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Technical Note

Study on Thermal Mixing of MHD Liquid Metal Free-Surface Film Flow

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Abstract — *In this study, the mixing of temperature-stratified liquid metal free-surface flow by a delta-wing obstacle installed on the channel bottom has been experimentally and numerically investigated in the presence of a transverse magnetic field. The surface temperature distribution of the channel was measured by using 25 thermocouples (TCs) embedded in the channel bottom, downstream of the obstacle, which was located upstream of the heater installed at the free-surface. The experiments were conducted for the turbulent flow region where Re = 12,000 and in the range of N = 0–5.02 in the presence of the transverse magnetic field. As for the laminar flow region, it is difficult to carry out the experiment, so the numerical simulations were conducted using Re = 2,300 and in the range of N = 0–10. According to the comparison of numerical results with and without the delta-wing obstacle in laminar flow region, the entire temperature distribution with the obstacle was warmer than that without the obstacle. This was consistent with the expectation that a delta-wing obstacle would increase thermal mixing.*

Keywords — *Thermal mixing, delta-wing, free-surface, MHD.*

Note — *Some figures may be in color only in the electronic version.*

I. INTRODUCTION

Recently, liquid divertor concepts in fusion reactor have been widely investigated for magnetic fusion reactors.[1,2] Free-surface liquid metal flow in fusion reactors has two problems: (1) the localized high heat flux on the free-surface induces a temperature stratification in the fluid that decreases heat transfer at the bottom wall,[3] and (2) the presence of strong magnetic fields directly induces liquid metal free-surface flow due to magnetohydrodynamic (MHD) effects.[1,2,4,5] Therefore, the thermal stratification must be broken by an appropriate vortex generator to enhance the thermal mixing in liquid metal free-surface flow.

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One good vortex generator is the delta-wing, which easily generates a long pair of vortexes that are parallel to the flow direction.[6] Moreover, the fluid of the free-surface is strongly dragged with the vortexes to the channel bottom. This phenomenon enhances the removal of high heat flux localized on the free-surface. Therefore, it can be expected that the vortex generated by the delta-wing obstacle will strongly interact with the vertical and/or transverse magnetic fields, and enhance the thermal mixing in MHD free-surface flow. The previous study[7] investigated thermal mixing in liquid metal ($Ga_{67}In_{20.5}Sn_{12.5}$) free-surface flow without a magnetic field by using various shapes of obstacles. It was concluded that the delta-wing strongly enhanced the thermal mixing. In the present study, the delta-wing obstacle was also used as the vortex generator, and its wake effects on the thermal mixing in liquid metal free-surface flow in the presence of a transverse magnetic field was experimentally investigated. The measurement system was the same as in the previous study.[7]

II. EXPERIMENTAL APPARATUS AND CONDITIONS

The experimental apparatus used in this study is called the "LMX (Liquid Metal Experiment)" located at the Princeton Plasma Physics Laboratory (PPPL). The LMX consists of a 0.80 m length, 0.10 m width acrylic channel as a test section, an electromagnet flow meter, an Archimedes-style screw pump, a heat exchanger cooled by de-ionized water, a set of electromagnets that generate a transverse magnetic field and a storage tank as illustrated in Fig. 1. The working fluid was a gallium–indium–tin ($Ga_{67}In_{20.5}Sn_{12.5}$) eutectic alloy that flowed through the channel with a mean depth of 0.014m at a flow velocity of $0.12ms^{-1}$. Argon gas was used to prevent oxidation of the liquid metal. 25 K-type TCs with an accuracy of ±0.1°C were installed on the bottom of the channel with mostly equal separation of 0.034 m as illustrated in Fig. 2. In order to calculate the heat loss and the mean temperature gradient of the flow for the heat flux evaluation, K-type TCs were installed inside the fluid at the inlet and outlet positions of the channel. The delta-wing configuration is illustrated in Fig. 2, the material of the delta-wing is acrylic resin. The delta-wing (black triangle in Fig. 3) was installed at the center of the flow channel and upstream of the heater that was installed at the free-surface. The obstacle's blockage ratio β was roughly 0.05. The experiments were performed at Re = 12000, and with the interaction parameter $0.56 < N < 5.02$ based on the equivalent hydraulic diameter, the mean flow velocity and the strength of magnetic field. The fluid circulation was driven by an Archimedes-style screw pump with a constant flow rate

