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Liquid Metal Flow Measurement (Sodium) State-of-the-Art Study

By
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ABSTRACT

Various types of flowmeters are described and their advantages and disadvantages as applied to liquid metal flow measurement are discussed. It is concluded that the permanent-magnet-type flowmeter most closely meets the requirements of the ideal flow measuring device for use in liquid metal systems.

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I. INTRODUCTION

Flow measurement in liquid metal systems presents unusual problems because of the severe operating environments usually associated with such systems. The two most important aspects of liquid metal systems which make the design of flowmeters, as well as most other process instruments, difficult are the high operating temperatures and the chemical reactivity of most liquid metals. Other significant design requirements for liquid metal flowmeters are the ability to withstand high gamma radiation levels and rapid thermal transients.

Historically, the permanent-magnet flowmeter has been used for flow measurement in most of the liquid metal systems. This is in contrast to common practice in other process systems where differential head type flowmeters utilizing orifice plates, venturi tubes, or flow nozzles are most often used. This difference is due not only to the difficulty of measuring differential heads in a high-temperature liquid metal system but also to the unique suitability of the permanent-magnet flowmeter for use on liquid metal systems.

There are other ways in which liquid metal flows can be measured, although their use has been either very limited or only speculatively proposed as a possibility. The description of the various types of flowmeters and their advantages and disadvantages as applied to liquid metal flow measurement are discussed in the following sections.

II. MAGNETIC FLOWMETERS

A. THEORY OF OPERATION

Magnetic flowmeter operation is based upon the physical phenomenon discovered by Faraday, namely, that a potential is developed across a conductor which is moving in a magnetic field. This potential is proportional to both the velocity of the object and the strength of the magnetic field and is developed at right angles to both the magnetic field and the direction of movement of the object.

Thus, when a fluid flows through a magnetic field, a voltage is developed across the fluid. (It should be noted that the pipe containing the fluid must be nonmagnetic.) In the ideal case, where the velocity is uniform throughout the fluid, the magnetic field is uniform and infinite, and the pipe wall is nonconducting, the induced electromotive force is uniform in all parts of the fluid stream and no electrical current flows within the fluid. In the practical case, however, where the fluid velocity is not uniform and the magnetic field is neither uniform nor infinite, there are circulating currents within the fluid which distort the magnetic field and induce forces within the fluid which distort the fluid velocity profile. These effects can be utilized as a measure of the fluid flow rate.

B. METHOD OF READOUT

As described in the foregoing section, there are three ways in which a signal indicative of fluid flow rate can be derived from a magnetic flowmeter: (1) induced voltage, (2) force, and (3) magnetic field distortion.

1. Induced Voltage

The readout method which has been used in virtually all magnetic flowmeter applications to date is to measure the voltage induced in the fluid. In the ideal case, the induced voltage is directly proportional to the average fluid velocity. With a known cross-sectional flow area, the induced voltage is therefore proportional to the volumetric flow rate. In the practical case, depending upon the fluid velocity, fluid conductivity, and pipe size, the induced voltage may not be directly proportional to flow rate due to the effects of eddy currents flowing in

the fluid. Magnetic flowmeters on liquid sodium systems exhibit linear flow/voltage characteristics on pipe sizes up to about 6 in. when the voltage sensing electrodes are centrally located in the magnetic field and the magnet pole faces are at least one pipe diameter long.

The high electrical conductivity of most liquid metals and the containing pipe allows proper flowmeter operation when the voltage sensing electrodes are attached to the outer surface of the pipe. The flowmeter output signal voltage is reduced somewhat due to the shunting effect of the pipe wall; however, this reduction is not great unless the electrical conductivity of the liquid metal is substantially less than that of the pipe wall material. (Care must be taken in the selection of electrode material and the method of attachment to the pipe so that generation of thermal emf's is minimized.) If the electrical conductivity of the pipe wall material is sufficiently greater than the electrical conductivity of the liquid metal to shunt nearly the entire output signal, some means of electrically insulating the pipe wall from both the liquid metal and the voltage sensing electrodes must be provided.

2. Force

The eddy currents which flow in the fluid due to the magnetic field gradient at the ends of the imposed magnetic field are in a plane perpendicular to the magnetic field. The interaction between these circulating currents and the magnetic field exerts forces on the fluid and on the magnetic field. The force on the magnetic field is translated to a force on the magnet structure.

The force on the magnet structure is proportional to fluid conductivity, magnetic flux density squared, fluid velocity, and pipe radius cubed.^{(1)*} Thus, for a given installation, the force is directly proportional to fluid conductivity and velocity. Since the fluid conductivity is a function of fluid temperature, this readout method has the disadvantage of being quite temperature sensitive. For example, the conductivity of sodium decreases by a factor of approximately 2.5 as the temperature is increased from 400 to 1200°F.

*Superscripts refer to the References listed at the end of this report.

3. Magnetic Field Distortion

A third readout method is based upon the distortion of the imposed magnetic field by the magnetic field produced by the eddy currents flowing in the fluid. The eddy currents which are produced by the magnetic field gradient at the ends of the imposed magnetic field generate magnetic fields which reinforce the imposed magnetic field at the downstream end and oppose it at the upstream end. The net result is that the imposed magnetic field appears to be dragged downstream by the flowing fluid. The degree to which the imposed magnetic field is distorted is a function of the fluid velocity and the conductivity of the fluid. This readout method can be applied to both dc and ac magnetic flowmeters.

C. TYPES OF MAGNETIC FLOWMETERS

There are a number of different ways to classify magnetic flowmeters: (1) by whether the magnetic field is steady or of varying magnitude and polarity, (2) by the readout method employed, (3) by the way that the magnetic field is produced, or (4) by other criteria. For the purposes of this report, magnetic flowmeters will be classified by the way that the magnetic field is produced: (1) permanent magnet, (2) dc electromagnet, and (3) ac electromagnet. Nearly all of the magnetic flowmeters used on liquid metal systems to date have been the permanent-magnet type. Direct-current electromagnet flowmeters have had little use. Alternating-current electromagnet flowmeters have rarely been used on liquid metal systems, but are extensively used to solve difficult flow measuring problems on a wide variety of other fluids.

1. Permanent-Magnet Flowmeters

Permanent-magnet flowmeters, as used on liquid metal systems, are the simplest type of magnetic flowmeter, consisting merely of a permanent magnet which establishes a magnetic field across a pipe section to which voltage sensing electrodes have been attached. This simplicity, and its attendant manifestations, is the reason for the predominant usage of this type of flowmeter on liquid metal systems. The high conductivity of most liquid metals means that an output voltage signal of usable magnitude (1 to 50 mv) can be generated with permanent-magnet structures of reasonable size and with the voltage sensing electrodes attached to the outer surface of the pipe rather than their being in contact with the liquid directly.

In the ideal case, where the magnetic field is constant and infinitely long, the pipe diameter is constant, the pipe wall is nonconducting, and the electrodes contact the fluid, the flowmeter output voltage equals the product of a constant (whose value depends on the system of units employed), the flux density, the inside pipe diameter, and the (average) fluid velocity. In the actual case, the magnetic field is not infinite and is not constant because of temperature effects on the magnet and distortions of the magnetic field which result from eddy currents in the fluid. The pipe diameter also changes slightly with temperature and the pipe wall is usually of a conducting material which results in some reduction of the flowmeter output voltage because of the shunting effect. All of these effects, except for the magnetic field distortion which causes it to be "dragged downstream," can be calculated with good accuracy. Experience has shown that the downstream displacement of the magnetic field is not generally a significant effect in magnetic flowmeters for 6-in. and smaller pipes. It has been shown in numerous cases that the calibration can be calculated with an accuracy of 1 or 2% on small flowmeters. In the larger flowmeters, where the voltage/flow relationship is not linear, calculation of the calibration has not been feasible. It is possible that research on magnetohydrodynamics (MHD) has provided sufficient information which would allow calculation of large flowmeter calibrations; however, no effort appears to have been expended in that area.

Early work by E. R. Astley and W. C. Gray⁽²⁾ of the General Electric Co. provided the basis for calculation of permanent-magnet flowmeter calibrations. The formula which they derived can be arranged as follows:

$$\frac{Q}{E} = \frac{3162 d k_4}{B k_1 k_2 k_3}$$

where:

Q = flow rate (gpm)

E = output signal (mv)

d = inside pipe diameter (in.)

B = magnetic flux density (gauss)

k_1 = pipe wall shunting effect correction factor

k_2 = end effect correction factor

k_3 = magnet temperature correction factor

k_4 = pipe expansion correction factor

$$k_1 = \frac{2d D}{D^2 + d^2 + \frac{\rho_f}{\rho_w}(D^2 - d^2)}$$

where:

D = outside pipe diameter

$\frac{\rho_f}{\rho_w}$ = the ratio of the fluid and pipe wall resistivities, which usually varies with temperature.

k_2 was derived experimentally by Astley and Gray and is shown as a function of the pole face length to pipe diameter ratio in Figure 1. k_3 is obtained from manufacturer's data on the reversible flux loss of Alnico-5 with temperature, shown in Figure 2. This shows the range of values which can result, depending on magnet configuration and manufacturer.

$$k_4 = 1 + \gamma (t - t_o)$$

where:

γ = thermal expansion coefficient for pipe wall material

t = pipe temperature

t_o = pipe temperature when d was measured

$k_4 \approx 1 + t \times 10^{-5}$ for 300-series stainless steels.

Astley and Gray determined that the magnetic flux density should be measured with a search coil of rectangular section with dimensions of d normal to flow, $d/2$ parallel to flow, and $d/2$ parallel to the flux.

Magnets which are intended for use in permanent-magnet flowmeters should be stabilized so as to limit changes in flux density while in use. Permanent magnets are sensitive to demagnetization by external magnetic fields, temperature changes, and mechanical shock. The magnet assembly can be stabilized

Figure 1. End Effect Correction

Figure 2. Magnet Temperature Correction

by subjecting it to demagnetizing influences greater than those expected in service. It has been common practice to stabilize against external magnetic fields by magnetizing the permanent magnet to saturation and then electrically demagnetizing to 90 or 95% of that value. Stabilization against mechanical shock is achieved by subjecting the magnet assembly to a number of mechanical shocks of predetermined magnitude (10 g, for example) until no further changes in flux density result. Most of the Alnico materials, including Alnico-5, are sufficiently insensitive to mechanical shock to normally allow elimination of mechanical shock stabilization requirements.

Temperature changes cause two different types of demagnetization: irreversible and reversible. Irreversible demagnetization is the reduction in room temperature flux density which occurs when the magnet temperature is increased or decreased and then returned to room temperature. Reversible demagnetization is the change in flux density with respect to the room temperature flux density when the magnet is at other than room temperature. The reversible change is an inherent property of the Alnico materials which cannot be appreciably altered by stabilization techniques. The irreversible change usually occurs only during the first three cycles to a given temperature, the change

becoming smaller with each cycle. Therefore, the irreversible change in flux density can be nullified prior to use of the magnet by cycling the magnet several times from room temperature to a temperature higher than that expected when the magnet is used in a flowmeter. One temperature stabilization procedure which has been used is four cycles from room temperature to expected operating temperature plus 200°F and back to room temperature. Some minimum time, 1 or 2 hr, should be specified for the rise from room temperature, the period at temperature, and the return to room temperature.

Magnets used for flowmeters on pipe sizes up to about 3 in. usually employ "C" magnets or "horn" magnets, shown as Figures 3(a) and 3(b). Larger flowmeters can use magnet assemblies as illustrated in Figures 3(c) and 3(d). The configuration shown in Figure 3(d) is appropriate in the very large sizes because of its economy and has the further advantage of lower temperatures for the magnetic material.

2. Direct-Current Electromagnet Flowmeters

Direct-current electromagnet flowmeters are identical in principle to the permanent-magnet flowmeters, the difference being that the magnetic field is supplied by a dc-excited electromagnet instead of by permanent-magnet materials. The dc electromagnet flowmeter has had very limited use on liquid metal systems because of the added complication and cost as compared to the permanent-magnet flowmeter. One application for which a dc electromagnet flowmeter could be effectively utilized would be in development efforts on large permanent-magnet flowmeters. Alteration of the configuration of a magnetized permanent magnet is very difficult; but changes in pole face shape, size, and orientation in an effort to optimize the magnet configuration would be very easy to make on a dc electromagnet flowmeter.

