981.

Zedan, M.F., and Teyssandier, R.G., "Effect of Errors in Pressure Tap Locations on the Discharge Coefficient of a Flange-Tapped Orifice Plate," *Journal of Flow Measurement and Instrumentation*, Vol. 1, No. 3, April 1990, pp. 141–148.

## 2-A.27 Meter Tubes

Stark, S., Foh, S., Caldwell, S, "White Paper: Orifice Meter Tube Specifications, API Chapter 14.3, Part 2, (AGA Report No.3, Part 2) Working Group," June 1997.

Zedan, M.F., and Teyssandier, R.G., "The Effects of Recesses and Protrusions on the Discharge Coefficient of a Flange-Tapped Orifice Plate," Technical Publication TP-13, Gas Processors Association, Tulsa, Oklahoma, 1985.

## 2-A.28 Flow Conditioner

Akashi, K., Watanabe, H., and Kenichi, K., "Development of a New Flow Rectifier for Shortening Upstream Straight Pipe Lengths for Flowmeters," Tokyo Flow Symposium, IMEKO, Paper 12b-5, Society of Instrumentation and Control, Tokyo, 1979, pp. 279–284.

Delanny, B., and Verstraete, Chr., "The Effectiveness of Perforated Plates Used as Flow Straighteners in Non-Symmetrical Flows," Applied Sciences Faculty, Department of Thermodynamics and Turbine Machines, Catholic University of Louvain, Belgium, 1977.

Erdal, A., "A Numerical Investigation of Different Parameters That Affect the Performance of a Flow Conditioner," *Journal of Flow Measurement and Instrumentation*, Vol. 8, No. 2, pp. 93–102.

Gallagher, J.E., LaNasa, P.J., and Beaty, R. E., "Development of Gallagher Flow Conditioner," FLOMEKO '94, 7th International Conference on Flow Measurement, National Engineering Laboratory, Glasgow, Scotland, June 1994.

Gallagher, J.E., and LaNasa, P.J., "Field Performance of the Gallagher Flow Conditioner," Gas Research Institute Third International Symposium on Fluid Flow Measurement, San Antonio, Texas, March 20–22, 1995.

Humphreys, J.S., and Hobbs, J.M. , "An Investigation of the Effectiveness of Flow Conditioners," *Proceedings of International Symposium on Fluid Flow Measurement*, American Gas Association, Arlington, Virginia, November 1986.

P. Jepson, and R. Chipchase, "The Performance of a Zanker Type Flow Straightener in Swirling Flow," British Gas Engineering Research Station Report R406, February 1973.

Karnik, U., "Measurements of the Turbulence Structure Downstream of a Tube Bundle at High Reynolds Numbers," *ASME Journal of Fluids Engineering*, Vol. 116, No. 4, American Society of Mechanical Engineers, New York, December 1994, pp. 848–855.

Karnik, U., "A Compact Orifice Meter/Flow Conditioner Package," Third International Symposium on Fluid Flow Measurement, San Antonio, Texas, March 20–22, 1995.

Lake, W.T., and Reed, J., "Optimal Flow Conditioner," Paper No. 1.3, North Sea Flow Measurement Workshop, National Engineering Laboratory, Glasgow, Scotland, October 1992.

Langsholt, M., and Erdal, A., "Design Parameters for Perforated Plate Flow Conditioners," FLOMEKO '98, June 15–17, 1998.

Laws, E.M., and Ouazzane, A.K., "A Further Evaluation of the Vaned Laws' Plate and Its Impact on Future Research," 1997 ASME Fluids Engineering Division Summer Meeting, June 22–26, 1997.

Laws, E.M., and Ouazzane, A.K., "The Design of Flow Control Devices," ASME FED-Vol. 221, Forum on Industrial and Environmental Applications of Fluid Mechanics, 1995.

Laws, E.M., and Livesey, J.L., "Flow Through Screens," *Annual Review of Fluid Mechanics*, Vol. 10, Annual Reviews Inc., Palo Alto, California, 1978, pp. 247–266.

Laws, E.M., "Flow Conditioning—A New Development," *Journal of Flow Measurement and Instrumentation*, Vol. 1, No. 3, April 1990, pp. 165–170.

Laws, E.M., and Ouazzane, A.K., "Effect of Plate Depth on the Performance of a Zanker Flow Straightener," *Journal of Flow Measurement and Instrumentation*, Vol. 3, No. 4, October 1992, pp. 257–269.

Laws, E.M., and Ouazzane, A.K., "Compact Installations for Orifice Plate Flow Meters," FLOMEKO '94, Seventh International Conference on Flow Measurement, National Engineering Laboratory, Glasgow, Scotland, June 13–17, 1994.

Laws, E.M., and Ouazzane, A.K., "Flow Conditioning for Orifice Plate Meters," Gas Research Institute Third International Symposium on Fluid Flow Measurement, San Antonio, Texas, March 20–22, 1995.

Laws, E.M., and Harris, R., "Evaluation of a Swirl-Vor-Tab Flow Conditioner," *Journal of Flow Measurement and Instrumentation*, Vol. 4, No. 2, April 1993, pp. 101–108.

Mickan, B., and Dopheide, D., "Systematic Investigations of the Efficiency of Flow Conditioners", FLOMEKO '98, June 15–17, 1998.

Morrow, T.B., and Behring II, K.A., "Effects of Swirl and Velocity Profile Asymmetry on Flow Conditioner Performance for Orifice Meters," FLOMEKO '98, June 15–17, 1998.

Reader-Harris, M.J., and Keegan, W., "Comparison of Computation and LDV Measurements of Flow Through Orifice and Perforated Plates, and Computation of the Effect of Rough Pipework on Orifice Plates," *Proceedings of International Symposium on Fluid Flow Measurement*, American Gas Association, Arlington, Virginia, November 1986.

Scott, J.L., and Lewis, M.A., "Flow Conditioner Tests for Three Orifice Flowmeter Sizes," NIST Technical Note 1367, U.S. Department of Commerce, National Institute of Standards and Technology, Gaithersburg, Maryland, May 1994. (Also: GRI-94/0096.)

Scott, J.L., Sindt, C.F., and Lewis, M.A., "Flow Conditioner Location Effects in Orifice Flowmeters," NIST Technical Note 1356, U.S. Department of Commerce, National Institute of Standards and Technology, Gaithersburg, Maryland, January 1993. (Also: GRI-92/0363.)

Scott, J.L., Sindt, C.F., and Lewis, M.A., and Brennan, J.A., "The Effects of Flow Conditioners and Tap Location on Orifice Flowmeter Performance," NIST Technical Note 1352, U.S. Department of Commerce, National Institute of Standards and Technology, Gaithersburg, Maryland, October 1991. (Also: GRI-91/0229.)

Sens, M., and Teule, C., "Etude Theorique et Experimentale d'un Noveau Redresseur d'ecoulement," Gaz de France, Paris, France, 1975.

Smid, J., "600 mm Orifice Plate Project, Part XIB: Flow Profile Measurements With Flow Straightener," NIST, Boulder, Colorado, and N. V. Nederlandse Gasunie, Groningen, NL, GRI Report No. GRI-88/0374.11B, December 1988.

Smith, C.R., Greco, J.J., and Hopper, P.B., "Low-loss Flow Conditioning for Flow Distortion/Swirl Using Concepts of Passive Vortex Generation Devices," Flow Measurement FLOMEKO, VDI Berichte 768, Germany, 1989, pp. 57–64.

Smith, C.R., Greco, J.J., and Hopper, P.B., "Low-loss Flow Conditioning Using Concepts of Passive Vortex Generation," Forum on Industrial & Agricultural Applications of Fluid Mechanics, ASME FED-Vol. 86, American Society of Mechanical Engineers, New York, 1989, pp. 59–63.

Smith, D.J., "The Effects of Flow Straighteners on Orifice Plates in Good Flow Conditions," Paper 5.3, *Proceedings of the International Conference on Flow Measurement in the Mid '80s*, National Engineering Laboratory, Glasgow, Scotland, June 1986.

Spearman, E.P., Sattary, J.A., and Reader-Harris, M.J., "A Study of Flow Through a Perforated-Plate/Orifice-Meter Package in Two Different Pipe Configurations Using Laser Doppler Velocimetry," *Journal of Flow Measurement and Instrumentation*, Vol. 2, No. 2, April 1991, pp. 83–88.

Spearman, E.P., Sattary, J.A., and Reader-Harris, M.J., "Comparison of Velocity Profiles Downstream of Perforated Plate Flow Conditioners," FLOMEKO '94, 7th International Conference on Flow Measurement, National Engineering Laboratory, Glasgow, Scotland, June 13–17, 1994.

Sprenkle, R.E., "Piping Arrangements for Acceptable Flowmeter Accuracy," *ASME Transactions*, American Society of Mechanical Engineers, New York, July 1945.

Sprenkle, R.E., and Courtright, N.S., "Straightening Vanes for Flow Measurement," Mechanical Engineering, American Society of Mechanical Engineers, New York, 1958, pp. 71–73.

Stuart, J.W., "Improvements in Flow Conditioner Design for Orifice Metering," AGA Distribution/Transmission Conference, Orlando, Florida, USA, May 1993.

Stuart, J.W., Park, J.T., and Morrow, T.B., "Experimental Results of an Improved Tube-Bundle Flow Conditioner for Orifice Metering," FLOMEKO '94, 7th International Conference on Flow Measurement, National Engineering Laboratory, Glasgow, Scotland, June 13–17, 1994.

Wilcox, P.L., Weberg, T., and Erdal, A., "Short Gas Metering Systems Using K-Lab Flow Conditioners," American Gas Association, 2nd International Symposium on Fluid Flow Measurement, Calgary, Alberta, June 6–8, 1990.

Zanker, K.J., "The Development of a Flow Straightener for Use with Orifice Plates in Disturbed Flows," Paper D-2, Symposium on Flow Measurement in Closed Conduits, Scotland, 1960.

## 2-A.29 Thermometer Wells

Bean, H.S., "Indications of an Orifice Meter," *American Gas Association Monthly*, July–Aug. 1947, p. 340.

Goldsmith, P.B., Botros, K.K., and Sawatzky, K.L., "Effect of Thermowell Location on Orifice Meter Accuracy," 1992 International Gas Research Conference, Orlando, Florida, November 16–19, 1992.

## 2-A.30 Pulsation Effects

Botros, K.K., Jungowski, W.M., and Studzinski, W., "On the Transfer Matrix of Orifice Plate with Flow," Noise-Con 88, Purdue University, West Lafayette, Indiana, June 20–22,1988.

Botros, K.K., Jungowski, W.M., and Petela, G., "Response of Gaugeline and DP Transmitter to Flow Pulsation Through Orifice Plate," Spring National Meeting of AIChE, Natural Gas Gathering and Transportation Session #101, New Orleans, March 29 – April 2, 1992.

Botros, K.K., Jungowski, W.M., and Petela, G., "Gauge Line Effects and DP Transmitter Response to Flow Pulsation Through Orifice Plate," *Journal of Flow Measurement and Instrumentation*, Vol. 3, No. 3, July 1992, pp. 130–144.

Gajan, P., Mottram, R.C., Hebrard, P., Andriamihafy, H., and Platet, B., "The Influence of Pulsating Flows on Orifice Plate Flowmeters," *Journal of Flow Measurement and Instrumentation*, Vol. 3, No. 3, July 1992, pp. 118–129.

Grenier, P., "Effects of Unsteady Phenomena on Flow Metering," *Journal of Flow Measurement and Instrumentation*, Vol. 2, No. 1, pp. 74–80, January 1991.

Husain, Z.D., and Teyssandier, R.G., "Effect of Flow-Induced Disturbances And The Frequency Response of Pressure Transducers on the Measurement of the Differential Pressure at the Flange Taps," ASME/Winter Annual Meeting, FE-1B Symposium on Differential Pressure Type Fluid Meters, New Orleans, December 1984. This was also published as a GPA Technical Publication TP-13.

Jungowski, W., and Petela, G., "Simulation of the Orifice Gauge Line Effect in Pulsating Flow," Canadian Acoustical Association Conference, Edmonton, Alberta, October 9–10, 1991.

Jungowski, W., Studzinski, W., and Szabo, J.L., "Orifice Meter Performance Under Pulsating Flow Conditions," Second International Symposium on Fluid Flow Measurement, Calgary, Alberta, June 6–8, 1990.

Jungowski, W.M., Botros, K.K., Studzinski, W., and Szabo, J.L., "Measuring the Transmission Characteristics of Pulsating Flows Through Orifice Plates and a Ball Valve," Measuring and Metering of Unsteady Flows—ASME FED-Vol. 40, American Society of Mechanical Engineers, New York, 1986.

McBrien, R.K., and Botros, K.K., "The Effect of Flow Pulsations on Mean Pressure Measurements Using Gaugelines," Gas Research Institute, 3rd International Symposium on Fluid Flow Measurement, San Antonio, Texas, March 20–22, 1995.

Studzinski, W., and Bowen, J., "White Paper: Dynamic Effects on Orifice Measurement, API Chapter 14.3, Part 2, Working Group," November 30, 1997.

Studzinski, W., Karnik, Geerligs, J., and McBrien, R., "GRI – 97/0378, Final Report, Pulsation Effects on 4-inch Orifice Meter Performance," November 1997.

