2nd Symposium on the Engineering Aspects of

MAGNETOHYDRODYNAMICS

a conference report by ***G. W. Sutton*** *and* ***Per Gloersen***

DURING the past few years, plasma physics and magnetohydrodynamics have been the topics of many scientific meetings. In these meetings, the emphasis was placed mostly on the physical principles and scientific accomplishment with little discussion of the potential applications. For this reason, the Basic Sciences Committee of the American Institute of Electrical Engineers organized a meeting on the engineering aspects of magnetohydrodynamics last year with sessions on several different subjects. These helped to give to the audience a variegated view of the potential applications of MHD and the progress which is being made in each field. Last year's meeting attracted an audience of about four hundred.

Sufficient progress was subsequently reported in the areas of plasma propulsion, MHD power generation, and thermonuclear fusion to persuade the organizing committee that a second meeting was warranted. This was held on March 9 and 10, 1961, at the Museum of the University of Pennsylvania under the general chairmanship of Clifford Mannal (GE). The attendance was again about 400.

In contrast to the first symposium, there was ample time for presentation and discussion. The discussion periods were well utilized for comments and rebuttals. Each of the four sessions (on Flight Applications, Power Conversion, Communications and Diagnostics, and Fusion) included a number of invited papers followed by contributed papers as well as several papers which were read by title only. The last category was an innovation for this year's session.

Once again, the sessions were held in the auditorium of the University Museum, which specializes in archeology, thus providing an interesting contrast between old and new technologies. The luncheons were served on the second floor in a large exhibition hall. These were pleasant enough, but revelry was somewhat thwarted by the austere stares from the mummy cases and the sceptical expressions of certain of the statues.

FLIGHT Applications, the first session, was under the chairmanship of G. S. Janes (AVCO) and was concerned with papers dealing either directly with plasma propulsion engines or related devices from which fundamental data were desired. Also discussed were the properties of plasmas with and without a magnetic field, created either in the sheath of re-entry vehicles or by some suitable arrangements simulating re-entry conditions.

A review of various proposed MHD applications to re-entry flight, with comments as to their practicality, was contained in the first invited paper in this session, given by R. X. Meyer (Aerospace). At this point in time, Meyer reached conclusions similar to those of others in the past: to wit, that the outlook was not promising for the reduction of heat transfer from the flow field to the vehicle by means of appropriate magnetic fields. At the other extreme was the prediction that magnetic fields might permit communication through the presently impenetrable re-entry plasma sheath.

W. E. Powers (AVCO) then listed very briefly some advantages of using propulsion devices with high specific impulse (greater than 1500 seconds). He mentioned that a number of MHD propulsion devices might fulfill this requirement and discussed a particular device which could conceivably convert electrical energy into azimuthal motion of plasma constituents. This was presumed to be convertible into axial motion in an appropriate nozzle. Finally, he discussed the distribution of electrical energy applied to a radial arc between coaxial electrodes in an axial magnetic field, neglecting for the time being the problem of converting what little rotational energy was experimentally observed in this particular arrangement into axial thrust. Essentially, the experiment consisted of measuring power input to the arc and power loss to the electrode, assuming that the difference is deposited in recoverable thermal and rotational plasma energies. The device under test appeared to be a quasi-electrothermal accelerator in which any energy not deposited thermally in the plasma or the electrodes is expended in creating a non-equilibrium degree of ionization and excitation in the plasma. Nonetheless the assumption was made that rotational motion eventually could be achieved (presumably after a 100% degree of ionization has been reached), as observed by Alfvén. This provided a basis for some speculative calculations indicating how such an hypothetical arrangement might perform in the high-specific-impulse range. Based on the experimental observation that heat loss to the electrodes is less at a given power level for lithium-contaminated plasma than for a pure helium plasma, it was deduced that lithium

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G. S. Janes, chairman of first session, introduces papers on flight applications.

might be a better propellant for these purposes than helium.

