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MAGNETIC STABILIZATION OF LMMHD TWO-PHASE FLOW†

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Abstract—Liquid metal magnetohydrodynamic (LMMHD) generators use two-phase flow, for example, of an organic vapor through mercury, for Rankine cycle operation. Unfortunately, the efficiencies achieved in such generators have been reported to suffer from inhomogeneity of the flow and even instability for very high void fraction. We suggest the use of the magnetic fluid concept—single domain iron particles suspended in the metallic carrier liquid making it a "magnetic" liquid, so to speak—to improve the stability of the flow. Through standard stability analysis, we will show that a magnetic field placed parallel to the flow indeed improves greatly the range of void fractions for stable flow. Universality and scaling properties of the results are also discussed.

1. INTRODUCTION

Two-phase flow systems have begun to play an interesting role in science and technology as signified by a recent review in the Annual Review of Fluid Dynamics (Drew 1983). Most usually, a flow of a vapor or gas through a liquid is considered. Recently, the flow of a vapor (or gas) through a metallic liquid under a **J** × **B** force (obtained by letting the liquid flow through a magnetic field perpendicular to the flow direction) has been studied (Yakhot & Branover 1982). In this paper, we consider a still more novel flow of a vapor (or gas) through a "magnetic" liquid metal—such as mercury in which are suspended colloidal particles consisting of single domain iron particles.

Two-phase flow is known to have various instabilities especially at high values of void fraction. The idea of considering magnetic fluid two-phase flow is simply this: the existence of a magnetic body force is expected to break up the individual bubbles, preventing bubble growth and thus preventing further instabilities to occur. However, in this paper, instead of proceeding with the dynamics of a single bubble, we concentrate on demonstrating stability of the magnetic fluid two-phase flow by means of the standard stability theory.

The outline of the paper is as follows. We begin by giving an overview of the developments in liquid metal magnetohydrodynamics (LMMHD), where the present considerations have the most pertinent application. Section 3 presents a short review of the ideas and developments in the field of magnetic fluids, which is a relatively new field. In section 4, we present the hydrodynamic flow equations, and their linear stability theoretic solution. And finally in section 5, the conclusions of the paper and the outlook for future research are presented.

2. LIQUID METAL MAGNETOHYDRODYNAMICS

This paper is primarily concerned with the liquid metal magnetohydrodynamic two-phase flow. Such flow is being and has been studied both in the U.S. and in Israel in connection with LMMHD generators (Pierson 1980). In LMMHD, the two-phase flow consists of the bubble flow of a vapor or a gas through a liquid metal such as mercury. The vapor or the gas is the thermodynamic fluid of the generator. Vapor is more suitable for

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Rankine cycle operation for relatively low-temperature sources, such as solar energy. Gas is used for Braton cycle operation. The liquid metal provides the electrical conductor; its motion through a magnetic field perpendicular to the flow generates the current. In effect the LMMHD generator is a combination of the conventional thermal turbine and electrical generator both in one system.

The components of a two-phase flow LMMHD generator is now standard. An organic vapor flows through a liquid metal in a pipe heated by the appropriate heat source, solar collectors for example, the vapor expands, the expansion of the vapor drives the liquid and the motion of the conducting liquid through the magnetic field generates the electric power, which is extracted by means of the usual electrode assembly.

Because of the high heat capacity of the liquid, it essentially acts as an infinite heat source for the expansion of the vapor. The vapor expansion thus can be regarded approximately as isothermal; it is this feature that accounts for the expectation of high efficiency of conversion in LMMHD.

There are two steps by which the heat extracted by the liquid from the collectors is being converted into electrical power. The first step, the almost isothermal expansion of the vapor, is easily achieved. The second step, however, involves the driving of the liquid by the expanding vapor; it is here that inefficiencies enter the operation. The vapor passes through the liquid metal in the form of bubbles. At the high liquid velocities to be achieved, the void fraction is sometimes as high as 80–90%. At such void fractions, bubbles grow and coalasce and instabilities arise.

We believe that the use of a colloidal suspension of single domain iron particles in the liquid mercury, along with an additional magnetic field parallel to the flow to align the magnetic suspension, will improve the stability of the bubble flow.

3. MAGNETIC FLUIDS

The combination of fluid and magnetic properties in the behavior of magnetic fluids makes these substances quite special (Neuringer & Rosensweig 1964). As one example, an ordinary magnet, a solid rigid body, will change its position and orientation in response to an external magnetic field. A ferrofluid, in addition to changes of position and orientation, will also exhibit changes in its shape.