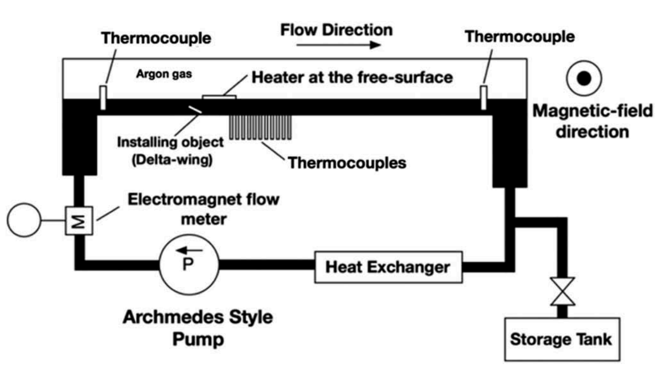

Fig. 1. Experimental apparatus (black area was working fluid; white area was injected argon gas).

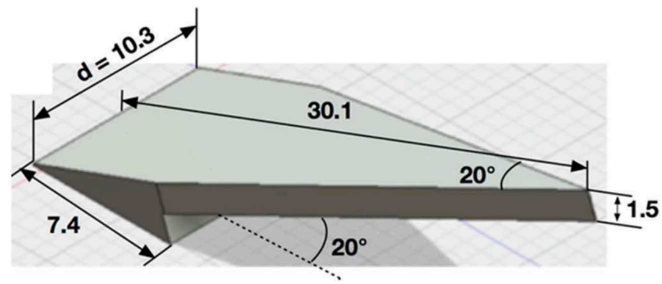

Fig. 2. Delta-wing configuration (all dimensions are mm).

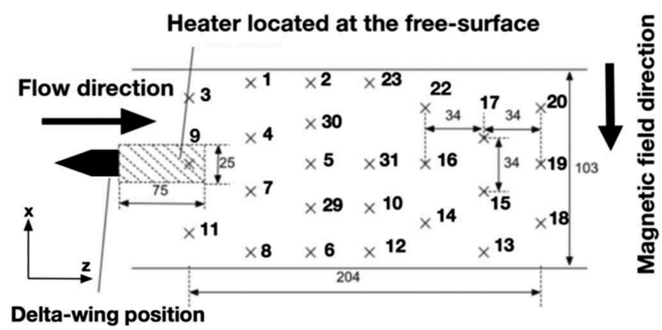

Fig. 3. Schematic of heater location and TCs mapping on channel bottom (bold numbers denote TC#; all dimensions are in mm; x-marks show TC locations).

with 5% fluctuation around the mean.[6] The heater plate was made of Aluminum Nitride ceramic measuring 0.075 m × 0.025 m placed on the free-surface. This heater injected a constant heat flux of 0.18 MWm^{-2} into the fluid, and raised the free-surface temperature by a few degrees. A heat exchanger installed behind the pump was used to cool the heated fluid back to its initial temperature. The experiments were conducted for only the delta-wing obstacle configuration, based on previous experiments.[7]

III. NUMERICAL SIMULATION

At first, in order to know the fundamental MHD free-surface flow behavior, the commercial Software package "STREAM" has been utilized for numerical simulation of the laminar MHD free-surface flow with the delta-wing obstacle. Figure 4 shows a rectangular channel with the same configuration as the LMX test section. To simulate the free-surface flow, the channel top was specified as a free-slip boundary, and no-slip boundary conditions were used for the three walls of the channel. The constant input power 80W was specified as a heat source with 0.075 m × 0.025 m area on the free-surface. The working fluid was $Ga_{67}In_{20.5}Sn_{12.5}$ and the test channel was filled with argon