Studzinski, W., Karnik, Geerligs, J., and McBrien, R., "Pulsation Effects on Orifice Meter Performance," FLOMEKO '98, June 15–17, 1998.

## 2-A.31 Miscellaneous

Bean, H.S., "Indications of an Orifice Meter," *American Gas Association Monthly*, July – August 1947, p. 340.

Bean, H.S., "Orifice Flanges," Letter to Paul La Nasa, May 2, 1980.

Beitler, S.R., "The Flow of Water Through Orifices," Bulletin 89, The Engineering Experiment Station, The Ohio State University, Columbus, Ohio, 1935.

Bosch, M., Grenier, P., Hebrard, P., and Klein, M., "Fundamental Study on the Flow Metering of Gases Using an Orifice Meter," 1992 International Gas Research Conference, April 1993, pp. 746–758.

Bosch, M., Donat, D., Strzeleck, A., Gajan, P., and Malard, L., "Study of Flows Encountered on Gas Networks and Their Influence on Flow Metering," 1994 World Gas Conference, June 1994.

Botros, K.K., Studzinski, W., and Barg, P., "Results of Nova's Gas Metering Research," Canadian Gas Association, Measurement School, Vancouver, May 26–29,1992.

Bower, J.R., "Backward Orifice Plate Causes Major Gas Flow Measurement Error," *Oil & Gas Journal*, Vol. 93, No. 33, August 14, 1995, pp. 43–44.

Brennan, J.A., McFaddin, S.E., Sindt, C.F., and Kothari, K.M., "Influence of Swirling Flow on Orifice and Turbine Flowmeter Performance," *Journal of Flow Measurement and Instrumentation*, Vol. 1, No. 1, October 1989, pp. 9–14.

Davis, R.W., and Mattingly, G.E., "Numerical Modeling of Turbulent Flow Through Thin Orifice Plates," National Bureau of Standards, Gaithersburg, Maryland, 1977.

DeOtte, Jr. R.E., Morrison, G.L., Panak, D.L., and Nail, G.H., "3-D Laser Doppler Anemometry Measurements of the Axisymmetric Flow Field Near an Orifice Plate," *Journal of Flow Measurement and Instrumentation*, Vol. 2, No. 2, pp. 115–123, 1991.

Durst, F., and Wang, A.B., "Experimental and Numerical Investigations of the Axisymmetric, Turbulent Pipe Flow Over a Wall Mounted Thin Obstacle," Seventh Symposium on Turbulent Shear Flows, *Proceedings*, Vol. 1, Stanford University, California, August 21–23, 1989, pp. 10.4.1–10.4.6.

Gajan, P., Hebrard, P., Millan,P., Giovannini, A., Al-Isber, A., Strzelecki, A., and Trichet, P., "Basic Study of Flow Metering of Fluids in Pipes Containing an Orifice Plate," Final Report, Gas Research Institute Contract No. 5086-271-1412, 1991.

Gallagher, J.E., and Beaty, R.E., "Orifice Metering Research—A User's Perspective," Paper No. 1.2, North Sea Flow Measurement Workshop, National Engineering Laboratory, Glasgow, Scotland, October 1992.

Ghazi, H.S., "A Pressure Index for Predicting the Effect of Flow Profiles on Orifice Meter Performance," *ASME Journal of Basic Engineering*, American Society of Mechanical Engineers, New York, pp. 93–100.

Gorter, J., "Investigation of the Flow Coefficient of a 600 mm Orifice Plate," 1989 International Gas Research Conference, pp. 334–343, April 1990.

Husain, Z.D., "The Effects of Abnormal Conditions of Orifice Meters," ISHM.

Kinghorn, F.C., "Flow Measurement in Swirling or Asymmetric Flow—A Review," *Flow-Con 77 Proceedings*, Institute of Measurement and Control, Gatton & Kent, England, 1977, pp. 45–71.

Langsholt, M., and Thomassen, D., "The Computation of Turbulent Flow Through Pipe Fittings and the Decay of the Disturbed Flow in a Downstream Straight Pipe," *Journal of Flow Measurement and Instrumentation*, Vol. 2, No. 1, pp. 45–55, January 1991.

Laufer, J., The Structure of Turbulence in Fully Developed Pipe Flow, NACA Report 1174, 1954.

McConaghy, B.J., Bell, D.G., and Studzinski, W., "How Orifice Plate Condition Affects Measurement Accuracy," *Pipeline Industry*, December 1989, pp. 21–26.

McLaughlin, D.K., and Tiederman, W.G., "Biasing Correction for Individual Realization of Laser Anemometer Measurement in Turbulent Flows," *The Physics of Fluids*, Vol. 16, pp. 2022–2088.

Mittal, R.C., and Sharma, P.K., "Numerical Solution of a Viscous Incompressible Flow Problem Through an Orifice," *Applied Scientific Research*, Vol. 44, 1987, pp. 361–375.

Morrison, G.L., "3-D Laser Anemometer Study of Compressible Fluid Flow Through Orifice Plates," Final Report to Gas Research Institute (September 1986 – December 1992), GRI Report No. GRI-93/0314, Chicago, April 1993.

Morrison, G.L., Panak, D.L., DeOtte, Jr., R.E., and Nail, G.H., "The Flow Fields Inside an Orifice Flow Meter," *Chemical Engineering Progress*, July 1990, pp. 75–80.

Morrison, G.L., DeOtte, Jr., R.E., Moen, M., Hall, K.R., and Holste, J.C., "Beta Ratio, Swirl, and Reynolds Number Dependence of Wall Pressure in Orifice Flowmeters," *Journal of Flow Measurement and Instrumentation*, Vol. 1., No. 5, 1990, pp. 279–277.

Morrison, G.L., DeOtte, Jr., R.E., Nail, G.H., and Panak, D.L., "Mean Velocity Field and Turbulence Characterization of the Flow in an Orifice Flow Meter," Fourth International Conference on Laser Anemometry, Advances and Applications, Cleveland, Ohio. Published in *Laser Anemometry Advances and Applications*, 1991 by ASME. Edited by A. Dybbs and B. Ghorashi, August 1991.

Morrison, G.L., Johnson, M.C., and Tatterson, G.B., "3-D Laser Anemometer Measurements in a Labyrinth Seal," Transactions of the ASME, *Journal of Engineering for Gas Turbines and Power*, Vol. 113, No. 1, January 1991, pp. 119–125.

Morrison, G.L., Johnson, M.C., Swan, D.H., and DeOtte, Jr., R.E., "Advantages of Orthogonal and Non-Orthogonal 3-Dimensional Anemometer Systems," *Journal of Flow Measurement and Instrumentation*, Vol. 2, No. 2, April 1991, pp. 89–97.

Nail, G.H., "A Study of 3-Dimensional Flow Through Orifice Meters," Ph.D. Dissertation, Texas A&M University, College Station, Texas, May 1991.

Norman, R.S., Mattingly, G.E., and McFaddin, S.E., "Decay of Swirl in Pipes," 1989 International Gas Research Conference, April 1990, pp. 312–321.

Panak, D.L., "3-D Laser Doppler Velocimetry Study of Incompressible Flow Through an Orifice Plate," M.S. Thesis, Texas A&M University, College Station, Texas, May 1990.

Patel, B.R., and Sheikholeslami, Z., "Numerical Modeling of Turbulent Flow Through Orifice Meters," Topical Report to Gas Research Institute, Report No. GRI-87/0315, March 1988.

Reader-Harris, M.J., and Sattary, J.A., "The Orifice Plate Discharge Coefficient Equation," *Journal of Flow Measurement and Instrumentation*, Vol. 1, January 1990.

Shen, J.J.S., and Ting, V.C., "Velocity Profile Measurement in an Orifice Meter Calibration System for Natural Gas," *Proceedings of International Symposium on Fluid Flow Measurement*, American Gas Association, Arlington, Virginia, November 1986.

Shen, J.J.S., and Ting, V.C., "Accuracy in Field Flow Measurement of Unprocessed Natural Gas," 1992 International Gas Research Conference, April 1993, pp. 723–732.

Shen, X., Yan, Y., Gao, J., and Ding, Z., "Turbulent Velocity Measurements in Orifice Pipe Flow with an Improved On-Axis 2-D LDV System," Fourth International Symposium on Applications of Laser Anemometry to Fluid Mechanics, Instituto Superior Tecnico, Av. Rovisco Pais, 1096 Lisboa Codex, Portugal, July 1988.

Steenbergen, W., and Voskamp, J., "The Rate of Decay of Swirl in Turbulent Pipe Flow," *Journal of Flow Measurement and Instrumentation*, Vol. 9 (1998), pp. 67–78.

Studzinski, W., Williamson, I., Jungowski, W., Botros, K., Sawchuk, B., and Strom, V., "NOVA's Gravimetric Meter Prover and Sonic Nozzle Facility," Canadian Gas Association, Measurement School, 1994.

Tennekes, H., and Lumley, J.L., *A First Course in Turbulence*, 12th ed., The MIT Press, Cambridge, Mass. and London, England, 1972, pp. 74–75.

Terrell, C.E., and Bean, H.S., (Editors), *AGA Gas Measurement Manual*, "Chapter X—Design of Meter and Regulator Stations," American Gas Association, Inc., 1963.

Teyssandier, R.G., and Husain, Z.D., "Experimental Investigation of an Orifice Meter Pressure Gradient," *ASME Journal of Fluids Engineering*, Vol. 109, No. 2, June 1987, pp. 144–148.

Teyssandier, R.G., and Wilson, Jr., M.P., "The Paradox of the Vena Contracta," ASME Paper 73-WA/FM-9, American Society of Mechanical Engineers, New York, December 1973.

Williamson, I.D., "Changes in Flow Through a Meter Station During Orifice Plate Changes," *Proceedings of the Sixth International Conference on Flow Measurement* (FLOMEKO '93), Seoul, Korea, 1993.

Williamson, I.D., Sawchuk, B.D., and Karnik, U., "The NOVA Meter Prover," Gas Research Institute, Third International Symposium on Fluid Flow Measurement, San Antonio, Texas, March 20–22, 1995.

# APPENDIX 2-B—ORIFICE METER INSPECTION GUIDELINES

Note: This appendix is not a part of this standard but is included for informational purposes only.

The following outline is intended to provide guidelines for preparing an orifice meter inspection checklist. The outline is provided so that uniformity may be achieved in what is to be inspected. The format of the checklist is left to the user, according to company preference. Although all the items listed may not be required at every inspection, the checklist should provide the pertinent information.

Note that the outline may not include all of a particular user's required information. The minimal information specified in the outline provides a basis for evaluating the quality of the meter run and orifice plate at the time of inspection.

I. Header

- A. Company name.
- B. Date of inspection.
- C. Tube location.
- D. Flow direction.
- E. Names of inspector(s) and witness(s).
- F. Any other information required.

II. General Information

- A. Serial number.
- B. Nominal pipe diameter.
- C. Fluid measured: gas or liquid (specify name).
- D. β-ratio limitations.

III. Meter Tube

- A. Type of orifice holder: flanges or fitting; single- or dual-chamber.
- B. Manufacturer.
- C. Serial number.
- D. Straightening vanes? Yes or no; if yes:
  - 1. Type of vane.
  - 2. How fastened? Pinned, welded, or flanged.
  - 3. Dimensions.
  - 4. Dimensional and quality specifications per AGA Report No.3, Part 2: pass or fail.
- E. Meter run type: single tube or multiple tube.
- F. Installation type (see Figure 2-6 and Table 2-7 or 2-8).
- G. Dimensional data:
  - 1. Length (see Figure 2-6 and Table 2-7 or 2-8).
  - 2. Upstream and downstream diameters (at least four measurements at each location):
    - a. Upstream pressure tap (also calculate the average of these values).
    - b. Downstream pressure tap.
    - c. First pipe connection.
    - d. Second pipe connection.
- H. Temperature of tube at time of measurement.
- I. Meter tube quality: cleanliness and measured roughness upstream and downstream.
- J. Average tube inside diameter at 68°F, as stamped on pipe or nameplate.
- K. Inside tube diameter used in flow computer, for calculations and data processing.

IV. Pressure Taps

- A. Orientation of primary differential pressure transducer connection (looking from inlet to outlet of meter tube).
- B. Location of static pressure transducer connection: upstream, downstream, or none.
- C. Number of differential pressure connections.
- D. Pressure tap size: 3.8 inch, 1.2 inch, or other.

E. Measured distance from centerline of tap hole to orifice plate surface, both upstream and downstream.
F. Condition of tap hole edge on inside diameter of meter run.
G. Manifold: manufactured or fabricated on site; full bore or restricted bore; three valves, five valves, or other.
H. Gauge line length.

V. Other Instrumentation

A. Measurement data on other tap connections made to the meter tube: size, location, and orientation.
B. Temperature probe: type and location.
C. Densitometer: manufacturer and type; insertion or sample line; size; inlet or outlet location.
D. Sampler: manufacturer and type; sample line size; inlet or outlet location.
E. Composition/energy analyzers: type; sample line size; inlet or outlet location.