Under an external magnetic field, a body force develops within a magnetic fluid which acts on any given fluid element, although its magnitude and direction may vary. Specifically, the body force arises from the interaction of the ferromagnetic dipole moment (of the magnetic particles of suspension) with the spatial gradient of the applied field.

In the case of two-phase bubble flow of a vapor through a magnetic field, this body force is expected to break up the bubbles and improve stability, as already mentioned. Also when magnetostriction effects are taken into account, the body force expression changes in an important way; anyhow the magnetic body force is responsible for an extra magnetic-pressure term in the hydrodynamic equations given below.

It is also interesting to point out that, by themselves, magnetic fluids are not particularly stable; the suspension tends to coagulate, sometimes in a matter of hours. However, we do not think that this should be a problem for the application of a magnetic fluid in the two-phase flow process because the flow of the gas will further "fluidize" the magnetic fluid. The vapor bubbles through the magnetic liquid act as dispersing agent preventing the formation of aggregates of the magnetic particles, complementing the magnetic action of the latter in stabilizing the bubble flow.

Available fluidized bed data lend credence to the above idea (Rosensweig 1979a). In fluidized bed experiments, a bed of solid particles is supported on a horizontal porous grid; a gas is then forced to flow through the bed. The flow causes a pressure drop, and at some minimum velocity (called the fluidization velocity) the pressure is sufficient to support the weight of the bed. The bed is then fluidized. Any excess kinetic energy of the gas is now conveyed to the bed, which leads to its expansion; thus, the bed acquires significant flow properties. Moreover, if magnetic particles are added to the bed and are aligned by the action of an external magnetic field parallel to the flow, experiments have shown that the bubble size of the gas flow is significantly reduced and the flow becomes much more homogeneous. And at the same time the magnetized fluidized bed also remains stable for long periods of time.

We have carried out some preliminary experiments which further confirm the conclusions of the fluidized bed data regarding the reduction of bubble size in magnetic fluid two-phase flow. For our experiments we used the magnetic liquid LIGNOSITE FML, manufactured by Georgia–Pacific—an aqueous colloidal solution of ferromagnetic iron lignosulfonate (magnetite molecules bonded to high molecular weight, asymtotically equal to 35000, lignosulfonate molecules). The magnetic particles of the colloidal suspension averaged 100 Å in diameter and the fluid has a saturation magnetization of about 150 gauss.

Our experimental apparatus consisted of the following components:

a. An air compressor capable of 0.28 MPa maximum pressure.

b. A storage tank with a variable pressure release valve which served as a continuously controllable pressurized air reservoir.

c. A 1-meter section of connecting tubing, inside diameter 0.5 mm, which served to provide a constant flow-rate pressure reduction for connecting the reservoir supply to the bubble column orifice.

d. A water (U-tube) manometer for real-time monitoring of the pressure of gas at the bubble orifice.

e. A vertical bubble column/chamber containing the magnetic fluid with an orifice at the bottom where bubbles are formed.

f. A set of permanent magnets (capable of generating over the column volume transverse magnetic fields in excess of 1000 gauss) and magnetic field coils (capable of generating longitudinal magnetic intensities 1000 Oe).

g. A Hall-effect gaussmeter for measuring magnetic field strength.

We established and maintained first, in the absence of a magnetic field, a slow but steady bubbling rate in the vertical bubble column containing the magnetic liquid with an orifice at the bottom where bubbles were formed. This was accomplished by connecting the orifice with a controllable pressurized air reservoir with the 1-m section of connecting tubing, and adjusting the reservoir pressure release valve until a minimum pressure and a slow but steady bubbling rate was established in the column with an approximately stable bubble size. We then applied magnetic fields both longitudinal and transverse to the bubble motion. While maintaining a constant feed pressure, the small diameter connecting tubing established the gas flow rate (at constant pressure drop), and thus allowed the bubble rate to be used to imply bubble size (size inversely proportional to rate).

Among our observations, we were able to confirm that longitudinal fields of even modest amounts (below the saturation intensity of the magnetic fluid) led to a clearly observable decrease in the bubble size for a given gas pressure at the generating orifice. In the future we plan to measure the bubble size directly with a conductivity probe (Dunn 1981) for various magnetic fields, and the detailed results will be reported when these measurements are completed.

We also studied the effect of a transverse magnetic field—for example, whether a transverse field, as is present in an actual generator, would cause aggregates of the iron particles, thus destabilizing the fluid. No such destabilizing effect was found even for the strongest transverse fields we used.

We are encouraged by these basic considerations and measurements to propose that the magnetic fluid's two-phase flow should have increased stability: the flow of bubbles through the magnetic liquid stabilizes the latter, while the magnetic stresses in the medium reduce bubble size to improve the stability of the two-phase flow.

