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LIQUID METAL CAVITATION - PROBLEMS AND DESIRED RESEARCH

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NOMENCLATURE

ρ_L	density of liquid, lbm/ft^3
ρ_v	density of vapor at saturation temperature, lbm/ft^3
μ	absolute viscosity, centipoise
σ	surface tension, lbf/ft
c	heat capacity of liquid, Btu/lbm-°F
k	thermal conductivity, $Btu/lbm\text{-}ft^2\text{-}°F/ft$
h_{f_g}	latent heat of vaporization, Btu/lbm
ρ_v	saturated vapor pressure at corresponding temperature, psia
T	temperature, °F
K_T	isothermal bulk modulus, psi
B	a coefficient, defined as $\dfrac{\rho_L\ c(\Delta T/\Delta H)}{\rho_v\ h_{f_g}}\ \dfrac{1}{\dfrac{\text{ft-lbf}}{\text{lbm}}}$
H	fluid head -- $\dfrac{\text{ft-lbf}}{\text{lbm}}$

I INTRODUCTION

At the present time many applications exist wherein liquid-handling machinery, capable of the utmost in performance, is required. Size and weight of the machinery must be held to a minimum either because of the nature of the application or because of the inherently higher cost of excessively bulky machinery. In many cases, unconventional fluids are involved under extreme conditions of temperature and/or pressure. Perhaps the most important of these fluids belong either to the class of cryogenic liquids or to the liquid metals. It is the latter with which this paper is primarily concerned.

The technical applications of primary importance use liquid metals either as heat transfer or heat engine fluids. Sodium, sodium-potassium alloy, bismuth, and lead-bismuth alloy all are presently in use or under serious consideration as heat transfer fluids in nuclear power plants. Mercury has been used in the past and is presently being used as the working fluid for high-temperature Rankine cycles. Also, it has been considered as a possible coolant for fast reactors. Sodium has been considered for the heat-engine working fluid of a power plant operating at very high temperature.(1) An examination of the physical properties of other liquid metals, especially sodium-potassium alloy and rubidium, shows the possibility of a similar use (see Table I).

In all of these applications it is necessary that the liquid metal be pumped. In some cases, depending upon the application, it may be extremely vital that the pumping equipment be of minimum size and weight, and in some cases quite limited equipment life is permissible. In all cases it is very desirable that the cost be minimized. In general these objectives can only be attained through an increase in pump rotating speed. However, this must be accomplished without an excessive increase in suction pressure. For a given pump output with fixed suction pressure, the maximum design rotating speed is fixed by the supposed imminence of cavitation, and its anticipated effects on pump performance and damage rates. Consequently, it is of great technological importance to obtain precise information regarding the likelihood of cavitation with various liquid metals under applicable operating conditions, and its damage and performance effects in the event of its occurrence.

In addition to the immediate practical application, a study of cavitation in liquid metals is of basic fundamental interest. Up to the present, most cavitation research has been conducted using water or, in some cases, other fluids of quite similar properties. Liquid metals offer a range of physical properties differing widely from those of fluids usually employed. Hence experimentation with liquid metals will greatly increase the spectrum of physical properties for which cavitation data is available, and will allow a testing of hypotheses, largely developed from consideration of water experiments, over a much greater range of applicability. This aspect will be considered in greater detail in the following paragraphs.

II LIQUID METALS AS FLUIDS FOR CAVITATION STUDY

Very generally, liquid metals offer the possibility of cavitation testing with fluids covering a very broad range of densities, of high thermal conductivity and low viscosity, of very low vapor pressure, of low gas solubility, and of volumetric heat capacity similar to that of water. In addition tests can be conducted at temperatures ranging from near ambient up to a maximum at which the fluid can be contained even with its low vapor pressure. The possibility of testing at high temperature is important to damage effects since the physical properties of structural materials as well as the rates of possible chemical reactions which may contribute to damage are a function of temperature. Those liquid metal properties deemed most significant to the cavitation phenomenon are tabulated where information exists in Table I. Comparison is made with water.

The disadvantages of liquid metals as cavitation research fluids are mainly those of handling and instrumentation, and the lack of transparency both of the fluid and of high temperature containers. These problems are discussed further in later paragraphs.

III ANTICIPATED PECULIARITIES OF LIQUID METAL CAVITATION

What do we not know about liquid metal cavitation? From the writer's viewpoint, a detailed answer to this question would also answer the more general question: What do we not know about cavitation? However, it is possible to consider the various significant aspects of the cavitation problem separately, and to consider in each case in what way we expect liquid metals to differ from more conventional fluids in their behavior. This is the approach which will be followed.

