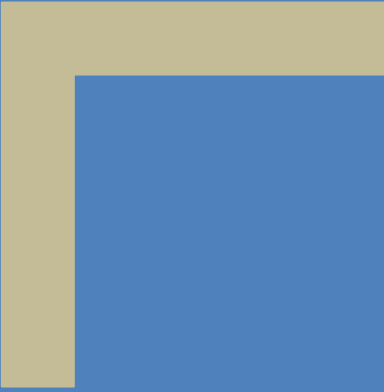




AGA Report No. 6

Field Proving of Gas Meters Using Transfer Methods

Prepared by
Transmission Measurement Committee

First Edition, March 2013



AGA Report No. 6

Field Proving of Gas Meters Using Transfer Methods

**Prepared by
Transmission Measurement Committee**



First Edition, March 2013

Copyright 2013 © American Gas Association
All Rights Reserved

Catalog # XQ1302

DISCLAIMER & COPYRIGHT

The American Gas Association's (AGA) Operations and Engineering Section provides a forum for industry experts to bring their collective knowledge together to improve the state of the art in the areas of operating, engineering and technological aspects of producing, gathering, transporting, storing, distributing, measuring and utilizing natural gas.

Through its publications, of which this is one, AGA provides for the exchange of information within the natural gas industry and scientific, trade and governmental organizations. Many AGA publications are prepared or sponsored by an AGA Operations and Engineering Section technical committee. While AGA may administer the process, neither AGA nor the technical committee independently tests, evaluates or verifies the accuracy of any information or the soundness of any judgments contained therein.

AGA disclaims liability for any personal injury, property or other damages of any nature whatsoever, whether special, indirect, consequential or compensatory, directly or indirectly resulting from the publication, use of or reliance on AGA publications. AGA makes no guaranty or warranty as to the accuracy and completeness of any information published therein. The information contained therein is provided on an "as is" basis and AGA makes no representations or warranties including any expressed or implied warranty of merchantability or fitness for a particular purpose.

In issuing and making this document available, AGA is not undertaking to render professional or other services for or on behalf of any person or entity. Nor is AGA undertaking to perform any duty owed by any person or entity to someone else. Anyone using this document should rely on his or her own independent judgment or, as appropriate, seek the advice of a competent professional in determining the exercise of reasonable care in any given circumstances.

AGA has no power, nor does it undertake, to police or enforce compliance with the contents of this document. Nor does AGA list, certify, test or inspect products, designs or installations for compliance with this document. Any certification or other statement of compliance is solely the responsibility of the certifier or maker of the statement.

AGA does not take any position with respect to the validity of any patent rights asserted in connection with any items that are mentioned in or are the subject of AGA publications, and AGA disclaims liability for the infringement of any patent resulting from the use of or reliance on its publications. Users of these publications are expressly advised that determination of the validity of any such patent rights, and the risk of infringement of such rights, is entirely their own responsibility.

Users of this publication should consult applicable federal, state and local laws and regulations. AGA does not, through its publications intend to urge action that is not in compliance with applicable laws, and its publications may not be construed as doing so.

Changes to this document may become necessary from time to time. If changes are believed appropriate by any person or entity, such suggested changes should be communicated to AGA in writing *and sent to: Operations & Engineering Section, American Gas Association, 400 North Capitol Street, NW, 4th Floor, Washington, DC 20001, U.S.A. Suggested changes must include: contact information, including name, address and any corporate affiliation; full name of the document; suggested revisions to the text of the document; the rationale for the suggested revisions; and permission to use the suggested revisions in an amended publication of the document. A form to propose changes has been added at the end of the document.*

Copyright © 2013, American Gas Association, All Rights Reserved.

ACKNOWLEDGEMENT

This report was developed by a Transmission Measurement Committee (TMC) task group initially under the chairmanship of **Walt Seidl** formerly with Colorado Engineering Experiment Station, Inc. (CEESI). Following Walt's retirement, the leadership was taken over by **Jim Witte**, the then representative to TMC from El Paso Corp., to finish the document for balloting. Subsequently, the leadership was provided by **John Hand** with Spectra Energy, who worked hard in reaching consensus for resolution of ballot comments. **Terry Grimley** with Southwest Research Institute (SWRI) provided substantial help in preparing the document for balloting and writing the final version. AGA acknowledges and sincerely appreciates their hard work and contributions.

