Optimizating Full-coverage Free Surface Flow for Liquid Metal PFCs

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Outline

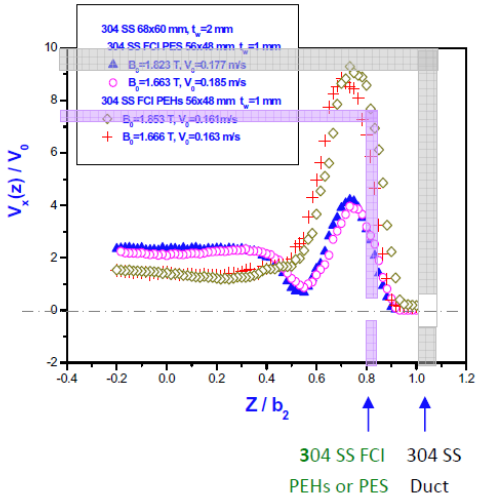
- Background & Motivation
- Experimental Phenomenon
- Flowing Incompressible Small Balls (FISB) Modeling
- Analysis & Flow Channel Design
- Experiment Verification
- Summary

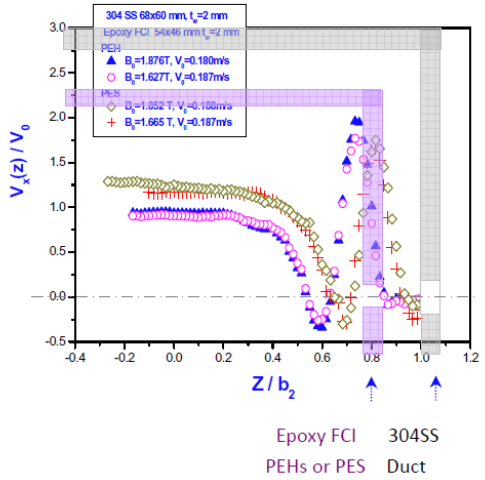
Background & Motivation

1. LMEL 1991- 2005 NaK (~11 m^3/h)
2. LMEL-U 2006 -2010 GnInSn (~2 m^3/h)
3. LMEL-U 2011 - GaInSn (~5 m^3/h)

Topic 1, MHD effects

(different geometry channels: circle, retangular, manifold, insulator coating, FCI)





Topic2, Free-surface flow

(jet flow, curve surface flow, wavy surface flow)

Background & Motivation

- **To develop a full-coverage free surface flow for liquid metal (LM) PFCs**

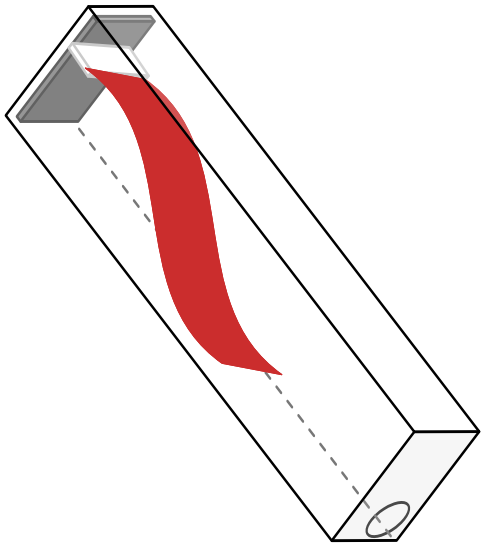
Advantage:

