Fundamental Thermofluid Experiments & Modeling

Subtask 3-1 of the US-Monbusho Collaboration Proposal

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Other US Institutions:
PPPL, ORNL, INEEL, ANL

US-Monbusho Collaboration Meeting
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Thermofluid Task Objectives

1. Understand Underlying Science and Phenomena for Flibe Flow and Heat Transfer Issues through:

   a. Conducting Experiments Using Flibe Simulants
   b. Modeling and Analysis of fundamental phenomena

2. Compare Experimental **and** Modeling Results to Provide Guidance and Design Database for both Flibe Blankets and Next Generation Stage of Larger Flibe Experiments.

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3. Identifying and assessing new innovative techniques for enhancement of Flibe heat transfer (a major feasibility issue for Flibe blanket designs)

Main Areas of Collaborative Scientific Interest

Hydrodynamics at liquid/vacuum interfaces and at solid walls of Flibe simulants flowing on flat and curved plates, and in closed channels and swirl pipes, with and without MHD effects

Heat transfer at liquid/vacuum interfaces and at solid walls of Flibe simulants flowing on flat and curved plates, and in closed channels and swirl pipes, with and without MHD effects

Sub-areas of Interest for Collaborative Efforts

Identification of instrumental and experimental techniques: Radiant heating, laser and ultrasonic surface topology reconstruction, infra-red temperature measurements, laser Doppler anemometety, others.

Development and benchmarking of new modeling techniques:
MHD/turbulence interactions and turbuelnce/free surface or wall interatctions in k-e, DNS, LES

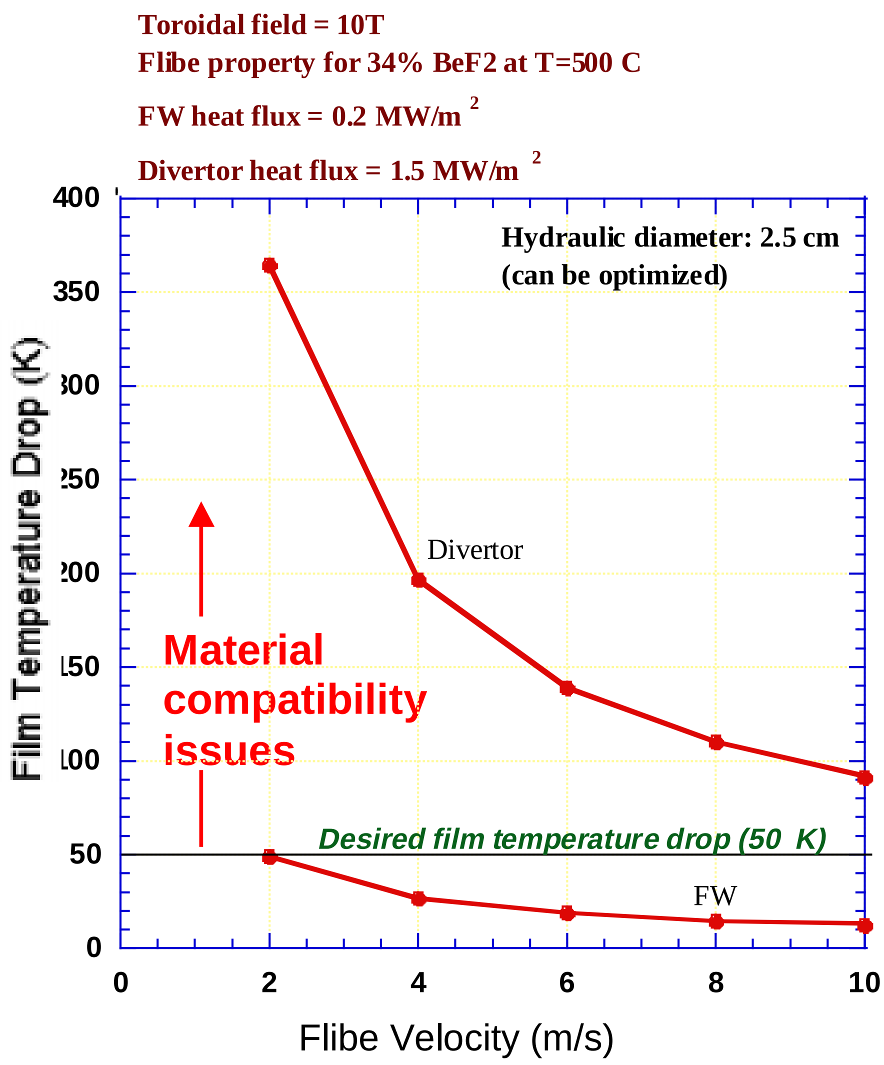
Heat Transfer Enhancement for FFHR-2 and LW High Heat Flux Application is critical

Inlet temperature for Flibe is > 500 C

Maximum operating temperature of FFHR structural material is estimated at < 600 C.