Members of the task group who devoted an extensive amount of their time and deserve special thanks are –

Paul LaNasa, CEESI Measurement Solutions
Dan Rebman, Universal Ensco
Dan Rudroff, Welker Flow Measurement Systems
Phil Whittemore, Dresser Meters and Instruments

Others who also contributed and deserve thanks are –

Khalid Al-Fadhl, Saudi Aramco
Mike Bermel, Southern California Gas Company
Jim Bowen, Sick Oil & Gas
Tod Bradley, Elster American Meter
Cary Carter, Boardwalk Pipeline Partners
Craig Chester, Williams Gas Pipeline
John Gerwig, Consultant
Zaki Husain, Chevron
Allen Knack, Consumers Energy
Brad Massey, Williams Mid-Stream, LLC
George Mattingly, GEM and Associates
Gary McCargar, Oneok Partners
Mark Pelkey, National Fuel Gas Supply Corporation
Warren Peterson, Alliance Pipeline
Tushar Shah, Eagle Research Corp.
Gordon Stobie, ConocoPhillips (UK) Limited
Fred Van Orsdol, SPL Inc
Duc T. Vuong, Integrys Energy Group, LLC
David Wiklund, Emerson Process – Rosemount

Christina Sames
Vice President
Operations and Engineering

Ali Quraishi
Director
Operations and Engineering

TABLE OF CONTENTS

DISCLAIMER & COPYRIGHT	III
ACKNOWLEDGEMENT	IV
TABLE OF CONTENTS	V
PURPOSE	1
1. SCOPE	1
2. TERMINOLOGY	1
3. THEORY	6
4. PROVING METERS USING CRITICAL FLOW DEVICES.....	9
4.1. INTRODUCTION	9
4.2. LABORATORY CALIBRATION OF CRITICAL FLOW VENTURI NOZZLES	10
4.3. CALCULATIONS.....	12
4.4. CFVN STAGNATION PRESSURE AND TEMPERATURE	13
4.5. PROVING METERS USING A CFVN	14
4.6. CRITICAL FLOW ORIFICE PROVER	16
4.7. OTHER CRITICAL FLOW PROVERS	16
5. PROVING FIELD METERS WITH MASTER METERS.....	17
5.1. INTRODUCTION	17
5.2. HIGH PRESSURE FIELD PROVING WITH A MASTER METER.....	18
5.2.1 <i>Permanently Installed Master Meter</i>	19
5.2.2 <i>Temporarily Installed Master Meter</i>	19
5.2.3 <i>Instrumentation and Calculations</i>	20
5.3. LOW PRESSURE FIELD PROVING WITH A MASTER METER	20
5.4. CALIBRATION OF THE MASTER METER	22
5.4.1 <i>Assessing Installation Effects for Master Meters</i>	23
5.5. CALCULATIONS.....	24
6. APPLICATION OF FIELD PROVING RESULTS	25
7. REFERENCES	26
APPENDIX A – MASTER METER CONSIDERATIONS	27
A.1. INTRODUCTION	27
A.2. CONSIDERATIONS OF VARIOUS METER TYPES FOR USE AS MASTER METERS	27
A.2.1 <i>Coriolis</i>	27
A.2.2 <i>Critical Flow Venturi Nozzle (CFVN)</i>	28
A.2.3 <i>Multi-Path Ultrasonic Flow Meter (UFM)</i>	28
A.2.4 <i>Orifice Meter</i>	28
A.2.5 <i>Positive Displacement (PD) Meters (Rotary and Diaphragm)</i>	28
A.2.6 <i>Turbine Flow Meter</i>	29
A.2.7 <i>Subsonic Venturi</i>	29
A.3. REFERENCES	30
APPENDIX B – CFVN INFORMATION.....	31
B.1. CFVN UNCHOKING TEST	31
B.2. PRESSURE DROP REQUIRED FOR CRITICAL FLOW.....	32
APPENDIX C – UNCERTAINTY	33

