J. Fluid Mech. (1984), *vol.* 148, *pp.* 461–476
Printed in Great Britain

Magnetohydrodynamic Flows and Turbulence: a report on the Fourth Beer-Sheva Seminar

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(Received 1 May 1984)

This paper is a summary of the Fourth Beer-Sheva Seminar on Magnetohydrodynamic (MHD) Flows and Turbulence held in Israel during 27 February–2 March 1984 with 67 participants from 13 countries. Reviews and contributed papers were presented on laminar and turbulent single-phase and two-phase MHD flows, turbulent and two-phase flows without magnetic fields, and applications of MHD in power generation, in nuclear fission and fusion and in metallurgy.

1. Introduction

The Fourth Beer-Sheva Seminar represented the continuation of the Beer-Sheva Seminars held in 1975, 1978 and 1981 (Branover 1976; Branover & Yakhot 1980; Branover, Lykoudis & Yakhot 1983). The opening session of the seminar was almost entirely dedicated to the memory of Professor Arthur Shercliff who passed away on 6 December 1983. Arthur Shercliff participated in all the previous Beer-Sheva seminars and was one of the most active members of the organizing committee. W. J. Worraker presented a lecture on Professor Shercliff's life and accomplishments. Memorial trusts have been established at Cambridge and Warwick Universities to enable students to study abroad.

The number of papers presented at this seminar was greater than at previous seminars, so that for the first time it became necessary to introduce parallel sessions. This caused a great deal of dissatisfaction among the participants, especially those who attended the previous seminars, and concern was expressed that if this trend goes on the seminar may lose its special intimate atmosphere and emphasis on exchange of ideas rather than formal presentation of papers. Therefore it was suggested that parallel sessions be avoided at future Beer-Sheva seminars. The Third Seminar already manifested a much stronger accent on applied studies. At the Fourth Seminar this accent became even stronger, especially in relation to the areas of liquid-metal MHD power generation, where construction of semi-industrial pilot plants was reported, and of MHD methods in metallurgy. MHD applications in fusion reactors was treated extensively in several papers. In the area of more basic studies much attention was paid to different aspects of two-phase flows with and without magnetic fields and to further progress in experimental and numerical studies in MHD as well as in HD turbulence.

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 the discussions are also listed.

2. Laminar MHD flows

Walker (University of Illinois) reviewed recent analytical studies of three-dimensional laminar liquid-metal duct flows with strong transverse magnetic fields. There were three primary focuses for this review: (1) the matrix of different combinations of geometries, wall conductivities and types of magnetic fields (uniform and non-uniform); (2) the restrictions on the magnetic-field strength for each case and current efforts to relax these restrictions; and (3) a phenomenological classification of these flows to guide specific design calculations, such as a thermal–hydraulic analysis for a tokamak liquid-lithium blanket.

Walker and Petrykowski (University of Illinois) presented a Galerkin method to treat the boundary layers on the walls of rectangular ducts with non-uniform magnetic fields parallel to these walls. If the trial functions for the method incorporate the basic physics of these layers, then excellent results are achieved with very few trial functions, while each trial function provides some physical insights into the layer structure. A method of generating trial functions which closely resemble the results of the one analytical solution (Petrykowski & Walker 1984) was presented.

Mestel (Cambridge University) presented analytical results for the flow in a channel induction furnace in which a pipe loop is added to the bottom of the crucible, while a ferromagnetic ring passing through the pipe loop is excited by an a.c. induction coil. Initially ignoring the crucible and treating the pipe as a closed torus, and initially assuming axisymmetry, the magnetic field of this 'transformer' is determined analytically. Under certain assumptions, the primary flow is then calculated numerically. Finally the ignored effects are treated as perturbations of the primary flow and field.

Hall, *Ludford* (Cornell University) and Walker (University of Illinois) presented an analytical treatment of Hartmann layers in a solidifying cylinder of liquid metal with azimuthal electromagnetic stirring. The two important lengths are the thicknesses of the Hartmann layer and of the solidification front. Previous treatments implicitly assume that the solidification front is much thinner than the Hartmann layer, so that the flow can be treated as a Newtonian flow with a solid boundary. However, if the two thicknesses are comparable, then the effective viscosity increases as the fraction of solid increases through the layer. In this case, the shear rate which controls the breaking of dendrites is related to the characteristics of solidification rather than to the viscosity of the pure liquid.

Herve (Université Française de l'Océan Indien) and *Vives* (Centre Universitaire) presented analytical results for the laminar flows between rotating disks with an axial, uniform magnetic field. One disk is an insulator and the other is a conductor, while either disk may rotate or be stationary. Solutions with and without radial flow were presented. Velocities, pressures and torques were expressed as functions of the Hartman number.

Librescu (Tel-Aviv University) investigated MHD flow effects on space vehicles entering the atmosphere, in particular the flutter (instability) boundary. The linearized equations are used – nonlinear terms influence the character of the boundary but not the boundary itself – assuming infinite electrical conductivity and no Hall effect. Two cases were considered: aligned and crossed magnetic fields. The effects can be very important.

Worraker (Cambridge University) described the analysis and initial experimental results from a well-planned thermoelectric MHD experiment. The only significant thermoelectric term is the Seebeck effect, and Ohm's law becomes $\boldsymbol{J} = \sigma(\boldsymbol{E} + \boldsymbol{V} \times \boldsymbol{B} - S\nabla T)$, where S is the Seebeck coefficient. The Seebeck term can cause high-speed layers along the walls parallel to $\boldsymbol{B}$, and these layers do affect the heat transfer. The experiment consists of a copper cylindrical vessel filled with mercury in a vertical 1 T field. Heat can be supplied to the centre of the cylinder's bottom or to the top part of the sidewall, and in both cases the bottom part of the sidewall is cooled. For the first case solid-body rotation at a velocity on the order of 1 cm/s is expected for a temperature difference of 100 K, and no high-speed layers. For the second case a high-speed layer approximately 1 mm thick with a velocity of approximately $\frac{1}{2}$ m/s along the sidewall is expected. Experiments have begun on the first case, and the rotation observed.