Maximum operating temperature for LW plasma compatibility is estimated at < 600 C

Film temperature rise must be < 50 C to keep operating window open



MHD Affects 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*
- ❑ *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 channels should be of interest to the US and Japan.*

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

$Nu/Nu_o = 1-1.2\ N$

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

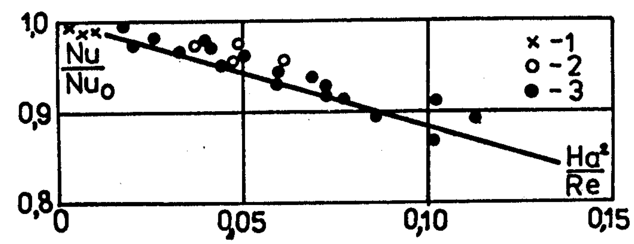


Fig. 6.8 Dependence of the total heat transfer intensity in the flow of an electrolyte in a transverse field on parameter Ha^2/Re at the values of Ha: 1 -- 3.7 (Ref. 6.6); 2 -- 18; 3 -- 31 (Ref. 6.3).

Problems in applicability of data

Taken over limited parameter range

- The above correlation is valid for $Re > Re_{cr}$ and $N < 0.1$;
- $Re_{cr} = 250\ Ha$ (Ha number based on hydraulic diameter)

Similarity issues with real fusion needs

- Data taken at Hartmann wall, not sidewall, in rectangular channel.
- Entrance effects may still dominate (transition of 3D turbulence seed, instead of generation of MHD turbulence
- Wrong aspect ratio duct, Proper definition of length scales

Need for Coupled Modeling Effort

Explanation:

Fusion designs require practical computational models that must utilize input data from more elaborate theory and experiments. (* Note that theory implies Large Eddy Simulation (LES) and Direct Numerical Simulation (DNS).)

Collaboration:

1. Enhance LES and DNS numerical techniques to:

- **understand near-wall and near-surface turbulence structures in magnetic fields, and**
- **provide input data for practical computational models.**

2. Develop practical computational models using input from experiments, LES and DNS.

Fusion Thermofluid Flow Facilities at UCLA

MeGA-Loop

- **Liquid Metal Flow Loop Coupled with Large Volume Magnetic Field Facility for open and closed channel MHD experiments**
- ***Status: Operating since 1992, Upgrade to toroidal magnet in progress***