A "self-excited" magnetic flowmeter proposed by the French for in-core use could be classified as either a permanent-magnet or dc electromagnet flowmeter, but for the purpose of this report will be arbitrarily placed in the latter category. This flowmeter has a small residual magnetism in the ferromagnetic material from which it is constructed and the emf induced in the liquid metal by this residual magnetism is utilized to supply a current through a coil of wire wound around the magnetic material. This coil is wound so that the current

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Figure 3. Flowmeter Magnet Configurations

produces a magnetic field which is of the same polarity as the residual magnetism, thus causing an increase in the flux density which increases the induced emf which increases the current which increases the magnetic flux, etc. The flowmeter, in effect, operates like a series-field dc generator. The object of this design is to eliminate the problems associated with permanent-magnet materials at very high temperatures in areas of intense gamma and neutron radiation. This is an interesting concept for a particular application; however, there may be significant problems of output linearity, temperature sensitivity, and retention of the residual magnetism.

3. Alternating-Current Electromagnet Flowmeters

Alternating-current electromagnet flowmeters utilize an alternating magnetic field supplied by an ac-excited coil. Alternating-current electromagnet flowmeters were developed for use with fluids of low conductivity or fluids subject to polarization. Use of an alternating magnetic field eliminates the polarization problem and provides an induced voltage signal which is easily amplified. This latter characteristic allows use of a weaker magnetic field than would be the case for a permanent-magnet or dc electromagnet flowmeter. There are three basic types of ac electromagnet flowmeters proposed for use on liquid metal systems: (1) transverse field, (2) eddy current, and (3) E-core.

a. Transverse Field AC Electromagnet Flowmeter

The transverse field ac electromagnet flowmeter utilizes an alternating magnetic field which is perpendicular to the flow path. The coils which establish the magnetic field are usually of basically rectangular shape, but curved to match the pipe surface, with the result that each coil is shaped somewhat like a saddle. The ac electromagnet consists of two such coils, which are located opposite to one another surrounding the pipe. (This coil configuration has also been used on a dc electromagnet flowmeter which was termed a "saddle coil" flowmeter.) The transverse field ac electromagnet flowmeter (TF-AC flowmeter) has been used considerably for metering flows of "difficult" fluids such as sewage, slurries, and latex.

This type is also directly applicable to liquid metal systems, but the close proximity of the coils to the pipe requires that the coils must be able to withstand high temperatures. Selection of the excitation frequency for flow

measurement of high-conductivity liquid metals in large pipes can also be a problem, since the frequency must be low enough so that the magnetic field completely penetrates the liquid (skin effect) but high enough to provide adequate frequency response and ease of amplification.

b. Eddy-Current AC Electromagnet Flowmeter

The eddy-current flowmeter utilizes the distortion of the imposed magnetic field as the means of measuring flow rate. A typical configuration for an eddy-current flowmeter would consist of three adjacent coils surrounding the pipe. The center coil would be ac-excited and the outer coils, of identical construction, would be connected series-opposing. Thus, with no flow, the magnetic field linking the outer coils to the center coil would be the same and the induced voltages in the outer coils would cancel for a net output of zero. Flow in the pipe would cause distortion of the magnetic field which would result in a higher induced voltage in the downstream coil than in the upstream coil. All other things remaining constant, this difference (which is the output signal) is a function of the fluid velocity. Analysis of the eddy-current flowmeter by David E. Wiegand of Argonne National Laboratory showed that the output signal is a function of fluid flowrate and velocity profile, fluid conductivity, and excitation frequency. At the excitation frequency which provides the maximum output voltage, the effect of variations of fluid conductivity (fluid temperature) are minimized; however, wide variations in fluid conductivity will cause appreciable changes in output at a given flow rate. Variations of velocity profile also cause an appreciable output variation, particularly the velocity profile change which occurs when a transition is made from laminar to turbulent flow. Wiegand's analysis shows that the output voltage is proportional to the 1.028 power of flow rate over the range of turbulent flow. One other possible problem brought out by this analysis is that the optimum operating frequency varies inversely as the square of the channel diameter; thus, there may be severe response time limitations in very large channels owing to the low excitation frequency which would be used.

c. E-Core Electromagnet Flowmeter

The E-core electromagnet flowmeter also uses the magnet flux distortion readout principle. The E-core flowmeter consists of an E-shaped core of magnetic material (hence, the name) with coils wound on each of the three "legs."

The center coil is excited and the outer coils are connected in series with opposing polarity. (Excitation of the outer coils, with center coil readout is also feasible.) The E-core flowmeter is a variation of the eddy-current flowmeter which is "portable," since it is simply applied to the outside of a pipe or vessel. The E-core flowmeter is most sensitive to the fluid velocity in its immediate vicinity and is therefore most appropriate for use as a device for measuring the presence or absence of flow rather than use as a true flow-metering device.

D. ADVANTAGES COMMON TO ALL MAGNETIC FLOWMETERS

There are a number of aspects of the magnetic flowmeter which are advantageous, as compared to other flowmeter types, when used on a liquid metal system. Some of these advantages are more prominent in one variation of the magnetic flowmeter than in another. There are, however, certain advantages inherent to the type (magnetic flowmeters) which apply to all variations.

1. Reliability

There are two aspects to the reliability of magnetic flowmeters: (1) their general simplicity and (2) the fact that piping penetrations are not required. None of the magnetic flowmeters have moving parts or are in contact with the liquid metal. The second aspect, lack of piping penetrations, is particularly important for system reliability and system safety. The lack of piping penetrations means that a piping section containing a magnetic flowmeter is no more likely to develop a leak than a similar section of pipe without a flowmeter.

2. Rangeability

Rangeability, as used here, refers to the ability to measure flow with reasonable accuracy over a wide flow range. Magnetic flowmeters have good rangeability since the output of magnetic flowmeters is approximately proportional to the fluid velocity. Having an output proportional to fluid velocity means that an appreciable output signal is available even below 5% of full flow rate. This is in contrast to the most common flowmeter type, the differential pressure type, where the output is proportional to the square of the flowrate. Thus, the output from a differential pressure type flowmeter is only 4% of the full-scale output at 20% of full flow and 1% at 10% of full flow.

In the case of magnetic flowmeters which do not have outputs proportional to flow, such as large permanent-magnet flowmeters with limited-size pole-faces, the rangeability is still good, since the output deviates from proportionality only at high flow rates. Thus, the output signal at 5% of full flow is greater than 5% of the full flow output signal.

3. Low Pressure Loss

Since magnetic flowmeters consist essentially of a normal section of the piping with some sort of imposed magnetic field and perhaps a set of electrodes attached to the pipe outer surface, the pressure loss in a magnetic flowmeter is very low. The pressure loss is that due to the fluid friction in the pipe plus that due to the retarding effect of the magnetic field on the fluid. The pressure loss due to the magnetic field can be calculated as follows:

$$P = \frac{k B^2 Q}{d \rho} ,$$

where

P = pressure loss (Newtons/m²)

k = a constant which varies somewhat depending on the characteristics of the magnetic field and eddy-current distribution. An average value of 0.14 can be used for an approximation.

B = flux density (Webers/m²) (Tesla)

Q = flow rate in m³/sec

d = inside pipe diameter (m)

ρ = fluid resistivity (ohm-meters)

In most cases, the pressure loss in a magnetic flowmeter is negligible; however, there may be special cases involving small magnetic flowmeters with high flux densities where the pressure loss must be considered.

4. Response Time

Magnetic flowmeters have potentially the fastest response of any type flowmeter because of their direct, electrical sensing of fluid velocity. The most common magnetic flowmeter for liquid metal system use, a permanent-magnet

flowmeter sensing the induced voltage, has a very short response time. No known attempts to measure this response time have been made, since it is generally agreed that the response of a permanent-magnet flowmeter is faster than that of the other sensors which would be required to make such a measurement. An indication of the rapid response of a permanent-magnet flowmeter is the high frequency content (that which is not electrical "noise" induced in the leads) of the output signal.

Other variations of magnetic flowmeters, such as ac electromagnet, force-readout, and eddy-current, will have slower response times than the permanent-magnet flowmeter. Even the response times of these variations, however, will be rapid as compared to most other flowmeter types.

E. DISADVANTAGES COMMON TO ALL MAGNETIC FLOWMETERS

Just as there are advantages inherent to magnetic flowmeters as applied to liquid metal systems, there are inherent disadvantages. The principal disadvantages are described in the following paragraphs.

1. Temperature Sensitivity

Temperature sensitivity (calibration changes due to changes in ambient or fluid temperatures) in magnetic flowmeters is primarily the result of temperature-induced changes in fluid resistivity, pipe-wall resistivity, and magnetic flux density. A secondary temperature effect, often negligible, is the temperature-induced change in pipe dimensions.

Changes in fluid temperature directly affect the calibration of magnetic flowmeters due to the resultant changes in fluid and pipe-wall resistivity, the degree of effect depending on the particular variation of the magnetic flowmeter in question. Fluid and/or ambient temperature changes can also affect the calibration of magnetic flowmeters by causing changes in the magnetic flux. The mechanism causing the flux change will vary depending upon which type of magnetic flowmeter is being considered. Flux changes in a permanent-magnet flowmeter will result when the temperature of the permanent-magnet material changes. Flux changes will also result from changes in the dimensions of the magnetic field caused by thermal expansion or contraction of the permanent-magnet assembly. This latter change is usually negligible. Flux changes in

ac or dc electromagnets can be caused by changes in the resistance of the electromagnet windings or changes in the magnetic reluctance of materials in the magnetic circuit of the electromagnet. Flux changes, usually negligible, can also result from temperature-induced changes in the dimensions of the electromagnet assembly. The effect of temperature on the coil resistance can be nullified by using a constant-current power supply for the electromagnet. The effect of temperature on the coil resistance, magnetic circuit reluctance, and dimensions of the electromagnet assembly can be nullified by using a magnetic flux sensor which controls the electromagnet power supply so as to maintain a constant flux density.

Changes in calibration due to changes in the pipe dimensions become appreciable only when large temperature changes are involved. For example, a fluid change from room temperature to 1200°F causes a change in pipe diameter (and hence flowmeter calibration) of about 1%.

2. Calibration Difficulty

A significant problem area for magnetic flowmeters is the difficulty of calibration. Since the resistivity of the fluid and the pipe wall have a significant effect on the calibration of a magnetic flowmeter, calibration must be done with fluid and pipe wall resistivities closely approaching those to be expected in service. For the utmost in accuracy, calibration must be performed under conditions duplicating the range of expected service conditions. Thus, a liquid metal system providing flow calibration capability and conditions at least approaching those expected in service must be available. Due to the infancy of liquid metals application and technology, such facilities are quite rare. Other types of flowmeters which can, at least theoretically, be calibrated using water or some other common fluid do not have this problem.

One compensating feature of magnetic flowmeters is that the calibration of magnetic flowmeters, all other factors being the same, is directly related to the strength of the magnetic field. Thus, once a magnetic flowmeter has been calibrated, the calibration of subsequent identical flowmeters can be derived from the calibration of the original simply by comparing the strength of the magnetic fields of the subsequent identical flowmeters to that of the calibrated original. These derived calibrations will not be as accurate as the original calibration, but will often be good enough.

3. Pipe Wetting

The calibration of magnetic flowmeters is affected by the electrical resistance between the pipe wall and the liquid metal. In most cases, the pipe wall is completely "wetted" by the liquid metal and this electrical resistance is effectively zero. However, there may be times when the pipe wall is only partially wetted or is completely unwetted by the liquid metal. In the case of sodium, the only time the pipe is unwetted is during the initial operation of a system, at low temperatures, before the sodium is cleaned up, or after a sodium system has been opened to the atmosphere. The amount of time required for the sodium to wet the pipe depends on the operating temperature, the cleanliness of the pipe, and the cleanliness of the sodium. In most cases, sodium will wet stainless-steel pipe in less than 24 hr when the operating temperature is greater than 400°F. The pipe is usually considered to be fully wetted when the flowmeter output signal at a given flowrate no longer increases with time. The effect of partial or nonwetting on a magnetic flowmeter depends on the readout method used. Those using the induced voltage readout method, as the majority do, are most affected by the degree of wetting. When the voltage sensing electrodes are attached to the outer pipe surface (the normal procedure), there will be no output signal when there is complete nonwetting of the pipe wall. Partial wetting will produce an output signal which is somewhere between zero and the full output signal.

