EXPERIMENTAL INVESTIGATION OF ROTATING MAGNETIC FIELD DRIVEN FLOW BY HIGHLY SENSITIVE POTENTIAL PROBE MEASUREMENTS

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Introduction. Electric potential difference probes (PDP) are mostly applied on laboratory scale to measure local velocities in electrically conducting media. Their principle of operation is based on Ohm's law $\mathbf{j} = \sigma(-\boldsymbol{\nabla}\phi + \mathbf{u} \times \mathbf{B})$, where ϕ, $\mathbf{B}$), $\mathbf{u}$ and σ, denote the electric potential, magnetic induction of the applied static measuring field, velocity, and the electrical conductivity. In the absence of electric currents $\mathbf{j}$ and provided a proper orthogonal arrangement, the voltage drop ΔU measured between the two electrodes spaced by $\Delta l(|\boldsymbol{\nabla}\phi| = \Delta U/\Delta l)$ is proportional to u and B.

Commencing with Faraday [1] (1832) who had tried vainly to measure the voltage induced across the river Thames by motion of the water in the Earths magnetic field, the acquisition of electromotive forces (e.m.f) in order to determine fluid velocities looks retrospectively at a long history. Only some of the milestones can be quoted in the scope of the present work. Kolin [2] (1943) proposed to use a probe consisting of two wires, insulated except at the tip, with a separation of the wire tips in the order of a few thousandths of an inch. With this sensor it should have been possible to access what is commonly referred to as local velocities.

The measuring field B can be applied either globally over the entire fluid volume or locally in the close vicinity of the wire tips. Again, Kolin [3] seems among the first who built an incorporated magnet probe employing a small electromagnet. The nowadays de facto standard for such probes comprises a small permanent magnet instead. A typical sensor as described by Ricou & Vives [4] (1982) had its electrodes mounted at the side of the cylindrical magnet. Because the field strength is weaker there, large magnets with an induction exceeding 1 T at the surface had to be used leading in turn to a comparably large wire spacing of $\Delta l \approx 5$ mm. Still the sensitivity was bound at its lower end to 1 cm/s. The authors claimed a resolution of 1 mm/s for a sensitivity of $\approx 3\,\mu$V/(cm·s^{-1}) being representative amongst their various probes.

Along with progress in analog electronics, results have recently been published [7] which reported on an increased resolution of almost an order of magnitude even for a smaller probe ($\varnothing_{\mathrm{mag}} = 2.5$ mm, $\Delta l \approx 3$ mm). From the data given in [7] and under a reasonable assumption about the field strength at the wire tips, the sensitivity of the sensor estimates to 5–6 μV/(cm·s^{-1}). As stated by the authors, all measurementswere conducted at least five times comprising 200 readings, each.

1. A glance at some basics of MHD.

Because static magnetic fields are known to damp flows (see c. f. [6]) questions may arise about the influence of the applied measuring fields. As a rule of thumb, damping becomes recognisable for a fluid of density ρ if the interaction parameter

$$N = \frac{\sigma B^2 L}{\rho u} \tag{1}$$

relating electromagnetic and inertial forces exceeds unity. With the characteristic length L according to the container dimensions in the case of the globally applied field we are concerned with the invasiveness of the measuring technique. If, on the other hand, the usually strong fields of permanent magnets lead to a nonvanishing N even for their small size, the flow may be damped in the vicinity of the sensor. That is to say, the response might be anticipated to be nonlinear.

Rotating magnetic field (RMF)driven flows in cylindrical containers comprise a recirculation in the meridional plane owing to an imbalance between centrifugal forces and pressure at the top and the bottom of the vessel. According to theory [8], the first transition of this flow is from a Stokes regime to a laminar boundary one, accompanied by a change in scaling of the primary swirl from $u \propto \mathrm{Ta}$ to $u \propto \mathrm{Ta}^{2/3}$, where the governing Taylor number is given by

$$\mathrm{Ta} = \frac{\sigma\omega B^2 L^4}{2\rho\nu^2} \tag{2}$$

with ν and ω denoting kinematical viscosity and field frequency. Note that such changeover phenomena do not show a sharp transition rather than occuring over a certain range of the control parameter which is expected to be $10^3 < \mathrm{Ta} < 10^4$.

