Pipe MAVS, a Deep-Ocean Flowmeter

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Abstract—An acoustic differential travel-time current sensor with 6000-m depth capability has been adapted to measure flow in a pipe, initially for hydrothermal vent flow studies. The acoustic measurement path, 9.8 cm long, is inclined 18 degrees to the axis of a 20.3-cm long, 2.54-cm inside diameter stainless steel pipe. The integrated component of flow along the acoustic axis is resolved to 0.04 cm/s with a standard deviation noise level near zero flow corresponding to 0.09 cm/s. That makes a threshold of detection of 0.45 cc/s or 0.03 liters/minute. The upper limit of flow that can be measured is 60 liters/minute. Uniform weighting of the measurement of velocity across the diameter of the pipe means that the annulus of fluid near the wall is underrepresented compared to the core of the fluid near the center. Therefore the radial profile of velocity enters into the calibration of the flowmeter. Furthermore, the profile depends on Reynolds number and the roughness of the boundary layer in the pipe, the former included in the calibration but the latter possibly showing sensitivity to accretions of material inside the pipe.

Flow measurements are important when a fluid source is diffuse yet the total volume and rate of flow of the source is needed. In the case of hydrothermal vents, the heat output of a diffuse vent requires both the temperature anomaly and the volume of fluid to be measured. In Pipe MAVS, three thermistors are provided: one to measure the external ambient temperature, and two inside the pipe to measure the temperature at the inlet and the outlet. A collecting structure covering the diffuse source concentrates the flow to be measured by Pipe MAVS. Since measurements are made rapidly, fluctuations in total flow are resolved and can be integrated for any period of interest to remove artifacts of the collector yet reveal variability in the flow. Momentarily closing the pipe establishes the zero offset in situ. Applications of Pipe MAVS to measure shallow water sources of fresh water in marshes and in coastal regions and of flow in either direction through a porous sea-floor are possible within the limits of the zero point resolution. Amplification of flow by increasing collection area is a better way to increase sensitivity than to decrease cross sectional area in the pipe since errors due to internal reflections and effects of the boundary layer near the wall of the pipe are worse with smaller pipe diameter. Pipe MAVS, with its 6000-m depth rating, can supplement current and temperature measurements in monitoring hydrothermal vent energetics.

I. Introduction

Acoustic travel-time measurements of velocity are insensitive to particle concentrations in the fluid. This recommends them for flow measurements at hydrothermal vents where particulates are highly variable and the MAVS (Modular Acoustic Velocity Sensor) [1-3] has been used successfully in deep-sea deployments at the Endeavor Field of the Juan de Fuca hydrothermal vents in 2000 and 2001 [4, 5]. MAVS is a 3-D vector velocimeter designed to measure unconstrained flow and has been used to measure the general near-bottom flow in this topographically complex region. Mapping the velocity field with the thermal field and the thermal gradient field has focussed attention on the contributions of the vents to the heat budget at ridges.

Venting of hydrothermal fluids appears to have multiple forms including black and white smokers and diffuse flow. High temperature point sources such as black smokers build chimneys of sulfides and other precipitates that concentrate the flow into a high velocity and extremely high temperature jet. Diffuse flow has low vertical velocity, temperature only a few degrees above ambient, and is concentrated in extended patches among rubble where the ambient tidal current swamps the velocity signal from the vent. In diffuse vents, total flow is a more useful measure and can be quantified by collecting fluid emitted over a known surface area and concentrating it into a pipe in which the total flow can be measured. The acoustic travel-time measurement of MAVS was selected to make the flow measurement in the pipe and a special Pipe MAVS sensor was substituted for the normal MAVS sensor with standard MAVS3 electronics and data acquisition software and logger.

A. Pipe Flow Measurement

Acoustic travel-time measurement of flow in a pipe is commonly used for metering delivery of fluids of many types. Systems are generally along axis or oblique; the former requires that the pipe have elbows while the latter permits straight through flow. Single path measurements are of necessity biased by the region of the flow sampled. Even when the calibration takes this bias into account, the velocity profile across the pipe may vary with changes in surface conditions and from upstream changes in the flow. Because velocities along the axis in the center of the pipe are higher than those near the wall, measurements of the velocity in the center overestimate the flow while oblique measurements are weighted by the lower velocities near the wall and do not overestimate the flow as much.