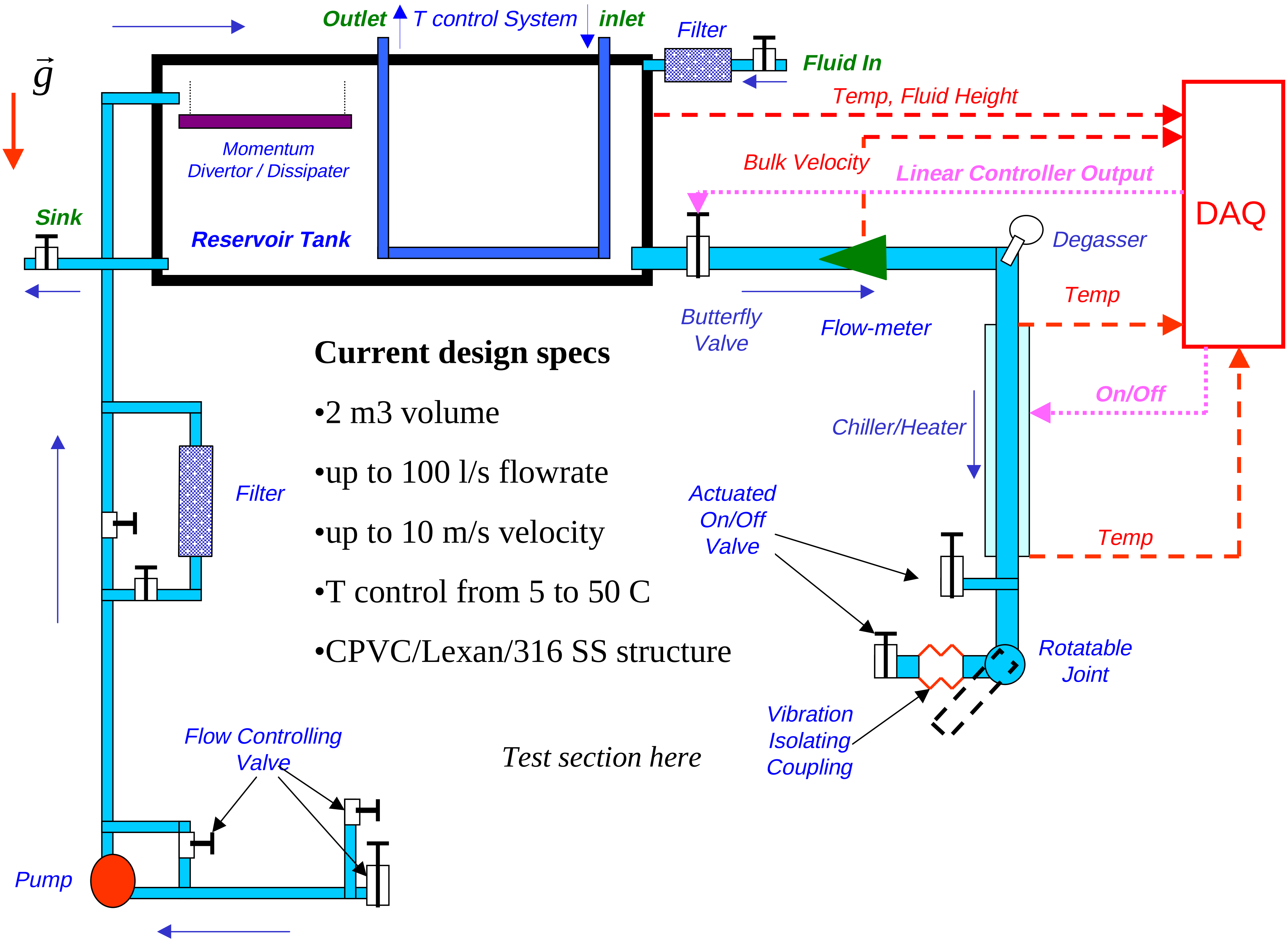
MeSO-Jet

- **Liquid Metal Flow Discharge System and Vacuum Enclosure**
- ***Status: Operational - rectangular jet deformation experiments underway***

Fli-Hy: Flibe Hydrodynamic Simulation Facility

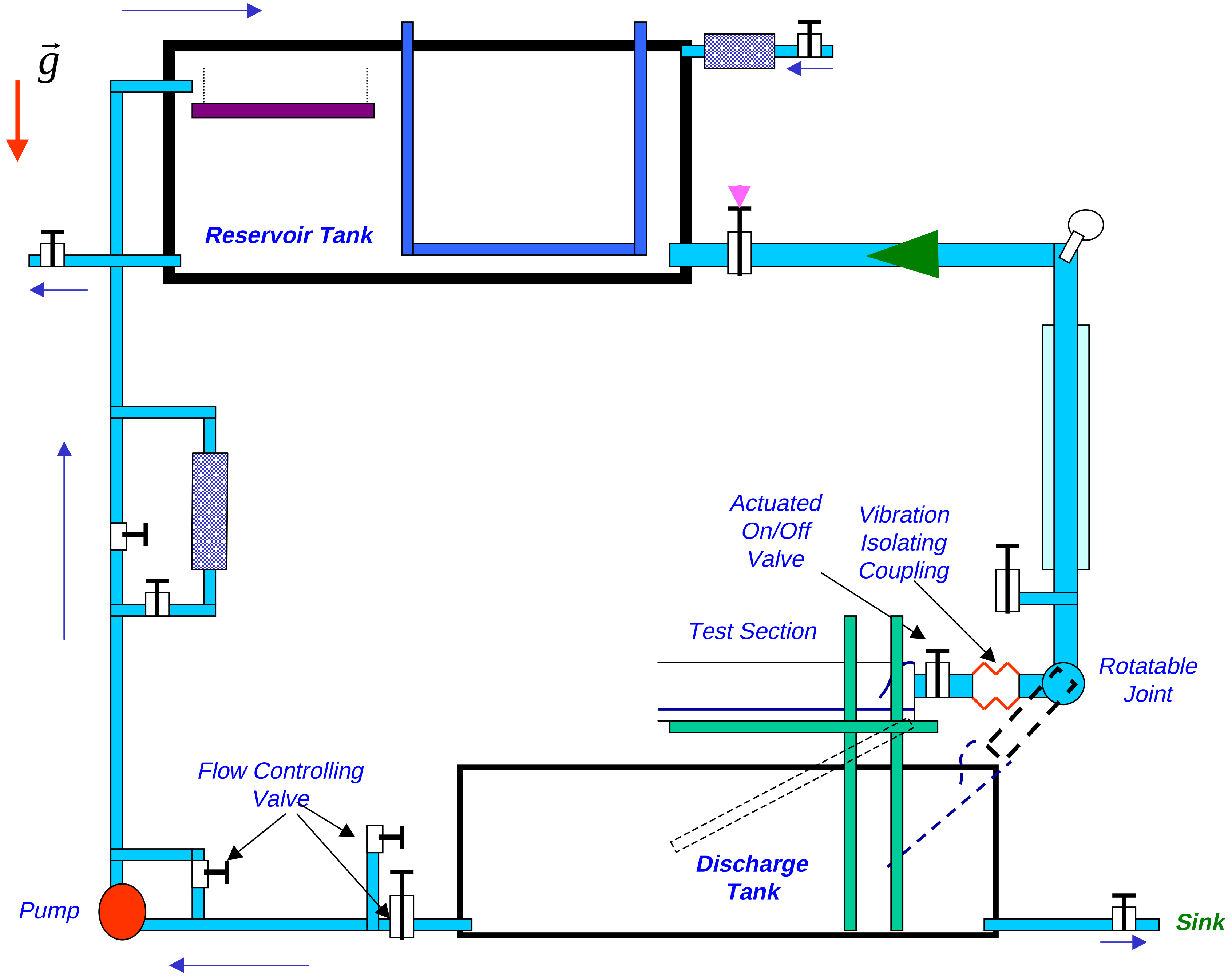
- **Water/KOH Discharge System and High Field Magnet**
- ***Status: Design and Construction***