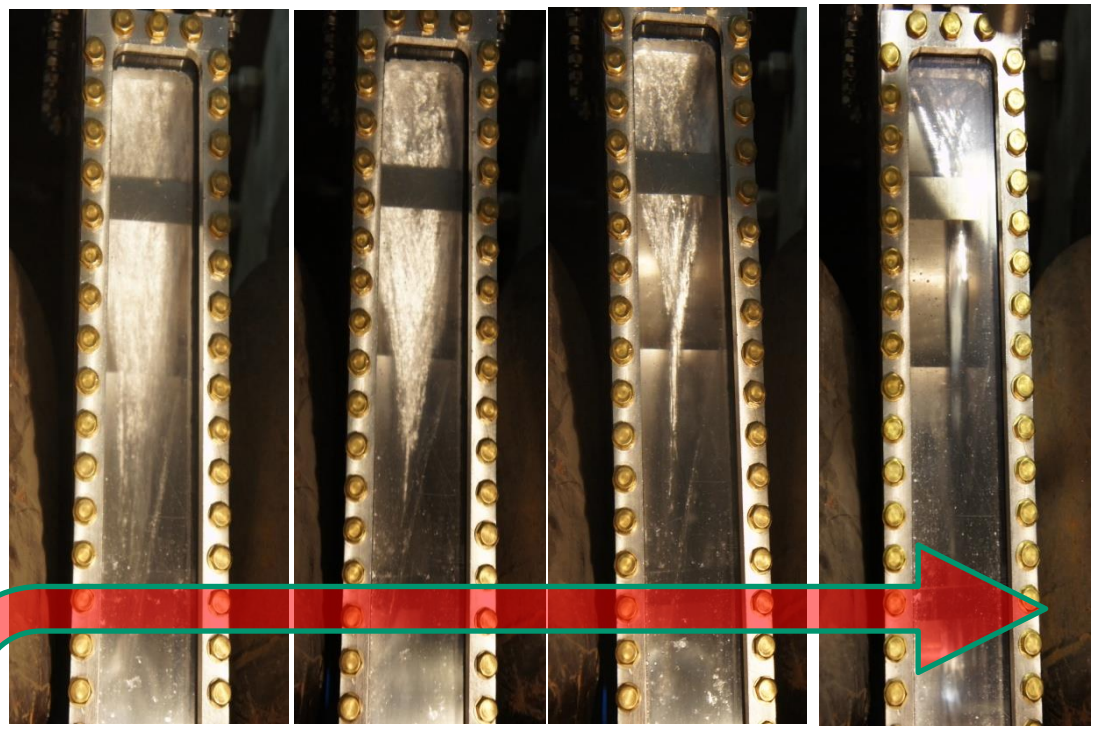
- **Very high heat load removing capability （by fluid volume control)**
- **No neutron radiation lifetime limitation (through LM circulation)**

Issues:

- **LM interaction with plasma**
- **LM splash during ELMs period**
- **Safety problem**
- **Rivulet flow (MHD enhancement the effect**

Experimental phenomenon（ 1)





Magnetic field （B，MHD） enhanced rivulet flow effect

LM free surface flow on the curve plate

V_0 = 1.20 m/s 68mm x700 mm x a_0 @5mm

B_0= 0 B_0= 1.228 T B_0= 1.567T B_0= 1.825T

Experimental phenomenon (2)

The superficial layer MHD effect, which indicates that rivulet flow is not significantly related to solid/liquid wet conditions.

