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THE EFFECT OF A MAGNETIC FIELD ON HEAT TRANSFER IN A SLOTTED CHANNEL

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Abstract

The results of numerical and experimental studies of liquid metal heat transfer in slotted channels in a transverse magnetic field are presented. Test results showed an improvement in heat transfer in a straight channel at low and moderate interaction parameter, N . The Nusselt number at small N (around 120) was up to 2 times higher than in turbulent flow without a magnetic field, Peclet number being equal. This effect of heat transfer enhancement is caused by the generation and development of large scale velocity fluctuations in the near heated wall area. Qualitative and quantitative correlations between heat transfer and velocity fluctuation characteristics are presented.

1. Introduction

Up to now, the aim of the main part of blanket-related magnetohydrodynamic (MHD)-studies was to define the pressure drop in a strong magnetic field, Kirillov et al. [1]. Only a few theoretical and experimental works have been carried out to study heat transfer in liquid metal (LM) MHD-flows in conditions close to or at least approaching fusion blanket conditions, though one can expect a significant influence of strong magnetic fields on convective heat transfer in blanket channels.

Analysis of data on MHD-flows in strong magnetic fields reveals two main mechanisms by which the magnetic field affects the flow pattern and, consequently, the heat transfer — the effect of the magnetic field on (a) the mean velocity distribution and on (b) velocity fluctuations (in time and space). Analyzing the role of the first mechanism, one takes into account two competing factors: (1) the increase of velocity and velocity gradients near side walls parallel to the magnetic field, Ying and Tillack [2], and (2) velocity (flow rate) re-distribution in the magnetic field direction.

The effect of the magnetic field on heat transfer via its influence on velocity fluctuations is caused by a number of competing factors: (1) turbulent fluctuation damping, Branover [3]; (2) transition to a two-dimensional structure, Someria and Moreau, Sukoriansky et al. [4, 5]; and (3) instability of high-gradient velocity profiles which generate large scale velocity fluctuations, Reed and Picologlou [6].

The competing effect of the aforementioned factors on heat transfer under blanket conditions depends on velocity, channel geometry, wall conductivity, etc., and at present cannot be estimated by means of numerical calculations, mainly because of insufficient understanding of the effect of the magnetic field on velocity fluctuations.

2. Test Conditions

A joint Russia-USA heat transfer test was conducted at the Argonne Liquid Metal Experiment (ALEX) facility, Argonne National Laboratory (ANL). The test section was of rectangular slotted channel geometry (the aspect ratio 10:1, the long

side was parallel to the applied magnetic field). The details of the cross-section, dimensions and coordinate system are shown in Fig. 1 and Table 1. The top (heated) wall was 6 mm thick (stainless steel), the remaining walls were made of a thin 1 mm (stainless steel) liner which was electrically insulated from its surrounding strongback.

Temperature and velocity profiles were measured by a traversing ThermalLEVI (Liquid metal Electromagnetic Velocity Instrument) probe at $y=0$ and $x/a=65.3$ (the origin for the x -coordinate is the leading edge of the heater block) and $z \leq 0$ (see Fig. 1). According to numerical and experimental data on the temperature distribution along the channel wall, at this x -coordinate, both temperature and velocity distributions can be considered fully developed (nondimensional values do not depend on x).

Theoretical predictions were prepared by both the Efremov Institute and ANL. At high M and N (see Table 1), the two predictions, based on somewhat different approaches to 2-D fully developed laminar MHD-flow, Hua et al. [7], and 3-D temperature distribution, yield essentially the same results.

The main part of the heat transfer tests was carried out at a constant magnetic field of about 2 T, heat transfer test conditions are shown in Table 2.