4. MAGNETIC STABILIZATION OF TWO-PHASE BUBBLE FLOW

In our discussion of the magnetic stabilization of two-phase magnetic liquid vapor bubble flow we consider macroscopic equations for the flow under an applied magnetic field parallel to the flow. For convenience, we refer to the liquid carrier phase as phase 1, and the dispersed phase, the gas bubbles, as phase 2. As usual, α denotes the void fraction. Then we choose

$$\alpha = \alpha_2$$

so that

$$1 - \alpha = \alpha_1 .$$

Correspondingly, we write the densities of the two phase as

$$\rho_1 = \rho_{10}(1 - \alpha),$$

$$\rho_2 = \rho_{20}\alpha.$$

The continuity and momentum equations for the two phases can be written down quite generally as follows. Liquid continuity equation (liquid density ρ_{10} is assumed constant):

$$\frac{\partial}{\partial t}(\alpha_1) + \nabla \cdot (\alpha_1)\mathbf{V}_1 = 0. \qquad [1a]$$

Gas continuity equation:

$$\frac{\partial \alpha_2 \rho_2}{\partial t} + \nabla \cdot (\rho_2 \alpha_2 \mathbf{V}_2) = 0. \qquad [1b]$$

Liquid momentum equation:

$$\rho_{10}(1 - \alpha)\frac{D\mathbf{V}_1}{Dt} = -(1 - \alpha)\nabla P + \mathbf{f}_{1,2} + F_{1H} + \tau_W + \mathbf{J} \times \mathbf{B}. \qquad [1c]$$

Gas momentum equation:

$$\rho_{20}\alpha \frac{D\mathbf{V}_2}{Dt} = -\alpha\nabla P - \mathbf{f}_{1,2} + \mathbf{F}_{2H}. \qquad [1d]$$

Here P denotes the pressure of the carrying phase (the liquid), and $\mathbf{f}_{1,2}$ is a force that arises from the momentum exchange between phases; $\mathbf{F}_{iH}$ is the force on the ith phase due to the magnetic field. τ_W is the wall viscosity and $\mathbf{J} \times \mathbf{B}$ is the force due to the transverse B field on a conducting fluid. D/Dt denotes the usual convective derivatives:

$$\frac{D}{Dt} = \left(\frac{\partial}{\partial t} + \mathbf{V} \cdot \nabla\right).$$

The magnetic fields responsible for the body force are solutions of Maxwell equations:

$$\nabla \times \mathbf{H} = \mathbf{J}; \quad \nabla \cdot \mathbf{B} = 0,$$
$$\nabla \times \mathbf{E} = -\dot{\mathbf{B}}; \quad \nabla \cdot \mathbf{E} = 0. \qquad [2]$$

On the basis of some quite general assumptions, Gogosov *et al.* (1980) have shown that the following relationships hold for the force terms in the above equations:

$$\sum_{i=1}^{2} \mathbf{F}_{iH} = \alpha \nabla \left(\frac{\partial \mu}{\partial \alpha} \frac{H^2}{2} \right) \qquad [3]$$

and

$$\mathbf{f}_{1,2} + \mathbf{F}_{1H} = -L_f(\mathbf{V}_1 - \mathbf{V}_2), \qquad [4]$$

where L_f (>0) is connected to the interphase viscosity and is a function of the voidage α.

Furthermore, it is found that (Gogosov *et al.* 1980)

$$\rho_2 \frac{D(\alpha/\rho_2)}{Dt} = -L_\alpha \left(P - P_2 - \frac{\partial \mu}{\partial \alpha} \frac{H^2}{2} \right),$$

where L_α is a coefficient which reflects the variation of the bubble volume and $P_2 = \rho_2 RT$, where T is the temperature, and P_2 is the thermodynamic gas pressure.

We now substitute these relationships in the flow equations [1a]–[1d] and obtain (after omitting the gas mass term for simplicity)

$$\frac{\partial \alpha}{\partial t} - \nabla \cdot (1 - \alpha)\, \mathbf{V}_1 = 0, \qquad [5a]$$

$$\frac{\partial \alpha}{\partial t} + \nabla \cdot (\alpha \mathbf{V}_2) = -L_\alpha (P - P_2 - f_M), \qquad [5b]$$

$$\rho_{10}(1 - \alpha) \frac{D\mathbf{V}_1}{Dt} = -(1 - \alpha)\nabla P - L_f(\mathbf{V}_1 - \mathbf{V}_2) + \tau_W + \mathbf{J} \times \mathbf{B}, \qquad [5c]$$

$$0 = -\alpha \nabla P + L_f(\mathbf{V}_1 - \mathbf{V}_2) + \alpha \nabla f_M, \qquad [5d]$$

where from now on we shall use the more comprehensive notation f_M for the magnetic-pressure term

$$f_M = \frac{\partial \mu}{\partial \alpha} \frac{H^2}{2}.$$

These equations are quite similar to the equations used by Rosensweig (1979b) for fluidized bed with one important difference. Our magnetic-body force term takes into account the effect of magnetostriction.

