EXPERIMENTAL AND COMPUTATIONAL SIMULATION OF FREE JET CHARACTERISTICS UNDER TRANSVERSE FIELD GRADIENTS

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ABSTRACT

In this paper, we present numerical and experimental studies of the behavior of a liquid metal jet in a constant and gradient magnetic field. The experiments were conducted in the Magnetic Torus Liquid Metal MHD flow test facility (MTOR). The experimental results have shown that free jets can be stabilized by the magnetic field. The Lorentz force signifcantly suppresses the motion of the liquid metal jet and delays the break-up position. Analysis based on linear theory has been applied to understand jet behavior under magnetic fields. In addition, numerical simulation based on B formulation has been performed and compared to the experimental results

I. INTRODUCTION

In a fusion device, the issue of how to protect the bottom part of the reactor interior is a problem. One solution to this problem is to use a divertor that consists of a liquid metal jet. To understand how liquid metal flows in a fusion environment, the three-dimensional effects associated with MHD free jet flows have to be investigated.

In order to generate physics deivce relevant field strength, a magnetic test facility has been constructed. This Magnetic Torus Liquid Metal MHD test facility consists of 24 electromagnets arranged in a magnetic torus geometry and a 3400A/180 V DC power supply. For safety purposes, we use a 16 liter actively pumped Ga-In-Sn flow loop, instead of Lithium which is used in NSTX. However, the physical properties of Ga and Lithium are quite different. Hence, to simulate conditions in NSTX, we use iron flux concentrator pieces to increase the magnetic field configuration by a factor of 2, so that M-Tor can reproduce the similar Hartmann number of Lithium under NSTX conditions. Also, a short nozzle piece is used to allow for break-up to occur further downstream.

For computational simulations, obtaining a 3D liquid metal MHD free jet solution is difficult, particularly because the free surface is involved. The complexities come from the actual description of physical phenomena and accurate mathematical description for the three components of the induced magnetic-field at the physical boundaries and interfaces, as well as proper handling of the numerical challenges encountered in mesh schemes. These facts could lead to an inaccurate solution. However, without using 3D formulations the numerical solutions may not capture the real essence of the problems, and produce misleading results.

Considering that at any given point in time the velocity field of the main hydrodynamic quantity can be directly interacting with the main electromagnetic one (the magnetic field) without any interference, it is possible to build a MHD module into an existing CFD code (FLOW-3D[1] in this case) which has a verified Navier-Stoke's solver for turbulent free surface flows. In the present model, the MHD Lorentz force caused by the induced current is derived from Ampere's law by solving the induced magnetic field equations. A conservative formulation similar to Salah[2] is applied, which leads to the introduction of a penalty factor to impose the local divergence free condition of the magnetic fields.

II. EXPERIMENTAL STUDY

II.1. Parameters of interest and scaling requirements

The purpose of the experiment is to simulate the environment of NSTX. In consideration of safety issues, we use Ga-In-Sn instead of Lithium. Since the physical properties of Lithium (used in NSTX) are quite different from Gallium (which we use in M-TOR), we need to increase M-TOR'S magnetic field in order to simulate magnetic conditions in the NSTX model. In table 1, we list the parameters of interest and scaling requirements. From the table, we can see that the Hartmann number is proportional to the square of σ/μ, and this value of Lithium is twice as high as Gallium. Hence, we need to increase the magnetic field of M-TOR by a factor of 2 to get the same Hartmann number as in NSTX. The Reynolds number is quite high under both conditions, which means that the viscous effect is very small when compared with the Hartmann effect. The Webber number is another important parameter by which we can predict the break up length of the liquid metal free jet. The Froude number is very high both in NSTX and M-TOR, which means the gravity effect is very small (although the density of the liquid metal is pretty high).

Table 1. Parameters and scaling requirements

Parameters of Interest	NSTX	M-TOR	
Fluid	Lithium	Ga-In-Sn	
Operating Temperature (T)	225 °C	35 °C	
Density (ρ)	485 kg/m^3	6400 kg/m^3	
Electrical conductivity (σ)	2.83×10^6 $(\Omega m)^{-1}$	$3.0 \times 10^6 (\Omega m)^{-1}$	
Surface tension (γ)	0.325 N/m	0.533 N/m	
Viscosity (μ)	5.3×10^{-4} kgm/s	2.05×10^{-3} Kgm/s	
Field Strength			
Toroidal	0.318- 0.523 T	0.6-1.12 T	
Poloidal	0.144-(-0.011) T		
Radial	0.02 – (-0.04) T		
Jet diameter (d)	5 mm	5 mm	5 mm
Jet velocity (V)	10 m/s	5 m/s	3 m/s
Flow length (L)	46 cm	45 cm	45 cm
Hartmann Number (Ha)	160.	164	164
Reynolds Number (Re)	4.57×10^4	7.8×10^4	4.6×10^4
Webber Number (We)	746	540	
Interaction Number(N)	0.5648	0.35	0.58
Froude Number (Fr)	14251	14661	13157

II.2. M-TOR facility

The jet experiments using Ga-In-Sn under the effects of a transverse field and a transverse field gradient have been conducted in the Magnetic Torus Liquid Metal MHD flow test facility (M-TOR). M-TOR consists of 24 electromagnets arranged in a magnetic torus geometry, a 3400A/180V DC power supply, and a 16 liter actively pumped Ga-In-Sn flow loop (see Figure 1). The M-Tor facility gives about 0.6 T at the inboard when it is run at the maximum current of 3400 A.

