Title: Balanced Flow Metering and Conditioning Technology for Fluid Systems

Paper Abstract:
Revolutionary new technology that creates balanced conditions across the face of a multi-hole orifice plate has been developed, patented and exclusively licensed for commercialization. This balanced flow technology simultaneously measures mass flow rate, volumetric flow rate, and fluid density with little or no straight pipe run requirements. Initially, the balanced plate was a drop in replacement for a traditional orifice plate, but testing revealed substantially better performance as compared to the orifice plate such as, 10 times better accuracy, 2 times faster (shorter distance) pressure recovery, 15 times less acoustic noise energy generation, and 2.5 times less permanent pressure loss. During 2004 testing at MSFC, testing revealed several configurations of the balanced flow meter that match the accuracy of Venturi meters while having only slightly more permanent pressure loss. However, the balanced meter only requires a 0.25 inch plate and has no upstream or downstream straight pipe requirements. As a fluid conditioning device, the fluid usually reaches fully developed flow within 1 pipe diameter of the balanced conditioning plate. This paper will describe the basic balanced flow metering technology, provide performance details generated by testing to date and provide implementation details along with calculations required for differing degrees of flow metering accuracy.
Balanced Flow Metering and Conditioning Technology for Fluid Systems
(Space Liquid Propulsion Systems)

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Large Rocket Engine Environments

- Very hot (~6000°F)
- Extreme cold (~-400°F)
- Vibration
- Volatile fluids (liquid oxygen, etc.)
- High pressures (~7,000 psi.)
- Extreme fluid velocities (flow rates, Reynold's numbers > 10^7)
- Fast control loops and failure propagation (<3 seconds to full destruction)
- Industry seldom operates in these regimes
- One failed ground test (turbine meter) ~$200M impact

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Problem

- Turbine failure resulted in no LOX flow meter for flight hardware
- Need safe flow metering technology for liquid rocket engines
- Failed past attempts
  - Turbines (work, but severe failure)
  - Vortex shedders
  - Ultrasonic
  - Venturi Tubes (work, but too large for flight)
  - Etc.

NASA Flow Meter Requirements

- Different fluids: LH2, LOX, RP1, etc.
- Different physical states: Gas, Liquid, Multi-Phase
- Wide range (both high and low) in temperature, pressure, vibration and flow conditions
- Very low flow intrusion with near full pressure recovery
- No moving parts
- Minimal piping requirements
- Drop-in replacement of an orifice-plate
- Robust mechanical design
- Highly accurate and repeatable flow measurement
- Easy calibration and maintenance
- Need for high through-put flow areas with low flow restriction

Most needs are common with industrial needs...
Balanced Flow Meter Solution

- NASA patented technology #10/750,628
- Allows engine measurements where none were before
- Ability to condition or measure flow while improving velocity or other profiles
- Provides flow measurement, conditioning, and controlled restriction performance
- Ability to function with minimal straight pipe run
- Measure mass flow rates, fluid volumetric flow rates and density simultaneously
- Sensor set up can provide a triple redundant measurement system
- Successfully fielded by industry

Possible configuration...

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What is Balanced Flow Technology?

- A thin, multi-hole orifice plate with holes sized and placed per a unique set of equations to produce mass flow, volumetric flow, kinetic energy, or momentum BALANCE across the face of the plate

Chevron-Texaco 18 inch Commercial Plate

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How Does It Perform?

Comparison of standard orifice to balanced flow meter, both with 27.1% open area
Results based on compressed gas testing

- 10X better accuracy
- 2X faster pressure recovery (shorter distance)
- 15X noise reduction
- 2.5X less permanent pressure loss
- Exclusively licensed through NASA by A+FlowTek for commercialization

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Configurations Tested in 2004

- Figure 1 Slotted Configuration
- Figure 2 Iron Cross Configuration
- Figure 3 Single Ring of Holes Configuration
- Figure 4 Custom Hole Configuration

Permanent pressure loss, accuracy and discharge coefficient comparable with a Venturi meter!

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Balanced Flow Meter Characteristics

- Minimal straight pipe run requirements—BFM has less than 0.5 X pipe diameter straight pipe requirement
- Only requires 0.25 to 0.5 inch thickness and approximately 3 PSI across the plate to condition and monitor flow
- Relatively low cost to build and operate
- Accuracy comparable to Venturi meters

- Cons—similar limitations as standard orifice
  - Not good for pulsing flow
  - Limited turn down

How Does it Work?

- Basic design based on multi-hole orifice plate
- Basic relation is the Bernoulli equation
  - Requires custom Cd calculation
  - Long for Bernoulli equation required for high accuracy applications
  - Highest accuracy applications require physical properties models
- Flow proportional to SQRT of delta P
  
  Key design factor is the hole distribution
Technical Basis—BFM Hole Layout

- Plate hole layout basic equation
  \[ \kappa_p A V^n = \text{Constant for each hole} = (\kappa_p A V^n)_1 = (\kappa_p A V^n)_2 \ldots = (\kappa_p A V^n)_i \]
  
  At \( \kappa_p A_i = \kappa_p A_i \)
  \[ A_i/A_i = (V_i/V_i)^n \]
  
  To simplify, let \( n = 1 \)
  \[ A_i/A_i = V_i/V_i \]

- Example, given a velocity distribution function
  \[ V_i/V_{max} = (1 - R_i/R_{wall})^{1/7} \]

- Radial velocity ratios
  \[ V_i/V_i = ((1 - R_i/R_p)/(1 - R_i/R_p))^{1/7} = A_i/A_i \]

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Technical Basis—BFM Hole Layout

Cont.

