Optimizating Full-coverage Free Surface Flow for Liquid Metal PFCs

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Abstract. In recently, more experiments were carried out on MHD effects of liquid metal free surface flow flowing on both a curve-surface plate and a flat surface plate. And the results indicated that free surface flow quickly become the rivulet flow on the curve-surface plate under transverse magnetic field, and on the flat surface plate even under no magnetic field condition. And especially, a superficial layer MHD effect was observed. Therefore, a rivulet flow physic mechanism was supposed that rivulet flow is due to secondary flow, which is driven by inter pressure profile changed in the cross section of free surface flow to ensure the pressure is the same on surface of the free surface flow. And a flowing incompressible small balls (FISB) model was developed to understand the formation of the rivulet flow. Then using to guide the secondary flow of the free surface flow, a wavy plate is designed for getting a full-cover free surface flow. And experimental results verified the feasibility of the design of the wavy plate. Comparing to free surface jet flow and free surface flow on curve-surface plate with multilayer meshes, the free surface flow on wavy plate maybe is the best one among the three kinds of full-coverage free surface flows as its simple.

1. Introduction

Liquid metal (LM) free surface, such as film flow, jet flow, capillary and so on, for LM divertor/limiter application have been studied in widely range in the last decades [1-22]. But up to now, how to format and keep a full-coverage free surface flow is remained one of key issues thought some new accepts and experimental results worked out in recently [14,16,17]. Such as, a full-coverage free curve-surface flow was obtained by curve plate with three layer meshes, but experimental results showed that a full-coverage free surface flow can't be obtained by a flat plate with meshes. And other new superficial layer MHD effect was observed. Therefore, a rivulet flow physic mechanism is supposed that rivulet flow is due to secondary flow, which is driven by inter pressure profile changed in cross section of free surface flow to ensure the pressure is the same on surface of the free surface flow. And a flowing incompressible small balls (FISB) model was developed base on the experimental results of the free surface flow to help us to understand the formation of the rivulet flow and to calculate the shape of rivulet flow. In the paper, it is also present that using FISB model to design a wavy plate for full-overage free surface flow and experimental verified.

2. Physics model and Application

2.1.FISB-model established

Basic on recent experimental results of MHD effect of liquid metal free surface flow, it was addressed that physics model of secondary flow driving rivulet flow formation in free surface flow. The experiments were carried out at Liquid Metal Experimental Loop Upgrade (LMEL–

U, work mass is $^{68}Ga^{20}In^{12}Sn$) facility in Southwestern Institute of Physics, China (see *FIG. 1 and 2*). From the experimental results of free surface flow MHD effects (*FIG. 3 and 4*), we can find that liquid metal free surface flow quickly become rivulet flow under transverse magnetic field except the free surface flow on curve-plate with three layer meshes and the free surface flow with a thin thickness, a_0, 1 mm, on a flat plate even if under without transverse magnetic field (*FIG.4*, right 2). Especially, a free surface flow is flowing with a superficial layer MHD effect (*FIG.4*, middle). These indicate that rivulet flow is not significantly related to solid/liquid wet conditions, or, the rivulet flow is due to the inherence causation of the free surface flow. As known, for the full development duct flow, to ensure the pressure is the same in anywhere of the cross section of the flow, the velocity is in parabolic type profile. For a free surface flow, we can supposed that to ensure the pressure is the same on surface of the free surface flow, the pressure profile in the cross section of the free surface flow will be re-established, and the rivulet flow will be made during the pressure profile establishing. The re-establishing process is dependent on inlet velocity profile and transverse magnetic field. The pressure changing in the cross section drives the secondary flow and forms the rivulet flow. In other word, for free surface flow, the surface shape and cross section must be changed to fit in with the same pressure on the surface, and the rivulet flow is formatted.

