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Magnetohydrodynamic flows and turbulence: a report on the Third Beer-Sheva Seminar

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This paper is a summary of the Third Beer-Sheva Seminar on magnetohydrodynamic (MHD) flows and turbulence, held in Israel in March 1981 with 67 participants from 9 countries. Reviews and research papers were presented on fundamental MHD and turbulence studies, both theoretical and experimental, including two-phase phenomena, and on applications of MHD to electrical generation (especially in two-phase systems), electromagnetic pumps, flow-couplers and flowmeters, thermonuclear fusion and a range of metallurgical problems, many involving free surfaces.

1. Introduction

The Third Beer-Sheva Seminar was held at Ben-Gurion University of the Negev, Israel. The previous two conferences in the series were actually called Bat-Sheva Seminars, though held in Beer-Sheva, because they had support from the Bat-Sheva Foundation. For the first time the seminar included participants from India and Japan, and half the sessions were held in Eilat.

The programme had a distinctly more *applied* flavour than the previous ones (Branover *et al.* 1979; Branover & Yakhot 1980), much attention being given to two-phase liquid metal MHD power generation and to applications in industrial metallurgy, whereas there was relatively little *pure* MHD, aimed at the unravelling of phenomena, *per se*. Those attending included pioneers of MHD such as Lundquist, Hide and Ludford, whose recent interests have been in fields other than liquid metal MHD, but whose participation and interjections into the discussions were fruitful.

In this review the name of the author who delivered the paper is printed in italics and some additional references cited by the authors or in discussions are listed.

2. Fundamental studies in MHD and turbulence

The long-established field of MHD duct flow theory was represented mainly by *Walker* (Illinois) who presented interesting new results (Walker 1981) concerning flow in ducts with walls parallel to the magnetic field when the walls are thin and finitely conducting and the field or the cross-section is non-uniform so that blocked flow and characteristic surfaces (Ludford & Walker 1980) occur. Inertia is neglected and the Hartmann number M is large, with

$$M^{-1} \ll c \ll 1,$$

c being a wall conductance parameter. On the walls parallel to the field, there is a thicker, *inviscid* layer outside the usual viscous layer of thickness $O(M^{-\frac{1}{2}})$, characterized mainly by electric current circulation in the streamwise direction. One implication is that end-losses at the edge of a magnetic field can be much higher than hitherto suspected.

In a stimulating review of two-dimensional turbulence, *Moreau* (Institut de Mécanique de Grenoble) explained that experiments in Riga, Purdue, Beer-Sheva (Branover & Gershon 1979) and Grenoble (Sommëria 1980) showed that weakly dissipative, quasi-two-dimensional turbulence existed, provided there were high values of M/Re and insulating walls perpendicular to the magnetic field. There are two basic mechanisms: electromagnetic 'diffusion' along the magnetic field lines (degenerate Alfvén waves), and the Hartmann effect (generalized so as to take account of inertia). If the eddy scale perpendicular to the magnetic field is large enough, the eddies are necessarily two-dimensional and are oriented perpendicular to the walls. MHD affords a good way of realizing experiments with two-dimensional turbulence, and allows velocity and vorticity to be deduced from measurements of the electric field.

Branover (Ben-Gurion University of the Negev) gave a comprehensive review of his own group's current work which involves the following themes: (1) turbulent MHD single- and two-phase flows in ducts in aligned and transverse magnetic fields; (2) metallurgical applications of MHD; (3) development of liquid metal two-phase MHD power systems for low grade heat sources. The applied work is referred to later. In relation to (1) the main interest is still in understanding the mechanism of turbulence suppression and distortion by magnetic fields of different orientations. The homogeneity of two-phase liquid-metal–vapour flows and the transport properties of such flows are also being studied. Theme (3) involves the study of a wide range of challenging problems having a fluid-dynamic character, e.g. the mixing of liquid metals with volatile liquids, the boiling of droplets dispersed in hot liquid metal and the flow patterns in the generator channel. In a separate paper, *Branover* & Claesson (Uppsala) presented experimental results on friction in turbulent and laminarized flow in rectangular channels with aspect ratios of 10 and 0·1 under a transverse magnetic field. The powerful 3 T magnet of Uppsala University permitted Hartmann numbers up to 600. As shown earlier (Branover 1978) for cross-sections long in the field direction, turbulence suppression is qualitatively similar to that in a streamwise field and friction falls strongly as an initially turbulent flow is laminarized, even though the channel has no settling length after transition from a circular section. The ratio of friction factors for the two investigated aspect ratios was reaching 8 at complete laminarization of the flow, which means that a flow control could be arranged by turning a magnet through 90° about a streamwise axis.

