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INFLUENCE OF EXTERNAL MAGNETIC FIELDS ON SLIP RATIO IN LMMHD TWO-PHASE FLOW

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The behavior of LMMHD two-phase flow in a transverse magnetic field has been investigated. In the frame of a close cooperation between LEGI-IMG and FZR two facilities with different fluids (mercury/air and sodium/argon, respectively) are involved in activities for establishing an experimental data base.In the this paper the main interest is focused on the effect of the magnetic field on the bubble slip ratio. Results on the momentum transfer in LMMHD two-phase flow are basically for a number of technological applications, in particular, the design of LMMHD-generators. Technological applications require simple, experimentally based models that are able to describe the average behavior of the flow. Theoretical predictions are obtained by using a one-dimensional bubbly flow model. The model will be introduced briefly and the results obtained from calculations will be discussed in comparison with the experimental data.

INTRODUCTION (BUBBLY FLOW MODEL)

LMMHD two-phase modeling is strongly dependent on the accuracy of the constitutive equations and the laws used to close the system of equations. Whereas in the case of ordinary two-phase flow semiempirical closure laws are well established, in the case of LMMHD two-phase flow many questions arise concerning the modification of the flow (interfacial dragging, wall friction, apparent electrical conductivity, etc.) due to electromagnetic forces.

In order to study the influence of the magnetic field on the interfacial momentum transfer, as a matter of principle we try to start with a simple model. Thus, a one-dimensional bubbly flow model has been developed for a rectangular duct flow immersed in a transverse as well as a longitudinal magnetic field. A detailed description of the model is given in [1].

The model is restricted to a steady and isothermal flow. The gaseous phase is treated as ideal gas and consists of spherical bubbles. Mass transfer between the phases is not considered. Moreover, effects of aggregation or breakup of bubbles are not included.

The low magnetic Reynolds number allows us to ignore the induced magnetic field.

From these assumptions we get the final system of six equations:

two continuity equations of each phase, a combined momentum equation, an equation of motion of a single bubble, and the bubbles mass conservation and ideal gas equation.

This system of equations is completed by the corresponding closure laws for

• frictional force density	←	Lockhart-Martinelli modeling
• local two-phase el. conductivity	←	Maxwell Petrick and Lee
• electromagnetic force	←	load factor K
• drag coefficient of a bubble	←	[2], [3]

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TABLE 1. Physical Properties and Dimensionless Parameters for Both Facilities

	Mercury/air facility of IMG	Sodium/argon facility of FZR
temperature [°C]	17	200
ρ_l [kg/m^3]	1.36×10^4	9.03×10^2
σ_l [1/Ωm]	1.00×10^6	7.46×10^6
$\beta = Q_g/Q_l$	0.24	0.015
d_H [m]	0.0175	0.0474
Re	240,000	10^4-10^5
Ha	350 (B_{max} = 0.77 T)	2700 (B_{max} = 0.45 T)
N	0.5	80-800
Mo	1.38×10^{-7}	1.02×10^{-8}
Eo	9.6	1.71
We	2.72×10^7	6.94×10^3

