MSFC-018—PAPER

DENSITY AND CAVITATING FLOW RESULTS FROM A FULL-SCALE OPTICAL MULTIPHASE CRYOGENIC FLOWMETER

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ABSTRACT

Liquid propulsion systems are hampered by poor flow measurements. The measurement of flow directly impacts safe motor operations, performance parameters as well as providing feedback from ground testing and developmental work. NASA Marshall Space Flight Center, in an effort to improve propulsion sensor technology, has developed an all optical flow meter that directly measures the density of the fluid. The full-scale sensor was tested in a transient, multiphase liquid nitrogen fluid environment. Comparison with traditional density models shows excellent agreement with fluid density with an error of approximately 0.8%. Further evaluation shows the sensor is able to detect cavitation or bubbles in the flow stream and separate out their resulting effects in fluid density.

INTRODUCTION

The basic thermochemical properties of cryogenic fluids make the control and optimization of these systems difficult. Cryogenic fluid flow systems inherently operate at or near the fluid's boiling point. In this environment, the liquid phase and gas phase may coexist in a two-phase flow. Any energy loss by the fluid through friction, thermal sources, collisional turbulence, or cavitation, will cause an increase transition from the liquid phase to the gaseous phase. This makes it difficult to make any measurements without understanding the density state of the fluid.

The quantification of volumetric or mass flow is one of the most difficult measurements to make in even a well-characterized fluid. This is made more difficult in a demanding environment such as a cryogenic fluid. The value determined often has great impact on the work being conducted, particular in liquid propulsion systems. Commonly used instrumentation measurement techniques include the use of differential producers. These are most commonly represented by turbine, Venturi-, flow nozzle- and orifice plate-type devices. The performance, in actual application in transient, multiphase cryogenic system, is much poorer than that stated by manufacturer specifications. These devices, while commonly applied, have embedded theoretical limitations that affect their accuracy, reliability and repeatability [1-6].

OPTICAL FLOW SENSOR

The optical sensor developed at Marshall Space Flight Center has been previously described in a variety of works [7-9]. In brief, it operates by determining the relative angular shift in two or more co-aligned optical beams at different wavelengths. The fluid is physically modeled as a multi-component dielectric (i.e. mixture of denser and less dense dielectric components). Effective medium theory models are then applied to this construct [10-13].

The sensor physically has been tested in a 5.08 cm outer diameter (2") tubing system, Figure 1. The device has an inner diameter of 4.62 cm (1.82") and mates between flanges using traditional sealing techniques. The current prototype is fabricated from aluminum and has been cryogenic operated for over 50 hours in submerged liquid nitrogen (see below). The sensor has been hydrostatically tested in excess of 204 atm (3000 psi) without failure. The device uses fiber optic coupling techniques for coupling light into and out of the flow stream. The optical elements only minimally protrude into the flow stream (0.034% of the diameter is obstructed). No pressure drop has been recorded across the optical elements, so any effects of the sensor on the flow are well below 0.0068 atm (0.1 psi).

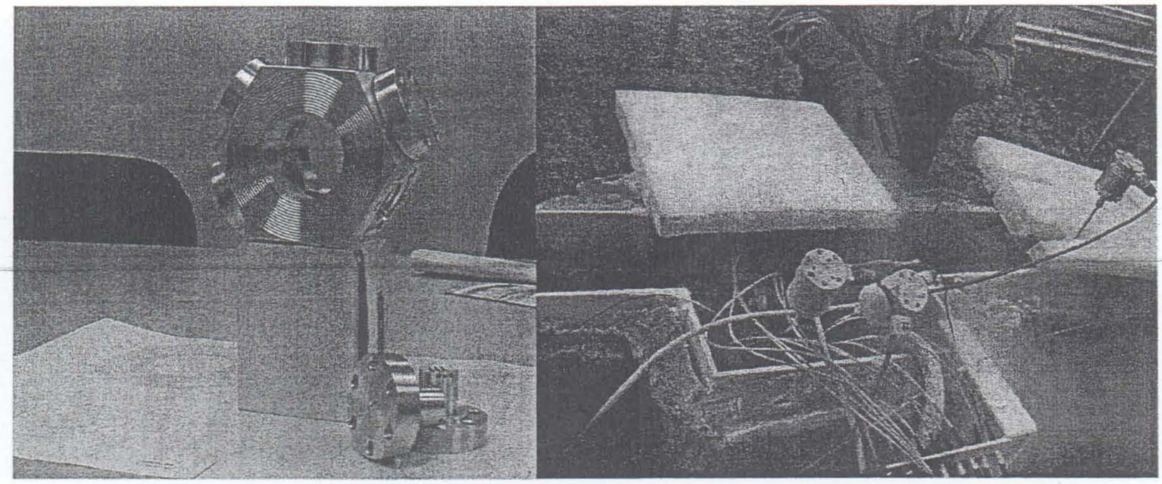

Figure 1. Mechanical frame of the optical flow sensor (left). The device has an inner diameter of 4.62 cm (1.82"). Optical sensor installed in the liquid nitrogen test bed (right).

CRYOGENIC TEST SYSTEM

A fluid test bed was designed and fabricated to test and validate the optical flow sensor. Liquid nitrogen (LN2) was chosen as the cryogenic fluid. It provides a real cryogenic environment common to propulsion and industrial systems alike while maintaining a reasonable safety measure and cost. One main concern was the control of the phase of the cryogenic fluid by minimizing the perturbations to the flow and external energy sources. To this end the entire fluid pipe system was designed to be immersed within a foam-insulated trough containing LN2, Figure 2. This liquid jacketing approach is not uncommon in critical flow systems, and helps maintain the uniformity of the pipe wall temperature. This removes a major source of thermal heating of the fluid flow.

The system was arranged in a linear fashion. The straightening of the system minimizes potential perturbations caused by elbows, bends, and splitting junctions common in typical flow systems. Additionally, the instrumentation was selected to minimize the intrusive nature of the fluid flow path. The LN2 flowing through the system was dumped directly onto the ground. This minimized any back pressure or restriction (choke) produced from the fluid exiting the system.

The design considerations to this point were directed toward maintaining the single phase liquid nitrogen fluid flow. A gaseous helium injection system was chosen to create and control the gas phase of the fluid. The boiling point of helium is over 73 Kelvin below that of nitrogen. This would insure that the helium maintained only a gas phase (GHe) in the presence of the LN2.