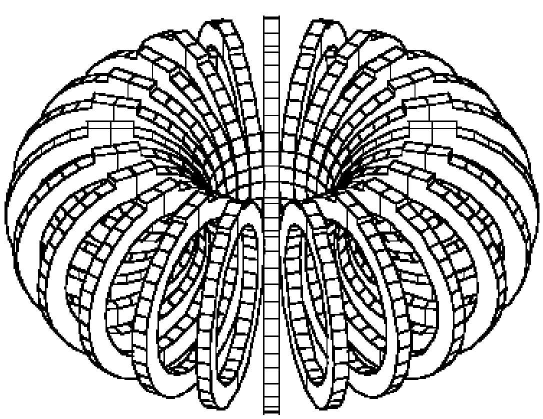

Fig. 1. The M-TOR facility

II.3. Transverse magnetic field configurations

To achieve a higher field, flux concentrators have been placed in M-TOR to alter local flux distribution and produce a stronger field in the experimental area (see Figure 2). The flux concentrators are shaped to provide a field gradient similar to that in NSTX. The concentrators assembly includes a pair of large iron circle disks, which grasp the flux and redistribute it into a small iron block region. These small iron pieces are shaped to a designed curve which can provide the proper magnetic field. The field strength depends on the distance between the pair.

We measured the transverse magnetic field with the iron flux concentrators in place (see Figure 3). When compared with NSTX's magnetic field, we found the gradient of the magnetic field to be nearly identical. However, the absolute value of the magnetic field in the toroidal direction produced by M-TOR is almost twice as high as NSTX's, which is precisely what we designed for, based on the parameter scaling analysis shown above. The free jet experiment, by using Ga-In-Sn under this M-TOR magnetic field, can simulate the conditions of Lithium in NSTX with a similar Hartmann number and other parameters. For the M-TOR simulated toroidal magnetic field, the average field gradient is about 1.3T/m, while the average field gradient of the surface normal field is about 0.36T/m.

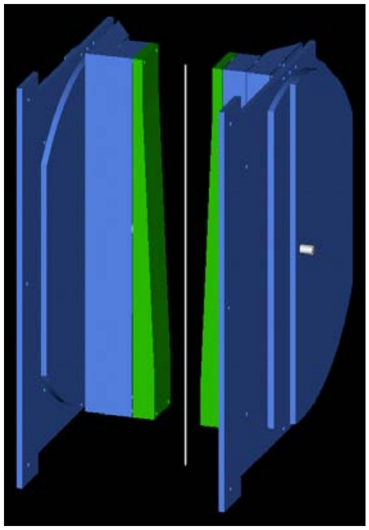

Fig. 2a. Tapered pole face to produce 1-D (toroidal) field gradient

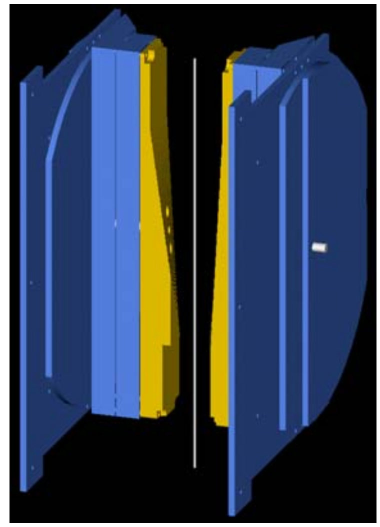

Fig. 2b. Twisted- tapered pole face to produce 2-D (toroidal and surface normal) field gradient