Fujii-e (Nagoya) reviewed his group's experimental work on liquid metal two-phase flow under both travelling and steady magnetic fields with applications to nuclear engineering. The work embraced sodium, potassium and mercury experiments, including boiling phenomena and heat pipes in the presence of magnetic fields. In two-phase flows, X-rays were being used to establish void fraction and effective conductivity was being measured by various methods. One application was to liquid metal two-phase induction generators, described elsewhere (Fujii-e *et al.* 1975).

The main contribution on basic two-phase MHD was by *Lykoudis* (Purdue) who presented an interesting survey of his group's recent work. In one experiment bubbles were released at the bottom of a cylinder, filled with water or mercury, and signals were taken with a hot-film probe, moving vertically at constant speed. Later, a grid was arranged to advance ahead of the probe to create turbulence. Turbulence intensities and spectra were presented for different sizes of bubbles and void fractions. A hot-film probe inserted in a small two-phase loop using mercury and nitrogen recorded the turbulence for different void fractions in the bubbly regime with and without a magnetic field (Gershon 1981). The facility for nucleate boiling of mercury in a magnetic field, also discussed at the first Beer-Sheva Conference (Lykoudis 1976) had yielded more data (Wagner 1981) and a theory was being developed.

There were several papers dealing with general, fundamental fluid mechanics, sometimes including MHD cases. Into this category came the review by *Hide* Meteorological Office, Bracknell, UK) of the elegant motions that can be produced in rotating laboratory systems and other fluid-mechanical phenomena that are relevant to earth and planetary science (Hide 1977; Hide & Mason 1975).

Narasimha (Bangalore, India) gave a lively review of relaminarization phenomena, including some MHD. He enumerated the main cases when relaminarization of a turbulent flow occurs, with particular attention to the response of a turbulent boundary layer to a favourable pressure gradient where, according to turbulent energy balance measurements, dissipation is less than production even under large pressure gradients. Narasimha & Sreenivasan (1973) suggested that in this case relaminarization occurs mainly not because the turbulent energy is dissipated, but rather because the pressure gradient dominates the slowly responding Reynolds stresses and a stable laminar sub-layer grows underneath a sheared flow carrying the relics of the original turbulent layer. For MHD duct flows the mechanism of laminarization and its dependence on the relative main flow and magnetic field directions was discussed.

There were three papers on basic fluid mechanics, without specific reference to MHD. *Timnat* (Technion, Haifa) described a laser technique for measuring instantaneous mean velocity and droplet size in multiphase flows. This technique had been used in an experimental facility in which the influence of changes in inlet geometry on the performance of a combustor was studied and compared with numerical calculations. *Naot* & Rodi (Technion, Haifa) presented a study of turbulent flow in an open channel where gravitational reflection of eddies at the free surface drives secondary flow which causes the maximum mean velocity to occur below the surface. Numerical calculations using the (k, ϵ) model agreed qualitatively with experiments and an order of magnitude theory involving surface tension was suggested to explain the shift in the observed spectrum. *V. Yakhot* (Weizmann Institut) applied 're-normalization group' methods to isotropic three-dimensional turbulence. The elimination of the small scales has been shown to lead to the Kolmogorov relations $E(k) \sim k^{-\frac{5}{3}}$ as $k \rightarrow 0$ (Martin & de Dominicis 1978). Elimination of the larger scales gives rise to a negative dissipation as the source of the small eddies is removed, and produces the spectrum $E(k) \sim k^{-\frac{5}{3}}/\log k$, which might be responsible for observed deviations from the Kolmogorov law. (See also V. Yakhot 1981.)