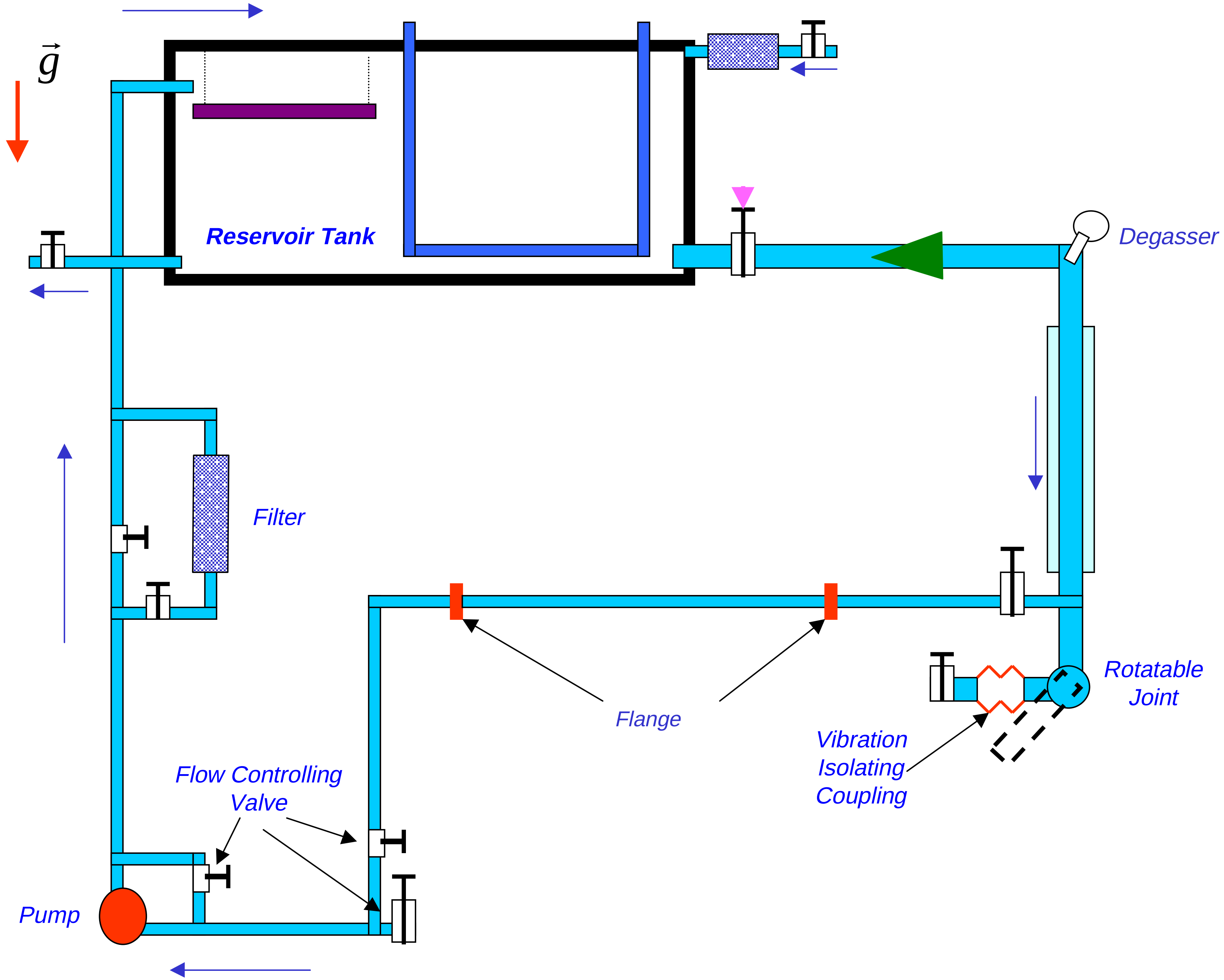
Other non-fusion UCLA flow facilites include water tunnels, wave tanks, and diagnostic systems for precision turbulence measurements.



Current design specs

- 2 m3 volume
- up to 100 l/s flowrate
- up to 10 m/s velocity
- T control from 5 to 50 C
- CPVC/Lexan/316 SS structure


$\vec{g}$
Reservoir Tank
Actuated
On/Off
Valve
Vibration
Isolating
Coupling
Test Section
Rotatable
Joint
Flow Controlling
Valve
Pump
Discharge
Tank
Sink



$\vec{g}$
Reservoir Tank
Degasser
Filter
Flange
Rotatable Joint
Vibration Isolating Coupling
Flow Controlling Valve
Pump

Fli-Hy Experimental Goals and Schedule

-1st collaboration year: **Loop construction at UCLA and shakedown tests**

1st through mid-2nd collaboration year

- **Free surface flow on curved backwall as simulation of thin liquid Flibe wall design.**
- **Free surface flow on long, inclined plane for benchmark of fully developed free surface turbulence simulations using k-e and DNS.**
- **Continued shakedown of various diagnostic techniques: e.g. fast photography, LDA, ultrasonic fluid height, holographic temperature**