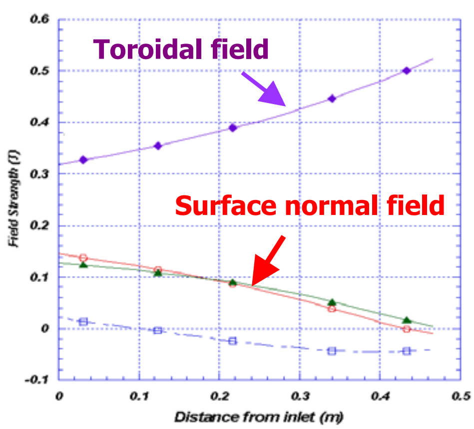

Fig. 3a. NSTX magnetic field

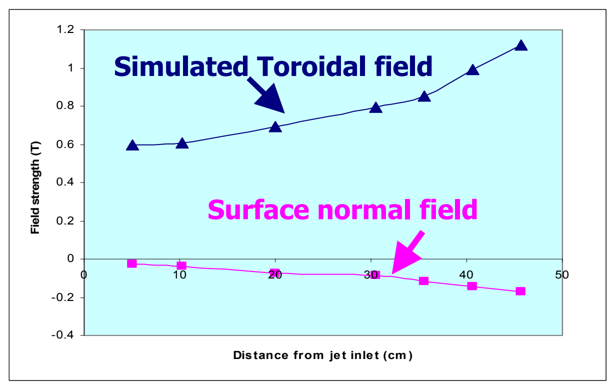

Fig. 3b. Simulated magnetic field

II.4. Nozzle configuration

Nozzle configuration plays a key role in the free jet experiment because a well-designed nozzle can produce a smooth, cylindrical and steady jet. In this experiment, a short nozzle with a specific contracting section is used to allow break-up to occur further downstream. We chose Acrylic as the construction material for the nozzle and test section because of its high strength, high transparency and , ease of machining. A uniform honeycomb is used to straighten the flow and reduce the initial disturbance. Because the honeycomb structures are arrays of tubular elements arranged parallel with each other and the axis of the free jet, it eliminates both large scale transverse velocity components and smaller scale irregularities present in the incoming flow. The free jet proceeds out of the 5mm circular nozzle and passes through a constant field and a gradient field before returning to the flow loop.

II.5. Experimental set-up

The experimental set-up includes the magnetic field set-up, the fluid flow loop, the free jet system, the cooling system and the visualization system (see Figure 4). Since the experiment was conducted in a high magnetic field, the magnetic forces cause the compression of the center of the flux concentrators and the pulling apart the edge of the flux concentrators. Hence, it is important to use a strong structure to support the iron flux concentrators, and all loose magnetic parts must be outside of the field.

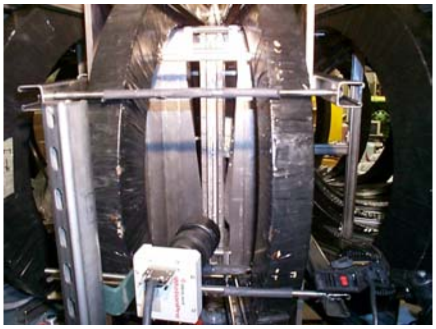

Fig. 4. M-TOR experimental setup with iron flux concentrators

III. RESULTS AND ANALYSIS

Experimental observations of Ga-In-Sn jet characteristics under the effect of transverse field and field gradients can be summarized as follows:

- The M-TOR NSTX-like magnetic field strength has significantly stabilized the jet by suppressing velocity perturbations
- The stabilizing effect of the magnetic field results in delaying jet break-up
- MHD Lorentz forces significantly dampen the vortex structure
- No quantifiable deflection has been observed on jets passing through an NSTX-like outboard divertor for both 1-D (toroidal) and 2-D(+surface normal) steady state transverse field and field gradients

These behaviors are consistent with the data analysis in the literatures[3-5]. A detailed discussion on each phenomena is presented below.

III.1 Deflection of the free jet

One important issue when using jets under a complex magnetic field environment is the predicting of the jet trajectory. For example, will the jet deflect under a transverse field gradient? To identify whether there is a deflection of the free jet, we designed a observing structure to observe the front-back image (see Figure 5).

The front-back jet images indicate that the front edge of the jet maintained the same position as the field turns on (see Figure 9). This implies that the free jet kept the same position without any deflection. It also implies that jet turbulence was greatly suppressed. These resutls can be verified by the following theoretical analysis.

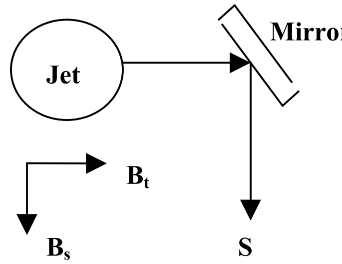

Fig. 5. Observing system to detect the deflection of the free jet

Considering that in our experiment, the Reynolds number is much greater than 1, we can perform a theoretical analysis of a three-dimensional jet based on the linear assumption[3]. For our experiment, although the free jet will pass through a gradient magnetic field in a vertical direction, we can consider that for every horizontal cross-section as a close current loop put into a uniform magnetic field (see Figure 6). Although the net magnetic torque is not equal to zero, the net force of such a loop is equal to zero. For an arbitrary distribution of current density **J,** we can treat it as the superposition of such loops. From the figure, we can see that for every fluid element which is accelerated by the Lorentz force, there is a corresponding element which receives an equal and opposite deceleration. Thus the Lorentz force can not change the linear momentum of the fluid, although it destroys kinetic energy.

Davidson [3] performed that

$$\int_V \vec{J}_i dV = \int_V \nabla \cdot \left(x_i \vec{J}\right) dV = 0 \qquad (6)$$

So we can get:

$$\int_V \vec{F} dV = -\vec{B} \times \int \vec{J} dV = 0 \qquad (7)$$

Similarly, we can show that the component of the angular momentum parallel to **B** can not be created or destroyed by the Lorentz force, i.e., it remains unchanged.

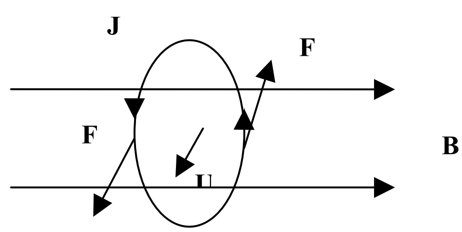

Fig.6 The horizontal cross-section of the free jet in the magnetic field

III.2 Change of cross-section and delay of free jet break up

Experimental results are shown in front view jet images as the jet proceeds downstream 22~24 inches in a 1-D magnetic field (see Figure 10a and Figure 10b). Comparing the pictures without magnetic field and with maximum magnetic field, we found that along the magnetic field direction the thickness increases by 15%, which means the cross-section elongates.

