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HEAT TRANSFER PROMOTED BY CYLINDRICAL OBSTACLES IN A MAGNETIC FIELD

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Heat transfer in a circular closed channel with conducting cylinders placed on the inner hot wall parallel to an axial uniform strong magnetic field has been studied experimentally. Stagnant zones stretched along the magnetic field above and below the cylinders arose. Intensive large scale two-dimensional vortical structures parallel to the magnetic field were generated due to flow around these zones. It has been shown that vortical structures provided a 5-6 times increase of transverse heat transfer as compared with the case of simple channel flow. The hot wall temperature decreased more than 3 times. Local characteristic have been used to provide an analysis of flow structure and redistribution of velocity and temperature fields.

1. Introduction

Some problems related to MHD applications (for example, with thermofusion blankets) are based mainly on the concept of heat transfer intensification either as a result of natural turbulence at large Reynolds and Hartmann numbers or the artificial generation of intense perturbations near a hot wall [1-4]. One of the most effective methods of intensification is the promotion of large-scale two-dimensional vortices by conducting inserts disposed on the channel walls perpendicular to the magnetic field [4, 5]. In these studies the principle was based on the excitation of the intense vorticity parallel to the magnetic field in the region of the conductivity jump on the wall leading to the formation of streamlined stagnant zones above inserts, which provided the original strongly unstable nonuniform velocity profile in the plane perpendicular to the magnetic field [6]. Under these conditions the Nusselt number was several times greater than in the channel without inserts. To judge from these results, the disposition of the conducting cylindrical obstacles protruding from the hot wall parallel to the magnetic field must also ensure shaping of the stagnant zones stretched along the field and excite intense vorticity with the vector along the field It has been recognized that, under a strong magnetic field, flow past a cylinder of finite length oriented perpendicular to the field has a tendency to change to two-dimensional flow in the plane perpendicular to the magnetic field [7], which strengthens in the strong magnetic field due to the shaping of the stagnant zones. That flow, having two-dimensional jet-wake signs, generates two-dimensional large-scale intense perturbations [8-10], which provide significant heat transfer from the hot wall to the flow.

2. Experimental Device and Parameters

The device was a closed circular channel 12 cm in outer diameter and 5.5 cm in inner diameter, 4.6 cm in height with copper walls parallel to the axial uniform magnetic field and containing the working liquid alloy InGaSn (Fig. 1). The walls perpendicular to the magnetic field were insulated. The working liquid had the following characteristics at 20°C: density $\rho = 6360$ kg/m^3, kinematic viscosity $\nu = 3.4 \cdot 10^{-7}$ m^2/sec, electrical conductivity $\sigma = 3.46 \cdot 10^6\ \Omega^{-1} \cdot \mathrm{m}^{-1}$, and thermal conductivity $\lambda = 38$ W/m·deg.

The electrical current was passed through the liquid in the radial direction between the side walls. The electromagnetic force $\mathbf{j} \times \mathbf{B}$ provided liquid motion in the azimuthal direction. The inner wall contained an electric heater, and the outer wall was cooled by water at 20°C. Unlike studies [4, 5], there are conducting cylinders, instead of conducting inserts, on a

