Thermo-fluid (MHD) modeling and experiments for free surface flows with emphasis on flibe

Ideas for U.S.-Japan Monbusho Collaboration

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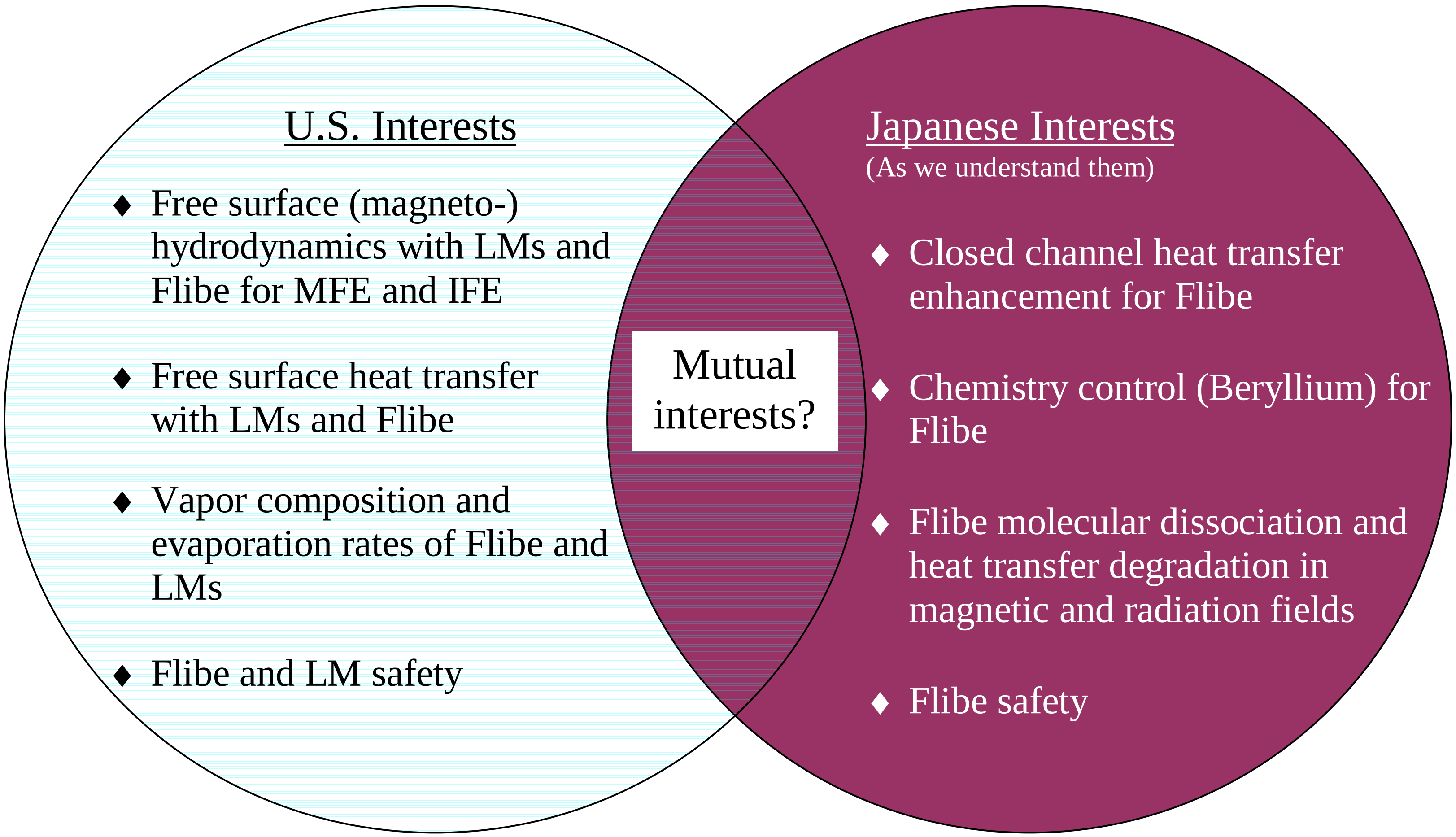
Overlap in U.S. and Japan Interests in thermal-fluid (MHD) for fusion plasma chambers



Thoughts on US-JA Monbusho Thermo-Fluid Collaboration

- **Sustain Strong Engineering Science and International Collaboration**
- **Foster Ingenuity, Encourage Innovation**
- **Understand Underlying Science, Phenomena, and Issues**
  - **Design Consideration for All Liquids**
    - **Flibe ? or**
    - **Sn-Li (Li)?**
    - **Closed Channel vs. Free Surface Flow**
  - **Conduct Modeling, Experiments, and Design Analysis**
  - **Provide Guidance and Data Base for Next Generation Stage of Larger Experiments**

The Issues of the "Thermo-Fluids" Become even more Interesting, but Challenging under the Influence of Magnetic Fields

MHD Affects the Heat Transfer for Low Electrically-Conducting and High Prandtl Number Fluids

- **Only a limited amount of data exist on the effects of MHD on heat transfer in a closed channel for high Prandtl fluids (exist only for aqueous electrolyte KOH)**
- **No data available on the effect of MHD on turbulent characteristics and heat transfer of high Prandtl fluids for free surface flows**
- **Therefore, data and models for both free surface and closed channel**s **should be of interest to** the **US and Japan.**

Available data shows that *the percentage decrease in the heat transfer at a **Hartmann wall** due to modificati of turbulent eddies by the magnetic field is correlated as:*

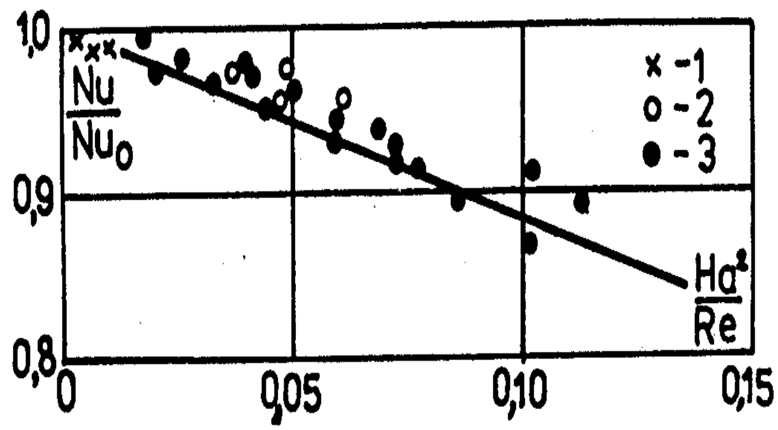
$$Nu/Nu_o = 1\text{-}1.2\ N$$

where N is the interaction parameter (based on the hydraulic diameter of the closed duct).