Gas Nuclei and Scaling Effects

Much attention has been devoted in recent years to these areas, both experimentally and analytically. The present thinking, along with results of recent water tunnel studies, has been well summarized in recent papers by Eisenberg (2) and Strasberg (3). Very briefly, the supposition of microscopic free gas "nuclei," perhaps entrained in crevices in impurity particles or on the container walls, is necessary to explain the common observation of cavitation at pressures approximately equal to the vapor pressure. These "nuclei" may grow either by the inward diffusion of gas from the liquid, if sufficient time is provided as in a boundary layer,(4,6) or by rapid vaporization of the surrounding fluid, provided the local pressure is sufficiently below the vapor pressure. This latter process obviously depends upon the heat capacity of the liquid and the heat of vaporization of the fluid,(5) and the thermal conductivity of the fluid. Bubble growth is also obviously affected by viscosity and surface tension. Because of the very complicated nature of the growth process when the bubble is of microscopic size, no clear understanding has yet been obtained of the relations which much be applied in scaling a cavitation test from model to prototype. However experimental evidence of the variation of incipient cavitation number with model size and velocity has been obtained.(6)

There are various physical properties of liquid metals which will render research in these areas somewhat unique. These are listed below with their anticipated effects:

a) Gas Solubility - Since the solubility for gases in liquid metals is generally almost zero, the possibility of bubble growth in the boundary layer from gas diffusion as observed by Daily(4) and Kermeen(6) with co-workers seems nearly non-existent. Therefore, very low cavitation numbers may be obtainable even without degassing.

Also because of low gas solubility, it would appear that the bubble contents would be only vapor from the fluid, so that collapse could not be cushioned by a non-condensible gas. This should tend to increase damage effects by increasing the violence of collapse and perhaps also by preventing bubble rebounds.

b) Entrained Gas - Entrained gas, to the extent that it exists in ordinary water, may or may not exist in liquid metals. Its existence obviously depends upon the tightness of the system and the opportunity for entrainment (as, for example, from an inert gas blanket in a pump casing). However, in reactor cooling systems the existence of impurities is a serious concern because of the possibility of induced radioactivity and reactor poisoning and, also, in the case of gas, reactivity changes due to void effects. Hence, it might be expected that such systems will be well degassed. In this event it is possible that cavitation will not occur under ordinary conditions. However, present experience with liquid metals does indicate the existence of cavitation when the vapor pressure is approached.(7,8) In tests of this kind no precise control of gas content has been possible.

c) Reynolds Number - It is to be expected that the Reynolds Numbers existing in liquid metal systems will be very large, especially with the heavier liquid metals (low kinematic viscosity - Table I). For this reason, the boundary layers will tend to be of smaller extent than for comparably sized room-temperature water systems, so that bubble growth mechanisms depending upon location in the boundary layer, and hence long existence within the low pressure region, will tend to be restricted. For this reason, too, low cavitation numbers for initiation might be expected.

d) Thermodynamic Effects - Because of the low vapor pressure at any feasible operating temperature for most liquid metals, the vapor within the cavitation bubbles should be of extremely low density. For this reason, principally, the volumetric proportion of vapor formed by a small reduction of pressure below the saturation pressure should be very large, as compared with water, especially hot water. This volumetric vapor fraction per unit depression of the static head should be proportional to the quantity

$$\left(\frac{\rho_L \, C \, \Delta T/\Delta H}{\rho_v \, h_{f_g}}\right)$$

shown in Table I. It is noted that the quantity is relatively very large for the liquid metals.* This would appear to indicate a more drastic effect on component performance due to a given head depression below the pressure corresponding to cavitation initiation for the liquid metals. Such an effect has previously been suggested(5) and also noted in tests comparing hot and cold water,(9) or petroleum products and cold water (cold water being analogous to the liquid metals in these examples).

Because of the high thermal conductivity of the liquid metals, and the fact that the volumetric heat capacities are similar to water, it would be expected that vaporization initiated by a local pressure depression would

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[*] If the vapor pressure were zero, the void volume, on this account, could be infinite. Of course, actually, many other factors are involved.

be especially effective, drawing upon the heat capacity of the surrounding fluid for additional vaporization. It would then be anticipated that for this reason the effects upon component performance would tend to be more significant with liquid metals.

e) Damage Effects - Various of the properties of liquid metals would be expected to significantly influence damage.

Liquid density varies over a factor of about 15 between the liquid metals of technical interest (Table I), and also between the heavier liquid metals and water. It certainly appears likely on mechanical grounds that damage rates will increase with increasing fluid density. Since it appears that damage is not always the result of purely mechanical action, and since, in any case, the damage mechanism is not presently understood, it is not possible to predict the form of a relationship between density and damage. It is suspected that such a relation is also, at the very least, a function of the fluid and container material.