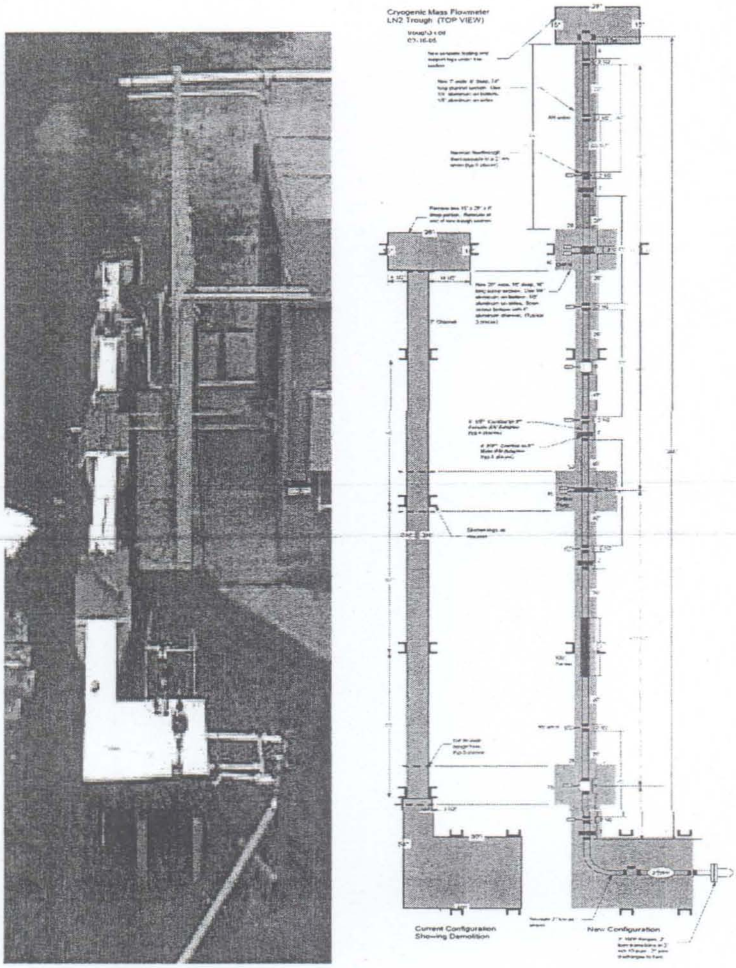

Figure 2. The liquid nitrogen and gaseous helium test bed used to test the optical sensor in transient multiphase flow conditions. The straight length of the system is approximately 8.5 m.

RESULTS AND DISCUSSION

Cryogenic flow testing was conducted of a wide range of flow conditions. Testing typically consisted of opening a set of pneumatic cryogenic valves with a period of stable flow and a reversed valve profile for closing. Parallel to the liquid flow routine, gaseous helium was injected from a high pressure feed system using a solenoid valve to create a controlled period of gaseous bursts. The first burst was approximately 2.5 seconds in duration and overlapped the liquid flow ramping phase. This provide a highly dynamic density and bubble profile. The second gas discharge was approximately 3.5 seconds in duration and coincided with the relatively stable period once the flow was established. Figure 3 illustrates the general testing profile compared to the measured density from the optical sensor. Note the spurious spin-down of the GHe turbine during the periods the gas system is closed to the flow system via solenoid valve. Data recorded at 40,000 samples per second. Supporting instrumentation was available for comparison of flow performance (liquid turbine, gaseous turbine, and various pressure and temperature sensors throughout the flow system).

It is clear from Figure 3 that the optical sensor and fluid model applied provide a method for coupling the optical response of the sensor to the fluid conditions of interest, mainly density.

Further, investigations into the response of the optical sensor showed the ability to detect bubbles in the flow. Figure 4 shows the bubble response from the same data set illustrated in Figure 3. The bubble response is directly related to bubble the individual bubble size. Further testing is required to characterize the sensor's response to particular bubble sizes.

An algorithm was created to separate the density-based response with the bubble response. The algorithm exploits the statistical relationship between the mode and the mean of the data set. When bubbles are not present the statistical mode and mean agree. In the presences of bubbles in the flow path however, the values of the mode and the mean separate.

