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ANISOTROPIC TRANSPORT IN MHD TURBULENCE: EXPERIMENTAL RESULTS USING SMALL GAS BUBBLES AS LOCAL TRACERS

S. Eckert,* G. Gerbeth,*
H. Langenbrunner,* W. Witke,*
O. A. Lielausis,† and I. Platnieks†

There is ongoing research in the FZR MHD group on local transport phenomena in a turbulent liquid-metal (LM) duct flow exposed to a transverse magnetic field. In this paper experimental results are presented concerning the local void distribution over the channel cross section depending on an external transverse magnetic field. The measured local dispersion of bubbles shows a significant anisotropy which can be explained in terms of 2D MHD turbulence. The coefficients of the turbulent dispersion of the gas bubbles perpendicular as well as parallel to the direction of the magnetic field were obtained from the local void distributions and displayed as functions of the Stuart number N. In addition to the measurements in the channel without inserts, special turbulence generators (system of cylinders with changeable angle (0-90°) between their axes and the magnetic field lines) have been installed in the region of gas injection in order to increase the level of 2D turbulence and to observe their influence on the bubble dispersion.

INTRODUCTION

2D turbulence is one of the most interesting phenomena observable in MHD flows. When the ratio Ha/Re is sufficiently high, the overall pressure drop corresponds to a mean laminar flow. However, turbulent fluctuations can still exist in the flow, as shown experimentally by several authors [1, 2, 3]. Simultaneously, velocity fluctuations become highly correlated in distant points aligned to the magnetic field [4]. These effects can be described by the model of 2D MHD turbulence. According to [5] turbulent disturbances in duct flows with insulated channel walls exposed to strong magnetic fields can be considered as a multitude of vortices with axes parallel to the field direction. Such two-dimensional fluctuations are not affected by the magnetic field.

A well-aimed excitation of two-dimensional turbulence was successfully obtained by means of bars inserted in the flow parallel to the magnetic field [6] or by copper inserts in the channel wall [7].

What are the consequences in such kind of flows regarding local transfer properties?

The existence of such two-dimensional vortices will considerably enhance the heat and mass transfer in comparison to a completely relaminarized flow. Moreover, the anisotropic character of the turbulence causes a difference of the transfer properties in the direction of the B-field and perpendicular to it, respectively. A distinct anisotropy in the concentration profile of passive impurities (in drops injected in a mercury flow) was found in a LMMHD flow behind an array of bars [8].

A considerable increase of the heat transfer due to two-dimensional perturbations was predicted as well as confirmed experimentally [9]. This fact is important for many technological applications, especially for the blanket design of nuclear fusion reactors. Since two-dimensional turbulence does not cause substantial momentum transfer, there is reasonable hope that a heat transfer enhancement can be obtained without a simultaneuos increase of the overall pressure drop.

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*Research Center Rossendorf (FZR), Germany.

†Institute of Physics, Latvian Academy of Sciences (LAS), Latvia.

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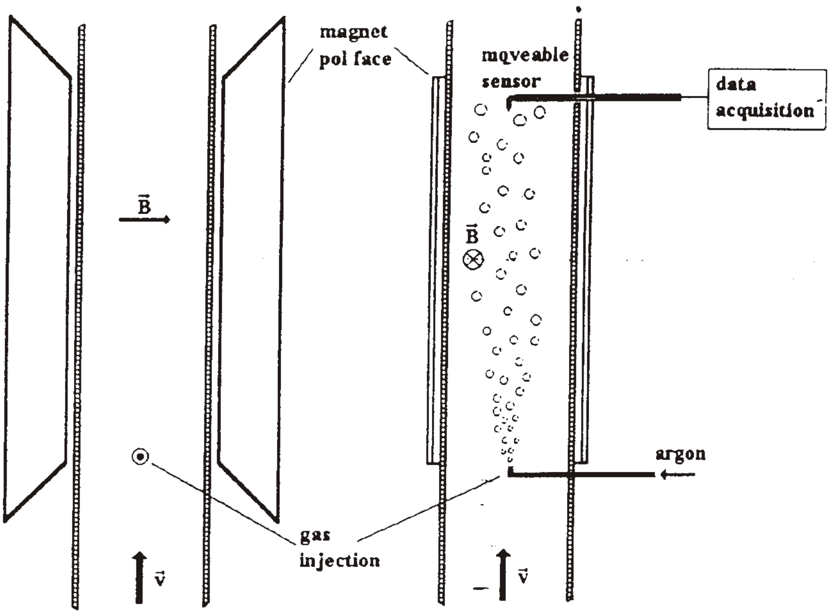


Fig. 1. Scheme of the two-phase test section.