The bulk modulus for mercury is considerably greater that that for water, and that for sodium considerably less. Values for the others are not readily available. It seems likely that greater damage should result from fluids with greater bulk modulus since the instantaneous pressures generated by bubble collapse would be greater. However, the form of any relation between the bulk modulus and damage cannot be predicted. The relation must also be a function of the stiffness of the container material. It would seem likely that the relation would become more sensitive to the rigidity of the container as the bulk modulus of the liquid were increased.

Surface tension and viscosity are other fluid properties expected to influence damage. Generally it would be expected that the greater the surface tension and the smaller the viscosity, the greater the violence of bubble collapse and the greater the damage. Examination of the table shows that the surface tensions are roughly of the order of water whereas the kinematic viscosities of the liquid metals are considerably less than for room temperature water. As previously mentioned the probable lack of significant quantities of non-condensible gases within the bubbles should lead to greater collapse violence.

The possibility of an increase in damage due to chemical reaction between the fluid and container always must be considered. It is obviously present in significant degree in some of the liquid metal and container combinations, and, of course, in some water applications. In the absence of cavitation this possibility must be minimized if the combination is to be of technical interest. For example, mercury with suitable additives in carbon or stainless steel, sodium in stainless steel even at very high temperature, bismuth in low chrome-moly alloy steel are combinations which exhibit sufficiently low corrosion rates to be of interest. Nevertheless a finite reaction rate is present, presumably a function of temperature. How these corrosion rates may be affected by the superposition of cavitation remains to be seen.

The high temperatures obtainable with liquid metal systems are important in connection with damage research. The strength and hardness of the container material are often substantially reduced at high temperature, so that presumably damage, strictly from mechanical effects, should be increased. In addition it is likely that corrosion rates will also be increased.

f) Scale Effect Problems - As previously mentioned, the relations governing scaling of cavitation performance tests are not sufficiently understood at present to allow reliable predictions between model and prototype with water. This is obviously also true of damage tests with water. At the present time it is certainly true that a more profound lack of knowledge exists for liquid metals with respect to cavitation scaling, since, in general, comprehensive and precise test results are not even available. It is to be hoped that experimental results with these fluids, with their quite different physical properties, will shed further light on the nature of the required scaling parameters, both for water and liquid metals.

IV RESEARCH APPROACHES AND ASSOCIATED PROBLEMS

Experimental research in liquid metal cavitation can take the form either of a flowing system as a tunnel facility, or a closed system where cavitation is induced by vibratory or acoustic methods. If the objective is to assist in the development of knowledge which will be of eventual application to fluid-handling machinery, it appears to the writer that the flow system is most suitable since it more closely models actual machinery. In any case, it would appear that little progress can be made with the evaluation of liquid metal cavitation effects without an experimental program. If a tunnel facility is used, it is possible to compare performance and damage effects between water and various liquid metals under identical conditions of geometry, velocity (or Reynolds Number if desired), temperature, container material, etc, under conditions where the velocity and pressure profiles can be accurately ascertained.

Whatever the experimental approach, the basic examination of the phenomenon is much more difficult with liquid metals than with water because of the opacity of the fluid, and also of the container when high temperatures are used, and because of the various instrumentation difficulties which exist with any liquid metal which may be chosen. In fact it appears that the problem of obtaining meaningful and precise data is mainly one of instrumentation. For example, if a tunnel with cavitating venturi is to be used, there must be ways of ascertaining the extent of the cavitating zone as well as the conventional flow parameters. Also if damage is to be investigated, some relatively simple method of examining and recording the results from the test section must be found. This is especially difficult with a liquid metal system because of the inherently small sizes which most probably must be employed and the difficulty and expense of breaking into and reassembling such a carefully sealed system.

The precise measurement of pressure and velocity is difficult and involves complicated, and sometimes not fully-developed, instrumentation with any liquid metal other than low-temperature mercury. Mercury, while free from plugging and freezing difficulties, presents a severe vapor-toxicity problem. Temperature measurement in all cases appears quite straightforward.

Determination of the location and description of the cavitation involves several possibilities. In some low-temperature cases it may be possible to use a transparent test section. Even though the liquid is opaque, it would appear that observation of the interface between liquid and container would suffice to delineate the location and extent of the cavitating region. Some other possible approaches are the following:

a) Sonic - It may be possible to use electronically recorded and observed sound pressure from cavitation to distinguish and measure the cavitation extent (degree of cavitation), and also violence or intensity. It would appear that this technique would be especially effective in determining the initiation point. Also some correlation between damage effects and sonic pressure may well exist.

b) Void Fraction - It may be possible to measure the volumetric "void fraction" in the cavitating region, employing the fact of differential absorption for X and gamma radiation between vapor and liquid phase. In this way the extent of the cavitation region as well as some of its propertities might be measured. Determination of precise results from such a technique should be easier with the heavier liquid metals than with water because of their greater absorption coefficients.

c) Performance - The efficiency of the diffuser of a venturi is very sensitive to the extent of cavitation, provided the cavitation covers a substantial region. This fact could be used to measure the extent of the cavitation in a suitably calibrated venturi, but would not be useful in determining its inception point.