The above correlation is valid for $Re > Re_{cr}$ *and* $N < 0.1$;

$N = Ha^2/Re$

$Re_{cr} = 250\ Ha$ ***(Ha number based on hydraulic diameter)***



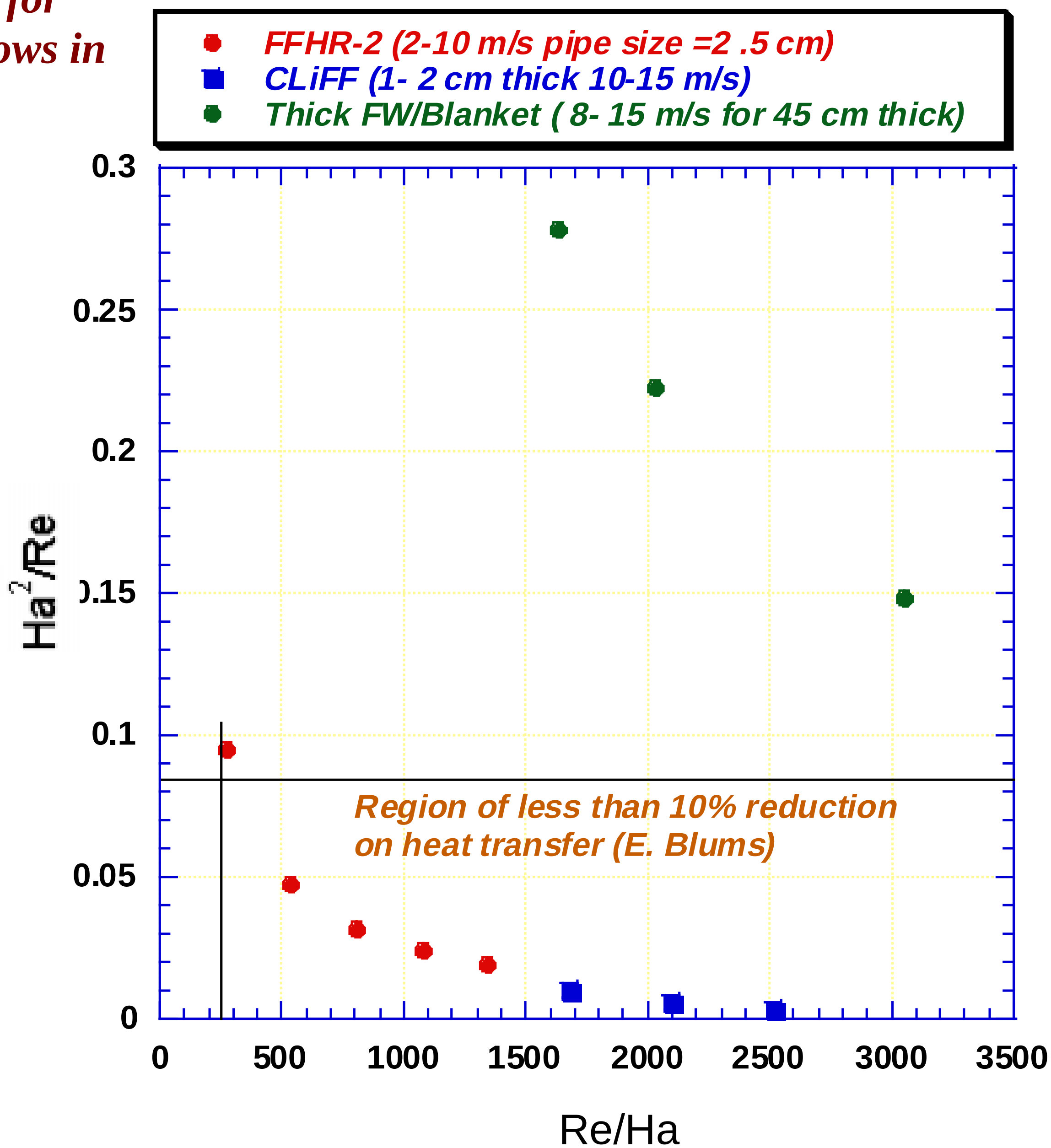
***Reference:** E. Blums et al., Heat and Mass Transfer in MHD Flows, Chapter 6*

Problems in applicability of data:

Hartmann wall
Entrance effects
Wrong aspect ratio
Proper definition of length scales

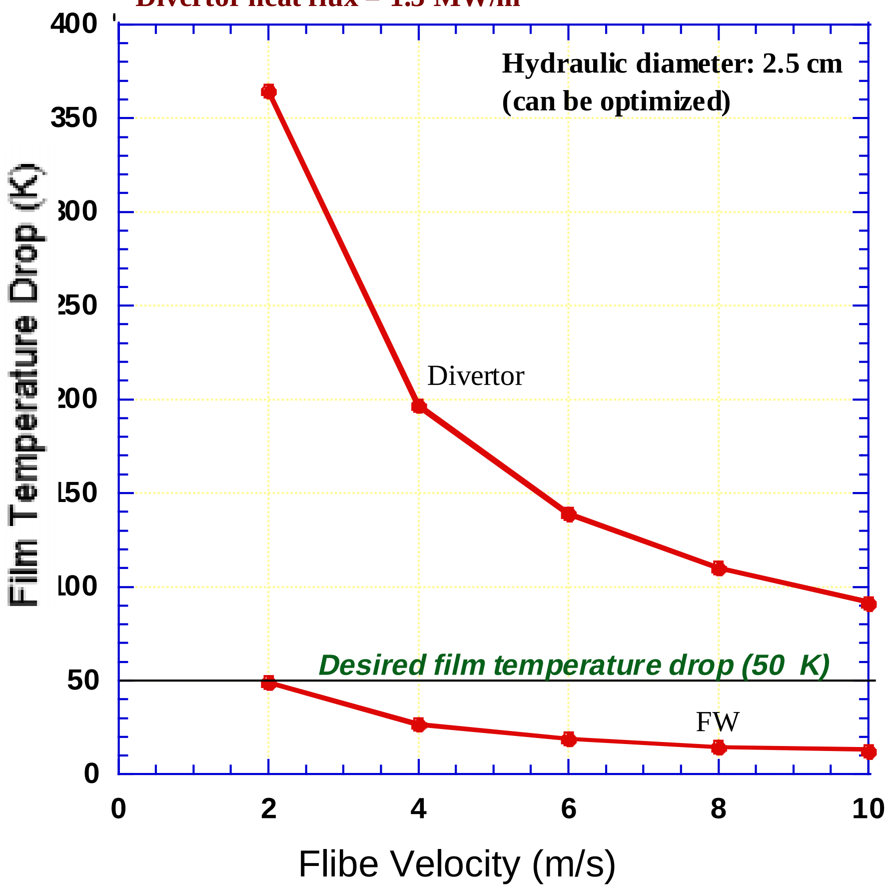
Parameter Space of Interest for MHD Interaction