S. T. Demetriades (Norair) gave the first of the contributed papers, describing the operation of an ExB channel placed across the exhaust of a plasma jet. He obtained as much as a two-fold increase in thrust at an efficiency around 40%. No direct measurements of the exhaust velocity were made. An experimental curiosity was the oscillations observed in the continuous thrust records, in synchronism with the pulsations created by the mechanical pump. The pump maintained the testing tank pressure at an average of 2 mm. Perhaps this is an ominous indication that these measurements would have little relation to those obtained at the considerably lower densities encountered in outer space, i.e., at considerably lower testing-tank pressures.

Some preliminary experiments on a segmented-electrode ExB accelerator with a plasma jet input were described by A. F. Carter (NASA-Langley). No conclusions were drawn from the early results other than that they did not agree with the theoretical predictions. J. Pearson (Republic) described the construction and preliminary test results of a prototype repetitively pulsed plasma rocket, and J. A. Fay (MIT) spoke of measurements of heat transfer to current-carrying electrodes immersed in plasma produced by detonation waves. The latter propagated in an acetylene-oxygen mixture seeded with potassium from a deposit of potassium acetylide on the shock-tube walls. Fay concluded that the change in heat transfer was equal to the product of the current, and combined plasma sheath potential and work function.

THE session on Power Conversion, with G. W. Sutton presiding, was devoted entirely to MHD generators, which use Faraday induction in plasmas at temperatures between 3000°K and 5000°K. Although last year's session contained mostly theoretical papers, this year most of the papers reported experimental results.

B. C. Lindley (Parsons, England) summarized the MHD power research in England. For example, in shock-tube experiments, Pain and Smy have generated 300 kw for a few microseconds. Lindley believes that MHD power generation is most suitable with a helium-cooled nuclear reactor since the higher temperatures which are required to increase the over-all thermal efficiency prohibit the use of turbines. To demonstrate such a unit, Parsons is constructing a helium-cesium closed loop, using electric-resistance heaters as the thermal source. The generator will operate at greater than Mach 2 at pressures lower than atmospheric. Since most of the work in this country is on subsonic open-cycle generators using combustion gases, Lindley's experiment will be an important contribution.

Next, C. DuP. Donaldson (Aeronautical Research Associates of Princeton) presented a theoretical discussion of vortex generators. To reduce the over-all size and weight of the generator, Donaldson suggested wrapping the flow into a spiral, which then results in a vortex. To calculate the efficiency, one must know the turbulent shear stress. Donaldson is analyzing plasma turbulence in a magnetic field. The analysis is not yet completed, but his approach appears extremely promising.

The last invited paper was by V. H. Blackman (MHD Research). In cooperation with Allis-Chalmers, Blackman has constructed a combustion-driven MHD generator ($1 \times 4 \times 16$ inches) with a magnetic field of 22 000 gauss. Several kilowatts of power have been generated for several minutes. He also found that MgO wall material had the lowest electrical losses of all materials tested at these temperatures. In addition, Blackman reported high-frequency noise, amounting to 20% of the signal. Although several explanations were advanced, it appears that this noise will have to be eliminated in a practical device.

T. Brogan (AVCO) presented a description of the Mark II experimental MHD generator. Combustion products of either alcohol or kerosene and oxygen are used in a wooden channel $3 \times 9 \times 60$ inches with segmented electrodes. With a magnetic field of 32 kilogauss, 100 kilowatts have been generated for 10 seconds. The distribution of the power generation was not uniform along the channel. Hall effects are important. Concerning future applications, Brogan believes that oxygen enrichment of the air used in combustion is necessary to achieve sufficiently high gas temperatures. Economy calculations show that 20% increase in over-all thermal efficiency is achievable, but at the expense of a 10% increase in total plant cost. The result is a 4% increase in power cost at the generating station. This should not necessarily be discouraging because it is difficult to estimate accurately the plant cost at this point.