Geffen (Tel-Aviv University) concluded that session by a general treatment of the MHD equations. She discussed the variational approach to the mathematical modelling of physical continua. She suggested that this approach could be exploited in MHD more than it currently is. Some examples from classical magnetogasdynamics were cited.

3. MHD and HD turbulence

In the area of turbulence special emphasis was given to the experimental as well as theoretical description of the transition from one mode of turbulence to another.

Sommeria (Institut de Mécanique de Grenoble) reviewed two MHD turbulence studies conducted at Grenoble. In the first one, carried out by Caperan and Alemany, a transition from a $k^{-\frac{3}{2}}$ law to a k^{-3} law was recorded for energy parallel to the magnetic field. The transition started at small eddies (owing to Joule dissipation of big ones) and propagated to bigger eddies with the flow. The flow characteristics were measured perpendicular to the magnetic field, and a Joule damping cone was observed. In a second experiment, conducted by Sommeria, the flow was generated by injecting an electric current by electrodes through the bottom of a closed box, in the presence of a vertical magnetic field. For 36 electrodes it was noticed that for small values of R_{h} (the ratio of the Hartman layer friction time to the turnover time) the flow is linear. For higher values of R_{h} random fluctuations take place till for a critical R_{h} all the energy is transferred to the largest-possible lengthscale – one global rotation is observed. These results agree with the inverse-cascade theory as well as with the numerical solutions of the one-dimensional vorticity equation obtained by Sommeria.

Brachet (CNRS, Observatoire de Nice) and *Sulem* (Tel-Aviv University) presented their numerical simulations of two-dimensional turbulence. The computations were carried out on a 1024×1024 mesh with some special symmetries in order to check the range of validity of some theoretical hypotheses. Indeed, for early times the energy spectrum displays a k^{-n} behaviour with $n = 4$, which is in agreement with Saffman's theory. Later on, there is a sharp transition to a $n = 3$ law inertial range, which is in agreement with the Batchelor–Kraichnan theory of enstrophy cascade.

Sukoriansky, Zilberman and Branover (Ben-Gurion University) presented results of hot-film investigations of turbulence intensity and spectra in a mercury flow with transverse magnetic field. This study was a continuation of the efforts already made at Ben-Gurion University for almost a decade (Branover & Gershon 1979) to separate entrance effects from phenomena characteristic of stabilized MHD turbulence. Honeycombs have been used to suppress effects related to flow entrance into magnetic fields. The channel was of a rectangular cross-section and Reynolds and Hartmann numbers were in the range $6\times10^4 \leqslant Re \leqslant 8\times10^4$ and $0 \leqslant Ha \leqslant 800$ respectively.

Sulem (Tel-Aviv University), *Sulem* (Ben-Gurion University) and Thual (Météorologie Nationale, Toulouse) presented their numerical simulation of three-dimensional convection in liquid metals. They investigated a layer of mercury heated from below. Convection appears for $Ra > 1807$. For higher Rayleigh numbers a three-dimensional instability is observed. For still-higher *Ra*, a modulation of the three-dimensional oscillations occurs. In the presence of a vertical magnetic field the appearance of the three-dimensional oscillations is postponed to a higher Rayleigh number while the modulation amplitude is reduced.

Papailiou (University of Patras) presented results of experimental and theoretical studies of the influence of a magnetic field on a turbulent vortex street created by a cylinder moving in mercury.

Dang and *Roy* (Office National d'Étude et de Recherches Aérospatiales) presented their numerical simulations of two different modes of turbulence. In the first one the mean velocity gradient was supplied by a strain and in the second one by rotation. In the first case, the reorientation of the turbulent flow tensors under two successive strains was investigated. As for the second case, the simulations indicated inhibition of the energy-transfer mechanism from 2-dimensional to 3-dimensional turbulence which exists in the case of zero rotation. Roy showed a ciné film which visualized the flow and emphasized the conclusions drawn from the simulations as well as the agreement with some experiments.

Naot (Center for Technological Education, Israel) presented investigations of the interaction of turbulent channel flow with the flow perimeter. He discussed three types of interactions: (*a*) interactions at free surfaces, which result in reflection of eddies thus enhancing secondary currents; (*b*) interactions with rough walls; and (*c*) influence of a gap in the channel wall, which induces large vortices near it owing to velocity parallel to the gap. The numerical results using the Patankar–Spalding algorithm agree qualitatively with experiments. Naot believes that this type of calculation can define more clearly the boundary conditions, thus making possible the use of simpler models for the inner parts of the flow.

Khait (Ben-Gurion University) reviewed recent developments in diffuse-gas discharges in turbulent flow for a wide range of pressures. His work offers interpretations to some observed phenomena, such as smoothing the discharge spatial and temporal characteristics and rapid gas-to-plasma transition. Rhait presented two ways to deal with the problem – a phenomenological one as well as a kinetic one based on non-equilibrium statistical physics.

Weil (Hebrew University) demonstrated the existence of homotopic invariants that are related to the 'linking number' of lines of constant magnetic-field direction. Whereas resistivity and viscosity destroy the physical invariants on a reconnection timescale, the homotopic invariants survive until the appearance of a null point, which is usually a much later event. An example of axisymmetric magnetic configuration with nested toroidal surfaces was given and named 'dag' owing to the similarity of the separatrix to a fish (*dag* in Hebrew). These dags give rise to more complicated geometries as well as to transition rules for turbulent flow.

4. Two-phase flow

In this seminar a special emphasis was given to two-phase flow. This fact reflects the recent advance in the development of two-phase liquid-metal MHD generators.

The two-phase flow sessions were opened by a film on two-phase flow regimes presented by *Hetsroni*. He also reviewed the studies dealing with the velocity of gas bubbles rising in liquids in vertical pipes. He indicated that, despite the fact that there are a number of serious papers dealing with this problem (Serizawa *et al.* 1975), both a satisfactory theory and reliable methods of calculation are still missing.