To describe the physics presupposition above by mathematics, a flowing incompressible small balls (FISB) model was established and the brief of its is showed in *FIG. 5*. The balls in FISB model can be distinguished seven different type balls (two types balls way from side walls are not showed in *FIG. 5*). Every ball is with initial velocity V_x and applied forces of gravity *(mg)*, reacting force (N), electromagnetic forces (f_{bx}, f_{by}) and viscous force (f_{vs}). And have other forces for some local balls: the friction force with solid walls f_{rb} , the friction force with the atmosphere of the top of free surface flow f_{ru} , the f_{rb} is related to wall wet ability and wall conditions. N and mg is balanced. Viscous force makes the liquid fluid special characterizers, such as, the shape of the flow, definite velocity distribution in cross section of the flow and so on. The f_{bx} , f_{by} and *mg* are considered as major forces causing secondary flow enhancement. For the flowing incompressible small balls, once a ball is moving from its position, the neighbor balls will move into fill the room from all directions. Theoretically, if known initial velocity profile in cross section of the free surface flow, the friction forces of f_{rb} and f_{ru}, the viscous force f_{vs} and the magnetic field profile as function B(x). Then every ball's motion trace can be calculated. Of course, that will be a big challenge. Therefore, the model is simplified that we only focus on a global behavior (all balls) rather than individual ball. Considering to endow one ball (such as, the ball at the position of [x=0,y=0,z=0]) with the flow characterizers, such as, average velocity of the flow, fluidity, viscosity and so on, and as a global (all balls) obey magneto-hydrodynamics laws (more detail see refer.[18])

Comparing electromagnetic forces (in commonly, it is large enough) with f_{rb}, f_{ru} *and* f_{vs} as well as initial velocity distribution effect, the f_{rb}, f_{ru} *and* f_{vs} can be ignored and an average instead of an initial velocity distribution. Then, they can be calculated that the average velocity V_x of free surface along X-direction, and the critical point, *Xc*, after the point, the free surface flow enter the stable 'line stream' flow, and the critical diameter, a_c, in a duct-like free surface flow (see *FIG. 5*), by established and solved a series Equations (Detail see refer.[18]).

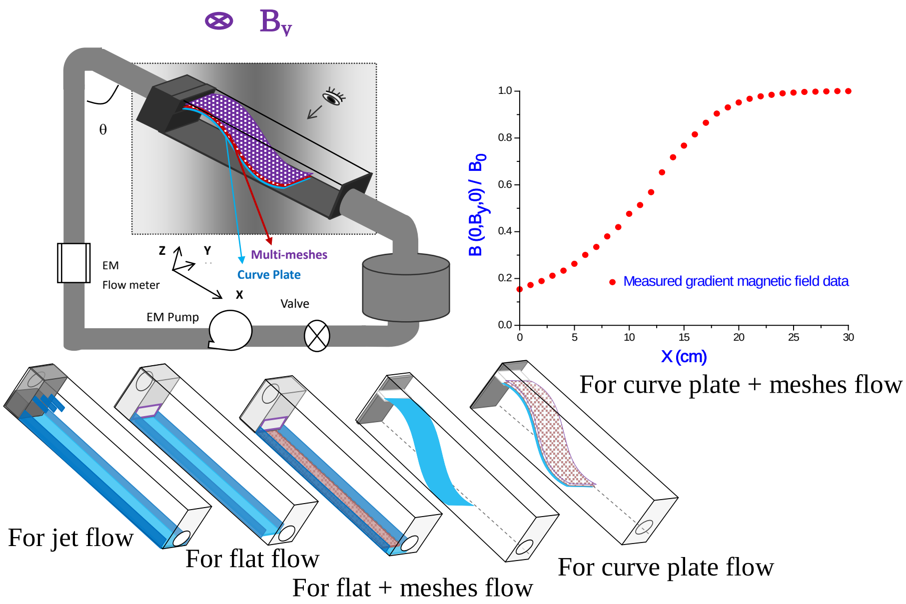
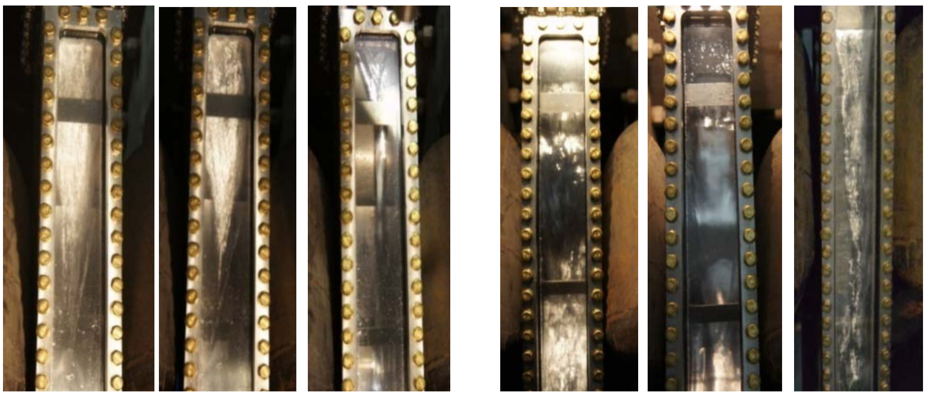