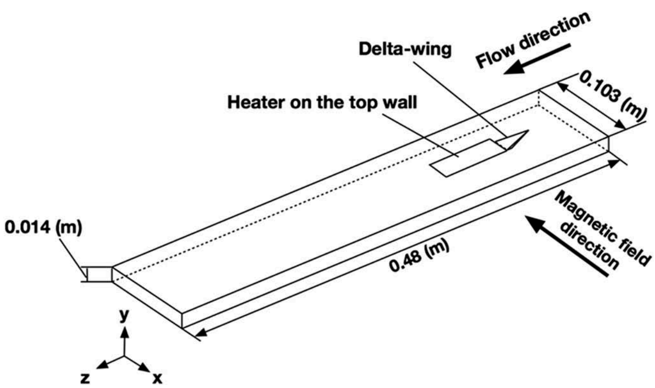

Fig. 4. Computational model similar to the LMX test section.

to prevent oxidation. The numerical simulations were conducted for two different configurations: (a) no obstacle and (b) the delta-wing obstacle. The size of the delta-wing is as same as used in the previous experiments.[7] Transverse magnetic field strengths of 0–0.08T were applied. The flow conditions were set to Re = 2300 and $0 \leq N \leq 10$. The computational mesh was $150 \times 22 \times 690$.

Figure 5 shows contours of the z component of vorticity 0.05m behind the delta-wing for each N. It is found that the vorticity decreases if N increases.

The bottom temperature distributions are illustrated is Fig. 6. Regardless of whether or not the transverse magnetic field is present, the maximum value of the wall temperature in the case of the flow with the delta-wing are higher than temperature distributions in case of the flow without an obstacle, and the higher temperature area is also larger than flow without an obstacle. Therefore, a pair of vortexes from the delta-wing transported heat efficiently. From these results, heat transport performance decreases for MHD flow under the transverse magnetic field even when the obstacle is put into the flow.

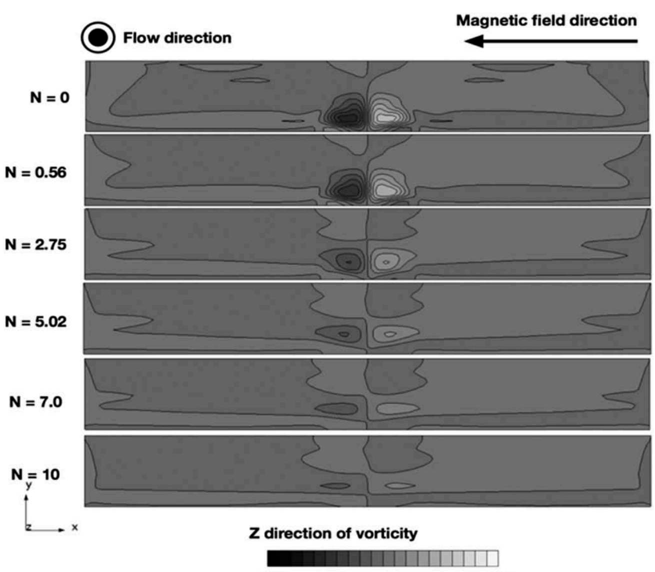

Fig. 5. Contours of the z component of vorticity 0.05 m behind the delta-wing for each N.

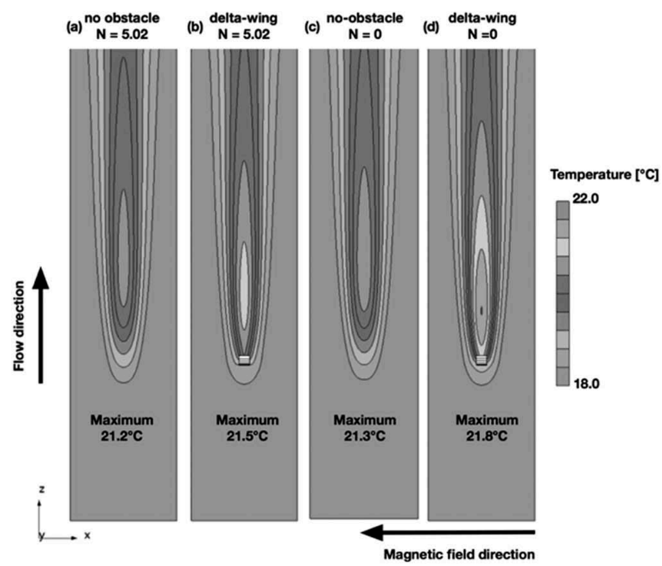

Fig. 6. Bottom temperature distributions: (a) flow without obstacle for of N = 5.02, (b) flow with the delta-wing for N = 5.02, (c) flow without obstacle for N = 0, (d) flow with the delta-wing for N = 5.02.

