EXPERIMENTAL INVESTIGATION OF THE INFLUENCE OF A MAGNETIC FIELD ON THE HEAT TRANSFER BETWEEN AN ARGON PLASMA FLOW AND THE CHANNEL WALLS

V. I. Rozhdestvenskii

Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, Vol. 9, No. 5, pp. 57-61, 1968

The influence of an external transverse magnetic field on the heat transfer between a low-temperature argon plasma flow and the channel walls is experimentally investigated for Reynolds numbers in the laminar and transition regions of the flow. It is shown that the magnetic field has only a slight effect on heat transfer within the range of parameters studied. Application of a magnetic field leads to a decrease in heat transfer.

From the general statements of magnetohydrodynamics, it is known [1] that an external magnetic field can have a pronounced effect on the flow of an electrically conducting medium and, in the case of nonisothermal flow, even on the heat transfer with the environment or with the channel walls. The nature of the influence of the magnetic field depends on various factors. The principal factors are: the relative orientation of the vectors of magnetic induction and of the mean flow rate; the flow regime; the specific characteristics of the conducting medium; the magnitude of magnetic-field induction; and the electrical conductivity of the channel walls.

Theoretical and experimental investigations of heat transfer in magnetic fields are concerned mostly with flows of electrically conducting fluids (liquid metals and electrolytes) in channels. A fairly complete survey of the progress in this field is to be found in [2].

Heat transfer involved in low-temperature plasma flows in a magnetic field is characterized by such specific features as the presence of appreciable temperature and conductivity gradients both across the flow and along the channel axis, the Hall effect, and ion recombination.

Methods based on approximate physical simulation of plasma flows by conducting fluids are suitable for studying heat transfer of plasma flows only within certain well established limits.

Only few papers [3,4] deal with the experimental investigation of the influence of magnetic fields on the heat transfer in low-temperature plasma channel flows. These papers deal primarily with qualitative determinations of the nature of the influence of a magnetic field in the turbulent range of Reynolds numbers.

The aim of the present investigation was to determine the nature and magnitude of the influence of a transverse magnetic field on the heat transfer at the inlet section of the channel for various flow rates, various wall temperatures, and various orientations of the cross section of a rectangular channel with respect to the magnetic field direction. The influence of a readily ionizable addition introduced into the flow on the behavior of heat transfer in the presence of an applied magnetic field is also studied.

1. The experimental equipment was composed essentially of a plasmatron, a mixing chamber, a useful channel length, a rear chamber, and an electromagnet (Fig. 1). The argon was conducted from standard cylinders via a reductor and flow meter to a dc plasmatron where it was heated. The argon flow rate was measured from the pressure drop at a measuring double diaphragm with a maximum random error of 3%, the flow rate being varied from 0.8 to 2.2 g/sec (in all the experiments performed). The plasmatron incorporated two coaxial water-cooled electrodes, a tungsten rod serving as the cathode, and a cylindrical copper nozzle, with an inner diameter of 5 mm and a length of 8 mm, as the anode. The plasmatron was fed by two independently excited dc generators. A ballast resistance with a step control from 0.15 to 3 ohm was switched into the plasmatron circuit. The plasmatron was started by discharging a high-voltage capacitor bank. The current and voltage at the plasmatron electrodes were measured in the experiments, together with the power released in the electric arc. A melt of alkali metals (80%K, 20%Na) was introduced by means of a special batcher, which ensured a constant flow rate, into the flow at the exit section of the plasmatron nozzle with the aim of increasing the electrical conductivity. The amount of this addition was 0.2% of the argon consumption. Behind the plasmatron was mounted a cooled mixing chamber inside of which was placed a cylindrical sleeve made from boron carbonitride with an inner diameter of 12 mm and a length of 55 mm. The mixing chamber served for mixing the argon with the alkali metal vapors, and also for partially damping the oscillations generated in the jet by the plasmatron arc. The outlet of the mixing chamber contained a small cylindrical section (l = 14 mm) with an inner diameter of 12 mm, the beginning of which was taken as the beginning of the channel. From the mixing chamber, the plasma flow was conducted to the useful length of the channel. Three series of experiments were performed for three different modifications of the useful length.