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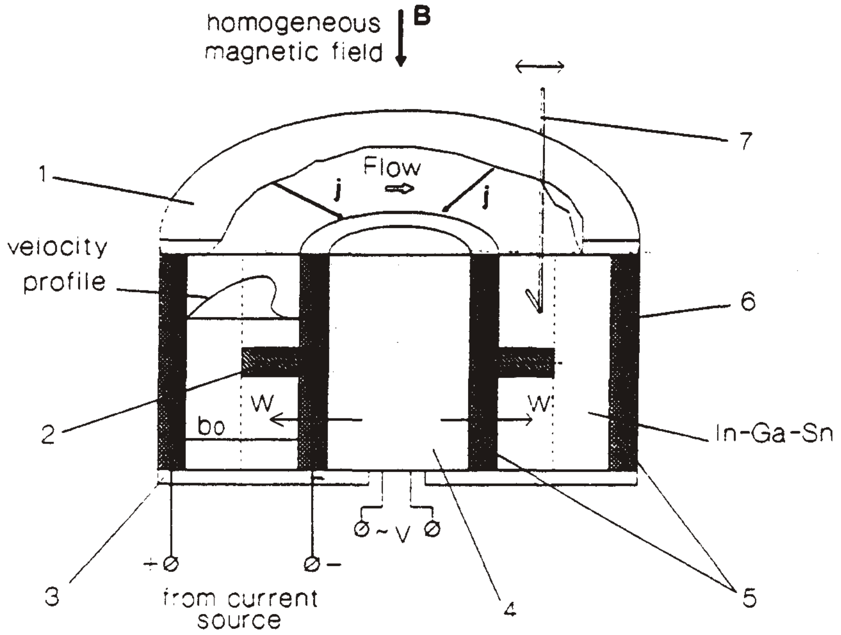

Fig. 1. Experimental operating channel for heat transfer study in the presence of a strong magnetic field: 1) cover, 2) cylinder, 3) bottom, 4) electrical heater, 5) copper electrodes, 6) cooler, and 7) Probe; In−Ga−Sn) working liquid.

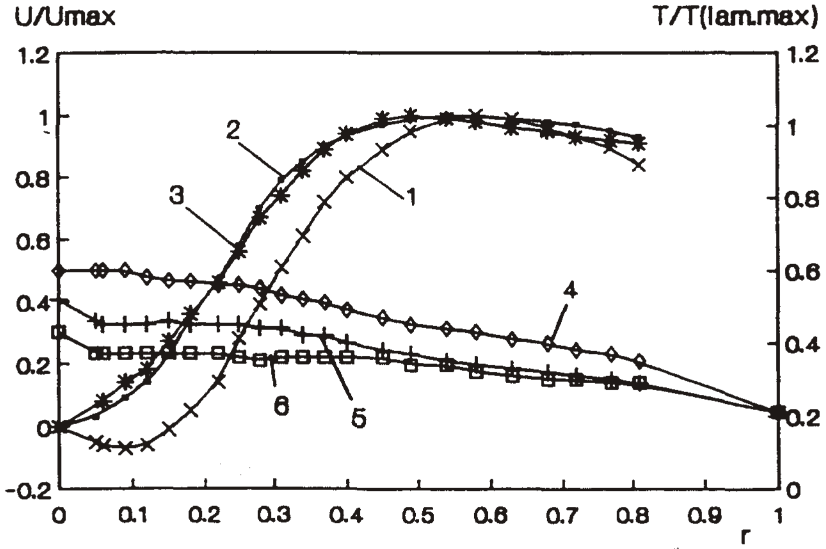

Fig. 2. Mean velocity and temperature profiles at B = 1.4 T and different S: 1) and 4) S = 1.4, 2) and 5) S = 4.66, 3) and 6) S = 9.56. Velocity and temperature, respectively: 1) U_{max} = 33.4 m/sec, 2) 32.6 m/sec, 3) 36.5 m/sec. T(lam. max) = 27.3°C is the temperature of the hot wall in the laminar regime. Rh = 42.7.

half height of the hot wall with various steps along the flow. The cylinders were 0.5 cm in diameter, 1.0 cm in length, and made of copper.

The channel was located inside a gap of an electromagnet with magnetic induction up to 1.5 T. The electric current varied in the range I = 0-70 A. The electrical heater provided heat flux through the inner wall up to 5.9 kW/m^2. The maximum velocity was about 50 cm/s, which corresponds to Reynolds number Re = $5 \cdot 10^4$. In the presentation of experimental data, the following dimensionless parameters were used: Re = $(b_0/\nu)[BI/(\rho 2a)]^{1/2}$, where $2a$ is the height of the channel along the magnetic field, and b_0 is the width of the channel. The modified Hartmann number is Ha = $(b_0/2a)Bb_0(\sigma/\mu)^{1/2}$, where μ denotes viscosity of the fluid; the parameter Rh = Re/Ha is the relation of the bottom friction time and inertial time