1) Laminar Flow: At low flow rates, viscous effects dominate and the velocity profile eventually assumes a parabolic form with zero velocity at the wall. This condition is observed when the Reynolds number, R, is less than 2000 [6] where,

$$R = Vd/\nu \qquad (1)$$

and V is the velocity, d is the diameter of the pipe, and ν at 0.0018 cm^2/s (0°C water) is the kinematic viscosity. For a 2.54-cm (1") pipe, this threshold is 1.4 cm/s. In a circular pipe, the velocity profile, v(r), develops sufficiently far from the inlet to:

$$v(r) = V - V\left(\frac{r}{d/2}\right)^2 \qquad (2)$$

where V is the velocity at the center and r is the radial distance from the axis. This profile is obtained by balancing the pressure drop along the pipe against the viscous stress of each laminar cylindrical shell.

The flow is the integral of the lamella-weighted velocity over the radius:

$$Flow = \int_0^{d/2} v(r) * 2\pi r \, dr = \frac{\pi V (d/2)^2}{2} \qquad (3)$$

where V is the velocity along the axis at the center and d is the pipe diameter.

For oblique measurements of velocity, the component of the flow along the measurement path, $z = r/\sin(\theta)$, is integrated uniformly over the measurement path from $-d/2\sin(\theta)$ to $+d/2\sin(\theta)$.

$$V_{ave} = \int_{-d/2\sin(\theta)}^{d/2\sin(\theta)} \frac{v(r)\cos(\theta)}{d} \sin(\theta) \, dr = \frac{2V\cos(\theta)}{3} \qquad (4)$$

In equation (4), θ is the angle of the measurement path to the axis of the flow.

In terms of the oblique velocity measurement, the flow is:

$$Flow = \frac{3V_{ave}\pi(d/2)^2}{4\cos(\theta)} \qquad (5)$$

where θ is the angle of the acoustic path to the axis of the flow as in (4).

2) Turbulent Flow: Depending on the surface roughness of the pipe, at Reynolds numbers above 2000 the flow becomes turbulent and viscosity is no longer the only source of fluid shear stress. The flow becomes fully turbulent when the laminar sub layer is thinner than the surface roughness and in this condition the flow becomes more plug-like with only small velocity gradients across the diameter. With a relative roughness of .01 or irregularities 1% of the diameter of the pipe, the transition from smooth pipe turbulence to rough pipe or fully turbulent flow takes place between 4000 and 100,000 [6] in Reynolds number. For the 2.54-cm pipe referred to before, this range is 2.4 to 70 cm/s. Within this range, the flow is neither parabolic nor plug-like and the exact profile depends on the actual surface roughness, the conditions before the flow enters the pipe, and actually can exist in several states much as smoke rising from a cigarette can be straight or curled. For purposes of comparison, if the flow is plug-like at velocities above 70 cm/s or with roughness greater than 1% at lesser velocities, v(r) = V. Flow in this case is:

$$Flow = V\pi(d/2)^2 \qquad (6)$$

and in terms of the oblique measurement,

$$Flow = \frac{V_{ave}\pi(d/2)^2}{\cos(\theta)}. \qquad (7)$$

B. Calibration for Oblique Measurement

The measurement of flow described in this paper uses an oblique path. For purposes of scale factor calibration, the default case is that of Eq. 7 for plug-like flow despite most flows falling between laminar and smooth to rough turbulence. In this case, d=2.54 cm, θ=18°, and the scale factor is:

$$Scale = \frac{Flow}{V_{ave}} = \frac{\pi(d/2)^2}{\cos(\theta)} = 5.33\frac{ml/s}{cm/s}. \qquad (8)$$

II. Construction

Pipe MAVS is constructed from stainless steel pipe with standard 1" National Pipe Thread (NPT) pipe threads and an inside diameter of 2.54 cm. Grooves are cut into the wall for wires and there are two cavities for insertion of a premolded insert containing the piezoceramic transducer and thermistor. These are glued in place, the wires are routed through the support stem to a pressure feedthru, and the cavities and grooves are filled with urethane as shown in Fig. 1. Fig. 2 shows the interior details of the sensor.