Magnetic flowmeters using the flux distortion or force readout methods will also be affected by the degree of pipe wetting, but not nearly to the extent of those using the induced voltage readout method. Magnetic flowmeters using the flux distortion and force readout methods are affected because the degree of wetting of the pipe wall affects the current flow in the pipe wall.

F. COMPARATIVE ADVANTAGES AND DISADVANTAGES

As discussed in the previous sections, there are advantages and disadvantages which are inherent to the magnetic flowmeter in all its variations. However, the degree of advantage or disadvantage may vary from one type of magnetic flowmeter to another. Likewise, some types of magnetic flowmeters will have advantages or disadvantages which are not shared by other types. This section is intended to discuss these comparisons within the general category of magnetic flowmeters.

1. Complexity

The permanent-magnet flowmeter utilizing the induced voltage readout method is the least complex of the magnetic flowmeters. It is also the least complex of any flowmeter type considered for liquid metal service. The relative complexity of the other variations of a magnetic flowmeter, from the simplest to the most complex, would range approximately as follows: (1) dc electromagnet with voltage readout, (2) permanent magnet with force readout, (3) dc electromagnet with force readout, (4) E-core, (5) eddy-current, and (6) the TF-AC electromagnet with voltage readout.

2. Temperature Capabilities

The ultimate temperature capability of the various magnetic flowmeters depends to a certain extent on the application. When used for measurement of flows in pipes, the permanent-magnet assembly of a permanent-magnet flowmeter can be designed so that the temperature of the magnetic material is essentially independent of the fluid temperature. Under these conditions, there is no temperature limitation for permanent-magnet flowmeters. However, in the case of flow measurement where the flowmeter is immersed in the fluid, such as primary sodium flow measurement in a pool-type reactor or in-core fuel channel flow measurement, permanent-magnet flowmeters have as an ultimate temperature limit the permanent-magnet material Curie point, usually 850 to 900°C. The practical limit is less than the Curie point, how much less depending on the degree of flux degradation which is acceptable.

Electromagnet flowmeter temperature limitations are dictated by the temperature limitations of the wire and the magnetic materials used in the electromagnet. When used for measurement of flows in pipes, the electromagnet can be designed so that the temperature of the windings is essentially independent of the fluid temperature. The temperature of the magnetic material is more likely to be affected by the fluid temperature, but is not likely to reach a temperature which causes problems. An exception to these generalizations is the TF-AC electromagnet flowmeter which is produced commercially for general process use. This configuration has the electromagnet windings in close proximity to the pipe. Therefore, application of this type flowmeter to high-temperature liquid metal flow measurement will require either use of special

high-temperature wire or forced cooling of the electromagnet windings. The temperature limits for immersed electromagnet flowmeters are potentially higher than that for permanent-magnet flowmeters, although there are significant technical problems to be solved before this potential can be realized. An electromagnet flowmeter especially designed for use immersed at high temperatures is the self-excited dc electromagnet flowmeter discussed in Section II.C.2.

3. Accuracy

Accuracy, here, will be considered to have two aspects: constancy of calibration with time and with flow conditions different from those at the time of calibration. Changes in calibration with time are most likely to result from changes in the strength of the magnetic field. The magnetic field strength of the electromagnetic flowmeters (both dc and ac) can be maintained essentially constant either by use of a constant-current power supply or by using a measured flux feedback signal for regulation of the power supply. The degree of constancy of the magnetic field strength of a permanent-magnet flowmeter is a function of the metallurgy of the permanent magnet, the stabilization techniques utilized, and the environment which the permanent magnet encounters. Experience with permanent-magnet flowmeters has shown a tendency for the magnetic field strength to decrease somewhat with time. Thus, the calibration of a permanent-magnet flowmeter is likely to change with time. This drawback can be overcome, at least to a certain extent, by including in the flowmeter design a means of measuring the magnetic field strength. If this is done, the calibration factors can be adjusted to take the change in magnetic field strength into account.

The other aspect of calibration stability concerns the effect of the fluid velocity profile on the calibration of the flowmeter. If the flowmeter experiences a velocity profile in service which is different from that when the flowmeter was calibrated, a change in calibration may result. Magnetic flowmeters which utilize the induced voltage readout method are not affected by velocity profile variations so long as the velocity profile is symmetrical about the pipe axis. Thus, velocity profile disturbances which are not asymmetrical, such as those caused by reducers or swirling flow caused by orthogonal upstream elbows, will not alter the calibration of these types of magnetic flowmeters. Eddy-current and E-core magnetic flowmeters are sensitive to any type of

velocity profile disturbance and are therefore more likely to experience calibration shift if in-service flow conditions are different from those at the time of calibration.

4. Temperature Sensitivity

As discussed in Section II.E.1, temperature sensitivity is one of the disadvantages shared by all magnetic flowmeters. The magnitude of this disadvantage, however, is not the same for all of the magnetic flowmeter variations. The electromagnetic flowmeters (ac and dc) which utilize the induced voltage readout method are generally less sensitive to temperature variations than the other types of magnetic flowmeters. This is because the magnetic flux density can be maintained constant by proper power supply control. This leaves only the temperature effects on pipe dimensional changes and pipe wall shunting (which is a function of the ratio of the pipe wall and fluid resistivities).

Permanent-magnet flowmeters are more affected by fluid temperature changes because these changes usually cause changes in the magnet temperature, with a resultant change in the strength of the magnetic field. The degree to which magnet temperature is affected by fluid temperature depends on the magnet configuration, the particular application, and the extent of other provisions to thermally isolate the magnet material from the fluid. The effect of fluid temperature variation on the magnet temperature and field strength for a permanent-magnet flowmeter measuring flow in a pipe (not submerged) is generally small (2% or less).

The eddy-current and E-core flowmeters will be the most temperature sensitive types of magnetic flowmeters when used to measure flows with appreciable temperature variations. However, if the fluid temperature variations are small, this type could exhibit the least temperature sensitivity. For example, the theoretical analysis of eddy-current flowmeters by David Wiegand of ANL showed a sensitivity variation of about 25% for a fluid temperature change from 600 to 320°C, but only about 1% for a fluid temperature change from 600 to 540°C.

5. Physical Size

The size of all types of magnetic flowmeters, except for the E-core flowmeter, is a function of the size of the pipe or flow channel to which they are

applied. The E-core flowmeter can be essentially the same size regardless of the application. There may be some difference in magnetic flowmeter size depending on which readout method is chosen. For example, it might be reasoned that since the force on the magnet structure is proportional to the flux density squared, the force readout method would allow use of smaller magnet structure than that required when the induced voltage readout method is used. This is only true, however, if it is equally easy to measure the resulting low-level forces and voltages. The same is true for the flux-distortion readout method as compared to the induced voltage readout method; the relative size of magnet required depends on the relative sensitivity of the flux distortion and induced voltage measurement devices.

One common apprehension concerning use of magnetic flowmeters (particularly permanent-magnet flowmeters) on large pipes is the probable size and weight of such units. There is no doubt that a permanent magnet for such a flowmeter will be big and heavy, but it must be kept in mind that the pipe itself is big and heavy. For example, one design for a permanent magnet for 32-in. pipe had an estimated weight of about 1700 lb. The 3-ft pipe section within the flowmeter, when full of sodium, would weigh about 1300 lb. Relatively speaking then, the size and weight of a permanent-magnet flowmeter for large pipe sizes is not particularly troublesome.

6. Signal Characteristics

The characteristics of the output signal of some variations of the magnetic flowmeters have certain advantages as compared to other magnetic flowmeter variations. The dc output signals of the permanent-magnet and dc electromagnet flowmeters make it easier to reject electrostatic and electromagnetic "noise" which may be induced in the signal leads. If rapid response to flow variations is not required, the "noise" can be very easily filtered out of the dc flow signal. Even if this advantage is precluded by requirements for rapid response to flow variations, the permanent-magnet and dc electromagnet flowmeters still have the advantage. For all practical purposes, these magnetic flowmeters can be considered to have "instantaneous" response to flow variations whereas the ac electromagnetic flowmeters have a response time which is related to the excitation frequency. Another favorable characteristic of the permanent-magnet and dc electromagnet flowmeters is that the output signal is zero at zero flow.

Of the ac electromagnetic flowmeters, the eddy-current and E-core flowmeters are typically configured to produce a zero output signal at zero flow. This usually is accomplished by an adjustment in the readout which compensates for the inevitable small variations in the characteristics of the output coils. Since this "zero-trim" is subject to drift or misadjustment, there can be small errors in the zero flow point — something which is not true for the permanent-magnet and dc electromagnet flowmeters. The TF-AC electromagnet flowmeter has the least desirable output signal characteristics in that it is susceptible to "noise" errors and does not have an inherent zero output at zero flow.

7. Cost

The cost of flowmeters will be considered to include the cost of the flow element and the readout device. The cost of calibration will not be included since this cost can be highly variable depending on the accuracy required, the number of identical units to be employed, etc. These cost comparisons will of necessity be generalized and may not be valid in any particular instance.

In small sizes (approximately 3-in. pipe size and smaller) the permanent-magnet flowmeter is generally the least expensive, especially if surplus magnetron magnets are used. (These magnets are better than new magnets in some respects since they are aged, have probably been mistreated, and are therefore likely to be more stable.) The E-core flowmeter is likely to be the next least expensive, the dc electromagnet and eddy-current flowmeters somewhat more expensive, with the TF-AC flowmeter likely to be the most expensive.

In large sizes, the E-core flowmeter will be the least expensive, since its size and cost can remain the same regardless of pipe size. However, it must be remembered that the E-core flowmeter does not have accuracy or general applicability comparable to the other types. The permanent-magnet flowmeter will generally be the next least expensive in large sizes. As in the small sizes, the dc electromagnet and eddy-current flowmeters would be next most expensive and the TF-AC flowmeter the most expensive. The difference in cost between the latter four types should decrease as the pipe size gets larger, since the cost of the readout for the TF-AC flowmeter (a substantial portion of its cost) remains the same regardless of pipe size.

Use of the force readout method instead of induced voltage readout on a permanent-magnet flowmeter would increase its cost but would probably not alter the ranking in the above comparison.

III. DIFFERENTIAL HEAD FLOWMETERS

A. THEORY OF OPERATION

Differential head flowmeters are probably the oldest and most widely used means of measuring the flowrate of a liquid. Differential head flowmeters are so named because they utilize the measure of the difference in head (inches of the liquid in question) between two points as indicative of the fluid velocity. This differential head is produced in a number of ways: (1) by a flow constriction which converts kinetic energy to potential energy, (2) by a device which senses the kinetic energy of the fluid directly, (3) by friction between the fluid and the containment, (4) by centrifugal force, or (5) by combinations of the above. All of these devices, regardless of how the differential head is produced, share the characteristic that the fluid velocity is proportional to the square root of the differential head. With a known cross-sectional flow area, this velocity can be converted to flow rate. Measurement of the differential head requires the use of a manometer, something which is often inconvenient or impractical. In the usual case then, the pressure differential is measured instead of the head differential. In this case, the differential pressure is a function of fluid velocity and fluid density.

B. METHOD OF READOUT

1. Manometer

As mentioned above, the only means of directly measuring the true differential head is a manometer which is filled with the fluid being metered. This manometer can simply consist of two standpipes which are open at the top and therefore have a common atmospheric reference, or the standpipes can be connected at the top and referenced to something other than atmospheric pressure. The first method is obviously impractical for application to measurement of flow of chemically reactive liquid metals. The second method can be used but presents the following difficulties:

- 1) The standpipe connected to the high-pressure sensing tap must be longer than the maximum differential expected

- 2) The standpipe temperatures must be maintained at the same temperature as the flowing fluid so that the fluid density is the same in both places
- 3) The height or level of the fluid in both standpipes must be accurately determined.

These difficulties explain why a manometer is rarely used as a readout method when measuring liquid metal flow rates. However, there may be occasions when a manometer is an appropriate means for measurement of small differential heads in liquid metal applications in the laboratory.