According to Davidson[4] linear analysis, if we define global dissipation E_D:

$$E_D = -(\rho\sigma)^{-1}\int_V \vec{J}^2 dV \tag{8}$$

we can get:

$$\frac{dE_D}{dt} = -2\int_V \vec{F}\cdot\frac{\partial\vec{u}}{\partial t}dV \tag{9}$$

This means that with the Lorentz effect, the global dissipation will always decline, and decline at a much greater rate than kinetic energy. Davidson [6] showed that the jet would preserve the linear and angular momentum through cross-section distortion. It can be shown that the momentum will diffuse out along the **B** lines and the **J** lines elongation along the **B** lines, which will minimize Joule dissipation (see Figure 7).

Shercliff [6] showed that in current-carrying fluid jets, 'sausage' and 'spiral' instabilities can occur. And if such instabilities occur, the cross-section area of the jet will diminish in places until jet break-up occurs.

As it is known, the Lorentz force decreases the velocity of the free jet. Thus the Webber number decreases correspondingly, which will cause the break-up length to decrease. One explanation to this paradox is that because in our experiment the Hartmann number is as high as 190, the Hartmann layer effect can be significant.

These observations suggest that the break-up length with a magnetic field can be expressed as:

$$L = \alpha L_{classic} \tag{12}$$

Where α is a coefficient related to the Hartmann number and varies from 1.05 to 1.13 within limited M-TOR data.

III.3 Change of the vortex structure

As it is known, if we ignore υ, and hence the process of energy removal via the energy cascade, the magnetic field will introduce anisotropy into the turbulence (as shown in Figure 8). This effect can be seen in Figure 11 where the jet turbulence structures at 4-6 inches downstream are shown and compared with different magnetic field strengths (as coil current increases the magnetic field increases).

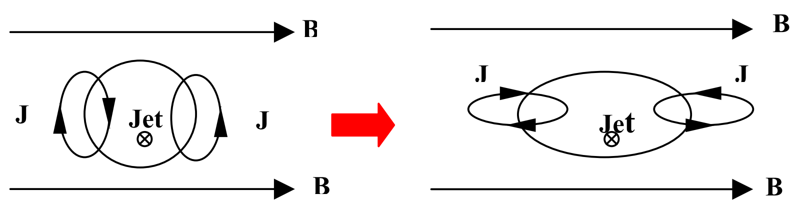

Fig. 7. Cross-section and current density changed with magnetic force

In our experiment, we observe the same, although we did not apply the current to the free jet flow. Figure 10a and Figure 10b show that when the velocity of the flow jet is equal to 3m/s, we can observe jet break-up, whereas when we increase the velocity to 5m/s, break-up is diminished. The interesting thing is that with the magnetic field increasing, the Lorentz force can delay break-up, which is different from what we thought before.

According to classic liquid jet theory (such as Phinney's correlation) the break-up length will increase with Webber number:

$$\frac{L}{d} = 55 + 1.085\sqrt{We} \tag{10}$$

Where

$$We = \frac{\rho U^2 L}{\sigma} \tag{11}$$

As shown, as the magnetic field increases, the MHD effect suppresses the turbulence significantly and the large vortex structure breaks up into several small vortex structures. At the same time, the vortex structure was dampened and stretches along the flow direction (perpendicular to the magnetic field).

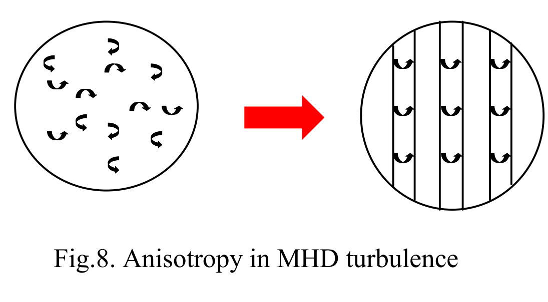

Fig.8. Anisotropy in MHD turbulence

IV. NUMERICAL METHODS

IV.1. Governing equations

The flow of an electrically conducting fluid under the influence of an external magnetic field is governed by the following equations, which express the conservation of mass, the momentum and the magnetic field equations,

$$\nabla \cdot V = 0 \tag{1}$$

$$\frac{\partial V}{\partial t} + (V.\nabla)V = -\nabla p + \frac{1}{\mathrm{Re}}\Delta V + N(j \times B), \tag{2}$$

$$\frac{\partial B}{\partial t} + (V \cdot \nabla)B = \frac{1}{\sigma\mu_m}\nabla^2 B + (B \cdot \nabla)V + \nabla q \tag{3}$$

Here, a penalty factor is introduced to force the magnetic divergence toward zero based on the technique discussed in reference[2]. Similar numerical schemes, as well as boundary condition treatments adopted in the reference[2], have been applied. Although a detailed treatment of properties at the free surface cells are considered in this session of this numerical scheme. Numerical analysis has been performed to simulate the M-TOR conditions. Due to the large computation time that is required, only the first 10cm of Ga-In-Sn jet behavior has been calculated. In this sense, we are not yet able to state with complete confidence whether or not the computational model and associated numerical method have been adequately described jet MHD behavior. However, these results have revealed correct phenomena when compared to other calculations in the literature.