In addition to these flow equations, we need several constitutive relationships. Of these, the constitutive equation for the magnetic field are

$$\mathbf{B} = \mathbf{H} + \mathbf{M}, \qquad [6a]$$

$$\mathbf{B} = \mu(\alpha)\mathbf{H}, \qquad [6b]$$

where, $\mathbf{M}$ is the magnetization and $\mu(\alpha)$ the permeabilty of the two-phase medium. In addition, there is a constitutive equation for the gas-liquid interaction which we shall treat via simple parametrizations available in the literature. A similar treatment will be given to L_α.

4.1. *Solutions for the steady state*

A simple solution of the flow equations is obtained under the assumption of a steady state: Uniform flow—that is, the gas and liquid velocities are constants in space and time, uniform magnetization and uniform and constant voidage.

The superscript 0 denotes steady state.

$$\begin{gathered} \mathbf{V}_1 = \mathbf{V}_1^0; \quad \mathbf{V}_2 = \mathbf{V}_2^0; \quad \alpha = \alpha^0, \\ \mathbf{H} = \mathbf{H}^0; \quad \mathbf{B} = \mathbf{B}^0; \quad \mathbf{M} = \mathbf{M}^0, \\ P = P^0. \end{gathered} \tag{7}$$

With these assumptions, the continuity equation for the liquid and the magnetic constitutive equations are identically satisfied, while the dynamical equations for the two phases give us the following relationships:

$$\nabla P^0 = \tau_W^0 \tag{8a}$$

and

$$\alpha^0 \nabla P^0 = L_f^0(\mathbf{V}_1^0 - \mathbf{V}_2^0). \tag{8b}$$

The continuity equation for the gas phase is also satisfied because

$$P^0 - P_2^0 - f_M = 0. \tag{9}$$

Obviously, the applied parallel magnetic field, being uniform and parallel to the flow, does not contribute to the steady state. It will, however, be crucial when we consider the first-order deviation from these steady-state conditions following the standard stability theory. The reason for resorting to the standard stability, that is, first-order perturbation theory with a plane wave assumption for the disturbance, is that we have seven unknown quantities (p, α, $\mathbf{V}_1$, $\mathbf{V}_2$, $\mathbf{H}$, $\mathbf{B}$, $\mathbf{M}$) with as many equations, which being nonlinear, is a very difficult system to solve.

4.2. *Stability theory*

We now come to the major theoretical calculation of the paper—namely, proving that the steady-state solution is stable against small perturbations of the void fraction α. The reason for expecting a major improvement in the conditions for stability as compared to the nonmagnetic case is, of course, the idea that the voidage perturbations will perturb the uniform applied magnetic field, and the lack of uniformity of the latter will now generate a magnetic body force, which is the crucial component of stability.

We can expand all of our variables to first order:

$$\begin{gathered} P = P^0 + P^1; \quad \alpha = \alpha^0 + \alpha^1, \\ \mathbf{V}_1 = \mathbf{V}_1^0 + \mathbf{V}_1^1; \quad \mathbf{V}_2 = \mathbf{V}_2^0 + \mathbf{V}_2^1, \\ \mathbf{H} = \mathbf{H}^0 + \mathbf{H}^1; \quad \mathbf{B} = \mathbf{B}^0 + \mathbf{B}^1, \\ \mathbf{M} = \mathbf{M}^0 + \mathbf{M}^1; \quad \mu = \mu^0 + \mu^1. \end{gathered} \tag{10}$$

We shall assume as usual that all the first-order quantities above are small and are plane wave disturbances, i.e. for any quantity V, we write

$$V = (\text{constant}) \exp(i\mathbf{k} \cdot \mathbf{x} - i\omega t),$$

where **k** is the wave number and ω the frequency. The treatment of the linearized equations satisfied by these quantities is standard (e.g. Rosensweig 1979b), so we shall omit all nonessential details.