Parameter Space for Various Flibe Flows in Toroidal Systems

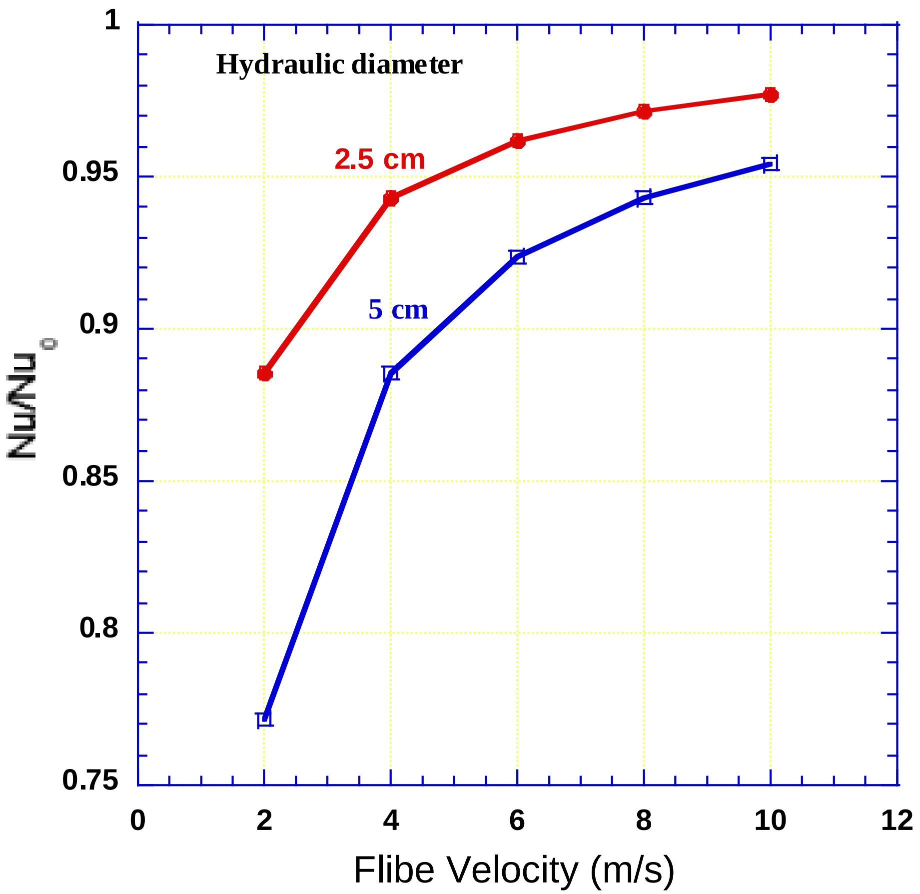


Identification of Heat Transfer Enhancement Techniques for FFHR-2 High Heat Flux Application may be more Important than the Investigation of MHD Effects on Flibe Heat Transfer

Toroidal field = 10T
Flibe property for 34% BeF2 at T=500 C
FW heat flux = 0.2 MW/m ^{2}
Divertor heat flux = 1.5 MW/m ^{2}



MHD Effects on Heat Transfer Reduction
(for different hydraulic diameters)



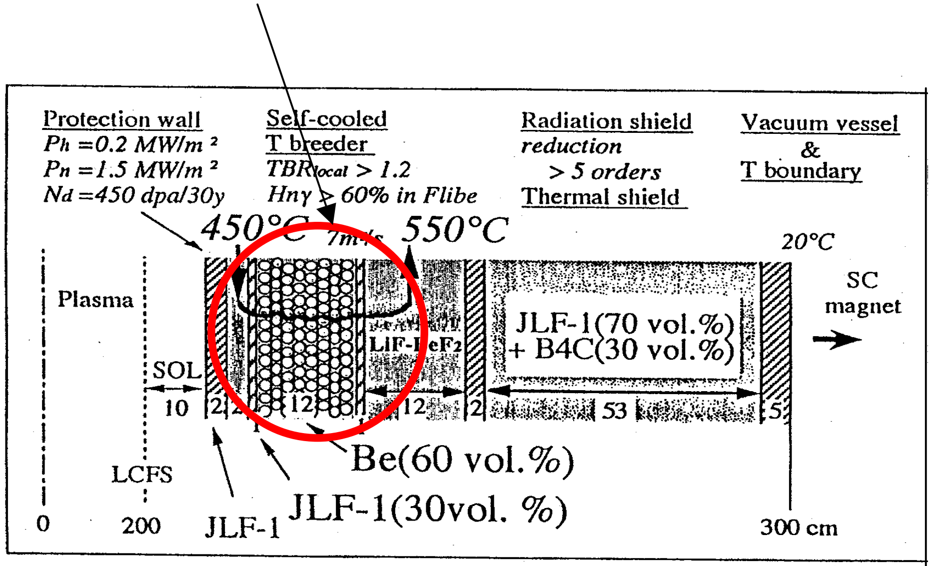
Beryllium Pebble Bed May Be a Good Area for US-JA Collaboration

Japan: Be pebble bed with flowing Flibe: thermo-physical properties of Be pebble/Flibe bed are important

US: On-going experiments and modeling on Be pebble/He bed thermo-physical properties

- **Beryllium in a pebble bed form is needed for a closed-loop Flibe system in order to achieve an adequate tritium production and to provide a proper chemistry control**
- **Effective thermal properties (unknown) of such a heterogeneous system are required to derive an meaningful design point**
- **Key Operating Parameters:**
  Temperature profile, Pressure drop, and Flow control

Region of Interest



Pressure Drop as a Function of Flibe Velocity
(packing fraction=0.6, Be particle size = 2 mm)

Flibe velocity	Pressure Drop per meter path
0.1 m/s	0.476 MPa
0.2 m/s	1.2738 MPa
0.5 m/s	5.6 MPa

Research Needs for FLIBE Free Surface Flows

Status: Modeling underway for APEX

- **3D commercial code for hydrodynamic configuration and heat transfer**
  limitation: no access to source for accommodation of complex boundary conditions or modification of equations for parallelization, MHD, or turbulence models
- **2-D and 3-D research codes with k-ε model for free surface heat transfer**
  limitation: requires adjustment for new physical situations like free surface and MHD

Data needed:

- To adjust the k-ε model for free surface MHD
  - k: u', v', w' as a function of Re and Ha
  - turbulent spectra to estimate size of surface eddies
  - surface temperature response to surface heat flux
  - near wall velocity profile u/u* as a function of Ha

Possible Data Source:

- Well-scaled experiments in conjunction with sophisticated DNS/LES modeling

Proposed Experimental Flow Facilities for APEX, IFE and US-JA Collaboration

Flow Loops

MeGA-Loop[1-*]
Liquid Metal Flow Experiment

WET-Test[3-**]
Water/Electrolyte Thermo-fluid Test Facility

Salt See-Saw[3-***]
Simplified Molten Salt Flow and Heat Transfer Experiment

Magnets

FLEX[2-***]
Flexible Geometry Magnet Facility

Micro-TOR[1-*]
Complete Toroidal Magnet System

1. *Already Operating, need small modifications*
2. *Partially Complete, larger investment needed*
3. *Design Exploration, depends on US budget*

*Number of * indicate relative applicability to US-JA collaboration*

Are there ideas to handle Flibe

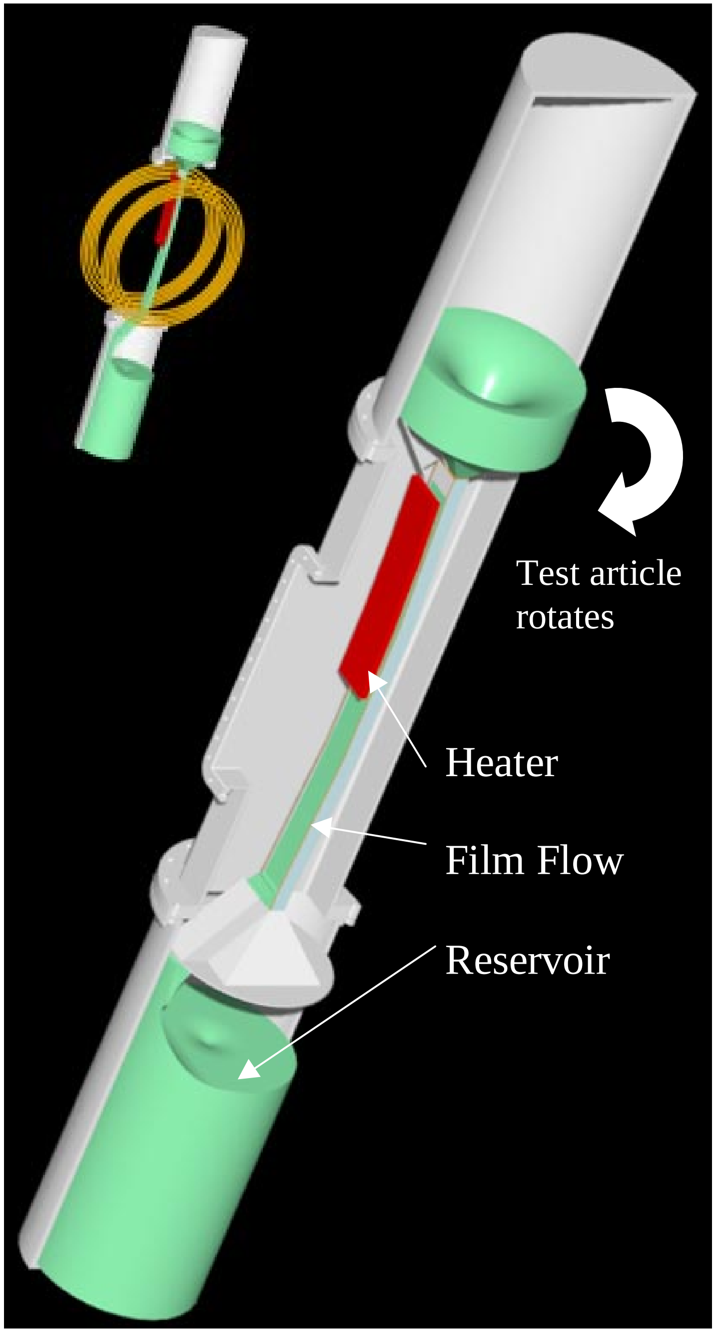
in thermofluid experiments

that may minimize safety concerns?