IV.2. Results and Analysis

The computational simulation results are based on a modified version of Huang's[7] program. The computational domain is 500mm×15mm×15mm and the total mesh is about 270000. The inlet velocity is 5m/s, the Reynolds number is 78048, and the Hartmann number is ~ 190. Figure 12a and Figure 12b are the x component velocity contours in y-z cross-section at 4cm and 6cm downstream without magnetic field, and with 1-D magnetic field gradient along the y direction. We can see with the MHD effect, the maximum velocity at these locations decrease about 15% when the field is on which result in the cross-section of the free jet increasing correspondingly (identical to the experimental results). Figure 13 shows the induced magnetic field Bx (where the maximum induced magnetic field is about 0.2% of the applied magnetic field) and the induced current density Jx contour lines. From this figure we can see the induced magnetic field and current density display complex vortex structures. The induced magnetic field is symmetric perpendicular to the original magnetic field and the induced current density displays symmetry along the original magnetic field.

V. CONCLUSION

This paper presents the experimental and numerical results of a free jet flow with MHD effects. The results show that as the magnetic field increases, the Lorentz force suppresses the motion and dampens the vortex of the liquid metal, and the jet flow becomes more stable. But the gradient of the magnetic field does not change the shape of the free jet.

The numerical method achieves good results for 3D free surface MHD flow at a high Hartmann number by assuming that the induced magnetic field equals zero at the outside boundaries of a thick insulated wall. The magnetic field is assumed to be continuous at the wall and fluid interface.

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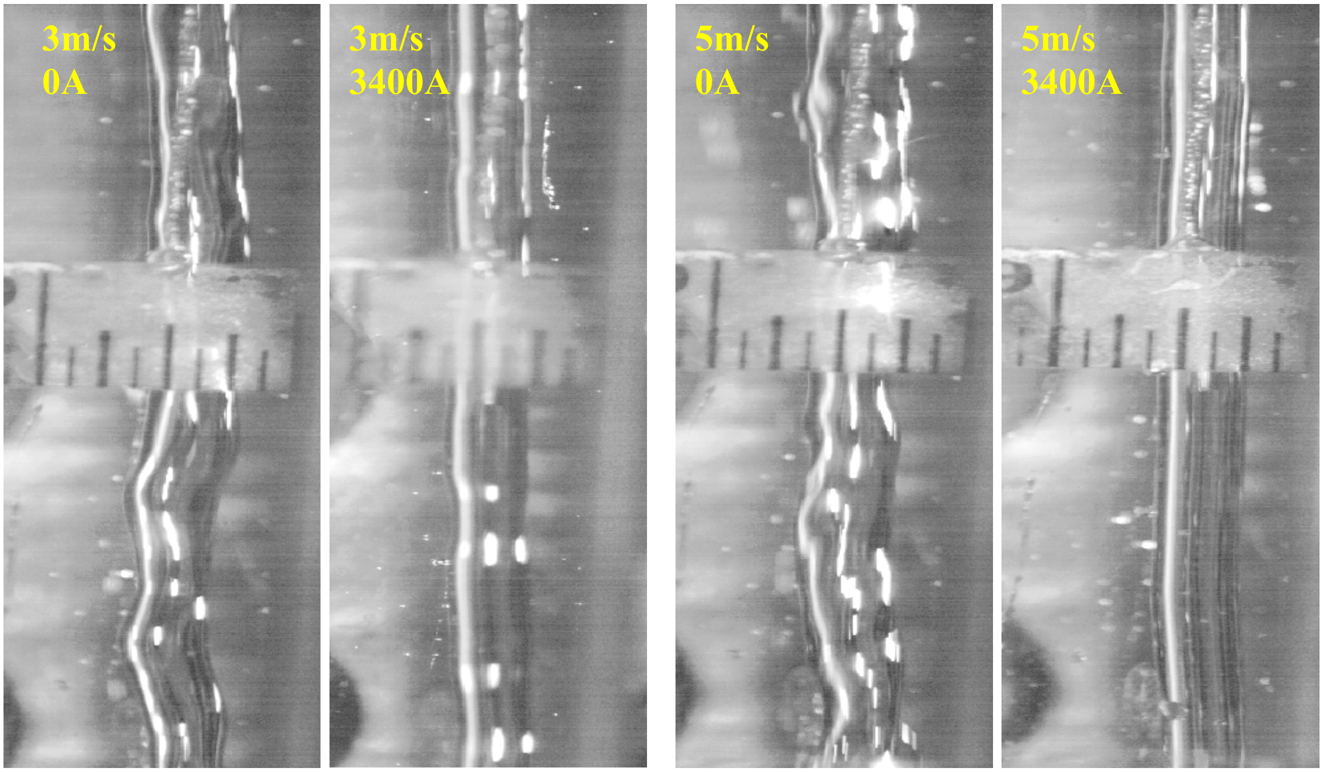