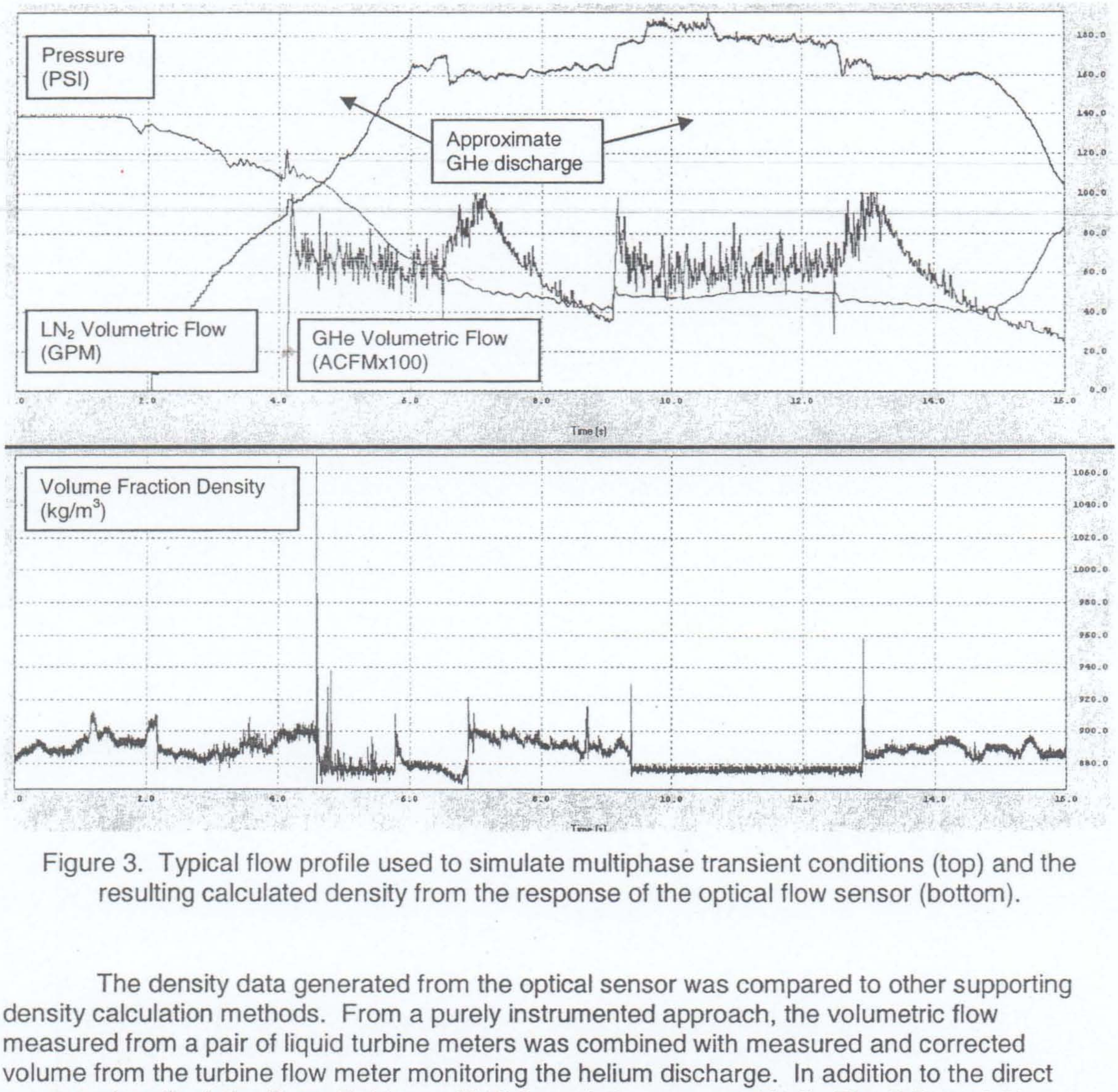

Figure 3. Typical flow profile used to simulate multiphase transient conditions (top) and the resulting calculated density from the response of the optical flow sensor (bottom).

The density data generated from the optical sensor was compared to other supporting density calculation methods. From a purely instrumented approach, the volumetric flow measured from a pair of liquid turbine meters was combined with measured and corrected volume from the turbine flow meter monitoring the helium discharge. In addition to the direct measured method, the Peng-Robinson (P-R) formulation was used [14]. The P-R model is a multiple parameter equation of state that can numerical provide accurate density conditions of the fluid using various tabulated parameters and measures temperature and pressure values. Since the optical sensor under test was based on the interaction of an optical beam through the fluid, a more basic bulk or Rayleigh scattering model was also applied used [15-16].

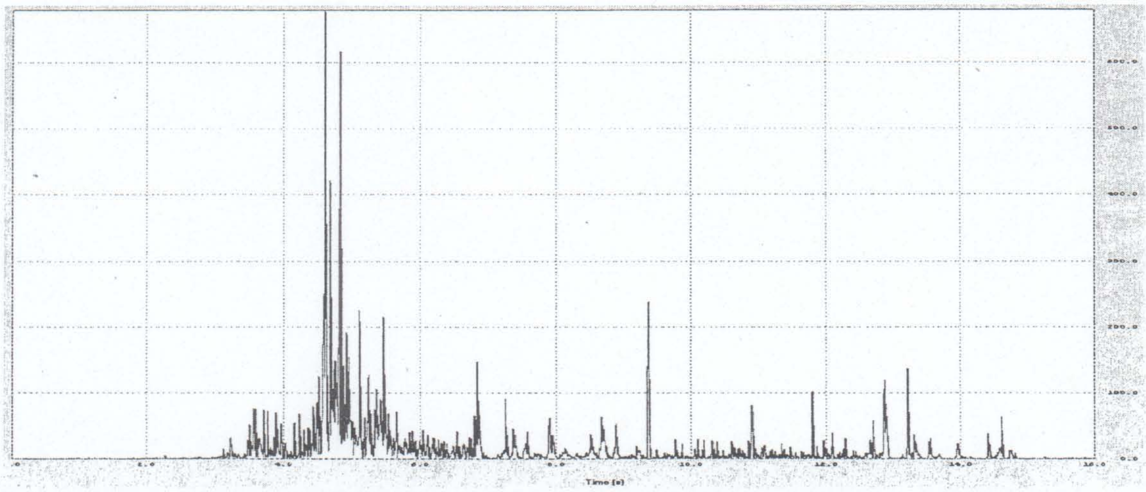

Figure 4. Optical response to the prescience of bubbles in the fluid flow stream. Signal amplitude is related to bubble size.

The various methods of density generation were compared for the sample test profile, Figure 5. Clearly the ranges and response of the primary optical method agree with the other two methods. A few observations are of note. The general trends of both optical methods agree, but they seem to follow the resulting density calculated from the P-R model. Comparison with the liquid flow and gaseous discharge shown Figure 3 illustrate in fact, that the P-R method is actually ahead of the valve events. As with any equation of state (ideal gas, van der Waals, Peng-Robinson, etc.) it relies on a condition of equilibrium. Since the input to the model is pressure and temperature, the model will additionally be subject to any latencies or artifacts of those measurements. This illustrates the limitations of current density correction methods in transient conditions.

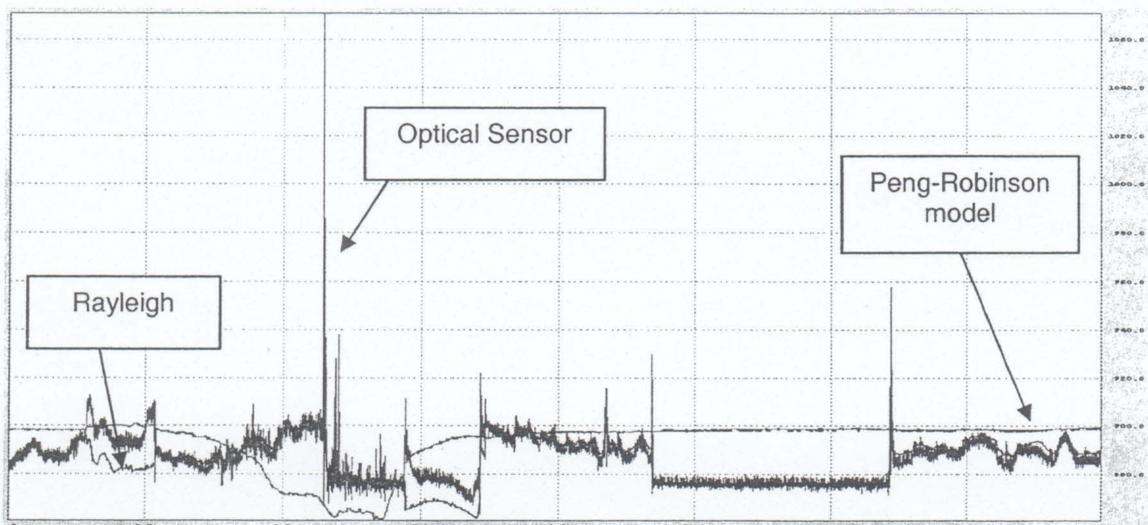

Figure 5. Comparison of the density measured by the optical sensor with the calculated density from a Peng-Robinson model and a bulk optical scattering (Rayleigh) measurement.