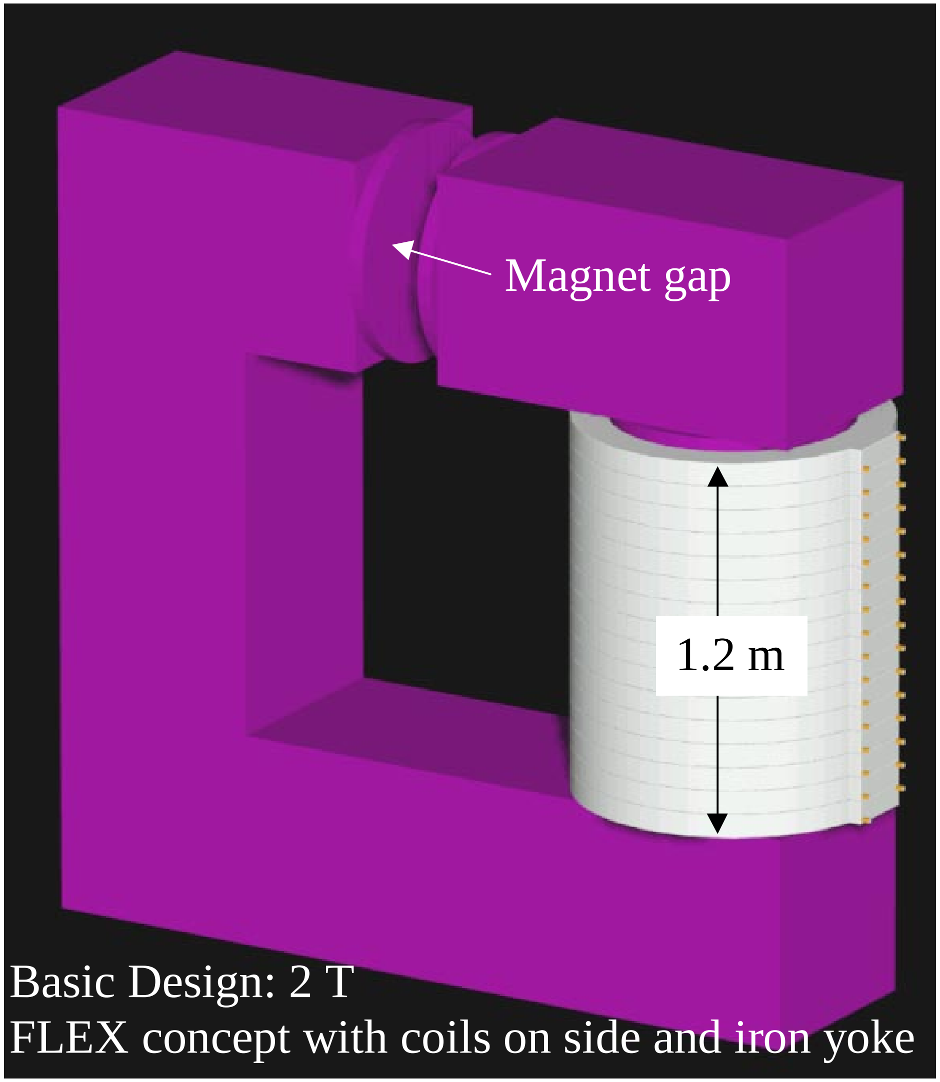
Salt See-Saw

Heat transfer experiments in open and closed channels

- **Molten Salt** flows from supply reservoir to collection reservoir through thermofluid test section of interest
- **System rotates with See-Saw action** reversing supply and collection reservoirs (no pumps or pump seals, no pipe connections)
- Many different tests possible, **including MHD in FLEX** (see inset picture)
- **Flibe safety**:
  - Completely enclosed system
  - Procedures need to be established in conjunction with INEEL safety experiments and local UCLA Environmental Health and Safety Office



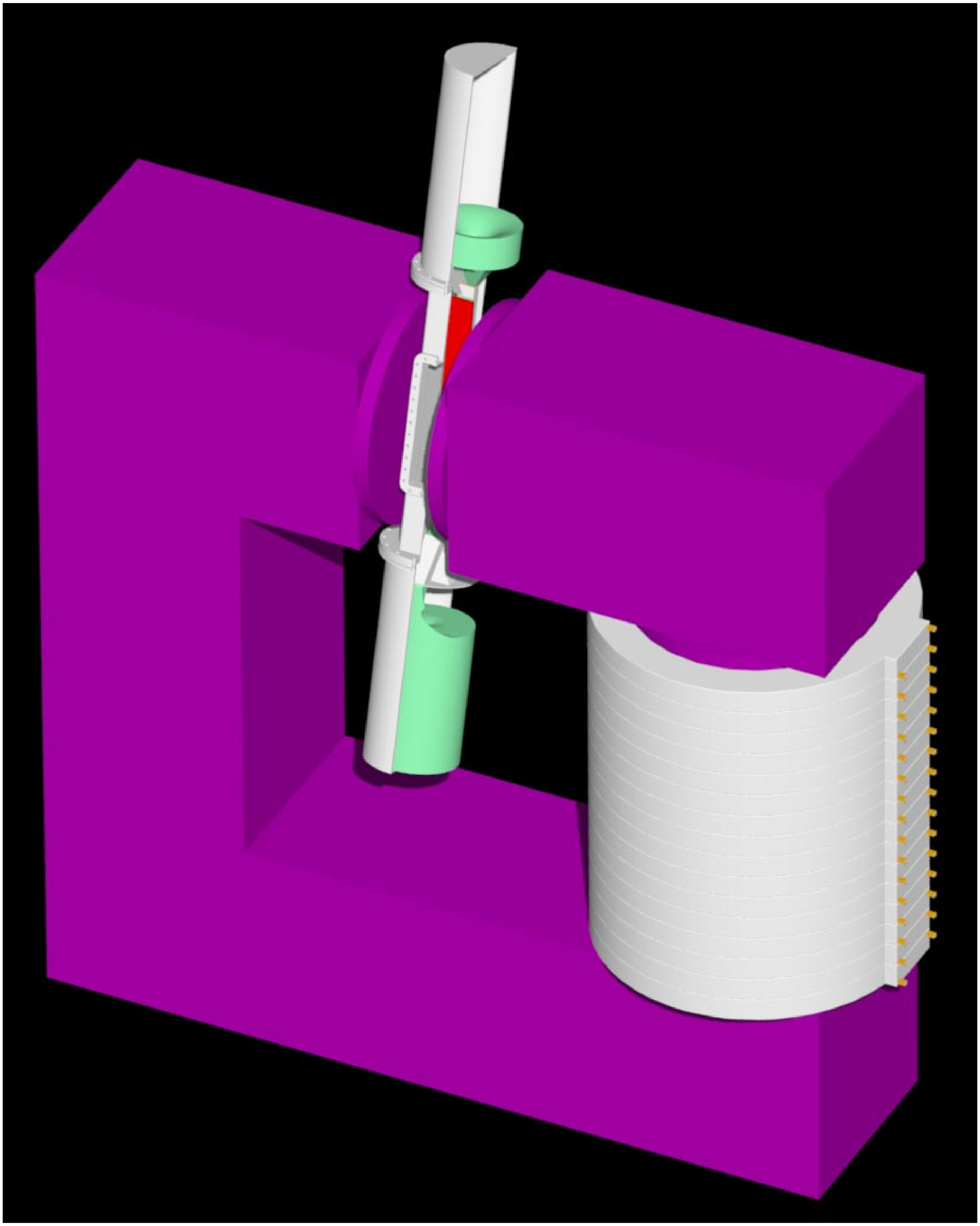
FLEX: Flexible Geometry Magnetic Field Facility



Basic design, Iron Core

- B > 1.8 T at 40 cm gap
- Adjustable gap size and shape using interchangeable fluxhorns
- Easy access to working volume
- Adjustable orientation to gravity
- Close coupling to the MeGA-Loop, Wet-Test and See-Saw flows and diagnostics
- Status: partially complete
  - 12 coils on hand (from TARA)
  - two power supplies on hand

If higher fields are needed for relevant heat transfer tests, then B > 4T possible with additional resources (US-Monbusho)



Key Physical Properties and Parameters of Interest for Scaling Analysis

Properties		*Flibe*	*KOH+Water*	*HTS*[3]
Working Temperature	C	500	50	400
Density	ρ (kg/m^3)	2035	1346	1760
Electrical Conductivity	σ (1/Ωm)	155	96	59
Dynamics Viscocity	μ(Kg/ms)	0.0148	0.0016	0.0011
Modified Reynolds Factor[1]	$\rho/(\sigma\mu)^{1/2}$	1343.6	3434.4	6910
Important Factors for Heat Transfer and MHD Effect Considerations				
Prandtl Number	$C_p\mu/k$	33.23	6.13	2.89
Hartmann Factor	$(\sigma/\mu)^{1/2}$	101	245	232
Interaction Factor[2]	(σ/ρ)	0.078	0.071	0.033