The remaining papers all referred to specific applications of magnetohydrodynamics.

3. MHD generation and electromagnetic flowmeters

At the sessions concerned with MHD generation most attention was directed towards two-phase systems in which a liquid metal 'armature' is to be accelerated by a second lighter phase, either at very high temperatures as in a proposed 'topping' device for coal-fired power stations or at lower temperatures, e.g. in cheap solar-powered systems. In some cases the papers were not primarily fluid mechanics and so are reported only briefly here.

There were several papers from the Argonne National Laboratory, USA. The paper by *Pierson*, Herman & Petrick concerned the conceptual design of a system using liquid copper, capable of being fitted retrospectively to existing coal-fired stations to raise their efficiency. The paper by *Pierson* & Herman was an engineering assessment of schemes for high-temperature systems driven by solar power mirror collectors, perhaps providing combined heat and power. Fabris' paper was presented by *Pierson* and discussed the controversial and conceptually difficult topic of energy losses due to slip between the two phases in an MHD generator. Fabris attempted to divide the pressure drop and work done into reversible and irreversible parts, but the theory did not correlate well with experiment.

The home team provided two papers on two-phase generation with a view to using solar power. *Branover*, Claesson, El-Boher & Yakhot (Ben-Gurion University of the Negev) presented the results of testing a number of two-phase MHD power systems with heavy liquid metals. Although the tests so far had been performed with very small demonstration models, these were noteworthy as being the first complete liquid metal MHD power systems to be built and tested. Models tested in Beer-Sheva and Uppsala used mercury with, respectively, Refrigerant-113 and *n*-pentane as the thermodynamic fluid, and developed up to 10 W net power. Unusual two-phase liquid metal/volatile vapour flow patterns were observed. Inhomogeneity of the two-phase flow probably explains the low efficiency of the systems and dictates the use of surfactants to improve the foamability of the liquid metal.

A. Yakhot & Branover developed a theory of the flow in a two-phase MHD generator by averaging the equations. Following Saito, Inoue & Fujii-e (1978), the inhomogeneity of void fraction over the cross-section was taken into account by correlation coefficients. The calculated characteristics showed fairly good agreement ($\pm 15\%$) with experimental data obtained at the Argonne National Laboratory, although slip was neglected. The critical parameters for choking to occur at the generator exit have been published elsewhere (Yakhot & Branover 1981).

Single-phase MHD generation using a high-speed combustion plasma stream was the subject of two papers by *Sluyter* (US Department of Energy) & *Jackson* (Washington DC) who reviewed the history, economic and environmental advantages and present status of such systems. There has been progress to a point where power levels of 50 MW, isentropic efficiencies of 70 % and channel lifetimes of 1000 h have been reached.

In contrast to the difficulties of turning MHD generation into a commercial success, the generator at zero load, i.e. the electromagnetic flowmeter, is a long established industrial product, backed by detailed theoretical understanding which allows optimal design, as was clearly revealed by *Baker* (Cranfield) in an authoritative review of recent developments. He categorized the various alternative types of flowmeter and outlined the theory for each, mentioning some recently published work on design, e.g. Kuromori, Kobayashi & Kanai (1978) and Sen (1978), concentrating mainly on the induced-voltage flowmeter. Revived interest in various types of electromagnetic velocity probe was noted. Finally the major unsolved problems such as zero-drift, installation effects, design and performance standards, and the increasingly demanding fluids to be metered were discussed.

