MHD liquid-metal-flow experiments and simulations for nuclear fusion applications.

Francisco Saenz¹

with J. Al Salami³, Z. Sun², A. Khodak², S. Smolentsev⁴, ¹B. Wynne and ¹,²Egemen Kolemen

¹Mechanical & Aerospace Engineering Department, Princeton University, USA
²Princeton Plasma Physics Laboratory, USA
³Kyushu University, Fukuoka, Japan
⁴Oak Ridge National Laboratory, USA
Research collaboration

- Francisco Saenz (PU): Experiments/Simulations
- Brian Wynne (PU): Experiments
- Andrei Khodak (PPPL): ANSYS
- Zhen Sun (PPPL): Experiments
- Sergey Smolentsev (Oak Ridge): FORTRAN
- Jabir Al-Salami (Kyushu U.): OpenFOAM
- Sergey Smolentsev (Oak Ridge): FORTRAN
Overview

• Motivation and description of LMX-U.

• Liquid metal flows in open channel:
  • Experiment and simulations.
  • Operational advantages and issues.

• Divertorlets:
  • Experiment and simulations
  • Projections.
Motivation

• Liquid metal flows for heat exhaust in divertors of fusion reactors.

• Non-evaporative liquid metal divertor is needed.
  o Fast flow ~ 1 m/s - 20 m/s for a standard divertor (length ~ 10 cm).

• Reactor scenario:
  • Severe MHD drag.
  • Free-surface stability of fast flows.
Liquid Metal R&D without plasmas

- **Aim**: To understand liquid metal flows at small scale.

- **New Divertor Ideas**: $j \times B$-forces to control of the LM flow and pumping.

- **Liquid Metal eXperiment Upgrade** (LMX-U) operating at PPPL.
  - Galinstan (GaInSn alloy).
    - Electrical conductivity: 3.1 MS/m, (Li: 3.43 MS/m).
  - Max. B: 0.33 T
  - Height-adjustable nozzle at inlet allows inlet depth to be changed:
    - Max. flow speed: 2 m/s
    - Removable nozzle
  - Channel liner: acrylic base. Width: 109 mm
  - Inclination angle range: $0^\circ$ - $7^\circ$.
  - Movable channel.

LMX-U publications by Kolemen group:
1. Kusumi, FEDC 111 1193 (2016)
2. Kusumi, FEDC 72,4, 796 (2017)
8. Hvasta, FST (2020)
Free Surface LM Flow in LMX-U Channel
MHD drag on liquid metal flows

- \( F_{\text{MHD}} = \sigma (E + U \times B) \times B \sim C_M \sigma |U||B|^2 \)

- Different conductive boundaries:
  - Cu: 58.7 MS/m, 2.36 mm wall thickness
  - Brass: 17 MS/m, 1.6 mm wall thickness.
  - AISI 316 (SS): 1.32 MS/m.

- Electromagnetic edges: 0 mm – 740 mm
MHD drag experiments

- Max. nozzle gap: 10 mm, nozzle exit position: \( x = -30 \) mm.

- \( Q = 16.3 \) L/min, brass walls, \( t_w = 1.6 \) mm.

- Hydrodynamic flow (0 T)
  - \( \text{Re} \sim 5200; \text{Fr} = 0.82 \) (nozzle), 0.37 (\( x = 85 \) mm)

- \( B = 0.3 \) T
  - \( \text{Ha} \sim 590, \text{Re} \sim 4270 \)
|B| affects liquid-metal pileup

- $F_{\text{MHD}} \sim C_M \sigma |U||B|^2$
- Measurement location: $x = 85$ mm.
- Brass walls, $t_w = 2.43$ mm, $Q = 16.3$ L/min, Inlet height: 5 mm
Wall conductivity is key for flow thickness

- $F_{\text{MHD}} \sim C_M \sigma |U||B|^2$

- Wall conductivity ratio $c_w = \frac{t_w \sigma_w}{b \sigma}$

- Closed-pipe-flow equations:

$$\Delta p = \lambda \frac{l}{2b} \frac{\rho U_m^2}{2} \quad \frac{\lambda}{\lambda_0} = \frac{1}{3} \frac{c_w}{c_w+1} H a^2.$$