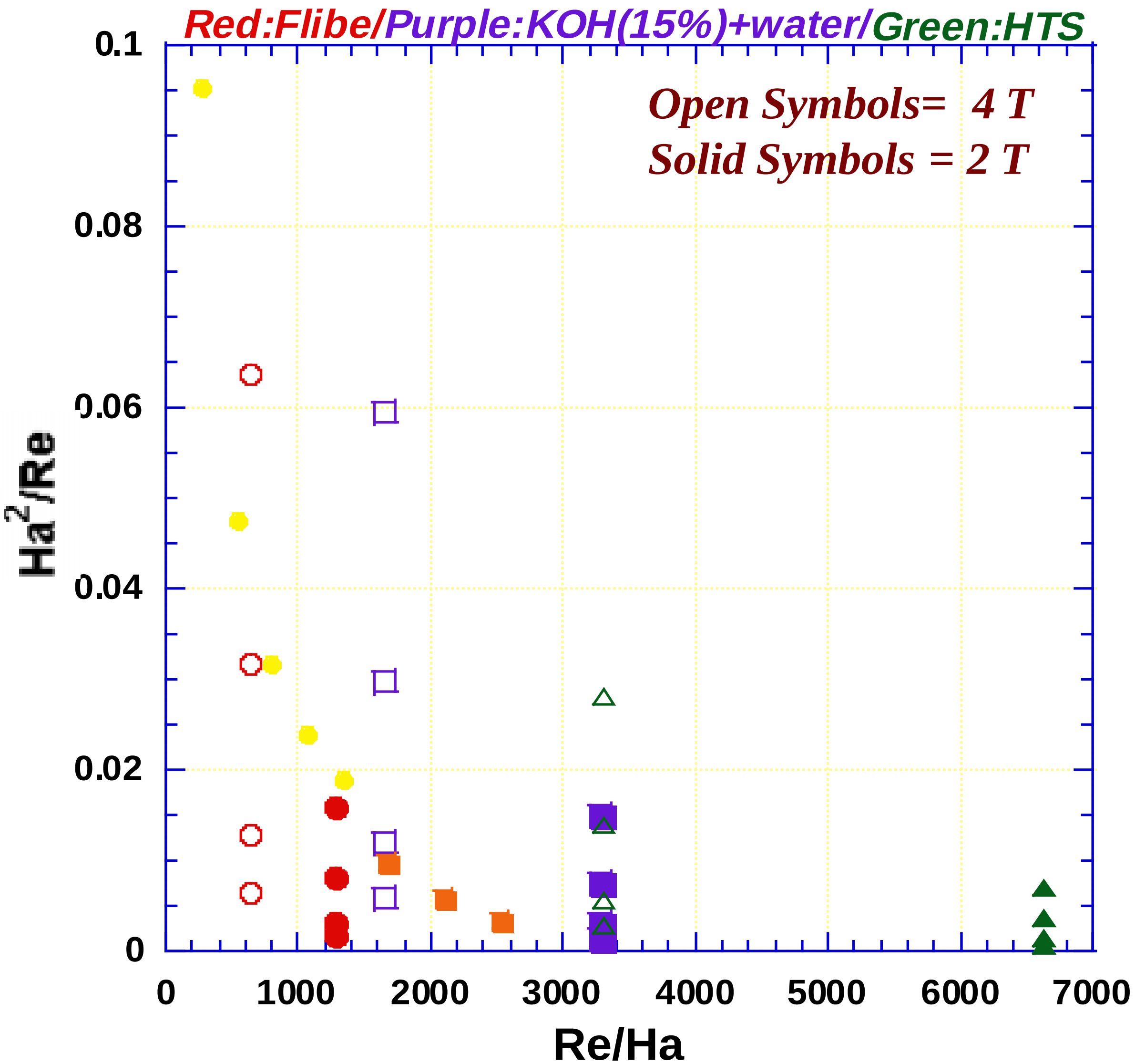
Notes

1. Modified Reynolds factor (scaling Re/Ha) determines the regime where the MHD effect on flow laminarization becomes important.
2. All Flibe designs are not fully laminarized. The interaction number indicates the amount of turbulent modification and heat transfer degradation.
3. If operational temperature is less than 400 C, HTS viscosity would increase while electrical conductivity would likely decrease making HTS less applicable for MHD heat transfer experiments.

KOH solution at elevated temperatures has high electrical conductivity for MHD heat transfer studies. (However, it is uncertainty whether the vapor pressure would create difficulties for free surface flow experiments.)

Experimental Space of the "*See-Saw/FLEX*" Test Facility using Different Simulant Materials

Average fall velocity = 1.917 m/s over a vertical fall distance of 75 cm
Film thickness = 1-10 cm



WET-Test: Water/Electrolyte Thermofluid Tests

Water flow facility with multiple Flibe simulation applications

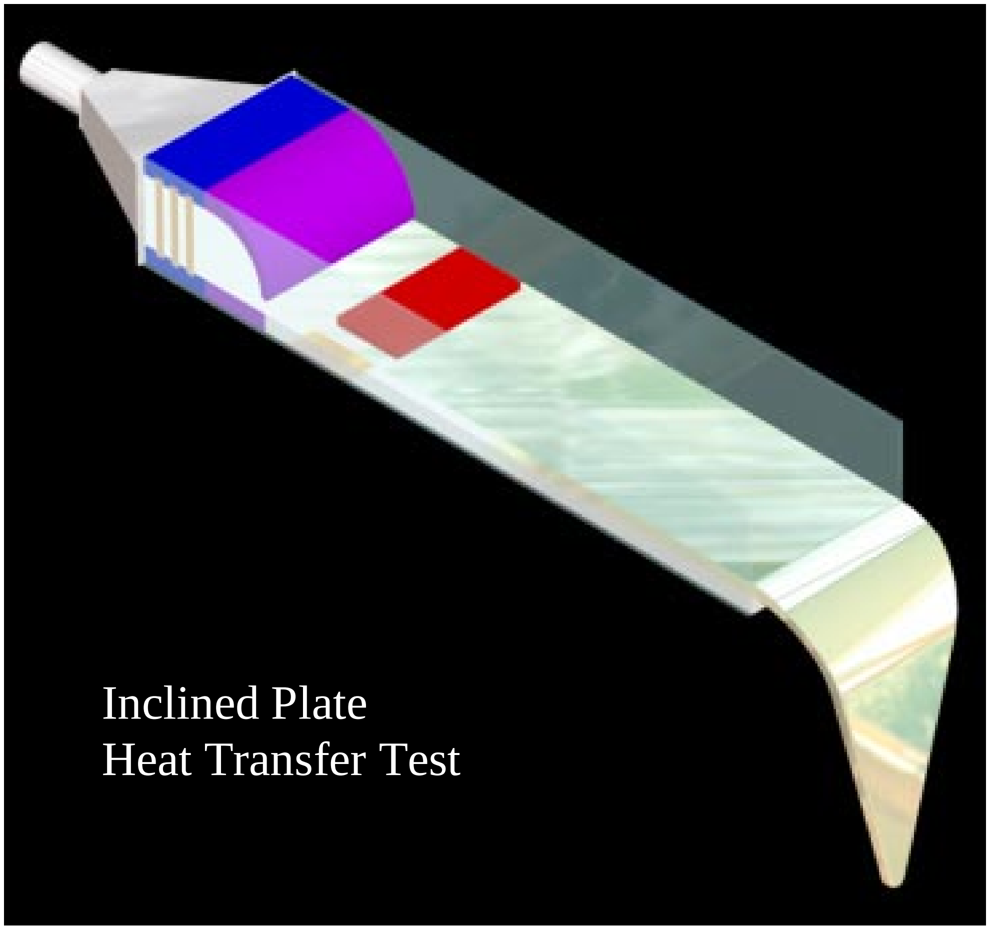
- Exploration of **hydrodynamic configurations** for APEX and IFE free surface geometries
  EXAMPLES:
  - *Flow on concave surface*: depth/velocity, surface wave, adhesion characteristics
  - *Free jets of various shape with impulse loading*: jet deformation and surface waves, droplet clearing efficiency
  - *Swirl flows inside cylinders*: depth/velocity, surface wave, adhesion characteristics