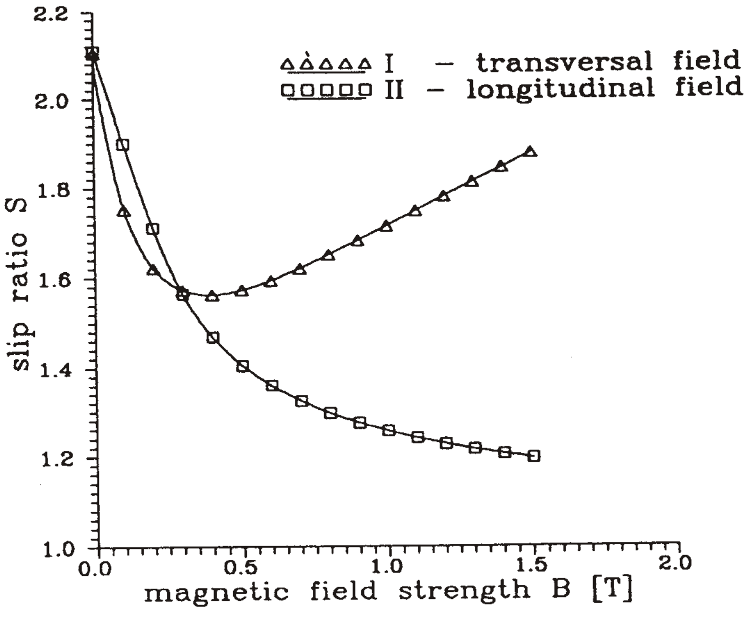


Fig. 1. Slip as a function of the transverse and longitudinal magnetic field, respectively.

Typical results obtained from the calculations are shown in Fig. 1.

A LMMHD two-phase flow exposed to a transverse magnetic field is influenced by two opposite effects, clearly reflected in the shape of curve I:

1) the braking influence of the magnetic field on the liquid metal

2) the enhancement of the bubble drag coefficient by the magnetic field.

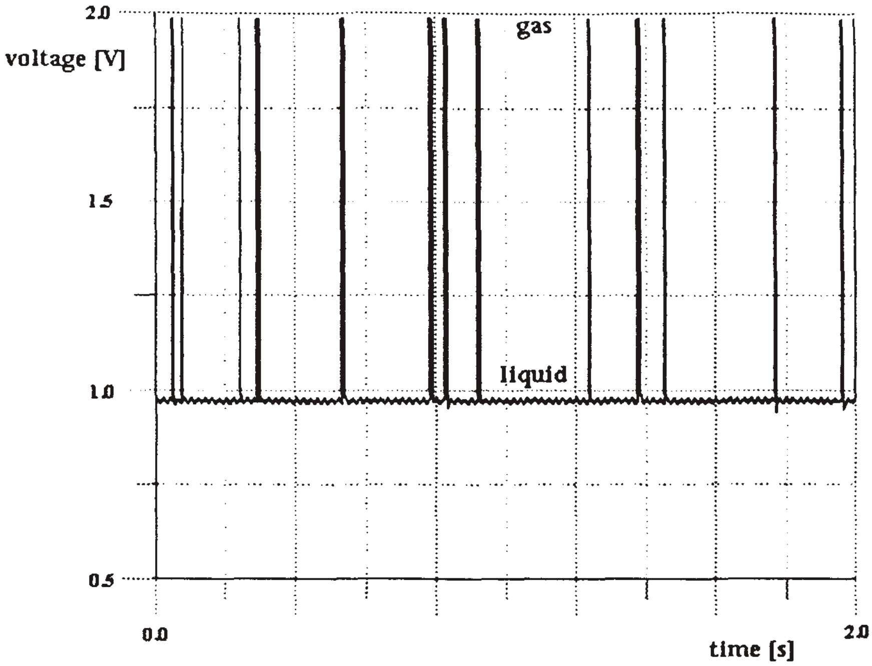


Fig. 2. Typical sample of a signal delivered by a single-wire resistivity probe in a sodium/argon bubbly flow.

While the reduction of the slip at lower values of the magnetic field is caused by the enhancement of the drag coefficient of the bubbles ($C_D \sim [1 + N^{1/2}]$), the braking effect on the liquid metal becomes more and more dominant with increasing field strength ($\vec{j} \times \vec{B} \sim B^2$). Thus, the curve shows typically a minimum, which location is dependent on the initial liquid velocity, the gas flow rate, the bubble diameter, etc.

However, in the case of a homogeneous longitudinal magnetic field a braking action of the magnetic field on the mean flow does not occur. So, a monotonous decrease of the slip with increasing field strength can be observed in curve II.

Now, our task consists in the experimental verification of the results obtained from the calculations.

VOID FRACTION MEASUREMENTS

Distributions of the void fraction were measured in a vertical sodium/argon (FZR) as well as in a mercury/air flow (LEGI-IMG).