Finally, there is the problem of determining and controlling the quantity of entrained gases. This appears especially difficult with liquid metals. It is important because of the probable effects upon cavitation initiation, scale effects, and perhaps damage. Perhaps possible methods of measurement are extraction under vacuum as in the Van Slyke technique for water*, utilization of the absorption capabilities of gas bubbles for sound energy as described by Strasberg(3), or some chemical technique. Needless

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* Since the solubility of gas in liquid metals is so very small, the problem of distinguishing between dissolved and entrained gas may be non-existent.

to say the difficulties will be increased many-fold for those liquid metals with melting points at elevated temperature.

V CONCLUSIONS

At the present time there is little or no precise data available on cavitation performance or damage effects with the various liquid metals of technological importance. On this account, there is a strong motivation for a research effort in this area. However, there is the additional motivation that data gained with the liquid metals, with their unique physical properties, are of great basic interest in expanding the applicability of present cavitation hypotheses, conceived largely on the basis of tests with water.

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TABLE I

LIQUID METAL PROPERTIES APPLICABLE TO CAVITATION

Fluid	Temp.	Density of Liquid	Vis- cosity	Surface Tension	Heat Capacity	Thermal Conductivity	Latent Heat of Vapor	Density of Vapor	Vapor Pressure	Coeffi- cient B ft.$^{-1}$	Bulk Modulus	Source (Ref. No.)
	T	ρ_L	μ	σ	c	k	h_{fg}	ρ_V	p_V	$\frac{\rho_V c(\frac{\Delta T}{\Delta h})}{\rho_L\ h_{fg}}$	K_T	
	^{o}F	$\frac{lbm}{ft^3}$	cp	$\frac{lbf}{ftx10^2}$	$\frac{Btu}{lbm°F}$	$\frac{BTU}{ft\text{-}hr\text{-}°F}$	$\frac{Btu}{lbm}$	$\frac{lbm}{ft^3}$	Psia		Psi	
H_2O	60	62.4	1.0	0.504	1.0	0.331	1060	$8.3x10^{-4}$	0.2563	$3.37x10^3$	$3.11x10^5$	(10),(11),(16)
	500	49.0	0.115	--	1.195	0.338	714	1.485	680.8	$3.07x10^{-3}$	$1.46x10^5$	
Hg	60	845	1.58	3.18	0.3329	4.96	127.7	$5.61x10^{-7}$	$1.57x10^{-5}$	$7.53x10^{10}$	$3.75x10^6$	(11),(12),(17)
	500	808	0.89	2.87	0.3238	7.73	126.5	$3.79x10^{-2}$	1.94	$1.61x10^4$	--	
Na	500	55.3	0.379	1.36	0.3155	45.1	1970	$7.48x10^{-7}$	$3.35x10^{-4}$	$1.42x10^9$	$6.55x10^3$	(12),(13),(15)
	1200	49.4	0.197	--	0.3222	34.8	1920	$1.36x10^{-3}$	1.055	$3.65x10^2$	--	
NaK**	500	50.5	0.31	0.685	0.258	15.6	--	$1.42x10^{-6}$	$4.12x10^{-4}$	--	--	(12),(13)
	1200	47	0.156	--	0.249	16.8	--	$4.62x10^{-3}$	2.32	--	--	
Bi	520*	645	1.776	2.58	0.0339	10.2		$1.01x10^{-14}$	$5.05x10^{-13}$	$2.82x10^{23}$	--	(11),(12)
	1200	598	0.901	2.40	0.0381	8.95	368	$6.22x10^{-7}$	$5.32x10^{-5}$	$8.66x10^{11}$	--	
Bi-pb	**500	646	1.895	--	0.035	6.05	--	--	--	--	--	(11),(12)
	1200	622	1.10	2.58	--	--	--	--	--	--	--	
Rb	500	91.8+	0.2784	--	0.0913	18.2	382	$5.75x10^{-5}$	$6.93x10^{-3}$	$4.06x10^4$	--	(11),(12)
	1200	--	--	--	--	--	--	$4.58x10^2$	9.55		--	

* At normal melting point

** Near eutectic point. NaK: Na, 22% wt.; K, 78% wt.

+ At normal melting point 102°F