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Engineering Technical Note

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The Theory and Operations of Meter Shop Sonic Nozzle Proving Systems for the Natural Gas Industry

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ABSTRACT

The use of sonic flow nozzles for the testing of residential and commercial gas meters (diaphragm, rotary, and gas turbine designs) has become the widespread practice for the natural gas distribution and transmission industry. Many gas meter shops, repair centers, manufacturers, and government utility commissions have accepted the “sonic nozzle prover” as the primary tool for measuring gas meter accuracy and performance. In many instances, the sonic nozzle prover has replaced the conventional bell-type prover for the testing of residential and light commercial meters.

The sonic nozzle prover uses venturi-type critical flow nozzles as the means to determine actual gas volume passed through a meter under test. The prover can marry gas meter performance with local meter characteristics (meter type, reasons for removal or test, and meter location) and forward this information to a utility database or network.

Critical flow — or sonic flow — nozzles provide the following benefits to gas meter proving operations:

- High level of accuracy and precision
- Faster meter testing methods for increased efficiency
- Self-contained diagnostics for calibration, maintenance, and troubleshooting concerns
- Measurement certification traceability to the National Institute of Standards and Technology (NIST)

Sonic nozzle provers also provide real-time measurement of pressure, temperature, and relative humidity, thereby decreasing the need for strict climate control.

This technical paper addresses the theory behind the critical flow sonic nozzle and how the sonic nozzle can be used as a means to measure gas meter accuracy and performance. This paper will often refer to The American Society of Mechanical Engineer’s publication, ASME/ANSI MFC-7M-1987, titled “Measurement of Gas Flow by Means of Critical Flow Venturi Nozzles,” as a reference for the development of sonic nozzle proving applications. It is the intention of this document to assist the reader in understanding the following:

- Sonic nozzle theory and design
- Sonic nozzle proving methods and the development of the gas meter “prover”
- The design requirements and operation of the modern sonic nozzle prover
- Calibration and certification of sonic nozzle provers
- Standard prover maintenance, measurement uncertainties, and calibration
- Features besides basic gas meter proving functions

1. SONIC NOZZLE THEORY

1.1. Definition of a Sonic Nozzle Element

A sonic nozzle, or critical flow venturi element, is a converging-to-diverging conduit for which the internal geometry creates a critical flow condition at the throat, or the smallest internal diameter and cross-sectional area of the nozzle. *Critical flow* is the maximum flow rate possible for a given venturi element — this maximum flow rate is equal to the local speed of sound at the nozzle throat. In other words, when critical flow exists, the throat velocity is equal to the local speed of sound, based on the given upstream condition. Fluid flow through a sonic nozzle is independent of downstream pressure changes and fluctuations, so long as the minimum allowable differential pressure across the nozzle element is not reduced below the threshold, or critical value.

To use sonic flow nozzles as a volumetric measurement device, the following measurements are required immediately upstream of the nozzle inlet plane:

- The absolute pressure
- The absolute temperature
- Gas composition (in the case of air, the relative humidity reading is required)

1.2. Sonic Nozzle Development and the Need for Its Use

The development of the sonic nozzle element reflects the need for higher accuracy in fluid flow measurement, particularly, in the natural gas industry. A secondary flow standard was suggested for both field use and as a fixed meter shop test device, replacing both bell-type standards and orifice metering.

The critical flow sonic nozzle provides the following advantages as a secondary volumetric standard:

- Once a minimal differential pressure is created across the nozzle element and maintained, the nozzle sets and controls the rate of flow, allowing for continuous flow and extended meter test volumes.
- Downstream flow disturbances do not affect the upstream and throat flow conditions.
- A recovery cone, or an exit diffuser, downstream of the nozzle throat limits the total pressure loss to/between 5% to 20% of the upstream total pressure. This recovery of pressure permits broader applications of the nozzle element.