Fig.9. Mirror images in 2-D magnetic field

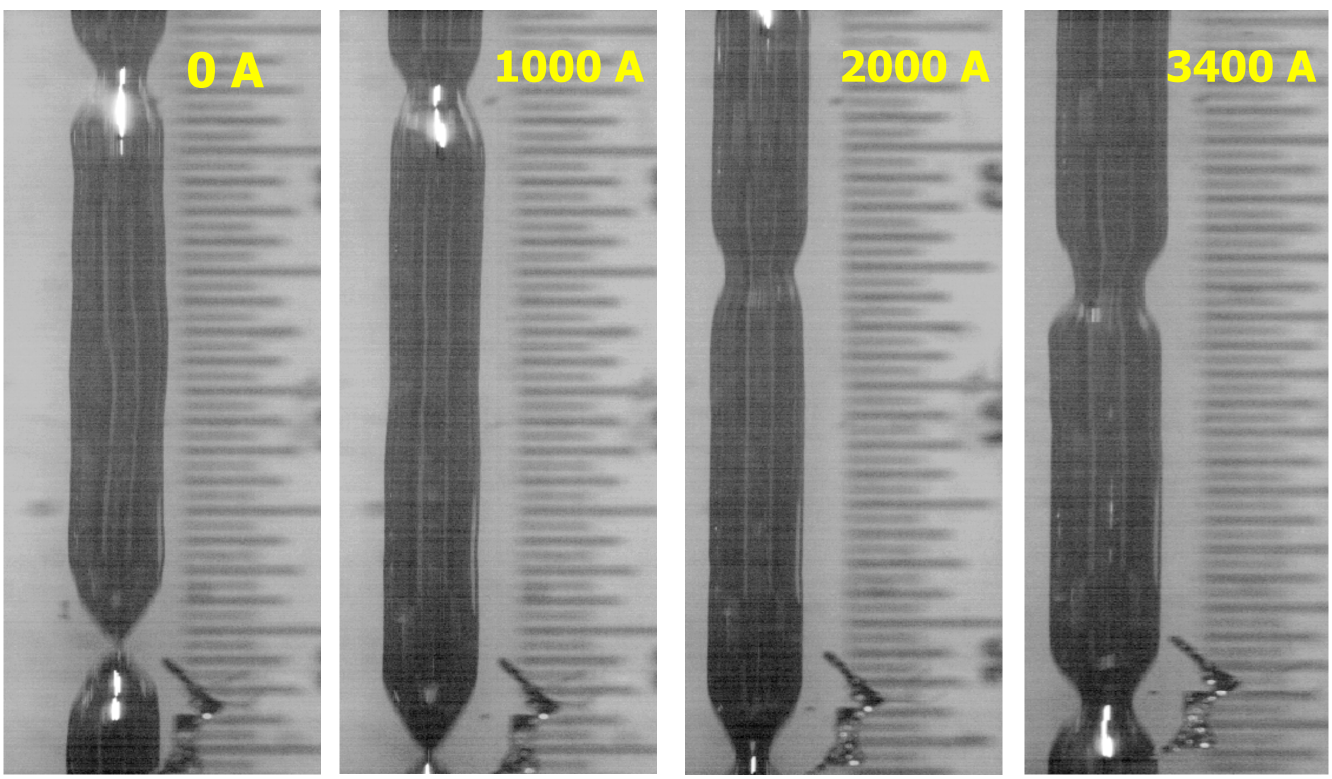

Fig.10a. Downstream 22-24 inches with velocity=3m/s in 1-D magnetic field

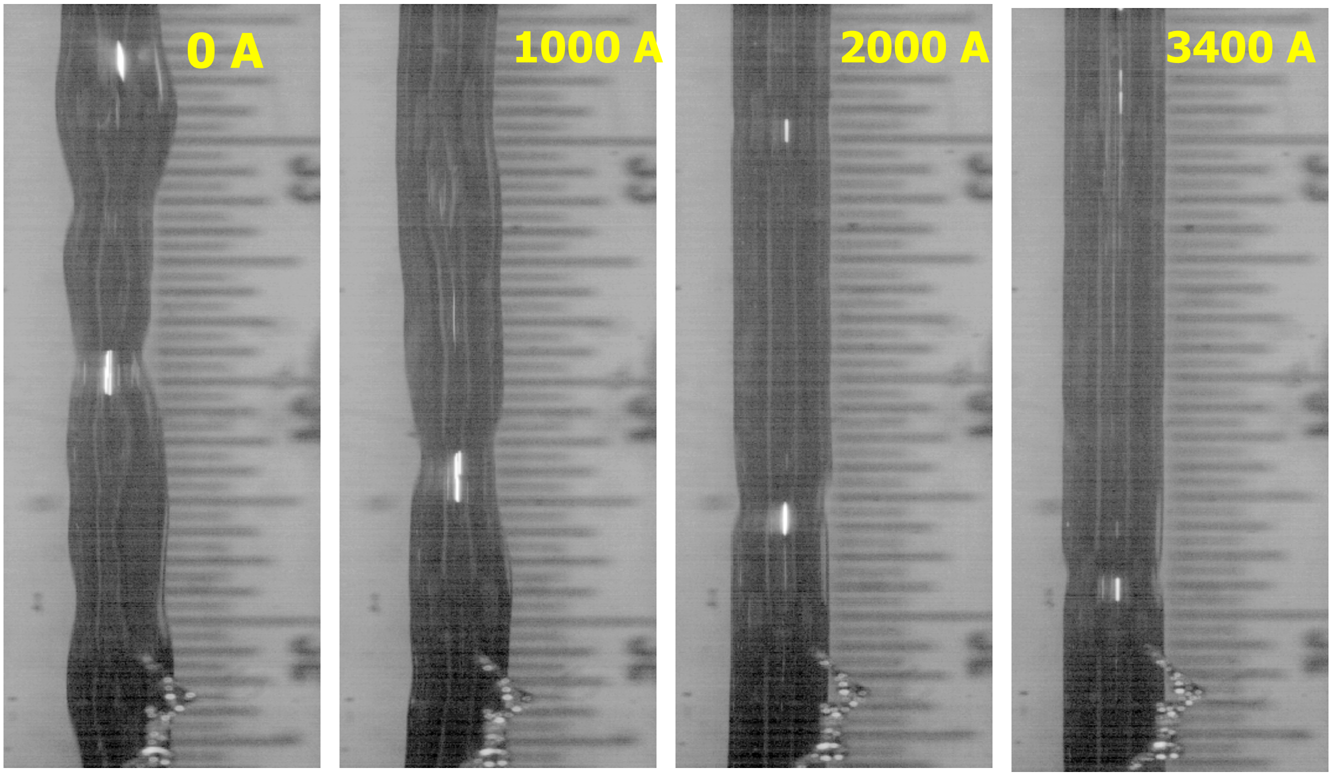