FIG. 1 Schematic diagram of liquid metal free surface flow MHD experimental program

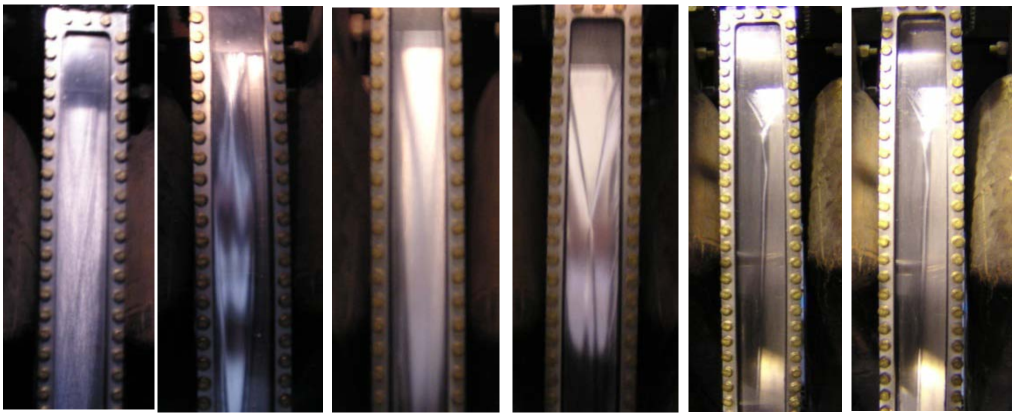
FIG.2 Photo of Liquid Metal Experimental Loop-Upgrade （LMEL-U）facility



V_0 = 1.20 m/s Curve Plate without mesh   Curve / flat (right)-plate with three-layer meshes

B_0= 0   1.228 T   1.851 T B_0= 0   1.851 T   1.851 T

FIG. 3 The experimental results of MHD effect of free curve-surface flow with/without multi-layer meshes（Refer to [14]）.



a_0 = 5mm	5mm	3 mm	2.3mm	1mm	1mm
V_0 =1.34ms^{-1}	134ms^{-1}	4.36 ms^{-1}	1.94ms^{-1}	0.40 ms^{-1}	0.40 ms^{-1}
B_0= 0	1.825 T	1.825 T	1.825 T	B_0= 0	1 .825 T

FIG. 4 The experimental results of MHD effect of flat free surface flow（Refer to [16]）.