2. The Experiment.

2.1. Setup. All measurements were carried out in a closed cylindrical cell of aspect ratio 1.5 ($H = 90\,\mathrm{mm}$, $\varnothing = 60\,\mathrm{mm}$). The PDPs were inserted into the fluid from above by threading them through a screw connexion furnished with a rubber sealing in order to avoid leakage and the formation of a rotation paraboloid. As an easy to handle liquid metal, eutectic InGaSn was chosen since it is liquid at room temperature.

In both the globally applied field (GF) and the incorporated permanent magnet (PM) type of PDPs, $\varnothing = 2\,\mathrm{mm}$ hollow ceramic rods guided the $\varnothing = 70\,\mu\mathrm{m}$ copper wires from their one end into the liquid metal. At the tip side, the wires in the simpler GF type were spread to the desired spacing of 1 .mm and let protruding by $\approx 2\,\mathrm{mm}$ from the tubes end. A rare earth CoSm magnet of $2 \times 2\,\mathrm{mm}^2 2$ crosssection was glued onto the frontal area of the tube in the case of the PM type sensor. On the other side of the magnet, the frustum of a pyramid served as a mechanical fixation of the supernatant wires which were cut to a protrusion distance of 0.25 mm leading to a tip spacing less than 1mm. Well agreeing numerical simulations and backward calculations of calibration data yielded a field strength of $\approx 110\,\mathrm{mT}$ at the wire tips.

For the creation of the RMF, the usual arrangement similar to the coil system of an asynchronous motor was implemented with an inner diameter of 36.5 cm and a height of 45 cm. Nonuniformities of the field were found to be less than 1% over almost the entire volume occupied by the liquid metal, except at a small circumferential region at half the height where it approaches 2.7%. Due to the large experimental volume and the coreless setup, it was necessary to feed the coil system with relatively strong currents. Precisely current controlled AC power amplifiers have been developed especially for that purpose [9] delivering up to $3 \times 160 A_{\mathrm{eff}}$ for any arbitrary waveform supplied to their input in the frequency range up to 1 kHz. The static field used in the measurements with the GF type probe was created by a large solenoid of $H = 45\,\mathrm{cm}$ and $\varnothing = 75\,\mathrm{cm}$. It was not possible to detect any inhomogeneities of the static field within the fluid volume at all.

2.2. Instrumentation and wiring. Having sensitivities of $\approx 260\,\mathrm{nV/(cm{\cdot}s^{-1})}$ in the case of PM, and even less with GFtype probes, it was vital to employ an extremely low noise preamplifier, which served as a basis of a multistage measuring/ filter chain. For the differential signal processing it was necessary to provide a proper common mode rejection. Since acquisition of velocity fluctuations does not allow any averaging, all potential sources of statistical errors had to be avoided. In particular, the electromagnetic noise was countered by a sophisticated wiring scheme. As systematic errors such as thermoelectric currents are detrimental, meticulously avoiding both temperature differences and materialrelated gradients

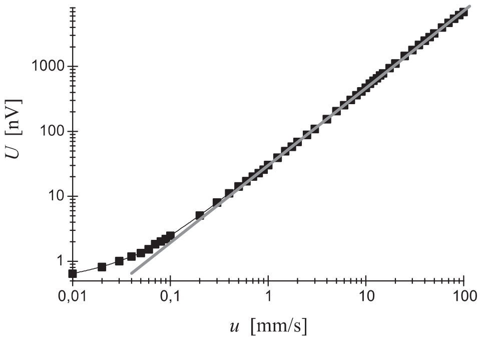

Fig. 1. Calibration curve of the permanent magnet sensor.

of Seebeck coefficients permitted to reduce their influence well below the level of the velocity signal.

3. Results.

3.1. Calibration. Fig. 1 shows a calibration curve of the PM type sensor. According to Eq. (1), the nonlinear range of responsewas to be expected for $u < 1.26$ cm/s. From the logarithmic representation it can be read that the linear scaling extends to values of the velocities more than one order of magnitude less. Surprisingly, this magnetic influence seems actually negligible for as high local interaction parameters as $N = 10$. It is reasonably assumed that the viscous damping in the boundary layer cannot be ignored if both the velocity and the sensor are very small. An observable effect may be expected for local Reynolds numbers $\mathrm{Re} = u \cdot \delta_p/\nu$ smaller than unity. With the protruding depth $\delta_p = 0.25$ mm of the electrodes into the fluid, the sensor should respond nonlinearly below 1.5 mm/s. Because this value is very close to that of commencing nonlinearity to be read from Fig. 1 and there was no detectable magnetic damping for $N = 10$, the actual response may be due to viscous damping alone or a combined action in the case of even larger interaction parameters.