The data generated by the optical sensor is also capable of observing shock or water hammer events that coincide with the flow conditions. Figure 6 shows a closer view of the region of the relatively stable liquid and gaseous flow. This fairly stable region was used to characterize the density response of the optical sensor. Calculations were made in this region based on the supporting instrumentation to generate a density via a fluid displacement method. Depending on the particular method up to a 2% error in density is observed. This would directly correspond to a 2% error in mass flow. Based on the purely volumetric values for the LN2 and GHe, the density shift should be approximately 1.5% to 1.7%. Numerous data were obtain at various flow conditions and density profiles including helium free flows. All the data agreed well and provide similar results as shown here.

No sensor exists capable of providing density information in these flow conditions. Error analysis was performed through repeated testing and statistical analysis. Based on a sample set of over 2 million points, the 3 sigma error in density of the optical sensor is 0.8%. The calibration for the optical sensor is based on the physical properties of the constituent of the flow. This may be done in the laboratory and does not require calibration or testing under the flow conditions. The calibration technique for the Rayleigh method requires fit parameters that where provide by the P-R model to provide general density range values (mean density).

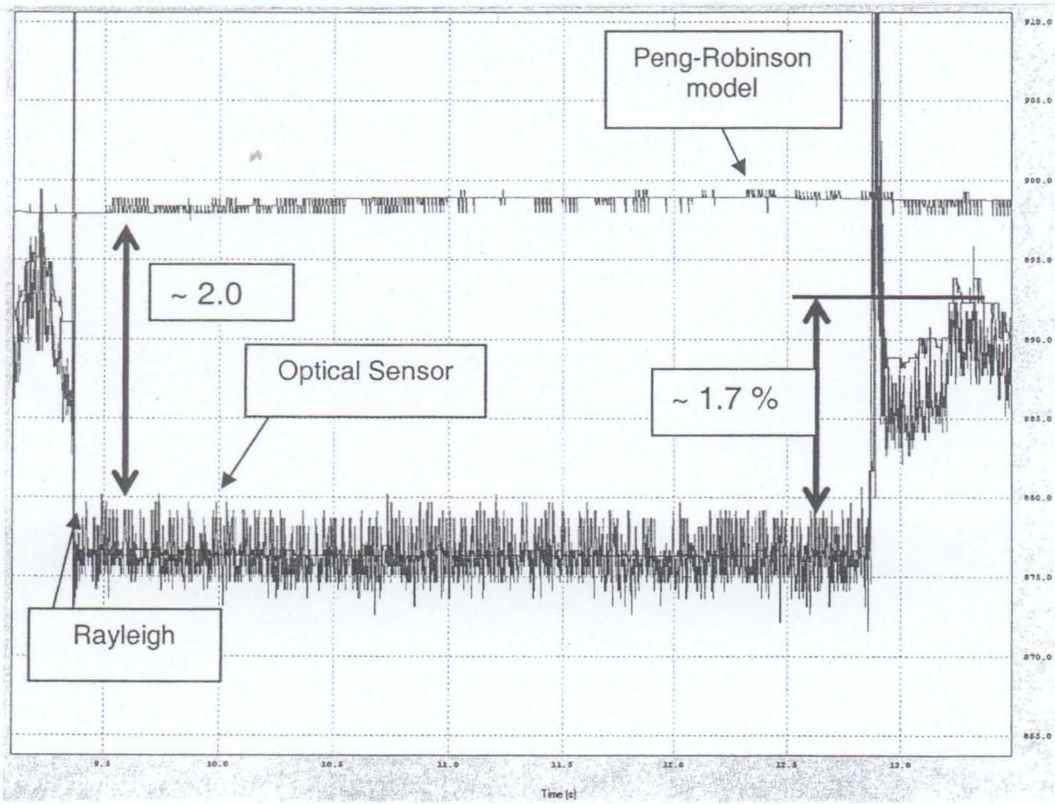

Figure 6. Closer view of the second gas release phase with relative density shifts.

In addition to the performance of the sensor describe here, the most recent testing has provided multi-dimensional data. From Figure 1 one can see that the sensor is capable of measure the above data in different 'slices' through the fluid. Recently, two slices were employed in flow testing. One slice was oriented vertically and the other was 60 degrees from vertical. From these two slices two additional slices were linearly interpolated and vertical symmetry was applied to generate a full cross-sectional view of the density and bubble conditions of the flow stream. Figure 7 shows the resulting density profile in a variety of views. The data is plotted as a deviation from the mean density (delta density). Likewise Figure 8 shows the response of the optical flow meter to the bubbles in the flow stream. Clear evidence is present in Figure 7 to observe the gaseous discharge response. Likewise Figure 8 shows the bubble response change from an initial large bubble size in the first gas region where the flow is still increasing to a smaller, more stable bubble distribution in the latter gas discharge phase.