1.3. Sonic Nozzle Design

There are two typical designs for sonic nozzles:

- Cylindrical throat sonic, or venturi, nozzle
- Toroidal throat sonic, or venturi, nozzle

Generally, sonic nozzle flow elements in the United States employ the toroidal throat design instead of the cylindrical throat design. Testing in the 1960s showed that the cylindrical throat design created flow instability. This flow instability made it difficult to determine the nozzle's discharge coefficient at varying nozzle inlet pressures. The *discharge coefficient* is a dimensionless ratio of the actual flow rate to the ideal flow rate that would be obtained with one-dimensional isentropic flow, given identical upstream conditions. The discharge coefficient is required for correcting for viscous and flow-field curvature effects and is an empirical function of the fluid Reynolds Number at the nozzle throat.

Since cylindrical throat sonic nozzles are not generally used in the natural gas industry for flow measurement, the remaining design discussion will focus on toroidal throat sonic nozzles only.

1.4. The Toroidal Sonic Nozzle Design

The toroidal throat sonic nozzle is widely used in the natural gas industry. A toroidal throat sonic nozzle enables accurate predictability of the nozzle discharge coefficient due to the internal shape and smooth transition from the nozzle's converging section to the nozzle throat, and expansion into the recovery cone, or diverging section. R. E. Smith and R. J. Matz designed and developed the modern toroidal throat sonic nozzle in the early 1960s; it's a design that has become the international standard for critical flow measurement devices.

Figure 1.1 shows the modern toroidal sonic nozzle design. Please note that the majority of the nozzle dimensions are in terms of the nozzle throat diameter (d).

