EXPERIMENTAL ANALYSIS OF SOAKER HOSE CONCEPT FOR FIRST WALL/DIVERTOR APPLICATION

Tomotaka Morikawa, Alice Ying, Jonathan Burris, Mohamed Abdou

Fusion Engineering Sciences Laboratory, University of California, Los Angeles, CA 90095
tmorikaw@ucla.edu

To analyze the effectiveness of the soaker hose concept experimentally, three cases of experiments; vertical, horizontal, and inclined, were conducted. The results have clearly shown that the Lorentz force acts on the liquid metal when current is applied perpendicularly to the magnetic field as seen in the previous numerical analysis. Specifically, the MHD Lorentz force has redirected the flow, modified the shape of the flow surface, and retarded the inlet flow. In particular, the effect of the Lorentz force is pronounced in the horizontal setting. In any settings, however, the surface tension and surface wetting play a significant role in determining flow characteristics. These are challenging problems that need to be resolved in order to put forward this concept for practical application.

I. OBJECTIVES

To allow the first wall/divertor to remove the intense radiative surface flux and to prevent it from being damaged, creating a liquid metal free surface wall is one of the constructive goals in the fusion engineering field. Several concepts related to the liquid metal wall have been considered including film flow and free surface jets [1,2]. However, these ideas may not be feasible due to the liquid metal flow crossing a magnetic field. In such a condition, the soaker hose idea was proposed for this first wall/divertor application by flowing liquid metal along the field lines or flowing toroidally [3]. Although numerical analyses have been performed for feasibility evaluations, few experiments have been carried out. The objective of this work is to analyze the effectiveness of the soaker hose concept experimentally.

II. CONCEPT OF THE SOAKER HOSE

In this concept, pentagonal shaped hoses, shown in Fig. 1, are placed parallel to each other to form a first wall/divertor. Liquid metal, lithium in the real application, is introduced into the plasma-facing surface of the first wall by the differential pressure head while current is applied to the liquid metal to create a Lorentz force to redirect the flow. The Lorentz force pushes the flow inward radially, and then the liquid metal flows toroidally along the surface of the hose. The liquid metal flows down between each hose, is collected, and is reused after being cleaned. Fig. 1 shows this concept schematically.

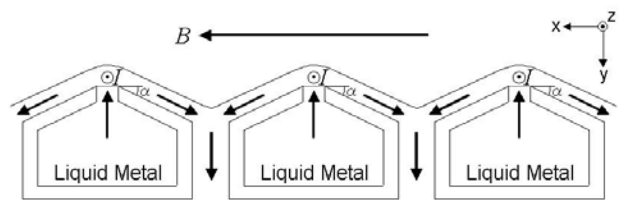

Fig. 1. Soaker hose concept

III. EXPERIMENTS AND RESULTS

III.A. Experimental Settings

In this study, the experimental setting shown in Fig. 2 was used. Three cases of experiments; vertical, horizontal, and inclined, were conducted by changing the angle of the pipe (③).

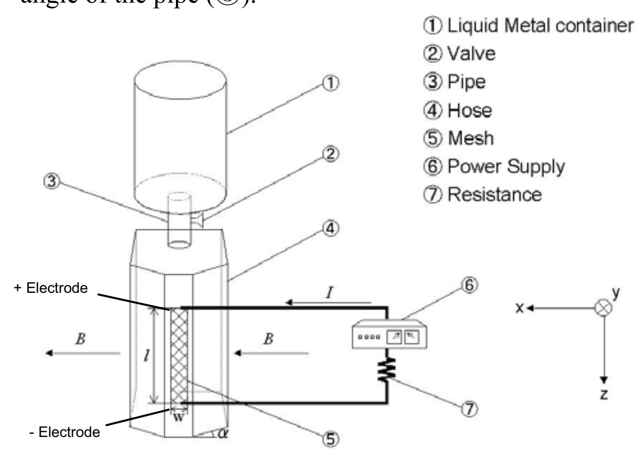

Fig. 2. Experimental setting (vertical case)