VI. Orifice Plate Centering-Type

A. Flange: plate alignment (pins, male/female, other, or none).
B. Fitting:
   1. Measurement from plate edge to pipe wall on primary pressure tap side.
   2. Measurement from plate edge to pipe wall on opposite side pressure tap.
   3. Half the difference between 1 and 2 above.
   4. Measurement from plate edge to pipe wall perpendicular to primary tap.
   5. Measurement from plate edge to pipe wall opposite to measurement in 4 above.
   6. Half the difference between 4 and 5 above.

VII. Orifice Fitting Leak Test (After Hydrostatic Testing)

A. Measurement of seat width.
B. Measurement of seal width.
C. Difference between A and B above.
D. Results of pressure tap leak test.
E. Results of plate bypass leak test.
F. Type of seal and material of construction.

VIII. Orifice Plate Inspection

A. Type of plate.
B. Material of construction.
C. Manufacturer.
D. Stamped (nominal) diameter at 68°F.
E. Edge sharpness: sharp or dull.
F. Plate flatness: flat or bent (measured departure from flatness).
G. Measured roughness of plate surface.
H. Any surface film patterning for plates just removed from service?
I. Micrometer measurement of at least four inside diameters of the orifice bore.
J. Average value of the measurements in I above.
K. Measured plate thickness.
L. Other data pertinent for identification.
M. Temperature at which plate was measured.
N. Names of inspector(s) and witness(es) and date, if not the same as for meter tube.
O. Is plate beveled or unbeveled? Bevel angle?

# APPENDIX 2-C—SPECIFIC INSTALLATION CALIBRATION TEST

Note: This Appendix is an inherent part of this standard.

Installation calibration tests can be performed for an orifice meter with a specific upstream fitting with or without a specific flow conditioner located at a defined position within the meter.

For the installation tests performed at the actual field installation, if the discharge coefficient values of the test data are within the uncertainty limits ($\pm 2\sigma$) of the 95% confidence level of the RG equation, the RG equation can be used to calculate the flow rate through the meter. If the test results deviate from the RG equation by more than the uncertainty limits of $\pm 2\sigma$, actual test results as a function of the Reynolds number should be used to calculate the flow rate through the meter.

For an installation test at a test facility different from the actual site, a Baseline Calibration (Section 2-C.1) and the Calibration Test (Section 2-C.2) must be performed. The Baseline Calibration should be performed with a meter tube that conforms to mechanical tolerances specified in Section 2.5. Preferably, the baseline test and the calibration test should be performed at the same Reynolds number range, β-ratio range, and line size as used in the field application. If the calibration test discharge coefficient values deviate from the baseline by more than one-half of the uncertainty limits of the RG equation, the actual calibration data as a function of Reynolds number must be used to calculate the flow rate through the meter. If the calibration test discharge coefficient values are within one half of the uncertainty limits of the 95% confidence level of the RG equation, then the RG equation can be used to calculate the flow rate through the meter. If the actual line size and/or the operating Reynolds number range cannot be achieved at the test facility, the test criteria and the setup for the baseline test and the installation calibration tests are described below.

The following are general guidelines and acceptance criteria of the Specific Installation Calibration Test:

a. For line sizes greater than 10 inches, a 10-inch meter can be tested to ascertain the installation effect; but the test installations must maintain geometric similarity to the actual field installation.

b. For line sizes less than or equal to 10 inches, it is preferred that the test be performed on the actual line size. For the line sizes 6 inches $\leq D_n \leq$ 10 inches, the test may be performed on a line that is one nominal size smaller than the actual line size.

c. For a geometrically similar installation on multiple line sizes, baseline and calibration test results of a 4-inch and an 8-inch line can be used for all line sizes.

d. For a test facility failing to achieve the operating Reynolds number range, tests must be performed at two different Reynolds numbers. The low Reynolds number test must be between $10^4$ to $5 \times 10^5$; and the high Reynolds number test must be at $10^6$ or higher. The ratio of the high-to-low Reynolds numbers must be 5 or greater. In the test with a flow conditioner installed, however, the range of Reynolds numbers and their ratios has to be determined from the rules specified in the Reynolds number sensitivity test in Appendix 2-D. The test results are then valid for any Reynolds number application.

e. If the highest Reynolds number achieved during the test is less than $10^6$, the validity of the test results are limited to the highest Reynolds number of the test.

f. If the same installation is to be used for multiple β-ratio plates, tests should be performed for the largest and the smallest β-ratio plates. If the results for the two β-ratio tests are valid, the whole β-ratio range is valid.

g. If any β-ratio test results (high or low) of the multiple β-ratio test fail to meet the performance criteria, then the test results are limited to the results of actual β-ratio plate tested; or new limits may be established by performing additional tests.

## 2-C.1 Baseline Calibration

A baseline (reference) calibration should be performed using the same orifice plate that will be used in the installation calibration test.

a. The baseline calibration should be performed at approximately the same value of Reynolds number as the installation calibration test.

b. The β ratio(s) for the test must be the same as the orifice plate(s) specific installation test(s).

c. The baseline calibration should be performed using a meter tube with a minimum straight upstream meter-tube length of $70D_i$. The flow at the entrance to the meter tube must be swirl-free (less than 2 degree swirl angle).

d. Baselines using large pipe diameters (16 inches and 24 inches) may prove to be difficult to perform due to space limitations in most laboratories. An alternative baseline configuration of a minimum of $45D_i$ and an oversized Sprenkle flow conditioner is acceptable. The oversized Sprenkle design must conform to that specified in NIST Technical Note 1264, or to ISO 5167, and one NPS larger.

e. To prove that the mechanical baseline configuration is valid, the baseline *Cd* values should lie within the 95% confidence interval for the RG equation.
f. To minimize the effects of instrumentation bias errors, the same measuring equipment should be used in both the baseline test and the calibration test.

## 2-C.2 Calibration Test

If possible, the test should be performed on the actual installation. If the test is performed on a replicated test setup, the same quality meter tube should be used. The test fixture must duplicate the pipefitting or installation immediately upstream of the orifice plate, including the location of a flow conditioner, if used, and the piping installations within 5*Di* downstream of the orifice plate. Any pipefitting or piping change in the field installation, that is within 25*Di* upstream of the piping installation that is being tested, must be duplicated for the calibration test. Any piping installation of the test facility upstream of the test setup must be followed by a flow conditioner, e.g., 1998 Uniform Concentric 19-Tube Bundle Flow Straightener, and must be at a minimum distance of 30*Di* from the inlet of the installation test setup being calibrated. The orifice meter must be calibrated at a minimum of four different pipe Reynolds numbers, of which one must be at ± 5% of the minimum, and another at ± 5% of the maximum of the baseline-test Reynolds-number range of the meter. The meter should be tested for the minimum and maximum β-ratio plates that are to be used in the field. The diameter ratio β in the field installation will be restricted to the maximum and minimum β-ratio limits of the calibration test. If the deviations (*Cd*) of the discharge coefficient data from the baseline are within the one-half-of uncertainty limits, ± 2σ of the RG equation, as defined in AGA Report No.3, Part 1, the actual flow rate can be calculated by using the RG equation. If the *Cd* data are beyond the one-half-of-uncertainty limits of ± 2σ of the RG equation, the actual calibration data of the discharge coefficient (*Cd*) as a function of Reynolds number, must be used to calculate the flow rate through the meter.

# APPENDIX 2-D—FLOW CONDITIONER PERFORMANCE TEST

Note: This Appendix is an inherent part of this standard.

The objective of performance tests for a flow conditioner is to prove that a tested device meets performance criteria within the specified tolerance limits for any type of piping installation upstream of the orifice meter at one line size and for a narrow range of Reynolds numbers (Test D1) or for all line sizes and Reynolds numbers (Test D2). This objective is broader than for a calibration test (Appendix 2-C), which deals with a specific type of an upstream installation of interest to the user.

Both types of flow conditioner performance tests contain the following common elements:

Test 1: Baseline Calibration—evaluating performance of the test facility.

Test 2: Good Flow Conditions—test evaluating impact of flow conditioner on fully developed velocity profile.

Test 3: Two 90-degree Elbows in Perpendicular Planes—testing of flow conditioner performance in handling a combination of a modest swirl (up to 15-degree swirl angle) and a nonsymmetrical velocity profile.

Test 4: Gate Valve 50% Closed—test evaluating flow conditioner performance in a strongly nonsymmetrical velocity profile.

Test 5: High Swirl—test assessing flow conditioner performance in flows with high swirl angle (more than 25 degrees).

The facility baseline has to meet acceptance criteria specified below and the results of Tests 2 through 5 will be evaluated in terms of the normalized deviation ($\Delta C_d$) between the measured discharge coefficient and the baseline discharge coefficient at the same β-ratio and Reynolds number.

There are two types of flow conditioner performance tests:

**D1.** *Application Test.* Approves the use of a flow conditioner for any type of upstream installation; however, just for the tested line size and a narrow range of Reynolds numbers associated with the tested β-ratio range and differential pressure range used. For these conditions, the five tests specified must be performed.

**D2.** *Type Approval Test.* Approves use of a tested flow conditioner for any type of upstream installation, any line size, and any Reynolds number. Such a broad approval of the flow conditioner applications requires performance of Tests 1 through 5 within the parameter ranges prescribed in equations 2-D.A and 2-D.B:

$$10^4 \le Re_l \le 10^6 \text{ and } Re_h \ge 10^6 \quad \text{such that} \tag{2-D.A}$$

a) for $\beta = 0.67 \Rightarrow f(Re_l) - f(Re_h) \ge 0.0036$

or b) for $\beta = 0.75 \Rightarrow f(Re_l) - f(Re_h) \ge 0.0030$

$Re_l$ is the low Reynolds number,

$Re_h$ is the high Reynolds number,

$f$ is the pipe friction factor obtained from (i) or (ii),

(i) the Colebrook-White equation

$$1/\sqrt{f} = 1.74 - 2\log_{10}\left[\,6.3\,R_a/D + 18.7\,/\,(Re_D\sqrt{f})\right],$$

(ii) the Moody diagram

$R_a$ is the absolute average roughness of meter tube.

$$D_i \le 4 \text{ inches and } D_i \ge 8 \text{ inches} \tag{2-D.B}$$

The following selection of tests must be performed:

Test a) *Disturbance.* Tests 1 through 5 for one Reynolds number range and at one pipe diameter selected from (2-D.A) and (2-D.B). The full sequence of β-ratio selection is defined in Section 2-D.1.

Test b) *Scaling.* Test 1, and one of the Tests 3 through 5, must be conducted using two pipe sizes (preferably at one pipe size as in Test a) selected from two prescribed diameter ranges in (2-D.B). Each pipe size test must be conducted at the same Reynolds number (preferably the one as in Test a) or at a Reynolds number chosen from the prescribed ranges in (2-D.A). To demonstrate scalability, the results from the two pipe sizes must demonstrate that, in both cases, the flow conditioner meets the specified performance criteria for the same meter tube lengths, UL and UL2. Selection of β-ratio should follow the procedure described in Section 2-D.1.

Test c) *Reynolds Number Sensitivity.* Test 1, and one of Tests 2 through 5, must be conducted, preferably at one of the pipe sizes used in Test b), and at two Reynolds numbers selected for a chosen pipe diameter and pipe roughness, in such a way that the condition (2-D.A) is fulfilled for β = 0.67 only; β = 0.75 may be used instead, if desired.

Example: A laboratory decides to use hydraulically smooth pipes, and selects $Re_h$ = 1.02 x $10^6$. At the Reynolds number, Moody diagram gives $f(Re_h) = 0.0116$. The Reynolds number sensitivity test will be conducted at β= 0.67; therefore, $f(Re_l) = f(Re_h) + 0.0036 = 0.0116 + 0.0036 = 0.0152$. This value of the friction factor corresponds to $Re_l$= 2.31 x $10^5$ for a smooth pipe at the Moody diagram. The tests can be conducted at the same facility, because $Re_h / Re_l$= 4.4 will not result in excessively high or low pressure differentials across the orifice plate.

The selection of two Reynolds numbers for Test c) requires use of an implicit formula or Moody diagram that may result in the ratio of Reynolds number even as low as 4 in facilities operating on liquids, and even higher than 10 in the facilities operating on high-pressure gas.

If the selected Reynolds number in Test a) is equal to or larger than 3 x $10^6$, and the manufacturer or user of the flow conditioner is seeking an approval for applications in the range $Re$ 3 x $10^6$, then the Test c) can be skipped.

In both types of performance tests, the use of the flow conditioner is restricted to those locations within the meter run where the $\Delta C_D$ of the tested flow conditioner was one-half of the uncertainty limits ± 2σ of RG equation.

An installation and/or flow conditioner test should be performed for values of upstream meter tube length and/or flow conditioner location that are appropriate for the installation. If desired, a sliding or fixed position flow conditioner test can be performed for a range of flow conditioner locations for one or more upstream meter tube lengths.

