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SOME RESULTS ON LIQUID–METAL MHD TWO-PHASE FLOW

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1. INTRODUCTION

Profound knowledge on liquid-metal two-phase flow with and without a magnetic field plays a key role in a variety of technological applications, in particular, in the design and development of liquid metal MHD generators. Our program in this field, being rather basic than applied, comprises the following approaches:

i) Development of a model and a numerical code for the overall behavior of the flow in the form of a one-dimensional description;

ii) Theoretical and experimental investigation of three-dimensional effects by consideration of local flow parameters.

The analysis is restricted to the bubbly flow regime. The three-dimensional model is valid for general liquid metal two-component systems, whereas the experiments are performed at our sodium test facility. In addition, one goal of the work was to develop resistivity probes for local measurements in sodium which could also be useful to other applications (for example, in sodium cooled fast breeder reactors).

In the present paper we report on some recent results in the frame of this program. The central aim of the first part is to predict the effects of various initial values on the bubbly flow, in particular, on the mean slip ratio. The analysis is focused on the influence of a magnetic field on the slip because of the decisive role of the slip ratio on the overall generator efficiency. In the second part we present experimental results on local void fraction distributions and the magnetic field influence on it for a vertical sodium-argon flow.

2. THE ONE-DIMENSIONAL BUBBLY FLOW MODEL

2.1 Description of the Model

We consider a vertical upwards flow of a liquid metal exposed to an external magnetic field. The flow direction is denoted by x, where $\mathbf{B} = Be_y$ in the case of a transverse magnetic field. The field is constant over a plateau length L and decreases exponentially outside this region with a characteristic length scale s. In the region of constant magnetic field there are highly conducting electrodes at the channel walls perpendicular to the magnetic field direction. The channel cross section is assumed to be constant. In order to describe the motion of a multitude of bubbles flowing in the moving liquid metal we partly follow and extend the papers of Kamiyama et al. [1] and Mond and Sukoriansky [2] which are founded on the well-known van Wijngaarden model of bubbly flow. The present approach is based on the following assumptions:

- The flow is isothermal due to the large heat capacity of the liquid metal;
- The gas phase consists of bubbles of a mean radius R(x), and there is no mass transfer between the phases;
- The flow parameters depend on the channel position x only and should be considered as cross-section averaged values. As a first step we do not take into account any influence of this averaging process which is possible, for example, via the introduction of correlation coefficients [3];

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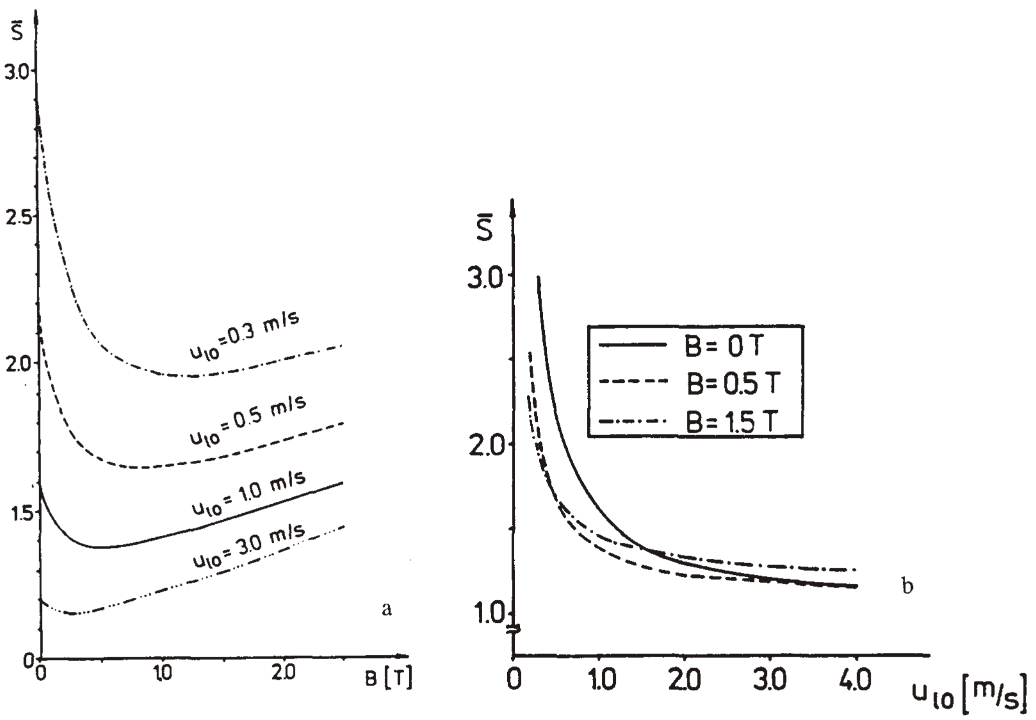

Fig. 1. Mean slip ratio depending on the magnetic field strength (a) and on the initial liquid velocity (b). transverse magnetic field.