A perturbative treatment of the constitutive equations [6] gives the first-order expression of the magnetic force term ∇f_m as

$$\nabla f_M = i\mathbf{k} f_m, \qquad [11]$$

with

$$f_m = -\Gamma \rho_1^0 V_A^{02} \alpha^1,$$

where

$$V_A^0 = H^0 \left(\frac{\mu^0(\alpha = 0)}{\rho_1^0} \right)^{1/2}. \qquad [12]$$

is, roughly speaking, the Alfven velocity; Γ is defined as

$$\Gamma = \frac{\chi^{02}}{[\mu^0 \cos\gamma_1 - (\mu^0 - 1)\cos\gamma_0 \cos\theta]^2}. \qquad [13]$$

The various angles appearing in the last equation are defined in figure 1.

We also need models for the variation of L_f and L_α on the void fraction α. Gogosov *et al.* (1980) used a simple linear dependence on α for both L_α and L_f; while, Rosensweig (1979b) used the Carman-Kozeny relationship derived for the case of laminar flow through a bed of packed particles. In the work that follows, L_α is assumed to vary linearly with α (Stokes Law). For L_f, however, we considered three models:

$$L_f \sim \alpha,$$
$$L_f \sim (1 - \alpha^2)/\alpha(\text{Carman-Kozeny}) \qquad [14]$$

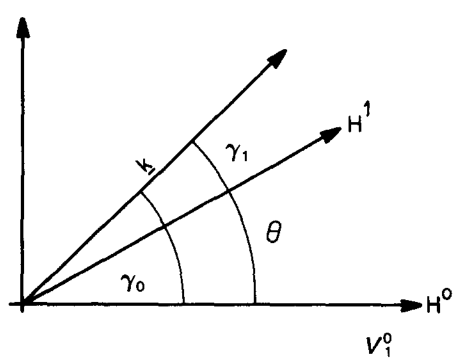

Figure 1. Sketch illustrating the angles between the vectors **k**, $\mathbf{H}^0$ and $\mathbf{H}^1$.

and

$$L_f \sim (1 - \alpha^2)\alpha.$$

The last relationship for L_f is a phenomenological model of the dependence of the interfacial forces on voidage. In contrast to both the linear and Carman-Kozeny models, it leads to correct flow equations at both limiting values of α.

The solution of linearized stability equations gives the following stability condition:

$$M_m \sqrt{N_\alpha} \begin{array}{ll} \geq & \text{, instability} \\ = 1 & \text{, neutral stability} \\ \leq & \text{, stability,} \end{array} \qquad [15]$$

where M_m is the magnetic Mach number

$$M_m = V_1^0 / V_A^0 \qquad [16]$$

and

$$N_\alpha = (1 - \alpha^0)^{-1}(1 - S^0)^2 \times \begin{array}{l} (1 - \alpha^0)^2 \text{ (Linear)} \\ (3 - \alpha^0)^2 \text{ (Carman-Kozeny)} \\ (1 + \alpha^0)^2 \text{ (Phenomonological),} \end{array} \qquad [17]$$

where

$$S^0 = (\mathbf{k} \cdot \mathbf{V}_2)/(\mathbf{k} \cdot \mathbf{V}_1) \qquad [18]$$

is the velocity ratio.

We have also derived a normalized growth factor for the instability. Defining a normalized wave number, $k_b = kD_b$, where D_b is a characteristic bubble size, the growth factor can be written as

$$\Omega = \{(k_b\alpha^0)^2/[1 + k_b\alpha^0)^2]\} \times \left(-1 + \left\{\left[\left(1 - \frac{(q/2)^2}{M_m^2 N_\alpha}\right)^2 + q^2\right]^2 + \left(1 - \frac{(q/2)^2}{M_m^2 N_\alpha}\right)\right\}^{1/2}\right), \qquad [19]$$

where

$$q^2 = \left(\frac{4AX_0}{E}\right)^2 \frac{(1 - \alpha^0)}{\Gamma} N_\alpha \qquad [20]$$

with

$$A = [1 + a(k)]\rho_l^0; \quad a(k) = L_f^0 L_\alpha^0/(k\alpha^0)^2, \qquad [21]$$

$$X_0 = (\mathbf{k} \cdot \mathbf{V}_1^0), \qquad [22]$$

$$E = L_f^0/\alpha^{02}(1 - \alpha^0). \qquad [23]$$

4.3. *Numerical results*

The stability criterion with the parameter N_α, specialized to reflect the various models of L_f, may be plotted to display transitions values of the magnetic Mach number M_m given by

$$M_m = 1/\sqrt{N_\alpha}.$$

The plot of this relationship demonstrates the dependence of the magnetic Mach number on both void fraction and velocity ratio. In figures 2 and 3, we have plotted this relationship for the Carman-Kozeny model of L_f, figure 2, and in figure 3, for the phenomenological model of L_f discussed above. In each case, a magnetic fluid two-phase flow system is unstable for any magnetic Mach number which lies above the curves (for a given velocity ratio) and stable for any magnetic Mach number which lies below the curves. It can be seen from these plots, that systems operating at high voidage will require larger magnetic fields; i.e. smaller magnetic Mach numbers, to achieve stabilization. Also, the plots reveal a rather dramatic (model independent) dependence on velocity ratio, especially at low value of voidage.