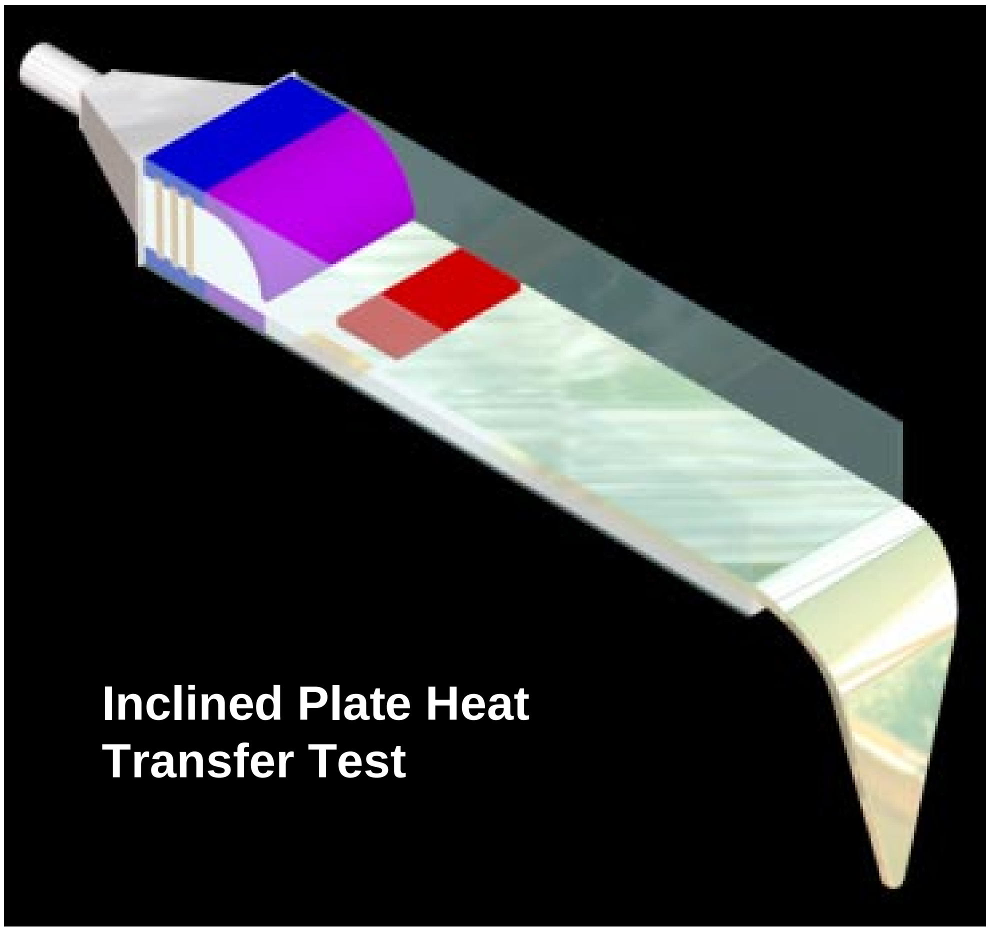
Mid 2nd through 3rd collaboration year

- **Exploration of various heat transfer enhancement techniques for open channel flows**
- **Testing of heat transfer enhancement techniques for closed channels**

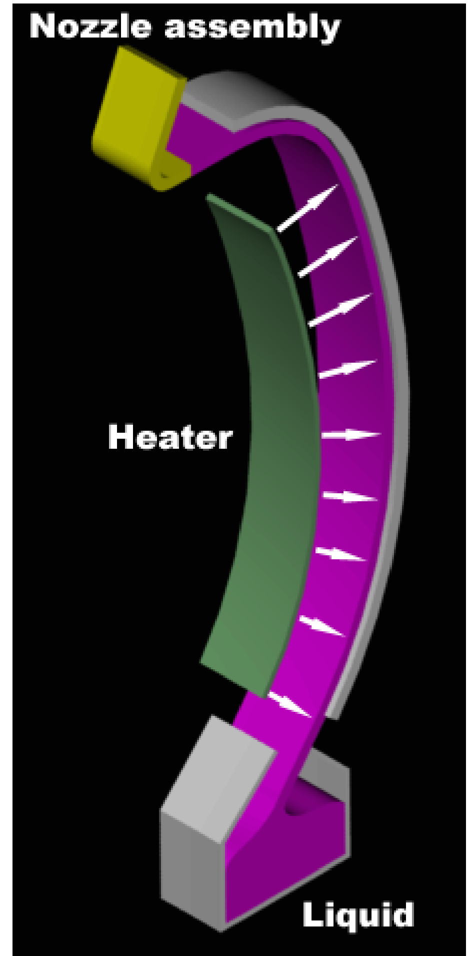
4th – 6th collaboration year (and beyond)

- **MHD/turbulence interactions and effect on heat transfer in closed and open channel tests**

Fli-Hy Example Test Sections



Inclined Plate Heat Transfer Test



Curved Plate Heat Transfer Test

INCLINED PLANE EXPERIMENTAL TEST SECTION

To deliver data on developing and fully-developed turbulence for comparison to DNS algorithm and k-e RANS modeling.