## 2-D.1 Orifice β Ratio

If it is known that an installation or a flow conditioner is successful in removing swirl from the downstream flow, then it is possible to limit the range of β ratios used in the performance test. However, if swirl is not removed by the installation and/or flow conditioner, it would be misleading and erroneous to rely on a single value of β to gauge the installation or flow conditioner's performance. It is recommended that either Test 3 or Test 5 be performed first for β = 0.40 and β = 0.67. If the $\Delta C_D$ values for both values of β are negligible, or if $\Delta C_D$ varies approximately as $\beta^{3.0}$ to $\beta^{4.0}$, then it can be concluded that swirl in the meter tube is not a significant influence. In this case, it is recommended that the other installation or flow conditioner performance tests be performed for a single value of β = 0.67. If the installation or flow conditioner passes the test for β = 0.67, experience shows that it will also pass the test for lower values of β. If the flow conditioner passes the test for β = 0.67, it can also be tested at a higher value of β, if desired.

If swirl effects are not removed by the installation and/or flow conditioner at β = 0.40 and β = 0.67, Test 3 and Test 5 will have to be performed for a complete range of β values between β = 0.20 and β = 0.75.

## 2-D.2 Meter Tube Length and Flow Conditioner Location

Some flow conditioners that were designed to comply with a particular flow meter standard may be retrofitted into existing meter tubes. In this case, the flow conditioner should be installed at the appropriate location, and its performance evaluated in a meter tube of the appropriate length. If the field meter tube was designed to comply with the AGA Report No.3, Part 2, 1991 revision, Figure 2-5—"Partly Closed Valve Upstream of Meter Tube," the flow conditioner performance should be evaluated in a meter tube with an upstream length of $17D_i$, with the flow conditioner located at UL2 = $7.5D_i$ upstream of the orifice plate. If the field meter tube was designed to comply with the ISO 5167 standard, the flow conditioner performance should be evaluated in a meter tube with an upstream length of $45D_i$, with the flow conditioner located at UL2 = $22D_i$ upstream of the orifice plate. Alternatively, if the field meter tube is significantly longer than the minimum recommended length (e.g., some natural gas transmission companies have meter tubes with an upstream length of UL = $25D_i$ to $29D_i$, and install a tube bundle straightening vane at UL2 = $12D_i$ upstream of the orifice plate), the performance test should be performed with the same installation conditions.

The flow conditioner performance test can be performed for more than one meter tube length, and for more than one flowconditioner location, if desired.

## 2-D.3 Test 1: Baseline Calibration

A baseline (reference) calibration should be performed using the same orifice plates and β-ratios that will be used in the application or type approval test(s) (D1 or D2).

a. The baseline should be performed using a meter tube with a minimum straight upstream meter tube length of $70D_i$. There must be swirl-free (less than 2 degree swirl angle) flow at the entrance to the $70D_i$ meter tube.

b. Baselines using large pipe diameters (16 inches and 24 inches) may prove to be difficult to perform because of space limitations in most laboratories. An alternative baseline configuration of a minimum of $45D_i$ and an oversized Sprenkle flow conditioner are acceptable. The oversized Sprenkle design must conform to that specified in NIST Technical Note 1264, or to ISO 5167, and one NPS larger.

c. To prove that the mechanical baseline configuration is valid, the baseline $C_d$ values should lie within the 95% confidence interval for the RG equation.

d. To minimize the effects of instrumentation bias errors, the same measuring equipment should be used in both the baseline test and Tests 2 through 5.

## 2-D.4 Test 2: Good Flow Conditions

This test is recommended to show that the installation or flow conditioner does not degrade the measurement performance of a meter tube under good (baseline) flow conditions. The upstream length of the meter tube or the flow conditioner location may be specified as appropriate for a retrofit installation. Otherwise, a sliding or fixed position flow conditioner test may be performed.

## 2-D.5 Test 3: Two 90-Degree Elbows in Perpendicular Planes

This test ensures that the installation or flow conditioner can remove normal amounts of swirl and provide good performance in a double out-of-plane elbow installation. The spacing between the exit plane of the first elbow and the entry plane of the second elbow should not exceed two pipe diameters. Since the out-of-plane elbows will produce swirl in the meter tube, the flow entering the first elbow should be swirl-free.

## 2-D.6 Test 4: Gate Valve 50% Closed

This test ensures that the installation or flow conditioner can accept a highly asymmetric profile of axial velocity without degradation of measurement performance. The 50% closed valve should be the primary source of the velocity profile asymmetry. Therefore, the velocity profile of the flow approaching the valve should be symmetric and swirl-free. In the flow conditioner performance tests, a full-bore gate valve was used. The gate was modified so that 50% of the flow area was blocked when the gate was lowered. The gate had to be raised to allow a sliding flow conditioner to enter the meter tube downstream of the valve.

For an evaluation of the performance of a flow conditioner at a fixed location, it is possible to substitute a segmented orifice plate mounted between two flanges for the gate valve. The segmented plate should block 50% of the flow through the meter tube. A segmented plate is employed in the high-level perturbation test described in the ISO/DIS 9951 standard for gas turbine meter installations. The open area of the plate should be adjacent to one of the orifice pressure tap pairs. The closed area of the plate should be adjacent to the pressure tap pairs on the opposite side of the orifice fitting.

## 2-D.7 Test 5: High Swirl

This test is recommended when the meter tube will be installed downstream of a header that may produce large axial swirl angles. The objective of the test is to prove that the flow conditioner is effective in high-swirl environments. The Chevron axial vane swirler is effective in generating a solid body type of rotation, with a linear distribution of swirl angle from near zero on the pipe centerline to a maximum value of 30 degrees near the pipe wall. The design of the Chevron swirler is as follows:

The basic design consists of a hub of 1.5 inches (38 millimeters) in diameter and 6 inches (152 millimeters) in length. The hub has a streamlined parabolic nose facing upstream and a blunt base [corner radius approximately 0.1 inch (2.5 millimeters)] facing downstream. The hub is supported and centered by struts from the stainless steel housing wall.

Ten vanes or blades are attached to the hub by shafts that pass through the housing wall and allow individual adjustment of each blade's angle. Outside the housing, a protractor is fitted to each shaft. The vanes can be rotated by turning the shaft from outside the housing. The degree of rotation is read from the affixed vernier. The thickness of each blade 0.2 inch (5 millimeters) is milled to a tapered profile to streamline the flow when the blades are aligned in the axial direction.

The Chevron swirler used in the installation and/or flow conditioner performance tests verification has a nominal diameter of 6 inches. With reducer fittings attached to front and back, it performed well in tests with $D_i$ = 4-inch pipe. For larger diameter pipe (8-inch, 10-inch or 16-inch) it will be necessary to design and fabricate a larger diameter device. If another swirl-generating device is used in place of the Chevron swirler, the swirl-generator device should produce a swirl angle of at least ± 24 degrees at a distance of $17D_i$. Confirmation of the swirl angle is to be obtained by measurement using an appropriate technique; for example, a multi-hole Pitot tube. The setting of the vane angle on the swirler is not considered to be a measure of the swirl angle at the location of the meter.

# APPENDIX 2-E—MAXIMUM ALLOWABLE ORIFICE PLATE DIFFERENTIAL PRESSURE

Note: This Appendix is an inherent part of this standard.

The following tables provide the calculated maximum allowable differential pressure limits for orifice plate thickness.

Table 2-E-1—Maximum Allowable Calculated Differential Pressure Across 304/316SS Orifice Plate at 150°F

| | 2" | | 3" | | 4" | | 6" | | | | 8" | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0.125 plate | | 0.125 plate | | 0.125 plate | | 0.125 plate | | 0.125 plate | | 0.1875 plate | | 0.250 plate | | 0.3125 plate | | |
| | Fitting | Flange | Fitting | Flange | Fitting | Flange | Fitting | Flange | Fitting | Flange | Fitting | Flange | Fitting | Flange | Fitting | Flange | |
| β-Ratio | In. $H_2O$ | In. $H_2O$ | In. $H_2O$ | In. $H_2O$ | In. $H_2O$ | In. $H_2O$ | In. $H_2O$ | In. $H_2O$ | In. $H_2O$ | In. $H_2O$ | In. $H_2O$ | In. $H_2O$ | In. $H_2O$ | In. $H_2O$ | In. $H_2O$ | In. $H_2O$ | β-Ratio |
| 0.20 | 1000[a] | 1000[a] | 1000[a] | 1000[a] | 1000[a] | 1000[a] | 480 | 1000[a] | 1000[a] | 1000[a] | 205 | 1000[a] | 1000[a] | 1000[a] | 1000[a] | 1000[a] | 0.20 |
| 0.25 | 1000[a] | 1000[a] | 1000[a] | 1000[a] | 1000[a] | 1000[a] | 440 | 1000[a] | 1000[a] | 1000[a] | 190 | 1000[a] | 1000[a] | 1000[a] | 1000[a] | 1000[a] | 0.25 |
| 0.30 | 1000[a] | 1000[a] | 1000[a] | 1000[a] | 1000[a] | 1000[a] | 405 | 1000[a] | 1000[a] | 1000[a] | 175 | 1000[a] | 1000[a] | 1000[a] | 1000[a] | 1000[a] | 0.30 |
| 0.35 | 1000[a] | 1000[a] | 1000[a] | 1000[a] | 1000[a] | 1000[a] | 385 | 1000[a] | 1000[a] | 1000[a] | 165 | 1000[a] | 1000[a] | 1000[a] | 1000[a] | 1000[a] | 0.35 |
| 0.40 | 1000[a] | 1000[a] | 1000[a] | 1000[a] | 1000[a] | 1000[a] | 365 | 1000[a] | 1000[a] | 1000[a] | 160 | 1000[a] | 1000[a] | 1000[a] | 1000[a] | 1000[a] | 0.40 |
| 0.45 | 1000[a] | 1000[a] | 1000[a] | 1000[a] | 1000[a] | 1000[a] | 350 | 1000[a] | 1000[a] | 1000[a] | 155 | 1000[a] | 1000[a] | 1000[a] | 1000[a] | 1000[a] | 0.45 |
| 0.50 | 1000[a] | 1000[a] | 1000[a] | 1000[a] | 1000[a] | 1000[a] | 345 | 1000[a] | 1000[a] | 1000[a] | 150 | 1000[a] | 1000[a] | 1000[a] | 1000[a] | 1000[a] | 0.50 |
| 0.55 | 1000[a] | 1000[a] | 1000[a] | 1000[a] | 1000[a] | 1000[a] | 345 | 1000[a] | 1000[a] | 1000[a] | 150 | 1000[a] | 1000[a] | 1000[a] | 1000[a] | 1000[a] | 0.55 |
| 0.60 | 1000[a] | 1000[a] | 1000[a] | 1000[a] | 1000[a] | 1000[a] | 345 | 1000[a] | 1000[a] | 1000[a] | 150 | 1000[a] | 1000[a] | 1000[a] | 1000[a] | 1000[a] | 0.60 |
| 0.65 | 1000[a] | 1000[a] | 1000[a] | 1000[a] | 1000[a] | 1000[a] | 355 | 1000[a] | 1000[a] | 1000[a] | 155 | 1000[a] | 1000[a] | 1000[a] | 1000[a] | 1000[a] | 0.65 |
| 0.70 | 1000[a] | 1000[a] | 1000[a] | 1000[a] | 1000[a] | 1000[a] | 375 | 1000[a] | 1000[a] | 1000[a] | 165 | 1000[a] | 1000[a] | 1000[a] | 1000[a] | 1000[a] | 0.70 |
| 0.75 | 1000[a] | 1000[a] | 1000[a] | 1000[a] | 1000[a] | 1000[a] | 395 | 1000[a] | 1000[a] | 1000[a] | 180 | 1000[a] | 1000[a] | 1000[a] | 1000[a] | 1000[a] | 0.75 |