Acrylic, an electrically isolated material, was used as the hose material (④) with copper tape attached on the surface. Although electric current is not completely confined inside the liquid flow with an electrically conductive coating, this copper tape coating plays a significant role to obtain better wetting between the surface and the liquid metal and consequently creates a more desirable flow. Gallium-Indium-Tin (Ga-In-Sn) alloy, whose properties are listed on TABLE 1, was used instead of the actual working fluid (lithium) as the experimental fluid. This Ga-In-Sn alloy is safer and easier to use at room temperature than Lithium. The liquid metal was stored in the container (①), and introduced through the stainless steel mesh (⑤) into the magnetic field, which was produced by placing two permanent magnets facing each other. Static pressure head was used to introduce the liquid. Mesh at the liquid flow path was used to obtain a larger velocity due to a smaller surface area. The mesh was 60 X 60 squares/inch with a wire diameter of .0075" and made of 316 stainless steel. The flow rate was adjusted by the valve (②) between the container and the hose. The resistance (⑦) was used to make the circuit stable since the resistance of the Ga-In-Sn alloy is relatively small. Using an available power supply (⑥), current applied to the liquid metal reached a maximum value of 40A, while the magnetic field at the center of the hose was measured at 0.24T in the vertical settings and 0.20T in the horizontal and inclined settings. In this study, current was flowing along the liquid flow path and perpendicular to the magnetic field, resulting in a Lorentz force perpendicular to the flow path. α, which is the incline of the hose surface as shown in Fig. 2, determines the value of the Lorentz force operating to redirect the flow since only the component parallel to the hose surface influences the flow direction. The fixed incline, $\alpha = 8°$, was used in the experiments, resulting in about 14% of the total Lorentz force acting parallel to the hose surface. In addition, the following fixed dimensions were used for the liquid flow path: $l = 1(inch)$, $w = 0.12(inch)$.

TABLE 1. Properties of Ga-In-Sn

Operating Temperature (T)	35 ℃
Density (ρ)	6400 kg/m^3
Electrical conductivity (σ)	3.0x10^6 (Ωm)$^{-1}$
Surface tension (γ)	0.533 N/m
Absolute Viscosity (μ)	2.05x10^{-3} kg-m/s

The parameters to be considered in this experiment were the inlet velocity and the strength of the Lorentz force (which is the cross product of the magnetic field and the current density).

III.B. Preparatory Experiments

Prior to the main three experiments, several preparatory experiments were conducted with the vertical hose settings to determine the position on which current is applied to the liquid metal and the appropriate way to obtain desirable steady flow from the hose.

To determine the position where current is applied, a hose with an extremely thin slit, *w*=0.003" (the thickness of a transparency), was used with no mesh attached at the liquid flow path and the experiment with two different current application points shown in Fig. 3 were conducted; one was with current applied inside the hose, as M. Kotschenreuther suggested in his memo [3], and the other was with current applied on the hose surface.

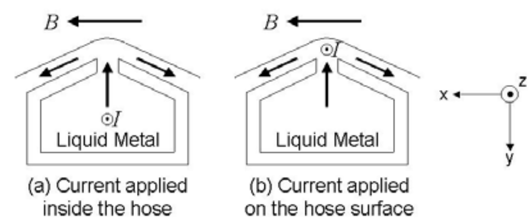

Fig. 3. Settings for the Preparatory Experiments

A small amount of current (up to 5A) was applied in both cases, with the magnetic field being 0.24T. The only difference in these experiments was the current application points and all the other conditions, such as the magnetic field and apparatus settings, were the same. Although no distinct changes in the flow were seen when the current was applied inside the hose, slight changes were seen when current was applied directly to the liquid surface. The flow was slightly flattened and widened by the Lorentz force. The resistance of the liquid metal at the flow path was high due to the extremely thin slit and current may only be confined inside the reservoir when it was applied inside the hose. On the contrary, the high resistance of the extremely narrow liquid path would hinder the current flowing into the reservoir when current was applied on the surface, and all the current could be considered to flow only on the surface. This result shows that the current needs to be applied directly to the liquid on the surface, not inside the reservoir. In the following experiments, current was applied on the hose surface.

In addition to the experiments above, it was also seen that with higher current, the flow was flattened more and spread wider on the surface. However, when current reached a certain amount, around 10A to 15A in this setting with a 0.003" slit, the liquid suddenly splashed out at the point where current was applied and a spark occurred at the edge of the wire. This indicated that the mass of the liquid was too small to hold those sizes of currents. A large mass of the flow was needed for the liquid metal to carry stronger currents, and a small inlet velocity was needed to prevent liquid from splashing out. Therefore, the use of mesh attached at the exit of the wider flow path was considered.