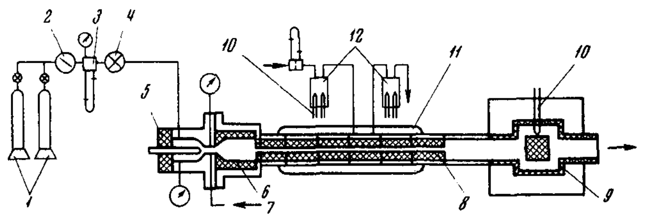

Fig. 1. Schematic drawing of the experimental equipment. 1) Argon cylinders, 2) reductor, 3) flow meter, 4) control valve, 5) plasmatron, 6) mixing chamber, 7) impurity batcher, 8) useful channel length, 9) rear chamber, 10) thermocouples, 11) electromagnet, 12) water mixers. The magnetic field is directed normal to the diagram

1) Experiments at a small mean flow rate were performed in a circular channel consisting of eight water-cooled copper cylinders separated from each other by paranite inserts, 0.5 to 0.8 mm thick. The channel as a whole was a circular cylindrical tube with an inner diameter of 12 mm, an outer diameter of 20 mm, and an over-all length of 380 mm. The length of the individual cylinders along the channel axis was 30, 20, 20, 20, 20, 35, 80, and 130 mm, starting at the channel inlet. The total relative length was 30 diameters, 10 of which were situated in the magnetic field.

2) Experiments with a large mean flow rate at low wall temperatures were performed with the same channel that was used in the first series; however, the first six cylinders were provided with cylindrical sleeves made from boron carbonitride, a material characterized by excellent insulating properties at high temperatures. The inner surface of the sleeves formed a channel of rectangular cross section measuring 6 × 3 mm. An identical sleeve was inserted into the outlet nozzle of the mixing chamber. By turning the sleeves over 90°, it was possible to vary the orientation of the rectangular cross section of the channel with respect to the direction of the magnetic field. The total relative length of the rectangular channel was 36 equivalent hydraulic channel diameters, 30 of which were situated in the magnetic field.

3) In the third series of experiments, the sleeves in the second, third, fourth, and fifth cylinders were exchanged for similar sleeves made from heat-resistant high-alumina concrete, which surpassed the mechanical strength of the former cylinders but had inferior heat-conduction properties. Thus, the third series permitted the use of higher surface temperatures in the rectangular channel, retaining, at the same time, the good insulating properties of the walls.

The rear chamber, located behind the test channel, incorporated a multichannel mixer, made from boron carbonitride, intended for measuring the flow temperature. In the mixer, the flow was distributed over six channels with chromel-aluminum thermocouples (0.35 in diameter) at the outlets. The channel axes were adjusted parallel to the axis of the test channel, in order to reduce the influence of the radiation from the plasmatron arc and the plasma column in the test channel on the temperature measurements. The thermoelectric power of the thermocouples was measured by an EPP-09 electronic potentiometer. The mixer was surrounded on all sides by a large number of molydenum foil screens in order to reduce the radiation losses of the thermocouple sensors. The outer surface of the rear chamber was thermally insulated by an asbestos fabric. From the rear chamber, the argon was made to flow at atmospheric pressure to the connecting piece of an exhaust fan.

The plasmatron, the mixing chamber, and the test channel were cooled with tap water supplied from a constant-pressure cylinder. The cylinder provided a constant water pressure of roughly 0.5 gauge atmospheres at the input of a water gauge. From a distributing manifold, the water flowed (separately for each heat exchanger) through the water gauge, the first mixing tank, the heat exchanger, and the second mixing tank before being discharged. The water flow through each heat exchanger was determined from the pressure drop at a measuring disk with the aid of a π-shaped differential manometer. All the water gauges were mounted on a water meter panel, and their recordings were photographed. Each water gauge was individually calibrated by a volumetric technique.

The difference in the water temperature in the mixing tanks (with a capacity of roughly 500 cm^3) was measured by differential four-junction chromel-copel thermocouples (thermopiles), the recordings being made by a 12-point electronic self-registering EPP-09 potentiometer or by a UPIP-60 apparatus.