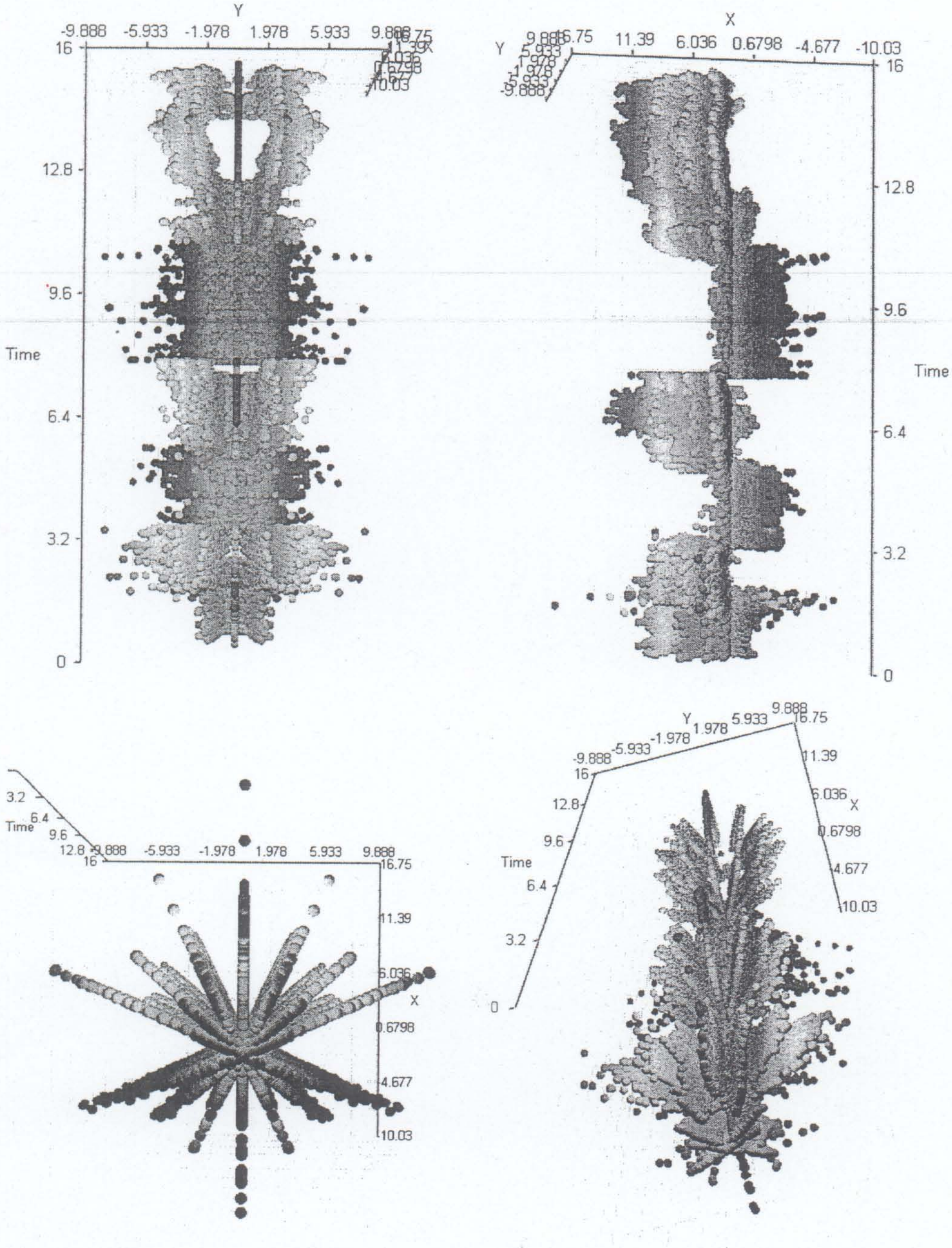

Figure 7. Cross-sectional measured distribution of the change in density generated by the optical flow sensor.

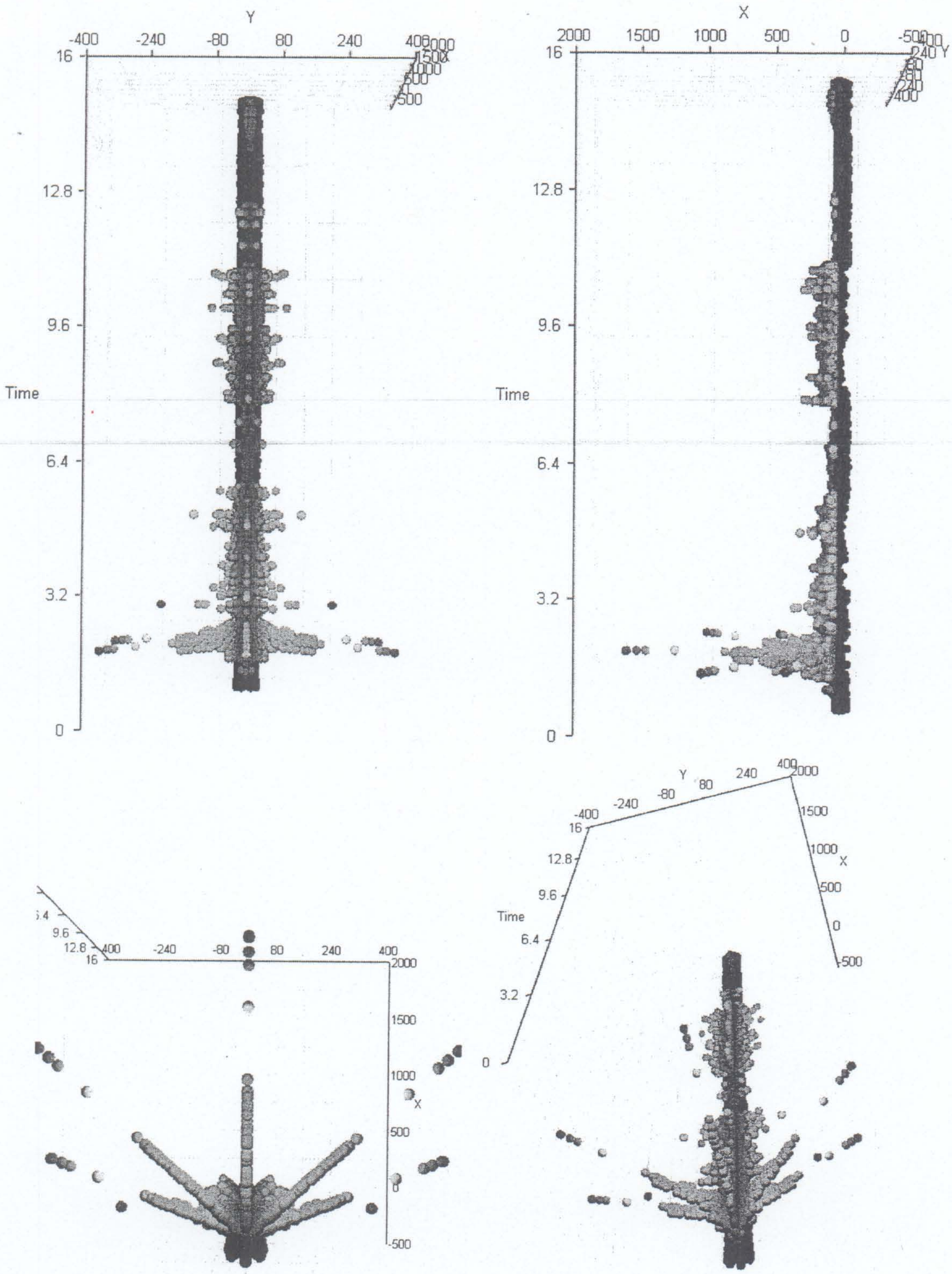

Figure 8. Cross-sectional measured bubble response generated by the optical flow sensor.