C.1.	DESCRIPTION OF THE UNCERTAINTY EVALUATION METHOD	33
C.1.1.	<i>Define the Measurement Process</i>	34
C.1.2.	<i>Identify Uncertainty Sources</i>	34
C.1.3.	<i>Estimate Uncertainties</i>	35
C.1.4.	<i>Combined Uncertainties</i>	35
C.1.5.	<i>Report the Results of the Uncertainty Evaluation</i>	35
C.1.6.	<i>Simplification of Uncertainty Calculations</i>	35
C.1.7.	<i>Proving by CFVN Uncertainty Evaluation Example</i>	36
C.1.8.	<i>Proving by Master Meter Evaluation Example</i>	39
C.2.	REFERENCES	40
APPENDIX D – CALCULATION EXAMPLES		41
D.1.	PROVING BY CRITICAL FLOW VENTURI NOZZLE	41
D.2.	FIELD PROVING BY MASTER METER	45
D.2.1.	<i>Proving by Master Meter Example 1</i>	45
D.2.2.	<i>Proving by Master Meter Example 2</i>	47
D.2.3.	<i>Proving by Master Meter Example 3</i>	49
D.3.	CALCULATION OF CFVN SIZE	50
D.3.1.	<i>Determine the Desired Flowing Conditions</i>	50
D.3.2.	<i>Calculate the Mass Flow Rate of Gas</i>	51
D.3.3.	<i>Determine the Critical Flow Factor, C*</i>	51
D.3.4.	<i>Calculate the CFVN Throat Area</i>	51
D.3.5.	<i>Calculate the CFVN Throat Diameter</i>	51
APPENDIX E – FLUID PROPERTIES		53
E.1.	AIR PROPERTIES	53
E.2.	NATURAL GAS PROPERTIES	53
FORM TO PROPOSE CHANGES		55

Purpose

The purpose of this document is to provide operating personnel with methods to prove gas flow meters in the field. The methods presented will include both current technology and previously presented technology that is still in use.

1. Scope

This report includes methods for proving gas flow meters and/or metering systems in the field using either critical flow or other transfer metering techniques. It is intended for use by both technicians and engineers to enable them to apply principles of engineering, physics, and mathematics to the process of proving, verifying, or checking a working meter or metering system by utilizing a calibrated, traceable master metering system with a documented uncertainty across the range over which the master metering system is applied.

This document is intended as an informational guide and not as a prescriptive document. It is the responsibility of those using the methods described to establish error limits, required operating test range, and other criteria for determining the acceptability of a meter proof and the situations in which these proving methods can be applied.

2. Terminology

For the purposes of this report, the following terms are defined:

Actual volume	a quantity of gas that occupies a specified physical volume at some specified pressure and temperature. This typically refers to the actual volume at operating conditions. <i>Contrasting term: standard volume.</i>
Actual volume flow rate	the rate of flow in units of actual volume per unit time. <i>Contrasting term: standard volume flow rate.</i>
Accuracy	a qualitative concept of the closeness in agreement of a measured value and an accepted reference value. <i>Contrasting term: "meter accuracy" that has a specific quantitative definition provided in this document.</i>
Adjustment	the mechanical or electronic operations required to create agreement between the test device output and the reference device as the result of information gathered during a calibration.
Beta	a dimensionless ratio of the measured throat diameter to the measured inlet diameter.
Boundary layer	the layer of slower flow adjacent to the boundary surface of a body containing a flowing fluid.
Calibration	the process of determining, under specified conditions, the relationship between the output (or response) of a

device to the value of a traceable reference standard with documented uncertainties. The relationship may be expressed by a statement, calibration function, calibration diagram, calibration curve or calibration table. In some cases, it may consist of an additive or multiplicative correction of the indication with associated measurement uncertainties. Any adjustment to the device, if performed, following a calibration requires verification against the reference standard. *Contrasting term: verification.*

CFVN	Critical Flow Venturi Nozzle. A flow measurement device utilizing the principle of critical flow to determine the flow rate through a system.
Choking pressure ratio	the ratio of the downstream (exit) absolute pressure to the inlet absolute pressure at which the velocity at the throat of a critical flow device becomes sonic.
Connecting volume	the volume of the gas in the pipe section between the master (reference) meter and the Meter Under Test (MUT).
Critical flow factor, C^*	a dimensionless function of the nature of the gas and the stagnation conditions, which characterizes the thermodynamic flow properties of an isentropic and one-dimensional flow between the inlet and throat of a CFVN.
Diffuser	a conical expansion section downstream of the throat of a CFVN. Used to decrease the pressure loss in a CFVN.
Discharge coefficient, C_d	the ratio of the actual to theoretical mass flow rate.
Error	the result of a measurement minus the true value of the measurand. Note: Since a true value cannot be determined, in practice a conventional true or reference value is used, as determined by means of a suitable standard device.
Field meter proving	a method of testing a MUT outside of a controlled environment such as a calibration facility or meter shop. The MUT is compared with a master meter to determine the accuracy and repeatability of the MUT.
Inlet static pressure	the absolute pressure of the gas at the nozzle inlet, measured at the wall of the inlet section. <i>Related term: static pressure.</i>

