Experimental, numerical and analytical evaluation Lorentz-force propulsion on liquid-metal channel flows for divertor applications at the NIFS Oroshhi-2 Facility

US-Japan and International Workshop on Power and Particle Control in DEMO Fusion Reactor by Liquid Metal Plasma-Facing Components

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Overview

- **Motivation**
  - Liquid metals for fusion applications.

- **Lorentz-force propulsion**

- **Experiments**
  - LMFREX/NIFS Oroshhi-2 Superconducting magnet facility.
  - Experimental setup.

- **Simulations**
  - Comparison with experiments
  - Projections

* Paper submitted to Nuclear Fusion Journal: "Experimental, numerical and analytical evaluation of Lorentz-force propulsion for fast-liquid-metal-flow-divertor systems of nuclear fusion devices". Article reference: NF-10599
Motivation
Liquid Metal R&D without plasmas.

- **Aim:** To understand liquid metal flows at the small scale
- **New Divertor Ideas:** \( j \times B \)-forces to control of the LM flow and pumping.
- **Non-evaporative liquid metal divertor for heat exhaust.**

MHD drag

- External magnetic field induce currents in liquid metals in motion.
- Induced currents cause a retarding force “MHD drag”.

Code validation

- Experiments in LMX-U with different conditions that affect MHD drag forces.
- 3D Liquid Metal Magnetohydrodynamics (3DLMM)
- MHD drag \( \sim \) flow speed \( \times |\mathbf{B}|^2 \)

Time: 0.1 s
Magnetic field turns on at \( t = 10 \) s

Lorentz-force propulsion
Lorentz-force propulsion

Current is induced

Current is injected

Electrodes

Plasma Control
NIFS Oroshhi-2 Superconducting magnet

For our experiments:

- Maximum $B_z$ is $\sim 1.4$ T.
- $B_z$ variation is $\sim 5\%$

LMFREX Channel

- **Galinstan (GaInSn alloy).**
  - Electrical conductivity: 3.1 MS/m, (Li: 3.43 MS/m).

*Schematic view of experimental apparatus of LMFREX (black area is GaInSn; shaded area is argon gas). Kusumi et al (2019)*

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Experimental setup

120 A, 0.1 T

Jump-like discontinuity!

Section B

Section A

Position along channel (cm)

h (mm)

u

j

B
Experimental Results: $j \times B$ thrust

60 A, 0.1 T

Flow speed [m/s] vs. MHD Thrust [N]

- ~0.7 Liter/min
- ~1.3 Liter/min
- ~1.9 Liter/min
Some observations during experiments

- Sensitivity to initial infill level of liquid metal:
  - Excessive thrust leaves an empty channel.
  - Flow detachment from walls.
  - Basin at the outlet causes accumulation.

8 A, 1.02 T
Simulations
Validation of 3DLMM

- Validation of simulation code with experiments.
- Theoretical solutions with Shallow-Free-Surface-Flow model (SFSFM).

\[
\begin{align*}
\frac{\partial u}{\partial x} + \frac{\partial w}{\partial z} &= 0 \\
\rho(U \cdot \nabla)u &= -\frac{\partial p}{\partial x} + (\mathbf{j} \times \mathbf{B})_x + \mu \nabla^2 u
\end{align*}
\]

\[
\begin{align*}
Q &= 0.7 \text{ L/min} \\
I &= -20 \text{ A} \\
B &= 0.61 \text{ T}
\end{align*}
\]

\[
\begin{align*}
Q &= 1.9 \text{ L/min} \\
I &= 60 \text{ A} \\
B &= 0.103 \text{ T}
\end{align*}
\]
Fringing currents

- Q = 1.9 L/min, I₀ = 60 A, B = 0.103 T
Effects of substrate conductivity

- $|B_n| = 1 \, T$, liquid lithium, $Q = 10 \, \text{L/min}$, $t_w = 2.5 \, \text{mm}$
  - Electrodes as long as channel to eliminate fringing currents.

![Graphs showing the effect of substrate conductivity on lithium flow](image-url)
Velocity gradients

- $|B_n| = 1 \, \text{T}$, liquid lithium, $Q = 10 \, \text{L/min}$.
  - Insulated substrate.

- Developing flow
  - Velocity Magnitude [m/s]
  - 0.00  0.35  0.70

- Axial currents
  - $J_x [\text{kA/m}^2]$
  - -20.0  0.0  20.0

(d) Stream-wise currents for $I_0 = 50 \, \text{A}$. $h$ is increased by a factor of 10.
Projections for power requirements

• Balance between MHD drag and \( j \times B \) thrust

\[
|\mathbf{j}_e| \sim \sigma C_M \frac{4Lq_0^2}{\pi k \rho c_p \Delta T^2} \frac{|B_\phi + B_n|^2}{|B_n|}
\]

• For an ITER-like reactor
  – Major radius \( \sim 6 \) m
  – Exposure length \( \sim 10 \) cm
  – Liquid metal thickness \( \sim 1 \) cm
  – Flow speed to avoid evaporation
Summary

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

• Liquid metals could be propelled with external currents, but systems are sensitive due to fringing currents/flow detachment.

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

• Power requirements are excessive for Lorentz-force propulsion, far from being attractive for fusion devices.
Thanks for your attention!
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MHD Drag experiments

- 3D Liquid Metal Magnetohydrodynamics (3DLMM)
Divertorlets

$q_{\text{divertor}}$

Top view
Divertorlets

Simulations/Analytical review/Projections

- Simulations confirmed the desired flow loop around slats.
- 10 MW/m² 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).

Temperature profile

![Graph showing temperature profile with labels](image)

External Current Density $j_0$ (MA/m²)

![Graph showing external current density](image)
Divertorlets

Projections at the reactor scale

100 A, 0.3T
Time: 2.01 s

I_e = 100 A