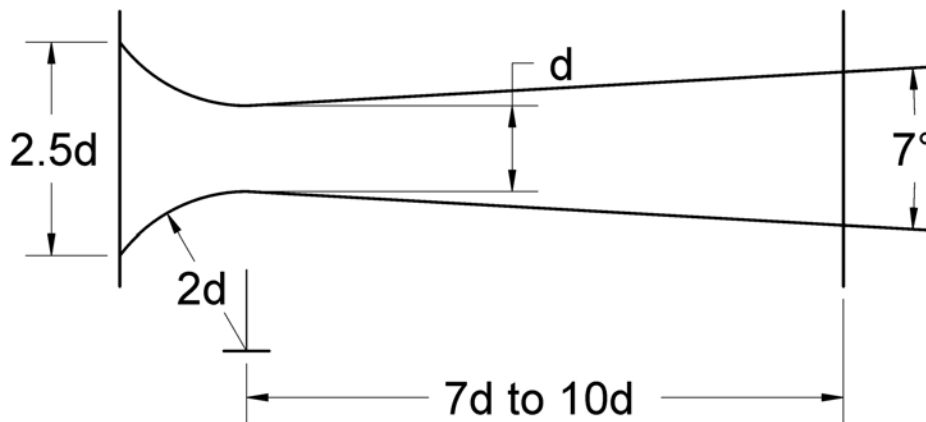


Figure 1.1: THE TOROIDAL NOZZLE DESIGN

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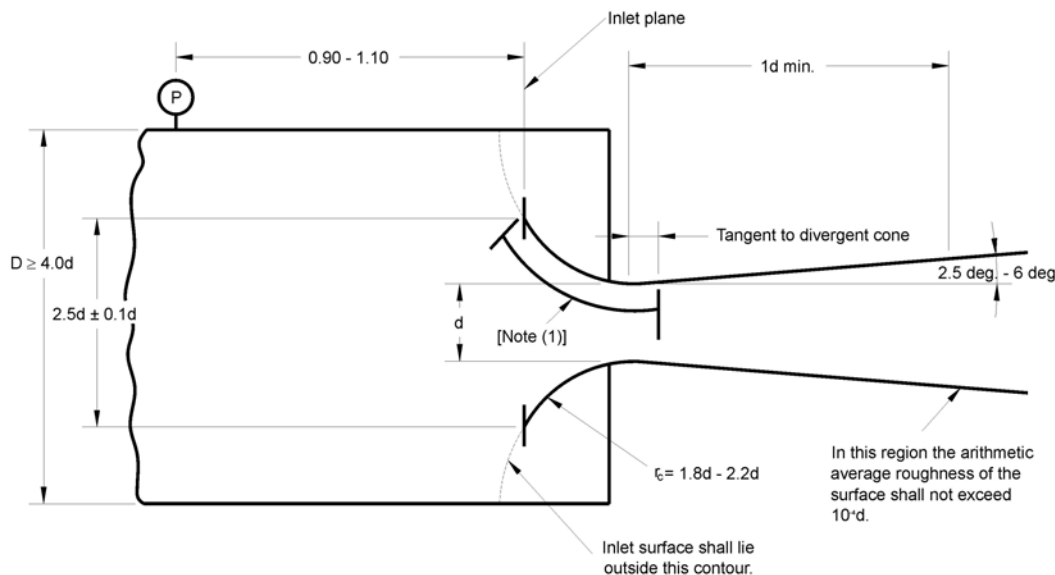
For a given throat diameter, d , the inlet plane of the nozzle element perpendicular to the axis of the symmetry of the throat diameter is equal to **2.5 times the throat diameter, or $2.5 \cdot d$** , with an allowable uncertainty of $\pm 0.1d$.

The converging part of the sonic nozzle converges from the inlet plane to the nozzle throat diameter with a radius of curvature equal to **2 times the throat diameter, or $2.0 \cdot d$** , with an allowable uncertainty of $\pm 0.2d$. The inlet convergent part of the nozzle actually extends through the throat and is tangent to the nozzle's recovery cone, or divergent section.

The nozzle divergent section, or recovery cone, forms a frustum of a cone with a half-angle between 2.5 and 6 degrees or a full cone angle between 5 and 12 degrees. The length of the recovery cone must be at least one times the throat diameter. Modern designs permit a recovery cone length between **7 times to 10 times the throat diameter, or between $7 \cdot d$ to $10 \cdot d$** , with a divergent angle between 7 or 8 degrees.

Smith and Matz originally designed their critical flow nozzle to have a recovery cone angle equal to 12-degrees. Further testing of sonic nozzle designs by the natural gas industry found that a more shallow recovery angle equal to 7 or 8 degrees actually provided better pressure recovery, meaning that the shallow nozzle design was more practical than the steeper 12-degree cone.

Figure 1.2 shows the ASME/ANSI standard nozzle design, from the MFC-7M publication. Please note that a specification has been chosen for the nozzle's internal surface roughness. A surface roughness no greater than $0.000015d$ is required in the convergent and nozzle throat section (the entire radius of curvature), and a surface roughness no greater than $0.001d$ is required in the nozzle recovery cone. The minimal surface roughness specification is required to guarantee that the fluid flow through the nozzle remains streamlined and attached to the internal wall, minimizing the boundary layer thickness.



NOTE:

- (1) In this region the surfaces shall not exceed $15 \times 10^{-6} d$ arithmetic average roughness and the contour shall not deviate from toroidal form by more than $0.001d$.

Figure 1.2: ASME/ANSI NOZZLE STANDARD

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The specified nozzle geometry outlined by Smith and Matz was developed to facilitate a more accurate method for calculating the nozzle's discharge coefficient. As stated earlier in this section, the discharge coefficient is required for computing deviations from ideal flow conditions, or deviations from one-dimensional isentropic flow. Distortions from ideal flow conditions are created from a finite boundary layer thickness between the fluid profile and the internal nozzle wall and the slight change in flow direction as the fluid (or gas) travels in through the nozzle inlet plane and through the convergent section. The Smith and Matz design has been thoroughly tested by the aerospace and natural gas industry to ensure that the value of the nozzle discharge coefficient is minimized.

1.5. Nozzle Flow Calculations

The standard sonic nozzle flow equation is expressed in terms of mass flow rate and is defined as follows:

$$Q_M = C_d * A_t * C' * P_P * (R_M T_P)^{1/2}$$

Where...