IV. DATA ANALYSIS

IV.A. Heat Flux and Efficiency of Heat Transport

The temperature data were measured by TCs on the channel bottom and TCs on the inlet and outlet of the test channel. The bulk temperature is assumed to be linear as $T_b = (T_{out} - T_{in})/L + T_{in}$. The local heat flux can be calculated as

$$q_w(x,y) = -k\frac{2(T_b - T_w(x,y))}{H} . \quad (1)$$

To evaluate how much heat is transported from the localized heating region on the free-surface to the channel bottom by the wake of the vortexes, an efficiency of heat transport, γ, can be defined as follows:

$$\gamma = \frac{S|q_w|}{Q_{in} - Q_{loss}} \times 100 . \quad (2)$$

The criteria of temperature rise ΔT_w was set to 0.6°C in this technical note. The efficiency of heat transport is evaluated as a scalar value, and indicates how much thermal energy is transported from the heater on the free-surface to the channel bottom.

IV.B. Spectral Analysis

The temperature fluctuation was primarily induced by vortex shedding from the delta-wing, and also by the turbulence of the flow. Vortexes are affected by magnetic field and identified by the spectral analysis of temperature fluctuation data based on the Fast Fourier Transformation (FFT) as follows:

$$\mathcal{F}\{T_t(t,x,y)\} = \sum_{n=0}^{M-1} T_t(n\Delta t,x,y)e^{-i2\pi nf/M} . \qquad (3)$$

The amplitudes are obtained by the taking the absolute value of Eq. (3). The reason for doing the spectral analysis is due to understanding heat transport characteristics and strength of the vortex rotation in each strength of the magnetic field.

V. RESULT AND DISCUSSION

In the previous study,[7] it was found that the heat loss was over 10% for Re < 10000 in LMX. Thus, this study focused on Re = 12000 with a heat loss of less than 10% in the experiment. The results of the calculation of the heat transport efficiency γ are 84% in the case of N = 0, 82% in the case of N = 0.56, 59% in the case of N = 2.75 and 63% in the case of N = 5.02. Figure 7 shows the heat flux contours in the range of N = 2.75–5.02. The heat flux q_w is defined as being from the channel bottom to the fluid, so that negative heat flux means the fluid temperature higher than the wall temperature. The amplitudes of average wall temperature fluctuations were obtained by spectral analysis for various N as shown in Fig. 8. It was observed that the amplitudes of temperature fluctuations decreased with increasing magnetic field strength. Moreover, the numerical results showed the vorticity decreased with increasing magnetic field strength. These two results suggested that the vortex strength showed the same tendency as the amplitude. Therefore, the amplitude can indicate the vortex strength variation if the presence of a magnetic field. The amplitudes decreased with increasing N, so the vortex strength may be weakened due to the transverse magnetic field.

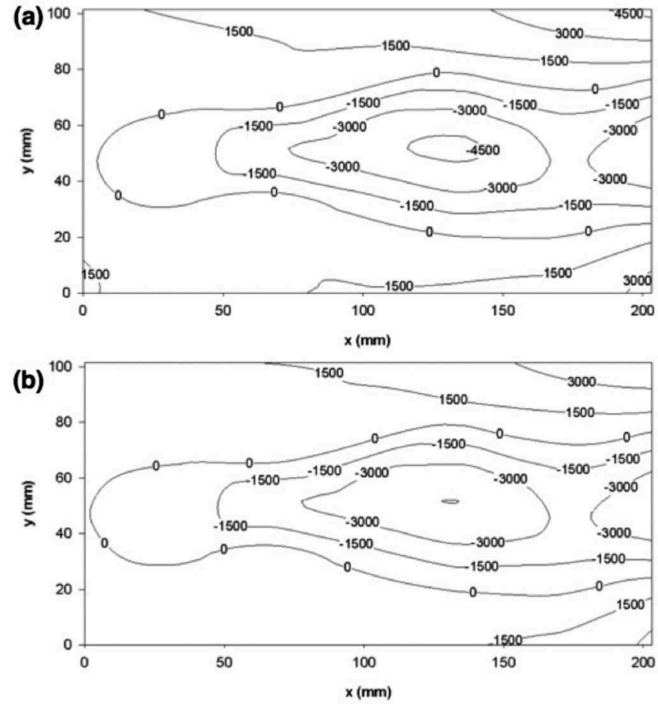

Fig. 7. Heat flux contours: (a) N = 2.75 and (b) N = 5.02.