In his two papers *Lykoudis* (Purdue University) coined a new term ('turbubblence') and introduced a new non-dimensional number (which was not named the Lykoudis number only because of its discoverer's sheer modesty). The term turbubblence describes a new type of flow which is the combination of the single-phase turbulence with the effect of a second gaseous (bubbly) flow. Experiments to measure this kind of flow conducted by the Purdue group were the subject of Lykoudis' first presentation. The experiments were carried out in a long vertical cylinder in which mercury flows upward and nitrogen bubbles are released at the bottom. The cylinder is immersed in an external magnetic field.

In one set of experiments a honeycomb was used in order to avoid entrance effects. With the aid of hot-film anemometry, void-fraction profiles and constant-void-fraction curves were recorded. The effects of growing magnetic fields on the local void fraction were investigated. Explanations for the qualitative observed phenomena were presented.

In his second paper Lykoudis modelled a bubble immersed in a superheated liquid metal in a uniform magnetic field as a cylinder. After the equations governing the evolution of such a cylinder were non-dimensionalized, a new non-dimensional number emerged and was named the 'boiling magnetic interaction number'. Asymptotic solutions agreed qualitatively with results of a computer code obtained from Los Alamos National Laboratory. The experimental boiling curves obtained by the Purdue group were reexamined in light of the new theory, and the new number was able to correlate the data quite well.

Kamiyama (Tohoku University) developed an analytical model of bubbly two-phase flows where the slip ratio was taken into account as well as the change of the bubbles' radii along the flow. From the numerical solutions he concluded that isothermal approximation as well as the homogeneous model give a good description of two-phase flows with small void fractions, as well as small duct expansion. Furthermore, he concluded that the effect of the bubbles' expansion on the flow characteristics is rather pronounced. Lastly, he showed that the choking velocity was reduced with application of a magnetic field and increased with increasing the loading factor and decreasing the void fraction.

Kamiyama also bravely presented on short notice the work of Morioka, Toma and Matsui (Institute of Engineering Mechanics, University of Tsukuba, Japan). The authors investigated oscillations and instabilities in two-phase bubbly liquid metal MHD channel flow. For the case without external magnetic field they found six modes of growing waves. For a non-zero interaction parameter the growth rate tends to be reduced for moderate void fractions. On the other hand, for very large or very small void fraction the growth rate is increased with increasing interaction parameter. Morioka, Toma and Matsui conclude that two-phase turbulence could not be reduced by strong magnetic fields, as is the case for single-phase liquid-metal turbulence.

Mond and Sukoriansky (Ben-Gurion University) presented an analytic model of two-phase bubbly flow. The conservation equations were written for each phase, thus allowing for relative motion between the two phases. The drag coefficient, which plays an important role in determining the slip, was modified (with a single parameter) to account for the presence of other bubbles. The numerical solutions indicated that, by properly choosing only one parameter which controls the above modification, the experimental results at Ben-Gurion University as well as Smissaert's empirical laws were obtained.

Unger, Branover, Zuckerman (Ben-Gurion University) and Kiel (Technical University Twente) presented a survey of literature on pressure drop and phase-velocity-ratio correlation in two-phase liquid–gas vertical flows. The conclusion drawn from this survey is that there is insufficient information on the abovementioned flow characteristics for the design of two-phase liquid metal MHD power systems. Therefore an experimental facility was built for direct measurement of these characteristics. For gas to liquid velocity ratios preliminary experimental results show that the Smissaert (1963) correlation is valid also for higher superficial velocities than originally given.

Igra, Ben-Dor and Rakib (Ben-Gurion University) described their work on the influence of dust and water droplets on the relaxation zone behind a strong normal shock wave. For high Mach numbers ($M > 10$) the internal degrees of freedom of the gaseous phase have to be considered, and collision–radiative interactions take place among the gaseous components. On the other hand, viscous and heat transfer between the phases affect the post-shock equilibrium. Also the evaporation, dissociation and ionization of the water droplets may significantly affect the post-shock equilibrium. These processes, however, were assumed to occur on a much smaller timescale than the relaxation time and were given as initial conditions.

Christea, *Mihai* and Lemneau (Institute of Scientific Research and Engineering, Romania) presented their numerical solutions of natural-gas burning with application to MHD combustion chambers.

Levy and Timnat (Technion, Israel) described a method to measure simultaneously the size and velocity of the particulate phase of two-phase flows.

5. MHD power generation and application to fission and fusion reactors

For the first time at the Beer-sheva Seminars several papers dealt with the design and construction of complete liquid-metal MHD power systems on a semi-industrial scale.

Petrick (Argonne National Laboratory) and Branover (Ben-Gurion University) described the evolution of the liquid-metal MHD (LMMHD) energy-conversion concept. All LMMHD cycles must have two-phase (gas–liquid) flow someplace in the cycle. The first LMMHD cycle, the so-called separator cycle, was proposed by Elliott (1962) for space applications using caesium as the thermodynamic fluid and lithium as the liquid metal. Other LMMHD cycles quickly followed: the condensing injector, the drift tube, and the slug-flow cycles (see Petrick 1966). All of these cycle concepts had large losses, and thus low efficiencies. A careful study aimed at minimizing losses resulted in the two-phase-generator cycle of Amend *et al.* (1970), which was the first commercially attractive LMMHD cycle. Experiments by Fabris *et al.* (1979) have shown that good generator efficiency is attainable.

Now a new LMMHD cycle – the optimized MHD energy conversion or OMACON cycle – is being developed by Argonne National Laboratory and Ben-Gurion University. Here the two-phase flow occurs in a vertical riser leading to a gravity separator, and the pressure difference between the pure-liquid downcomer and the two-phase riser drives the liquid metal through the pure-liquid MHD generator. Initial performance results look very attractive. Like all of the LMMHD cycles, it can be operated over almost any temperature range by the proper choice of the working fluids and multiple stages can be used to improve performance. Small-scale prototypes are now under construction (see El-Boher, Branover and Petrick, below).