The shape & size of the rivulet flow is not related to B

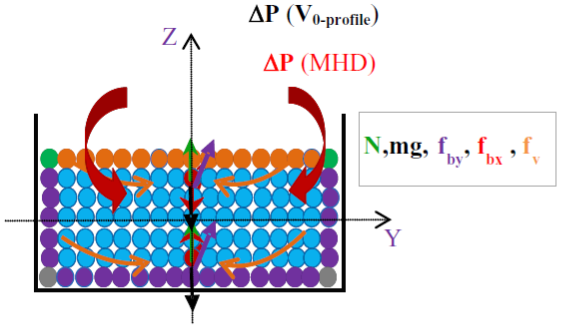
Physics assumption

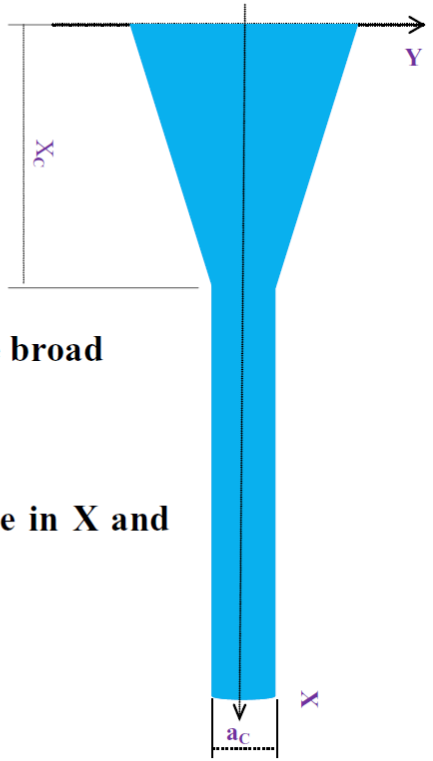
Physics assumption：

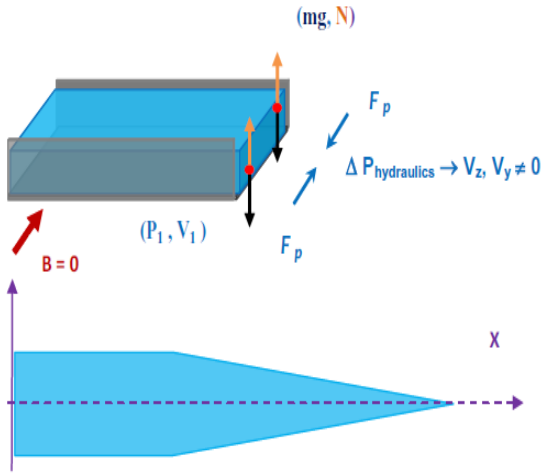
- To ensure the pressure is the same on surface of the free surface flow, the pressure profile in the cross section of the free surface flow will be re-established.
- A rivulet flow will be created owing to the pressure re-establishing.

FISB Modeling （2）

Flowing Incompressible Small Balls (FISB)







N - reacting force from plate broad

mg - gravity

f_{bx},f_{by}- the electromagnetic force in X and Y direction, respectively

f_{vs} - Viscous force

f_{bx} - implied in ΔP

- **They can be calculated that width，w_x, thickness a_x, and the average velocity,V_x of free surface flow as well as the critical point, *Xc, and the* critical diameter, a_c, by established and solved a series Equations**

Parameters: At the critical point, Xc

$$x_c^{\,2}(c_2 - \underline{v}_{xc})^2 =$$

$$16c_1[a_0^{\,2}(w_0 + k_1^2\pi a_0/4)(k_1 B(x_c)\underline{v}_{xc} - B(x_0)\underline{v}_0)B(x_c) + \kappa x_c^{\,2}\int_0^{x_c} B^2(x)dx]$$

$$\underline{v}_0 w_0 a_0 = k_1^2 \pi a_0^{\,2}\underline{v}_{xc}/4$$

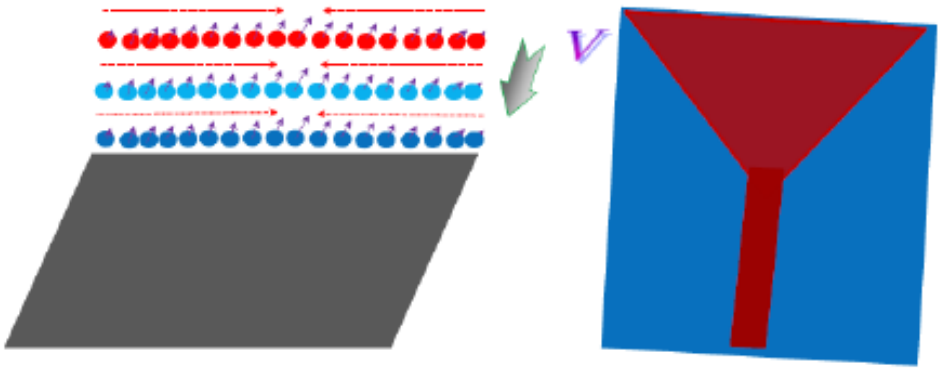
$$C_1 = \frac{k_1 a_0 \sigma_f}{2\rho}$$

$$\underline{V}_0 W_0 a_0 = \frac{\pi a_c^3 B(x_c)\underline{V}_{xc}}{64}\sqrt{\frac{\sigma_f}{\eta}}$$

$$C_2 = \frac{4\underline{V}_0 W_0}{k_1^2 \pi a_0}$$

- Detail refer to: Xu.etal, Advances and Applications in Fluid Mechanics V17 (2) 2015 pp. 165-182