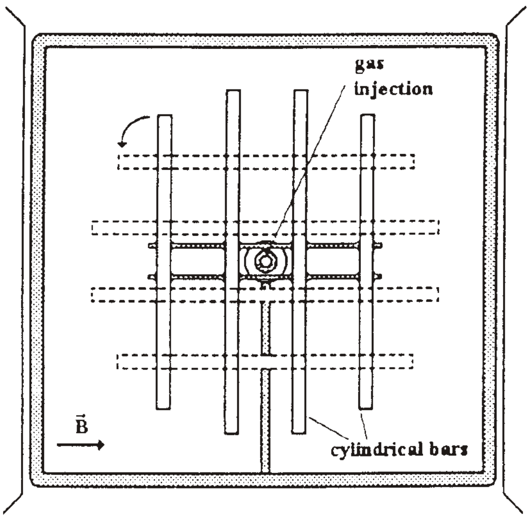
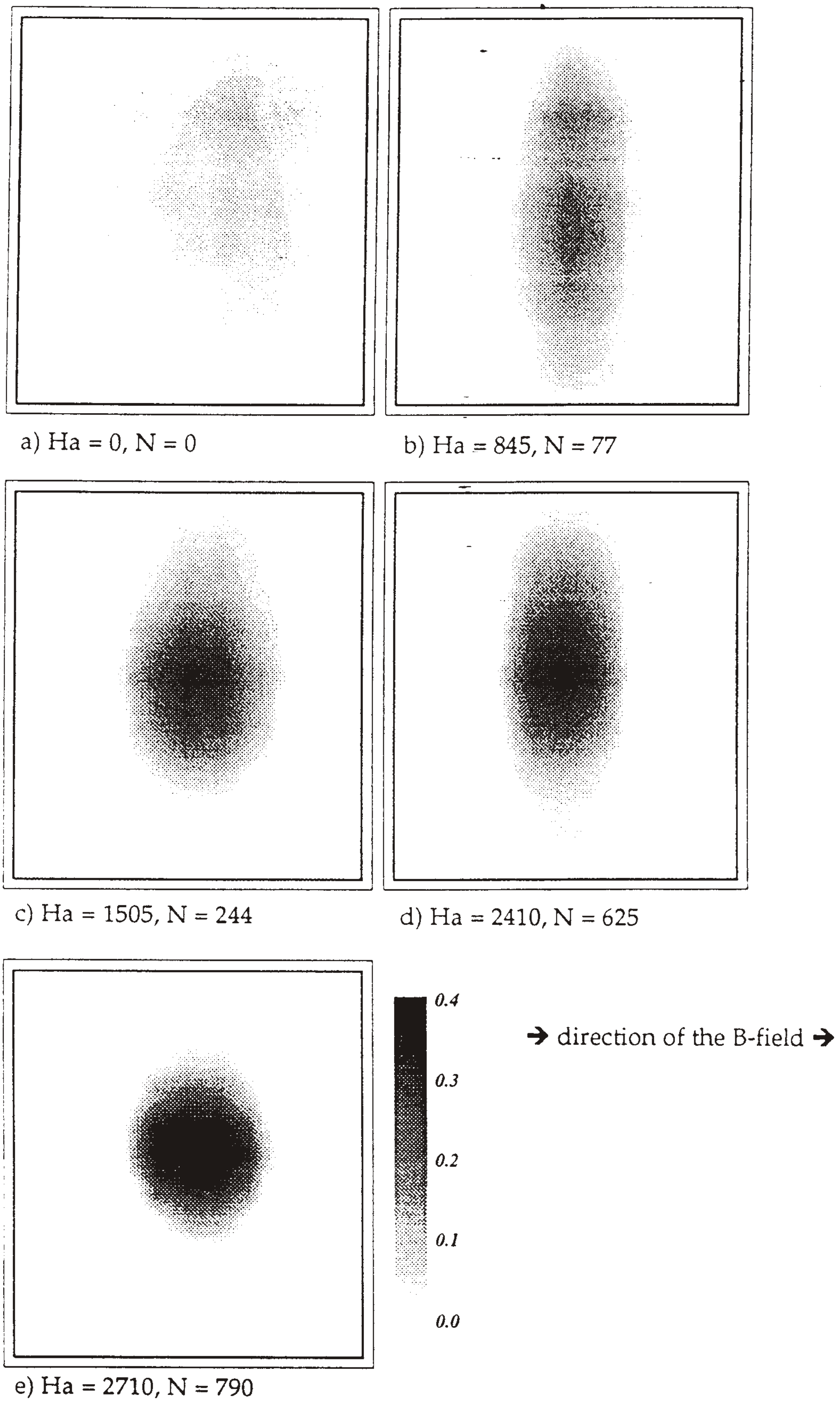