Q_M = mass flow rate (lb./sec.)

C_d = nozzle discharge coefficient (dimensionless)

A_t = nozzle throat area (in.²)

C' = nozzle critical flow factor, which is = $(k)^{1/2} (2 / (k+1))^{(k+1) / (2(k-1))}$
where k = ratio of specific heats for the fluid or gas

P_P = nozzle inlet plenum pressure, absolute (psia)

R_M = gas constant = 48.03 / (Molecular Weight)

T_P = nozzle inlet plenum temperature, degrees Rankine (°R)

Since the need for sonic nozzles in the natural gas industry is mostly for volume measurement and analysis, the calculation of volumetric flow rate of gas or air through a nozzle is more convenient than that of mass flow rate. The volumetric flow rate through the nozzle can be expressed in terms of the upstream stagnation pressure and temperature.

The volumetric flow rate is defined as...

$$Q_V = C_d * A_t * C^* * Z_P * (R_V T_P)^{1/2}$$

Where...

Q_V = volume flow rate (cubic feet per second) at an upstream pressure and temperature

Z_P = compressibility factor upstream of the nozzle

R_V = gas constant = 2.398 / (Molecular Weight)

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The terms in the above equation are fixed for a given nozzle and gas composition. The sensor measurements required to calculate the nozzle volumetric flow are upstream pressure and temperature. Future discussions will mention the need to measure relative humidity when air is used as the flow medium (to correct for changes to the specific gravity of air due to water vapor content).

With the theory of volumetric flow through a sonic nozzle element defined, the task at hand is to take this theory and apply the math and technology toward the natural gas industry to measure the performance and accuracy of gas metering equipment.

2. APPLICATIONS OF SONIC FLOW NOZZLES

As stated in the previous section, the sonic flow nozzle element restricts upstream volumetric flow by achieving local sonic velocity at the nozzle throat. The local sonic velocity at the nozzle throat is defined as critical flow. Critical flow is maintained through the nozzle element, as long as a minimum of 10% of the absolute upstream inlet pressure is maintained. Therefore, a given sonic nozzle element, of a given size and throat diameter, will produce a given volumetric flow rate.

The sonic flow nozzle can be used as a metering device for air or natural gas. The use of a sonic nozzle within a flow regime will restrict the rate of flow of gas or air, as long as the minimum differential across the nozzle is maintained. Similarly, the sonic nozzle can be used as a gas meter proving device — measuring the accuracy and performance of a gas meter by passing a defined volume of air or gas through the gas meter and sonic nozzle over a specified period of time. Volume measured by the gas meter can be compared with actual volume passed through the meter and controlled by the sonic nozzle element to determine the accuracy of the gas meter.

2.1. Calibration Methods of Sonic Flow Nozzles

There are two ways in which the volumetric flow rate through a sonic nozzle element can be determined:

- Physical measurement of the nozzle throat diameter
- Calibration using a volume standard

Physical measurement is the easiest method to determine the nozzle flow rate. Once the nozzle throat diameter is measured, its cross-sectional area is known, and the nozzle volumetric flow rate can be calculated based on the relationship described in section 1.5.

Physical measurement of nozzle throat diameters, however, is not always practical. For example, domestic and light commercial gas meters are commonly tested at flow rates of less than one hundred cubic feet per hour. For a sonic nozzle to restrict flow below 100 cfh, its nozzle diameter must be machined to an orifice size of less than 0.1 inches. As a nozzle throat diameter becomes smaller, the effect of the boundary layer thickness can be interpreted as the nozzle discharge coefficient.

The larger the nozzle throat diameter, the less effect the nozzle discharge coefficient has on the actual flow traveling through the throat. Therefore, larger nozzle throats (greater than one inch) can be measured to determine the volumetric flow rate of the sonic nozzle element at specific conditions (with minimal uncertainty).