Analysis

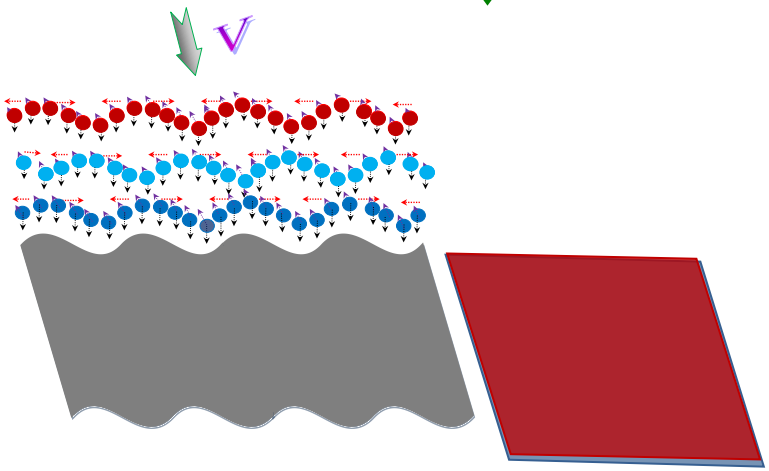


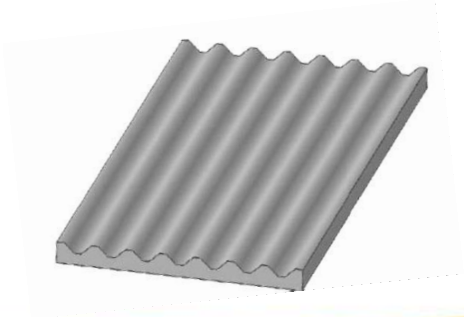
The superficial layer MHD effect--- centralization

↓

Anywhere can be as a center--- decentralization

→ Full-coverage free surface flow





Flow Channel Design -- Wavy Plate

Wavy Plate for full-coverage free surface flow:

68mm x 700 mm x 4 mm @ R=2.5mm x 2mm

(**Test Box:**

76 mm x1000 mm x 300 mm)

Free surface flow:

The thickness:

a_0 = 5mm, 1mm

(Chamber : ~10 Pa Air)