2. Differential Pressure Transducer

The readout method usually employed for differential head flowmeters in process applications is a differential pressure transducer. Differential pressure transducers can take many forms but generally deduce the pressure differential by measuring the movement of a diaphragm, bellows, or other means which seals between the high- and low-pressure portions of the transducers. In the usual process application, the process fluid is admitted directly to the transducer. This approach is usually not feasible for liquid metal flowmeters because the transducer mechanism either cannot withstand the high temperatures typical of a liquid metal system or is appreciably affected by the high temperatures. Operation of the direct-connected transducer at some temperature appreciably lower than system temperature is avoided because of the likelihood of oxide migration to this colder area with consequent plugging of small passages in the transducer. Work is in progress to develop a transducer which can withstand the operating temperature of liquid metal systems.⁽³⁾ This transducer uses the thermionic diode principle to detect bellows motion. Successful development of this transducer will eliminate the above problems.

The problems associated with use of conventional pressure transducers on high-temperature liquid metal systems can be solved in another way. The transducer can be isolated from the liquid metal environment by use of a seal and a liquid-filled capillary to transmit the system pressure to the transducer. The seal, typically a diaphragm or bellows, has the process fluid on one side and the fill liquid on the other. With the volume enclosed by the seal, capillary, and transducer chamber completely filled with an incompressible liquid, seal

deflection caused by system pressure changes is sensed by the pressure transducer. Two seal-capillary units are required for a differential pressure transducer. High-temperature differential pressure transducers using this technique have been successfully used on liquid metal systems. NaK, which remains liquid over a very wide temperature range (20°F to over 1400°F at 1 atm pressure), is used as the fill liquid.

A third type of differential pressure transducer which has been used in the laboratory might be thought of as a combination of the manometer and differential pressure transducer methods. In this method, a relatively short standpipe is connected to each pressure tap. These standpipes are not connected together at the top, as in a manometer; they are connected to separately controlled gas supplies. These gas supplies are controlled so that the sodium level in each standpipe is maintained at a constant level, regardless of the static pressure at each tap. If the sodium levels are the same in each standpipe, the differential sodium pressure is equal to the differential between the gas pressures in the standpipes. This differential can be measured relatively easily by a differential pressure transducer at ambient temperature which is connected between the gas supplies. This has certain advantages where accuracy requirements are stringent, since the gas differential transducer can be piped with threaded connections. This allows recalibration of the gas differential transducer at any time. Recalibration of the NaK-filled transducers is difficult, since the seal is welded into the sodium system and the seal-capillary-transducer volume which is filled with NaK is also welded and cannot be opened. Even if a NaK-filled transducer is removed from a sodium system and recalibrated, the effects of removal from the system, cleaning of the sodium from the seals, and rewelding into the system leave doubt as to the installed accuracy of the transducer.

3. Bypass Flow

A third readout method which has been proposed for use with large differential head flowmeters in liquid metal service is the bypass flow method. In this method, the differential head is not measured but is indirectly deduced by measuring the flow rate between the high-pressure and low-pressure taps when these taps are interconnected. The flowrate through this small "bypass" line should be proportional to the square root of the differential head and therefore (theoretically, at least) directly proportional to the flow through the main flow

element. It is probable that there would be some deviation from direct proportionality over at least some part of the flow range and that this readout method would be more sensitive to upstream flow conditions and oxide deposits than the other differential head readout techniques. The potential advantages of the bypass flow readout method are higher reliability and lower cost if a permanent-magnet flowmeter is used to measure the bypass flow rate.

C. TYPES OF DIFFERENTIAL HEAD PRIMARY ELEMENTS

There are many different types of differential head primary elements. (The primary element is that portion of the flowmeter which produces the differential head.) No attempt will be made to discuss all of the types and possible variations; the discussion in this report will be limited to those types which are commonly used in the process industry and/or have been considered for use in liquid metal systems. None of these have been extensively used for measurement of liquid metal flows to date.

1. Venturi Tube

The venturi tube is one of the oldest types of differential head primary elements. It is based upon the original work of Giovanni Battista Venturi, which was reported in 1797. In 1887, Clemens Herschel, using Venturi's basic work, developed a commercial venturi tube. The Herschel venturi tube is characterized by a gradual entrance section and a very narrow-angle exit cone.

Figure 4 shows the critical dimensions and design data for venturi tubes as shown in the 1959 ASME publication "Fluid Meters — Their Theory and Application." According to this publication, a venturi tube fabricated to these specifications will have a discharge coefficient within 0.75% of the value given in the publication. If this accuracy is sufficient, such a venturi can be used without calibration. Many variations of the venturi tube, including rectangular, eccentric, short form (short, wide-angle exit cone), and truncated exit cone, have been made and used. These variations of the venturi tube have not been investigated as much as has the Herschel venturi and cannot, therefore, be used with the same confidence.

The accuracy of a venturi tube is affected directly by the fabrication and finish of the inlet cone and throat sections and indirectly by the angle of the exit cone. Use of too large an angle in the exit cone in order to reduce the length

D = Pipe diameter inlet and outlet

d = Throat diameter as required

a = $0.25 D$ to $0.75 D$ for $4 \text{ in.} \leq D \leq 6 \text{ in.}$; $0.25 D$ to $0.5 D$ for $6 \text{ in.} < D \leq 32 \text{ in.}$

$b = d$

$c = d/2$

δ = $3/16 \text{ in.}$ to $1/2 \text{ in.}$ according to D ; annular pressure chamber with at least 4 piezometer vents.

$r_1 = 0$ to $1.375 D$

$r_2 = 3.5 D$ to $3.75 D$

$\alpha_1 = 21 \pm 2 \text{ degrees}$

$\alpha_2 = 5$ to 15 degrees

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Figure 4. Proportions of Herschel-Type Venturi Tubes Recommended by the Committee on Flow Measurement of the International Organization for Standardization

of the venturi tube can lead to unstable flow conditions and fluctuating pressure differentials, a condition which leads to additional inaccuracies in the flow measurement. When space does not permit the use of a full-length, low-angle exit cone, the use of a truncated low-angle exit cone is preferable to the use of a shorter, larger, included-angle exit cone. The pressure recovery of the venturi tube is primarily affected by the exit cone.

2. Orifice Plate

The orifice plate was originally developed for measurement of the flow rate of large volumes of natural gas. The original experiments were with the sharp, square-edged, thin-plate, concentric orifice. This type orifice plate is still considered to be the standard orifice plate and has been the subject of the greatest amount of experimentation. A cross section of a standard orifice plate, including the critical dimensions, is shown in Figure 5.

Numerous variations of the orifice plate have been produced to fit special circumstances or to overcome special problems. Eccentric or segmental orifices have been applied where buildup of particulate matter ahead of a concentric orifice plate can alter the orifice calibration or where the ability to

$t \leq d/8, D/50, \text{ and } (D-d)/8$

$r \leq 0.025 \text{ of } d$

That portion of the plate inside the pipe should be flat within 0.01 in./in.

Eccentricity of the opening not more than 3% of D .

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Figure 5. Critical Dimensions of a Square-Edged, Thin-Plate, Concentric Orifice Plate

completely drain the line is important. A number of special orifice profiles have been developed to extend the flat portion of the discharge coefficient curve to lower Reynolds numbers. A general problem with these special profile orifice plates is their sensitivity to slight changes in the profile. Thus, as a general rule, they are not considered to provide flow measurement as accurately as that provided by the standard orifice plate.

A number of standards for location of the pressure taps of an orifice plate flowmeter have been used. In the original work by Thomas R. Weymouth of United Natural Gas Company, the pressure taps were located in the flanges containing the orifice plate at positions 1 in. upstream and downstream from the orifice plate. These locations, called flange taps, have become the predominant standard in the U.S. Other standards which have been used are: (1) full pressure taps at 2-1/2 pipe diameters upstream and 8 pipe diameters downstream, (2) vena contracta taps at 1 pipe diameter upstream and at the point of minimum pressure downstream, (3) taps at 1 pipe diameter upstream and 1/2 pipe diameter downstream (an approximation of vena contracta taps), and (4) "corner taps" which sense the pressures immediately upstream and downstream from the orifice plate. "Corner taps" is the predominant standard for pressure tap location in Europe.

3. Flow Nozzle

Several flow nozzle designs are commercially available. Figure 6 shows a typical flow nozzle which is characterized by a smoothly curved approach which leads tangentially into a short throat section. The calibration of the flow nozzle is relatively unaffected by the exact shape of the approach section and is therefore often used to measure high-velocity flows where erosion of the primary element is likely. The relatively rugged construction of the flow nozzle is also advantageous in such applications.

Corner taps were accepted as the standard pressure tap location in the early work with flow nozzles. Later experiments showed that pipe wall taps 1 pipe diameter upstream and 1/2 pipe diameter downstream showed less scatter with some types of flow nozzles than that found in the early experiments using corner taps.

$$\begin{aligned} r_1 &= d \\ r_2 &= 2/3 d \\ L &= 0.6 d \\ t &= 1/8 \text{ TO } 1/2 \text{ in.} \\ t_2 &= 1/8 \text{ in. TO } 0.15 D \end{aligned}$$

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Figure 6. ASME Long-Radius Flow Nozzle for $(d/D) < 0.5$

4. Flow Tube

A number of proprietary flow tube designs have been developed with the objective of providing a primary element with even less pressure loss (expressed as a percentage of the differential produced) than the classical Herschel venturi tube. Most of these flow tubes employ a combination of differential producing techniques, such as flow constriction plus kinetic energy sensing, to produce a differential which is greater than would be produced by one technique alone. Thus, the indicated differential is greater than the true differential and the pressure loss, expressed as a percentage of the indicated differential, is very low. As a corollary to these advantages, these devices tend to have the disadvantages of substantial sensitivity to upstream flow conditions and a higher critical Reynolds number (the Reynolds number above which the discharge coefficient is nearly constant). At least one of the proprietary flow tubes also has the disadvantage that its flow-differential pressure curve does not always follow the theoretical square-root relationship.

5. Pitot Tube

The pitot tube operates on the basis of measuring fluid velocity by directly sensing the fluid kinetic energy. The pitot tube was developed by Henri Pitot in

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Figure 7. Pitot Tube

the early 18th century but has never found wide commercial use for flow measurement. A major application has been for measurement of the velocity of ships and airplanes. Figure 7 shows a typical pitot tube flowmeter. A double pitot arrangement with one pointing upstream and the other downstream is sometimes used to provide a greater differential. Since the pitot tube is a point velocity sensing device, measurement of volumetric flowrate with a pitot tube requires accurate knowledge of the velocity profile. This, plus the tendency of the pitot tube to be fouled by foreign particles in the fluid, explains the lack of widespread use for flow measurement.

6. Elbow Meter

The elbow meter measures flow by determining the head differential between the inner and outer radii of the elbow which is due to the centrifugal force of the fluid in the elbow. Special elbows have been designed for this purpose, but standard elbows are generally used. Equations are available for estimating the calibration of an elbow meter; however, there is considerable scatter in the data from which these formulae are derived. In view of this and the wide tolerances to which standard elbows are manufactured, an individual calibration is required if any degree of accuracy is to be achieved. Elbow meters are typically used with 45-degree pressure taps (i. e., pressure taps in the middle of

the elbow). Some tests have indicated that pressure taps 22-1/2 degrees instead of 45 degrees after entrance to the bend produce a differential reading which is more stable and less affected by upstream flow conditions. An elbow meter with 45-degree taps has the rather special characteristic of being able to measure flow in either direction without any adjustment or reconnection or of lacking the ability to determine flow direction, depending on one's viewpoint. Another special characteristic is that an elbow meter introduces no system pressure loss, provided, of course, that an elbow which is a necessary part of the system is used.

7. Other Inherent System Pressure Differentials

Another possible primary element for a differential head meter is any inherent system differential. Any loop component such as a length of straight pipe, a valve, or a heat exchanger could be used. Ordinarily, a component is chosen whose characteristics are expected to remain constant. On this basis, heat exchangers subject to fouling and valves would be eliminated. Individual calibration is required if accurate flow measurement is necessary. The elbow meter discussed above could be considered as part of this category and, if so, seems to be the best choice, since it produces an appreciable differential head and is small enough that it can be readily tested in a conventional calibration facility.

D. ADVANTAGES COMMON TO ALL DIFFERENTIAL HEAD FLOWMETERS

Certain characteristics of differential head flowmeters are advantageous, as compared to other flowmeter types, for liquid metal system use. Some of these advantageous characteristics are more prominent in one type of differential head flowmeter than in another. The advantageous characteristics which tend to apply to all differential head flowmeters are discussed in the following paragraphs.