Thibault, Jousselin, Laborde and Alemany (Institut de Mécanique de Grenoble) described a tin–steam MHD system at the Institut de Mécanique de Grenoble. The system is designed to produce 10 kW electric power and will work at 573 K high temperature in the cycle. Water will be injected directly in preheated liquid tin and boiled through direct-contact heat exchange. The system has already been assembled, but, instead of the two-phase flow MHD channel, a vertical pipe is installed and flow tests have been started.

The paper presented by *El-Boher*, Branover (Ben-Gurion University) and Petrick (Argonne National Laboratory) described the ETGAR ('challenge' in Hebrew) liquid-metal MHD programme developed at Ben-Gurion University in cooperation with Argonne National Laboratory, which has been progressing for several years. At present this programme has reached the stage of construction of an 8 kW_e fully engineered pilot plant called ETGAR-3. There has been an iterative process of design, and from a number of versions a two-phase system with single-phase liquid-metal generator was chosen. The high temperature in the cycle will be 423 K.

In another paper from Ben-Gurion University by *Branover*, El-Boher, Lesin and Marcus another liquid-metal MHD system was described. This system, called ER-4, is able to produce 0.5 kW_e at the design point and is presently under operation. It works with mercury and steam at 438 K and its main purpose is to provide information on physical phenomena and component performance for the ETGAR programme of Ben-Gurion University.

Pierson (Purdue University Calumet), Jackson (HMJ Corporation), Berry, Petrick and Dennis (Argonne National Laboratory) first reviewed the previous performance and economic studies for the two-phase-generator LMMHD system operating on a Brayton or gas cycle, i.e. using helium as the gas and sodium or lithium as the liquid metal (Pierson & Herman 1983). The present program is a comparison of the same solar LMMHD cycle with a conventional (reference) steam cycle coupled to a sodium-cooled solar receiver. The first phase is to quantify the impact of the significant parameters – receiver temperature and pressure, generator inlet and exit void fractions – on the attainable cycle efficiency. Sodium was chosen because of the lack of suitable containment materials for high-temperature lithium. This put an upper limit of 920 K receiver exit temperature because of sodium-vapour carryover with the helium leaving the separator. The best performance is obtained if a gas turbine is used along with the MHD generator. The optimum top pressure is approximately 50 atm, because for lower pressures the liquid-metal flow rate and associated losses are large, while for higher pressures the liquid flow rate is small enough that the temperature changes become significant and decrease the efficiency. Peak thermal efficiencies close to 40 % were attained, and these are more competitive with the reference steam cycle.

Alemany, *Jousselin*, Laborde, Thibault (Institut de Mécanique de Grenoble) and Werkoff (Commissariat a L'Énergie Atomique, Grenoble) described a lithium–caesium LMMHD power system for space applications, specifically to power an orbital transfer vehicle. The specifications are a heat source of 1200–1400 K, a condenser temperature of 600–1000 K, a radiator surface area less than 90 m^2, an electrical power of 100–300 $\mathrm{kW_e}$, and a d.c. voltage of $\sim$ 1500 V. Two LMMHD cases were considered: two-phase and single-phase generators, the latter also with a self-excited a.c. induction generator. A computer code was developed to design the system. A maximum efficiency of $\sim$ 20 % was obtained with a converter weight of 2.5–5 $\mathrm{kg/kW_e}$ and a total mass of 10–14 $\mathrm{kg/kW_e}$ including the reactor, etc. Several questions were asked about the high efficiency and low specific weight compared with previous studies.

Preliminary assessment of the feasibility to apply liquid-metal MHD power systems to utilization of biomass was made by *Malcolm* (D. G. Malcolm and associates).

Merck (Eindhoven University of Technology) described results from the 5 MW thermal Eindhoven blowdown experiment. Up to 380 $\mathrm{kW_e}$ has been produced from a 5 kg/s argon–caesium flow in a 5 T magnetic field. Two significant problems have been observed, as in previous non-equilibrium plasma experiments: as the magnetic flux density is increased, a large pressure rise is observed in the downstream half of the generator: and the current flows primarily in streamer-like structures. The former appears to be caused by boundary-layer separation, and this is consistent with the results presented for the two-dimensional Patankar & Spalding (1970) method calculation of the turbulent MHD boundary layer. No adequate model exists to predict the behaviour of the streamers. Flinsenberg and *Uhlenbusch* (Eindhoven University of Technology) developed a streamer model based on experimental data. Streamers act like arc discharges exposed to the externally applied magnetic field and gas flow (see Uhlenbusch 1976). Typically the caesium (1–2 % of the total mass) is fully ionized in a streamer, where the temperature is 4000–5000 K, as contrasted with 2000 K in the bulk gas. The gas velocity is approximately 1000 m/s, and the streamer velocity is approximately 100 m/s slower. The experimentally measured streamer geometry and temperature profile are used to obtain an analytical solution. The flow-field calculation shows the existence of backflow in the streamer (due to the large $\boldsymbol{J} \times \boldsymbol{B}$ force), and the backflow region is larger than the current-flow region, increasing the flow-blocking area of the streamer. The streamers act like solid bodies for the main flow.

A few papers were devoted to MHD applications to fission and fusion reactors. In a review lecture, Picologlou, Reed, Nygren and *Roberts* (Argonne National Laboratory) described potential fusion reactors and the critical engineering issues of the first wall, the lithium blanket, and the tritium inventory. In 1983–1984 tremendous progress has been made on plasmas and the approach to breakeven, but not on blankets and first walls. For mirror reactors, access for the liquid-metal coolant is easy and $B \sim 4$ T. For the tokamak, access is harder, especially to the inner blanket area, $B \sim$ 6–8 T, and the geometry is much harder to analyse. The pumping powers are manageable, but the pressures are too high for easy containment (thicker walls mean still higher pressures and pumping powers). One scheme to decrease the pressure difference was shown, but the structure may be too complex to be practical. There are no experiments in the range of interaction and Hartman numbers of interest for fusion, i.e. 10^4–10^5. An experimental programme aimed at values $> 10^3$ and including local velocity measurements was described. The experiment will include bends, gradients, etc., and not just straight, fully developed flows. Another serious problem is the tremendous pressure that would result from a disturbance in $\boldsymbol{B}$ because of induction effects. In response to a question from Branover, the pressure difference is $\sim$ 3 MPa and the pumping power is $\sim$ 5–10 % of the total plant output power.