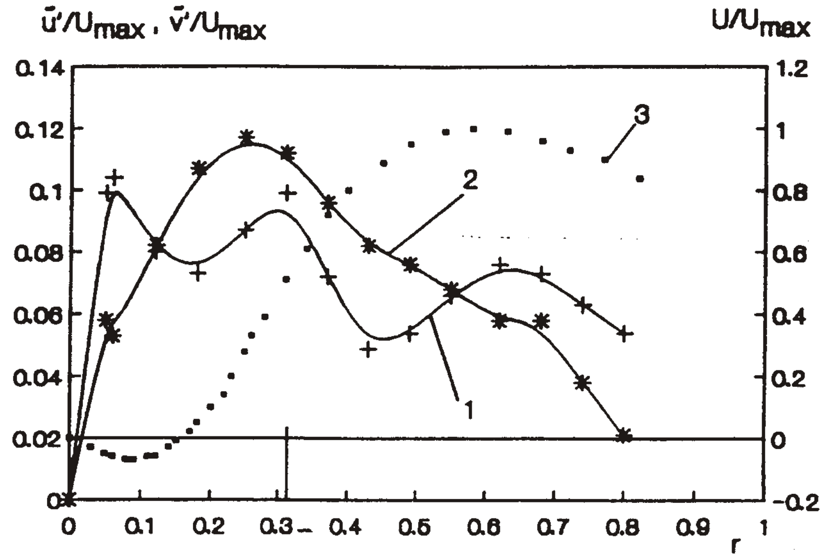

Fig. 3. Distributions of velocity pulsations at B = 1.4 T and Rh = 42.7. 1) u'/U_{max}, 2) v'/U_{max}, and 3) U/U_{max}. S = 1.4.

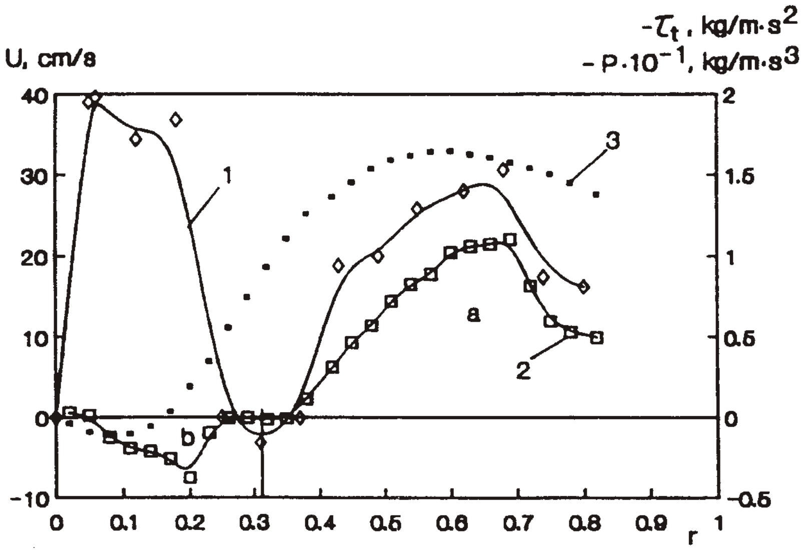

Fig. 4. Distributions of turbulent stress and energy production at B = 1.4 T and Rh = 42.7. 1) Turbulent stress, τ_t, 2) energy production P, and 3) U. S = 1.4.

(this parameter determines flow instability), and the Nusselt number $Nu = \alpha b/\lambda$, where $\alpha = W/[F(T_h - T_c)/2]$, W denotes heater power, $F = 4\pi r_0 a$, T_h and T_c denote hot and cold wall temperatures, $b = r_0 \ln(R/r_0)$ is the modified width of the channel, and r_0 and R denote the inner and outer wall radii. Flow and temperature measurements were made from a conductance anemometer and thermocouple. The anemometer probe electrodes were made of 0.33-mm-diameter copper wire with varnish insulation and the sensor element of the thermocouple was 0.3 mm in diameter. Probes were moved to the radial direction in a middle plane of the channel.