– The flow is steady;
– The pressure difference between gas and surrounding fluid is neglected;
– The gas phase is treated as an ideal gas;
– The electric field E_z is constant in the electrode region due to the very high conductivity of the electrodes.

Based on these assumptions, the final system of equations is given by

$$\text{continuity: } d\{(1-\alpha)u_l\}/dx = 0,\ d(\alpha\rho_g u_g)/dx = 0; \tag{1}$$

combined momentum equation:

$$\alpha\rho_g u_g(du_g/dx) + (1-\alpha)\rho_l u_l(du_l/dx) = -dp/dx - (\alpha\rho_g + (1-\alpha)\rho_l)g - f_R - \sigma_t B^2 u_l(1-K); \tag{2}$$

equation of motion of a single bubble:

$$d(\rho_g V_B u_g)/dt = -V_B(dp/dx) - \rho_g V_B g - F_D - F_{vm}; \tag{3}$$

where $F_D = 0.5\rho_l \pi R^2 C_D(u_g - u_l) \mid u_g - u_l \mid$ is the drag force, and $F_{vm} = 0.5\ \rho_l u_g d(V_B(u_g - u_l))/dx$ is the virtual mass force;
bubble's mass conservation and equation of state:

$$\rho_g R^3 = \text{const},\ p = \text{const}\cdot\rho_g. \tag{4}$$

Here α, ρ, u, and V_B denote void fraction, density, velocity, and bubble volume, respectively. The subscripts l and g refer to the liquid and gas phase, respectively. This system is complete if the expressions for the frictional force density f_R, the

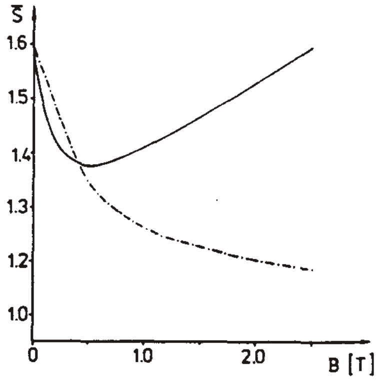

Fig. 2. Mean slip ratio depending on the magnetic field. $u_{l0} = 1.0$ m/s. —— transverse field, —.— longitudinal field.

electrical conductivity σ_t of the two-phase mixture, the load factor K(x) and the drag coefficient C_D are specified. In our calculations this is realized by:

- a Lockhart–Martinelli modeling of the frictional force;
- the Maxwell relation for σ_t;
- a selection of $K_0 = K(x)u_l(x)/u_{l0}$ by trial and error in order to adjust the external current which depends on the load resistance R_l) to the value induced at the electrodes (the subscript 0 refers to the initial value at the channel entrance);
- using a semiempirical law [2] for relating the drag coefficient C_D to that of a single bubble C_{D0}:

$$C_D = C_{D0}(1 - \alpha)^4. \tag{5}$$

The single bubble drag is given by [4]

$$C_{D0} = C(1 + \sqrt{N}) \tag{6a}$$

in the case of a transverse magnetic field $\mathbf{B} = B\mathbf{e}_y$, and

$$C_{D0} = 0.33\sqrt{N} \tag{6b}$$

in the case of a longitudinal magnetic field $\mathbf{B} = B\mathbf{e}_x$. Here C is taken from the standard drag curve for the corresponding value of the local bubble Reynolds number, and $N = \sigma_l R B^2/\rho_l \mid u_g - u_l \mid$ denotes the local interaction parameter.