3. Test Results

Before analyzing the heat transfer data one has to consider briefly the experimental results of the hydrodynamics of MHD-flow in a slotted test channel. Pressure drop data shows that under the conditions studied (except $B=0$) the flow

in the channel can be considered laminarized ($\Delta p \propto V$). Comparison of experimental ($N=133$ and $N=625$) and numerical data on the velocity distribution revealed a quantitative discrepancy at low and moderate interaction parameters studied in the experiment; test values of the velocity near the heated wall are essentially lower than the numerical ones, no high velocity jet was observed in the experiments, Fig. 2. It should also be emphasized that the experimental velocity distribution depends on the interaction parameter (maximum velocity increases with the increase in N), though according to theoretical assumptions in fully developed flow, the velocity distribution depends only on M .

The discrepancy of experimental and numerical data can be explained by the presence of velocity fluctuations near the heated wall. Experiments revealed the existence/generation of large scale velocity fluctuations, the normalized root mean square (RMS) of which can attain 0.9, see Fig. 3. The RMS maximum at low and moderate N is located near the heated wall. Velocity fluctuations enhance energy transfer in the near wall area and thus flatten the M-shaped velocity profile. An increase in N (starting from some arbitrary value) causes damping of fluctuations (or changes the conditions of their generation) and thus decreases the energy transfer, that leads to velocity increase in the near wall area. One may expect that at high N (more than $2 \cdot 10^3$ for the conditions of the present experiment) an M-shaped velocity profile, close to numerical predictions for the laminar regime, will exist in the flow.

Thus, the aforementioned data shows that though the flow can be considered as laminarized (with respect to pressure drop), strong velocity fluctuations exist in the flow and under such conditions one should expect that the main mechanisms by which the magnetic field influences (at constant B) heat

transfer will be related to the interaction of the magnetic field with the fluctuations and the effect of the magnetic field on the conditions of velocity fluctuation generation.

In Fig. 4, temperature profiles are shown for $B=0$, and $B=2$ T, displaying the effect of an increasing magnetic field while keeping Pe constant. The temperatures in Fig. 4 are normalized by the complex based on; the applied heat flux, half of channel's "radial" dimension (a), and NaK thermal conductivity. It can be seen that for $B=2$ T the temperature profile is more flat than for $B=0$ T, which means that the heat transfer is enhanced by the magnetic field. Comparison of Nusselt numbers ($Nu = qa/k(T_{z=-1} - T_{bulk})$, $T_{z=-1}$ was estimated by extrapolation of test data at $y=0$ and T_{bulk} is a geometric mean temperature at $y=0$) for these conditions shows an increase of Nu number by a factor of 2.

The dependence of Nu number versus coolant velocity, presented in Fig. 5 as a $Nu=f(N)$ dependence, shows a drastic decrease in heat transfer as velocity decreases (increase in N). It should be noted that qualitatively the $Nu=f(V)$ dependence within the range of interaction parameters studied here is similar to the one typical for turbulent flow without a magnetic field ($Nu=A+C \cdot Pe$, solid line on Fig. 5. Constants A and C were chosen arbitrarily, just to show the similarity of the two curves; their values do not correspond to real turbulent flow). A similar qualitative curve for laminar flow ($Nu \propto Pe^{0.4}$) is shown by a dashed line. This shows that at moderate N the energy from the heated wall is predominately transferred by velocity fluctuations and consequently the main mechanism by which the magnetic field affects the heat transfer under the conditions studied is defined. One should keep in mind, that, even though the $Nu=f(V)$ dependence obtained at $B=2$ T is similar to the one in turbulent flow without a magnetic field, the

mechanisms defining these dependencies are essentially different: the RMS is constant at $B=0$ and varies at $B \neq 0$.