Inlet stagnation pressure	the absolute pressure the gas at the nozzle inlet attains when brought to rest isentropically. <i>Related term: stagnation pressure.</i>
Isentropic exponent	the ratio of the relative variation in pressure to the corresponding relative variation in density under elementary reversible adiabatic (isentropic) transformation conditions.
K factor	is expressed in pulses per unit volume; also referred to as the “pulse factor.” It is associated with the electronic pulse output of the meter to produce a volume for an ancillary device (flow computer). If a meter has more than one electronic pulse output, then more than one K-factor may be appropriate.
Mach number	the ratio of the fluid speed to the speed of sound at a set of specified operating conditions.
Mass flow rate	the flow rate through a meter stated in units of mass per unit of time.
Master meter	a meter (transfer standard or reference), metering system, or CFVN with known characteristics used to prove another meter (MUT).
Measurand	The quantity intended to be measured.
Meter accuracy	$\frac{\text{Actual Volume}_{\text{MUT}}}{\text{Actual Volume}_{\text{REF}}} 100\%$ or $\frac{\text{Mass}_{\text{MUT}}}{\text{Mass}_{\text{REF}}} 100\%$ or $\frac{\text{Standard Volume}_{\text{MUT}}}{\text{Standard Volume}_{\text{REF}}} 100\%$ <i>Note that “meter accuracy” is a specific numerical quantity defined by the above equations and should not be confused with the qualitative concept of “accuracy” (when the word is used alone) as defined previously.</i>
Meter error	$\left[\frac{\text{Actual Volume}_{\text{MUT}}}{\text{Actual Volume}_{\text{REF}}} 100\% \right] - 100\%$ or $\left[\frac{\text{Mass}_{\text{MUT}}}{\text{Mass}_{\text{REF}}} 100\% \right] - 100\%$ or $\left[\frac{\text{Standard Volume}_{\text{MUT}}}{\text{Standard Volume}_{\text{REF}}} 100\% \right] - 100\%$
Meter factor	a number by which the result of a measurement is multiplied to compensate for systematic error. The non-dimensional multiplying value is determined for each flow rate at which the meter is proved. The number is calculated by dividing the value from the

	master meter by the indicated value from the meter under test.
Meter Proof	$\frac{\text{Actual Volume}_{\text{REF}}}{\text{Actual Volume}_{\text{MUT}}} 100\%$ or $\frac{\text{Mass}_{\text{REF}}}{\text{Mass}_{\text{MUT}}} 100\%$ or $\frac{\text{Standard Volume}_{\text{REF}}}{\text{Standard Volume}_{\text{MUT}}} 100\%$
MUT	Meter Under Test or Metering System Under Test.
NIST	National Institute of Standards and Technology, United States of America.
Primary flow standard	a flow standard with direct traceability to fundamental units, such as mass, length, temperature and time.
Proving	the process of determining the relationship between the output (or response) of a MUT to the value produced by a master meter.
Rangeability	for a flow meter, this is the ratio of the maximum to the minimum flow rates in the range over which the meter meets specified error limits.
Repeatability	the closeness of the agreement between the results of successive measurements of the same measurand carried out under the same conditions of measurement. These conditions include the same measurement procedure, the same observer, the same measuring instrument, used under the same conditions, the same location and repetition over a short period of time.
Reproducibility	the closeness of the agreement between the results of measurements of the same measurand carried out under changed conditions of measurement. The changed conditions may include principle of measurement, method of measurement, observer, measuring instrument, reference standard, location, conditions of use and time.
Reynolds number	a non-dimensional parameter that compares the inertial with the viscous forces in a flowing fluid. Useful for correlating flow meter performance.
Secondary flow standard	a flow measuring device with documented traceability and uncertainty that is traceable to a primary flow standard.
Sonic	relating to the local speed of sound of the gas.