This sensor is connected to a standard MAVS by replacement of the sensor on the endcap as shown in Fig. 1. MAVS is battery-powered, logs data on compact flash, and can sample velocities and log them at 10 Hz. Standard MAVS3 software is used in Pipe MAVS meaning that the four axes of velocity normally measured and logged contain three axes with no acoustic returns. The first axis alone is used.

III. Calibration

Since much of the measurement regime of interest falls between laminar and plug-like flow, it is necessary to calibrate a pipe flowmeter with actual flows that are compared to measured velocities.

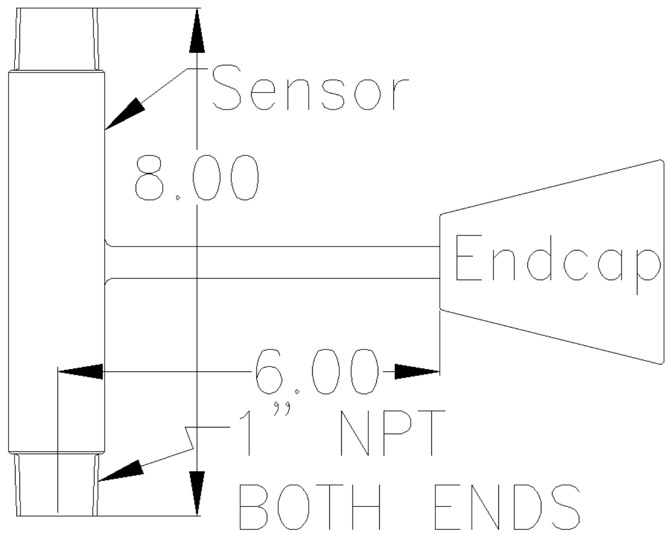

Fig. 1. Pipe sensor on endcap, dimensions in inches

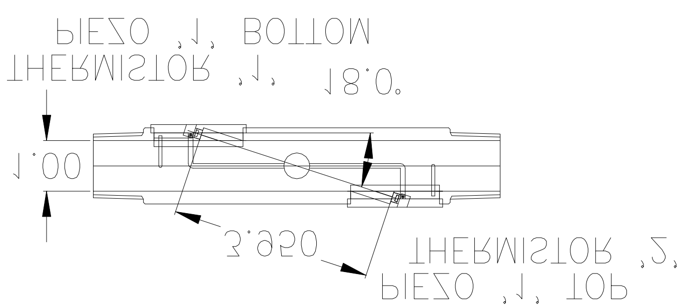

Fig. 2. Pipe MAVS sensor, dimensions in inches

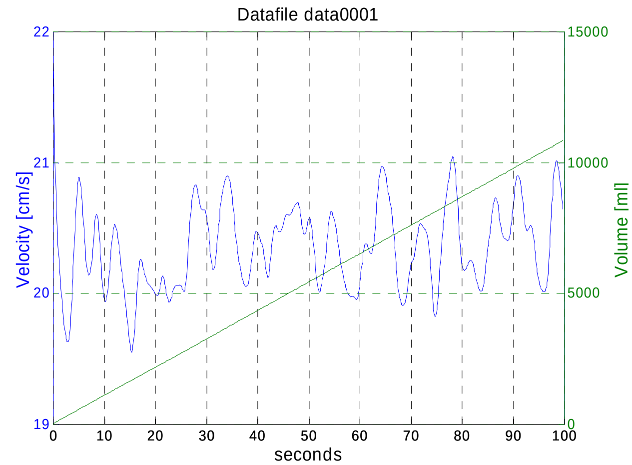

Fig. 3. 133.3 ml/s flow. Sloped line is volume

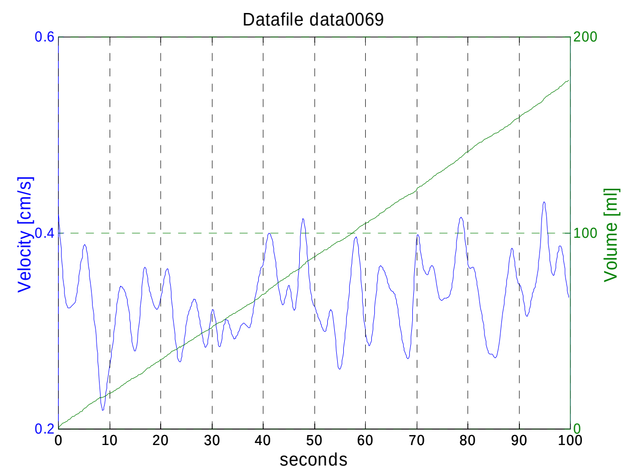

Fig. 4. 0.48 ml/s flow. Sloped line is volume

A. Calibrating Pipe Flow – Continuous Flow Method

The flow can be a steady stream and the velocity can be integrated during the time that the flow is steady to give two measurements. In this case, the Pipe MAVS measurements are compared to the steady flow rate as measured before and after the run in the MAVS. A series of runs were performed at University of Washington with steady flows from 250 ml/s to 0.48 ml/s, calibrated by running the steady flow into a graduated cylinder and timing the fill rate. The steady flow calibrations were done using an electric centrifugal pump with a full-bore gate valve to control the rate of flow. Figs. 3 and 4 show a high and low velocity run.

The most useful calibration from MAVS measured speed to flow rate is the linear fit to all the measurements by the continuous flow method. This is shown in Fig. 5. The calibration constant is well represented by this slope as: $7.21\frac{ml/s}{cm/s}$

B. Investigating Pipe Flow –Discrete Flow Method

Plotting a range of these calibration runs and fitting the points with a polynomial on a semilogarithmic plot gives some insight into how the calibration factor compares to the scale factor predicted for plug-like flow in Eq. 8. This is shown for the high end of the continuous flows used in calibrations in Fig. 6.

Small zero offsets in velocity are not serious for large flows but can strongly bias the scale factor in very small flows. A separate calibration was run at Woods Hole Oceanographic Institution with the setup shown in Fig. 7. In this method, a tank was filled with water, the Pipe MAVS was submerged in the tank with a hose on one end, a fixed volume of water was poured into the tube at a constant rate, and the velocities were recorded and later integrated. This was repeated for velocities from 2 mm/s to 55 cm/s or a flow from 0.7 ml/s to 220 ml/s.