The Westinghouse programme of developing direct-current electromagnetic pumps and flow couplers for nuclear power stations also includes studies of optimal design of a d.c. MHD duct. These studies have been reflected in a paper by McNab, Alexion and Keeton presented by *Nathenson*. The difficult problem of designing a sealed channel with insulating sidewalls and high-conductivity electrodes is sometimes solved by use of very thin sidewalls, having relatively high electrical resistance, welded directly to the electrodes. The question then is: how much do the shunting currents reduce the efficiency of such a channel? The authors tested a thin-conducting-wall channel and compared the results with tests of a channel with insulating walls. The difference in efficiency was about 3–5 %.

Alexion, Keeton, McNab and *Nathenson* (Westinghouse Research and Development Center) presented experimental results for a flow coupler, as previously described by Thatcher (1978). A flow coupler consists of an MHD generator in one flow loop driving an electromagnetic pump in another flow loop, with the generator and pump connected electrically in series and located in a single magnet. To maximize efficiency it is important to minimize the wall conductivity, provide good electrical connections, and optimize the fringing $\boldsymbol{B}$ to minimize end losses. The experimental generator and pump are each 2 in. by $2\frac{1}{4}$ in. by $9\frac{1}{4}$ in. long with a flow capacity of 250 g/min of NaK. The measured performance gave extremely good agreement with theory, and the peak efficiency was approximately 60 %. For an LMFBR (liquid-metal-cooled fast-breeder reactor) the flow coupler promises improved reactor design and high reliability and maintainability.

Garnier and Werkoff (Institute de Recherches Technologiques de Développement Industriel) discussed MHD effects in the liquid-metal fast-breeder reactor (LMFBR). The magnetic Reynolds numbers R_{m} for the sodium flows in the LMFBR are quite large because of the large pipe size and the relatively fast flow, and this is extremely rare in an engineering liquid-metal flow. Small magnetic fields may be present for a number of reasons. For example, the thermoelectric properties of sodium and stainless steel will lead to electric-current circuits and magnetic fields, or a field may be present for an electromagnetic flowmeter. With very large R_{m} this small field can be magnified by a very large factor, perhaps a thousand, by the dynamo effect; even self-excitation is possible. Future experiments on the Phenix were detailed. The dynamo effect will be even greater for the larger Super Phenix. Analytical results for magnetic-field amplification in a converging duct were presented.

6. Metallurgical applications

As in the previous Beer Sheva seminars a great number of papers dealt with MHD phenomena related to stirring of liquid metals, shaping of liquid-metal jets, melting and crystallization, etc.

Garnier (Institut de Mécanique de Grenoble) reviewed the application of MHD or electromagnetics (EM) to metallurgical processes. EM stirrers have the advantage of producing better-quality metals – reduced slag and inclusion densities. The physical and mathematical approaches to determining a good stirrer were described. The physical approach uses, for example, the extent of sulphur prints, which are defects. Problems to be solved include: (1) determining magnetic fields, powerful techniques are available to 50 Hz, but for higher frequencies there are problems; (2) modelling flows, especially with turbulence and a.c. magnetic fields; (3) understanding thermal phenomena, and their influence on property variations and solidification; and (4) understanding transfer phenomena, especially the influence of turbulence on coalescence and solidification. Two potential new applications of MHD were described.

The first, continuous casting of hollow ingots, can use EM forces to get slag away from both walls, which is not possible by conventional methods. The second is EM shaping of metal jets into flat ribbons which can be rapidly cooled to produce amorphous alloys. In conclusion, Garnier stated that energy use is a problem for the metals industry, and MHD or EM can help to improve existing techniques or develop new techniques. In answer to a question on present MHD applications, Garnier said that in four to five years all continuous casters will have EM stirrers. Block said there are now more than 150.

Bertram and Zanner (Sandia National Laboratories) examined the vacuum arc remelting process, because the desired good alloy properties are not always obtained. It is necessary to understand the flow in the liquid pool, in particular the balance between Lorentz and buoyancy forces and the coupling of the flow with the formation of the dendritic mesh (see Bertram and Zanner 1984). High-speed ciné film of the process showed multiple arc spots ($\leqslant 100$ A/spot, ~ 5 kA total), and how the spots start at the centre of the ingot, move to the edge, climb the sides of the ingot, and are extinguished. Based on this, two distinct models were developed: (1) a smooth current path model; and (2) an arc with coherent cathode-spot motion. Both models yield separate MHD and thermal-gradient flow cells, with a large slow-flow region in the centre. The latter corresponds to a chaotic region of solidification in the ingot. The thermal cells slow the solidification process, which is not good, and they are below the MHD cells, so that MHD mixing does not help.

Moros, Hunt (Cambridge University) and Lillicrap (Electricity Council Research Centre) explained the channel induction furnace, when a small electromagnetic device heats a large volume. The electromagnetic section is a transformer, with the channel forming a single-turn short-circuited secondary. Understanding is important to avoid excessively high temperatures in the channel and to obtain a rapid energy transfer to the main volume. The authors split the problem into two idealized models and companion experiments: the first focused on the channel alone, the second on the channel and throat regions. The first experiment, designed to eliminate bulk flow, is complete, but no measurements are available. The velocity will be measured with the drag probe developed by Moore & Hunt (1984). The finite-element analysis shows two (probably) recirculating flows starting from the corners.

Gagnoud and Delage (Institut de Mécanique de Grenoble) modelled a cold crucible and compared the results with experiments. The actual crucible has 16 water-cooled copper sectors, but the analysis used one sector with one very narrow split. Two models were developed: one with horizontal closure of the induced currents, and one with a potential difference between sectors (across the split). The former agreed well with the 16-sector crucible; the latter fitted the one-sector crucible. As the number of sectors increases, the induced currents tend to be horizontal and the potential difference between sectors becomes zero. The one-sector crucible is better for levitation because of the favourable magnetic-field gradients. The models cannot describe the magnetic field near the crucible walls because of the influence of the split.