- $c_w$ for different liners:
  - Cu: 0.9, Brass: 0.16, SS: 0.012

- $B = 0.3 \, \text{T}, \, Q = 16.3 \, \text{L/min}, \, \text{no nozzle.}$
Simulations

- **OpenFOAM:**
  - Full 3D MHD

- **Parameters:**
  - $Q = 16.3$ L/min
  - $t_w = 2.36$ mm
  - Cu walls
  - No nozzle for flow inlet

![Diagram showing velocity magnitude and time at 0.1 s. Magnetic field turns on at $t = 10$ s.]
OpenFOAM

- $t_W = 2.36\text{mm}$
- Cu walls
- No nozzle
- $Q = 16.3 \text{ L/min}$
- Full 3D MHD.

Credits to J. Al-Salami, Kyushu University

ANSYS CFX

Credits to A. Khodak
Inclined-flow simulations (FORTRAN)

- Different wall conductivity ratios

\[ h_{in} = 1 \text{ cm}, \ U_{in} = 1 \text{ m/s}, \ L = 0.7 \text{ m}, \ W = 0.1 \text{ m}, \ \text{Alfa} = 7 \text{ Degree} \]

Credits to S. Smolentsev.
Inclination angle

B=0.3 T, U_in=2 m/s, L=0.7 m, W=0.1 m, h_in=1 cm
Plexiglas

Inlet speed

h_in=1 cm, B=0.3 T, L=0.7 m, W=0.1 m, Alfa=7 Degree
2 mm steel

B-field strength

2 mm Steel, U_in=1 m/s, L=0.7 m, W=0.1 m, h_in=1 cm, Alfa=5 Degree

Credits to S. Smolentsev.
Issues at the reactor scale

• Non-evaporative liquid metal divertor is needed.
  
  o Fast flow ~ 1 m/s - 20 m/s for a standard divertor (length ~ 10 cm).

• We need:
  
  o Smaller power requirements.
  o Smaller liquid lithium inventory.
  o Stable liquid metal flows.
Can we reduce flow-speed requirements?

- Is it possible to reduce the speed?
  - **Solution:** Alternative designs

\[ t_{cr} = \left(\frac{\Delta T}{2q}\right)^2 \pi k \rho c_p \]

\[ v_{cr} = \frac{L}{t_{cr}} \]

Jaworski [NF, 2017]
Divertorlets

- Smaller $L$ leads to smaller speed requirements.
- Reduction of MHD drag, viscous drag, and splashing.

Saenz [NF, 2022]
Operational principle of divertorlets

• Lorentz forces pump the flow.

• Balance between:
  
  o $\mathbf{j} \times \mathbf{B}$ pumping
  
  o MHD drag $\sim C_M \sigma |\mathbf{U}| |\mathbf{B}|^2$
  
  o viscous drag $\sim C_D \rho |\mathbf{U}|^2$

Saenz [NF, 2022]

Fisher [NME, 2020]
Experimental tests of divertorlets in LMX-U

• Peak-valley deformations on the free surface.

• Surface tension should increase with thinner channels and get rid of deformations.

• $L = 10 \text{ mm}$
Simulations/Analytical review

- COMSOL simulations confirmed the desired flow loop around slats.
- Average upward velocities were compared to experimental results.
- Experiments and simulations were analytically reviewed.

Saenz [NF, 2022]
Projections at the reactor scale

- 10 MW/m$^2$ uniform heat load.
- Liquid lithium below 450°C.
- Less than 1% of power output of DEMO (500 MW).
- 100-micron tungsten 3D printing capability available (DUNLEE).
Summary/future work

• Liquid metal flows encounter MHD drag when subject to magnetic fields, which generate piles of galinstan on free-surface flows.

• Simulations of free surface liquid metal flows are executed and in agreement with experimental results.

• The divertorlets concept is an alternative to fast-flow liquid metal concepts for divertor solutions.

• A divertorlets prototype was built and tested in LMX-U. Experiments and simulations were reproduced with analytically reviewed.

• Projections of divertorlets are promising for reactor scenarios.

• Integration of cooling system for divertorlets/TEMHD analysis.
Thank you for your attention!
References