- Test section width is determined taking into account boundary layer

$$width = 2\times\delta + \text{effective test section}$$

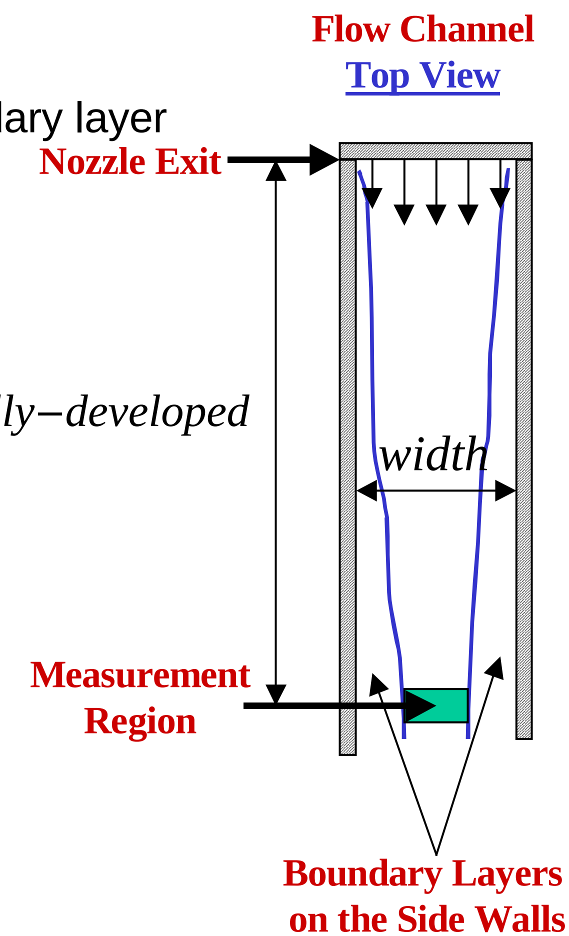
$$\delta = 0.16\,x^{6/7}\left(\frac{\rho U}{\mu}\right)^{-1/7} \qquad \delta = 0.0315\ m$$

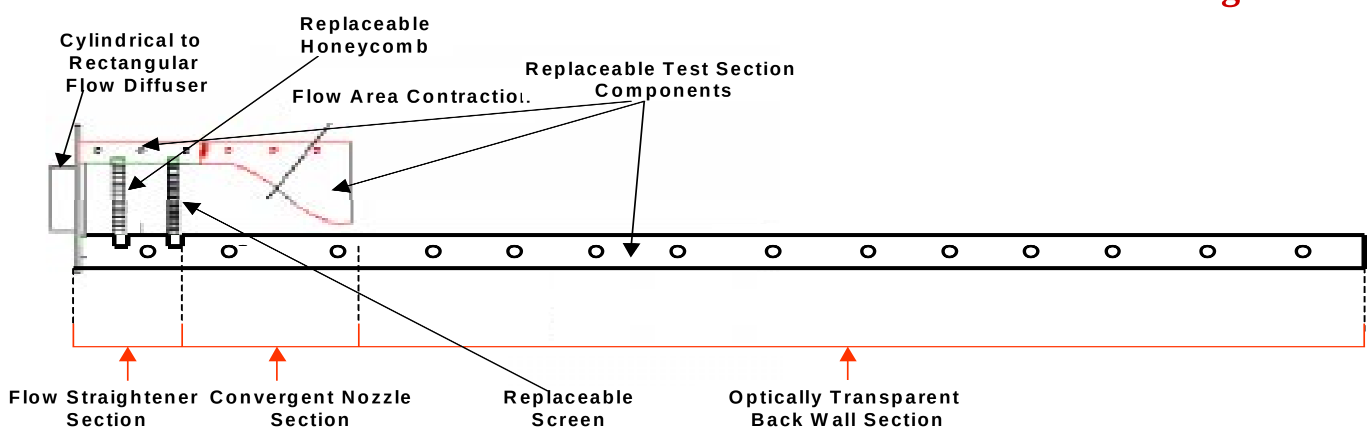
$$for\ U = 5\ m/s\ \ at\ \ x = 2\ m$$

- To obtain a fully developed turbulent liquid layer in the test section, the distance required from the nozzle exit is