Fig.10b. Downstream 22-24 inches with velocity=5m/s in 1-D magnetic field

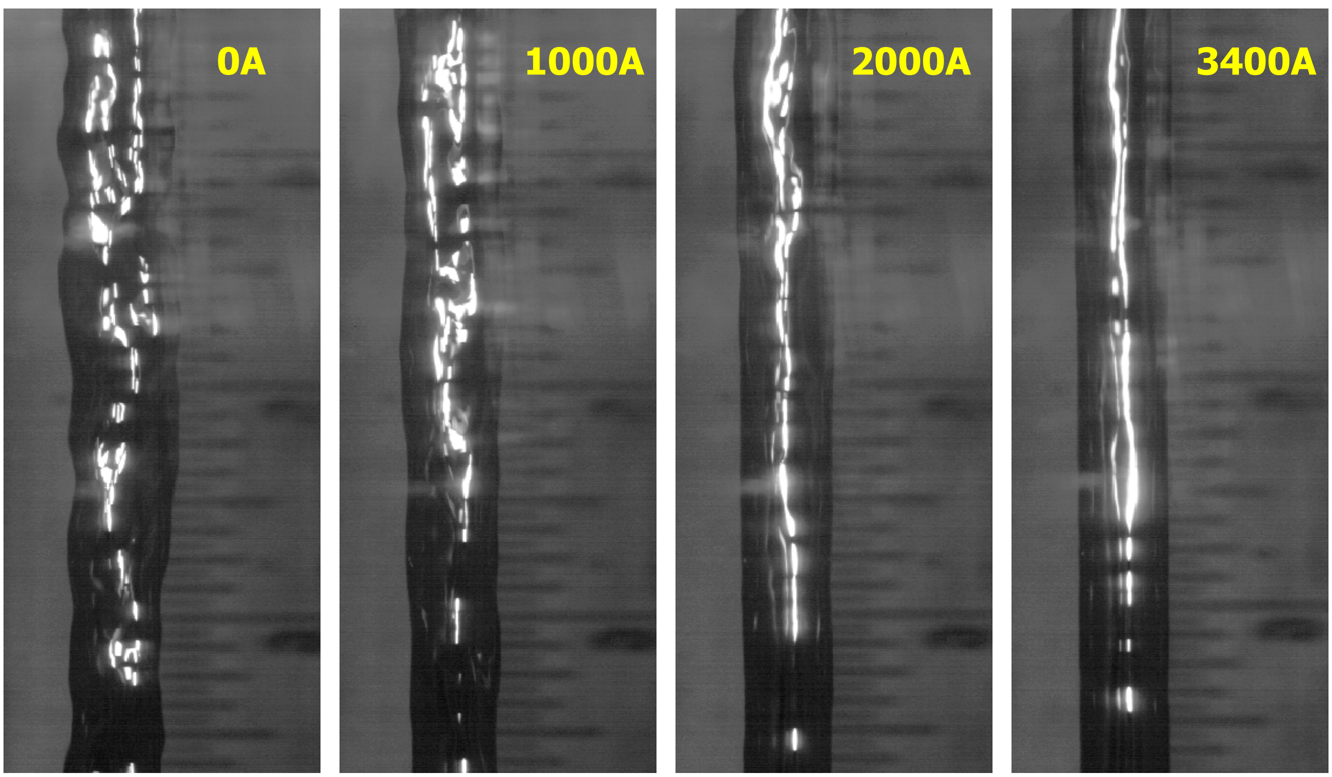

Fig.11. Downstream 4-6 inches with velocity=3m/s in 2-D magnetic field

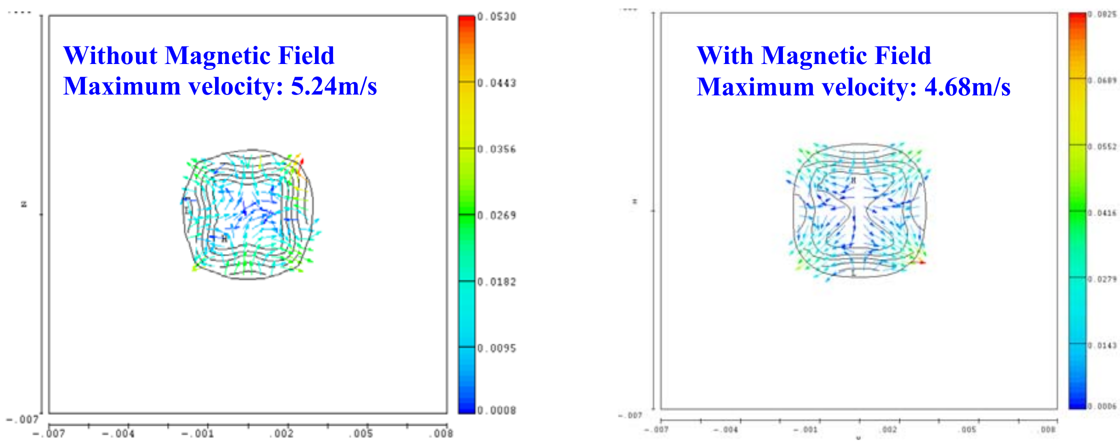

Fig.12a. X-component velocity contours at downstream 4cm