In the experiments described in the following sections, a slit of $w = 0.12''$ with mesh attached along the flow path (shown in Fig. 2) was used. Desirable steady flow was obtained with this setting due to the high friction of the mesh, and the liquid metal came out from all over the mesh. In addition, this setting could hold a higher amount of current than before, up to 40A, which was the maximum current that the power supply used in this experiment could supply.

III.C. Horizontal Setting

In this horizontal setting, in which the liquid metal was introduced into the magnetic field perpendicularly upward, both the gravitational force and the Lorentz force plays a role to push the liquid down to the hose surface. The following values were used in this experiment: $I = 0 \sim 40(A)$, $B = 0.20(T)$, where I is the externally applied current, B is the magnetic field. v_0, the inlet velocity, was calculated from the decrease in the liquid metal in the container, and was about 3.0 cm/s. The experiment time was so small that the change of the static head in the container was negligible. In addition, the thickness of the liquid metal on the hose surface, estimated by flow pictures, was 0.02", and thus the initial toroidal velocity v_1 was about $9.0(cm/s)$ from continuity. Fig. 4 below is the top view pictures of the flow surface profile evolutions subjected to the Lorentz force acting on the liquid metal.

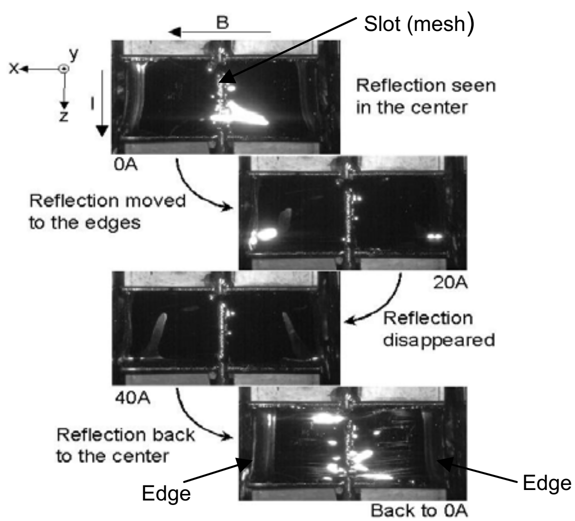

Fig.4. Pictures of the flow surface profiles vs. externally applied currents (horizontal setting)

This figure shows that the Lorentz force smoothes the surface, which can be seen from its reflection changes. This surface modification makes this soaker hose concept useful even in the horizontal wall/divertor, where gravitational force holds the liquid onto the surface. White lines in the last picture (the picture of 0A case) are the oxidized liquid metal. This experiment was conducted in the normal air, and oxidization, which could interfere the flow, was one of the big concerns. Non-oxidization is an important factor for the further successful experiments, which can be achieved by covering the apparatus with an inert gas such as Argon.

TABLE 2 shows the effects of the MHD force on the inlet velocity in this horizontal setting. In this table, the inlet velocity was calculated from the amount of the liquid released from the container over a certain time. The velocity drop, outward inertia force, and Lorentz force were calculated as follows;

$$\text{Velocity Drop} = \frac{v_{0(\text{w/o current})} - v_{0(\text{w/ current})}}{v_{0(\text{w/o current})}} \times 100(\%) \quad (1)$$

$$\text{Outward Inertia Force} = \rho A v_0{}^2 = \rho l w v_0{}^2 \quad (2)$$

$$\text{Lorentz Force} = l(\boldsymbol{I} \times \boldsymbol{B}) \quad (3)$$

where, ρ is the density of the Ga-In-Sn, A is the area of the flow path on the hose, v_0 is the inlet velocity, l and w are the length and width on which current is passed, $\boldsymbol{I}$ is the current, and $\boldsymbol{B}$ is the magnetic field.

TABLE 2. Experimental Result in the Horizontal Settings

Current		Inlet Velocity v_0 (cm/s)	Velocity Drop (%)	Outward Inertia Force F_{out} (N)	Lorentz Force F_{BxJ} (N)
40A	OFF	3.11	4.30	4.80×10^{-4}	0.2032
	ON	2.98		4.40×10^{-4}	
30A	OFF	3.23	3.63	5.18×10^{-4}	0.1524
	ON	3.12		4.81×10^{-4}	
20A	OFF	2.97	2.96	4.38×10^{-4}	0.1016
	ON	2.88		4.12×10^{-4}	
10A	OFF	2.34	1.36	2.71×10^{-4}	0.0508
	ON	2.31		2.64×10^{-4}	

*Note that the surface tension force calculated as $\frac{\gamma}{\omega} \times A$ is about 0.0257N, where ω is the mesh size and A is the liquid flow path area.