A transverse magnetic field was generated by an electromagnet. The effective area of each magnet tip was 120 × 25 mm. For a pole spacing of 21 mm, the maximum magnetic induction at the middle of the gap was 2 tesla. All parameters of the equipment were measured in the steady-state mode. The transit time to steady-state operation was 15 to 20 min. The accuracy of the heat flow measurements was assessed from the thermal balance of the equipment.

2. Data processing. The mean value of the heat flux density at the test-channel wall was determined for each cylinder from the formula

$$q = \frac{cG\Delta t}{\pi d l},$$

where c, G, and Δt are, respectively, the specific heat, the flow rate, and the temperature difference of the water measured in the mixers mounted at the inlet and outlet of each cylinder; d is the tube diameter or the equivalent hydraulic diameter of the rectangular channel equal to the ratio of the quadruple cross-sectional area to the wetted perimeter; and l is the cylinder length along the channel axis.

Owing to the high thermal conductivity of copper and the small wall thickness, the inner-surface temperature of the circular channel wall differed only slightly from the temperature of the cooling water and, therefore, varied within a relatively narrow range (290 to 370° K) as compared to the variation of the mean mass flow temperature. Because of this, a constant wall temperature of 340° K was taken for calculating the heat-release coefficient in the circular channel.

Since the thermal conductivity of boron carbonitride is rather high (five times that of high-alumina concrete), the temperature of the inner surface of the channel wall formed by high-alumina concrete sleeves was also taken constant and equal to 340° K.

The temperature of the inner surface of the rectangular-channel wall formed by high-alumina concrete sleeves was calculated from the values of the heat flux and the outer-surface temperature of the sleeves. A relation describing the temperature dependence of high-alumina concrete [5] was used for this purpose.

Here, use was made of a formula describing the heat transfer through a cylindrical wall with an inner diameter equal to the equivalent diameter of the rectangular channel. The temperature of the sleeve outer surface was taken constant and equal to 340° K.

The wall temperature of a channel consisting of high-alumina concrete, determined in this way, varied from 600 to 1300° K.

The accuracy of heat flux measurements for all flow conditions employed was assessed by evaluating the thermal balance of the equipment. It was found that the unbalance with respect to the power expended in the plasmatron arc did not exceed 5% for a circular channel and 10% for a rectangular channel.

The mean mass flow temperature for various channel cross sections was calculated from the thermal balance of the channel length downstream from the cross section studied to the rear chamber, where a sudden change in the flow temperature occurs. At the inlet of each cylinder of the channel, the mean mass flow temperature was determined from the formula

$$T = T_- + \frac{c}{c_p G_{\text{Ar}}} \sum \Delta t G,$$

where T_- is the flow temperature in the rear chamber.

Assessment of possible errors involved in the determination of the mean mass flow temperature showed that our method is more accurate than another frequently used method, in which the temperature is determined from the thermal balance of the plasmatron, the mixing chamber, and the channel length in front of the cross section studied.

The temperature dependence of the thermophysical parameters of argon was taken from [6].

The Nusselt number N, averaged over each channel cylinder, was determined from the formula

$$N = \frac{qd}{(T_+ - T_c)\lambda},$$

where T_+ is the mean mass flow temperature at the middle of a cylinder, and λ is the heat transfer coefficient of argon at the temperature T_+.

The data obtained experimentally for a viscous gravitational laminar flow in a horizontal circular tube with conducting walls are given in Fig. 2, where N_m and N_0 are Nusselt numbers determined with and without an applied magnetic field, respectively.

Analysis of data obtained for the case examined shows that:

1) Application of an external transverse magnetic field leads to a decrease in heat transfer. This probably is due to the influence of the magnetic field on the motion of a gas under the effect of free convection forces; the heat transfer drop occurs precisely over the channel length exposed to a strong magnetic field.

2) The maximum heat transfer drop does not exceed 15%, and corresponds to the temperature at the tube inlet, which is equal to 4200° K at a Reynolds number

$$R = \frac{4G_{\text{Ar}}}{\pi d \mu} = 530.$$

With a further increase in temperature (which for a given argon flow rate corresponds to smaller Reynolds numbers), we observed a decline in the rate of heat transfer decrease,

3) With increasing flow rate (from R = 600 to R = 1600) at a temperature T = 3700° K, the influence of the magnetic field diminishes. The experiments showed that alkali metals added to the flow condensed at the cold surface of the tube. This was accompanied by an insignificant increase in heat release and a smaller influence of the magnetic field.