2.2 Results for the Mean Slip Ratio

The interest is focused on the mean slip ratio defined by

$$\bar{S} = 1/L_g \int_0^{L_g} dx\, u_g(x)/u_l(x),\ L_g = L + 2s. \tag{7}$$

The calculations are performed for a vertical sodium-argon flow with the following set of parameters: quadratic cross section $a = 0.1$ cm, L = 0.4 m, s = 0.1 m, T = 300°C, $\alpha_0 = 0.2$, $p_0 = 3$ bar, $u_{l0} = 1.0$ m/s, $u_{g0} = 1.08$ m/s, $R_0 = 3.0$ mm, $R_l = 0.1$ mΩ.

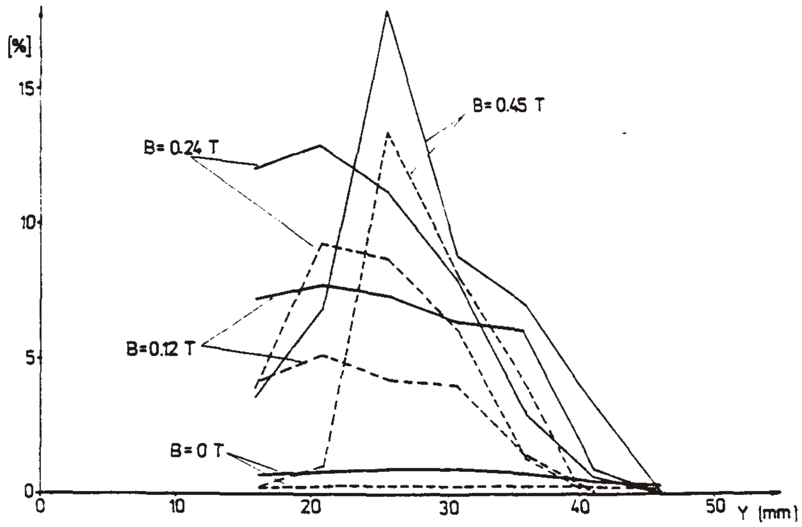

Fig. 3. Measured local void fraction in the direction perpendicular to the magnetic field for various liquid velocities and magnetic field strengths.—— u_l = 0.4 m/s, – – – u_l = 0.7 m/s.

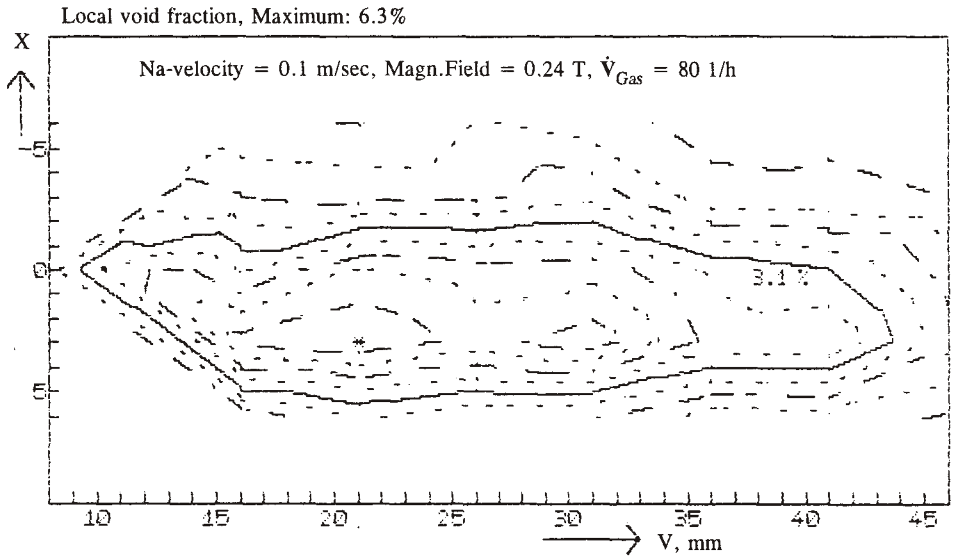

Fig. 4a. Isoplots of the measured local void distribution. Direction of the magnetic field: x, B = 0.24 T. The point of maximum void fraction is marked by *.

The described system is numerically solved by us of the Runge–Kutta method. Figures 1a, b show results for the dependence of $\bar{S}$ on u_{l0} and B in the case of a transverse magnetic field. The influence of B on the mean slip is determined by two effects:

i) The magnetic field has a braking effect on u_l (Eq. 2);

ii) The magnetic field enhances the bubble drag coefficient (Eq. 6a).

Competition between these two effects leads to the results shown in Fig. 1.