This table shows a linearly increasing tendency of the velocity drop with the current, which means that the Lorentz force has resulted in decreasing inlet velocity as the supplied current increases. Although its magnitude is relatively small, it is about a 5% decrease at a supplied current magnitude of 40A. This shows that the Lorentz force resulted in not only spreading out the liquid but also slowing down the velocity of the liquid coming out. In addition, the outward inertia force calculated from the inlet velocity was much smaller than the total Lorentz force acting on the liquid. This result indicated that only a small amount of current was flowing in the flow path (otherwise liquid metal did not come out but was pushed back to the inside hose by the stronger Lorentz force) while most of the current flowed over the liquid metal surfaces.

III.D. Vertical Setting

In the vertical setting, shown in Fig. 2, only the Lorentz force plays a role to push the liquid onto the hose surface. In this experiment, the following values were used: $I = 0 \sim 40(A)$, $B = 0.24(T)$, $v_0 \approx 3.0(cm/s)$. The same estimated numbers are used for the thickness of the liquid on the surface as in the horizontal case, that is 0.02", and thus $v_1 \approx 9.0(cm/s)$. Fig. 5 below shows the result of this experiment.

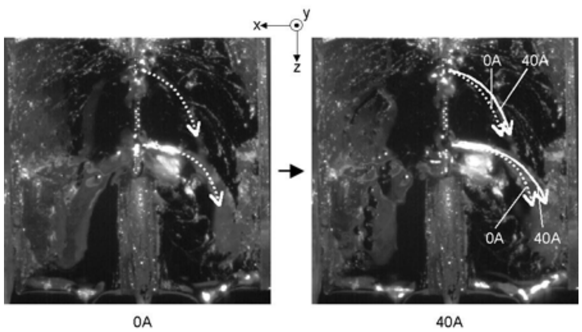

Fig. 5. Flow trajectories at 0A and 40A (vertical setting)

As can be seen in this figure, the Lorentz force redirected the flow. That is to say that the liquid metal flowed toroidally when current was applied and the shape of the flow looked parabolic. It was also seen in the experiment that a stronger current, which created a stronger Lorentz force, spread the liquid more toroidally. Huang et al. have performed numerical analysis on the soaker hose [2], and this experimental result could justify their result although their analysis was a two-dimensional case and this experiment was three-dimensional. Even though the flow change could be seen in this setup, a much larger Lorentz force (much larger magnetic field and/or current) and a higher initial toroidal velocity are needed to allow the liquid metal to completely cover the whole surface under the vertical setting condition where the liquid metal was pulled together quickly and dropped down immediately by gravity rather than being pushed toroidally by MHD forces.

In the first picture, the liquid flowed toroidally even when no current was applied. This may be due to the relatively large surface tension of the liquid metal. The inward surface tension force is about 0.0257N (same as calculated in the horizontal setting), while the outward inertia force at no current is about 4×10^{-4} N (calculated with $v_0 \approx 3.0(cm/s)$). The inertia force is negligibly small compared to the surface tension force. This may have caused the liquid not to shoot out but to percolate through the mesh, and consequently to flow toroidally along the surface due to its wetting. Also, the flow from the top of the mesh and the one from the bottom are slightly different, with the flow from the bottom spreading more. This is because the static pressure was larger at the bottom than at the top by about 10%. Consequently, the initial toroidal velocity at the bottom was larger.

Fig. 6 shows the trajectory of this flow calculated for the experiment with the same values used in the experiment, assuming that all the current flowed on the hose surface. Surface tension was neglected in this calculation.