The most important feature of the stability plots is that they provide a range of operating conditions, that is, magnetic Mach numbers, for which stable operation is possible. In the next subsection, we will compare this range of Mach numbers to those which would arise from real world magnetic liquid metal magnetohydrodynamics experiments.

Next, we examine numerically the predictions of our theory regarding the growth and decay rates of disturbances in the stable and unstable regions. In figure 4, we have plotted the normalized growth rate, as a function of the normalized bubble wave number, k_b =

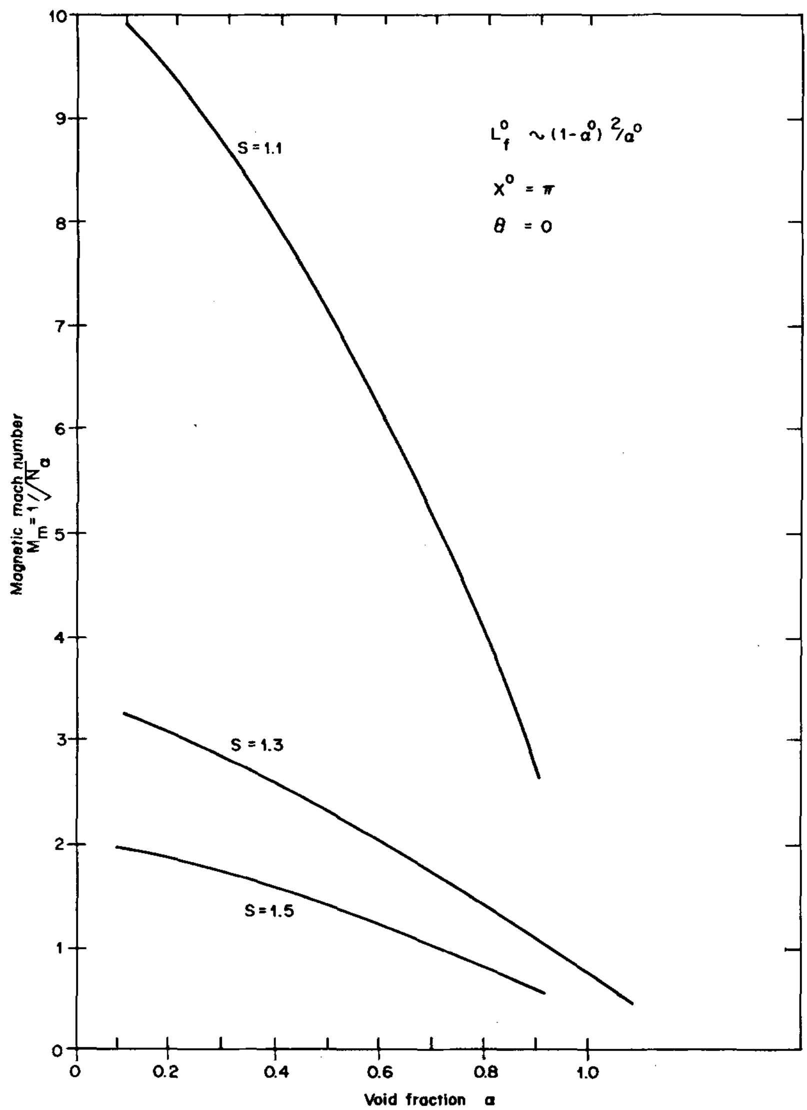

Figure 2. The magnetic Mach number plotted as a function of void fraction for the Carman-Kozeny model of L_f.