Fig. 2. Grid consisting of 4 cylindrical bars in the channel cross section.

The goal of this paper is to provide a contribution to the investigation of local turbulent transport properties of LMMHD flows. The interest is focussed on the mass transfer in a turbulent sodium flow exposed to a transverse magnetic field. Using sodium as liquid gives the advantage that high MHD parameters (Ha = 3000, N = 800) can be reached with moderate values of magnetic field (B = 0.5 T). On the other hand, the material properties of sodium cause considerable difficulties with respect to any local measurements in the flow (velocity, fluctuation intensities). Thus, the idea was born to use small gas bubbles (argon) as local tracers for the analysis of the flow structure. Void fraction measurements over the channel cross section allow the characterization of the transfer properties of gas bubbles dispersed in the turbulent flow.

EXPERIMENTAL CONFIGURATION

The scheme of the experiment is displayed in Fig. 1. The test section consists of a vertical rectangular channel with a cross-sectional area of 45 × 50 mm^2. A wall conduction ratio on the order of magnitude of 10^{-2} results from the stainless steel channel walls with a thickness of 5 mm. The flow is immersed in a transverse magnetic field (length: 320 mm, max. field strength: 0.45 T).



a) Ha = 0, N = 0

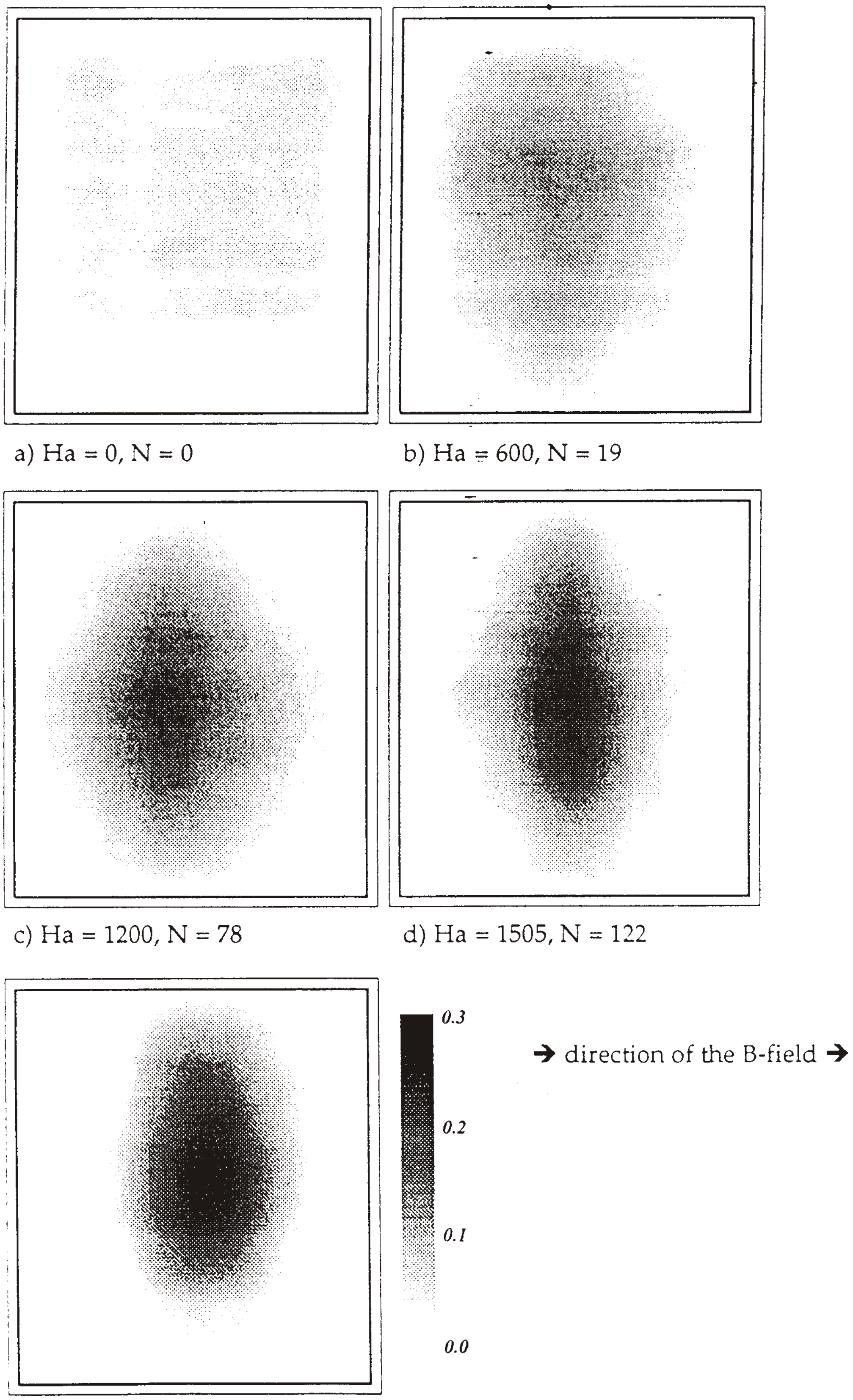
b) Ha = 845, N = 77

c) Ha = 1505, N = 244

d) Ha = 2410, N = 625

e) Ha = 2710, N = 790

Fig. 3. Void fraction distributions at Re = 9300.