3. Measurement Results and Discussion

Typical azimuthal velocity and temperature profiles in a strong magnetic field at different steps of cylinder disposition for three dimensionless steps of $S = (s - d)/(b_0 - h)$, where s is the distance between cylinders, d is the cylinder diameter, b_0 is the channel width, and h is the cylinder length, are shown in Fig. 2. It is seen from this figure that the velocity profiles

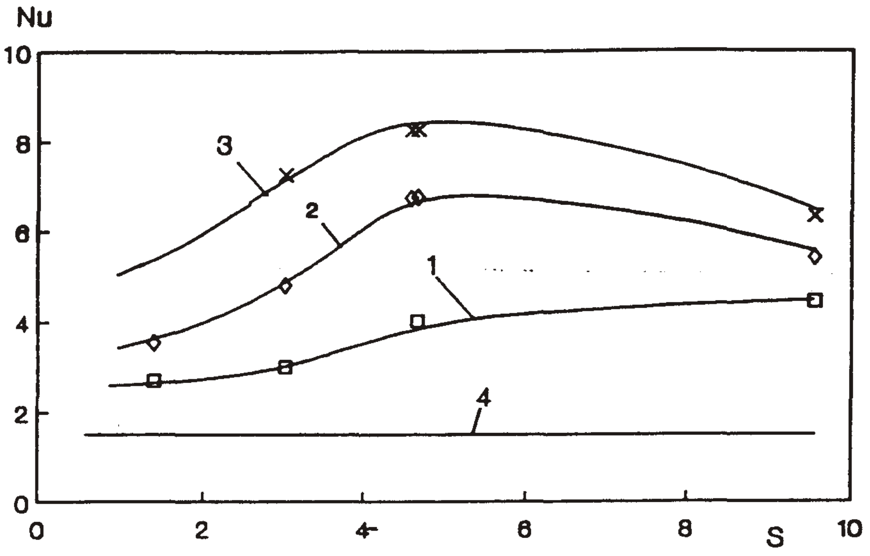

Fig. 5. Dependences of the Nusselt number on the step parameter at B = 1.4 T and Rh: 1) 42.7, 2) 47.0, 3) 51.5, 4) without cylinders at Rh = 42.7.

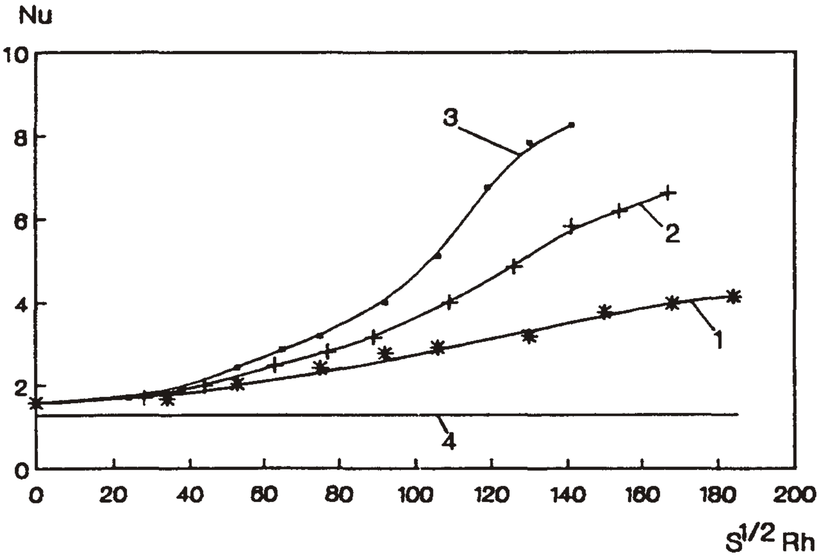

Fig. 6. Dependences of the Nusselt number on combined accounting cylinder step parameter at S = 4.66 and the magnetic field B: 1) 0.73, 2) 1.0, 3) 1.4 T, 4) without cylinders at B = 1.4 T.

practically coincide along the entire channel cross-section for large values of the parameter S. At S = 1.4, the negative values of the velocity are explained by the narrow disposition of the cylinder and the emergence of the bound vortices behind the stagnant zones. The mean temperature profiles for these flows have an almost uniform character in the range of r up to approximately 0.3 in which the velocity profile is essentially nonuniform and large scale two-dimensional perturbations occur.