The significant differences in the material properties of the liquids used in both facilities allow us to reach a wide range of nondimensional parameters (see Table 1). Due to its moderate Stuart number the mercury/air pair tends to behave as an ordinary two-phase flow regarding the velocity profile. On the contrary, the sodium/argon with its high N is controlled by the electromagnetic forces. Moreover, because of the large difference between the ratio of the flow rates, different flow regimes have to be expected. In the FZR experiment a very low volumetric quality ($\beta < 0.1$) leads to a pure bubbly flow regime. On the other hand the LEGI-IMG facility usually works with considerably higher gas flow rates. There is also a remarkable difference regarding the electrical boundary conditions of the test sections. While the FZR test section consists of a simple stainless steel channel (thickness of the walls 5 mm), the LEGI-IMG configuration, which includes segmented copper electrodes and an external load resistance, is more similar to a MHD generator.

Single wire resistivity probes were used for the detection of the void fraction. Because of the enormous difference in the electrical conductivity between the liquid metal and the gas these probes supply sharp signals that are easy to analyze (see Fig. 2).

In the sodium flow the probes deliver reproducible results for at least 50 operating hours.

The quantity measured by the local single wire resistivity probes is the ratio between the gas contact time on the probe tip and the measuring time. A movable probe allows one to measure the distribution of the void fraction in the channel

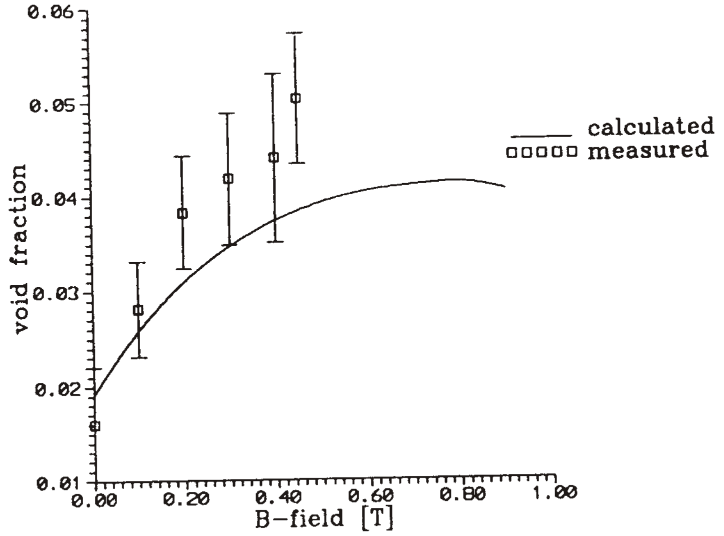


Fig. 3. Void fraction as a function of the transverse magnetic field (Re = 9300, v_{So} = 0.1 m/s).

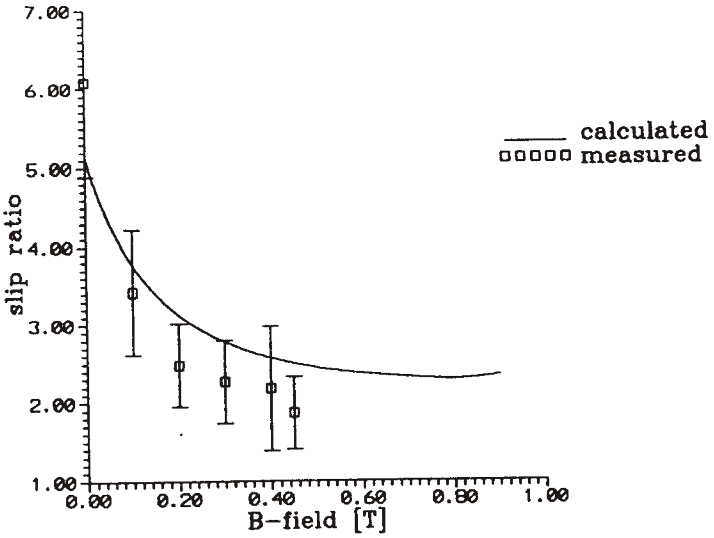


Fig. 4. Slip as a function of the transverse magnetic field (Re = 9300, v_{So} = 0.1 m/s).

cross section. Provided that the flow can be assumed as steady-state, we get the two-dimensional space-averaged void fraction $\alpha(x)$ as follows

$$\alpha(x) = \frac{1}{A_C} \int_{A_C} \alpha_t(x, y', z') dy' dz' \qquad (1)$$

(A_C is the cross-sectional area, x is the flow direction); $\alpha_t(x, y, z)$ denotes the ratio between the gas contact time of the probe and the measuring time in the point (x, y, z).