a) Ha = 0, N = 0

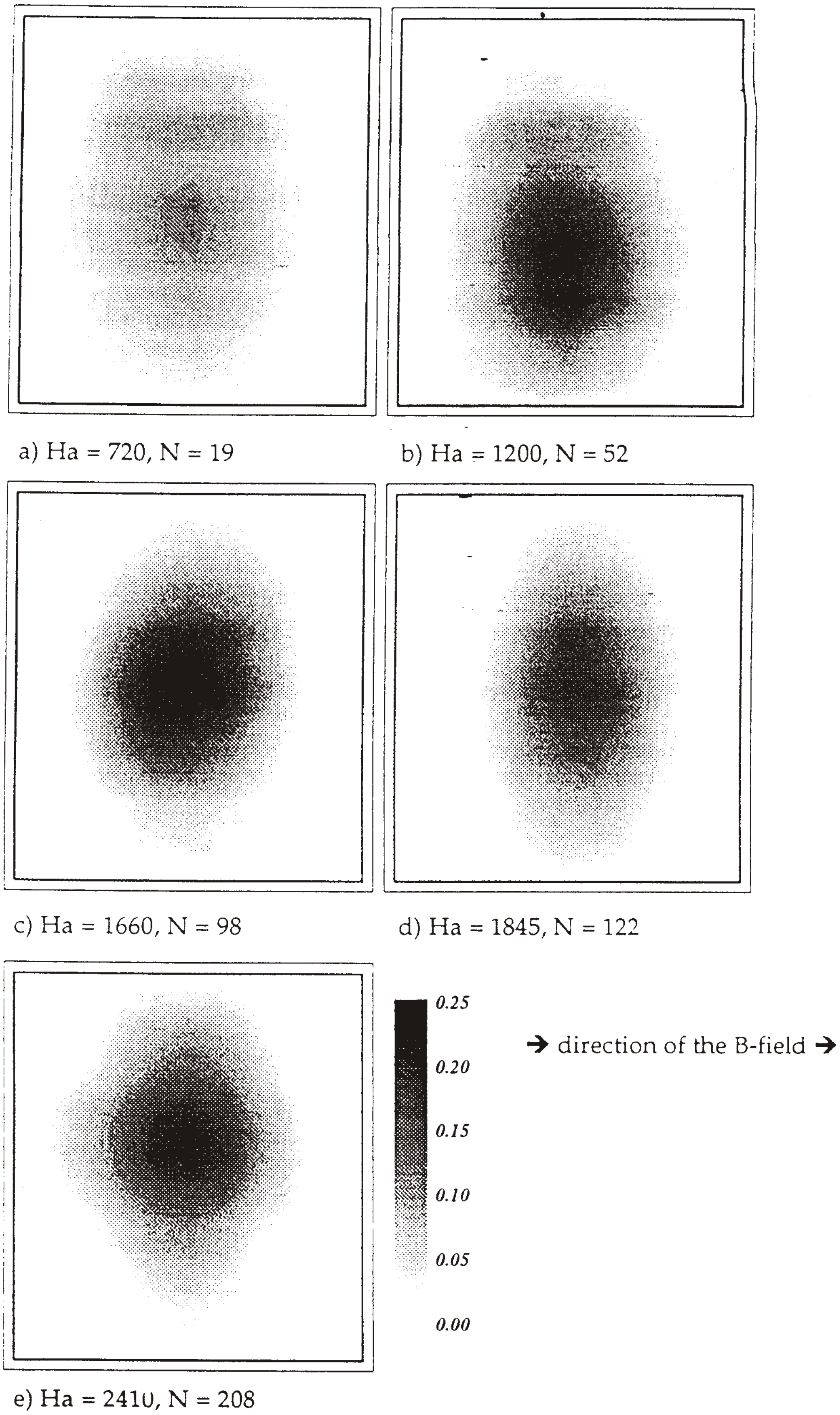
b) Ha = 600, N = 19

c) Ha = 1200, N = 78

d) Ha = 1505, N = 122

e) Ha = 2710, N = 395

Fig. 4. Void fraction distributions at Re = 18,600.



a) Ha = 720, N = 19

b) Ha = 1200, N = 52

c) Ha = 1660, N = 98

d) Ha = 1845, N = 122

e) Ha = 2410, N = 208

Fig. 5. Void fraction distributions at Re = 27,900.

At first 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. In order to ensure a pure bubbly flow regime, the volume gas rate Q_g was limited to values of the volumetric quality β lower than 0.1 ($\beta = Q_g/Q_g + Q_l$). Measurements of the local void fraction were carried out by means of single-wire resistivity probes [10]. The probe is installed at the end of the homogeneous magnetic field region. It is connected with a traversing mechanism allowing one to move the probe over the channel cross section. The vertical distance between the injector and the probe is 290 mm.

In the second step a system of four cylindrical bars was installed in the channel a few centimeters beyond the magnetic field entrance. The bars are rotatable mounted, so that any angle from 0-90° between the bars and the field lines can be selected. This system of bars is combined with a single orifice allowing one to inject the bubbles approximately 1 cm above the cylinders (see Fig. 2).

LOCAL VOID MEASUREMENTS

Distributions of the void fraction over the channel cross section have been measured for a mean sodium velocity of 0.1-0.3 m/sec (Re = 9300-27,900) and a magnetic field strength up to 0.45 T ($\mathrm{Ha}_{\mathrm{max}} = 2710$).

Figures 3a-e show two-dimensional void distributions at a Reynolds number of 9300 and different values of the Stuart number N. The gas flow rate was selected as 60 liters/h ($\beta \approx 0.07$). In the case of vanishing magnetic field a nearly constant void fraction was measured over the cross section. Already, a magnetic field of 0.14 T ($N = 77$) causes a serious concentration of the gas phase to its region of injection. Further increase of the field strength intensifies this tendency. The damping of turbulent fluctuations by the external magnetic field is the reason for this focussing action.

A clear anisotropy of the bubble dispersion can be noticed for Stuart numbers $39 \leq N \leq 625$. The void distribution parallel to the magnetic field lines is more extended compared to the distribution perpendicular to the field direction. This can be explained with the preferred elongation of two-dimensional vortices along the magnetic field lines as described above. For $N = 790$ the distribution of the void fraction becomes very sharp and almost isotropic. Thus, the two-dimensional perturbations are also damped and a nearly relaminarized flow occurs at higher values of the B-field. It must be stressed here that there are no special turbulence promoters in the channel; only the magnetic field entrance serves as promoter for the origin of two-dimensional perturbations. Thus, only a relatively weak persistence of typical two-dimensional MHD turbulence phenomena can be expected.