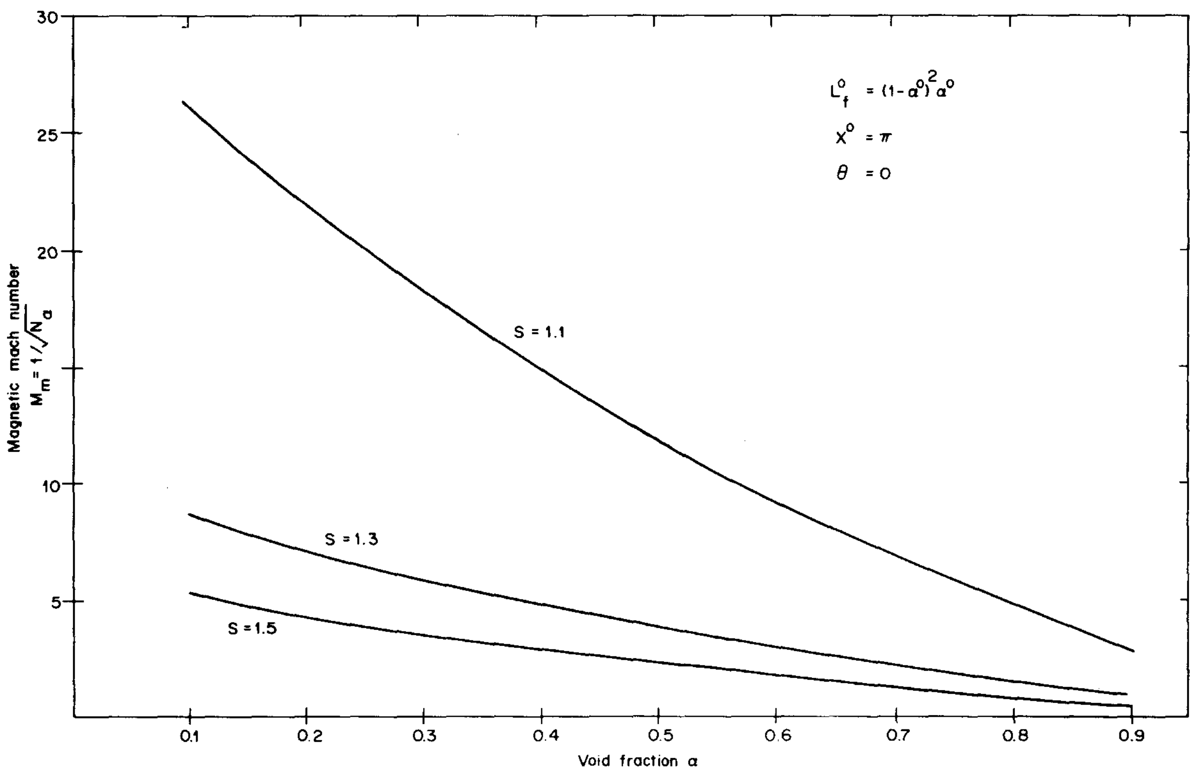

Figure 3. The magnetic Mach number plotted as a function of void fraction for the phenomenlogical model of L_f employed in this paper.