- Subsequent radial areas
  \[ A_i = A_i/((1 - R_i/R_p)/(1 - R_i/R_p))^{1/7} \]

- Radial area equation
  From \( \beta^2 = A_{total}/A_{pipe} \)
  And multiple holes,
  \[ A_0 + A_1 + A_2 + \ldots + A_n = A_{total} = \beta^2 A_{pipe} \]

- Hole diameters at radius \( i \)
  \[ D_i = (4A_i/\pi N)^{1/2} \]

Sheer stresses typically lower than standard, single-hole orifice!
Tech Basis-Bernoulli Equation

- Bernoulli Equation—longer form
  \[(P_a-P_b)/\rho + g(Z_a - Z_b)/g_c + (\alpha_a V_a^2 - \alpha_b V_b^2)/2g_c - h_f = 0\]

- Equation of Continuity
  \[(\rho AV)_a = m = (\rho AV)_b\]

- Simplified Bernoulli Equation—assume constant density (incompressible), frictionless fluid (zero viscosity), and no elevation changes
  \[(P_a-P_b)/\rho + (V_a^2 - V_b^2)/2g_c = 0\]

- Equations from ISO 5167-1, API 14.3.1, etc. Derivations in multiple texts.

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Tech Basis-Bernoulli Equation

- Beta area ratio
  \[(\beta)^2 = A_b/A_a\]

- Flow Equation
  \[m = C_D Y_b (2g_c \rho (P_a - P_b)/(1 - \beta^4))^{1/2}\]

- There can be longer equation forms with many other factors, such as expansion factors, compressibility factors, meter correction factors, etc.

  Typical Uncertainties
  - Gas Flow: +/- 0.67% (API 14.3.1)
  - Liquid Flow: +/- 0.57% (API 14.3.1)
  - Spec values are EXTREMELY conservative

  BFM Lab Accuracies
  - +/- 2% without calibration
  - +/- 1.0% long equation
  - Calculated +/- 0.1% custom equation, calibrated
  - BFM calculated value: +/- 0.25% (Directly measured)

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MSFC Water Calibration Facility

- National Institute of Standards and Test (NIST) certified
- Volumetric system
- 5000 gallons
- Pump or gravity fed
- Quad deionized water
- 0.25% flow accuracy over unit of time between level sensors
- 0.15% repeatability at given flow set point

MSFC Gas Calibration Facility

- Positive displacement, inverted cylinder system
- NIST certified
- Multiple gases including N, He, Air, Argon, Freon
- 0.01 to 3000 psi operation
- .01 to 400 SCFM
- Accuracy & repeatability???
Cd and K Factor Comparisons

Balanced Flow Meter plate performance,
from minimum flows to sonic

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<th>BETA</th>
<th>0.25</th>
<th>0.500</th>
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<th>0.650</th>
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<td>0.010</td>
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<td>Avg K Val</td>
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<td>13.2</td>
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<td>0.53</td>
<td>0.16</td>
<td>1.23</td>
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Note: Venturi values do not include downstream losses.

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BFM vs. Orifice Flow Equation

\[ y = 45.94x \quad R^2 = 0.9985 \]
\[ y = 37.781x \quad R^2 = 0.9695 \]

Note: The images contain graphs and equations related to flow measurement and comparison between different flow meter types. The graphs illustrate the relationship between differential pressure and air flow, showing linear regressions with high correlation coefficients.

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BFM Calibration Cd

ORIFICE/VENTURI COEFFICIENT (Cd) PLOT
Balanced Inline and Staggered beta 0.50 Flat side upstream.xls

Will change this chart—simplify by removing 2 plots and change y axis scale like next chart

NOTE: PIPE ID = 1.5 INCH

BFM K Factor Plots

VELOCITY HEAD LOSS CONSTANT (K) PLOT
Balanced Inline beta 0.650.xls

Theoretical lines, not Real data
BFM vs. Standard Orifice Pressure Recovery

Pressure Recovery % versus Air Flow %

BFM vs. Orifice Acoustic Noise

Flow Meter Noise @ 1 ft and 90% Air Flow
Why Does This Matter?

- Believe will meet NASA liquid engine flow meter requirements—test program on-going
- Provides safe, rugged, robust flow meter
- Provides drop-in orifice meter replacement
- Increases fluid system efficiency to save $$$
- Provides multiple benefits with relative low-cost
  - Reduced piping requirements
  - Reduced noise generation (EPA regulations)
  - No moving parts, simple design
  - Capable of simultaneous fluid metering and flow profile conditioning
  - Robust calibration—well defined and characterized traditional techniques
  - Typical +/- 0.15% accuracy of measured flow throughout measurement range
  - Reduced pump energy requirements
    - High pressure recovery
    - Low permanent pressure loss

Lessons Learned

- Always double check flow meter vendor claims, flow equations, and calibration techniques
- There are hundreds of emerging flow metering technologies—stringently define your unique requirements
- Determine best calibration method for your application—in-situ system level calibration vs. typical individual component calibration
- Test/Calibrate as you intend to use the meter—if possible, test your new meter!
- Follow standards for instrument placement, uncertainties, etc., but not for plate thickness!
Useful References

- The measurement, instrumentation, and sensors handbook, John G. Webster, CRC Press & IEEE Press

What about current standards...can we use them or do we have to modify equations?
- Any knowledge of cryogenic calibration facility?