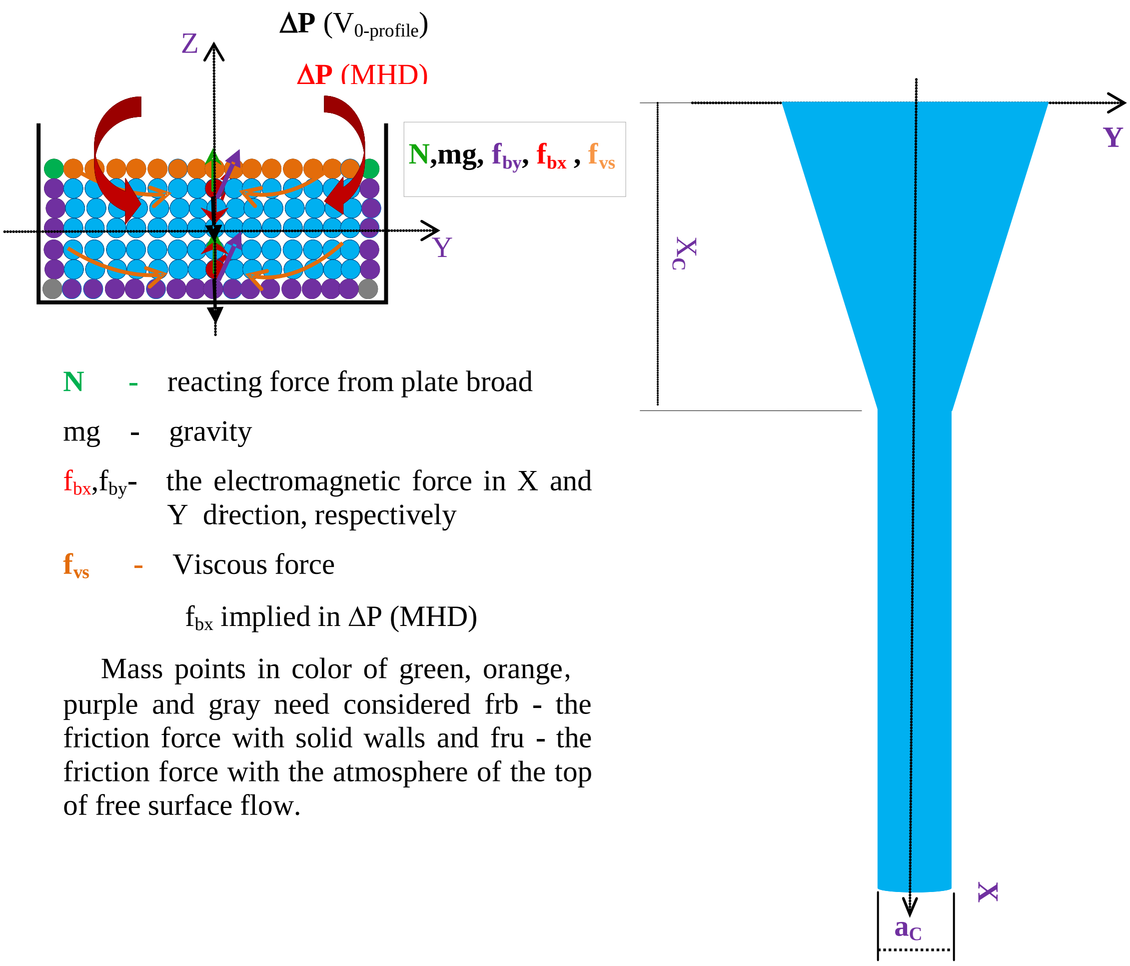


FIG. 5 Brief of FISB model, if ignored viscous force and friction force, the critical point (see FIG 3 left 3 and FIG4 right 1), after the point, the free surface flow enter the stable 'line stream' flow, the free surface flow is in a duct-like flow, the critical length, X_c and the critical diameter, a_c, can be calculated from FISB model's equations [18].

2.2.A wavy plate designed

How to understand the results of superficial layer MHD effect (*FIG.4*, middle) and of a flat plate flow without transverse magnetic field (*FIG.4*, right 2)? Considering the free surface flow flowing in several layers is a hydraulics characterizer. According to FISB model, the construction of the cross section of the free surface flow is showed in *FIG.6* (left). It can be found that every FISB in every flowing layers of the free surface flow are forced by transverse force, which is caused by ΔP ($V_{0\text{-profile}}$), ΔP (mg) and ΔP (MHD) to keep the same pressure on over all surface of the free surface flow, to make them moving in Y-axis direction at $V_{y\text{-Layers}}$. For superficial layer, at $V_{y\text{-S}}$ and for bottom layer, at $V_{y\text{-B}}$, .if $V_{y\text{-S}} \sim V_X >> V_{y\text{-B}}$ and $V_{y\text{-B}} \sim$ zero, then the superficial layer free surface flow will quickly flows in rivulet flow and keeping 'line stream' flow. In other words, if superficial layer in both layer thickness and velocity match to the transverse magnetic field, the superficial layer MHD effect will be appeared (*FIG.6 right* and *FIG.4* middle). The results of the thin free surface flow (with 1 mm in thickness, see *FIG.4 right 1and 2*) on a flat plate with/without transverse magnetic field, they were as the same as the results of the superficial layer flow, or, they were only one layer free surface flow.