Table 2-E-1—Maximum Allowable Calculated Differential Pressure Across 304/316SS Orifice Plate at 150°F (continued)

| | 10" | | | | | | | | 12" | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0.125 plate | | 0.1875 plate | | 0.250 plate | | 0.3125 plate | | 0.1875 plate | | 0.250 plate | | 0.3125 plate | | 0.375 plate | | |
| | Fitting | Flange | Fitting | Flange | Fitting | Flange | Fitting | Flange | Fitting | Flange | Fitting | Flange | Fitting | Flange | Fitting | Flange | |
| β-Ratio | In. $H_2O$ | In. $H_2O$ | In. $H_2O$ | In. $H_2O$ | In. $H_2O$ | In. $H_2O$ | In. $H_2O$ | In. $H_2O$ | In. $H_2O$ | In. $H_2O$ | In. $H_2O$ | In. $H_2O$ | In. $H_2O$ | In. $H_2O$ | In. $H_2O$ | In. $H_2O$ | β-Ratio |
| 0.20 | 100 | 545 | 335 | 1000[a] | 800 | 1000[a] | 1000[a] | 1000[a] | 175 | 1000[a] | 420 | 1000[a] | 820 | 1000[a] | 1000[a] | 1000[a] | 0.20 |
| 0.25 | 90 | 555 | 310 | 1000[a] | 735 | 1000[a] | 1000[a] | 1000[a] | 160 | 1000[a] | 385 | 1000[a] | 755 | 1000[a] | 1000[a] | 1000[a] | 0.25 |
| 0.30 | 85 | 585 | 285 | 1000[a] | 680 | 1000[a] | 1000[a] | 1000[a] | 150 | 1000[a] | 355 | 1000[a] | 700 | 1000[a] | 1000[a] | 1000[a] | 0.30 |
| 0.35 | 80 | 640 | 270 | 1000[a] | 640 | 1000[a] | 1000[a] | 1000[a] | 140 | 1000[a] | 335 | 1000[a] | 655 | 1000[a] | 1000[a] | 1000[a] | 0.35 |
| 0.40 | 75 | 725 | 255 | 1000[a] | 610 | 1000[a] | 1000[a] | 1000[a] | 130 | 1000[a] | 315 | 1000[a] | 620 | 1000[a] | 1000[a] | 1000[a] | 0.40 |
| 0.45 | 70 | 850 | 245 | 1000[a] | 590 | 1000[a] | 1000[a] | 1000[a] | 125 | 1000[a] | 300 | 1000[a] | 595 | 1000[a] | 1000[a] | 1000[a] | 0.45 |
| 0.50 | 70 | 1000[a] | 240 | 1000[a] | 575 | 1000[a] | 1000[a] | 1000[a] | 120 | 1000[a] | 295 | 1000[a] | 575 | 1000[a] | 995 | 1000[a] | 0.50 |
| 0.55 | 70 | 1000[a] | 240 | 1000[a] | 570 | 1000[a] | 1000[a] | 1000[a] | 120 | 1000[a] | 290 | 1000[a] | 565 | 1000[a] | 980 | 1000[a] | 0.55 |
| 0.60 | 70 | 1000[a] | 240 | 1000[a] | 575 | 1000[a] | 1000[a] | 1000[a] | 120 | 1000[a] | 285 | 1000[a] | 560 | 1000[a] | 970 | 1000[a] | 0.60 |
| 0.65 | 70 | 1000[a] | 245 | 1000[a] | 590 | 1000[a] | 1000[a] | 1000[a] | 120 | 1000[a] | 290 | 1000[a] | 565 | 1000[a] | 980 | 1000[a] | 0.65 |
| 0.70 | 75 | 1000[a] | 255 | 1000[a] | 615 | 1000[a] | 1000[a] | 1000[a] | 125 | 1000[a] | 295 | 1000[a] | 575 | 1000[a] | 1000[a] | 1000[a] | 0.70 |
| 0.75 | 80 | 1000[a] | 275 | 1000[a] | 655 | 1000[a] | 1000[a] | 1000[a] | 125 | 1000[a] | 305 | 1000[a] | 595 | 1000[a] | 1000[a] | 1000[a] | 0.75 |

Table 2-E-1—Maximum Allowable Differential Pressure Across 304/316SS Orifice Plate at 150°F (continued)

| | 16" | | | | | | | | 20" | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0.250 plate | | 0.375 plate | | 0.4375 plate | | .500 plate | | 0.250 plate | | 0.3125 plate | | 0.375 plate | | 0.4375 plate | | 0.500 plate | | |
| | Fitting | Flange | Fitting | Flange | Fitting | Flange | Fitting | Flange | Fitting | Flange | Fitting | Flange | Fitting | Flange | Fitting | Flange | Fitting | Flange | |
| β-Ratio | In. $H_2O$ | In. $H_2O$ | In. $H_2O$ | In. $H_2O$ | In. $H_2O$ | In. $H_2O$ | In. $H_2O$ | In. $H_2O$ | In. $H_2O$ | In. $H_2O$ | In. $H_2O$ | In. $H_2O$ | In. $H_2O$ | In. $H_2O$ | In. $H_2O$ | In. $H_2O$ | In. $H_2O$ | In. $H_2O$ | β-Ratio |
| 0.20 | 200 | 1000[a] | 690 | 1000[a] | 1000[a] | 1000[a] | 1000[a] | 1000[a] | 100 | 640 | 200 | 1000[a] | 345 | 1000[a] | 550 | 1000[a] | 825 | 1000[a] | 0.20 |
| 0.25 | 185 | 1000[a] | 630 | 1000[a] | 1000[a] | 1000[a] | 1000[a] | 1000[a] | 90 | 650 | 185 | 1000[a] | 320 | 1000[a] | 505 | 1000[a] | 755 | 1000[a] | 0.25 |
| 0.30 | 170 | 1000[a] | 585 | 1000[a] | 930 | 1000[a] | 1000[a] | 1000[a] | 85 | 685 | 170 | 1000[a] | 295 | 1000[a] | 470 | 1000[a] | 700 | 1000[a] | 0.30 |
| 0.35 | 160 | 1000[a] | 545 | 1000[a] | 870 | 1000[a] | 1000[a] | 1000[a] | 80 | 750 | 160 | 1000[a] | 275 | 1000[a] | 440 | 1000[a] | 655 | 1000[a] | 0.35 |
| 0.40 | 150 | 1000[a] | 515 | 1000[a] | 820 | 1000[a] | 1000[a] | 1000[a] | 75 | 850 | 150 | 1000[a] | 260 | 1000[a] | 415 | 1000[a] | 620 | 1000[a] | 0.40 |
| 0.45 | 145 | 1000[a] | 495 | 1000[a] | 785 | 1000[a] | 1000[a] | 1000[a] | 70 | 995 | 145 | 1000[a] | 250 | 1000[a] | 395 | 1000[a] | 595 | 1000[a] | 0.45 |
| 0.50 | 140 | 1000[a] | 480 | 1000[a] | 760 | 1000[a] | 1000[a] | 1000[a] | 70 | 1000[a] | 140 | 1000[a] | 240 | 1000[a] | 385 | 1000[a] | 575 | 1000[a] | 0.50 |
| 0.55 | 135 | 1000[a] | 470 | 1000[a] | 745 | 1000[a] | 1000[a] | 1000[a] | 70 | 1000[a] | 135 | 1000[a] | 235 | 1000[a] | 380 | 1000[a] | 565 | 1000[a] | 0.55 |
| 0.60 | 135 | 1000[a] | 465 | 1000[a] | 740 | 1000[a] | 1000[a] | 1000[a] | 70 | 1000[a] | 135 | 1000[a] | 235 | 1000[a] | 375 | 1000[a] | 560 | 1000[a] | 0.60 |
| 0.65 | 135 | 1000[a] | 465 | 1000[a] | 740 | 1000[a] | 1000[a] | 1000[a] | 70 | 1000[a] | 135 | 1000[a] | 235 | 1000[a] | 375 | 1000[a] | 565 | 1000[a] | 0.65 |
| 0.70 | 140 | 1000[a] | 475 | 1000[a] | 755 | 1000[a] | 1000[a] | 1000[a] | 70 | 1000[a] | 140 | 1000[a] | 240 | 1000[a] | 385 | 1000[a] | 575 | 1000[a] | 0.70 |
| 0.75 | 140 | 1000[a] | 485 | 1000[a] | 775 | 1000[a] | 1000[a] | 1000[a] | 70 | 1000[a] | 145 | 1000[a] | 250 | 1000[a] | 395 | 1000[a] | 595 | 1000[a] | 0.75 |

Table 2-E-1—Maximum Allowable Differential Pressure Across 304/316SS Orifice Plate at 150°F (continued)

| | 24" | | | | | | | | | | 30" | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0.250 plate | | 0.375 plate | | 0.4375 plate | | 0.500 plate | | 0.5625 plate | | 0.375 plate | | 0.4375 plate | | 0.500 plate | | 0.5625 plate | | |
| | Fitting | Flange | Fitting | Flange | Fitting | Flange | Fitting | Flange | Fitting | Flange | Fitting | Flange | Fitting | Flange | Fitting | Flange | Fitting | Flange | |
| β-Ratio | In. $H_2O$ | In. $H_2O$ | In. $H_2O$ | In. $H_2O$ | In. $H_2O$ | In. $H_2O$ | In. $H_2O$ | In. $H_2O$ | In. $H_2O$ | In. $H_2O$ | In. $H_2O$ | In. $H_2O$ | In. $H_2O$ | In. $H_2O$ | In. $H_2O$ | In. $H_2O$ | In. $H_2O$ | In. $H_2O$ | β-Ratio |
| 0.20 | 60 | 360 | 215 | 1000[a] | 340 | 1000[a] | 510 | 1000[a] | 725 | 1000[a] | 105 | 610 | 170 | 965 | 255 | 1000[a] | 365 | 1000[a] | 0.20 |
| 0.25 | 55 | 365 | 195 | 1000[a] | 310 | 1000[a] | 465 | 1000[a] | 665 | 1000[a] | 95 | 615 | 155 | 980 | 235 | 1000[a] | 335 | 1000[a] | 0.25 |
| 0.30 | 50 | 385 | 180 | 1000[a] | 290 | 1000[a] | 435 | 1000[a] | 615 | 1000[a] | 90 | 650 | 145 | 1000[a] | 215 | 1000[a] | 310 | 1000[a] | 0.30 |
| 0.35 | 50 | 420 | 170 | 1000[a] | 270 | 1000[a] | 405 | 1000[a] | 580 | 1000[a] | 85 | 710 | 135 | 1000[a] | 205 | 1000[a] | 290 | 1000[a] | 0.35 |
| 0.40 | 45 | 480 | 160 | 1000[a] | 260 | 1000[a] | 385 | 1000[a] | 550 | 1000[a] | 80 | 805 | 130 | 1000[a] | 195 | 1000[a] | 275 | 1000[a] | 0.40 |
| 0.45 | 45 | 560 | 155 | 1000[a] | 250 | 1000[a] | 370 | 1000[a] | 530 | 1000[a] | 75 | 945 | 125 | 1000[a] | 185 | 1000[a] | 265 | 1000[a] | 0.45 |
| 0.50 | 45 | 690 | 150 | 1000[a] | 240 | 1000[a] | 360 | 1000[a] | 515 | 1000[a] | 75 | 1000[a] | 120 | 1000[a] | 180 | 1000[a] | 260 | 1000[a] | 0.50 |
| 0.55 | 45 | 880 | 150 | 1000[a] | 240 | 1000[a] | 360 | 1000[a] | 510 | 1000[a] | 75 | 1000[a] | 120 | 1000[a] | 180 | 1000[a] | 255 | 1000[a] | 0.55 |
| 0.60 | 45 | 1000[a] | 150 | 1000[a] | 240 | 1000[a] | 360 | 1000[a] | 510 | 1000[a] | 75 | 1000[a] | 120 | 1000[a] | 180 | 1000[a] | 255 | 1000[a] | 0.60 |
| 0.65 | 45 | 1000[a] | 155 | 1000[a] | 245 | 1000[a] | 365 | 1000[a] | 520 | 1000[a] | 75 | 1000[a] | 120 | 1000[a] | 185 | 1000[a] | 265 | 1000[a] | 0.65 |
| 0.70 | 45 | 1000[a] | 160 | 1000[a] | 250 | 1000[a] | 385 | 1000[a] | 540 | 1000[a] | 80 | 1000[a] | 125 | 1000[a] | 190 | 1000[a] | 270 | 1000[a] | 0.70 |
| 0.75 | 50 | 1000[a] | 165 | 1000[a] | 265 | 1000[a] | 400 | 1000[a] | 570 | 1000[a] | 85 | 1000[a] | 135 | 1000[a] | 200 | 1000[a] | 285 | 1000[a] | 0.75 |

[a] Although the structural integrity of the flange mounting will allow calculated values for the maximum orifice plate differential pressures in excess of 1000 inches of water, the coefficient of discharge database is limited to 1000 inches of water.

Assumptions for determining maximum differential pressures across orifice plates in orifice fittings:

1. Support diameter ($D_s$) is 0.2 inches less than outside orifice plate diameter.
2. Internal diameter ($D$) is the largest diameter in Table 2-4 of AGA Report No. 3 (API *MPMS* Chapter 14.3, Part 2).
3. Maximum differential values are for orifice plates at a flowing temperature less than or equal to 150°F ($T_f \leq 150°F$).

Note: Measurement uncertainty is increased if the ratio of the differential to static pressure (both expressed in psia) exceeds 0.2 or 20%. Care should be taken to not violate the recommendations or tolerances stated in Table 2-3 and Appendix 2-E.

American Gas Association

# Engineering Technical Note

PREPARED BY OPERATING SECTION
*Transmission Measurement Committee,*
*Differential Pressures Above 100 Inches Water Column —Task Group*
400 N. Capitol St., N.W., 4th Floor
Washington, D.C. 20001
U.S.A.
Phone: 202-824-7000
Fax: 202-824-7082
Web site: www.aga.org

## Guidelines for Using High Differential Pressures for Measuring Natural Gas with Orifice Meters

This technical note contains reference information for the use of differential pressures above 100 inches water column with orifice meters, including the effects of orifice plate deflection, discharge coefficient equation, expansion factor, tap hole location and seal ring leakage.

This document is to be used in conjunction with
*AGA Report No. 3/API Chapter 14.3, Orifice Metering of Natural Gas and Other Related Hydrocarbon Fluids.*

## FOREWORD

This Engineering Technical Note provides guidelines for the use of high differential pressure orifice flow measurement to be used in conjunction with the AGA Report No. 3, Orifice Metering of Natural Gas and Other Related Hydrocarbon Fluids. This document addresses several technical issues with respect to using differential pressures higher than 100 inches water column (w.c.), such as the effects of plate deflection, discharge coefficient, expansion factor, change in tap hole location and seal ring leakage.