Comparison of data presented in Figs. 3 and 5 points to a correlation between the RMS of velocity fluctuations and the corresponding Nu. An Nu dependence on velocity fluctuations is shown in Fig. 6 as a function of normalized Nu (Nu/Nu_0) versus normalized RMS (ϵ/ϵ_0), where Nu_0 and ϵ_0 are the Nu and RMS at $B=0$, since in this experiment velocity fluctuations at $B=0$ were not measured, $\epsilon \cong 0.05$ was taken as ϵ_0 for $z=-0.95$, Comte-Bellot [8]. In this figure, the results of experiments [5, 9] are shown as well. It should be mentioned that normalized Nu is not equal to 1 at normalized RMS equal to 1, because this point corresponds to MHD-flow, not an ordinary turbulent flow and, consequently, the structure of the flow and velocity fluctuations is different from the one at turbulent flow at $B=0$. Nu- ϵ dependence is similar qualitatively in all three experiments — an increase in velocity fluctuations leads to an increase in Nu number. The quantitative discrepancy of the data from different experiments can be attributed to a number of factors: different channel geometries and wall conductivities, different mechanisms of velocity fluctuation generation — using grid bars, Sukoriansky et al. [5], and instability of velocity distribution, Miayzaki et al. [9], and the present experiment — and consequently different mechanisms of magnetic field-velocity profile-fluctuation interaction.

4. Discussion

Thus, the experimental data show heat transfer enhancement by velocity fluctuations generated in a magnetic field in comparison to both turbulent flow without a magnetic field and laminar MHD-flow. Therefore, the possibility of the

existence and generation of velocity fluctuations under fusion reactor blanket conditions is of primary interest. One has to take into consideration both the "artificial" generation of velocity fluctuations by grids or other local disturbances (evidently, it is the best way to generate velocity fluctuations in channels with nonconducting walls) and the magnetic field-induced generation of fluctuations in channels with conducting walls.

Field-induced generation is defined by velocity gradients and the inflection point of the velocity profile near the side wall. The most pronounced M-shape velocity profiles are generated in zones of 3-D flow — in case of straight channels, this would be the entry zone of the magnetic field. So one can assume that the magnetic field-induced fluctuations are generated in the zone where the flow enters the magnetic field (see for example the results of Branover's experiments [10]). The magnetic field tends to convert such fluctuations into two-dimensional form. The decay of such fluctuations in the magnetic field is rather weak, and thus they can "survive" long distances from the entry zone.

Since velocity gradients and inflection point position are correlated with side layer thickness, to a first approximation, one can assume that the critical Reynolds number corresponding to generation of velocity fluctuations depends, first and foremost, on the thickness of side layer δ_s : $Re_{cr} = f(\delta_s)$. For example, according to the theoretical analysis of [11] the critical conditions of velocity fluctuation generation in fully developed flow in a channel with conducting walls could be expressed in the following form: $\delta_s \propto M^{-1/2}$. At present there is not sufficient experimental data to validate the boundary curve relationship. The data from experiments [5,9,12] and the present experiment, allow only an estimate of a first approximation of the critical conditions $Re_{cr} \propto \delta_s^2$, of magnetic field-induced

velocity fluctuation suppression, see Fig. 7. Analyzing this curve, one should keep in mind the difference in test section geometries, wall conduction ratio and the distance from the 3-D flow area, at which fluctuations measurements were made.

A number of points taken from Sukoriansky et al. and Reed [5, 12] and from the present experiment corresponding to the "fully developed" velocity fluctuation conditions are presented on Fig. 7, as well. One can see that most of them lie above the critical line. A point corresponding to the conditions of ITER inner blanket ($B \approx 11$ T, $a \approx 20$ mm, $v \approx 1-2$ m/s) also lies above the critical line (see Fig. 7) and shows the possibility of the existence of velocity fluctuations under ITER blanket conditions.

As was mentioned above, test results on velocity and temperature distributions differ from numerical results at low and moderate interaction parameters, because of strong velocity fluctuations existing in the flow. But at high N (about $2 \cdot 10^3$) these fluctuations are suppressed (or at least not generated) and good agreement is observed between the numerical and experimental temperature profiles, Fig. 8. The value of Nu obtained at high N is about 1.5.