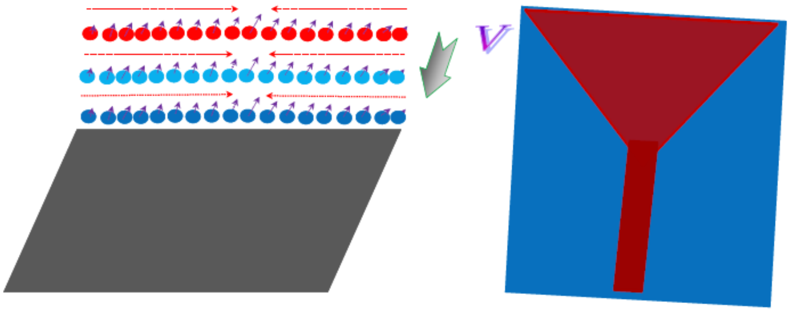


FIG.6 Schematic diagram of the cross section of the free surface flow analyzed by FISB model and the superficial layer MHD effect.

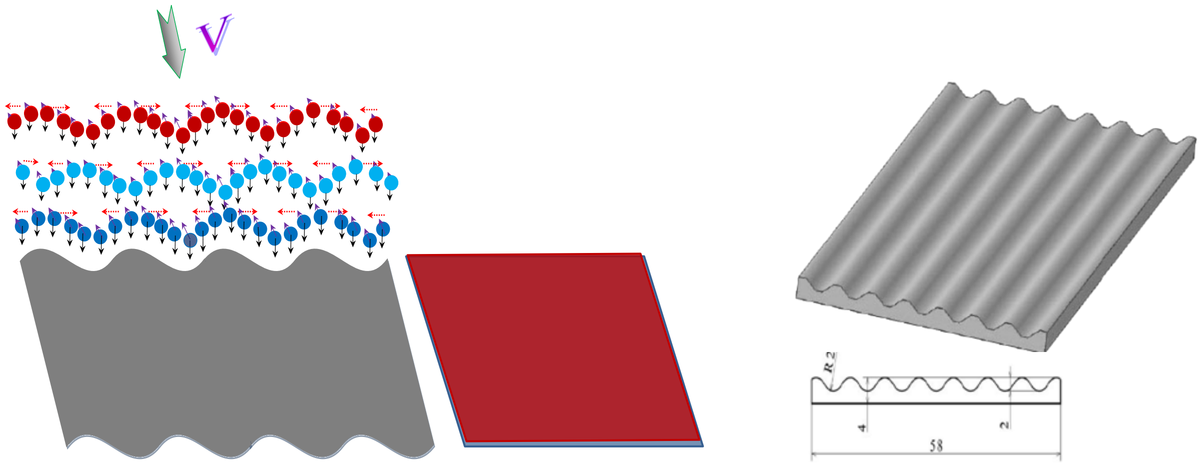


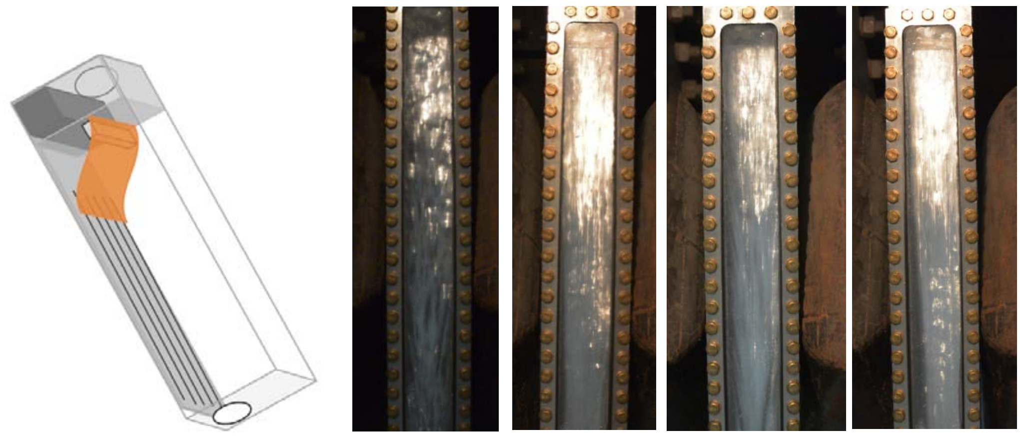
FIG.7 Schematic diagram of analyzed of wavy plate for full-cover free surface flow.

From above section, we knew that for free surface flow, the rivulet flow is due to secondary flow caused by the pressure profile changed in the cross section to keep the same pressure on over all surface of the free surface flow**,** or**,** for free surface flow**,** the secondary flow is inevitable. Therefore, to obtain full-cover free surface flow may be only way of to guide the secondary flow of the free surface flow. From *FIG. 3* and *4*, the experimental results show that the rivulet flow is centring. If the surface of the free surface flow there are many centres, then the free surface flow will become a full-cover the surface flow. The schematic diagram of a detail design and analysis of wavy plate for full-cover free surface flow is shown in *FIG.7*.