G. J. Mullaney and E. A. Luebke (GE) reported on electrical conductivity and economy studies. In his experiments with conduction in seeded combustion gases, Mullaney has measured an effective scattering cross section of 10^{-15} cm^2, which is somewhat smaller than expected. The electron elastic-scattering cross sections of potassium and cesium were found to be very much smaller than the published values. In addition, the cathode and anode voltage drops were found to be zero. This is in contrast to the AVCO measurements which indicate electrode voltage drops of 60–80 volts at currents of 2 amperes.

One of the central problems of MHD power generation is the fact that to obtain a long lifetime for generator materials, low gas temperatures are desirable, but to obtain improved efficiency a high gas temperature is necessary. Luebke has therefore analyzed a combined MHD-steam plant as a function of maximum-combustion gas temperature. The results show that the gain in efficiency is 17.5% at 2800°K, with a duct length of 32 ft, but the gain is only 6.8% at 2200°K with a duct length of 472 ft.

The reason that the higher gas temperatures yield a shorter calculated duct length is that the degree of ionization, and hence the electrical conductivity, of the gas is increased. However, J. L. Kerrebrock (MIT) has observed experimentally conductivities 10^2 larger than those calculated by means of equilibrium equations for a mixture of argon and potassium vapor at one atmosphere pressure. At very low pressures, this phenomenon is a low discharge. The low electron-energy loss per collision and the small electron cross section of argon permit this phenomenon to occur at atmospheric pressure when the gas is preheated to 1000°K or greater. Although argon is not a practical gas for an MHD generator, it is possible that this effect can be observed in some other gas. Kerrebrock used an externally applied electric field to heat the electrons. It will be interesting to see if Lindley finds the same phenomenon when the electric field is induced by the high velocity of the helium through the magnetic field of the generator.

The electrodes in a homopolar generator and the resulting dc power represent complications whose elimination is desirable. Toward this objective, Fanucci, et al. (RCA), presented a theoretical analysis of an electrodeless ac generator. They conclude that the wavelength of the magnetic field must be larger than the channel height, and that the magnetic Reynolds number must be small, even though this leads to a poor power factor. This is in contrast to the paper by H. H. Woodson and A. T. Lewis (MIT), who conclude that the magnetic Reynolds number must be very large. Examination of the RCA paper reveals the possibility of a different interpretation; namely, that the magnetic interaction parameter should be large. It appears that extremely high temperatures will be required for generation of ac power. A further point of the RCA study is that, for reasonable magnetic fields and channel lengths, the generated frequency is of the order of 1000 cps. Inversion equipment to couple to the conventional power network is thus necessary.

In the papers presented by title only, W. Jackson, E. Pierson, and D. West (MIT) consider the use of liquid-metal pump-generator combinations for the purpose of dc voltage transformers. They conclude that the important parameter is the ratio of electrical conductivity to density. On this basis, NaK should be superior to Hg. S. Way (Westinghouse) gave additional data on his combustion MHD generator, which was the first such successfully operated. He concludes that any practical generator must have small thermal and electrical leakage losses. Finally, S. Hamilton (Pratt and Whitney) discussed some possible MHD cycles and methods for obtaining alternating current.

COMMUNICATIONS and Diagnostics, a session held under the chairmanship of C. B. Wharton (Livermore), commenced with an invited paper by A. W. Trivelpiece (Berkeley) who discussed the necessity of considering the dissipation of energy by propagation of space-charge waves when using a transverse microwave probe to determine electron density and collision frequency. He showed that the energy carried away by such waves was sufficiently large to cause a significant error when failing to take this process into account in the calculation of collision frequencies from the microwave data.

The second invited paper of this session was given by A. L. Gardner (Livermore), who reported having used several experimental techniques to determine the properties of a plasma produced by a modified PIG discharge. One especially clever technique was to study the shape of various spectral lines (e.g., He II 4686 A) by means of a scanned interference wedge. The etalon plates were tilted slightly to produce an off-center set of fringes. The interference pattern near the central image was focused on an appropriate slit-photomultiplier assembly. The etalon was pressurized to permit operation in various wavelength regions. Scanning was accomplished by passing a narrow beam of parallel rays through a beam shifter consisting of a rotating square block of lucite. The purpose was to permit entry of the beam at varying points along the face of the etalon. The photomultiplier signal could be constantly monitored and rapidly recorded from an oscilloscope screen. The horizontal sweep was synchronized with the rotation of the lucite block. Comparative records of the He I and He II line profiles were most striking, in that the latter were considerably more broadened than the former because of the first-order Stark effect.