SUMMARY AND CONCLUSIONS

The optical sensor described here is unique in its ability to not only directly measure the density and bubble presence within a transient and multiphase cryogenic flow, it also has the ability to provide multi-dimensional data that begin to approach numerical fluid modeling performance. The sensor has been fully tested in a liquid jacketed liquid nitrogen system using gaseous helium discharges to simulate various density profiles and provide multiphase flow conditions.

FUTURE WORK

Continued testing is planned of the optical sensor. Current efforts are underway to incorporate multi-dimensional velocity data and provide real-time mass flow values in addition to density and bubble distribution. Future testing is also planned to calibrate the bubble response. In additional to the flow system and sizes mentioned here, hardware is in development for a smaller and larger device (1.3 cm and 20 cm respectively) with the added capability of operating in LOX and Hydrazine compatible environments.

ACKNOWLEDGMENTS

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MSFC-018-PRESENTATION

Density and Cavitating Flow Results from a Full-Scale Optical Multiphase Cryogenic Flowmeter

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John T. Wiley (NASA/MSFC)
Kevin Pedersen (NASA/MSFC)
Dr. Don A. Gregory (UAH)

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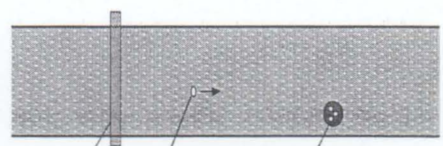
Introduction

Fundamental Flow Measurement



Area (cross-section) $[m^2]$ **X** Velocity $[m/s]$ **X=** Density $[kg/m^3]$ = *Volumetric Flow* $[m^3/s]$ = *Mass Flow* $[kg/s]$

Introduction to Flow Measurement for Propulsion Applications

Combustion Fuel/Oxidizer Environment
- Multiphase
- Multi-component
- Highly Transient
- Volatile

Specific Impulse $$I_{sp} = \frac{\int_0^t F_{thrust}\, dt}{g_o \int_0^t \dot{m}\, dt}$$

"It is difficult to measure the propellant flow rate accurately…therefore [specific impulse] is calculated from propellant weight"

From *Rocket Propulsion Elements*, George Sutton.

Current Flow Measurement Methods

Lineage of Modern

•A steady-state and streamline

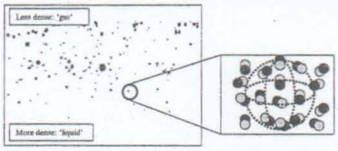
ρ_{fluid} The fluid density term is the culprit.

"There are numerous tabulated values for various fluids under many thermodynamic conditions. These values have some associated errors that propagate through the measurement…Accurate thermodynamic conditions are rarely sufficiently known to do anything more than approximate or extrapolate from tabular values. "

From *Flow Measurement Engineering Handbook*, R.W. Miller

Density and Cavitating Flow Results from a Full-Scale Optical Multiphase Cryogenic Flowmeter

Effective Medium Theory for a Multiphase System



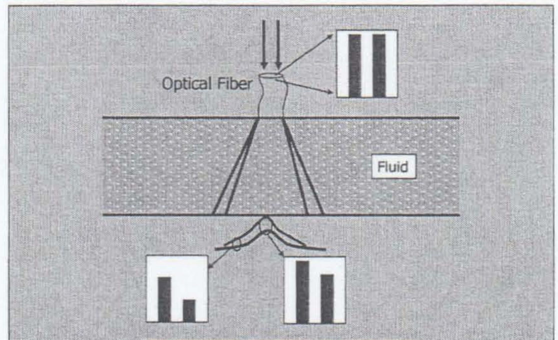
$$\eta_{liquid}\left(\frac{n_{liquid}^2 - n^2}{n_{liquid}^2 + 2n^2}\right) + \eta_{gas}\left(\frac{n_{gas}^2 - n^2}{n_{gas}^2 + 2n^2}\right) = 0$$

$$n = \frac{1}{2}\sqrt{\left(n_{gas}^2\left(2 - 3\eta_{liquid}\right) + n_{liquid}^2\left(-1 + 3\eta_{liquid}\right) + \sqrt{8n_{gas}^2 n_{liquid}^2 + \left(n_{liquid}^2\left(1 - 3\eta_{liquid}\right) + n_{gas}^2\left(-2 + 3\eta_{liquid}\right)\right)^2}\right)}$$

Index of refraction expressed as a function of volume fraction

Density and Cavitating Flow Results from a Full-Scale Optical Multiphase Cryogenic Flowmeter

Optical Sensor Concept

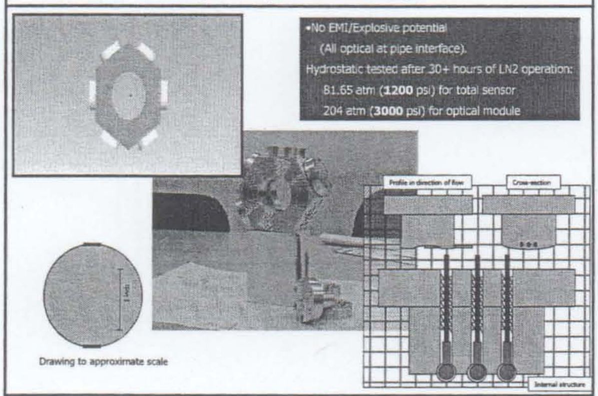


Measured irradiance as a function of index of refraction.