1. Calibration Ease

Differential head flowmeters are easy to calibrate in that they can be calibrated using water, and the calibration can then be translated to other fluids at other conditions. This can be particularly advantageous when the flowmeter is to be used with some uncommon fluid, as water calibration facilities are readily available whereas those for uncommon fluids rarely are. Theoretically,

correction of the water calibration to take account of the different hydraulic characteristics of another fluid at other operating conditions can be accomplished with the accuracy to which the fluid characteristics are known. In actual practice, if stringent accuracy requirements are applicable, some caution must be used in this approach. The theoretical basis for these corrections is well understood, but there has been very little experimental verification of the theory. Tests by D. Halmi of BIF Industries have shown as much as 2% change in the discharge coefficient at low Reynolds numbers (less than 50,000 on a 4-in. meter) when the only test parameter change was an increase of water temperature from 80 to 120°F. It is probable that the theoretical basis for translation of the water calibration to a calibration for another fluid is applicable at least to that part of the flow range above the critical Reynolds number; however, there is little or no experimental evidence to verify this assumption, particularly if the translation is to calibration for sodium at 1200°F.

2. Calibration Stability

There are two aspects concerning the stability of the calibration of a differential head flowmeter: (1) the stability of the primary element characteristics and (2) the stability of the readout device calibration. The characteristics of the primary element will change only if the primary element physically changes or if there are changes in the flow conditions upstream of the primary element which result in appreciable changes in the velocity profile at the primary element. Physical changes in the primary element should not occur if the type of primary element and the material from which it is fabricated are consistent with the application. Changes in upstream flow conditions might result from changes in the position of an upstream valve or changes in the roughness of the upstream piping due to corrosion or erosion. In applications where flowmetering accuracy is important, proper system design would include location of any valves so that the effect of valve position on the velocity profile at the flowmeter would be negligible. Changes in the inner pipe surface due to erosion or corrosion are a function of the loop design and pipe material. Such changes do not usually occur in a sodium system since the contaminants in the sodium are maintained at very low concentrations.

Calibration stability of the readout device would depend on the particular readout technique adopted. The manometer and standpipe-differential pressure

readout techniques would likely be the most stable readouts because of the direct nature of the manometer and the proven design and ease of recalibration of the gas differential pressure transducer used in the standpipe-differential pressure readout. Calibration stability of NaK-filled or other high-temperature differential pressure transducers would probably be somewhat worse. Further experience with such units will provide a better estimate of the performance of these units. The calibration stability of the bypass flow readout technique depends, of course, on the type of flowmeter used to measure the bypass flow rate.

E. DISADVANTAGES COMMON TO DIFFERENTIAL HEAD FLOWMETERS

Just as there are some inherent characteristics of the differential head flowmeter which are advantageous as applied to measurement of liquid metal flow rates, there are some inherent disadvantages.

1. Rangeability

Differential head flowmeters have inherently poor rangeability due to the square-root relationship between the differential pressure and fluid velocity. This means that the developed differential head is only 25% of full scale at 50% of full flow rate and only 1% of full scale at 10% of full flow rate. Thus, a differential head flowmeter with a single readout is considered to be usable over a flow range of only about 3:1, which corresponds to a 9:1 range on the readout device. It is sometimes possible to extend this usable range by using multiple readout devices with different sensitivities so that the rangeability of the readout is effectively increased, which in turn increases the usable range of the flowmeter. This technique may not be as effective for liquid metal applications owing to the uncertainty (as explained above) in translation of a water calibration to that for a liquid metal at high temperatures. This uncertainty is primarily in the low flow range below the critical Reynolds number. This uncertainty has the effect of limiting the usable range of the primary element, and thus the flowmeter, regardless of what is done to increase the usable range of the readout. Another technique sometimes used to permit measurement of a wide range of flow rates with differential head flowmeters is to use two or more flowmeters, of the same size or of different sizes, in parallel. This technique also has a serious drawback when contemplated for liquid metals applications because of the difficulty of assuring, particularly in large line sizes, tight shut-off of the isolating valves which are necessary in this technique.

The ability to measure a wide range of liquid metal flow rates is often particularly important in a flowmeter used to measure reactor coolant flow rate. In those reactors which operate with a relatively large temperature difference from core inlet to core outlet, as most liquid-metal-cooled reactors do, it is necessary to carefully control the rate of heat removal from the core after a "scram" to avoid excessive thermal shocks. In a liquid-metal-cooled reactor, this requires the ability to accurately measure and control the flow rate at considerably less than 10% of full flow — thus the importance of flowmeter rangeability.

2. Temperature Sensitivity

Differential head flowmeters are affected by temperature in three different ways: (1) by the temperature-induced change in the "throat" area of the flowmeter, (2) by the temperature-induced change in fluid density, and (3) by any temperature-induced changes in the calibration of the readout device. The first two effects are always present and are predictable to the extent that the expansion characteristics of the flowmeter material and the density-temperature characteristics of the fluid are known. The effects of temperature on the calibration of the readout device will depend on the design of the particular readout chosen and will probably not be predictable with the same degree of confidence as that of the expansion and fluid density temperature effects.

The expansion of the "throat" area affects the calibration of the differential head flowmeter because this flowmeter actually measures velocity and volume flow rate is deduced from the measured velocity and the cross-sectional area through which it flows. The temperature correction is proportional to the square of the temperature coefficient of linear expansion and is on the order of 2% at 1200°F when a Type 300 series stainless steel is the material from which the flowmeter is fabricated. This correction applies to pitot tube and elbow flowmeters, even though they do not have a "throat" in the conventional sense, since the expansion of the pipe containing the pitot tube or the elbow has the same effect.

Fluid density changes directly affect the calibration of a differential head flowmeter because the readout is usually not in inches of the fluid being measured but is in inches of water or mercury or in pounds per square inch. The differential pressure developed across a primary element is proportional to the

fluid density and the square of the fluid velocity. Thus, the calibration is directly affected by temperature-induced changes in fluid density. This temperature correction factor is appreciable for liquid metals applications owing to the wide range of operating temperatures typical of such systems. The flow constant, C , where flow rate $Q = C\sqrt{\Delta P}$, is inversely proportional to the square root of fluid density for volumetric flow rate and directly proportional to the square root of fluid density for mass flow rate. The volumetric flow rate fluid density temperature correction is about 7% for sodium when the temperature is increased from 300 to 1200°F. Since the fluid density temperature correction factor for mass flow rate is the reciprocal of the volumetric flow rate correction, the percentage change is about the same.

The effect of temperature on the readout device for a differential head flowmeter is usually a shift in the zero of the readout. This can be caused by differential expansion within a direct-connected high-temperature transducer or by differences in the volume of the two chambers of a NaK-filled differential pressure transducer. If the temperature effect on the readout is limited to zero-shift, this effect can be minimized by re-zeroing the transducer (at zero flow) when the operating temperature is changed.

3. Response Time

The response time of a differential head flowmeter is primarily a function of the design of the readout device. The speed of response of the readout device is determined by the time required to sense the change in differential pressure and the time required to transmit this information to the readout. Those readouts, such as the manometer and the standpipe-differential pressure transducer, which require an appreciable displacement of fluid to indicate a change in differential head, have a relatively long response time (on the order of seconds) because of the time required to sense the change. The NaK-filled differential pressure transducer has limited volume and therefore senses the change rapidly, but is very slow to transmit this information through the capillary to the transmitter and then to the readout. For example, the time constant of Barton NaK-filled differential pressure transducers was measured and found to be about 1 sec with 10-ft-long capillaries and about 5 sec with 100-ft-long capillaries.⁽⁴⁾

Future successful development of a direct-coupled high-temperature differential pressure transducer with electrical readout, such as a thermionic diode device, may eliminate slow response time from the list of inherent disadvantages of differential head flowmeters for liquid metals applications.

4. Reliability

Differential head flowmeters have certain characteristics which lead to less reliable operation on liquid metal systems than with some other flowmeter types. The first of these characteristics is that at least two pipe penetrations are required, something which is undesirable from a system reliability and safety standpoint. Another is that at least some part of the readout device must be in contact with the sodium. This means that routine maintenance of the readout is either very difficult or impossible and that replacement of a faulty readout device requires draining of the system. A third undesirable characteristic is that the liquid metal in the readout device is generally at a temperature lower than the system temperature and oxide or other impurities tend to collect in this area. Thus, one of the problems encountered with differential head flowmeters on liquid metal systems is partial or full plugging of the pressure taps, with resulting error in or complete absence of the readout signal.

F. COMPARATIVE ADVANTAGES AND DISADVANTAGES

The above discussions covered those characteristics of differential head flowmeters used on liquid metal systems which tend to be advantageous or disadvantageous regardless of the particular type of differential head flowmeter considered. The following is a discussion of those characteristics in which one type of differential head flowmeter has an advantage over another type.

1. Pressure Loss

The pressure loss of differential head flowmeters, expressed as a percentage of the developed differential, varies from zero for an elbow flowmeter or other inherent system differential to a value approaching 100% for a very restrictive orifice plate or flow nozzle. The pressure loss of a pitot tube flowmeter is a function of the pitot tube design and the comparative sizes of the pitot tube and the pipe in which it is installed. In most cases, the pressure loss of a pitot tube flowmeter ranges from very small to negligible.

The pressure loss of orifice plates, flow nozzles, venturi tubes, and flow tubes varies with the ratio of "throat" size to pipe size (β). The pressure loss of these devices is often given as a function of β ; however, for comparative purposes, it is better to give the pressure loss as a function of flow capacity. Using the flow capacity of an orifice plate with a β of 0.55 as the point of comparison, the pressure loss (expressed as % of measured differential) of various differential head flowmeters is approximately as follows: (1) orifice plate with flange taps and flow nozzles 70%, (2) short-form venturi tube 19%, (3) long-form venturi 12%, and (4) flow tube (Dall) 6%.

2. Accuracy

The flow measurement accuracy of a differential head flowmeter is a function of the primary element and the accuracy of the readout device.

The standard venturi tube is considered to provide the best uncalibrated accuracy. The ASME considers that a venturi tube constructed to their specifications will have a flow coefficient within 0.75% (95% confidence) of the value given in their publication. Orifice plates, flow nozzles, and flow tubes are usually credited with 1% uncalibrated accuracy. Pitot tubes and elbow flowmeters should be calibrated if accuracy is of importance.

The basic calibrated accuracy of all differential head primary elements is dependent only on the capabilities of the calibration facility. Normal calibration accuracies are 0.25% for line sizes to 12 in. and 0.5% for 12- to 48-in. line sizes. Special calibration accuracies of 0.1% are available for elements in line sizes to 12 in.

The installed accuracy of a differential head primary element depends on the accuracy of the calibration and how closely the in-service fluid velocity conditions match those encountered during the calibration. When the primary element is calibrated, the usual procedure is either to reproduce the flow conditions which will be encountered in service by simulation of the in-service piping configuration or to provide a sufficient straight pipe run ahead of the primary element so that the fluid velocity profile will be "normal." It is often, particularly in large pipe sizes, not possible to simulate the in-service piping configuration in the calibration facility or to provide a sufficient straight pipe run in either the calibration facility or in the actual system so that the primary element

encounters a "normal" velocity profile. The net result is that the installed accuracy is somewhat worse than the basic calibrated accuracy. This added inaccuracy depends on the design and type of primary element chosen. Those primary elements which constrict the flow are less affected by upstream flow conditions because the constriction of the fluid tends to "normalize" the velocity profile. The greater the degree of constriction, the less effect upstream conditions have. This can be seen in the recommendations for straight pipe upstream from a primary element — devices with a β of 0.5 require less straight pipe upstream than the same type device with a β of 0.75.

Based on the above and on the operating principle of the device, the pitot tube should be most affected by upstream flow conditions and the elbow meter next most susceptible. The relative susceptibility of orifice plates, flow nozzles, and flow tubes depends on the type of upstream disturbance and on the particular design of the orifice plate, flow nozzle, or flow tube. ASME publications and reports should be consulted for detailed information on a particular situation. Venturi tubes are less sensitive to upstream flow conditions than other types of differential head devices. One of the reasons, perhaps the major one, for this relative lack of susceptibility to upstream flow conditions is that piezometer rings with at least four circumferential taps each are generally used for both the upstream and throat pressure-sensing connections. The averaging effect of these piezometer rings tends to cancel some of the error which would otherwise result from asymmetrical fluid velocity profiles.