Finally, the slip ratio $S(x)$ is determined by the following relation [4]

$$S(x) = \frac{\beta[1 - \alpha(x)]}{\alpha(x)[1 - \beta]} \qquad (2)$$

with the volumetric quality $\beta = Q_g/(Q_l + Q_g)$ ($Q_{g,l}$ are the volumetric flow rates).

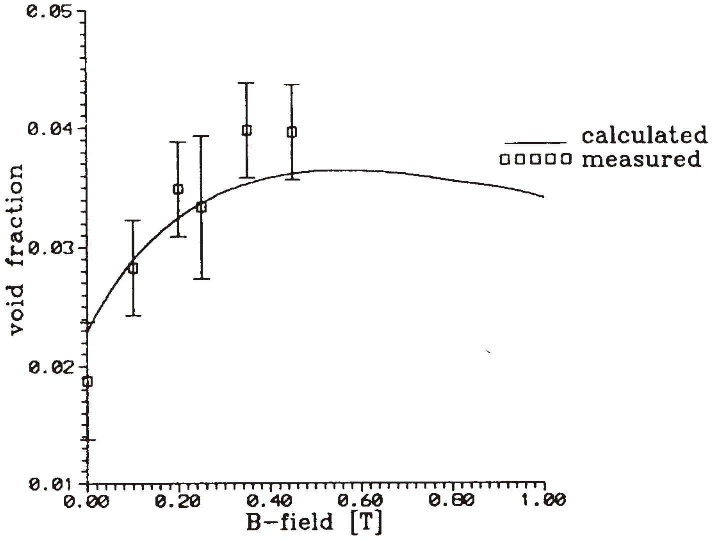


Fig. 5. Void fraction as a function of the transverse magnetic field (Re = 18,600, v_{S_0} = 0.2 m/s).

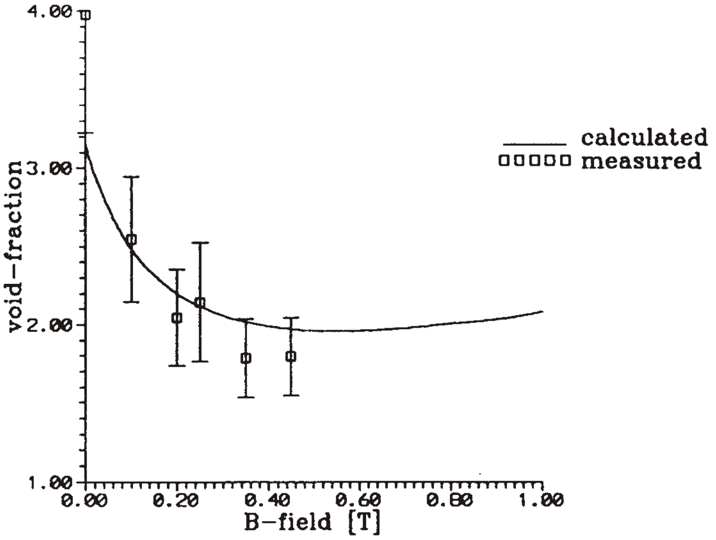


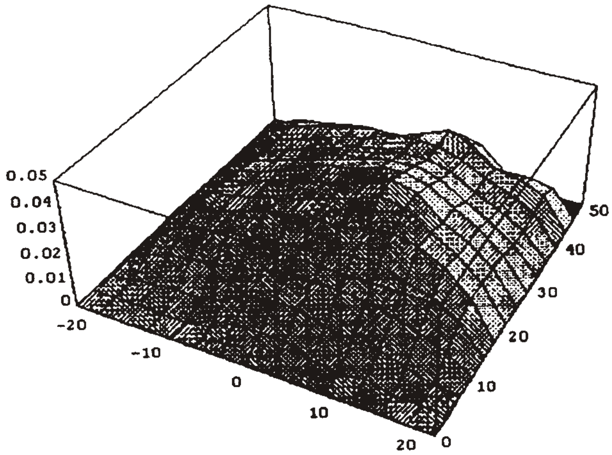
Fig. 6. Slip as a function of the transverse magnetic field (Re = 18,600, v_{S_0} = 0.2 m/s).