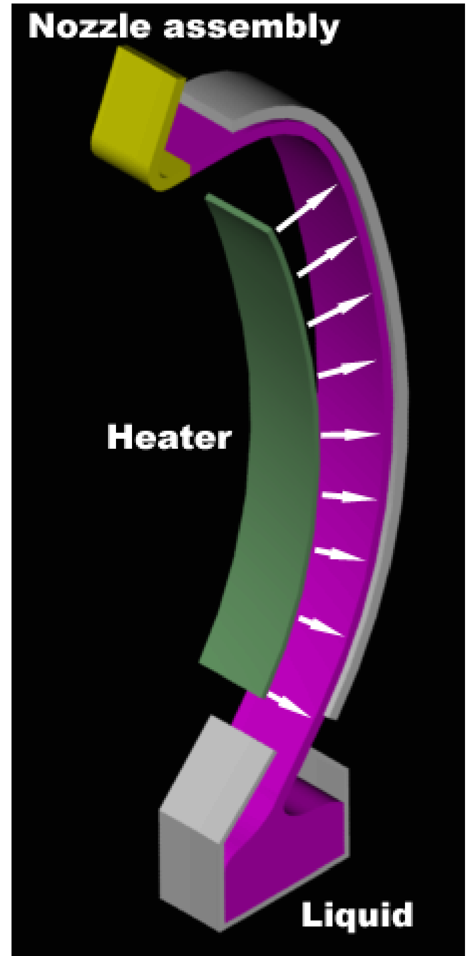
- Exploration of **high Prandtl No. MHD heat transfer**** for free surface and closed channels
  - B-field in either FLEX or Micro-TOR field facilities
  - KOH electrolyte for finite electrical conductivity
  - LDV point turbulence measurements
  - Surface and bulk temperature measurements

**Of particular interest for US-JA collaboration

WET-Test: Water/Electrolyte Thermofluid Tests

Example test sections





Curved Plate
Heat Transfer Test

Suggested Modeling Collaboration for Flibe Thermofluid Flow

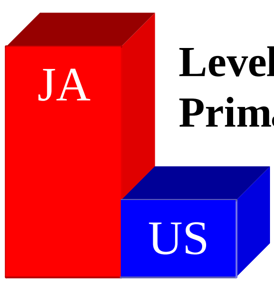
Main Focus

Detailed study of near-wall and near-surface turbulent structures in strong magnetic fields

Techniques

LES and DNS calculations including:

- Modeling free surface deflection by energetic eddies
- mechanisms of turbulence suppression by magnetic field.



Level of Effort:
Primarily Japan

Main Focus

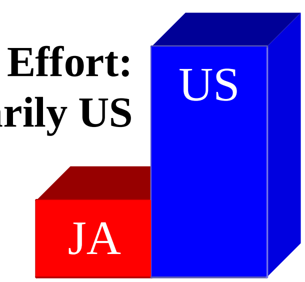
Computational simulations and heat transfer calculations for real flow geometries (liquid first wall, blanket) in the range of flow parameters relevant to APEX.

Techniques

Accurate RANS-type k-ε turbulent models for free surface and closed duct MHD flows

- k-ε model reformulated for MHD and free surface
- Adjusted with relevant data from DNS/LES modeling and experiments

Level of Effort:
Primarily US



Research Needs for LM-MHD Free Surface Flows

(possible additional area of collaboration for US-JA)

Status: Modeling underway

- 1-D and 2-D research codes:
  - coupled interaction with the magnetic field
  - mapping and VOF free surface tracking
  - simplifications of field and flow geometry

Data needed:

- Experimental validation of predictions of simplified models for constant magnetic field and spatial/temporally varying magnetic fields