A flow disturbance which is particularly troublesome to differential head flowmeters, and whose effect is not diminished even by piezometer rings on a venturi tube, is swirling flow such as produced by two or more elbows in orthogonal planes. The effect of swirling flow can persist even after a long straight pipe section. For example, tests by BIF Industries on an 8-in. venturi tube with a β of 0.75 showed an error of more than 0.5% with the venturi tube separated from two elbows in orthogonal planes by a straight pipe run, 40 pipe diameters long. Straightening vanes are the only effective and positive means of eliminating errors due to this type of flow disturbance.

Of the differential head flowmeter readout devices, the manometer and the standpipe-differential pressure transducer should provide the best installed accuracy. Unfortunately, these readouts are really only suitable for laboratory

use. The NaK-filled or other high-temperature differential pressure transducers which are commercially available have claimed accuracies of $\pm 1\%$ of full scale or worse. The difference in the accuracy specification for the differential pressure transmitters, expressed in percent of full scale, and that for the primary element, expressed in percent of reading, is emphasized here because of the effect of this difference on the accuracy of less-than-full-scale flow measurements. Since the differential pressure is proportional to the square of the flow rate, the differential pressure is 25% of full-scale at 50% flow and 1% of full-scale at 10% flow. With a 1% of full-scale accuracy differential pressure transducer, the possible error in the differential pressure measurement alone is 4% of reading at 50% flow and 100% of reading at 10% flow. These ΔP errors correspond to flow errors of about 2 and 41%, respectively. This aspect of flow measurement accuracy with a differential head flowmeter must be remembered when accuracy is quoted in percent of reading.

3. Cost

The cost of a differential head flowmeter includes the cost of the primary element, the readout device, and calibration (when performed). For purposes of this report, the cost of the readout device will be assumed to be the same for all differential head flowmeters, regardless of the type of primary element. This assumption will also be made regarding the calibration cost. Using these assumptions, the relative cost of the various differential head flowmeters depends on the relative costs of the primary elements. This ranking will not necessarily hold true, particularly in small pipe sizes, if the accuracy or installation requirements are such that a more expensive primary element will suffice without calibration whereas less expensive primary elements would require calibration.

The least expensive primary element is an elbow or other inherent system pressure drop. The only cost for these primary elements is the cost of the pressure taps. The cost of the other primary elements is related to their physical size and complexity. The orifice plate and pitot tube are relatively small and simple primary elements and are therefore generally the next least expensive. The flow nozzle is next in cost, followed by the flow tubes and short-form venturi tubes. The classical Herschel venturi tube is the largest and most expensive differential head primary element. Regarding the size of various

flowmeter types, it may be of interest to note that a 30-in. commercial cast-iron venturi tube designed for 250-psig service (not liquid metal) weighs 9500 lb.

One aspect of the cost of a differential head flowmeter which has not been included in the above discussion is the pumping cost associated with the pressure loss through the flowmeter. This cost is so dependent on the particular installation that generalizations cannot be made; however, this cost should certainly be considered in any selection analysis. Consideration of this cost often shows that a venturi tube or flow tube has the least overall cost.

IV. TRANSIT TIME FLOWMETERS

A. THEORY OF OPERATION

Transit time flowmeters measure fluid velocity by measuring the time required for a "disturbance" in the fluid to travel a known distance from one point to another. This "disturbance" can be intentionally induced, such as a sonic pulse, or can be a random temperature or pressure variation which is inherent to the system. Two transit time flowmeters have been proposed for liquid metal use. The first type, which is being developed by Aeroprojects Incorporated, utilizes an externally introduced sonic pulse. The second type is based upon the use of noise analysis techniques to measure the transit time of inherent system temperature fluctuations. This latter type has been tested by the British and is under development at Atomics International.

B. TYPES OF TRANSIT TIME FLOWMETERS

There are many possible variations of the transit time flowmeter, but discussion in this report will be limited to the two types which are presently being investigated for applicability to liquid metal flow measurement. These two types are the ultrasonic flowmeter and what shall be called here the noise analysis flowmeter.

1. Ultrasonic Flowmeter

The ultrasonic flowmeter presently being developed by Aeroprojects Incorporated utilizes an ultrasonic transmitter mounted approximately flush with the pipe wall midway between two flush-mounted receivers. The receivers are mounted in the pipe wall opposite the transmitter, with one upstream from the transmitter and the other downstream. Two methods of operation have been contemplated for this flowmeter: pulse and continuous operation. In the pulse mode, an ultrasonic pulse is emitted from the transmitter and the difference in the time required for this pulse to reach the upstream and downstream receivers is measured. In the continuous mode, ultrasonic energy is continuously emitted by the transmitter and the difference in the transit time to the two receivers is determined by measuring the phase-angle difference between the upstream and downstream receiver signals.

The theoretical equation for the relationship of fluid velocity and the time difference⁽⁵⁾ is:

$$\frac{\Delta t = 2dV \cot \theta}{C^2} ,$$

where:

Δt = the time difference for receipt of signal at receivers

d = pipe inside diameter

V = fluid velocity (assumed uniform across pipe)

θ = angle between line connecting transmitter and receiver with respect to flow direction

C = velocity of sound in the fluid.

Early work by Aeropprojects has shown a linear relationship between Δt and V , although with considerable data scatter, but with a substantial difference between the experimental results and the theoretical prediction.

2. Noise Analysis Flowmeter

The noise analysis flowmeter is based upon the time required for some random fluctuation of a fluid property to pass from one point to another point a known distance away. This random fluctuation can be of any measurable fluid property, such as resistance or temperature. Since these random fluctuations are very small, special techniques must be used to detect these fluctuations and measure the time required for the fluctuations to travel from one point to another. The techniques required to make these measurements, while ignoring the effects of extraneous signal fluctuations generated within the system or within the instrumentation, falls within the general area of "noise analysis," hence the designation for this type of flowmeter. The specific noise analysis technique which has been used in experiments on liquid metal systems is cross spectral density analysis.

The experiments on liquid metal systems have been based upon the measurement of the random temperature variations in the fluid. These experiments have shown that the best results are obtained when the transit time is between 0.1 and 1 sec. The lower limit is due to the thermal response time of the

thermocouples while the upper limit is related to the effects of the relatively rapid diffusion of the temperature fluctuations in the fluid owing to the high thermal conductivity of the NaK test fluid.

C. ADVANTAGES COMMON TO TRANSIT TIME FLOWMETERS

The implicit advantages in the concept of flow measurement by the transit time technique are discussed in the following paragraphs.

1. Rangeability

Since the transit time is directly related to fluid velocity, the output signal from a transit time flowmeter is linearly related to the flow rate. Thus, a transit time flowmeter provides the capability of measuring a wide range of flow rates.

2. Pressure Loss

Since the transit time flowmeters have no constriction of the fluid path, the only pressure drop is that caused by a disturbance or obstruction of the flow path by the sensors. In the case of the ultrasonic flowmeter, the transmitter and readouts will be positioned nearly flush with the pipe wall but will cause some pressure drop because of the wall discontinuity, particularly at the transmitter. The overall pressure drop should, however, be relatively small.

The pressure loss in a noise analysis flowmeter based on temperature fluctuations will depend on the number and depth of insertion of the thermocouples sensing the fluid temperature. The pressure loss could be zero if pipe wall thermocouples would suffice, but experiments to date have shown that the slow thermal response of the pipe wall makes this technique ineffective. A typical noise analysis flowmeter using just a few insertion thermocouples should have a minimal pressure loss.

3. Cost Relationship to Pipe Size

The cost of a transit time flowmeter should be essentially independent of the pipe size on which it is being applied. In the case of the ultrasonic flowmeter, for example, it might be necessary to increase the power capacity of the ultrasonic transmitter in order to use it on a larger pipe. The only part of the cost of a noise analysis flowmeter (based on temperature fluctuations) which would be affected by pipe size would be the added cost due to the increased size

and perhaps number of thermocouples required. The effect of pipe size on the cost of other types of transit time flowmeters will depend on the specific design; however, in general, the cost of the readout will be the predominant part of the total flowmeter cost which, therefore, will be little affected by pipe size.

D. DISADVANTAGES COMMON TO TRANSIT TIME FLOWMETERS

The disadvantages which tend to be inherent in the concept of transit time flowmeters are discussed in the following paragraphs.

1. Reliability

The potential reliability of transit time flowmeters is compromised in two respects: (1) most require piping penetrations which imply an added likelihood of system leakage and (2) the readout tends to be complicated.

The safety and systems reliability considerations associated with piping penetrations have been covered previously and need not be discussed further. The complexity of the readout will depend on the particular type of transit time flowmeter, but the two types considered here provide good examples of the readout complexity which might be expected. The prototype ultrasonic flowmeter used in the Aeroprojects experiments had a time difference for receipt of the ultrasonic signal at the upstream and downstream receivers of only about 200 nanosec at a water velocity of about 5 ft/sec. Instrumentation which can accurately measure these very short time intervals is undoubtedly more complex than normal process instrumentation and is therefore likely to be less reliable. The same is true, probably even more so, for the instrumentation which can perform the cross spectral density analysis of the very small temperature fluctuations in a noise analysis flowmeter used on a liquid metal system.

2. Accuracy

The accuracy capability of transit time flowmeters is not likely to be good owing to the complexity of the readout devices and to their sensitivity to velocity profile changes. In the ultrasonic flowmeter, some compensation for velocity profile variation is achieved since the upstream and downstream signal paths are through the same velocity profile (disregarding the profile disturbance caused by the transmitter). However, since the effective signal path lengths

are different due to the apparent downstream shift of the ultrasonic signal source caused by the fluid motions, the effect of the velocity profile between the transmitter and receivers is not completely cancelled. Changes in the velocity profile in that portion of the fluid outside the ultrasonic signal path would not effect the transit times at all; therefore, any changes in the velocity profiles in these areas will cause an error in the flow measurement.

A noise analysis flowmeter utilizing two thermocouples measures only the fluid velocity between these two points. Therefore, the total fluid velocity profile must be measured, or assumed, if this velocity measurement is to be translated to a flow measurement. The noise analysis technique has been used to measure velocity profiles by utilizing a number of thermocouple pairs which are located at various radial positions and penetrations. The number of thermocouples required to determine the velocity profile with sufficient accuracy to provide an overall flow measurement accuracy of 1 or 2% would seem to limit this concept to very special applications.

3. Calibration Difficulty

Transit time flowmeters are difficult to calibrate because of their sensitivity to the fluid velocity profile as discussed above and because the operation of the device is likely to be affected by the fluid characteristics. The sensitivity of transit time flowmeters to changes in the fluid velocity profile requires careful attention to similarity of the upstream flow conditions in the calibration facility and the service installation.

The calibration of the ultrasonic flowmeter is affected by the characteristics of the fluid utilized during calibration because the difference in arrival time for the ultrasonic signal at the receivers is inversely proportional to the square of the velocity of sound in the fluid. Thus, a water calibration would require correction to take into account the difference in the velocity of sound in water and the liquid metal in which the transit time flowmeter is to be used. Since the early experiments showed a significant difference between the experimental and theoretical calibration, it is possible that a correction of the water calibration according to the theoretical relationships would not be adequate.

Operation of the noise analysis flowmeter is affected by the magnitude of the temperature fluctuations in the fluid. The magnitude of these fluctuations is

affected by the thermal conductivity of the fluid and by the characteristics of the fluid system which causes these fluctuations. Thus, calibration of a noise analysis flowmeter with another fluid under different conditions might not be representative of the intended service due to substantial differences in the magnitude of the temperature fluctuations.

E. COMPARATIVE ADVANTAGES AND DISADVANTAGES

Some comparative advantages and disadvantages of the two types of transit time flowmeters discussed in the previous sections are presented in the following paragraphs.

1. Response Time

The ultrasonic flowmeter responds quickly to flow changes, the speed of response being limited by the transit time of the ultrasonic signal from the transmitter to the receivers and by the response speed of the readout. Since the transit time of the ultrasonic signals would normally be in the microsecond range and since the readout is electronic, the ultrasonic flowmeter can be expected to have very rapid response to flow changes.