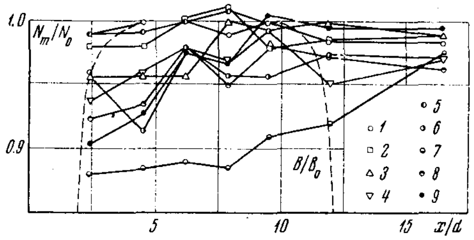

Fig. 2. Relative changes in heat release for laminar flow in a horizontal circular tube under various flow regimes. Each regime is defined by the mean mass flow temperature, in °K, and by the Reynolds number in the first cylinder of the channel, as given, respectively, below: 1) 3200, 860; 2) 3300, 1600; 3) 3400, 650; 4) 3700, 600; 5) 3700, 1600; 6) 3800, 1300; 7) 4200, 530; 8) 4300, 500; 9) 4600, 490.

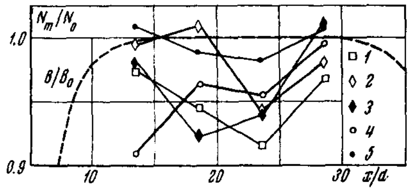

Fig. 3. Relative change in the heat release in a rectangular channel with nonconducting walls for various flow regimes. Each regime corresponds to the mean mass flow temperature, in °K, and the Reynolds number in the first channel cylinder, as given, respectively, below: 1) 2400, 3600; 2) 3300, 4200; 3) 3400, 4100; 4) 3700, 4000; 5) 4000, 3900.

Fig. 3 gives experimental data for flow in a rectangular channel at Reynolds numbers corresponding to laminar-turbulent transition. The presence of a transverse magnetic field leads, in this case, to a decrease in heat transfer (up to 10%); no increase in the influence of the magnetic field on heat transfer was observed when alkali metal additions were introduced into the flow. Nor did experiments performed for various orientations of the channel cross section relative to the direction of the magnetic field reveal any noticeable difference in the influence of the magnetic field on heat transfer. It is noteworthy that an argon plasma jet generated by a plasmatron possesses a certain nonequilibrium electrical conductivity, which at a given temperature is comparable to the equilibrium electrical conductivity of argon containing a readily ionizable addition. Since the measurement of the nonequilibrium conductivity of argon in the present conditions is highly complicated, the experimental data obtained can not be represented as a function of the Hartmann number, as is conventionally done in magnetic thermal physics of electricity conducting fluids.

REFERENCES

1. A. G. Kulikovskii and G. A. Lyubimov, Magnetohydrodynamics [in Russian], Fizmatgiz, Moscow, 1962.

2. E. Ya. Blum, M. V. Zake, U. K. Ivanov, and Yu. A. Mikhailov, Heat and Mass Transfer in an Electromagnetic Field [in Russian], Zinatne, Riga, 1967.

3. V. Kh. Blekman, "Investigation of a steady MHD flow," collection: Ion-, Plasma-, and Arc-Engines for Rockets [in Russian], Gosatomizdat, Moscow, 1961.

4. V. J. Raelson and P. J. Dickerman, "Heat transfer from partially ionized gases in the presence of an axial magnetic field," Trans. ASME, Ser. C. J. Heat Transf., vol. 84, no. 2, 1962.

5. V. Ya. Chekhovskii, A. I. Romanov, A. A. Kaulenas, and G. I. Stavrovskii, "Thermal conductivity of heat-resistant high-alumina concrete within the temperature range from 200 to 1500° C," Teplofizika vysokikh temperatur, vol. 5, no. 5, 1967.

6. L. I. Grekov, Yu. V. Moskvin, V. S. Romanychev, and O. N. Favorskii, Principal High-Temperature Properties of Some Gases, Reference Book [in Russian], Mashinostroenie, Moscow, 1964.

15 June 1968 Moscow