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HELIUM-FLOW MEASUREMENT USING ULTRASONIC TECHNIQUE*

John H. Sondericker

Brookhaven National Laboratory

Upton, New York 11973

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INTRODUCTION

While designing cryogenic instrumentation for the Colliding Beam Accelerator (CBA) helium-distribution system it became clear that accurate measurement of mass flow of helium which varied in temperature from room to sub-cooled conditions would be difficult. Conventional venturi flow meters full scale differential pressure signal would decrease by more than an order of magnitude during cooldown causing unacceptable error at operating temperature. At sub-cooled temperatures, helium would be pumped around cooling loops by an efficient, low head pressure circulating compressor. Additional pressure drop meant more pump work was necessary to compress the fluid resulting in a higher outlet temperature. The ideal mass flowmeter for this application was one which did not add pressure drop to the system, functioned over the entire temperature range, has high resolution and delivers accurate mass flow measurement data. Ultrasonic flow measurement techniques used successfully by the process industry, seemed to meet all the necessary requirements.

An extensive search for a supplier of such a device found that none of the commercial stock flowmeters were adaptable to cryogenic service so the development of the instrument was undertaken by the CBA Cryogenic Control and Instrumentation Engineering Group at BNL.

MASTER

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ULTRASONIC FLOWMETER FUNDAMENTALS

Many basic methods of detecting flow velocity have been used in the past but the travel time difference (longitudinal contrapropagating time of flight) is the most popular. A typical arrangement consists of a pair of transducers located in the center of uniform fluid flow separated by a known distance. The velocity of a sound wave propagated by the transmitter in the direction of flow is the sum of the fluid velocity and the sound velocity of the fluid at rest. If the downstream receiver is then used as a transmitter the velocity of the sound wave propagated against the flow direction is the difference between the sound velocity of the fluid and its flow velocity. Therefore:

$$\begin{aligned} t_1 &= d/(v_s + v_f) \\ t_2 &= d/(v_s - v_f) \\ \Delta t &= t_2 - t_1 = 2dv_f/(v_s^2 - v_f^2) \end{aligned} \quad (1)$$

where d is the distance between transducers, v_s is the sound velocity of the fluid, and v_f is the fluid flow velocity and t_1 and t_2 are the transmitter to receiver times of flight with and against the direction of flow. Since v_f is usually much smaller than v_s , equation 1 can be simplified with negligible error to

$$v_f = \frac{\Delta t (v_s^2)}{2d} \quad (2)$$

Equation 2 has a serious drawback in that the calculated value of v_f depends heavily upon the accuracy to which the sound velocity of the fluid is known. However, equation 1 can be manipulated once more to yield

$$v_f = \frac{d}{2} \left(\frac{1}{t_2} - \frac{1}{t_1} \right) \quad (3)$$

From equation 3 it can be seen that flow velocity is now independent of flow sound velocity and only depends upon transducer spacing and the difference between reciprocal times of flight.

To convert velocity to mass flow measurement, fluid density and pipe inner diameter must also be known. Then:

$$\dot{M} = (v_f) (\rho) (a)$$

Where ρ is the fluid density at temperature and pressure, a is the cross sectional area of the pipe carrying the process fluid

and $\dot{M}$ is the mass flow. All of the above assumes single phase uniform flow over the length of measurement. For liquids and heavy gases, a mass flow correction must be made to account for the shape of the flow velocity profile across the pipe if flow conditions are laminar or in the transition region. Fortunately, when measuring helium flow, profile effects are generally not a problem because the very low viscosity of the gas produces uniform turbulent flow at most operating conditions.

FLOWMETER DETAILS

Different types of commercial piezoelectric transducers were tested to assess their characteristics in helium over the desired operating temperature range. Many designs were unusable because the crystals were suspended by rubber mounts which hardened at low temperatures completely damping the transducer element. Acoustic impedance mismatch losses¹ between the transducer and helium was expected to be greater than 50 db so a low frequency device with high transmitting and receiving sensitivity held the best promise of success. Massa Products Inc. Model TR-89B, Type 23 proved to be the most efficient transducer tested. It consisted of a bender type PZT element cemented to an inner diaphragm face of a one piece aluminum housing. The device is commonly used for intrusion alarms and costs ten dollars per unit. Figure 1 shows the parallel and series resonant frequencies of the transducer as a function of temperature.

An electronic system was designed and constructed to pulse switch the transducers and measure acoustic time of flight. The block diagram of the electronic system is shown in Figure 2. The circuitry pulse shocks alternate transmitting transducers at a one second repetition rate leaving ample time for the sound to completely decay between pulses. The receive transducer is switched to a preamplifier and band pass amplifier combination whose bandwidth encompasses the crystals shift of resonant frequency with temperature.

When the transmitter is pulsed a 10 MHz up counter is started. The receive signal appears as a burst of decaying sound waves of enough amplitude to cause saturation of the amplifier. A level detector is switched by the receipt of the first wave which enables a two cycle delay circuit. After the two cycles are received a zero crossing detector stops the counter. Contents of the counter are jammed into latches and decoded for seven segment local display. One second later the role of the transducers are reversed. The process takes place again using the same electronics to minimize error caused by offset and drift. The display shows alternating up and down stream times of flight in 100 nanosecond time units plus an added constant time

Figure 1.

factor caused by electronic delay. A switch changes the display mode to show differential time of flight by displaying the contents left in the counter after up and down counting two successive cycles.