4. Electromagnetic pumps and flow-couplers; fission and fusion applications

Liquid sodium is the accepted coolant for fast breeder fission reactors and electromagnetic pumping is therefore an alternative to the mechanical pumping which has been used so far in fast reactors. A recent resurgence of interest in this possibility was exhibited by some of the American papers at the Seminar.

McNab, Alexion, Keeton & Ciarelli (Westinghouse, Pittsburgh) presented experimental results from their large NaK loop, updating their earlier results (McNab 1980). A new channel had been installed and other improvements made. Pressure and electric potential distributions were measured in the DC pumping regime with applied currents up to 18 kA and transverse fields up to 1·2 T, giving interaction parameters of 5 at flows of 53 l/s. The pressure distributions in the end zones showed peculiar features. In the discussion, it became clear that, although much work had been done on DC MHD pumps in the 50s and 60s, it had used primitive models of the flow. The Westinghouse loop could provide experimental data which might allow a better understanding of the flow and hence improvements in efficiency. The discussion also revealed the difficulties of sealing MHD channels with two electrodes and two insulated walls.

In another paper, *McNab*, Alexion (Westinghouse, Pittsburgh) & Winkleback (EPRI, Palo Alto) presented theoretical results for flow-couplers for use with pool-type reactors. In a flow-coupler the pumping of the primary coolant takes place exactly as in a DC pump, but the necessary current is supplied by an adjoining liquid metal DC generator in the secondary coolant circuit. The advantage is that an external high-current power supply (or a drive to a mechanical pump) is no longer required to penetrate the reactor vessel. The secondary coolant pump is outside the reactor. Earlier British work has been published elsewhere (Davidson & Thatcher 1974).

There were several theoretical papers on flow in electromagnetic pumps. *Hughes* (Carnegie-Mellon) & McNab described a simple quasi-one-dimensional model used to study the effect of design parameters on overall performance. Allowance was made for sidewall conductivity and current fringing at the field edges. In the discussion reference was made to earlier work such as that of Rossow (1960), Shercliff (1956) and Sutton & Carlson (1961). Numerical models for two-dimensional MHD duct flows were presented by *Alexion* & Hummert (Westinghouse, Pittsburgh) and by *Winowich* & Hughes (Carnegie-Mellon) using finite differences and finite element methods respectively. Each assumed laminar flow with either a parabolic or slug upstream profile for various values of Hartmann and Reynolds numbers. M-shaped profiles were predicted, persisting, according to the latter study, over 50 electrode widths downstream. Criticism of all these papers centred on the lowness of the Reynolds number considered ($\leqslant 2000$) and the neglect of turbulence. Moreau suggested that turbulent vortex stretching might be important in these flows.

MHD aspects of fusion technology received relatively little attention at the Seminar. Itoh & *Fujii-e* (Nagoya) reported work on imploding cylindrical shells of falling liquid metal for use in novel schemes for thermonuclear fusion, in relation both to inertial and magnetic confinement. In the latter case, an initial vertical magnetic field inside the shell is compressed, along with the plasma. In the former the aim is to generate a liquid 'first wall' surrounding the reaction zone. Both numerical simulations and experiments with NaK were described. In a second paper Itoh, Kanagawa, Miyakazi & *Fujii-e* (Nagoya) examined the geometrical integrity of an imploding thin cylindrical metal liner, proposed for fusion reactors and experiments. Experiments had been performed on solid potassium, regarded as a Bingham fluid. For liquid liners, the use of additional high-frequency fields to give stability has been studied theoretically. The reflection of the pressure waves due to the rapid magnetic compression could cause cavitation. The discussion recalled a paper by Colgate, Furth & Halliday (1960) in which solid sodium was deformed by pulsed fields, and Lundquist remarked how a lightning conductor could be 'forged' by the current flowing along it.

Magnetohydrodynamic problems of the cooling of fusion reactors were represented by the paper by *Michael* (Kernforschungszentrum, Karlsruhe) who had experimentally investigated the pressure drop in sodium flow in a tightly meandering channel with a strong generally transverse magnetic field up to 4·2 T, in order to demonstrate the effect of multiple bends. There was a very large increase in pressure drop as compared with a straight pipe of the same length.