When this document is used with AGA Report No. 3, readers will be able to operate confidently orifice fitting at differential pressures of 150 to 1000 inches w.c., depending on plate geometry. This will result in significant capacity increases and reduce the cost of building new and/or expanding existing metering facilities. The document also highlights items to be cautious of, including higher meter run velocities and permanent pressure loss.

Revisions to this manual may become necessary from time to time. Whenever any revisions are deemed advisable, recommendations should be forwarded to the *American Gas Association*. A form is included for that purpose at the end of this manual. To purchase additional copies of this standard, contact: *AGA Distribution Center*, P.O. Box 79230, Baltimore, MD 21279-0230; Fax: (301) 206-9789; Phone: (301) 617-7819.

# ACKNOWLEDGEMENTS

This Technical Note is the result of contributions from the members of the AGA Transmission Measurement Committee —Differential Pressure Above 100 Inches Water Column (W.C.) Task Group, Chaired by Michael T. Brown, TransCanada Transmission. The Past Chair of this task group, Philip P. Barg, TransCanada Transmission, initiated and made significant effort in the development of this document. Much of the information contained within this document is based on the valuable work and efforts of the NOVA Research & Technology Centre, in particular the efforts of Umesh Karnik.

Others who contributed and need to be recognized are:

Ed B. Bowles, Southwest Research Institute
Paul T. Brunton, Southern California Gas Company
Cary Carter, Williams Gas Pipeline
Peter A. Cistaro, PSE&G
Fred de Busk, Daniel Measurement and Control
Jeffery M. Dowdell, CNG Transmission Corporation
Brian Elliott, NICOR Gas
Jim Gallagher, Savant Measurement Corp.
Dale Goodson, Daniel Measurement and Control
Don W. Griffies, Perry Equipment Corporation
Danny G. Harris, Columbia Gas Transmission
Zaki Husain, Texaco
Fred Kaczor, UGI Utilities
Paul LaNasa, CPL & Associates
John Lansing, formerly of Instromet, Inc.
George E. Mattingly, NIST
Kevin M. Moir, Michigan Consolidated Gas Co.
Tom Morrow, Southwest Research Institute
John R. Naber, Daniel Measurement and Control
Warren Peterson, Kenonic Controls
Henry Poellnitz, Southern Natural Gas
Ali Quraishi, American Gas Association
Joe Ranney, Southern California Gas Company
Tushar K. Shah, Eagle Research Corporation
John Stuart, Pacific Gas and Electric Company
Jim Witte, Tennessee Gas Pipeline Company
James F. Wunderlin, Southwest Gas Corporation

Lori Traweek, Vice President
Operating & Engineering Section
American Gas Association

## CONTENTS

## 2-F.1 Introduction

The Transmission Measurement Committee of the American Gas Association submits the following reference information for measuring natural gas with orifice meters with differential pressures above 100 inches of water column (w.c.). The purpose of this document is to provide discussion of the significant technical issues regarding the use of high differential pressures, and provide formal recommendations to be applied to existing or future orifice metering facilities.

## 2-F.2 Scope

This document is to be used in conjunction with AGA Report No. 3, *Orifice Metering of Natural Gas and Other Related Hydrocarbon Fluids* (also published as API MPMS Chapter 14.3, and ANSI 2530). It is intended to be used as an operating guideline, not as a standard.

A number of technical issues have been addressed with respect to using differential pressures higher than 100 inches w.c. with simply-supported, flange-tapped orifice meters. These topics include the effects of orifice plate deflection, the discharge coefficient equation, expansion factor, change in tap hole location, and seal ring leakage.

## 2-F.3 Background

Until the 1970s, orifice measurement of natural gas according to AGA Report No. 3 was typically limited to maximum differential pressures of 100 inches w.c. The meters used mercury manometers to record differential pressure, and this equipment was not generally used for differentials above 100 inches w.c. With the advent of dry flow meters in the 1970s, it became possible to measure higher differentials, generally limited to 200 inches w.c., and this was done by some companies.

These limits were primarily due to:

❐ High diameter ratio plates ($\beta$ from 0.60 to 0.75) could be used to achieve higher capacity, therefore there was little incentive to go to higher differential ranges;

❐ The original Ohio State orifice coefficient data was based on relatively thick, flange held plates, whose resistance to flexing is much higher than fitting-held plates. Also, there was not a lot of operating data to support the use of higher differentials;

❐ A gas company's existing calibration equipment did not typically support higher differential pressures; and

❐ Chart processing with a wide range of differential pressures was more prone to errors than processing a limited number of ranges.

During the late 1980s, with the advent of electronic measurement, more flexibility was available to users of orifice meters, since flow is calculated at the meter. In addition, the use of high diameter ratio plates (0.60 to 0.75) is now understood to increase measurement uncertainty. Some studies were initiated to investigate the effect of high differential measurement on accuracy, so that diameter ratios less than 0.6 could be used to measure higher volumetric flow rate. Additional work was then completed to develop operating guidelines for the use of high differential pressures.

## 2-F.4 Symbols

This document contains the following symbols which are in general, technical use for orifice flow measurement applications.

| Symbol | Represented Quantity |
|---|---|
| $\beta$ | Ratio of orifice plate bore diameter to meter tube internal diameter ($d/D$) |
| $\beta_s$ | Ratio of orifice plate bore diameter to the orifice plate support diameter ($d/D_s$) |
| $\delta\theta_d$ | Fractional change in the orifice plate deflection angle, $\theta_d$ |
| $\delta C_c$ | Fractional change in contraction coefficient, $C_c$ |
| $\delta d$ | Fractional change in orifice bore diameter, $d$ |
| $\delta m$ | Fractional change in mass flow rate, $m$ |
| $\theta_d$ | Angle of orifice plate deflection ($\theta_d = 90°$ when plate is perpendicular to pipe axis) |
| $\sigma$ | Mechanical stress |
| $\Delta P$ | Orifice differential pressure |
| $A$ | Area of orifice bore |
| $C_c$ | Contraction coefficient—the ratio of the area of the vena contracta to the area of the orifice bore |
| $C_d$ | Orifice plate coefficient of discharge |
| $d$ | Orifice plate bore diameter calculated at flowing temperature, $T_f$ |
| $D$ | Meter tube internal diameter calculated at flowing temperature, $T_f$ |
| $D_s$ | Orifice plate support diameter |

| | |
|---|---|
| $E$ | Orifice plate thickness |
| $E^*$ | Modulus of elasticity of orifice plate material |
| °F | Temperature, in degrees Fahrenheit |
| $k$ | Stress coefficient |
| $k_1, k_2, k_3$ | Numerical coefficients for the calculation of the contraction coefficient, $C_c$ |
| $k_d$ | Deflection coefficient |
| $m$ | Mass flow rate |
| $\rho$ | Density |
| $P$ | Static pressure |
| $T_f$ | Temperature at flowing conditions |
| $y$ | Maximum deflection of orifice plate |
| $y_L$ | Orifice plate deflection limit |

## 2-F.5 Plate Deflection

As the differential pressure across the orifice increases, the plate is elastically deformed. Beyond a certain point, this deformation will result in a shift in the characteristics of the meter, resulting in increased measurement uncertainty.

A simply-supported model of an orifice fitting (Figure 2F.5-1a.) can be used to define the maximum allowable differential pressure, based on elastic deformation. This limit is dependent upon the thickness ($E$), support diameter ($D_s$), and the diameter ratio ($\beta$). This relationship demonstrates that for a given diameter ratio, the allowable differential pressure is a function of the ratio of support diameter to plate thickness ($D_s/E$). The maximum amount of plate deflection due to elastic deformation can be approximated using the following equation:

$$y = \frac{k_d \Delta P D_s^{\,4}}{16 E^* E^3} \qquad \text{(2-F.5-1)}$$

The value for the deflection coefficient ($k_d$) is a function of diameter ratio ($\beta$), and can be obtained from tables in *Mark's Standard Handbook* [12].

The tolerance for orifice plate flatness is specified in AGA Report No. 3, Part II [1]. However, the tolerance is specified for static conditions only. AGA Report No. 3, Part II [1] does not specify a flatness (deflection) tolerance for when a differential pressure is applied across an orifice plate. As a reasonable limit, it is recommended to use the same flatness limit for dynamic conditions as is already specified for static conditions, as shown in Equation (2-F.5-2). Therefore, under dynamic conditions, the maximum deviation from flat could be as much as twice the recommended static limit for a given orifice plate geometry.

$$y_L = 0.005(D - d) \qquad \text{(2-F.5-2)}$$

Analysis of linear elastic theory and orifice metering shows that the contraction coefficient ($C_c$) will increase, and that the orifice plate bore diameter ($d$) will change with an increase in differential pressure ($\Delta P$) across the orifice plate.

## 2-F.6 Flow Equation Analysis

The total error in orifice metering due to high differential pressure and elastic deformation can be obtained by evaluating the common form of the mass flow rate through an orifice, as shown in Equation (6-1). This form of the orifice metering equation is derived from the Bernoulli equation and the continuity equation [3,10,11].

$$m = C_c \frac{A}{\sqrt{1 - C_c^2 \beta^4}} \sqrt{2\rho \Delta P} \qquad \text{(2-F.6-1)}$$

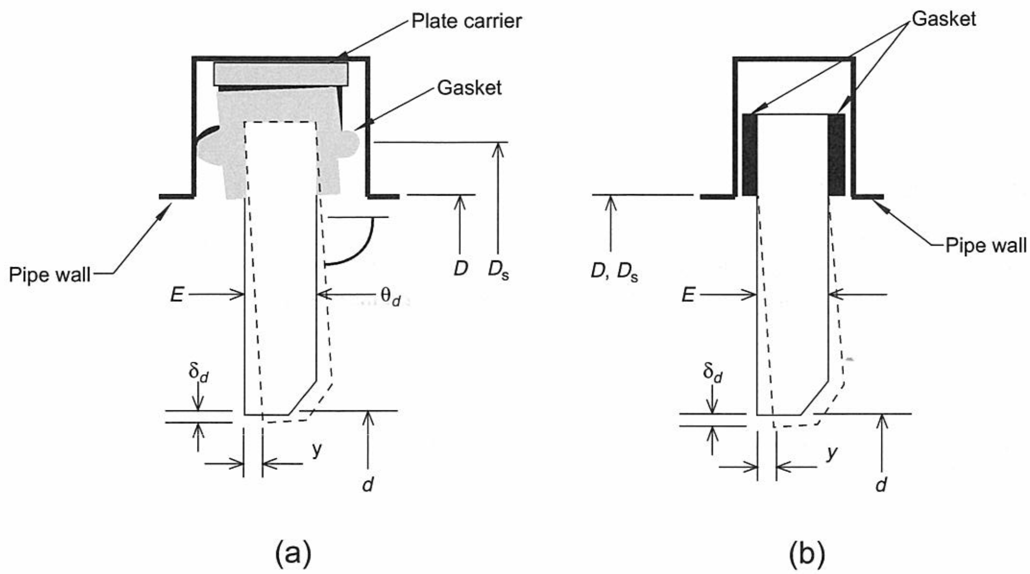



Figure 2F.5-1—Models of (a) Simply-Supported Orifice Plate, and (b) Flange-held (Clamped) Orifice Plate Showing Plate Deflection

Through the evaluation of the partial differential equations, the relative error in terms of mass flow rate is given by:

$$\frac{\delta m}{m} = \frac{1}{\left[1 - C_c^2 \beta^4\right]} \frac{\delta C_c}{C_c} + 2\frac{\delta d}{d} \tag{2-F.6-2}$$

Therefore, the focus of the equation analysis will be on changes in the contraction coefficient ($\delta C_c$) and the orifice plate bore diameter ($\delta d$) caused by plate deflection.

Addendum 1 provides an example analysis using the above method to determine the expected error introduced by high differential pressures.

### 2-F.6.1 ORIFICE PLATE BORE DIAMETER (*d*)

It has been shown[10], for plate deflection less than twice the thickness of the orifice plate ($E$), the orifice bore diameter ($d$), at the upstream edge, reduces slightly. This reduction in the orifice bore diameter will result in a larger pressure drop across the orifice plate and, therefore, an over estimation of the flowrate.

The decrease in bore diameter has been quantified using two methods, the first relates the change to lateral stress due to normal loading and is shown in the following equation [10]:

$$\frac{\delta d}{d} = -\frac{\sigma}{E} = -\frac{k \Delta P D_s^2}{4 E^* E^2} \tag{2-F.6-3}$$

Where the stress coefficient ($k$) is determined by the following equation [12]:

$$k = 2.75086 - 2.67169 \times \beta_s \tag{2-F.6-4}$$

The fractional change in the orifice bore diameter can also be quantified using the geometry of the deflected plate as [5]:

$$\frac{\delta d}{d} = \frac{E\delta\theta_d}{d} \tag{2-F.6-5}$$

### 2-F.6.2 CONTRACTION COEFFICIENT ($C_C$)

The contraction coefficient ($C_c$) is the ratio of the area of the vena contracta to the area of the orifice bore. For orifice plate deflections in the direction of flow, the contraction coefficient ($C_c$) increases [10]. An increase in the contraction coefficient implies that the gas equation would tend to under estimate the flow. The contraction coefficient may be represented by the equation:

$$C_c = k_1 + k_2\theta_d + k_3\theta_d^2 \tag{2-F.6-6}$$

In equations (2-F.6-5) and (2-F.6-6), $\theta_d$ is in radians. The fractional change in contraction coefficient can be estimated by differentiating equation (2-F.6-6) as:

$$\delta C_c = (k_2 + 2k_3\theta_d)\delta\theta_d \tag{2-F.6-7}$$

Values for $k_1$, $k_2$, and $k_3$ in equations (2-F.6-6) and (2-F.6-7) are shown in Table 2-F.6-1[10] for various diameter ratios (β).