Density and Cavitating Flow Results from a Full-Scale Optical Multiphase Cryogenic Flowmeter

Improved Optomechanical Design

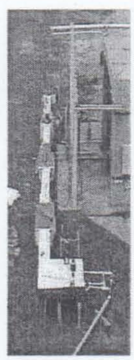
- No EMI/Explosive potential
  (All optical at pipe interface).
- Hydrostatic tested after 30+ hours of LN2 operation:
  81.65 atm (**1200** psi) for total sensor
  204 atm (**3000** psi) for optical module

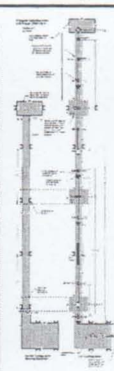


Drawing to approximate scale

Density and Cavitating Flow Results from a Full-Scale Optical Multiphase Cryogenic Flowmeter

Liquid Nitrogen Test Bed

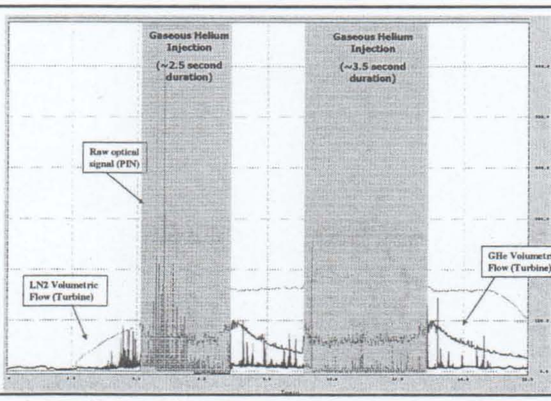




- Full Scale test bed: 8.5 m (~30 ft) length and 4.5 cm (~2 inch) pipe diameter.
- Fully instrumented.
- Flow system is submerged in liquid nitrogen.
- LN2 flow with injected GHe for bulk density/two-phase testing.

Density and Cavitating Flow Results from a Full-Scale Optical Multiphase Cryogenic Flowmeter

Liquid Nitrogen Testing



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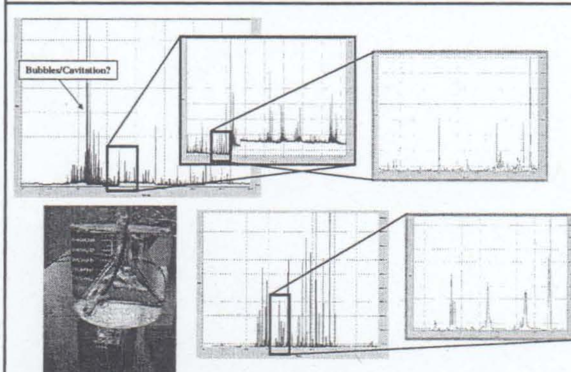
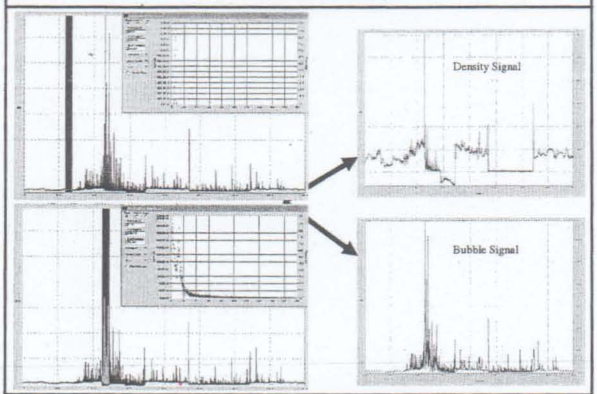
Bubble Analysis



Density and Cavitating Flow Results from a Full-Scale Optical Multiphase Cryogenic Flowmeter

Bubble Separation Technique



Density and Cavitating Flow Results from a Full-Scale Optical Multiphase Cryogenic Flowmeter

Comparison Density Models

- Standard thermodynamic state equation.
- Optical transmission though a medium.

$$I = I_o \cdot e^{-\left\{N\cdot L\cdot\left[\frac{24\pi^3 c^4}{N^2\lambda^4}\right]\cdot\left[\frac{n^2-1}{n^2+2}\right]^2 F_k\right\}}$$

$$a = \frac{0.45724 R^2 T_c^2}{P_c}$$

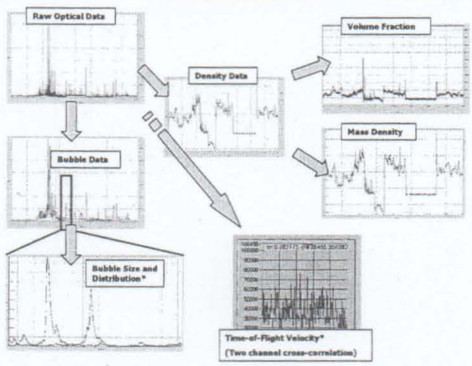
$$b = \frac{0.07780 RT}{P_c}$$

$$\rho = \frac{\ln\left(\frac{I}{I_o}\right)}{A}$$

$$T_r = \frac{T}{T_c}$$

Density and Cavitating Flow Results from a Full-Scale Optical Multiphase Cryogenic Flowmeter

Data Reduction



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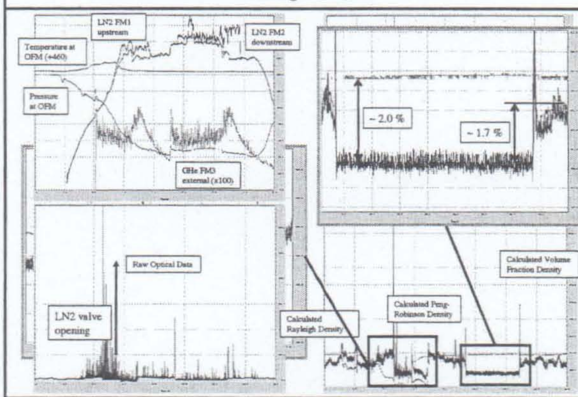
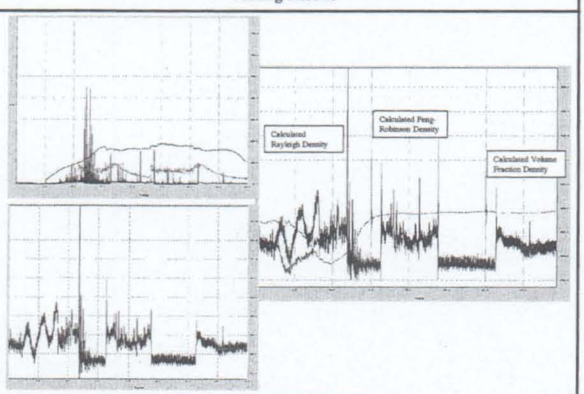
Testing Results