Braun (Studsvik Energiteknik) described the approach used by his company to apply their MHD expertise to practical problems. The steel industry needed to measure liquid levels independently of the vessel lining. A two-coil (transmitter and receiver) technique was developed to determine the level and also to detect the approach of slag. In addition, a two-coil electromagnetic generator and detector of surface waves was developed for crack detection.

Brancher (O. Sero Guillaume) and de Framond (Institut de Mécanique de Grenoble) (presented by *Garnier*) investigated shaping of a free jet by high-frequency currents in coils located at the corners of a square. The magnetic Reynolds number and skin depth were both assumed to be negligible, and gravity was not considered (two-dimensional solution). The method used was to minimize the energy, controlled by the ratios of the surface-tension energy to the magnetic energy, and the length of one side of the square to the radius of the undeformed jet. The problem was solved with conformal mapping combined with the method of images to resolve the transformed field. Good agreement was obtained with experiments, with one problem – the coil cross-sections are not negligible and the induced currents affect the inducing current locations, so that the equivalent current locations are unknown. Stability analysis showed the jet to be stable even if it is not inside the conductor square. A question elicited that this is static stability only.

Meyer, Ernst and *Durand* (Institut de Mécanique de Grenoble) described analysis and experiments aimed at understanding the effect of motion on the solidification process. An aluminium alloy containing 2 % copper was used in a rectangular mould with one vertical side cooled. A linear motor winding on the cooled side circulated the metal. For this geometry the effect of convection on $\boldsymbol{B}$ was negligible ($R_m \ll 1$), and $\boldsymbol{B}$ was calculated first using a two-dimensional approximation. The measured field agreed well with the theory with and without the metal, and the aluminium reduced $\boldsymbol{B}$ only slightly because of the low frequency. The calculated velocity field gave a good general representation of the measured velocities with the correct value and location of the maximum. Similar agreement was obtained for the temperature profiles. The net calculated result was that the metal cooled to the solidification temperature much faster and more uniformly with stirring, but solidification took longer to start.

Ricou and Vives (Centre Universitaire) studied the effect of an electromagnetic shield on the electromagnetic-stirring process in the continuous casting of ingots with the goal of improving the ingot surface. The field is produced by a one-turn coil. The local velocity, current density, and $\boldsymbol{B}$ were measured. Without a shield the metal flows in a single loop, and the resulting ingot surface is not as flat as desired, and contains folds and pinholes. The impact of the shield, a solid water-cooled metal ring, is to change the orientation and magnitude of $\boldsymbol{B}$ as seen by the liquid metal. As the shield is moved toward the coil, the velocity decreases and with further insertion the eventual result is two velocity loops. In answer to a question, Ricou stated that with the shield braking the flow the surface is better.

Taberlet and Fautrelle (Institut de Mécanique de Grenoble) presented experimental and numerical results for the turbulent flow in an induction furnace for electric-current frequencies from 50 to 5000 Hz. At the lower frequencies, electromagnetic effects are distributed throughout the crucible, but, at higher frequencies, the magnetic field from the solenoid can only penetrate a small distance, namely the skin depth, into the metal, so that the Joule heating and the electromagnetic body force are confined to a thin region near the crucible wall. Previous experimental studies have dealt primarily with the lower frequencies. As the frequency increases, the body force increases, but its domain decreases, so that there is some intermediate frequency for maximum stirring. The experimental result for this optimal frequency agrees well with previous theoretical work (Barbier *et al.* 1982).

Block and Julius (Institut für Eisenhüttenkunde der RWTH, Aachen) presented analytical results for the effects of the finite widths of inductors used to stir liquid metals in continuous castings. Previous treatments assumed infinitely wide inductors, while actual stirrers have narrow inductors. There is a need for much more analytical sophistication with liquid metals than with solid stators, because spatially variable forces that integrate to zero produce no net force on a solid, but do produce significant stirring in a liquid metal. The primary magnetic fields resulting from currents in the inductor windings including end turns are described by current sheets, while the electrical fields and electromagnetic body forces are deduced from higher vector potentials.

7. Concluding session

The seminar ended with a discussion under the title: 'Questions to ponder for the next three years.' Five panellists, representing different areas of interest, opened the discussion.

The most classical and traditionally theoretical area of MHD research, flow in pipes and ducts under complete or partial inertialess conditions, was surveyed by *Walker* (University of Illinois). Despite some views expressed at the previous Beer-Sheva Seminar that there is little hope for the use of lithium blankets in fusion reactors, it was demonstrated by Picologlou, Reed, Nygren and Roberts at the present seminar that lithium blankets are viewed now as very promising, and therefore studies of pipe flows in strong magnetic fields are getting a new and strong momentum.

The unique feature of these flows is that the interaction parameter is extremely large, namely 10^4–10^6. This means that the electromagnetic effects are ten thousand to one million times larger than the hydrodynamic effects. To treat these flows correctly we must stop thinking as hydrodynamicists and must start thinking as electrical engineers. The most important variables are the magnetic field, electric field and the electric-current density. The flow does what the electromagnetic variables tell it to do. Once we have a complete voltage map we can infer flows, pressure drops, heat transfers, etc., but, if we measure pressures, we can infer very little. This is actually an advantage, since it is easier to measure voltages than velocities in a liquid-metal flow.

For very strong magnetic fields, we find a role reversal in the governing equations. In MHD we think that the momentum equation determines the velocity and that Ohm's law determines the electric current. For fusion blankets there is no velocity in the momentum equation, which instead determines the electric current needed to produce the electromagnetic body force to balance the pressure gradient. Similarly, Ohm's law determines the velocity needed to produce the induced field to balance the electric field. Any numerical approach which uses the momentum equation to solve for velocity and Ohm's law to solve for electric current will fail at sufficiently large interaction parameters, and is therefore inappropriate for fusion-reactor liquid-lithium blankets.