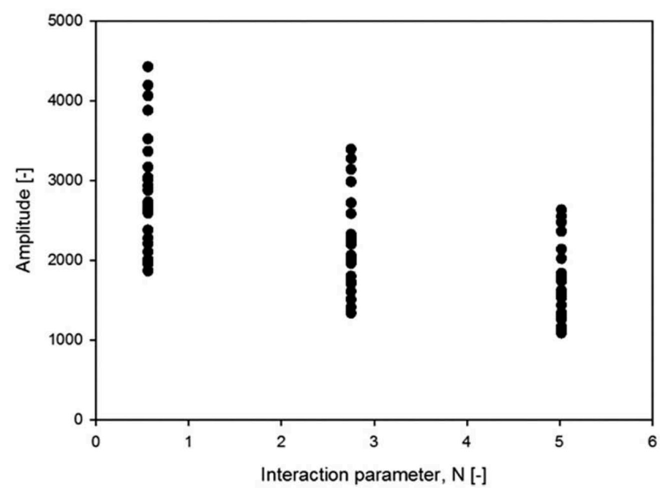

Fig. 8. Amplitudes of average wall temperature fluctuations for various interaction parameters (N).

VI. CONCLUSION

In this study, the thermal mixing of liquid metal ($Ga_{67}In_{20.5}Sn_{12.5}$) free-surface flow with a delta-wing obstacle as a vortex generator under various strengths of transverse magnetic field was investigated.

Based on comparisons among the heat flux contours, the efficiency of heat transport and the laminar numerical simulation, it was concluded that the transverse magnetic field prevented the enhancement of heat transport from the free-surface to the bottom wall. However, according to the comparison of temperature distributions, it was found that the delta-wing obstacle can efficiently enhance the thermal mixing more than that of the no-obstacle case obtained by laminar numerical simulation. The remaining issue to be solved is to understand the reason why there is an inflection point of the efficiency of heat transport between N = 0.56 and 2.75.

Nomenclature

B = magnetic field [T]
d = width of the delta-wing [m]
$\mathcal{F}$ = discrete Fourier transform
H = fluid depth [m]
Ha = Hartman number ($\mathrm{Ha} = Bl\sqrt{\sigma/\rho\upsilon}$) [-]
k = thermal conductivity of fluid [$\mathrm{Wm^{-1}K^{-1}}$]
L = length of the test channel [m]
l = characteristic length($l = 4A/(2H + W)$) [m]
M = number of temperature data on TC [-]
N = interaction parameter ($\mathrm{N} = \mathrm{Ha}^2/\mathrm{Re}$) [-]
Q_{in} = input power [W]
Q_{loss} = heat loss [W]
q_w = heat flux from the wall [$\mathrm{Wm^{-2}}$]
Re = Reynolds number ($\mathrm{Re} = Ul/\nu$) [-]
S = higher temperature area [$\mathrm{m^2}$]
T_b = bulk fluid temperature [°C]
T_{in} = inlet temperature [°C]
T_{out} = outlet temperature [°C]
T_t = measured temperature at time t [°C]
T_w = bottom wall temperature [°C]
t = temperature measuring time [s]
U = mean velocity [$\mathrm{ms^{-1}}$]
W = width of the channel [m]
W = width of the channel [m]
ΔT_w = higher temperature rise at the wall [°C]
Δt = time interval of measuring temperature [s]
β = blockage ration ($\beta = d/W$) [-]
γ = efficiency of heat transport [-]
ρ = density of fluid [$\mathrm{kg\ m^{-3}}$]
σ = electrical conductivity of fluid [$\mathrm{Sm^{-1}}$]
ν = kinematic viscosity [$\mathrm{m^2\ s^{-1}}$]

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