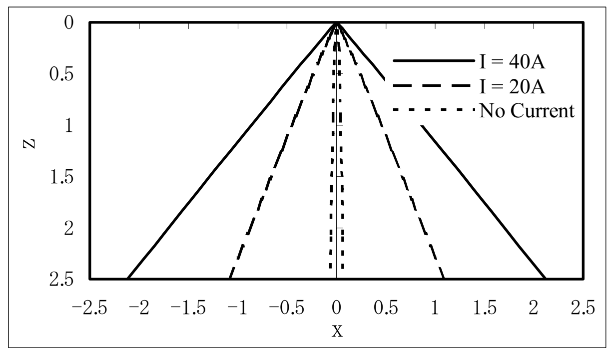

Fig. 6. Sample trajectory of the flow (unit: cm)
($B = 0.24(T)$, $v_1 = 9.0(cm/s)$)

This figure shows that the larger current, which leads to a stronger Lorentz force, spreads the flow more widely. However, this trajectory is rather a line than a parabola, which is different from the experimental result shown in Fig. 5. Current may have flowed more in the center and less at the edge, and this could explain the cause of the trajectory. Strong surface tension of the liquid metal may be another reason. In addition, the initial toroidal velocity v_1 needs to be extremely high for the liquid to cover all the surface with this setting since the initial velocity dominates the width of spread. Changing the angle of hose surface, shown as α in Fig.2, is another option to obtain wider spread of the liquid since larger α causes a stronger Lorentz force parallel to the hose surface.

TABLE 3 shows the effects of the MHD force on the inlet velocity in this vertical setting. This table shows similar results as seen in the horizontal setting case, such that the inlet velocity decreased due to the Lorentz force, the velocity drop increased as the Lorentz force increased, the maximum difference was about 5% at 40A, and the outward inertia force was much smaller than the Lorentz force.

TABLE 3. Experimental Result in the Vertical Settings

Current		Inlet Velocity v_0 (cm/s)	Velocity Drop (%)	Outward Inertia Force F_{out} (N)	Lorentz Force F_{BxJ} (N)
40A	OFF	2.64	4.97	3.46×10^{-4}	0.2438
	ON	2.51		3.12×10^{-4}	
30A	OFF	3.04	4.20	4.59×10^{-4}	0.1829
	ON	2.91		4.21×10^{-4}	
20A	OFF	2.82	2.50	3.94×10^{-4}	0.1219
	ON	2.75		3.74×10^{-4}	
10A	OFF	2.99	1.81	4.44×10^{-4}	0.0610
	ON	2.94		4.28×10^{-4}	

*Note that the surface tension force is about 0.0257N, same as on TABLE 2.

III.E Inclined Setting

The inclined setting experiment was conducted with a hose angle of 45 degrees upward from the horizontal. The same values were used as in the horizontal settings. In the inclined settings, the flow change was observed more clearly than that in the vertical case (Fig. 5.) since the gravitational force, which had no effect to redirect the flow in the vertical setting, helped push the liquid metal down to the surface and spread the liquid. Under the present experimental conditions, the soaker hose works better as an inclined liquid wall than as a vertical wall.

IV. CONCLUSIONS

IV.A. Summary

From the several experiments conducted so far, this soaker hose concept may be a feasible way to create a liquid metal first wall/divertor. As its theory and numerical calculations suggest, the Lorentz force redirected the flow and the liquid metal flowed toroidally. In addition, the force could also modify the flow surface, similar to that of film flow. At these current magnitudes up to 40A, horizontal settings worked better than the vertical settings due to the gravity. However, if a much higher current was available such that it could create a much stronger Lorentz force, this soaker hose could be utilized on a vertical wall.

IV.B. Improvement for the Further Study

In this work, the maximum obtainable current was 40A, while the magnetic field was about 0.2T. Under these conditions, the Lorentz force is not sufficient and gravitational force is inevitably large, especially in the vertical settings, where the liquid metal immediately dropped down before MHD force redirected the flow toroidally. To prevent this, a much stronger Lorentz force is needed. The strength of the magnetic field is not easily adjustable in the fusion reactor, and therefore the strength of the current has to be increased. Consequently, the hose settings may need to be modified to be able to hold a high current. Moreover, careful attention should be paid to obtain steady flow at any time since a gap in the flow stream could cause an electric spark. Also, a large amount of liquid metal is needed to hold a high current.

The wetting is another big issue. The wettability of the material of the hose surface determines the quality of the flow. Although copper tape attached on the acrylic surface could obtain good wetting with the liquid metal, more desirable surface material may exist, such as Inconel.

In addition, oxidization is also a big issue in the experimental conditions since oxidization causes several undesired effects, such as closing the holes on the mesh or disturbing the flow. The experiments in this work were conducted in open air, which caused oxidization easily. Further experiments need to be conducted with at least the hose surrounded by an inert gas such as Argon.

ACKNOWLEDGMENTS

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