Experiment Verification

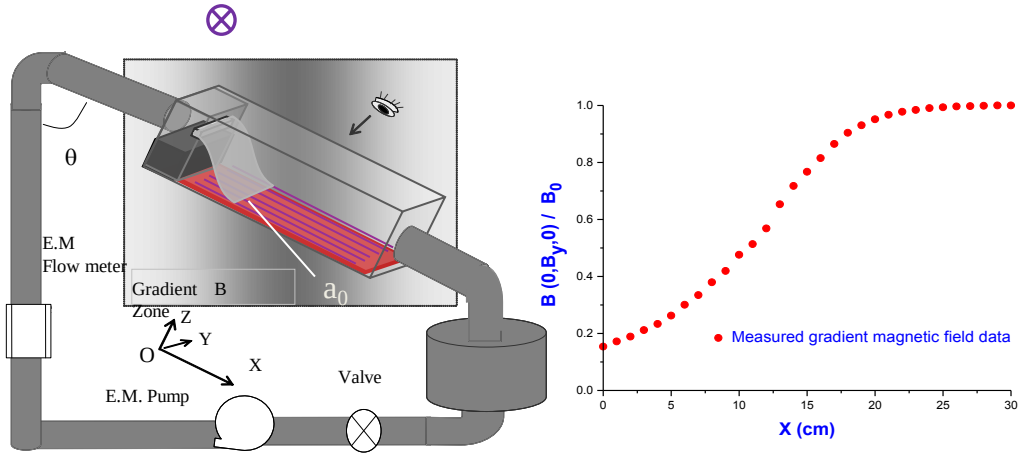


Photo of Liquid Metal Experimental Loop-Upgrade （LMEL-U）facility

Facility's Major Parameters

Work mass: $^{68}Ga^{20}In^{12}Sn$ （80L）

B : 0 ~ 2.0 T

Uniform B space: 80D×170W × 740L

EM pump : ～25000 kg/h

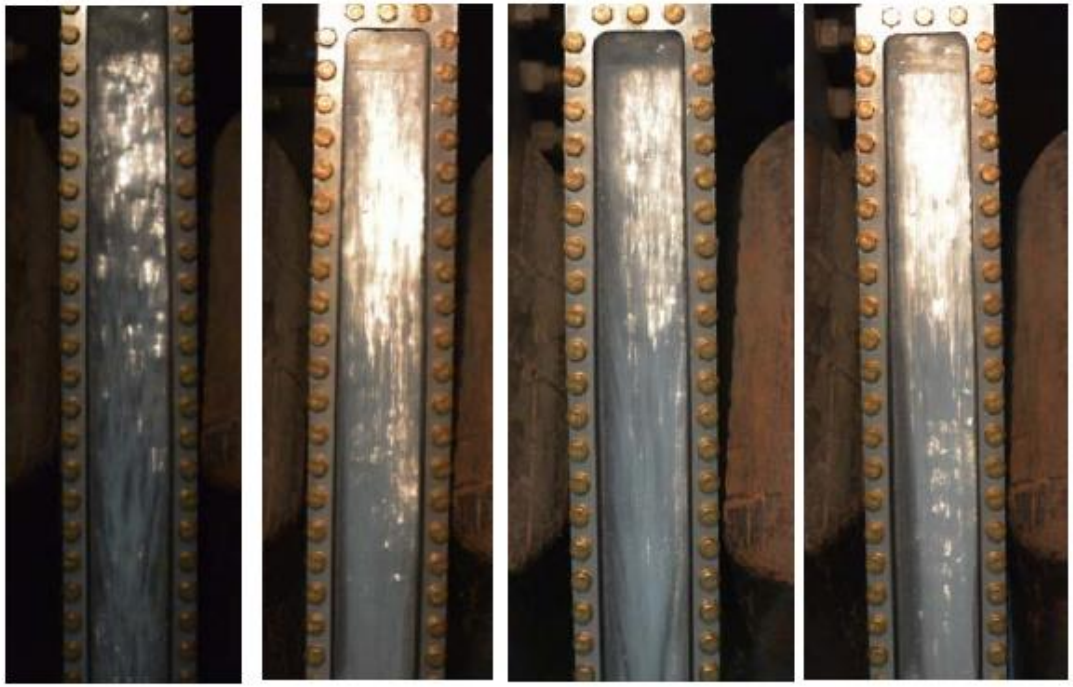
Flow-meter: ~ 1.2%

Pressure distinguish: 18 Pa

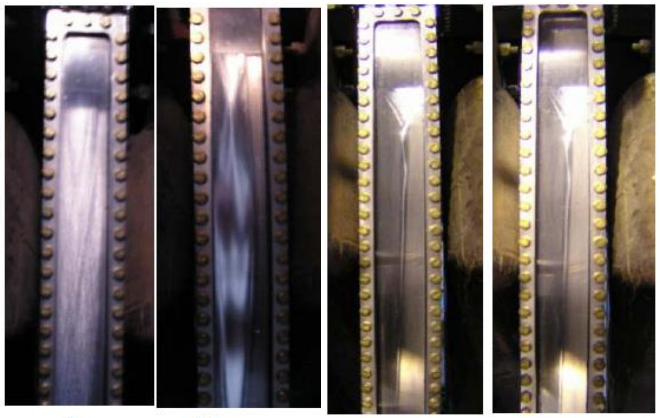
Data acquisition: 26 bit (NI PXI 4071)

Experimental results

Full-coverage Free Surface Flow *on wavy plate* :



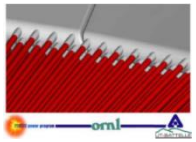
a_0=5mm		a_0=1mm	
B_0=0	1.825T	B_0=0	1.825 T
V_0=0.63ms^{-1}	0.83 ms^{-1}	V_0=2.95 ms^{-1}	2.67 ms^{-1}