EXPERIMENTAL RESULTS

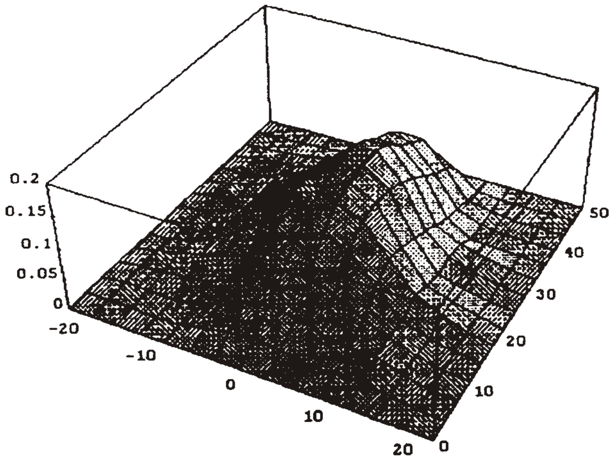
a. Sodium/Argon Facility

The facility of FZR operates with a sodium/argon flow in a vertical test section with a cross-sectional area of 45 × 50 mm^2. The flow passes a transverse magnetic field (length: 320 mm, max. field strength: 0.45 T). The gas is injected through a single orifice located in the center of the channnel cross section just at the beginning of the magnetic pole face region. The resistivity probe is installed at the end of the homogeneous magnetic field region in a traversing mechanism required to move the probe over the channel cross section.

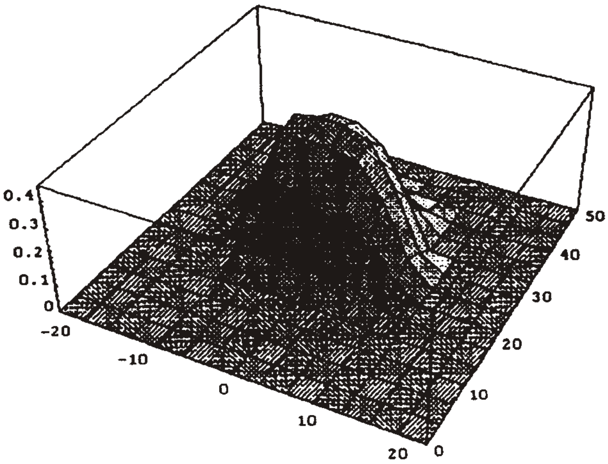
Results are obtained for liquid velocities of 0.1-0.3 m/s (Re ≈ 27900). The magnetic field can be varied from zero to 0.45 T (Ha ≈ 2710). A small value for the volumetric quality (β = 0.05-0.09) was selected in order to ensure a pure bubbly flow regime.



a) B = 0 T



b) B = 0.2 T



c) B = 0.45 T

Fig. 7. Distributions of the local void fraction at different values of the magnetic field (Re = 9300).

In order to get a precise time-averaged value of the local void fraction it is necessary to measure for a sufficient long time due to the statistical character of the two-phase flow. Recording times of 200 s and more for each point lead to a relative tolerance of about ±3-10% dependent on the bubble impaction rate. Thus, a good compromise between accuracy and duration of the measurements was achieved.