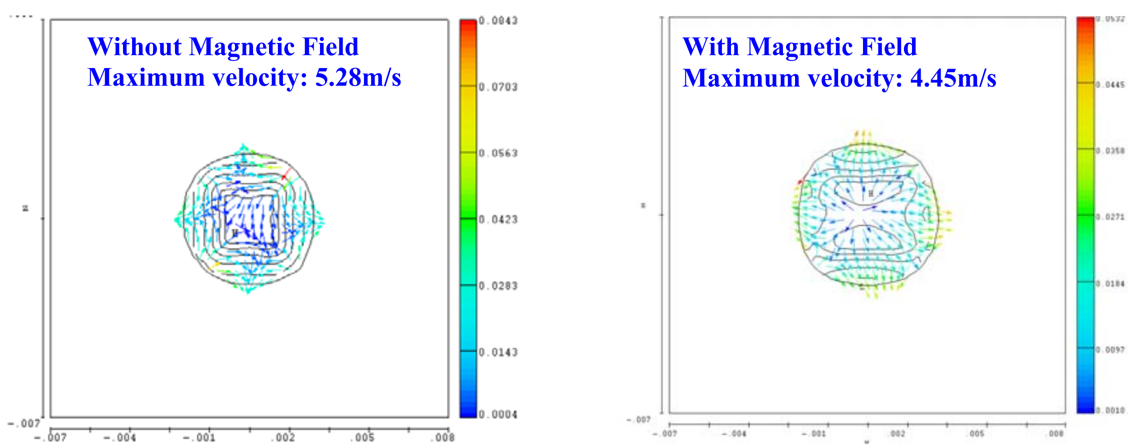

Fig.12b. X-component velocity contours at downstream 6cm

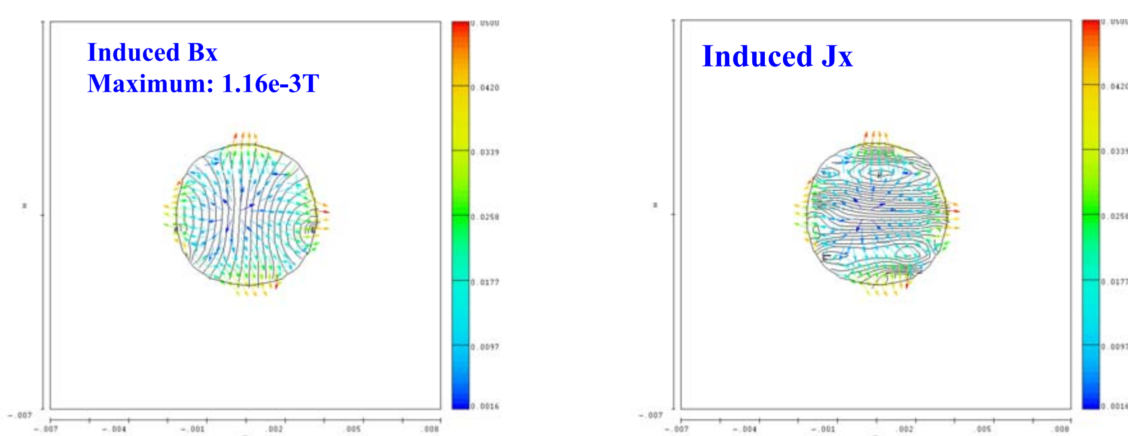

Fig.13. Downstream 6cm with velocity=5m/s in 1-D magnetic field