The results of measurements of the azimuthal and radial velocity fluctuations, shown in Fig. 3, indicate a high level of perturbation intensities in the flow. The fluctuation distributions show that the intensity is about 12% of the maximum velocity. The azimuthal component has three prominent maxima, whereas the radial component has one expressed maximum. These distributions indicate that there are large intense vortices in the flow, which are of the same order as the transverse scale of the flow. In similar shear flows [4, 5, 9, 10], analogous structures arose in a strong magnetic field. This result agrees with the result obtained by free liquid surface visualization in the channel with the top cover removed.

Under these conditions, the turbulent stress $\tau_t = -\rho\langle u'v'\rangle$ is positive in practically the entire flow field in spite of the different signs of the mean velocity gradient across the channel, whereas if the turbulent energy production $P = \tau_t r\partial(U/r)\partial r$ is positive in the main part of the flow, then P is negative near the hot wall (zones (a) and (b) in Fig. 4). The change of sign of the production P near the hot wall corresponds to the change of the mean velocity direction in this region (curve 3).

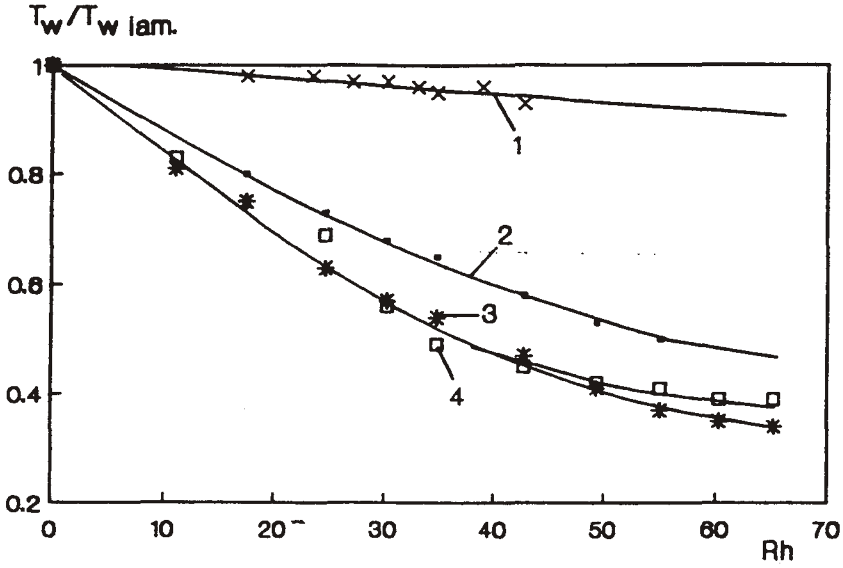

Fig. 7. Dependences of hot wall temperature on the Rh parameter at B = 1.4 T and different S: 1) without cylinders, 2) 1.4, 3) 4.66, 4) 9.56. $T_{w\ lam.}$ = T(lam. max).