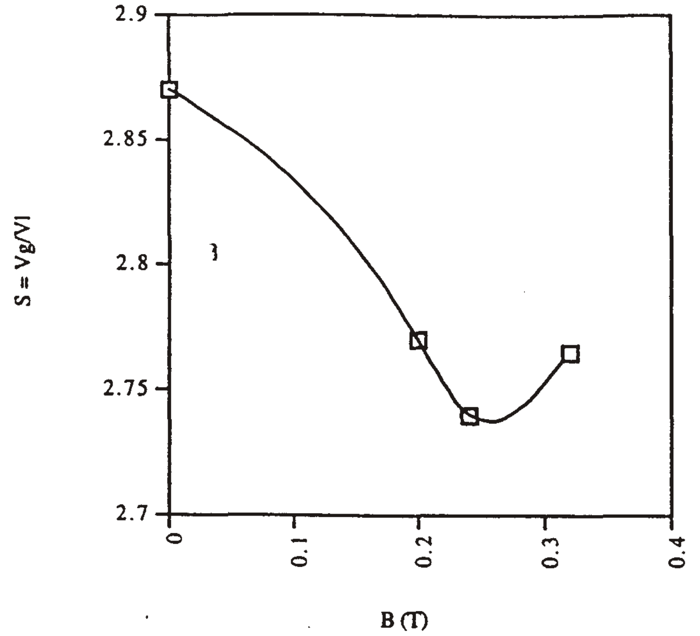


Fig. 8. Evolution of the slip ratio with increasing magnetic induction (mercury/air).

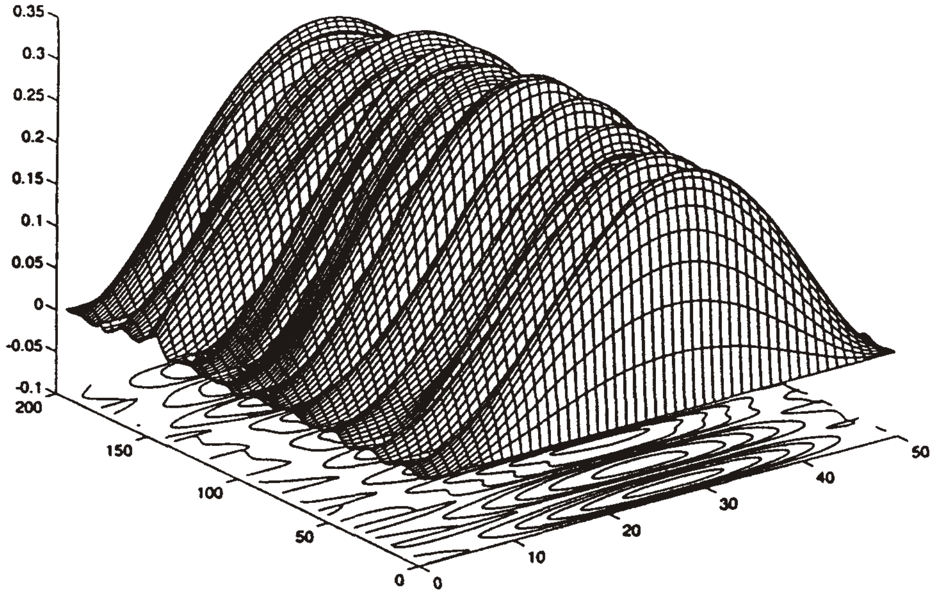


Fig. 9. Juxtaposition of void fraction profile (mercury/air). Magnetic field measuring from front (0 T) to back (0.8 T).

In the frame of this paper the analysis of the experimental data was focused on the cross section-averaged values of the void fraction and the slip ratio. Both quantities as functions of the external magnetic field are depicted in Figs. 3-6.

At both Reynolds numbers (9300 and 18600) a decreasing behavior of the slip ratio and a rise of the mean void fraction, respectively, can be observed for an increasing magnetic field strength. This fact confirms qualitatively the theoretical results obtained by means of the bubbly flow model. The distinct minimum of the slip ratio as a function of the transverse magnetic field visible in Fig. 1 was not detectable because of the field strength limitation. But, according to the calculated results the minimum of the slip moves to lower values of the *B*-field with increasing mean velocity of the liquid. For our experimental conditions this minimum should be detectable for mean sodium velocities greater than 0.5 m/s.