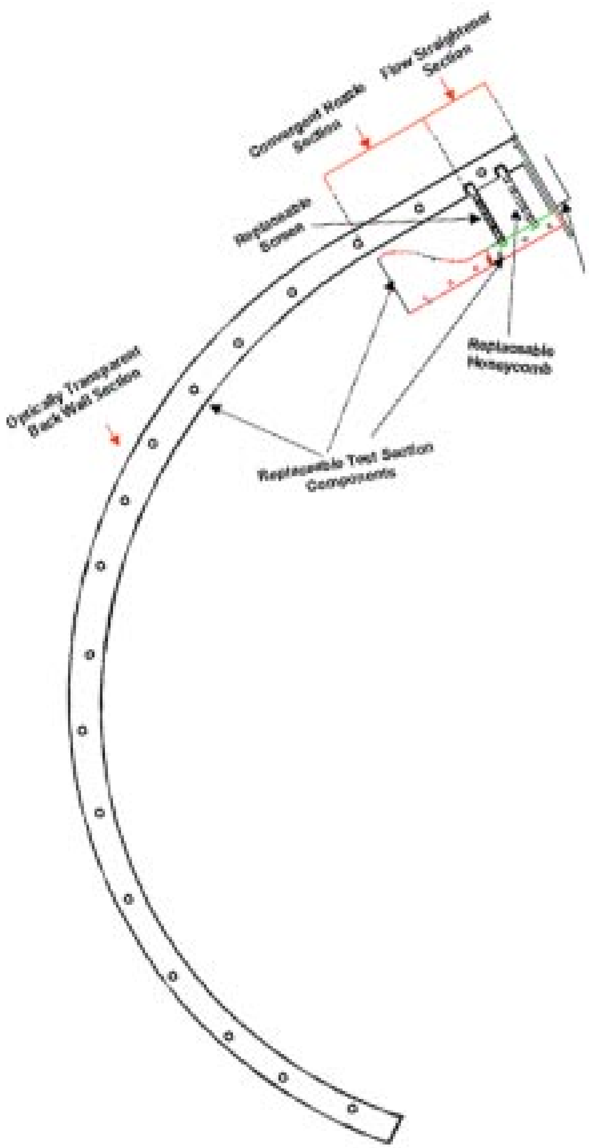
$$for \quad h = 0.005\,m \quad width = 0.4\,m$$

$$L_{fully\ \ developed} \approx 60\ \ D_h \approx 1.17\ \ m$$





CURVED WALL EXPERIMENTAL TEST SECTION



Designed to achieve similar hydrodynamic conditions of the thin liquid flibe wall base case

Observe the gross behavior of flow: i.e. attachment, wave trains, flow depth near sidewall

- High Speed Camera 1000 frame/s, 512*256 pixel
- Strobe with variable frequency

Measure flow rate and fluid depth for comparison to numerical models

- Pressure sensors, flow meter and thermocouples
- Ultrasonic and laser height measurement technique

