PREFACE

Recent scientific and technological advances have brought a great awakening of interest in the exploitation of the phenomena encountered in magnetohydrodynamics, the study of flows of electrically conducting fluids in the presence of electromagnetic fields. Ten years ago many of these phenomena interested only a small group of astrophysicists and geophysicists; today nearly every university and many industrial and government laboratories support teams of engineers and scientists working on some aspects of these problems. Present and proposed applications include the pumping of conducting liquids, central-station power generation, plasma confinement for the fusion reaction, and propulsion and flight control for rocket and hypersonic aerodynamic vehicles. In addition, there is the continuing hope that these studies will increase our understanding of gaseous physics and the structure of cosmic bodies.

This book presents analyses for three flows of viscous, incompressible, electrically-conducting fluids in high-aspect-ratio rectangular channels subjected to transverse magnetic fields. The situations considered, turbulent flow in the presence of a d-c magnetic field and both laminar and turbulent conditions in induction-driven flows, are motivated by the first two applications listed above, pumping and power generation. These are among the simplest types of magnetohydrodynamic flows and, because of their close relations to hydrodynamic channel flows, are termed here hydromagnetic channel flows.

The relative simplicity of these flows occurs because the interaction between the magnetic field and the mechanical motion of the fluid is primarily one way. The magnetic field often has a substantial effect on the mechanical motion, but the mechanical motion seldom effects much change in the magnetic field; these flows usually operate with low values of the magnetic Reynolds number. Viewed mechanically, these flows resemble conventional hydrodynamic flows in which are superposed additional pressure gradients and shear stresses caused by electromagnetic forces. Viewed electrically, they resemble conventional rotating machines in which the rotating armature is replaced by the moving fluid and the shaft torque by the mechanical pressure and friction loading.

Because of the close relationships between hydromagnetic channel flows and other well-understood engineering devices, equipments using these flows provide today the technically most advanced applications of magnetohydrodynamics. Several varieties, including both d-c and induction types, of electromagnetic pumps for the liquid metals used as coolants and solvents in nuclear reactors have been technical realities for about five years. Recently, the schemes for magnetohydrodynamic power generation have progressed beyond their long-held status as inventors' dreams for the production, without the intervention of mechanical devices with highly stressed moving parts, of useful electric power from thermal energy to the point where they are subject to hard technical and economic evaluation.

The application of hydromagnetic flows to date have been in lower-power devices where efficiency of energy conversion has not been a major factor. For this reason, the details of the electromechanical interactions within these flows have been more a matter for scientific curiosity than practical concern. Pump designers have done very well by applying a background of experience in electric machine design and the analogy noted here between hydromagnetic pumps and electric motors, without concerning themselves much with the mechanical aspects of the flow. As the power level of hydromagnetic equipment increases, however, the efficiency of these machines and the effects of flow structure on performance will become more important. The major purposes of the analyses presented here are the development of an intuitive picture of the internal structure of a turbulent hydromagnetic flow and of calculation techniques for the estimation of the power division in these flows.

The differences between this work and that of previous investigators concerned with turbulent hydromagnetic flows are caused by a difference in the starting points of the analyses. Earlier workers started with the solutions for laminar hydromagnetic flows provided by J. Hartmann about twenty years ago and tried to estimate conditions causing the onset of turbulence and the ensuing changes in flow structure. Thy physical experiment most relevant to this approach consists of setting up a pressure-driven laminar hydromagnetic flow, then increasing the pressure gradient until the flow becomes turbulent. In this book we start with the solutions for a turbulent hydrodynamic flow, which also have been known for over twenty years, and attempt to estimate the changes in flow structure occurring as an increasing magnetic field is applied to the channel. The experiment relevant to this approach consists in establishing a turbulent pressure-driven flow with an electrically conducting fluid, then applying a continually larger transverse magnetic field until the flow conditions become laminar. The important differences between these approaches, however, are associated not with the corresponding thought experiment, but rather with the analytical techniques natural to each. Investigators taking the first approach relied mainly on the mathematical tools of electromagnetic field theory and classical hydrodynamics. The approach taken here leads naturally to use of the "semi-empirical" techniques of modern fluid mechanics which depend on the combined use of the basic mathematical laws, a dimensional analysis, and the results of experiments. The relative success of this work merely indicates that turbulent hydromagnetic flows are more closely related to turbulent hydrodynamic flows than to laminar hydromagnetic flows.

The results described here are derived from a thesis submitted to the Department of Electrical Engineering in partial fulfillment of the requirements for the degree of Doctor of Science. During the long course of study and research culminating in this thesis, the author has incurred many more debts to teachers and colleagues than can be acknowledged here. Several persons, however, have been particularly helpful in recent times. Professors D. C. White and H. H. Woodson introduced the author to the study of magnetohydrodynamics and freed him from other duties when the course of this research was established. Professor P. F. Chenea suggested the application of the "semi-empirical" techniques of hydrodynamics to turbulent hydromagnetic channel flows when other methods of analysis had proven fruitless. Professor W. D. Jackson, who served as thesis supervisor, contributed valuable advice, encouragement, and criticisms during many discussions. Mr. J. W. Poduska performed most of the calculations and contributed many suggestions that have been incorporated here.

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