These results are generally confirmed by void fraction measurements at Re = 18,600 (Figs. 4a-e) and Re = 27,900 (Figs. 5a-e). In order to keep constant the volumetric quality the gas flow rate was raised to 120 and 180 liters/h, respectively. Measurements at higher Reynolds numbers are limited to lower values of the Stuart number:

$$N_{\mathrm{max}} = 395 \text{ at Re} = 18{,}600,$$
$$N_{\mathrm{max}} = 263 \text{ at Re} = 27{,}900.$$

COEFFICIENTS OF TURBULENT DISPERSION

In order to get a quantative description of the anisotropic transport properties in the flow, turbulent dispersion coefficients are determined parallel as well as perpendicular to the magnetic field lines.

The bubble dispersion is simply modeled in a first approximation by a two-dimensional diffusion equation:

$$\bar{u}_g \frac{\partial \alpha}{\partial x} = D_y \frac{\partial^2 \alpha}{\partial y^2} + D_z \frac{\partial^2 \alpha}{\partial z^2} \tag{1}$$

The mean flow is considered as one-dimensional in the x-direction immersed in a transverse magnetic field parallel to the y-direction.

Outgoing from an ideal δ-distribution at the place of gas injection ($x = 0$) we obtain for the local void fraction α at the position $x = x_{\mathrm{m}}$ the following expression:

$$\alpha(x_m, y, z) = \frac{Q_g}{2\pi x_m \sqrt{D_y D_z}} e^{-\frac{1}{2}\frac{\bar{u}_g(y-y_0)^2}{x_m D_y}} e^{\frac{1}{2}\frac{\bar{u}_g(z-z_0)^2}{x_m D_z}} \tag{2}$$

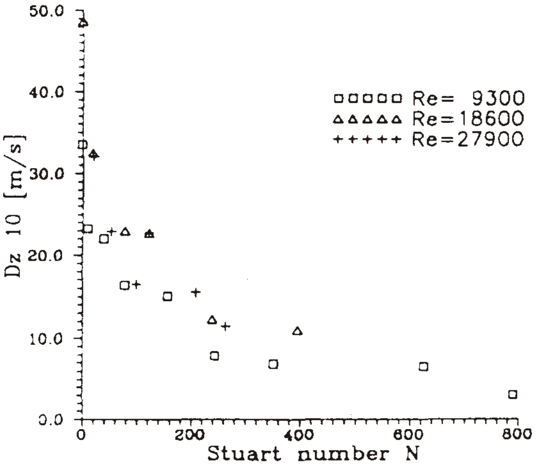


Fig. 6

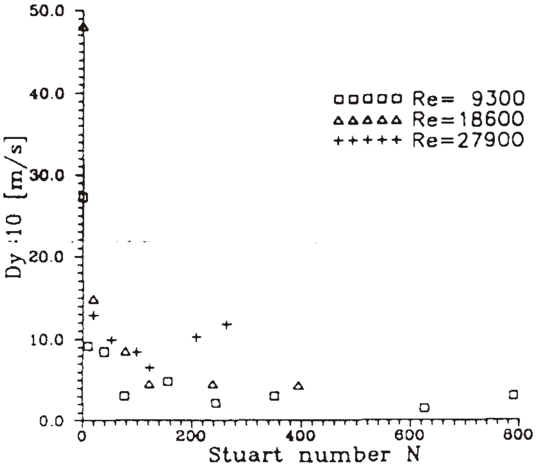


Fig. 7

Fig. 6. Dispersion coefficient D_z perpendicular to the magnetic field versus N.

Fig. 7. Dispersion coefficient D_y parallel to the magnetic field versus N.

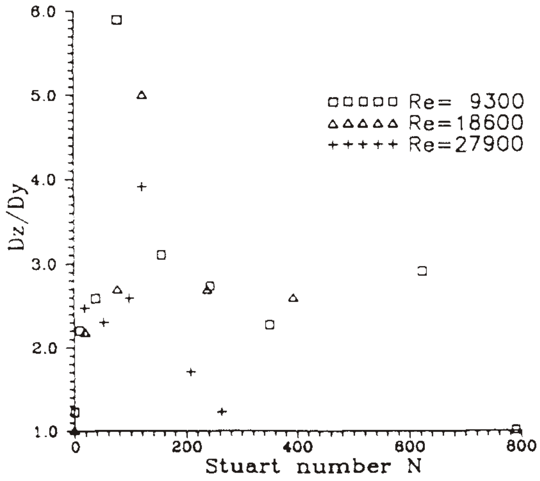


Fig. 8. Ratio between D_z and D_y versus N.