Garnier (Institute Recherche Technologique et de Développement Industriel) pointed out a number of crucial and interesting areas of future studies related to metallurgical applications of MHD, some of them also including problems of turbulence. He discussed in particular turbulence in thin layers in metallurgical and casting devices influenced by pulsating magnetic fields when the skin effect is strong. A variety of important questions are connected with another phenomenon – solidification of liquid metals in the presence of magnetic fields. Transport properties in the liquid near solidification regions are of especial interest together with some specific chemical problems. Different kinds of instabilities appearing at solidification conditions have also been mentioned.

Problems of two-phase flow were discussed by Hetsroni (Technion, Israel). He said that future efforts in this area would most likely be focused in three areas: (1) theory of immiscible mixtures (Bedford and Drumheller), where there is considerable uncertainty on how to specify the balance equations for each constituent of the mixture – either by postulating or by various averaging techniques – and there is more uncertainty on the formulation of the constitutive relations and what simplifications can be used; (2) separate-effects experiments in order to guide theoreticians and to provide verification of complex computer codes; and (3) numerical computations of multiphase systems – in this area the question to be resolved is whether the current computer codes converge to a correct solution or whether the numerical diffusion dominates.

Lykoudis (Purdue University) spoke mainly about turbulence in single- and two-phase flows with and without magnetic fields. He complained that because of funding problems most of the work done in this area is related to specific applications and very little is done regarding the fundamentals. He also pointed out that, as reflected in papers given at the present seminar, nothing important was done in development of new experimental methods for studying turbulence and two-phase flows. Regarding the recently developed big codes for numerical simulation of turbulence, it was suggested that in many cases these 'monstrous' codes contribute very little to understanding of the phenomena, and therefore simple experiments, and in some cases more old-fashioned semi-empirical theories, would be preferable.

Lykoudis addressed also the area of fusion-blanket research. He believes that the first priority ought to be given to simple overall heat-transfer experiments in geometries of interest to the designers but that, eventually, in order to understand the nature of flow at high interaction parameters, local measurements will be needed. The only medium for which such experiments are possible is mercury. Unfortunately, because of mercury's high density and low conductivity, large electromagnets are necessary both in geometry (especially of large gap) and magnetic-field intensity. He did disagree with John Walker that mapping of electric voltage for such flows is adequate to get an insight into such flows.

Pierson (Purdue, Calumet) pointed out that with time the seminar has shifted from theoretical to application orientation, and this is an indication of success for MHD. For high-interaction MHD flows, the interesting question is whether analytical or numerical techniques will yield the best future progress. The first high-interaction experimental data is eagerly awaited. For LMMHD power systems, the first experimental data from a complete power system, ETGAR 3, is expected shortly and will significantly affect the future of LMMHD. The introduction of the new OMACON concept reminds the participants that new and more attractive ideas may yet be developed. Also of interest is understanding the two-phase flow in an MHD generator, and why the gas–liquid velocity difference approaches zero for large interactions. In another area, the French LMFBR experiment on self-excitation should help establish the significance of this potential problem.

In the discussion that followed, Braun stated that to sell MHD it is necessary to have the proper interface, to pinpoint the problem to be solved, to explain things in terms industry understands and needs, and to avoid mentioning MHD or turbulence. Bertram said that there will be opportunities to solve interesting MHD problems while helping industry, but do not sell MHD to obtain support.

Branover (Ben-Gurion University), who chaired the panel session, briefly summarized the panellists' presentations, concentrating mainly on power generation and metallurgical applications and also calling for more effort for understanding the still obscure transfer processes in turbulence influenced by magnetic fields. He also reminded us that at the Third Beer-Sheva Seminar views were expressed that teaching MHD to undergraduates and graduate students presents a unique opportunity for development of broad and advanced engineering and scientific perception. There are still very few places where such courses are taught.

Braun, Block and a number of other participants took part in the discussion, addressing mainly applicative questions.

A unanimous desire to hold the next Beer-Sheva Seminar in early spring of 1987 was expressed.

REFERENCES

(Talks given at the Seminar are indicated by an asterisk)

ALEMANY, A., JOUSSELLIN, F., LABORDE, J. P., THIBAULT, F. & WERKOFF, F.* Investigation of a lithium–caesium Faraday converter for space applications.

ALEXION, C. C., KEETON, A. R., MCNAB, I. R. & NATHENSON, R. D.* Demonstration of a flow coupler.

AMEND, W. E., HSU, C., PETRICK, M. & ROBERTS, J. J. 1970 In *Proc. 11th Symp. on Engineering Apects of MHD, California Institute of Technology, Pasadena*, p. 154.

BARBIER, J. N., FAUTRELLE, Y. R., EVANS, J. W. & CREMER, P. 1982 *J. Méc. Theor. Appl.* **1** (3).

BEDFORD, A. & DRUMHELLER, D. S. 1983 *Intl J. Engng Sci.* **21**, 863.

BERTRAM, A. & ZANNER, F. J. 1984 In *Metallurgical Applications of MHD: Proceedings of an IUTAM Symposium* (ed. M. R. E. Proctor). The Metals Society.

BERTRAM, L. A. & ZANNER, F. J.* Current paths and magnetohydrodynamics in vacuum arc remelting.

BLOCK, F. R. & JULIUS, E.* Electromagnetic force of narrow stirring inductors.

BRACHET, M. E. & SULEM, P. L.* Direct numerical simulation of two-dimensional turbulence.

BRANCHER, J. P. & DE FRAMOND, R.* Shaping of liquid-metal cylinders.

BRANOVER, H. (ed.) 1976 *MHD-Flows and Turbulence: Proceedings of the Bat-Sheva International Seminar*. Wiley.

BRANOVER, H., EL-BOHER, A., LESSIN, S. & MARCUS, B.* Tests of ER-4 mercury–steam power generation research facility.

BRANOVER, H. & GERSHON, P. 1979 *J. Fluid Mech.* **94**, 629.

BRANOVER, H., LYKOUDIS, P. & YAKHOT, A. (ed.) 1983 *Liquid-Metal Flows and Magnetohydrodynamics: Progress in Astronautics and Aeronautics*, vol. 84. AIAA.