5. Metallurgical magnetohydrodynamics

All the papers in this category came from Europe and it was interesting to see the advances made since Euromech 70 (Hunt & Moreau 1976) at which the early stirrings of metallurgical MHD were becoming apparent.

Stirring phenomena indeed are one of the main (and generally desirable) consequences of having electromagnetic forces in molten metals, and received attention in two papers, one experimental, one theoretical. *Moore* & Hunt (Cambridge) described an experimental study of the motions which occur in a coreless induction furnace. The laboratory simulation used a stainless-steel tank containing mercury stirred by a single-phase, 50 Hz winding. The recirculating flow pattern and turbulence were deduced from the drag on a small hollow sphere which had been perforated to eliminate vortex shedding and increase drag, a useful technique first developed by Rosenbrock & Tagg (1951) for atmospheric measurements. It was found that, in the furnace, the mean flow consisted of a double toroid with the axial velocity relatively uniform in the central core and a return flow concentrated near the wall, as anticipated by Hunt & Maxey (1980). The turbulence was vigorous and there were intense low-frequency swirl components, probably due to instability of the toroidal vortex. Crude turbulence models validated in pipe flow were clearly inappropriate in such circumstances.

Fautrelle (Institut de Mécanique de Grenoble) presented a theoretical study of the induction furnace problem in two cases: (i) an endless cylinder in a transverse magnetic field (see also Sneyd 1971, 1979) and (ii) a finite cylinder in an axial field. The motions were calculated by using $\mathbf{j} \times \mathbf{B}$ forces found by neglecting the motion. In case (i) solutions valid for high frequencies, were calculated and compared with numerical solutions. Case (ii) was studied numerically and discussed physically (see also Fautrelle 1981).

If mixing by stirring is one aim in metallurgy, at other times separation of undesirable ingredients is another. In two complementary papers *Vivès* & Ricou (Avignon) and *Marty*, Alemany (Institut de Mécanique de Grenoble), Ricou & Vivès (Avignon) studied MHD DC separation methods for particles of impurity in melts, both theoretically and experimentally. They examined the pressure and velocity fields near an impurity in a fluid subject to an otherwise irrotational $\mathbf{j} \times \mathbf{B}$ force field. The impurity usually perturbs the existing $\mathbf{j} \times \mathbf{B}$ forces so that they become rotational, causing local motions and forces on the particle which depend on its conductivity, shape and orientation relative to the field. A direct analogy with Archimedes' principle is only possible in special cases.

Another pair of related papers was presented by *Shercliff* (Cambridge) and Garnier & *Etay* (Institut de Mécanique de Grenoble), respectively theoretical and experimental. They concerned the use of vertical conductors bearing high frequency AC which produces magnetic pressure upon a falling liquid metal column so as to shape it as it solidifies, perhaps avoiding the wear or poor surface finish which occurs when moulds are used in continuous casting. Shercliff's two-dimensional theory, combining complex variable and numerical work, is more fully reported elsewhere (Shercliff 1981). A film of the Grenoble experiments, using mercury, with a skin depth about one fifth of the column diameter, clearly demonstrated the expected effects. The configuration was different from that now widely used for electromagnetic continuous casting of aluminium.

Garnier (Institut de Mécanique de Grenoble) described both theoretically and with the aid of a film electromagnetic devices for confining a stream of liquid metal away from its containing walls. Both high- and low-frequency techniques may be exploited (Garnier 1979) in subtly different ways.

The last paper concerned with liquid metal with a free surface, confined magnetically, was by *Mestel* (Cambridge) who developed the theory of axisymmetric magnetic levitation as used for melting reactive metals without contact with a crucible. In the limit of high surface tension, a perturbation analysis about a sphere enabled the shape and laminar flow to be calculated numerically, illustrating the asymptotic constancy of the potential vorticity for high Reynolds number. Numerical shapes were also presented for the case of very high frequency when the flow and surface shape do not interact.