No special care was taken to match transducers or signal drive stages. Instead, drive power supply voltage was trimmed so that at zero flow conditions $t_1 = t_2$. Extensive electrostatic and magnetic shielding was necessary to attenuate noise and crosstalk at the amplifier input terminals. Long term stability and accuracy of the electronics is ± 1 count.

Figure 2. Ultrasonic Flowmeter Electronic Block Diagram.

EXPERIMENTAL SYSTEM

To test the flowmeter our cryogenic heat load measurement test bed² was used. It consisted of two universal ends shown in Figure 3, instrumented with thermometers, calorimeters, a Hastings ambient temperature helium thermal mass flow meter and various control valves. A 100 watt refrigerator connected to He IN and He OUT supplied flow. A special vacuum jacketed interconnect was made to hold the ultrasonic transducers one meter apart in the center of 1.5 inch tubing. Little work was necessary to adapt the test bed to flow measurement because a process control computer monitored most process variables and was able to calculate helium mass flow from the thermophysical properties program already installed in the machine.

At elevated temperatures valve CDBP was closed and most of the refrigerator flow was bypassed through valve PC. A small flow was tapped off the main stream and sent past the ultrasonic transducers. Upon exiting, flow went back to warm return through

Figure 3. Cryogenic Test Bed Piping and Instrumentation Schematic.

a warmup heat exchanger and the Hastings flow meter. Calorimeter heaters were manually adjusted to hold acoustic flowmeter temperatures stable. When temperatures were reasonably stable, time of flight data was manually entered from the operator's keyboard and stored on disc along with other necessary process data for reduction at a later time. At 40 K, Hastings, calorimeter and ultrasonic mass flow data was taken to compare results. In order to get temperatures below 40 K, warm return flow bypassing the refrigerator had to be shut off and CDBP opened. Mass flow data at lower temperatures was derived from only calorimeter and ultrasonic methods.

EXPERIMENTAL RESULTS

When data taking began, equation 3 was used to calculate v_f because it seemed the simpler method. Contrapropagating times of flight (t_1 , t_2) were recorded and adjusted for electronic circuit delays. As temperature decreased the amplitude of the first wave of the received burst decreased to a point where the level detector triggered on the second wave. This shift added an additional 42 microseconds to the times of flight causing error. Since there was no way to know which wave triggered the detector, equation 3 was abandoned in favor of equation 2. Use of differential time of flight (Δt) reduced data to one term which could be easily monitored. The burden of calculating the sonic velocity of the fluid (v_s) was not a problem since the thermophysical properties program must be run to find helium density. The addition of the sound velocity subroutine was inconsequential.

Well over one hundred data records were analyzed covering nine temperature from 321 to 6 K. Table 1 shows the results of flowmeter comparisons in reduced form.

TABLE 1. COMPARISON OF FLOWMETER DATA

T (K)	v_s (M/s)	v_f (cm/s)	M (g/s)	δ_{HS} (%)	δ_{CS} (%)
321	1055	256	0.66	0.3 + 1.4	-
158	740	190	1.1	2.5 + 1.0	-
87	550	140	1.5	2.6 + 1.0	-
80	527	133	1.6	2.8 + 1.2	-
60	460	109	1.6	1.8 + .5	-
40	375	87	2.2	.41 + .5	2.9 + 1.5
11.5	198	52	3.7	-	4.7 + 3.3
10.6	190	50	3.7	-	6.0 + 3.3
6.0	132	30	4.6	-	-2.7 + 1.9

δ_{HS} is the mean error in percent of the Hastings mass flowmeter normalized to the ultrasonic device results. δ_{CS} is the mean error when compared to calorimeter results. Combined maximum error of the Hasting flowmeter when reading 1.5 grams/second (half scale) was thought to be 3%. Since the calorimeter was not corrected for heat leak or thermometer calibration offsets, errors in the 5% range were expected.

CONCLUSIONS

Data derived from the three different mass flow devices demonstrates that, even under the somewhat crude conditions of the test, the ultrasonic method of determining mass flow is at least as accurate as the Hastings and calorimeter. Ultrasonic mass flow meter accuracy is limited only by timing crystal and calculated density and sound velocity errors. The acoustic device affords the user the advantages of negligible flow obstruction, independence of calibration, and high resolution with linearity over wide flow ranges. In the test configuration one count of differential time was equivalent to a change in mass flow of approximately .013 grams/second from 321 K to 6 K. As temperature decreased, sound velocity of the gas decreased but the value of minimum resolvable mass flow was compensated by increasing helium density resulting in an instrument with essentially constant minimum mass flow sensitivity over the entire operating temperature range.

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REFERENCES

1. L.C. Lynworth, Part 2, "Generation and Propagation of Pulses in Single Path Contrapropagating Flowmeters," Trans. Inst. of Measurement & Control, Vol. 4, No. 1, p. 2-24, 1982.
2. A.P. Werner, D.P. Brown and W.J. Schneider, "Heat Load Measurement of Prototype Cryogenic Magnets and Leads for the ISABELLE Project," Advances in Cryogenic Engineering, Vol. 27, Plenum Press, New York, 1982.