The noise analysis flowmeter has inherently very slow response owing to the random nature of the temperature fluctuations and the consequent necessity for long sample times to reduce the statistical errors. British experimenters have concluded that sample times of a minimum of 10 min are necessary if reasonable accuracy (on the order of 5%) is to be achieved on a liquid metal system.

2. Temperature Capability

The maximum temperature capability of the ultrasonic flowmeter depends on the temperature limitations of the ultrasonic transmitter and receivers and on how well these ultrasonic elements can be isolated from the process temperatures. Common piezoelectric ultrasonic transducers have temperature limitations well below the operating temperatures typical of liquid metal systems. Aeroprojects has developed a technique for transmission of the ultrasonic signals through a metal rod such that the ultrasonic transducer will experience a temperature lower than the system temperature. The ultimate temperature capability will be determined in future tests.

The noise analysis flowmeter will operate at any temperature for which thermocouples are available; thus, for all practical purposes, it has unlimited temperature capability.

3. Temperature Sensitivity

The major effect of temperature changes on the calibration of the ultrasonic flowmeter is due to the change of the velocity of sound in the fluid as the fluid temperature changes. In the case of sodium, for example, the velocity of sound decreases approximately 9% when the temperature is increased from the melting point to 1000°F. This sound velocity change would cause the time difference to change about 21% for a given fluid velocity (refer to equation in Section IV.B.1). A minor, and predictable, temperature effect is the linear expansion of the distance between the ultrasonic transmitter and the receivers.

The noise analysis flowmeter is relatively unaffected by temperature. There is the minor effect of the thermal expansion of the distance between the thermocouples. Another possible effect would be an increase in the magnitude of the temperature variations as the temperature is increased. This could mean enhanced flowmeter operation at higher temperatures.

V. OTHER FLOWMETER TYPES

A. TURBINE FLOWMETERS

1. Description

A turbine flowmeter is one which has a rotating element that is driven by the flowing fluid. The rotational velocity of the rotor is a function of the fluid velocity and readout of the flow rate is achieved with a transducer which senses the rotor velocity, usually by counting the number of rotor revolutions per unit of time. Turbine flowmeters are manufactured with two rotor configurations. In one, the rotor axis is parallel to the flow axis and in the other the rotor axis is perpendicular to the flow axis. The first type is the most common and will be referred to as a coaxial rotor. The second type will be termed a paddle-wheel rotor. The motive force for paddle-wheel rotors is derived from an upstream, off-center orifice so arranged that a jet impinges on one side of the wheel. Coaxial rotors have the blades set at an angle to the flow axis so that a component of force acts radially on each blade. For liquid alkali metal service, the rotor material is generally austenitic or martensitic stainless steel.

A trunion and journal extends from each end of the rotor shaft and fits into a bearing which is attached to the housing. Both radial and thrust loads are imposed on the bearings.

Coaxial rotor turbine flowmeters can be hydraulically designed to minimize or even eliminate the thrust load in order to increase bearing life and decrease the rotor stall speed. The following bearing material combinations have been used for liquid metal service:

<u>Journal</u>	<u>Bearing</u>
Carboloy-883 (94% tungsten carbide, 6% cobalt)	Carboloy-883
Carboloy-608 (83% chromium carbide, 2% tungsten carbide, 15% nickel)	Carboloy-608
Kantanum K-162B (52% titanium, 25% nickel, 13.2% carbon, 5% molybdenum, 4.5% cobalt, 0.3% tantalum)	Armco Iron

The bearings were designed for film lubrication. Care must be exercised on the design and use of carbides because of their brittleness and their low coefficient of thermal expansion relative to stainless steel. Use of molybdenum or cobalt in a carbide binder improves ductility. (Information on bearing materials for application in liquid alkali metals can be obtained from A. G. Grindell at Oak Ridge National Laboratory.)

The rotor velocity transducer is mounted in the outer shell of the turbine flowmeter and does not come in contact with the fluid. Two transducer techniques are used. One is based on the change in coil inductance when a magnetic material is moved past the coil. The other is based on the voltage induced in a coil when a magnetic field sweeps across it. A rotor made from a martensitic stainless steel, such as Type 430, is used with the first transducer type. One or more magnets are encapsulated in an austenitic stainless-steel rotor when the second type transducer is used.

In the idealized case, where there is no drag on the turbine due to bearing friction or to the transducer and where the fluid velocity is the same at all points in the pipe, the relationship of the rotational velocity of a coaxial rotor (ω) and the fluid velocity (V) can be expressed as:⁽⁶⁾

$$\omega = \frac{V \tan \alpha}{R} ,$$

where:

α = angle between the blade and the flow axis

R = radius of the blade center of pressure.

In actual practice, the relationship departs from linearity at both low and high fluid velocities. The departure at low fluid velocities is due to the static bearing friction. The rotor stall fluid velocity can be as high as 2 ft/sec on decreasing flow and 4 ft/sec on increasing flow. The departure at high fluid velocities is due to bearing friction and transducer drag at high rotor speeds. The degree of departure from linearity and the fluid velocity at which departure occurs are functions of the fluid density.

A special turbine flowmeter configuration which greatly extends the linear range has been developed by Dr. F. F. Liu of Quantum Dynamics. This turbine

flowmeter employs two turbines of identical blade construction — a slave turbine with a long shaft and a measurement turbine which is mounted on the slave turbine shaft. Since the slave turbine turns nearly as fast as the measurement turbine, the bearing load on the measurement turbine remains low even at very high rotor speeds. The transducer is also designed to produce very low rotor drag.

2. Advantages

a. Accuracy and Ease of Calibration

Since the calibration of a turbine flowmeter is relatively independent of fluid characteristics in the linear operating range, the turbine flowmeter can be expected to provide accurate flow measurements over a wide range of operating temperatures. This characteristic also means that a turbine flowmeter can be calibrated in one fluid and used in another with little or no calibration correction required. Insensitivity to fluid density changes was demonstrated by tests conducted by J. Cuthbert of Potter Aeronautical Corp.⁽⁷⁾ These tests showed no appreciable calibration change for flow rate measurements of air at 4-1/2 and 40 atm and water over a 10-to-1 flow range. A 1-1/2% difference in the flow coefficients for air at 4-1/2 and 40 atm was measured when the flow range was increased to 1-2/3 decades.

Tests by Grey⁽⁶⁾ showed errors of about 2.2, 1, and 0.2%, respectively for 1/2-, 3/4-, and 2-in. turbine flowmeters due to the velocity profile change caused by a factor-of-5 change in kinematic viscosity. It would appear from these data that this effect would be negligible in turbine flowmeters larger than 2 in.

One correction factor which must be taken into account if the potential accuracy of a turbine flowmeter is to be maintained in liquid metal service is that for the expansion and contraction of the turbine and housing caused by temperature changes. Referring to the previously given formula for rotor speed (ω):

$$\omega = \frac{V \tan \alpha}{R} = \frac{Q \tan \alpha}{(A_h - A_r)R}$$

where:

Q = volumetric flow rate

α = rotor blade angle

A_h = internal cross-sectional area of housing

A_r = maximum cross-sectional area of turbine

R = average radius of the blade center of pressure.

From this formula it can be seen that at a given volumetric flow rate, the change of ω with temperature is inversely proportional to the linear expansion coefficient cubed. Thus, a 500°F temperature change would cause a reduction in rotor speed of about 1-1/2% at a given volumetric flow rate.

b. Response Time

Turbine flowmeters generally have fairly rapid response to flow changes. The response time will vary with design and flow rate. A typical value of response time given for a standard commercial turbine flowmeter is 2 to 5 msec for a step change in flow rate.⁽⁸⁾ This is the mechanical time constant of the rotor. The time constant for the readout will vary depending on the transducer signal frequency and whether the readout has been optimized for accuracy or response time. Maximum readout accuracy is achieved by counting pulses over a long sample time; but this leads to very slow response. The fastest readout response is achieved by measuring the time interval between zero crossings of the alternating signal, but this leads to reduced accuracy. It should, however, be possible to design a 4-in. or smaller turbine flowmeter which would have an overall response time of 10 msec or less and a basic accuracy of 1/2% or better.

c. Rangeability

The frequency of the output signal from a turbine flowmeter is linear with flow rate over a minimum 10-to-1 flow range. Thus, flow can be measured with good accuracy over a wide range of flow rates. The range of flow rate measurement of standard turbine flowmeters is usually 16-to-1 or 20-to-1, at least for intermittent service, with specially designed units having 50-to-1 or greater capability.

d. Temperature Capability

The operating temperature limits of a turbine flowmeter are determined by the operating limits for the bearings and the transducer. Successful operation of turbine flowmeters at temperatures up to 1500°F was achieved at ORNL in

the 1955 to 1958 period. This work, in association with the ANP project, was terminated before extended experience at these temperatures could be obtained. However, the potential for operation at very high temperatures has been shown.

3. Disadvantages

a. Reliability

The primary disadvantage of turbine flowmeters for liquid metal service is the questionable reliability of the rotor bearings. There is insufficient experience to firmly state whether this fear is well founded, but the limited experience to date would indicate that it may not be. Turbine flowmeters have been successfully operated for 1700 hr at LASL⁽⁹⁾ and for 1500 to 2000 hr at ORNL.⁽¹⁰⁾ Bearing failures which have occurred were caused by brittle fracture of the carbides, not by galling.

Other operating difficulties experienced with turbine flowmeters were caused by electrical interference in the transducer from nearby electromagnetic pumps. Shielding provided a successful solution to this problem in one case but not in the other.

Based upon the design concept of a turbine flowmeter (a moving part in the liquid metal and a moderately complex readout system) the probable reliability of a turbine flowmeter in liquid metal service is questionable.

b. Pressure Loss

The pressure loss across a turbine flowmeter is not as low as with many other flowmeter types. The standard turbine flowmeter of Potter Aeronautical Corp. has a 4-psi pressure loss in water at the maximum flow rate for continuous service.⁽⁸⁾ The pressure loss for other fluids can be calculated with the following formula:⁽⁸⁾

$$P = \mu p_s P_w$$

where

μ = absolute viscosity (cp)

p_s = specific gravity

P_w = pressure drop for water.

One characteristic of turbine flowmeters which should be considered, particularly since their reliability in liquid metal service is questionable, is the pressure drop if the rotor should jam or become locked up. The pressure drop under this condition could increase to as much as 36 psi.⁽¹¹⁾

c. Cost

Turbine flowmeters tend to be expensive because of the precision required in manufacture of the housing, bearings, and rotor and because of the moderate complexity of the readout. The readout cost is the same regardless of flowmeter size, but the cost of the flowmeter itself can be expected to increase substantially with line size.

d. Electrical Noise Susceptibility

As previously mentioned, some turbine flowmeters have been troubled by electrical noise. Since the readout must be sensitive to moderately low-level ac signals, some difficulty (particularly at 60 hz and its harmonics) may be encountered in liquid metal systems employing electromagnetic pumps or electrical heaters.

B. THERMAL FLOWMETER

1. Description

Thermal flowmeters are those in which the transfer of heat to the flowing fluid is a basic part of the technique. There are two basic operating principles used in thermal flowmeters: one in which the effect of transferring a known quantity of heat to the fluid is measured and the other in which the effect of the flowing fluid on a heated body is determined. The first type typically consists of a heater which is preceded and followed by temperature measuring instruments. The flow rate is then derived from the temperature difference, the heat input, and the specific heat of the fluid. An example of this concept was an experimental meter designed for use as a FARET fuel channel flowmeter. This flowmeter measured only a portion of the fuel channel flow rate because of the excessive power required to produce a measurable temperature difference in the total fuel channel flow.⁽¹¹⁾

In the second type, typified by the hot-wire anemometer, the flow rate is determined by the rate at which heat is transferred from a heated wire or other

heat source to the flowing fluid. The rate of heat transfer can be determined by measuring the temperature of a heater with constant power input or by measuring the power required to maintain the heater at a constant temperature. This type of thermal flowmeter has been developed in several forms for gas flow measurements. This flowmeter type must be calibrated because the operation is dependent on the heat transfer characteristics of the fluid. A thermal flowmeter of this type for liquid metal use would require a heater which is electrically insulated from the fluid because of the high electrical conductivity of liquid metals.