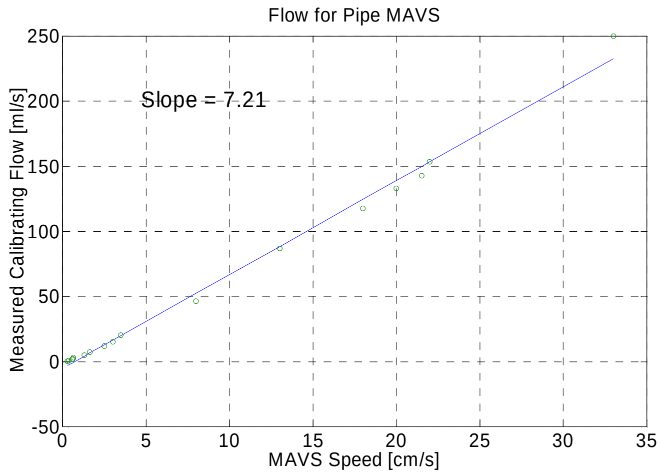

Fig. 5. Calibration of Pipe MAVS with continuous flow

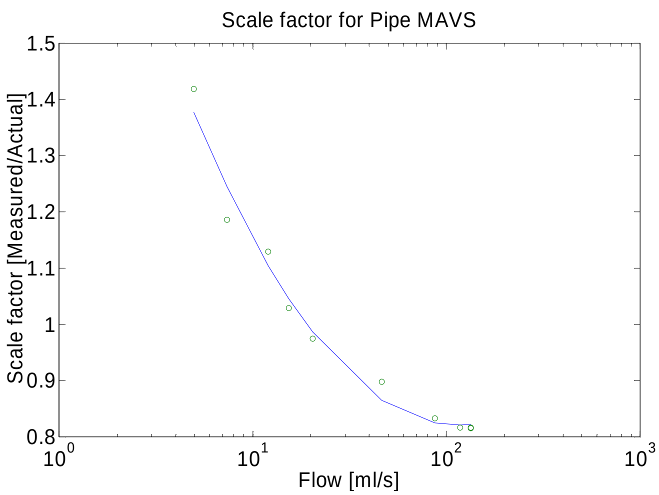

Fig. 6. Ratio of flow measured in Pipe MAVS to actual flow

A typical calibration run is shown in Fig. 8 in which the zero point was noted after the run was completed and that value was subtracted from the entire velocity data set before integration. This produced the calibration curve shown in Fig. 9. This is expressed as scale factor where the measured flow based upon the velocity is divided by actual flow rate. More precisely, the integral of the velocity from the start of the pour until the end of the pour is divided by the volume of the pour. A refinement of the technique was to start with the beaker prefilled to the mark and to stop the pour when the measured volume ran out. At that moment, the beaker was quickly removed from the funnel to obtain sharp start and stop conditions for subtraction of the background signal.

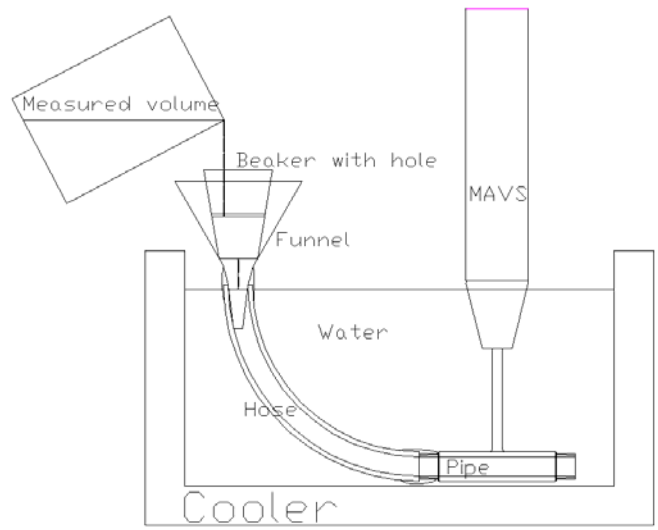

Fig. 7. Pipe MAVS calibration bath

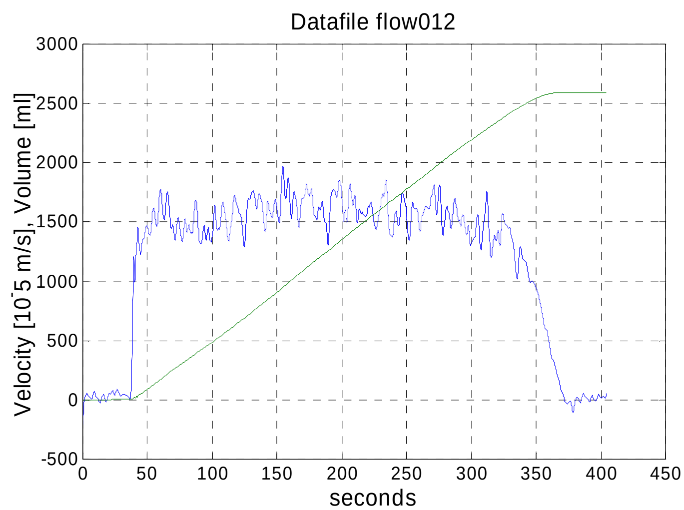

Fig. 8. Integrated flow measurement for 2440 ml. Sloped line is volume

IV. Field Deployment

Three Pipe MAVS flowmeters will be deployed at the Juan de Fuca hydrothermal vent field in August 2002. Figs. 10 and 11 show the collector and plumbing to the flowmeter. This housing is connected to an innertube collector via 5/8" OD polypropylene tubing. The innertube is filled with an extremely salty solution of calcium chloride giving the whole collector over 7 pounds of negative buoyancy in saltwater, not much but should be enough to allow the compliant innertube to seal well with the surface. The instrument package image shows the whole assembly held together with elastic cords for deployment by ROPOS, a remotely operated vehicle.