The other mechanism by which the magnetic field affects heat transfer in slotted channels (through velocity profile changes) was studied at St. Petersburg State Technical University under the following conditions: $a/b=10/100$, $c_w \approx 4 \cdot 10^{-2}$, magnetic field up to 0.9 T; the working fluid was In-Ga-Su eutectic alloy. It should be mentioned that the mean velocity value for this experiment was chosen in such a way that the flow could be considered laminar, even at $B=0$ T ($Re=250$); no velocity fluctuations were observed in the flow under the test conditions and, thus, the magnetic field could affect heat transfer in this experiment

only through changing the velocity profile. The results of these experiments show that at low Hartmann numbers (0 - 20) the increase in magnetic field leads to a decrease in Nu (temperature profiles were measured at $y=0$) due to velocity profile flattening in the direction of magnetic field. Further increase of Hartmann number up to 145 did not affect Nu. This result was confirmed by numerical calculations. It should be mentioned that according to numerical calculations at high M (about several thousand) a slight increase of Nu with an increase in M is predicted; this Nu increase results from the high velocity near wall jets. However, this range of M has not been achieved in the experiments conducted so far, so this theoretical results is still not confirmed experimentally.

5. Conclusions

Heat transfer tests performed on two test sections of similar slotted geometry show the following:

1. Field-induced generation of large scale velocity fluctuations strongly enhances heat transfer in laminarized MHD-flow. Test data point to a definite correlation between the RMS of fluctuations and Nu. The maximum increase of Nu obtained under test conditions reported here was about a factor of 2.
2. Under conditions of laminar MHD-flow, velocity re-distribution in the magnetic field direction leads to a decrease of heat transfer at low Hartmann numbers.

Nomenclature

B	magnetic field
T	temperature
ϵ	RMS of velocity fluctuations
δ	side layer thickness
c	wall conduction ratio ($=\sigma_w t_w / \sigma a$)
σ	electrical conductivity
ρ	density
ν	viscosity

Subscripts

w	wall
s	side wall
0	at $B=0$
cr	critical

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Table 1.

"Radial" dimension, $2a$	14 mm
"Toroidal" dimension, $2b$	140 mm
Interaction Parameter, $N = \sigma B^2 a / \rho V$	$30 - 2 \cdot 10^3$
Hartmann Number, $M = Ba \sqrt{\sigma / \mu}$	400 - 900
Average coolant velocity, V	0.05 - 0.7 m/s
Peclet Number, Pe	12 - 200
Surface Heat Flux, q	$8.5 - 9.5 \cdot 10^4 \text{ W/m}^2$

Table 2.

B=0 T	B≈2 T
M=0	M≈880
Pe=194, N=0	Pe=196, N=122
-	Pe=97.3, N=248
-	Pe=41.2, N=562
-	Pe=25.2, N=993
-	Pe=12.8, N=1754

Figure Captions

Fig. 1 Slotted channel test section geometry

Fig. 2 Velocity profiles

Fig. 3 The effect of magnetic field on velocity fluctuations in a slotted channel

Fig. 4 The effect of a magnetic field on the temperature distribution in a slotted channel

Fig. 5 Nusselt number dependence versus the interaction parameter

Fig. 6 Correlation between the Nusselt number and velocity fluctuations

Fig. 7 The area of velocity fluctuations existence in the channels with conducting walls

Fig. 8 Comparison of numerical and test temperature distributions at high N

FIG. 1 SLOTTED CHANNEL TEST SECTION GEOMETRY

FIGURE 2

FIGURE 3

Fig. 4. The effect of magnetic field...

Fig. 5
The effect of magnetic field

Fig 6.
The effect of magnetic field

***** Lower boundary curve , data /5,9,12/ and present exp.
 ##### fluctuations exist in the flow, data from /12/
 ##### fluctuations exist in the flow, data from /5/
 ##### fluctuations exist in the flow, data from present exp.
 (*) ***** ITER conditions

Fig.7

"The effect of magnetic field"

FIGURE 8

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