Stagnation pressure	the pressure a fluid attains when brought to rest isentropically. <i>Related term: inlet stagnation pressure.</i>
Standard volume	a specified volume of gas at specified standard conditions of pressure and temperature. This volume of gas has a specific mass, related to the standard pressure, temperature, and gas composition. <i>Contrasting term: actual volume.</i>
Standard volume flow rate	the rate of flow in units of standard volume per unit time. <i>Contrasting term: actual volume flow rate.</i>
Static pressure	the potential pressure exerted in all directions by a fluid or gas at rest. For a fluid or gas in motion, static pressure is measured in a direction at right angles to the direction of flow. The pressure measured using a properly manufactured perpendicular wall tap. <i>Related term: inlet static pressure.</i>
Throat	the narrowest internal cross-section of the CFVN.
Traceability	"requires the establishment of an unbroken chain of comparisons to documented references each with a documented uncertainty," as defined by NIST.
Transfer prover	a portable, self-contained system used for proving meters in the field consisting of a master meter, instrumentation, and data collection equipment all of which have both their traceability and uncertainty documented.
Uncertainty	a parameter, associated with the result of a measurement that characterizes the dispersion of the values that could reasonably be attributed to the measured quantity. The dispersion could include all components of uncertainty, including those arising from systematic effect. The parameter is typically expressed as a standard deviation (or a given multiple of it), defining the limits within which the measured value is expected to lie with a stated level of confidence.
Verification	the process of confirming or substantiating that the output of a device is within the specified requirements. <i>Contrasting term: calibration.</i>

3. Theory

The method of transfer proving consists of passing a known gas or gas mixture, such as air or pipeline quality natural gas, through a MUT and a transfer standard (master meter) in series under steady-state conditions of flow rate, pressure, temperature and gas composition (Figure 3-1). Under these steady-state conditions, assuming no leakage into or out of the system, the mass rate of flow through the master meter and the MUT is the same.

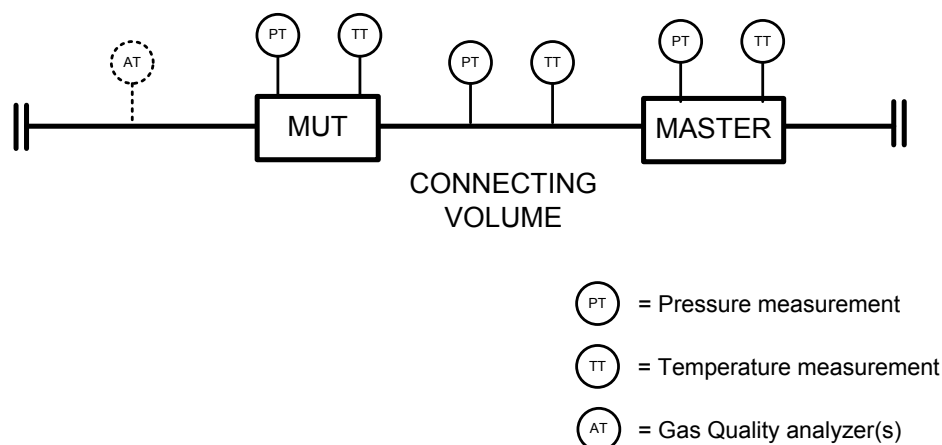


**Figure 3-1: MUT and master meter in series with connecting volume.
Flow can be in either direction.**

If unsteady flow occurs because of the configuration between the MUT and the master meter or because of changing operating and flowing conditions upstream and downstream of the meters during the period over which performance of the MUT is established, the line pack (mass contained in the connecting volume) between the MUT and the master meter can affect the results of the calibration. The larger the connecting volume or longer the distance between the MUT and the master meter, the greater the potential effect on the calibration of the MUT. In addition, the differences in pressure and temperature at the MUT and the master meter may result in different compressibility factors at the two meters. These effects can lead to additional calibration uncertainty that should be considered during meter proving. See Appendix C for equations to be used where the effect of the connecting volume on the measurement uncertainty for the in-situ calibration is to be considered. Examples in Appendix D are given, assuming that the effect of connecting volume for the in-situ calibration is not considered.

The relationship between the flow recorded by the MUT and the transfer standard is an indication of MUT accuracy relative to the transfer standard. When expressed as a ratio it is referred to as “meter proof at a specified rate of flow.” The proof equations presented in this document are not applicable to unsteady flows. During unsteady flows, the effect of mass storage in the piping between the master meter and the MUT must be considered.

Meter proof may vary from flow rate to flow rate. Other factors, such as pressure, temperature, gas density and composition may also influence the meter proof and should be held as constant as is practical. In some cases an operator will calculate a single flow-weighted proof for a MUT and will use that value to develop a single adjustment factor to be applied to all data throughout the meter's range of operation. These data often are used to either adjust meter output in a flow computer, electronic corrector or to mechanically adjust meter output by changing gear ratios within the meter itself.

A series of proofs may be performed at several points across the MUT's range of flow. The data may be used to create a single point adjustment, an adjustment table, a series of linear adjustments, or an adjustment curve that will bring the MUT into tolerance across the MUT's entire range of operation.