3.2. Mean flow. Concerning GF type measurements, it is often practised to either neglect the measuring field or to perform a series and extrapolate towards the case $B = 0$. Highly accurate and sensitive velocity measurements allow to quantify the systematic deviations to be anticipated an example of which is depicted in Fig. 2. Even for fields as weak as 20 mT, the damping amounts to 5% and is still detectable at a quarter of a mT. Whereas such an accuracy may suffice in several cases, the influence of the measuring field can be much larger in others. In Fig. 3 it is shown that the changeover in flow structure (c. f. Section 1) is retarded by

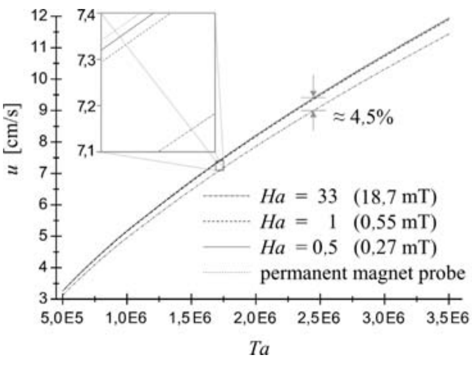

Fig. 2. Influence of the strength of the measuring magnetic field onto the swirling flow in an RMF.

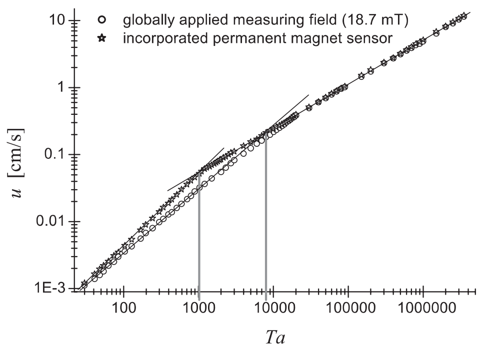

Fig. 3. Scaling of RMFdriven flow in the Stokes and laminar boundary layer regimes.

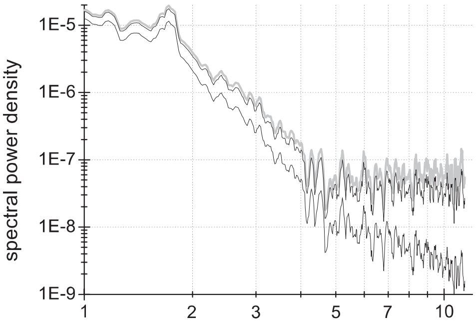

Fig. 4. Influence of tip spacing on turbulence spectra. Gray: backcalculated [10] from 1 mm; black: 1 and 5 mm.

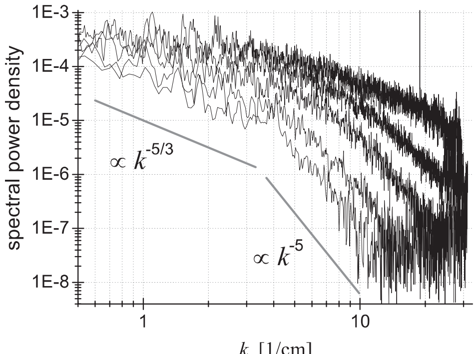

Fig. 5. Wavenumber spectra for various values of the Taylor number: 3.2E5, 5.6E5, 1.3E6, 2.9E6, and 7.9E6.

almost an order of magnitude. As the scaling of the velocity is affected, that is to say the measuring field influences the dependence on the governing parameter (c. f. Eq. 2)).

3.3. Velocity fluctuations. On the one hand, the measurement of turbulent velocity fluctuations puts a severe restriction on the size of the sensor in order to resolve all scales of potentially significant vortices. This means that the finite spacing of the electrodes acts as a lowpass filter with respect to the time domain. Selfevidently on the other hand, as well no averaging is allowed as the amplitude of the fluctuations is small compared to that of the mean velocity. Fig. 4 evinces on the maximum allowable wire spacings according to [10]. The performance of the measuring chain allowed for the acquisition of RMFdriven velocity fluctuations even in the transitional regime slightly above the critical Taylor number Ta^c. The wavenumber spectra $E(k) \propto k^c$ calculated via Taylors hypothesis were well resolved up to the end of the inertial range and showed a steep decrease with $c > 4$.

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