The analysis was extended to the case of a longitudinal magnetic field by omitting the electromagnetic term in Eq. (2). The action of the magnetic field on the flow is via the drag coefficient (6b) only. This leads to an overall decrease of $\bar{S}$ with increasing B as shown in Fig. 2.

The results shown in Figs. 1, 2 are a promising indicator of the opportunity of definitely influencing the mean slip ratio by use of an external magnetic field. In particular, the application of a longitudinal magnetic field (which has a negligible effect

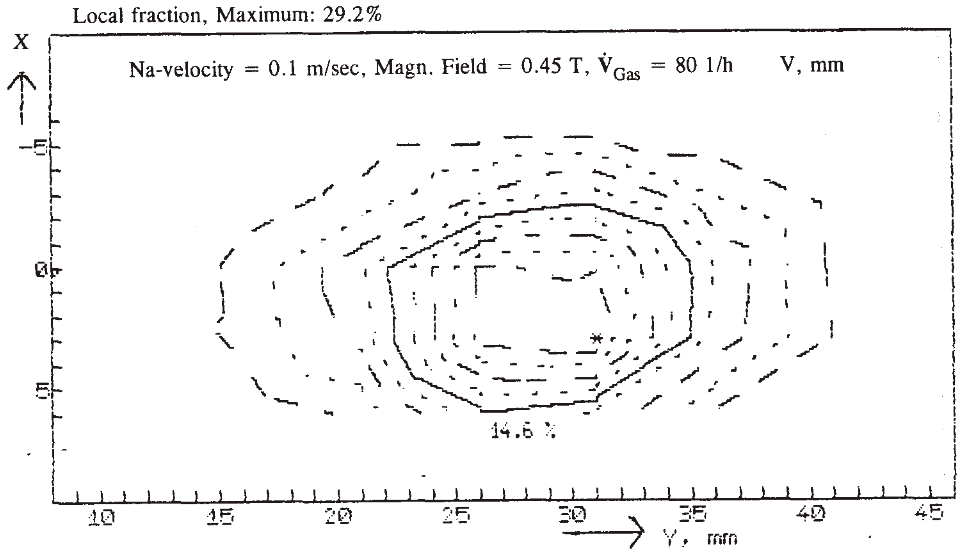

Fig. 4b. Isoplots of the measured local void distribution. Direction of the magnetic field: x, B = 0.45 T. The point of maximum void fraction is marked by *.

on the pressure drop in the channel, and can be realized simply with a solenoid) leads to a significant decrease of $\bar{S}$. This could be of practical use, for example, in the riser of a OMACON system.

3. LOCAL VOID FRACTION MEASUREMENTS

To study local properties of liquid metal MHD two-phase flows the local void distribution was measured in a vertical sodium-argon flow. In order to investigate the lateral dispersion process of the bubbles, argon was injected into the test section through a single orifice (diameter 0.9 mm, centered in the channel cross section). The injector is just at the beginning of the magnetic pole face region, the probe at the end of it. The length of the pole faces is 320 mm, the distance between the injector and the probe is 290 mm. The single wire resistivity probe made by use of a tungsten-glass pair yields reproducible results over a period of several hours. A transversing mechanism allows the probe to be moved nearly completely across the channel cross section (size of which is 45 mm × 50 mm). Results of these measurements are shown in Figs. 3, 4. They clearly indicate the focussing effect of the external magnetic field on the local void distribution. Without a magnetic field, a constant void fraction level (on the order of 1%) was measured over the cross section. The focussing effect in the direction perpendicular to the magnetic field is represented in Fig. 3 for different sodium velocities. The isoplots in Fig. 4a show that the suppression of bubble dispersion is more pronounced in the field direction (x) than perpendicular to it. This different influence on the dispersion process in the direction parallel and perpendicular to the field direction decreases with further increasing magnetic field strength as shown in Fig. 4b. Of course, the maximum void fraction value is considerably increased in Fig. 4b compared to Fig. 4a due to the overall focussing effect of the magnetic field.

4. SUMMARY

In the present paper we report briefly on some recent results in our liquid metal MHD two-phase flow program. A one-dimensional code was developed for an overall description of the flow parameters. The mean slip ratio can be significantly changed by application of an external magnetic field. The lateral dispersion process of bubbles is experimentally studied in our sodium test facility. A strong focussing effect of the magnetic field was verified with different strength in the direction parallel and perpendicular to the field.

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