2. Advantages

a. Mass Flow Measurement

Thermal flowmeters are basically mass flow measurement devices and can, therefore, be of advantage where measurement of mass flow rate instead of volumetric flow rate is desired. When a volumetric flow measurement is made and the temperature of the fluid is varying, corrections for density change must be made if the mass flow rate is the required measurement. This correction can be appreciable in liquid metal systems which operate over a wide temperature range. Thermal flowmeters, however, are not completely independent of temperature-induced changes in fluid characteristics. The first type of thermal flowmeter strictly measures mass flow only if the fluid specific heat does not vary with temperature. In the case of sodium, the variation of specific heat from 400 to 1000°F is only about $\pm 1-1/2\%$; therefore, this concept would approach true mass flow measurement in sodium. The second type of thermal flowmeter would depart further from strict mass flow measurement of sodium because the heat transfer coefficient is more affected by temperature than is the specific heat.

b. Low Pressure Loss

Thermal flowmeters tend to have a small pressure loss due to the minimal flow disturbance presented by the heater or heated object. A thermal flowmeter such as the experimental FARET fuel channel flowmeter which segregates and measures only part of the flow would have a slightly higher pressure drop because of the flow segregation mechanism.

3. Disadvantages

a. Accuracy

The accuracy of thermal flowmeters tends to be less than that available from more conventional flowmeter types for several reasons. In the first type of thermal flowmeter, it is usually impractical to measure the total flow because of the large amounts of power required to create a temperature rise of sufficient magnitude for accurate measurement. Therefore, the usual technique is to measure a portion of the flow and infer the total flow by multiplying the measured flow portion by a constant. This leads to inaccuracies since the proportion of the total flow which passes through the measuring section is affected by upstream flow conditions. Another accuracy limitation of the first thermal flowmeter type is that the measured temperature differentials tend to be small and the flowmeter output signal level is therefore in the hundreds-of-microvolts range. This low signal level is difficult to measure precisely and is more subject to "electrical-noise"-induced errors.

The accuracy of the second type of thermal flowmeter is also affected by upstream flow conditions since the flowmeter measures the fluid velocity only in that portion of the fluid stream which contacts the heated wire or body. Since this type of flowmeter must be calibrated and since its calibration is affected by the heat transfer characteristics of the fluid, an accurate calibration can only be performed with the fluid with which it is to be used. The scarcity of liquid metal flow calibration facilities prevents this in many cases. The alternative is to calibrate with another fluid, typically water, and then correct the calibration to take into account the differences in heat transfer characteristic of the calibration and service fluids. This technique cannot be expected to provide a highly accurate calibration owing to the uncertainty in the experimental values for liquid metal heat transfer coefficients.

b. Reliability

The reliability of thermal flowmeters is questionable from the standpoint of both system reliability and the reliability of the instrument itself. System reliability is compromised because piping penetrations are required and objects projecting into the fluid stream are connected to these penetrations. Particular attention to the mechanical integrity of a thermal flowmeter would be required for liquid metal service where fluid velocities often exceed 10 or 15 ft/sec.

The reliability of the flowmeter itself for liquid metal service is questionable because of the requirement for precise operation of heaters and thermocouples at high temperatures and of the moderately complicated electronics required for the readout of these devices.

c. Response Time

The electrical conductivity of liquid metals requires that the heater in a thermal flowmeter be electrically insulated from the fluid. This generally means that the heater is also somewhat thermally insulated from the fluid. This thermal insulation between the heater and fluid leads to a relatively slow response of the flowmeter to flow changes. The time constant of a thermal flowmeter designed for liquid metal service would probably be on the order of 1 sec.

C. POSITIVE DISPLACEMENT FLOWMETER

1. Description

Positive displacement flowmeters are devices which divide the flow into increments of known volume and which then derive the volumetric flow rate from the time-rate of these incremental volumes. Positive displacement flowmeters can take a number of forms: (1) lobed, intermeshing impellers (similar to a Rootes-type compressor); (2) a nutating disc (or wobble-plate); or (3) a device with volume chambers separated by a diaphragm or bellows. The latter type is the most likely for liquid metal service since the first two types depend upon maintenance of sliding seals for proper operation. The positive displacement flowmeter with two chambers separated by a diaphragm or bellows utilizes a mechanical connection to the diaphragm or bellows to actuate valves which alternately fill and empty the two chambers. This mechanical connection also supplies the readout information in the form of the number of fillings of each volume chamber.

2. Advantages

a. Accuracy

The primary advantage of a positive displacement flowmeter is its accuracy. Since it is a true volumetric device, its accuracy is unaffected by upstream flow conditions, by fluid density changes, or by other changes in fluid characteristics. The only temperature effect is that of the change in chamber volume resulting from thermal expansion.

b. Ease of Calibration

Those characteristics of a positive displacement flowmeter which lead to the good accuracy as outlined above also lead to its ease of calibration. Since the positive displacement flowmeter calibration is essentially independent of fluid characteristics, a water calibration is directly applicable to other fluids with only the simple temperature correction for thermal expansion.

3. Disadvantages

a. Reliability

The primary disadvantage of a positive displacement flowmeter for liquid metal service is its questionable reliability under those conditions. Proper operation of this type of flowmeter requires that a seal be maintained between the volume increments which are being measured. This seal is a sliding type in the intermeshing lobe and nutating disc types of flowmeters. The diaphragm or bellows type flowmeter does not have a sliding seal, but there is an inlet and an outlet valve from each chamber which must seal if accuracy is to be maintained. The probable reliability of these seals, the mechanisms which must operate in the liquid metal, and the diaphragm or bellows itself is questionable when the wide operating temperature range, the likelihood of contaminants in the liquid metal, and the cyclic operating mode are considered.

b. Pressure Loss

Positive displacement flowmeters tend to induce a relatively large pressure loss, since the energy loss in the seals and mechanisms must come from the fluid. The pressure loss will depend on the particular design of this type of flowmeter but can certainly be expected to exceed that of the magnetic flowmeter or other low-pressure-loss flowmeter types.

c. Response Time

The response time of positive displacement flowmeters is a function of the mechanical inertia of the flowmeter moving mechanism and the response time of the mechanism velocity sensing device. The mechanical inertia would increase with pipe size so that large positive displacement flowmeters could be expected to have slower response times than small ones. The exact value would depend upon the size and design but could be expected to be in the range of one to a few seconds.

D. HYDRAULIC OSCILLATION

1. Description

A flowmeter based upon swirl-induced fluid oscillation has been recently developed by the American Radiator and Standard Sanitary Corporation. Commercial development of this concept has been licensed to the Fischer and Porter Company. The operation of this flowmeter is based upon a phenomenon of hydraulic oscillation downstream from a region of substantial fluid swirl. This phenomenon was termed a "vortex whistle" by early investigators and the flowmeter based on this phenomenon has been tradenamed the "Swirlmeter."

The Swirlmeter induces swirl in the flowing fluid with fixed vanes which are upstream of a venturi-like area of reduced cross section. In the region where the cross section increases again, the swirling flow precesses, or rotates, about the longitudinal axis of the flowmeter. The interesting property of this device is that the frequency of precession of the fluid swirl center is directly proportional to the fluid velocity over a certain flow range and is independent of other fluid properties such as density, viscosity, and temperature. Early gas flow experiments have shown that this range of direct proportionality of flow and frequency covers a flow range of up to 100:1 with precession frequencies of 10 to 1000 cps. The rangeability for liquid flow measurement is expected to be somewhat less, with present estimates of a minimum rangeability of 20:1.

Readout of the precession rate can be accomplished in several ways. An acoustic microphone was used in the early work, but this technique was troubled by intrusion of other system pressure pulses and hydraulic noise. Use of two diametrically opposed microphones allowed cancellation of the axial pressure waves while remaining sensitive to the transverse pressure pulses. Differential pressure transducers were also used successfully in other flow experiments. The first commercial meters, not yet available, will use a thermistor with a close thermal link to the fluid to detect the cyclic variations in local fluid velocity (and, therefore, heat transfer characteristics). The first commercial models will have a temperature limit of 500°F due to the thermistor transducer used. Recent developments in diamond thermistors may allow use of this readout technique at temperatures up to 1200°F.

Another readout technique which might be applicable for a liquid metal Swirlmeter would be similar to a permanent-magnet flowmeter but with the magnet oriented so that the magnet flux is at some appreciable angle (30 to 45 degrees) to the pipe axis. A "magnetic flowmeter" oriented in this manner would be sensitive to lateral as well as axial fluid velocities and might provide a signal modulated at the fluid precession frequency. An E-core electromagnet flowmeter oriented for sensitivity to radial fluid velocities might also be an applicable readout technique for liquid metal service.

2. Advantages

a. Accuracy

If this concept realizes the potential indicated by the early experiments, it will offer significant advantages in terms of installed accuracy. There will be no added flow measurement error due to correction of a water calibration for differences in fluid characteristics. The only correction required will be the minor, and predictable, correction for thermal expansion of the meter cross section at increased fluid temperatures. Another significant aspect of installed accuracy is the relative insensitivity of the Swirlmeter to upstream flow conditions, since a substantial fluid swirl is purposely produced in the Swirlmeter itself. A third significant accuracy consideration is that the accuracy is unaffected by appreciable changes in the magnitude of the oscillation signal, since only the frequency of this signal is measured.

b. Calibration Ease

Those characteristics of the Swirlmeter which lead to its good installed accuracy also make the calibration of a Swirlmeter relatively easy. Since the Swirlmeter is essentially unaffected by fluid characteristics and by upstream flow conditions, it can be calibrated with any convenient fluid without particular attention to the configuration of the calibration facility.

c. Rangeability

The rangeability of the Swirlmeter in liquid flow measurement is not definitely known at this time. Since the output signal is linear with flow over the operating range, the only limit to rangeability is the flow range over which this oscillation can be established and maintained in the linear relationship. This

flow range has been found to be as much as 100:1 for gas flow measurement. The flow range in liquids is expected to be at least as good as a turbine meter and perhaps as much as 40:1 or 50:1.

3. Disadvantages

a. Unproven Device

The primary disadvantage of a Swirlmeter at this time is that it is an unproven device. This means that the reliability (particularly concerning the mechanical integrity of the swirl vanes), temperature capability, and other important characteristics are unknown. It also means that those desirable characteristics which are indicated by the early laboratory experimental work are unproven in the field. Only time and experience can resolve these questions.

b. Pressure Loss

The one disadvantage of the Swirlmeter which can be discussed with some confidence is the pressure loss across the device. This pressure loss is due to the swirl-producing inlet vanes. The pressure loss on the first production flowmeters (which are intended for gas service) is expected to be about 10 velocity heads ($\rho V^2/2g$). This would mean a pressure loss of about 10 psi with a sodium velocity of 13 ft/sec. This magnitude of pressure loss is deemed excessive by Fischer and Porter and the Swirlmeter for liquid service will be designed to produce a lesser pressure loss. Their design target is a pressure loss as low as a turbine flowmeter, but this has not yet been achieved.

VI. CONCLUSIONS

There is no one flowmeter type which is best for all liquid metal flowmetering applications.

The permanent-magnet flowmeter is the closest to meeting the requirements of the "ideal" liquid metal flowmeter. The only significant disadvantages of this type are the calibration difficulty (except in small sizes) and the calibration changes with time and temperature. The advantages of this type are numerous and very significant.

Differential head flowmeters offer the potential of good accuracy; but particular attention to calibration procedures, flowmeter location, and differential pressure readout accuracy is required if the potential accuracy is to be realized, especially in large sizes.

Turbine type flowmeters may be the best choice in small line sizes where accuracy considerations are paramount and where long-term reliability is not required.

The noise analysis flowmetering technique may be useful for measurement of long-term calibration stability of standard flowmeters.

The Swirlmeter flowmeter appears to have considerable promise for liquid metal flow measurement. Cognizance of development work on this flowmeter should be maintained and experiments utilizing this flowmeter concept for liquid metal flow measurement should be instituted if and when further development and experience warrants.

Further development effort to determine the optimum magnet configuration and/or electrode location for large permanent-magnet flowmeters is required and justified. This development effort should be conducted with a dc electro-magnet flowmeter because of the difficulty of altering the configuration of a magnetized permanent magnet.

A volumetric liquid metal calibration test should be performed with a differential head flowmeter, preferably a venturi tube, which has been previously water-calibrated. This test will then prove whether a water calibration of a differential head flowmeter can be translated to a liquid metal calibration without addition of significant errors.

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