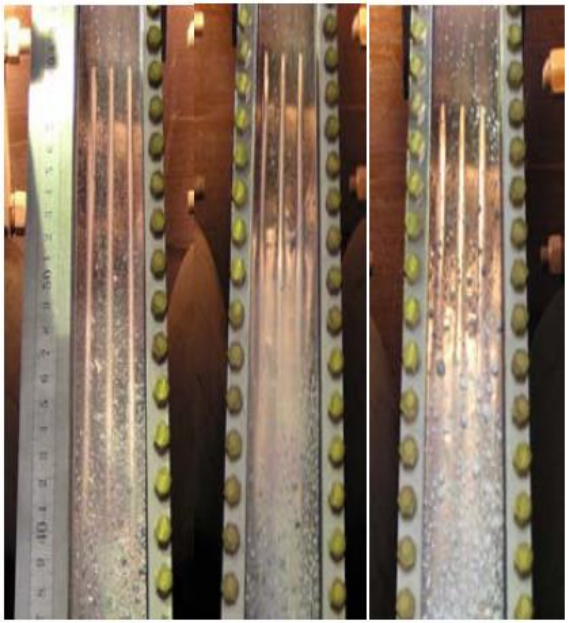


a_0 = 5mm	5mm	1mm	1mm
V_0 =1.34ms^{-1}	134ms^{-1}	0.40 ms^{-1}	0.40 ms^{-1}
B_0= 0	1.825 T	B_0= 0	1 .825 T

Three kinds of full-coverage free surface flow

Free surface jet flow



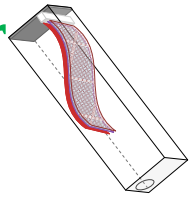


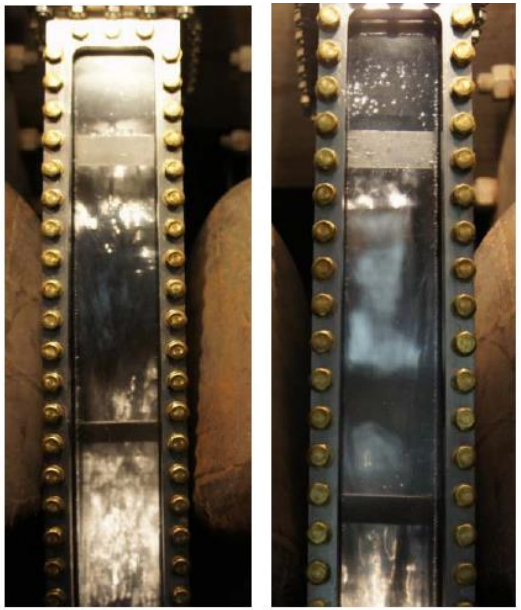
V_0= 2.91 m/s

B_0= 0 B_0= 1.540T B_0= 1.925T

FST 46 DEC. 2004 pp 577-585

Free surface flow on Curve plate with three layer meshes



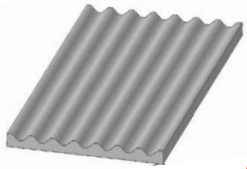


V_0 = ~1.20 m/s

B_0= 0 1.851 T

IAEA FEC 2012 CD-ROM FTP/P1-06

Present: Free surface flow on Wavy Plate



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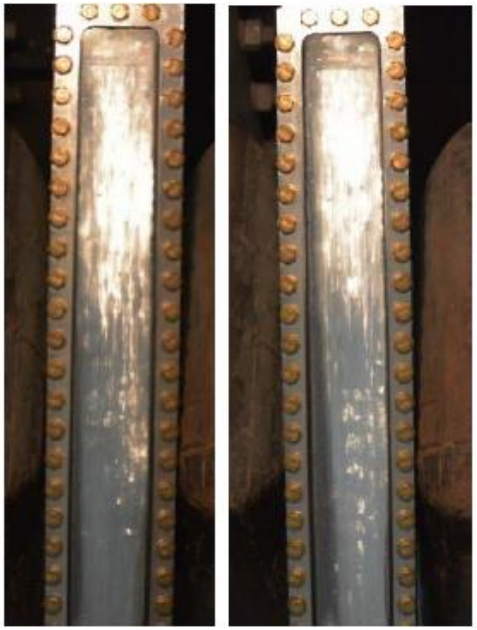

a_0=5mm a_0=1mm

B_0=1.825T

V_0=0.83 ms^{-1} 2.67 ms^{-1}

Summary

- **The rivulet flow of free surface flow is due to secondary flow caused by the pressure profile changed in the cross section in order to keep the same pressure on all top surface of the free surface flow.**
- **A full-coverage free surface flow can be obtained by guiding the secondary flow of the free surface flow.**
- **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 plates.**
- **The best one may be free surface flow on wavy plates since it's easily available.**

Thank you for your attention!

Annexation (2 Video)

Flow on curve – plate

Flow on Wavy plate