A meter proof in the field may differ from a prior proof measured in a laboratory. Each proof is the result of the overall uncertainties associated with the respective tests. Typical laboratory uncertainties are smaller than those that can be obtained in field proofs. Differences may be due to many factors, including installation effects, contamination, worn components, and differences in gas composition. The differences may also be due to faulty test methods or test equipment. Field proofs should not be used to replace the initial calibration factor(s) of the MUT obtained in a qualified laboratory unless the reason for the differences can be determined.

The master meter should have a lower uncertainty than the uncertainty required for the MUT. The uncertainty requirements for the transfer standard should be determined by performing an uncertainty analysis of the overall proving process as described in Appendix C.

Under steady-state conditions all necessary parameters, such as pressure, temperature, and meter output such as frequency (or pulses and time), are recorded. Sufficient pulses must be accumulated to achieve the desired uncertainty. In order to perform uncertainty calculations for the proof, multiple data points will be required at each flow rate. For transfer standards and MUTs that indicate flow in units of actual volume, a proof requires conversion to mass units or standard volume units at a common pressure and temperature base condition. Using the master meter performance data, measured parameters and fluid properties, the mass rate of flow through the transfer standard and the MUT may be calculated. By using the indicated flow rate from the transfer standard, MUT measured parameters and fluid properties for the MUT, the meter factor(s) for the MUT may be calculated.

It has been shown that with some flow meters, the meter factor at elevated operating pressures may be significantly different than a meter factor ascertained by proving at or near atmospheric pressure. Therefore, it is recommended that the MUT be proved at typical operating conditions whenever possible.

Master meters, piping and associated piping components should be sized to ensure similar flow dynamics through the master meter and the MUT. Using much smaller valves and/or piping, and using master meters that may test only a small portion of a MUT's operating range will increase the uncertainty of the resulting test and is not recommended.

Flow meters, including both the master meter and the MUT, can be affected by installation issues such as asymmetric velocity profile, swirl, and pulsation. These effects may be minimized by following the appropriate AGA Reports and other relevant industry standards. During field proving, operators should be aware of the potential influence of any installation effects on both the MUT and the master meter. By proving the MUT in its normal operational installation, these effects may be more readily accounted for in the field proving results.

The interval between meter proofs should be determined by meter history, operating conditions, regulatory requirements or contractual requirements, or by performing a risk analysis. If from one proving to the next, the meter factor shifts beyond the meter's repeatability requirement, remedial measures should be taken to prevent such shifting and a shorter interval should be considered for the next proving.

When selecting a master meter, consideration should be given to the following attributes:

- Quality
- Repeatability
- Reproducibility
- Traceability
- Known uncertainty
- Well characterized dependence on process conditions
- Rangeability
- Installation requirements
- Output interface requirements
- Pressure loss
- Diagnostic capability or the ability to verify the measurement integrity

Appendix A includes a discussion of these attributes as related to different potential master meter types.

Regardless of the meter used as the master meter, it is critical that all the flow that passes through the MUT also passes through the master meter. Therefore, any valves that could allow gas to enter or exit between the master meter and the MUT or that could allow gas to bypass either of the meters should be capable of being verified. Double block and bleed valves are one solution because they possess dual seats integral to the valve with the capability to bleed the space between the seats and verify that the valve is sealing properly.

4. Proving Meters Using Critical Flow Devices

4.1. Introduction

Critical flow venturi nozzles (CFVN) are devices that accelerate the flowing gas to the maximum possible velocity by restricting the flow. This restriction is usually in the form of a converging section called the “inlet,” followed by a section of minimum area called the “throat,” and optionally followed by a section called the “diffuser,” where the area is expanded and some pressure recovery occurs.

When the pressure is the same upstream and downstream of a CFVN, no flow occurs. With a constant inlet pressure, if the downstream pressure is now decreased, the flow rate will increase. At some point, the mass rate of flow does not increase with additional decrease in downstream pressure. At this point the CFVN is said to be choked and the velocity of the gas in the throat is equal to the local speed of sound. This condition is also known as “critical” or “sonic flow.”

The most common inlet geometry is a circular arc with the most common radius of curvature equal to two times the throat diameter. In this section, the gas is accelerated gradually from the lower velocity in the inlet piping to the local speed of sound in the throat.

The most common throat design is one of zero length, where the inlet curvature is continued through the throat until it is tangent to the diffuser.