Density and Cavitating Flow Results from a Full-Scale Optical Multiphase Cryogenic Flowmeter

Testing Results



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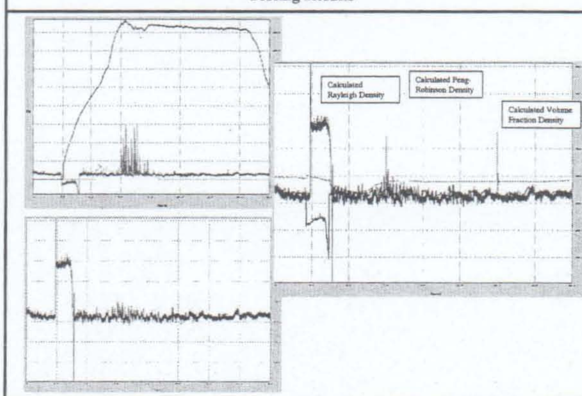
Testing Results



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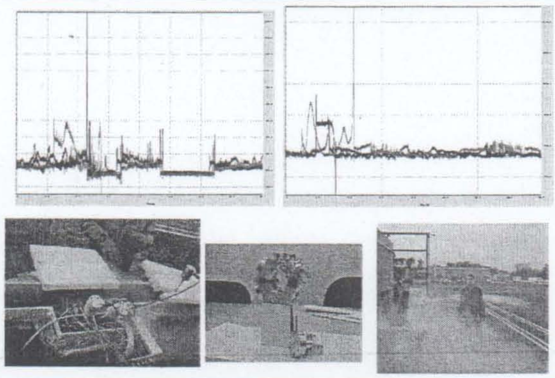
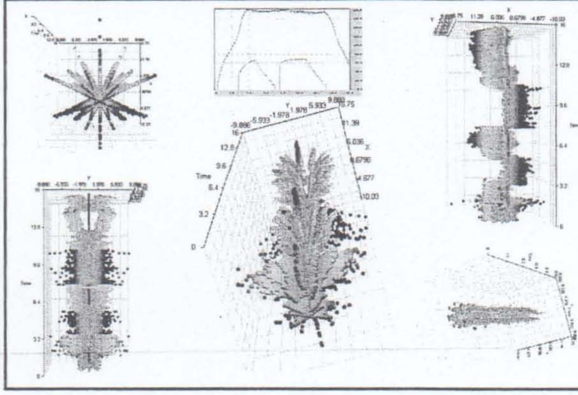
Testing Results



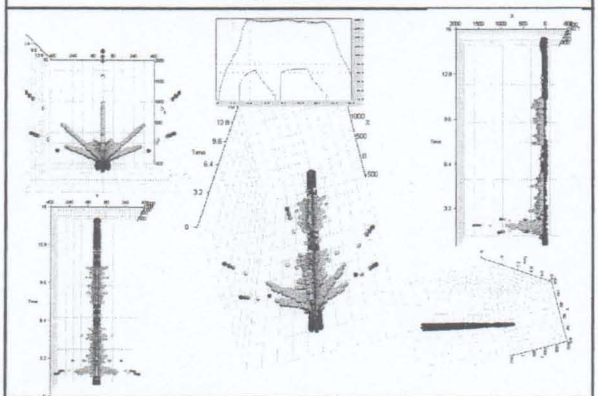
Density and Cavitating Flow Results from a Full-Scale Optical Multiphase Cryogenic Flowmeter

2-D Density Deviation



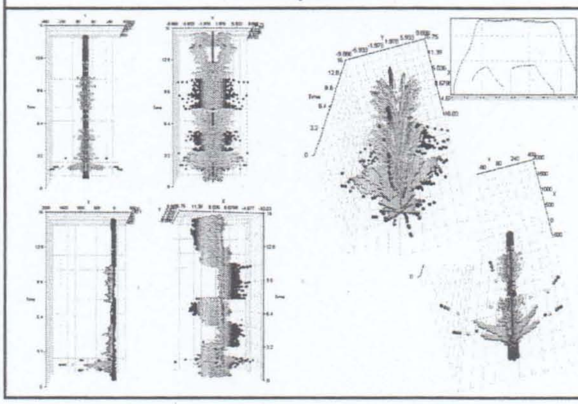
Density and Cavitating Flow Results from a Full-Scale Optical Multiphase Cryogenic Flowmeter

2-D Bubble Distribution



Density and Cavitating Flow Results from a Full-Scale Optical Multiphase Cryogenic Flowmeter

2-D Comparisons



Density and Cavitating Flow Results from a Full-Scale Optical Multiphase Cryogenic Flowmeter

Results

Difficult to quantify in a standard fashion since *no other* NIST traceable instrument exist to compare to.

Calculate relative statistical error:

- known and stable flow conditions (region of 2nd GHe release).
- all test samples (~2 million data points).
- 3 sigma relative error (99.7% confidence) in density.

Density error of 0.8%

- Currently have an optical sensor capable of determining volumetric and mass flow by directly measuring the fluid density and fluid velocity.
- Detection of cavitation/bubbles (presence, size and distribution).
- Optical interface to the fluid is not powered and non-conduction (no EMI) hazard.
- Detector electronics offer low power and fast response ~1-10 microseconds. Can be located separate from optical interface (fiber optic transmission).
- Cryogenically cycled and hydrostat tested to 1200 psi (entire sensor) and 3000 psi (optical interface).
- Operated in transient, multiphase cryogenic fluid 30+ hours.
- Does not require any other supporting instrumentation (no pressures, no temperatures, etc.)

Density and Cavitating Flow Results from a Full-Scale Optical Multiphase Cryogenic Flowmeter

Possible Applications (Ground Test/Flight)

- Placed on the outlet of a tank would provide fast and accurate density and fluid velocity.
- Replace wet/dry sensors.
- Function as a cavitation/bubble sensor. Further testing needed to determine bubble size and distribution.
- Provide a *sole* density measurement to support other fluid instrumentation or control systems.
- Function as a primary flow sensor in a wide operational flow range without supporting instrumentation.
- Complete fluid characterization instrument for high-end component or systems analysis using multiple 'slices' and/or sensors.
- Multi-phase/component detection (liquid/gas/solid – ice and debris).
- Support mass gauging/tank volume measurements.