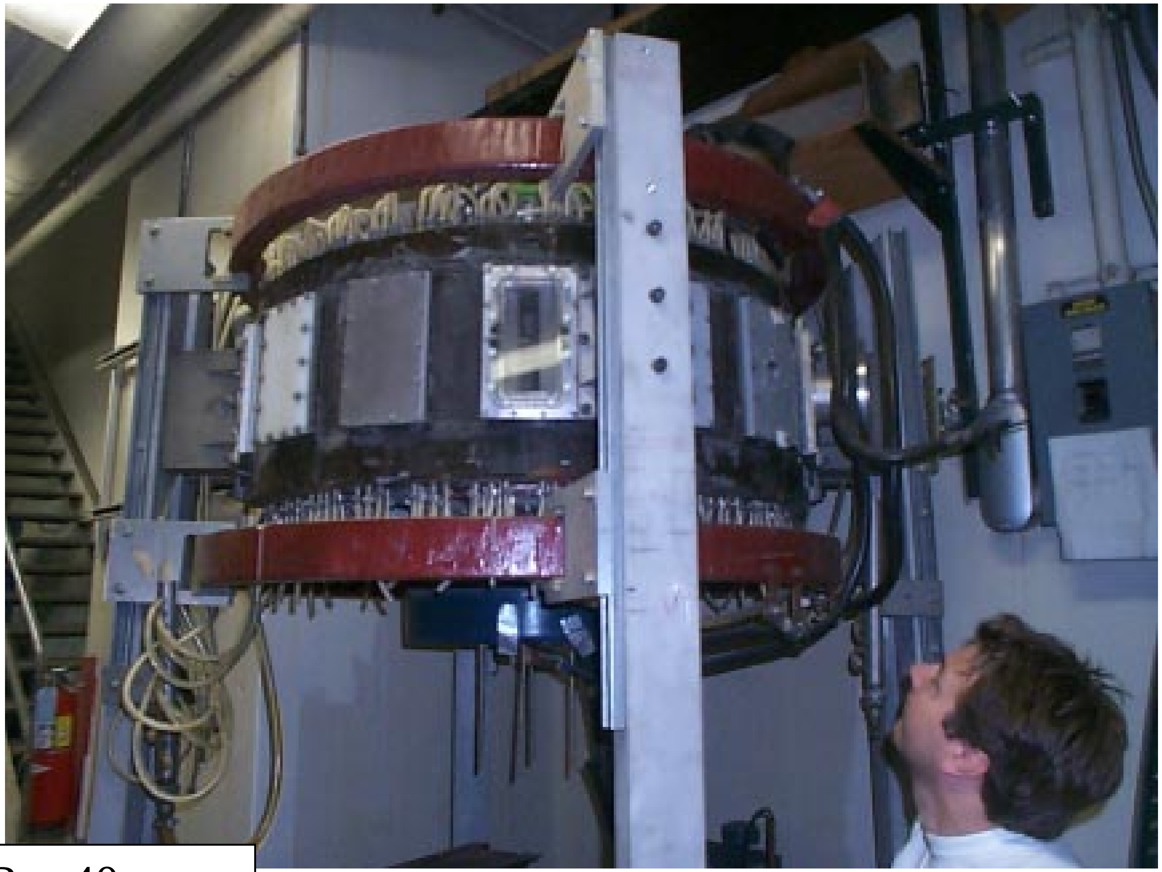
Possible Data source:

- MeGA-loop experiments in FLEX and Micro-TOR
- Other experimental facilities?

Micro-TOR: Complete Tokamak Magnet System

(Former plasma physics device is being transferred from Physics to Technology Lab)

- **Real Tokamak Field Variations**
- **B_T > 1 T on axis for long pulse**
- **Many access ports and good vacuum capability**
- **Quasi-Axisymmetric experiments possible**
- **Plasma current and disruption simulation with single turn coil upgrade**



R = 40 cm
a = 10 cm

Advanced Diagnostics Systems are Required For Characterization of Turbulence and Free Surface Topology

Use of Flibe, water or water+KOH electrolyte may be an <u>optically transparent fluid</u>. Therefore,

- *Advanced hydrodynamic diagnostic systems (LDA,PIV, etc)* may be utilized to

    - perform detailed measurements (accuracy, multiple dimensions, etc.)
    - minimize the perturbation to the hydrodynamic characteristics of the flow.

- *Flow visualization techniques* (O_2 bubble, strobe & high speed digital photography, etc. techniques) may be used to obtain information about the flow field, turbulence characteristics and free-surface topology of the experimental flow system.

- *He-Ne laser and 2-D photo-diode array configurations* with high speed data acquisition systems may be utilized to obtain information about the thickness, surface wave angles, etc. of the flow.

Diagnostics Systems for Free Surface Flow Heat Transfer Experiments may be an Area For Collaboration

Sophisticated diagnostic systems are required for turbulence structure characterization and dynamic surface temperature measurements.

Areas of Collaboration

Various advanced flow/heat transfer diagnostic systems may be jointly investigated to :

- Identify compatibility of diagnostic technique to the proposed experimental study.
- Evaluate the resolution needed for the modeling and simulation.
- Investigate the diagnostic needs to test section design.

Free Surface Heating Technique Remains a Challenging Issue for Flibe Free Surface Heat Transfer Study

- Working fluid is optically transparent.

- Enabling instrumentation are under investigation/design-process in order to deliver similar base design operating condition to experimental facility.

    - Heating flowing fluid surface with minimum disruption to the flow.

    - Tailoring of the heat source wavelengths (filtering, etc) for uniform heat deposition along the constant operating fluid depth.

    - Characterization of free surface heat deposition both in planar on the flow and depth into the flow surface using advanced diagnostic systems.

- Use of infrared temperature measurement techniques to determine the flow surface temperatures for on wavy free-surface flows.

Capabilities at UCLA

Instrumentation

- Laser Doppler Velocimetry
- Micrometer flow depth probes
- Bubble flow visualization
- Holographic temperature profiling

Laboratory Facilities

- Space and high load crane
- Vacuum systems
- Multiple Flow loops
- Magnets
- Low voltage high current power supplies

Computational Tools

- DNS/LES codes
- Free Surface Codes
- MHD Codes
- Parallel computing clusters

Brain Power

- Areas of expertise in UCLA Fusion Science and Technology Group

  - Mohamed Abdou: Fusion experiments, modeling and design
  - Alice Ying: Fluid Heat Transfer
  - Neil Morley: Free surface, MHD
  - Mahmoud Youssef: Photon Transport
  - Sergey Smolentsev: Turbulent MHD
  - Karani Gulec: Experimental Fluid
  - Tom Sketchley: Experimental Design

- Interest in collaboration by other UCLA faculty with worldwide reputations

  - Nasr Ghoniem: Fusion materials
  - John Kim: DNS and MHD
  - Robert Kelly: Free surface flow
  - Vijay Dhir: Fluid heat transfer

<u>Summary</u>

UCLA's Suggested Small Scale Laboratory Experiments and Modelling for US-JA Thermo-Fluid Collaborative Efforts (primarily on *See-Saw/FLEX* like test facility)

1. Turbulent structures at liquid/vacuum interfaces and at solid walls
of Flibe and Flibe simulants flowing on flat and curved plates, and swirl pipes with and without MHD effects

2. Heat transfer at liquid/vacuum interfaces and at solid walls with and without MHD effects
Radiant heating, **laser surface and IR temperature measurement of Flibe and Flibe simulants flowing on flat and curved plates, and swirl pipes**

- ❑ To validate the applicability of k-ε model for turbulent free surface and MHD flow
- ❑ To provide data for **benchmarking DNS/LES techniques**
- ❑ To provide experimental data and empirical correlations for use in Flibe designs

<u>Sub-areas of Interest for Collaborative Efforts</u>

- ➢ **Further Evaluation and Identification of Flibe Simulants (for example HTS, Electrolytes, ?)**
- ➢ **Identification of Instrumental Techniques**