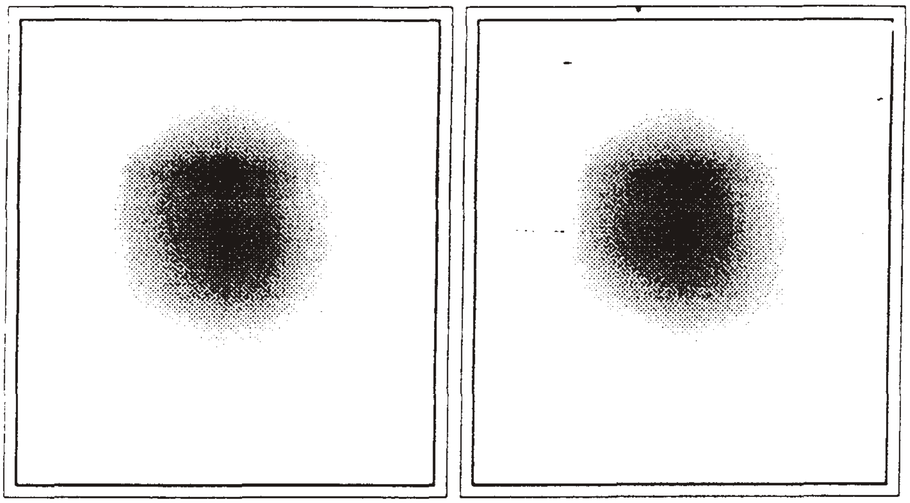
where Q_g is the volumetric gas flow rate; $\bar{u}_g$ is the mean bubble velocity; D_y, D_z are the coefficients of the bubble dispersion; and y_0, z_0 are the y- and z-positions of the single gas injector.

Due to the action of the transverse magnetic field, a remarkable difference between the dispersion coefficient in the field direction and the dispersion coefficient perpendicular to the B-field has to be expected, as shown in the void fraction distributions presented in Figs. 3-5.

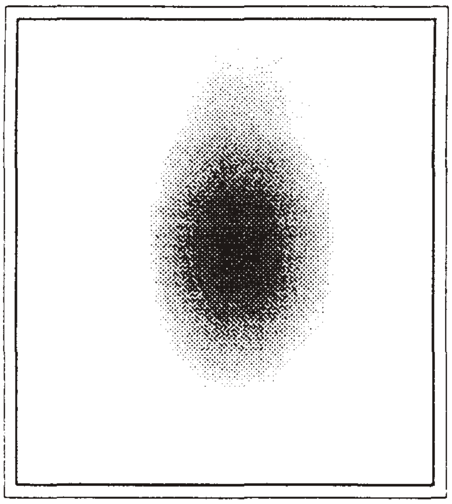
From the measured distributions the void fraction values are taken along the chords parallel and perpendicular to the field lines, respectively, and fitted to a Gaussian curve. Then, the respective dispersion coefficient can be calculated from the standard deviation (see (2)).

The coefficients of the turbulent dispersion perpendicular (D_z) and parallel (D_y) to the transverse magnetic field are depicted in Figs. 6 and 7 as functions of the Stuart number N. It can be seen that the turbulent mass transfer is generally reduced by the magnetic field. While the dispersion of the bubbles parallel to the magnetic field is already damped rapidly for small values of N, the decrease of the turbulent dispersion coefficient perpendicular to B is more slight.

Figure 8 displays the ratio between D_z and D_y versus N. A distinct maximum is perceptible at Stuart numbers of about 120. Here the bubble dispersion perpendicular to the field lines is approximately 4-6 times higher than in the parallel direction. For further increase in the field strength the ratio decreases and finally reaches unity at $N \approx 800$.



a) bars perpendicular to B-field b) bars parallel to B-field



➔ direction of the B-field ➔

c) without bars

Fig. 9. Void fraction distributions at Re = 9300, Ha = 1505, N = 244.

BUBBLE DISPERSION IN PRESENCE OF FLOW INSERTS

In the next step a carefully-directed enhancement of the mass transfer perpendicular to the magnetic field will be tried. To this purpose a system of four cylindrical bars (Fig. 2) was inserted in the flow. The experiment is based on the idea of an additional creation of two-dimensional vortices by means of cylinders aligned parallel to the external magnetic field.

In this paper first preliminary results are presented regarding the turbulent bubble dispersion in the presence of the described inserts.