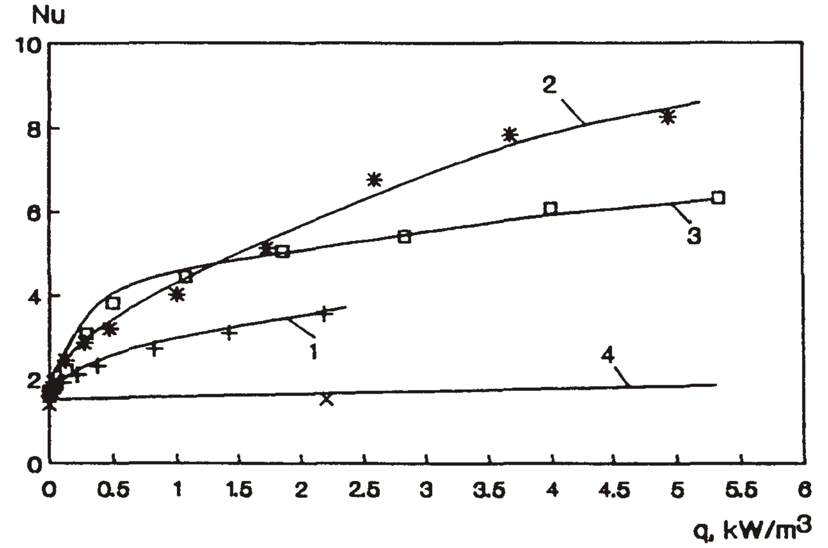

Fig. 8. Dependence of the Nusselt number on power spent to create fluid motion at B = 1.4 T and different S: 1) 1.4, 2) 4.66, 3) 9.56, 4) without cylinders, B = 1.4 T.

The graphs in Fig. 5 indicate that the two-dimensional large-scale structures provide high intensity of heat transfer from the hot to cold wall at different values of the Rh parameter and various S parameter. Upon enhancement of Rh, the value of velocity pulsation intensity grows and Nu increases up to 8.24. However, if the Nu number is calculated using the temperature measured by the probe in the middle of the channel, then the Nu number becomes 12.36. This situation resembles the case of no closed channel, when the flow takes heat away (in the experiment heat elimination was provided by the outer wall). In Fig. 5, it is seen also that as the free channel (without cylinders) the Nu number becomes only 1.5 on reaching Rh = 55.6.

The growth of large vortex contribution to the heat transfer is illustrated by the curves, shown in Fig. 6, at various magnetic fields. If the magnetic field is 0.73 T, the middle-scale perturbations play the main role in the heat transfer process, and the Nu number becomes 4.12 on reaching $S^{1/2}Rh$ = 185. In the presence of a magnetic field 1.4 T, Nu reaches values up to 8.24 at $S^{1/2}Rh$ = 138. Extrapolation of these data shows that for flow velocity V_0 = 1 m/sec and magnetic field **B** = 5 T, $S^{1/2}$ Rh = 105 and Nu = 5.3.

This heat transfer intensification is confirmed also by measuring the hot wall temperature, which is presented in Fig. 7 at various values of S. It is seen that in the case of a free channel the hot wall temperature decreases by only 10% (curve 1). In the channel with cylindrical promoters, the temperature of this wall decreases by 70% at two large values of S (curves 3 and 4).

At large Rh, the slower decrease of the wall temperature is due to the instability of primary two-dimensional large perturbations, leading to the decrease of their intensity and, consequently, efficiency of heat transfer.

The relationship between the Nu number and powder $q = I\Delta\Phi/V$ spent for fluid motion creation in volume unit ($\Delta\Phi$ denotes the potential difference between the inner and outer walls, V channel volume), shown in Fig. 8, indicates that the ratio Nu/q for the channel with cylinders is 5.5 times greater than for the free channel (curve 2 and 4). At high values of S, the smaller values of the ratio (curve 3) are connected with the decrease of intensity perturbations mentioned above.

4. Conclusion

The efficiency of heat transfer considerably depends on the flow structure and perturbation scales near the hot wall. Without special measures the turbulence remains small-scale at large Reynolds and Hartmann numbers, and the Nusselt number does not exceed 1.5 in this case. The disposition of conducting cylindrical obstacles on the wall parallel to the magnetic field creates conditions for the generation of large turbulent vortices commensurate with the scale of the flow, which give a Nusselt number of 8.24 (or 12.36 if the Nu number is calculated from the temperature in the middle of the flow).

At the same power spent to create the motion, the ratio of the Nusselt number for flow with cylindrical promoters to the Nusselt number for free channel flow reaches 5.5. It should be noted that Nu = 5.3 can be obtained at the assumed parameters of fusion blankets.

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