3. Experimental verifying

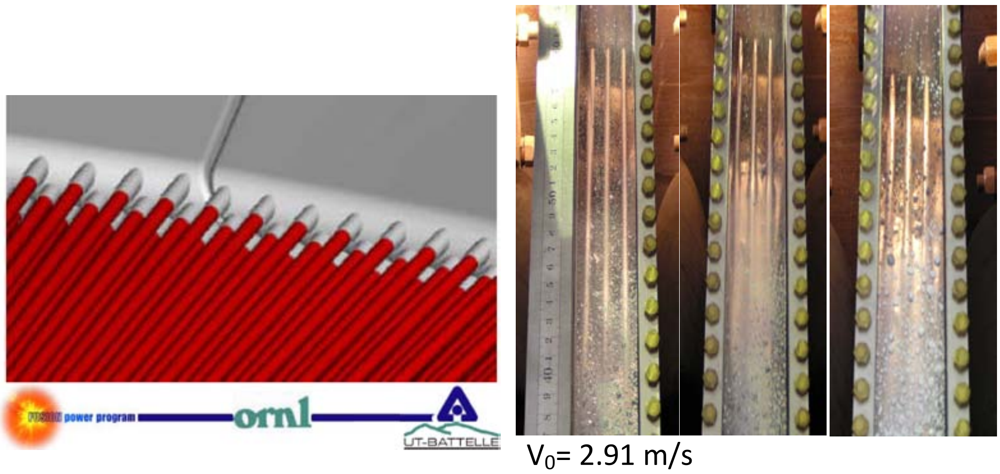
The major experimental parameters are below. The EM pump with a capacity of 25000kg/h drives the liquid metal ($Ga^{68}In^{20}Sn^{12}$) circulation, an electromagnetic (EM) meter measured the generally average velocity (V_0) and the error was better than 1.2%. The non-uniform magnetic field space was in 80x100x1000mm, the maximum value of the magnetic field, B_0, was 2 Tesla. All data are acquired by NI PXI 4071 Digital Multi-meters (26 bits resolution).The free surface flow are measured in the space of 58 mm in width, 1000 mm in length and a_0 in the flow thickness from 1.0 mm to 5.0 mm. The average velocity of the free surface flow reaches to 2.95 m/s under the magnetic field of 1.851 T

The experimental results of free surface flow on wavy plate are shown in *FIG. 8*. It can be seen that the free surface flow can cover well on the surface of the wavy plate for both 5 mm and 1mm in thickness of the free surface flow. *FIG.9* shows that other full-coverage free surface flow is composed with free surface jets. Counting free curve-surface flow with multilayer meshes in, now, there are three kinds of full-coverage free surface flow for options of liquid metal PFCs. But the free surface flow on wavy plate maybe is the best one as it’s simple.



a_0=5mm		a_0=1mm	
B_0=0	1.825T	B_0=0	1.825 T
V_0=0.63ms^{-1}	0.83 ms^{-1}	V_0=2.95 ms^{-1}	2.67 ms^{-1}

FIG.8. The MHD experimental results of free surface flow on wavy plate.



V_0= 2.91 m/s

B_0= 0 B_0= 1.540T B_0= 1.925T

FIG.9. Other full-coverage free surface flow is composed with free surface jets. Right 1to3, the experimental results is represented from [6].Left diagram is from International seminar on Electromagnetic Control of Liquid Metal Processes, Coventry University（KU）June27-29,2001

4. Summary

The rivulet flow of free surface flow is due to secondary flow caused by the pressure profile changed in the cross section to keep the same pressure on over all surface of the free surface flow. A full-cover free surface flow on wavy plate is obtained by special design with FSIB-model analysis to guide the secondary flow of the free surface flow. Up to now, at the viewpoint of MHD effect, for liquid metal PFCs, there are three types of full-coverage free surface flows for options: free surface jet flow, free curve surface flow on curve-plate with multi-layer meshes and free surface flow on wavy plate. But the best one maybe is free surface flow on wavy plate as it's simple.

Appendix 1: Reference

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