The majority of sonic nozzle elements used in distribution measurement, however, have nozzle throat diameters much smaller than one-inch, and therefore calibrated nozzle volumetric flow rate must be determined using a volume standard.

2.2. Bell Prover Calibration of Sonic Flow Nozzles

Sonic flow nozzles can be calibrated against a known volume standard. In the natural gas industry, the most common and practical volume standard is the bell prover.

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Sonic flow nozzles can be calibrated in two different ways using a bell-type prover: under positive pressure or at atmospheric pressure.

Figure 2.1 shows a sonic nozzle calibration using a bell-type prover under positive pressure. Compressed air is regulated upstream of the nozzle element using a precise flow regulator. A dead-weight tester loaded to the required nozzle inlet pressure ensures that the regulator controls

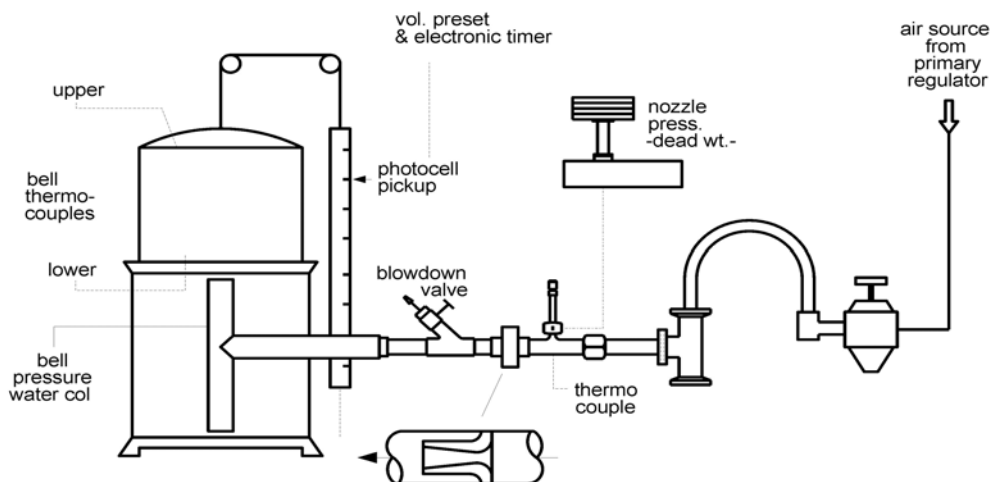


Figure 2.1: POSITIVE PRESSURE BELL CALIBRATION OF NOZZLES

the compressed air pressure. Temperature and pressure measurements are made at the nozzle inlet plane in accordance with the ASME/ANSI MFC-7M standard (see reference).

Once the compressed air has traveled through the nozzle element, the air fills the bell prover. Again, pressure and temperature measurements are made at the bell prover. An electronic timer device (such as an optical pick-up) “gates” the amount of bell volume passed by recording bell prover scale increments.

The calibration of the sonic nozzle element is normally standardized to a base condition, so that the element can be inserted into various field applications with varying pressure and temperature ranges. When a sonic flow nozzle is calibrated under positive pressure, the standard conditions are normally 60° F, 14.696 psia, and dry air (0% relative humidity).

Figure 2.2 shows a sonic nozzle calibration using a bell-type prover at an atmospheric condition. A bell prover filled with air under nominal bell prover pressure (1.5 inches or 2 inches water column (wc) is placed upstream of the nozzle under calibration. A vacuum generator or mechanical pump physically draws the air out of the bell prover and through the nozzle element. Pressure and temperature measurements are taken at the bell prover and at the nozzle inlet plane. A gauge placed downstream of the sonic nozzle element monitors the exit pressure to guarantee sonic velocity at the nozzle throat. As the bell prover empties air through the nozzle, an electronic timer device (optical sensor) monitors the cubic foot graduations of the bell scale. For an atmospheric nozzle calibration, standard conditions are normally 60° F, 14.696 psia, and dry air (0% relative humidity).