Table 2-F.6-1—Coefficients for Contraction Coefficient Equation at Various Diameter Ratios (β)

| | Coefficients | | |
|---|---|---|---|
| Diameter Ratio (β) | $k_1$ | $k_2$ | $k_3$ |
| 0.7 | 0.895 | −0.190986 | 0.0372862 |
| 0.6 | 0.908 | −0.225363 | 0.0437708 |
| 0.5 | 0.923 | −0.257831 | 0.0510659 |
| 0.4 | 0.934 | −0.278203 | 0.0543082 |
| 0.3 | 0.944 | −0.294118 | 0.0567399 |
| 0.2 | 0.948 | −0.300485 | 0.0567400 |

## 2-F.7 Discharge Coefficient Equation

The discharge coefficient (Cd) equation was developed from test data that included differential pressures up to 400 inches w.c. on flange-held (clamped) orifice plates with special "o" ring gaskets that provide better support than a fitting-held plate. Subsequent testing up to 1000 in w.c. has shown that the equation is valid to considerably higher differential pressures on some run sizes, provided other assumptions are valid. The primary assumptions are that the differential pressure (psi) to static pressure (psi) ratio does not exceed 0.20, and that the plate is not deformed beyond a certain prescribed maximum (see previous section).

## 2-F.8 Expansion Factor

The expansion factor is an empirical factor that corrects for the difference between compressible and incompressible fluids, as described in Section 3.4.6 of AGA Report No. 3, Part III[1]. The expansion factor is valid for differential pressures ($\Delta P$) up to 20% of the operating pressure ($P$). When using high differential pressures, especially at lower operating pressures (below 700 psig, or 5000 kPa), the ratio of $\Delta P$ to $P$ should be checked to ensure that the limit of 0.20 is not exceeded. The ratio of $\Delta P$ to $P$ can also significantly affect the uncertainty of the expansion factor. The expansion factor uncertainty, and how it relates to $\Delta P$ and $P$, is described in Section 1.12.4.2 of AGA Report No. 3, Part I[1].

## 2-F.9 Tap Hole Location

On some size meters, it is possible to use a thicker plate than the orifice fitting was designed for by altering the design of the gasket. This may allow higher differential pressures to be used without other modifications.

Research conducted on eight inch diameter fittings[8,9] has shown that a change of 1/16 inches (1.6 mm) in the effective tap hole locations does not significantly affect measurement uncertainty. This change in tap hole location is within the original allowable variance in pressure tap hole location, as defined in AGA Report No. 3, Part II[1], for diameter ratios up to 0.65. However, this is not allowed due to Section 2.5.4.1 of the AGA Report No. 3, Part II[1] without re-drilling of the tap holes. It will be recommended that this statement be modified in a future revision of AGA Report No. 3 to allow thicker plates in the cases properly supported by research data.

## 2-F.10 Seal Ring Leakage

Operating at high differential pressures can magnify problems associated with an imperfect match between the gasket and the sealing surface. This can be caused by such things as: a damaged gasket, a damaged or improperly machined sealing surface, or a mismatch between the sealing surface and gasket.

Note: At high pressures, orifice fittings have been known to distort, resulting in leaks that were not present at atmospheric pressure.

Often leaks caused by a small imperfection will seal at high differential pressures due to the force on the orifice plate. Testing for leaks in the orifice seal can be done in-situ, or during manufacturing and fabrication. Orifice fitting manufacturers can provide details on testing procedures.

## 2-F.11 Conclusions

Using differential pressures higher than 100 inches wc (25 kPa) can significantly reduce the costs for expansion of certain meter stations, as well as the cost of new orifice metering facilities. Higher differential pressures can also reduce the need to use high diameter ratios ($\beta$ over 0.60), which have been shown to increase measurement uncertainty.

Operators should be aware, for a given orifice plate size, that when there is a wide swing from high to low flows, significant measurement errors will occur during the low flow period if the orifice plate is left unchanged. It is generally accepted that operation between 10% and 90% of the calibrated differential span is considered good practice. Rangeability can also be increased using today's digital (electronic) transmitters. The effects on the accuracy of transducers and/or transmitters used for wide range should be evaluated versus installation cost savings.

Orifice fitting manufacturers should be consulted to determine the maximum allowable differential pressure during the changing of orifice plates under flowing conditions. The high forces associated with using high differential pressures may make it difficult to remove, and possibly damage, the orifice plate.

Higher differential pressures will result in higher meter run gas velocities and higher permanent pressure losses. It is recommended that the gas velocities be evaluated on a individual installation basis for such things as noise, erosion, and thermowell vibration. The meter run velocity is dependent on several different factors, and each individual user will have different practices and limits on velocity. Higher permanent pressure losses should also be evaluated, and may result in the need for additional compression. Therefore, the following allowable maximum differential pressures do not consider meter run gas velocity and permanent pressure losses.

Table 2-F.11-1 shows the maximum allowable differential pressures for various sizes of orifice meter fittings. These limits are based on limiting the amount of elastic deflection of the orifice plate as described in Section 2-F.5. Based on the error analysis approach described in Section 2-F.6, these differential pressures will not result in changes in measurement greater than ± 0.1%.

Table 2-F.11-1—Maximum Allowable Differential Pressures for Commonly Used Sizes of Simply Supported Orifice Fittings

| Nominal Size | Plate Thickness | | $D_s/E$ Ratio | 316 Stainless and Carbon Steel | | Monel | |
|---|---|---|---|---|---|---|---|
| | in. | mm | | in. wc | kPa | in. wc | kPa |
| 2 | 0.125 | 3.2 | 17 | 1000[a] | 250 | 1000[a] | 250 |
| 3 | 0.125 | 3.2 | 25 | 1000[a] | 250 | 1000[a] | 250 |
| 4 | 0.125 | 3.2 | 32 | 1000[a] | 250 | 1000[a] | 250 |
| 6 | 0.125 | 3.2 | 49 | 345 | 85 | 315 | 79 |
| 8 | 0.125 | 3.2 | 65 | 150 | 38 | 140 | 35 |
| 8 | 0.250 | 6.4 | 32 | 1000[a] | 250 | 1000[a] | 250 |
| 10 | 0.250 | 6.4 | 41 | 570 | 143 | 530 | 133 |
| 12 | 0.250 | 6.4 | 48 | 285 | 71 | 265 | 66 |
| 16 | 0.250 | 6.4 | 61 | 135 | 34 | 125 | 31 |
| 16 | 0.375 | 9.5 | 41 | 465 | 116 | 430 | 108 |
| 20 | 0.375 | 9.5 | 51 | 235 | 59 | 230 | 58 |
| 24 | 0.375 | 9.5 | 62 | 150 | 38 | 140 | 35 |
| 24 | 0.500 | 12.7 | 47 | 360 | 90 | 330 | 83 |
| 30 | 0.500 | 12.7 | 59 | 180 | 45 | 165 | 41 |

Assumptions:

1. Support diameter ($D_s$) is 0.2 inches less than the outside orifice plate diameter.
2. Internal diameter ($D$) is the largest diameter in Table 2-4 of AGA Report No. 3, Part II [1].
3. Maximum differential is calculated for worst-case diameter ratio (typically ß between 0.5 and 0.6). Other diameter ratios may be able to go to higher differential pressures.
4. Maximum differential values are for orifice plates at a flowing temperature less than or equal to 150°F ($T_f \leq 150$°F).

[a]All calculated maximum differential pressures greater than 1000 in. water column have been reduced to a maximum of 1000 in. water column due to limitations in the coefficient of discharge database.

Notes:
1. See Addendum 2 for an expanded set of data for 316 stainless steel orifice plates.
2. Ensure differential pressure to operating pressure ratio does not exceed 0.20 (see Section 2-F.8).

# ADDENDUM 1—ERROR ANALYSIS EXAMPLE

The following example steps through the analysis of the error due to plate deflection for the mass flow rate through a simply supported orifice plate (316 stainless steel).

| | | |
|---|---|---|
| $D$ | Internal pipe diameter | 8.071 in. |
| $D_s$ | Orifice plate support diameter | 8.237 in. |
| $d$ | Orifice plate bore diameter | 4.500 in. |
| $E$ | Orifice plate thickness | 0.125 in. |
| $\Delta P$ | Differential pressure | 125 in. wc |
| $T_f$ | Gas temperature | 150°F |

The modulus of elasticity for a 316 stainless steel orifice plate can be found by applying a curve fit to Table C-6 in ASME/ANSI B31.3 [2].

$$E^* = (28.8 - 0.0053\,T_f) \times 1E + 6 = 28.0E + 6 \text{ psi}$$

The diameter ratio and support diameter ratio are:

$$\beta = \frac{d}{D} = \frac{4.500}{8.071} = 0.5576$$

$$\beta_s = \frac{d}{D_s} = \frac{4.500}{8.237} = 0.5463$$

The deflection coefficient ($k_d$) can then be determined from a table in *Marks' Standard Handbook* [12]. The following equation for the deflection coefficient is based on a curve fit to that table.

$$k_d = -2.9381\beta_s^{\,5} + 11.387\beta_s^{\,4} - 12.167\beta_s^{\,3} + 2.4404\beta_s^{\,2} + 0.5918\beta_s + 0.6772 = 0.6164$$

The deflection coefficient is then entered into Equation (2-F.5-1) to determine the amount of plate deflection.

$$y = \left[\frac{0.6164}{16}\right]\left[\frac{125 \times 0.03609}{28E+6}\right]\left[\frac{8.237^4}{0.125^3}\right] = 0.01463 \text{ inch} \qquad \text{(2-F.5-1)}$$

The plate deflection ($y = 0.01463$ inch) is within the limit specified in AGA Report No. 3, Part II [1] ($y_L = 0.018$ inch).

From a curve fit to Table 2-F.6-1, $k_1 = 0.9156$, $k_2 = -0.2405$, and $k_3 = 0.0471$ are calculated and entered into the contraction coefficient equation for a flat orifice plate ($\theta_d = \pi/2$ radians).

$$k_1 = -0.1161\beta^2 - 0.005248\beta + 0.9546 = 0.9156$$

$$k_2 = 0.3683\beta^2 - 0.1103\beta - 0.2935 = -0.2405$$

$$k_3 = 0.05994\beta^3 - 0.1736\beta^2 + 0.07692\beta + 0.04775 = 0.04706$$

$$C_c = k_1 + k_2\theta_d + k_3\theta_d^{\,2} = 0.9156 - 0.2405\frac{\pi}{2} + 0.04706\left[\frac{\pi^2}{2}\right] = 0.6539 \qquad \text{(2-F.6-6)}$$

The angle of the orifice plate deflection ($\theta_d$) is calculated based on the orifice plate geometry.

$$\theta_d = a\cos\left(\left(\frac{y}{\frac{D_s}{2}-\frac{\beta D}{2}}\right)\right) = a\cos\left(\frac{0.01463}{\frac{8.237}{2}-\frac{0.5576\times 8.071}{2}}\right) = 1.5630 \text{ radians}$$

The change in the contraction coefficient is then calculated using Equation (2-F.6-7).

$$\delta C_c = -(-0.2405 + 2\times 0.04706\times 1.5630)\times\left(\frac{\pi}{2}-1.5630\right) = 0.00073 \qquad \text{(2-F.6-7)}$$

The orifice bore diameter partial differential is evaluated based on Equation (2-F.6-3).

$$\frac{\delta d}{d} = -\frac{k\Delta P D_s^2}{4\,E^*\,E^2} = \frac{-(2.75086 - 2.67169\times 0.5463)}{4}\times\frac{125\times 0.03609}{28E+6}\times\frac{8.237^2}{0.125^2} = -0.00023$$

Finally, the resulting change in mass flow rate is determined using Equation (2-F.6-2).

$$\frac{\delta m}{m} = \frac{1}{\left[1-C_c^2\beta^4\right]}\left[\frac{\delta C_c}{C_c}+2\frac{\delta d}{d}\right] = 1\times 100\times\frac{1}{[1-0.6539^2\times 0.05576^4]}\left[\frac{0.00073}{0.6539}+2\times -0.00023\right]$$

$$\frac{\delta m}{m} = -0.0695\%$$

Therefore, the error in mass flow rate through the orifice meter due to a differential pressure of 125 inches wc is found to be – 0.0695%. If an orifice plate with a thickness of 0.250 inch is used in the above example, the error is found to be – 0.003%. If the 0.125-inch thick plate in the above example had a differential pressure of 200 inches wc applied to it, the orifice plate deflection would exceed the AGA Report No. 3, Part II [1] limit of 0.018 inch.