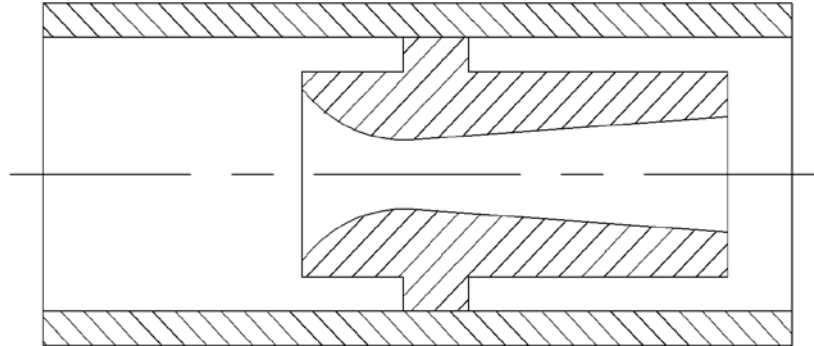


Figure 4-1. Example Cross Section of a Toroidal Throat CFVN with a Diffuser (Flow is from left to right)

A diffuser is commonly added to the nozzle making it a venturi nozzle. The diffuser allows the low pressure at the throat to gradually increase until it approaches the pressure at the inlet, resulting in a lower unrecovered pressure loss. Depending on the CFVN size, the total unrecovered pressure losses may be as low as five percent of inlet absolute pressure.

There exist multiple nozzle geometries that can achieve critical flow. The cylindrical throat nozzle is another common geometry where the inlet arc radius equals the throat diameter and the throat diameter is held for a one diameter

length, forming a cylinder. The cylindrical throat geometry is illustrated below in Figure 4-2.

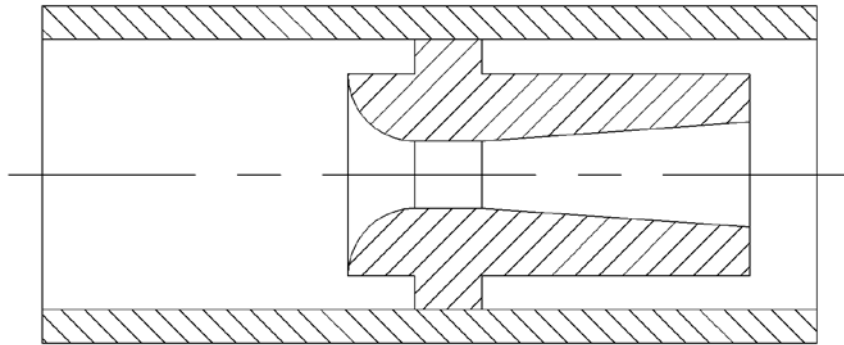


Figure 4-2. Example Cross Section of a Cylindrical Throat CFVN with a Diffuser (Flow is from left to right)

The actual volumetric flow rate of a critical flow device is approximately fixed. As the upstream, or inlet, pressure is varied, the volumetric flow rate does not vary to a great degree.

The results of a CFVN calibration are typically stated as a discharge coefficient — the ratio of the actual mass flow rate to the mass flow rate calculated using one-dimensional, isentropic flow theory. The discharge coefficient is usually correlated using the throat Reynolds number.

More information about the design, installation and use of a CFVN may be found in References 1 and 2.

4.2. Laboratory Calibration of Critical Flow Venturi Nozzles

A CFVN should be calibrated before use to provide traceability to recognized national or international standards and to allow measurement uncertainty calculations to be performed.

A CFVN may be calibrated by several methods. The methods below are listed in order of decreasing uncertainty.

- Measurement of throat diameter.
- Flow tested against secondary flow standards.
- Flow tested against primary flow standards.

The simplest form of calibration is the measurement of the throat diameter of the CFVN. Traceability is provided through the calibration of the instrument used to measure the throat diameter and through CFVN performance data published in the public reference literature. Uncertainties may be higher than other forms of calibration since a generalized discharge coefficient equation from a critical flow standard document must be used, and the standard equations do not account for variations due to manufacturing defects and boundary layer transitions.

The equations [1] and [2] from ANSI/ASME MFC-7M (Reference 1) used to describe the behavior of the discharge coefficient are as follows:

For laminar flow in the throat boundary layer

$$C_d = 0.99844 - 3.032(\text{Re}_d)^{-0.5} \quad [1]$$

For turbulent flow in the throat boundary layer

$$C_d = 0.99844 - 0.06927(\text{Re}_d)^{-0.2} \quad [2]$$

Since it is theoretically possible for boundary layer transition to take place between throat Reynolds numbers of 50,000 and 10,000,000 and the difference between laminar and turbulent discharge coefficients may be substantial, the uncertainty in discharge coefficient will be greater in the transition range (Figure 4-3). A laboratory calibration of the CFVN will characterize the discharge coefficient in the transition range and reduce uncertainty.