BRANOVER, H. & YAKHOT, A. (ed.) 1980 *MHD-Flows and Turbulence: Proceedings of the Second Bat-Sheva Seminar*. Israel Universities Press.

CAPERAN, P. & ALEMANY, A.* Transition from three-dimensional to two-dimensional grid turbulence.

CRISTEA, E. D., MIHAI, D. & LEMNEAN, N.* Modelling of flow patterns – use of computer modelling of natural-gas burning with application to MHD combustion chambers.

DANG, K. & ROY, P.* Numerical simulation of homogeneous turbulence submitted to two successive plane strains and rotation.

EL-BOHER, A., BRANOVER, H. & PETRICK, M.* The Etgar liquid-metal MHD project.

ELLIOT, D. G. 1962 *ARS J.* **32**, 924.

FABRIS, G., PIERSON, E. S., POLLACK, I., DANZVARDIS, P. F. & ELLIS, W. 1979 In *Proc. 18th Symp. on Engng Aspects of MHD, Butte, Montana*, p. D-2.2.1.

FLINSBERG, H. J. & ULENBUSCH, J.* Streamer dynamics in MHD generators.

GAGNOUD, A. & DELAGE, D.* Electromagnetic modellization of cold crucibles.

GARNIER, J. & WERKOFF, F.* MHD effects in liquid-metal fast-breeder reactors.

GEFFEN, N.* Magnetohydrodynamics – A theme with variations.

HALL, F. S., LUDFORD, G. S. S. & WALKER, J. S.* Hartman layers in solidifying liquids.

HERVE, P. & VIVES, C.* Applications of magnetohydrodynamic flow between rotating disks.

HETSRONI, G.* Bubbly rise velocity – A review of recent literature.

Hetsroni, G.* Two-phase flow regimes.

Igra, O., Ben-Dor, G. & Rakib, Z.* The effect of dust and water droplets on the relaxation zone developed behind strong normal shock waves.

Kamiyama, S.* Analysis of two-phase MHD flow in converging–diverging ducts.

Khait, Yu. L.* Electrogasdynamic and kinetic phenomena in diffuse electric discharges in turbulent gas flows.

Levy, Y. & Timnat, Y.* Two-phase flow measurements using a modified laser-Doppler anemometry system.

Librescu, L.* Unsteady magnetohydrodynamic supersonic flows past oscillating thin bodies and lifting surfaces.

Lykoudis, P.* Cocurrent upward two-phase flow of liquid mercury and nitrogen in the presence of a horizontal magnetic field.

Lykoudis, P.* Magneto-fluid-mechanic bubble growth in the presence of a uniform magnetic field.

McNab, I. R., Alexion, C. C. & Keeton, A. R.* Experiments on a large thin-wall duct.

Merck, W. F. H.* Interaction of wall currents and turbulent boundary layers in closed-cycle MHD experiments.

Messerle, H. K.* Disk generator flow studies.

Mestel, A. J.* On the flow in a channel induction furnace.

Meyer, J. L., Ernst, R. & Durand, F.* Stirring an aluminium ingot mould with a linear motor; electromagnetic, hydrodynamic and thermal effects.

Mond, M. & Sukoriansky, S.* Simple analytical models of two-phase bubbly flows.

Moore, D. J. & Hunt, J. C. R. 1984 In *Metallurgical Applications of MHD: Proceedings of an IUTAM Symposium* (ed. M. R. E. Proctor). The Metals Society.

Morioka, S.* Instabilities in two-phase liquid metal MHD channel flow.

Moros, T., Hunt, J. C. R. & Lillicrap, D. C.* Study of the electromagnetic features in channel induction furnaces.

Naot, D.* Hydrodynamic response of turbulent flow to the interactions of the eddies at the channel perimeter.

Papailiou, D. D.* Magneto-fluid-mechanic laminar and turbulent vortex streets.

Patankar, S. V. & Spalding, E. B. 1970 *Heat and Mass Transfer in Boundary Layers: A General Calculation Procedure.* Intertext.

Petrick, M. 1966 *IEEE Spectrum* **2**, 137.

Petrick, M. & Branover, H.* Liquid-metal MHD energy conversion – evolution and status.

Petrykowski, J. C. & Walker, J. S. 1984 *J. Fluid Mech.* **139**, 309.

Picologlou, B., Reed, C., Nygren, R. & Roberts, J.* Magneto-fluid-dynamic issues for fusion first wall and blanket systems.

Pierson, E. S. & Herman, H. 1983 In Branover, Lykoudis & Yakhot (1983).

Pierson, E. S., Jackson, W. D., Berry, G., Petrick, M. & Dennis, C.* High-temperature liquid-metal MHD solar thermal systems.

Ricou, R. & Vives, C.* Shield effects in continuous electromagnetic casting.

Serizawa, *et al.* 1975 *Intl J. Multiphase Flow* **2**, 235.

Sommeria, J.* Two-dimensional behaviour of electrically driven flows at high Hartman numbers.

Sukoriansky, S., Zilberman, I. & Branover, H.* Spectra and r.m.s. studies in turbulent MHD channel flow.

Sulem, P. L., Sulem, C. & Thual, O.* Direct numerical simulation of three-dimensional convection in liquid metals.

Taberlet, E. & Fautrelle, Y. R.* Investigation of the turbulent flow in an induction furnace supplied with various frequencies.

Thibault, J. P., Jousselin, F., Laborde, R. & Alemany, A.* Tin–water Faraday generator.

Ulenbusch, J. 1976 *Physica* **82C**, 61.

Unger, Y., Zuckerman, B., Branover, H. & Kiel, J. H. A.* Two-phase liquid-metal–gas flows with medium and high void fractions.

WALKER, J. S.* Laminar duct flows in strong magnetic fields.

WALKER, J. S. & PETRYKOWSKI, J. C.* Approximation side-layer solutions for a liquid-metal flow in a rectangular duct with a strong non-uniform magnetic field.

WEIL, D.* Homotopic structural invariants in HD and MHD turbulence.

WORRAKER, W. J.* Experiments in thermoelectric MHD.