Starting the section of contributed papers was M.

C. W. Little confers with the meeting organizers, N. Mather and C. Mannal, during a coffee break.

Epstein (U. of Southern California) who investigated theoretically the propagation of plane waves through a partially ionized plasma in which the electrons and neutrals were considered as hard spheres. This led to the additional assumption of constant mean free path rather than that of the usual constant collision frequency. As a result, a nonlinear relationship arises between the current density and the field strength which, in turn, leads to a larger wave attenuation at higher frequencies and a lower wave velocity at lower frequencies as compared to the linear case. N. C. Jen (City College of New York) discussed theoretical studies of plane waves in an unbounded plasma with nonuniform magnetic fields and densities. S. Zivanovic (Bendix) investigated theoretically the frequency-multiplication properties of a nonlinear plasma irradiated by plane monochromatic waves. For the very special case where the plasma contains a thin sheet of 217 kev electrons (with collisions), and the condition that the amplitude of the wave should be less than 10^{-4} v/m sec times its frequency, the reradiation appears to consist mostly of the second harmonic. F. L. Tevelow (Diamond Ordnance Fuze Labs) discussed some experimental studies of shock-produced plasmas in impure argon using microwave techniques similar to those used by S. C. Lin.

FUSION was dealt with in a session under the chairmanship of C. W. Little. In the first of two invited papers, M. Gottlieb (Princeton) reviewed instabilities found in pinch and mirror machines. In spite of the instabilities, he was optimistic about eventual stabilization of the plasma. R. Post (Livermore) then reviewed the economics of fusion power, based on the ratio of power output to losses. The total capital investment in the magnetic field using sodium conductors was calculated to be \$51/kw, for a power density of 14 watts/cm^3. The use of superconductors should substantially reduce this cost. He considered the other costs to be negligible. Thus, the capital cost of fusion power would be half that of steam power! Neither Gottlieb nor Post indicated a belief that radiation would be a major loss of energy.

Among those presenting contributed papers, L. D. Smullin (MIT) described the hollow cathode arc which is used to produce a plasma of $10^{13}-10^{14}$ ions per cubic centimeter. Experiments are in progress in which a 14-kv electron beam is scattered by the plasma. M. Gourdine discussed a novel method of heating a plasma by viscous dissipation. Radial electric and axial magnetic fields at both ends of the container cause the plasma at each end to rotate in opposite directions. The shear at the center converts the rotational kinetic energy into thermal energy. The decreases in electrical conductivity with increasing temperature should permit the rotational velocity to be increased. In addition, the increase in viscosity with higher temperature should increase the efficiency of thermal conversion. So far, only very preliminary experiments have been performed.

In the papers presented by title only, C. C. Chang (University of Michigan) proposed a transient version of the Astron, in which two plasma rings are injected at either end. The collision of these rings and further magnetic compression are used to heat the plasma. Fessenden (MIT) pulsed a resonant cavity with an S-band magnetron. The electron density was determined to be about 10^{14} per cubic centimeter. Finally, W. F. Westendorp (GE) described a single-turn magnet which produces 115 000 gauss from a 400 000-mega-joule capacitor bank. Spark gap switches allow a rise time of 7 μsec for 3×10^6 amp.

On the day following the sessions, a field trip to the Princeton project was arranged by N. Mather to provide a first-hand view of the C-Stellerator and associated equipment.

The presentations were oral at last year's meeting, but those who attended felt that preprints and a permanent record would have been desirable. This year most of the papers were available in an attractive spiral binding. Arrangements are being made for Columbia University Press to publish the proceedings. Although there is some question as to the permanent value of a collection of progress reports in magnetohydrodynamics, such a book should be of great value to workers in this field.