Compared to the mean void fraction over the channel cross section obtained by our measurements the bubbly flow model delivers values of the void fraction that are too high for the no-field case or being too low for the case of an applied magnetic field. A reason could be the one-dimensional limitation of the model. In the one-dimensional model naturally an equal distribution over the cross section of the void fraction is assumed, or, in other words, the distribution parameter introduced by Zuber and Findley [5] (drift flux model) is unity. Generally, this condition is not fulfilled in the experiment. The profiles of the local void fraction and the sodium velocity are strongly affected by the external magnetic field. Whereas in the case $B = 0$ an ordinary Pousseuille flow can be assumed, the velocity profile is flattened by the magnetic field. Moreover, at higher values of the field strength the profile becomes M-shaped [6], i.e., the core of the flow becomes a low velocity region compared to the side-wall jets. Simultaneously, the void fraction distribution changes from a flat profile to a sharp concentration at the channel center (Fig. 7). So, the parabolic velocity profile combined with the flat void profile lead to an overestimation of the cross section-averaged void fraction in the model, whereas an underestimation for the case of an applied magnetic field can be expected.

In order to be able to discuss this influence quantitatively and to adapt the model to the experiment (introduction of so-called correlation coefficients), detailed measurements of the sodium velocity profile depending on the magnetic field are planned.

b. Mercury/Air Facility

The facility of LEGI-IMG operates with mercury/air flow in a vertical test section with a cross-sectional area of 70 × 10 mm^2 and a 1 m length. This rectangular channel comprises, similarly to a Faraday generator, two insulated walls perpendicular to the B field and nine 0.1 m pairs of electrodes connected to an external electric circuit. It is placed in the gap of a conventional electromagnet which produces a uniform and adjustable (0 to 0.8 T) transverse magnetic field. The mean flow in the loop is driven by natural circulation (no pump). Due to the gas injection the apparent density decreases in the upcomer (including the test section), meanwhile in the downcomer (after separation) the flow is only liquid. The liquid flow rate varies between 8 and 10 kg/s and the volumetric quality between 0.2 and 0.45, but in this kind of loop these parameters cannot be adjusted independently. Consequently the flow configuration (slug or churn flow) is not as clean as in the FZR one but closer from a real two-phase flow generator, which also means very difficult measurements. Figure 8 gives the evolution of the slip ratio as a function of the B field. The slip ratio is not directly measured but deduced from measurements (void fraction and flow rates); thus the possible error can be very large (about 50%). Nevertheless this curve is still very interesting because the explored B field domain allows one to exhibit the minimum in the slip ratio predicted by the models. Figure 9 demonstrates that for the mercury/air pair (poorly conducting) the flow configuration (void fraction) is not qualitatively affected. Figure 9 is a juxaposition of a series of void fraction profiles with increasing magnetic field (from 0 to 0.8 T). This was expected because of the very low value of the ratio between the Reynolds and Hartmann numbers.

CONCLUSIONS

We present here a joint work between FZR and LEGI-IMG. It comprises both a modeling and an experimental part. The one-dimensional models developed include modified semi-empirical constitutive equations specific to LMMHD two-phase flows. One of the very specific results obtained concerns the slip ratio between liquid and gas in the transverse magnetic field: B case. When B increases from 0 (ordinary two-phase flow) to a large enough value (i.e., 0.5 T) the slip ratio is not monotonously varying. First of all the slip decreases due to the enhancement of the interfacial dragging, then it increases when the first effect is dominated by the braking influence of the electromagnetic forces on the liquid metal.

The two experiments of the program allow one to explore two very different situations: a highly conducting flow at FZR (sodium/argon) and a poorly conducting one at LEGI-IMG (mercury/air). The evolution of the slip ratio previously described is observed in both experiments. In addition almost no change was observed on the flow configuration for the poorly conducting flow (i.e., mercury/air) while a strong change appears on the highly conducting flow (i.e., sodium/argon). There are still many experimental difficulties to overcome in order to obtain extensive data bases and to give better quantitative results, but it seems that the qualitative agreement between model and experiment is very good.

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