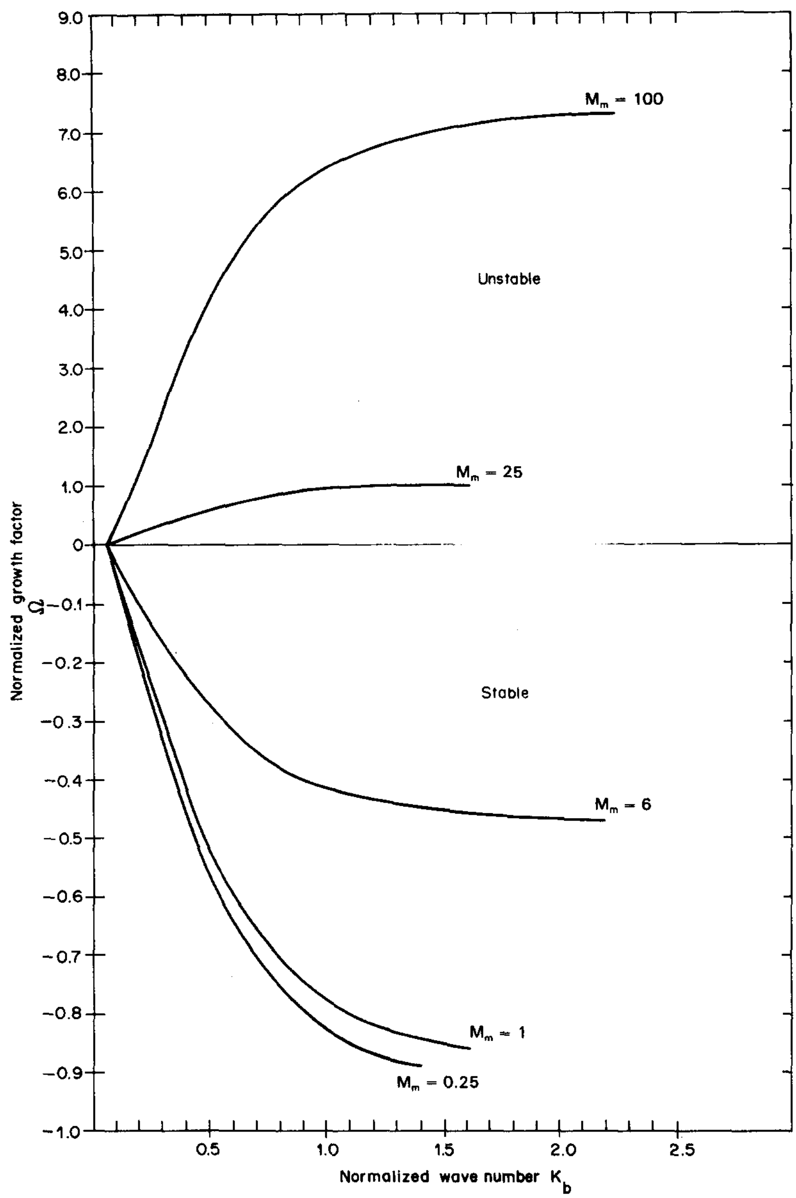

Figure 4. The plot of normalized growth factor as a function of the normalized wave number of the plane wave disturbance.

(kD_b), for representative value of magnetic Mach number, M_m, at a void fraction equal to 0.5. All of the curves show a rapid change with the normalized bubble wave number until the wave number k becomes comparable to the bubble size; after which, the growth factor becomes largely independent of bubble size. Also, we see that for large magnetic field (small M_m) the amplitude decays most rapidly. As the magnetic field is increased without limit, the normalized growth factor, Ω, eventually attains the limiting value of $\Omega = -1$.

4.4. *Parametric study*

As we pointed out in the previous subsection, the most important result of the stability analysis is that it provides a range of magnetic Mach number for which stable operation of MLM two-phase flow system should be possible. Our numerical analysis shows that the acceptable range is probably 1 to 15 for reasonable values of void fraction and velocity ratio.

Recently, Petrick (1981) has reported on the two-phase flow liquid-metal MHD experiments carried out at the Argonne National Laboratory (ANL). These were high-temperature experiments using Na as the working fluid and involved field velocities as high as 10 meters/sec. The void fraction varied across the flow attaining a maximum value of about 0.8 at the center. Velocity ratios were in the range >1–2.5 in the generator region and less than 1.5 prior to entering this region. The only magnetic field was the generator field which was relatively large, 1.2 tesla.

The magnetic Mach number for an equivalent MLM two-phase flow system, assuming a 10 m/sec magnetic fluid velocity and a modest 0.1 tesla magnetic field directed parallel to the flow, is about 3.2 for liquid mercury. These magnetic Mach numbers are clearly in the acceptable range predicted by our theory.

5. CONCLUSION AND OUTLOOK

Thus according to our theory, magnetization is able to prevent instabilities in liquid-metal two-phase flow systems. The applied field is most advantageously oriented parallel to the flow direction. The magnetic-field intensity required for stabilization depends on the average field velocity, void fraction and velocity ratio. However, the magnitude of this field need not be large (by MHD standards). In the MLM two-phase flow analog of the ANL experiment cited above, only a 0.1 tesla, a field intensity typically achieved in MHD systems would be required.

We are thus suggesting that magnetic stabilization via the use of a magnetic liquid-metal in the LMMHD generator is highly desirable for reasons of enhanced stability. Additional insight as to how this enhanced stability helps the generator efficiency is obtained by the following qualitative consideration of the relative velocity in an LMMHD generator. In the ordinary generator, a large, favorable pressure gradient exists which exerts equal specific force on both the liquid and the gas phase. However, the Lorentz force due to the generator field, $\mathbf{J} \times \mathbf{B}$, acts to preferentially decelerate the liquid. Thus the relative velocity tends to be large. On the other hand, at large void fractions, due to the semiannular nature of the flow, the interfacial frictional coupling between the two phases is weak. What happens if we magnetically stabilize the (magnetic) liquid prior to channel entry is (a) the stable flow ensures a stable value of the gas-liquid interfacial friction to remain high even at high void fraction, and (b) the gas now has the additional magnetic stress term arising from the transverse generator field (c.f. [5d]). Now a reference to figures 2 and 3 will show that if the relative velocity is high (corresponding to high-velocity ratio S), high magnetic fields are necessary to stabilize the two-phase flow. But as the velocity ratio tends to 1, the value of the needed stabilizing field decreases dramatically. Thus, it is a very gratifying aspect of the LMMHD generator using a magnetic fluid that the system has a bootstrap element built into it: the better the magnetic stabilization, the lower is the relative velocity loss; the lower the relative velocity loss, the lower is the needed value of the stabilizing field. These apsects of magnetic liquid-metal two-phase flow generator are now under quantitative study and will be reported elsewhere.

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