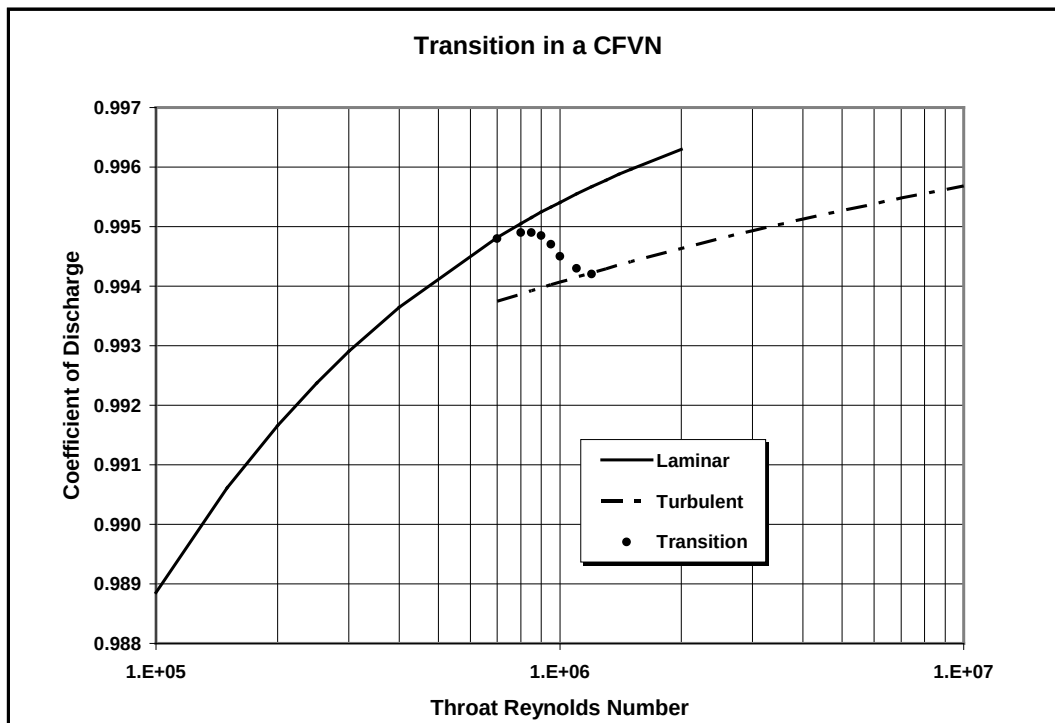


Figure 4-3. Example of CFVN Transition

The CFVN may also be calibrated against another CFVN with documented traceability and uncertainty. The two CFVNs are connected in series and multiple data points are obtained over the operating throat Reynolds number range of the CFVN which is to be used to prove other MUTs. For this method to be used, the throat diameter of the second nozzle must be larger than that of the first nozzle to allow both nozzles to operate with critical flow at the nozzle throats.

The CFVN may also be calibrated using primary flow standards, where the traceability is to fundamental standards such as mass, length and time. These types of calibrations may yield the lowest uncertainties of ± 0.1 percent or lower.

4.3. Calculations

The mass flow rate may be calculated by:

$$q_m = \frac{P_o A^* C_d C^*}{\sqrt{\frac{R}{M} \frac{T_o}{g_c}}} \quad [3]$$

Where,

P_o = CFVN inlet absolute stagnation pressure

A^* = CFVN throat area

C_d = Coefficient of discharge

R = Universal gas constant

M = Molecular mass of the gas

g_c = Dimensional conversion constant

T_o = CFVN inlet absolute stagnation temperature

C^* = Critical flow factor

An alternative form of equation [3] can be found in ASME/ANSI MFC-7M.

The coefficient of discharge, C_d , is a function of the throat Reynolds number, Re_d ,

$$C_d = f(Re_d) \quad [4]$$

The throat Reynolds number is calculated by

$$Re_d = \frac{4 q_m}{\pi d \mu_0} \quad [5]$$

Where,

d = CFVN throat diameter

μ_0 = Absolute viscosity, based on CFVN inlet temperature