The voice of practical industry was represented by *Block* (Institut für Eisenhuttenkunde, Aachen) who gave an account of important new techniques for determining the level in the mould in continuous casting of steel and the thickness of the solidified skin of the billet. The technique employs an electromagnetic field which penetrates the thick walls of the copper mould. The theoretical basis for the method was presented and supported by recent measurements. It appeared that the best application of MHD to the steel industry was in connection with instrumentation.

6. Concluding session

The Seminar closed with an unstructured but productive discussion. Despite concern about the future of certain kinds of MHD research in the face of the current economic climate, several forward-looking points were made. The tendency under funding pressures to neglect the kind of basic research which enables phenomena to be properly understood so that applied work can be done more effectively was noted and deplored. A good example is provided by the way in which ill-founded turbulence models are being freely applied to MHD flows in metallurgy while the development and validation of better models for the magnetically driven recirculating turbulent flows which occur in metallurgy are being neglected. Delegates from several countries noted some decline in the extent to which MHD was being formally taught to students despite its pedagogic virtues for inducing a good grasp of both fluid mechanics and electromagnetism simultaneously. Lundquist and Hide commended it particularly as a way of broadening the education of physicists. The modern engineering student seems to be too preoccupied with immediate applicability for his studies. If fusion technology builds up as expected, increased interest in MHD may result, although American opinion inclined to the view that *liquid* lithium was out of favour for blanket design.

MHD turbulence, particularly the two-dimensional kind, received much attention in this discussion, as it was felt that many problems remain unsolved, e.g. the exact way in which upstream field edge effects can generate the eddies which lead to two-dimensional turbulence downstream. The need for valid turbulence models was referred to repeatedly, e.g. in order that mixing of ingredients in metallurgy can be accurately predicted. Moreau, in response to a query from Klebanoff, was optimistic that magnetic fluctuations could now be measured so as to throw more light on MHD turbulence. It was clear that, in several areas, notably two-phase MHD, many more and better *internal* measurements would have to be made before proper understanding could be reached and it became possible to discriminate between rival models and theories.

Many speakers referred to the obscurities surrounding two-phase MHD, especially at high void fractions, whether involving bubbles of gas in MHD generators or solid impurities, to be removed or dispersed in metallurgical processes. It was pleasing to note that Lykoudis planned an extended research programme into the basic phenomena, including heat transfer aspects and boiling (when three phases may occur!). The changes in bubble size are more drastic than in ordinary two-phase flow because of magnetically induced pressure changes, as Branover pointed out. Petrick, Pierson and others remarked that interest in two-phase MHD was high because of the increasing activity on liquid metal MHD power systems.

Moreau usefully divided metallurgical MHD research into two categories: the development of better design guides for existing devices; and the testing and developing of ideas for wholly new devices and processes, not yet accepted in industrial contexts. However, magnetic continuous casting of aluminium had rapidly been adopted. Block reminded all that a better product was the aim, not just intriguing ideas! Mechanical devices were often preferable in the stringent environment of industrial metallurgy. He also remarked how the aluminium and steel industries differed greatly in the scope they offered for MHD applications, e.g. because hydrostatic heads were so much greater in steel.

The neglect of metallurgical MHD by the MHD fraternity in the USA in comparison with Europe was commented on by Ludford, who said that most American work had been done by metallurgists. In this connection the forthcoming (September 1982) IUTAM Symposium to be held in Cambridge, England, was greatly to be welcomed as a means of bringing the MHD and metallurgical communities together. As a contrast, Baker remarked on the very thoroughgoing liaison between academics and industrialists which prevailed in the well-established field of electromagnetic flow-measurement.

Finally the host and organizer, Herman Branover, brought to a close what was generally agreed to be the most interesting of the Beer-Sheva Seminars so far.

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