In Fig. 9 the local void distributions at N = 244 (Re = 9300, Ha = 1505) are shown for the cases with the bars directed along the magnetic field lines as well as perpendicular to the field and without any inserts, respectively. However, a distinct anisotropy can only be observed if the bars are removed from the flow. Moreover, the direction of the bars does not influence the results remarkably. The impression that the cylinders cause not an enhancement but rather a damping of the mass transfer perpendicular to the magnetic field is confirmed by the presentation of the bubble dispersion coefficients in Figs. 10 and 11.

The following reasons may serve as a first explanation of these preliminary results:

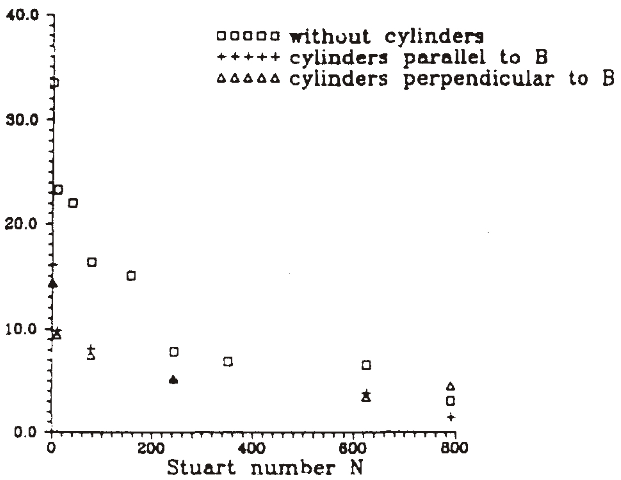


Fig. 10

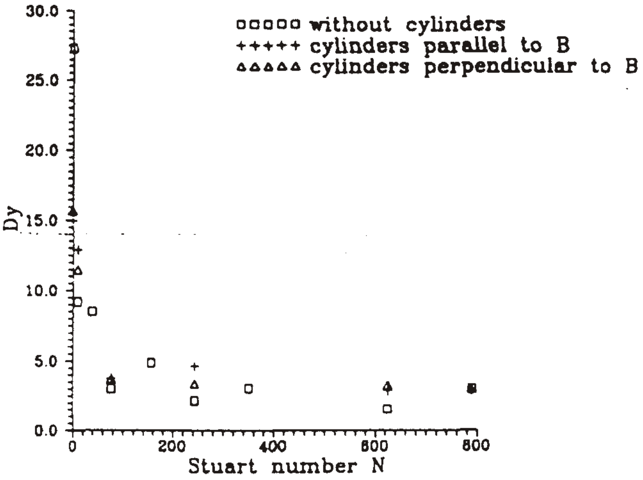


Fig. 11

Fig. 10. Dispersion coefficient D_z perpendicular to the magnetic field versus N (Re = 9300).

Fig. 11. Dispersion coefficient D_y parallel to the magnetic field versus N (Re = 9300).

For technical reasons the size and length of the bars were limited. Thus, in this case disadvantages regarding turbulence enhancement prevail. A considerable stimulation of two-dimensional turbulence was not reached (small diameter of the bars). Moreover, measurements of the channel velocity profile by means of potential probes show a low velocity region behind the bars in the core flow region, while higher values of the velocity arise near the channel walls in both directions. But a decrease of the liquid metal velocity supports the closure of the induced currents. Thus, the damping of the two-dimensional perturbations is intensified. This fact may be the reason for the reduced mass transfer perpendicular to the magnetic field in comparison to the situation without grid.

CONCLUSIONS

The effect of a transverse magnetic field on the gas dispersion in sodium/argon bubbly flow has been studied. The measured distributions of the local void fraction clearly indicate the existence of two-dimensional perturbations. Generally, the mass transfer was reduced by the magnetic field. However, at moderate values of the interaction parameter ($50 < N < 600$) the ratio between the dispersion coefficients in the direction perpendicular and parallel to the field lines is on the order of 4-6.

A first attempt to promote two-dimensional disturbances by means of an inserted grid consisting of 4 cylindrical bars was not successful. As the next steps new improved versions of inserts will be tested. The measurements will be continued as well as extended (sodium velocity, potential probes, velocity and size of the bubbles, double wire resistivity probes).

The use of gas bubbles as local tracers proved to be a good tool for investigating turbulent transport processes in LMMHD flows since considerable difficulties regarding local measurements can be partially overcome.

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