With the 0.250-inch orifice plate in the above example, the differential pressure can be increased to 1,000 inches wc without exceeding the deflection tolerance or introducing significant error to the flow rate calculation, and the maximum flow rate is increased dramatically.

# ADDENDUM 2—EXPANDED DATA FOR 316 STAINLESS STEEL SIMPLY SUPPORTED ORIFICE PLATES

Maximum Allowable Differential Pressure

| Plate Size (ID): | 2" (2.067") | 3" (3.068") | 4" (4.026") | 6" (6.065") | | 8" (8.071") | | |
|---|---|---|---|---|---|---|---|---|
| Plate Thickness: | 0.125" | 0.125" | 0.125" | 0.125" | 0.1875" | 0.125" | 0.250" | 0.3125" |
| BETA | in. wc | in. wc | in. wc | in. wc | in. wc | in. wc | in. wc | in. wc |
| 0.20 | 1000[a] | 1000[a] | 1000[a] | 480 | 1000[a] | 205 | 1000[a] | 1000[a] |
| 0.25 | 1000 | 1000 | 1000 | 440 | 1000 | 190 | 1000 | 1000 |
| 0.30 | 1000 | 1000 | 1000 | 405 | 1000 | 175 | 1000 | 1000 |
| 0.35 | 1000 | 1000 | 1000 | 385 | 1000 | 165 | 1000 | 1000 |
| 0.40 | 1000 | 1000 | 1000 | 365 | 1000 | 160 | 1000 | 1000 |
| 0.45 | 1000 | 1000 | 1000 | 350 | 1000 | 155 | 1000 | 1000 |
| 0.50 | 1000 | 1000 | 1000 | 345 | 1000 | 150 | 1000 | 1000 |
| 0.55 | 1000 | 1000 | 1000 | 345 | 1000 | 150 | 1000 | 1000 |
| 0.60 | 1000 | 1000 | 1000 | 345 | 1000 | 150 | 1000 | 1000 |
| 0.65 | 1000 | 1000 | 1000 | 355 | 1000 | 155 | 1000 | 1000 |
| 0.70 | 1000 | 1000 | 1000 | 375 | 1000 | 165 | 1000 | 1000 |
| 0.75 | 1000 | 1000 | 1000 | 395 | 1000 | 180 | 1000 | 1000 |

| Plate Size (ID): | 10" (10.136") | | | | 12"(12.090") | | | |
|---|---|---|---|---|---|---|---|---|
| Plate Thickness: | 0.125" | 0.1875" | 0.250" | 0.3125" | 0.1875" | 0.250" | 0.3125" | 0.375" |
| BETA | in. wc | in. wc | in. wc | in. wc | in. wc | in. wc | in. wc | in. wc |
| 0.20 | 100 | 335 | 800 | 1000[a] | 175 | 420 | 820 | 1000[a] |
| 0.25 | 90 | 310 | 735 | 1000 | 160 | 385 | 755 | 1000 |
| 0.30 | 85 | 285 | 680 | 1000 | 150 | 355 | 700 | 1000 |
| 0.35 | 80 | 270 | 640 | 1000 | 140 | 335 | 655 | 1000 |
| 0.40 | 75 | 255 | 610 | 1000 | 130 | 315 | 620 | 1000 |
| 0.45 | 70 | 245 | 590 | 1000 | 125 | 300 | 595 | 1000 |
| 0.50 | 70 | 240 | 575 | 1000 | 120 | 295 | 575 | 995 |
| 0.55 | 70 | 240 | 570 | 1000 | 120 | 290 | 565 | 980 |
| 0.60 | 70 | 240 | 575 | 1000 | 120 | 285 | 560 | 970 |
| 0.65 | 70 | 245 | 590 | 1000 | 120 | 290 | 565 | 980 |
| 0.70 | 75 | 255 | 615 | 1000 | 125 | 295 | 575 | 1000 |
| 0.75 | 80 | 275 | 655 | 1000 | 125 | 305 | 595 | 1000 |

## Maximum Allowable Differential Pressure

| Plate Size (ID): | 16" (15.250") | | | | 20" (19.250") | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Thickness: | 0.250" | 0.375" | 0.4375" | 0.500" | 0.250" | 0.3125" | 0.375" | 0.4375" | 0.500" |
| BETA | in. wc | in. wc | in. wc | in. wc | in. wc | in. wc | in. wc | in. wc | in. wc |
| 0.20 | 200 | 690 | 1000 | 1000[a] | 100 | 200 | 345 | 550 | 825 |
| 0.25 | 185 | 630 | 1000 | 1000 | 90 | 185 | 320 | 505 | 755 |
| 0.30 | 170 | 585 | 930 | 1000 | 85 | 170 | 295 | 470 | 700 |
| 0.35 | 160 | 545 | 870 | 1000 | 80 | 160 | 275 | 440 | 655 |
| 0.40 | 150 | 515 | 820 | 1000 | 75 | 150 | 260 | 415 | 620 |
| 0.45 | 145 | 495 | 785 | 1000 | 70 | 145 | 250 | 395 | 595 |
| 0.50 | 140 | 480 | 760 | 1000 | 70 | 140 | 240 | 385 | 575 |
| 0.55 | 135 | 470 | 745 | 1000 | 70 | 135 | 235 | 380 | 565 |
| 0.60 | 135 | 465 | 740 | 1000 | 70 | 135 | 235 | 375 | 560 |
| 0.65 | 135 | 465 | 740 | 1000 | 70 | 135 | 235 | 375 | 565 |
| 0.70 | 140 | 475 | 755 | 1000 | 70 | 140 | 240 | 385 | 575 |
| 0.75 | 140 | 485 | 775 | 1000 | 70 | 145 | 250 | 395 | 595 |

| Plate Size (ID): | 24" (23.250") | | | | | 30" (29.25") | | | |
|---|---|---|---|---|---|---|---|---|---|
| Plate Thickness: | 0.250" | 0.375" | 0.4375" | 0.500" | 0.5625" | 0.375" | 0.4375" | 0.500" | 0.5625" |
| BETA | in. wc | in. wc | in. wc | in. wc | in. wc | in. wc | in. wc | in. wc | in. wc |
| 0.20 | 60 | 215 | 340 | 510 | 725 | 105 | 170 | 255 | 365 |
| 0.25 | 55 | 195 | 310 | 465 | 665 | 95 | 155 | 235 | 335 |
| 0.30 | 50 | 180 | 290 | 435 | 615 | 90 | 145 | 215 | 310 |
| 0.35 | 50 | 170 | 270 | 405 | 580 | 85 | 135 | 205 | 290 |
| 0.40 | 45 | 160 | 260 | 385 | 550 | 80 | 130 | 195 | 275 |
| 0.45 | 45 | 155 | 250 | 370 | 530 | 75 | 125 | 185 | 265 |
| 0.50 | 45 | 150 | 240 | 360 | 515 | 75 | 120 | 180 | 260 |
| 0.55 | 45 | 150 | 240 | 360 | 510 | 75 | 120 | 180 | 255 |
| 0.60 | 45 | 150 | 240 | 360 | 510 | 75 | 120 | 180 | 255 |
| 0.65 | 45 | 155 | 245 | 365 | 520 | 75 | 120 | 185 | 265 |
| 0.70 | 45 | 160 | 250 | 385 | 540 | 80 | 125 | 190 | 270 |
| 0.75 | 50 | 165 | 265 | 400 | 570 | 85 | 135 | 200 | 285 |

Assumptions:

1. Support diameter ($D_s$) is 0.2 inch less than outside orifice plate diameter.
2. Internal diameter ($D$) is the largest diameter in Table 2-4 of AGA Report No. 3, Part II [1].
3. Maximum differential values are for orifice plates at a flowing temperature less than or equal to 150°F ($T_f \leq$ 150°F).

[a] All calculated maximum differential pressures greater than 1,000 in. wc have been reduced to a maximum of 1,000 in. wc due to limitations in the coefficient of discharge database.

## 2-F.12 References

1. *Orifice Metering of Natural Gas and Other Related Hydrocarbon Fluids*, AGA Report No. 3, 3rd Edition, 1990.

2. *Chemical Plant and Petroleum Refinery Plant Piping* ASME/ANSI B31.3, 1993 Edition.

3. Gerhart, P.M., and Gross, R.J., *Fundamentals of Fluid Mechanics*, Addison-Wesley Publishing Company, pg. 485 – 486, 1985.

4. Gorter, J., "Buckling of Orifice Plates and Resulting Errors in Flow Measurements by Means of Orifice Meter Runs," Flow Con 77, *Proc. of Symp.*, "The Application of Measuring Techniques," Brighton, 1977.

5. Gorter, J., "Deformation of Orifice Plates, Theory and Practice," *Flow Measurement of Fluids*, 1978.

6. Hannisdal, N-E., "Metering Study To Reduce Topsides Weight," North Sea Flow Measurement Workshop, Norway, 1991.

7. Husain, Z., and Teyssandier, R., "The Effects of Plate Thickness and Bevel Angle in a 150 mm Line Size Orifice Meter," International Conference on Flow Measurement in the Mid-80s, Norway, 1986.

8. Husain, Z., and Roussel, J., "Measurement Accuracy of ¼" Thick Orifice Plate Installed in 8" Orifice Fitting Designed for ⅛" Thick Plate," Gas Measurement Research Council, San Antonio, Texas, 1997.

9. Karnik, U., "Effect of Increasing Plate Thickness on the Metering Accuracy of an 8 Inch Orifice Meter," *AGA Operating Section Proceeding*, pg. 605-625, 1996.

10. Jepson, P., and Chipchase, R., "Effect of Plate Buckling on Orifice Meter Accuracy," *Journal Mechanical Engineering Science*, 1975.

11. Mason, D., Wilson, M.P. and Birkhead, W.G., "Measurement Error Due to the Bending of Orifice Plates," ASME Annual Meeting, Houston, 1975.

12. *Marks' Standard Handbook for Mechanical Engineers*, *Mechanics of Material*, 9th Edition, Editors: Avallone, E.A., and Baumeister III, T., McGraw Hill, pg. 5-52.

13. Morrow, T., "Orifice Meter Installation Effects in the GRI MRF," 3rd International Symposium on Fluid Flow Measurement, San Antonio, Texas, 1995.

14. Norman, R., "A Further Investigation Into the Effect of Orifice Plate Deformation on Metering Error," Report No. ERS R.2554, British Gas Engineering Research Station, 1982.

15. Norman, R., Rawat, M.S., and Jepson, P., "Buckling and Eccentricity Effects on Orifice Metering Accuracy," International Gas Research Conference, 1983.

16. Norman, R., Rawat, M.S., and Jepson, P., "An Experimental Investigation Into the Effects of Plate Eccentricity and Elastic Deformation on Orifice Meter Accuracy," presented at the International Conference on Metering of Natural Gas and Liquified Hydrocarbon Gases, 1984.

17. Rawat, M.S., and Norman, R., "An Experimental Investigation Into the Flow Measurement Errors Caused by Elastic Deformation of Orifice Plates," Report No. ERS R.2713, British Gas Engineering Research Station, 1983.

18. *Hydraulics Engineering*, Editor: Rouse, H., John Wiley & Sons Inc., 1950.

19. Shapiro, A.H., *The Dynamics of Thermodynamics of Compressible Fluid Flow*, Vol. 1, John Wiley & Sons Inc., 1953.

# PROPOSAL TO REVISE AGA REPORT NO.3, PART 2

**Send to:** **Operations and Engineering Section**
**American Gas Association**
**400 North Capitol St., N.W., 4th Floor**
**Washington, DC 20001**
**U.S.A.**
**Fax: (202) 824-7082**

**Name:**__________________________________________________________

**Company:**_____________________________________________________

**Address:**______________________________________________________

**Phone:** ________________ **Fax:**_________________**E-mail**____________________

**Please Indicate Organization Represented (if any):**_____________________________

**1. Section/Paragraph :**________________________________________________

**2. Proposal Recommends: (check one):** ☐ **new text** ☐ **revised text** ☐ **deleted text**

**3. Proposal (include proposed new or revised wording, or identification of wording to be deleted, use separate sheet if needed):** [Proposed text should be in legislative format; i.e., use underscore to denote wording to be inserted (inserted wording) and strike-through to denote wording to be deleted (~~deleted wording~~).]

**4. Statement of Problem and Substantiation for Proposal (use separate sheet if needed):** (State the problem that will be resolved by your recommendation; give the specific reason for your proposal including copies of tests, research papers, etc.)

**5.** ☐ **This proposal is original material.** (Note: Original material is considered to be the submitter's own idea based on or as a result of his/her own experience, thought or research and, to the best of his/her knowledge, is not copied from another source.)
☐ **This proposal is not original material; its source (if known) is as follows:** __________

__________________________________________________________________

**Type or print legibly. If supplementary material (photographs, diagrams, reports, etc.) is included, you may be required to submit sufficient copies for all members of reviewing committees or task forces.**

*I hereby grant the American Gas Association the non-exclusive, royalty-free rights, including non-exclusive, royalty-free rights in copyright, in this proposal and I understand that I acquire no rights in any publication of the American Gas Association in which this proposal in this or another similar or analogous form is used.*

Date: ________________ Signature (Required) ____________________________

**FOR OFFICE USE ONLY**

**Log #** __________________

**Date Rec'd** ________________