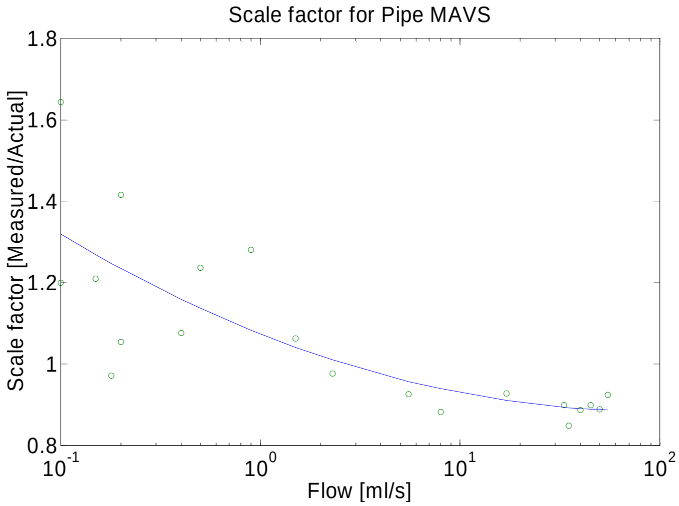

Fig. 9. Ratio of integrated flow to total volume

Fig. 10. Field deployable Pipe MAVS in PVC housing with titanium handle for deployment by ROV

IV. CONCLUSIONS

The Reynolds number of the flow is 2000 for a velocity about 1.4 cm/s and this corresponds to a flow of 7.5 ml/s about where the scale factor crosses unity. At higher flow rates, the scale factor is less than 1, approximating 0.85 while for flow rates less than 1 ml/s, the scale factor is greater than 1 and may be biased by zero offsets that are present and not subtracted. The low flow rates correspond to laminar flow where the velocity profile is parabolic across the pipe. In this case, the velocity overestimates the actual flow because the velocity weighting is uniform across the diameter while most of the volume is in the low velocity fluid near the wall. Above the critical Reynolds number, the flow becomes more plug-like and the velocity more accurately represents the flow. In fact, the velocity underestimates the flow. This 15% underestimate may be from back eddies at the transducers where there is a discontinuity in the inner wall of the pipe.

Fig. 11. Innertube collector filled with dense saline solution on the left and Pipe MAVS with hose in PVC case on the right. T bar handle permits ROV to position the collector over a diffuse hydrothermal vent.

Calibrations where the velocity is measured when the flow is stopped permit measurements over three orders of magnitude to be made with less than 10% error after correction with the calibration curves presented here. The remaining errors are due to variability in the speed during calibrations and to inherent variations in the onset of laminar and turbulent flow.

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REFERENCES

[1] Thwaites, F.T., and A.J. Williams 3rd, 1997. "New Current Meter Development", Sea Technology, April 1997, pp. 108-112.

[2] Williams, A.J. 3rd, 2000. Power, Packaging, and Multiplexing Considerations in an Acoustic Travel-Time Current Meter, *Oceans 2000*, IEEE Cat. No. 00CH37158, pp. 975-980.

[3] Williams, A.J. 3rd, 2001. Acoustic Current Meter Zero Offset Drift, *Oceans 2001*, IEEE Cat. No. 01CH37295, pp. 916-921.

[4] Johnson, P.H., S.L. Hautala, M.A. Tivey, C.D. Jones, J. Voight, M. Pruis, I. Garcia-Berdeal, L.A. Gilbert, T. Borklund, W. Fredericks, J. Howland, M. Tsurumi, T. Kurakawa, K. O'Connell, L. Thomas, S. Bolton, J. Turner, 2002. Survey Studies Hydrothermal Circulation on the Northern Juan de Fuca Ridge, EOS Vol. 83, Feb. 19, 2002, pp. 73,78-79.

[5] Williams, A.J. 3rd and M.K. Tivey, 2001. Tidal Currents at Hydrothermal Vents, Juan de Fuca Ridge, Sea Technology, June 2001, pp. 62-64.

[6] Mark's Mechanical Engineers' Handbook, 1958 Sixth Edition, McGraw-Hill Book Co., Baumeister, T. editor. Section 3-70:72.