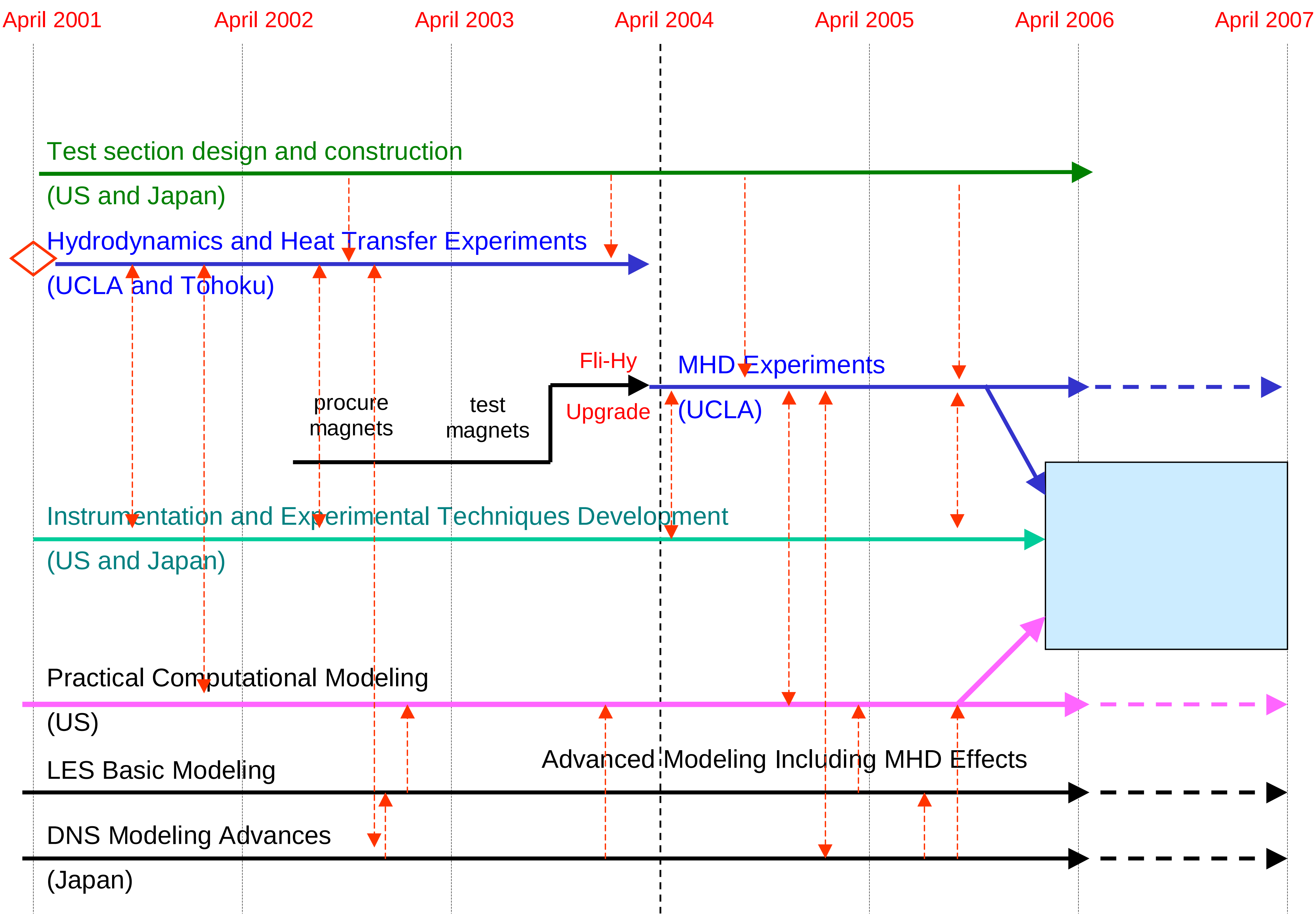
Velocity fluctuation diagnostics

2-D LDA (Laser Doppler Velocimetry):

- System Spectra Physics Model 165 Argon-Ion laser: 514.5 nm green, 488 nm blue
- Isomet 1201E-1 Acoustic-Optic Modulators (f_{center}:40 MHz)
- Isomet 221A-2 digital drivers (frequencies 40 Mhz and 43 MHz)
- Hamamatsu R928 PMT (converts light into voltage versus time signal)
- A Gage Compusscope 265 A/D card (130 MHz)
- Labview Development Suite

Flow field visualization and velocity distribution measurement using O_2 bubble (compatibility with KOH not yet determined)

- **anode:** 25 μm platinum wire,
- **cathode:** tungsten wire 200 mm downstream.


April 2001
April 2002
April 2003
April 2004
April 2005
April 2006
April 2007
Test section design and construction
(US and Japan)
Hydrodynamics and Heat Transfer Experiments
(UCLA and Tohoku)
Fli-Hy
Upgrade
MHD Experiments
(UCLA)
procure magnets
test magnets
Instrumentation and Experimental Techniques Development
(US and Japan)
Practical Computational Modeling
(US)
Advanced Modeling Including MHD Effects
LES Basic Modeling
DNS Modeling Advances
(Japan)

Unique thermo-fluid capabilities at UCLA in cooperation with other US/Japan institutions makes for a successful collaboration

Instrumentation
- Laser doppler velocimetry
- Micrometer & ultrasonic flow depth probes
- Bubble/dye flow visualization
- Holographic temperature profiling

Laboratory Facilities
- Multiple flow loops
- Multiple magnets
- Low voltage high current power supplies (from PPPL and MIT)
- Special materials handling capabilities (Be, Flibe)
- High bay space and high load crane
- Vacuum systems

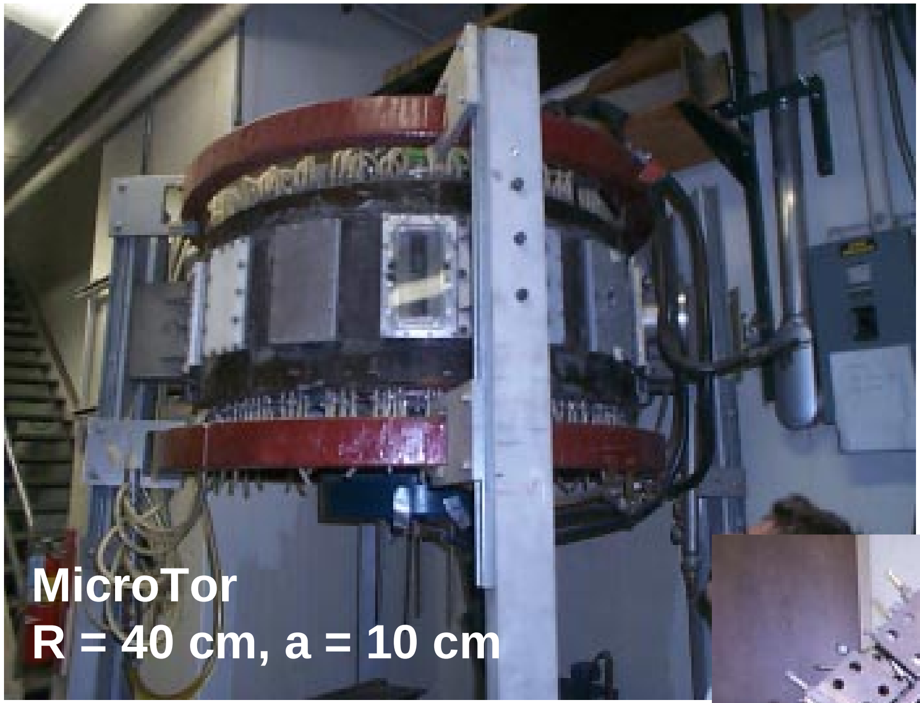
Computational Tools
- DNS/LES/MHD codes
- Free Surface Codes
- Parallel computing clusters

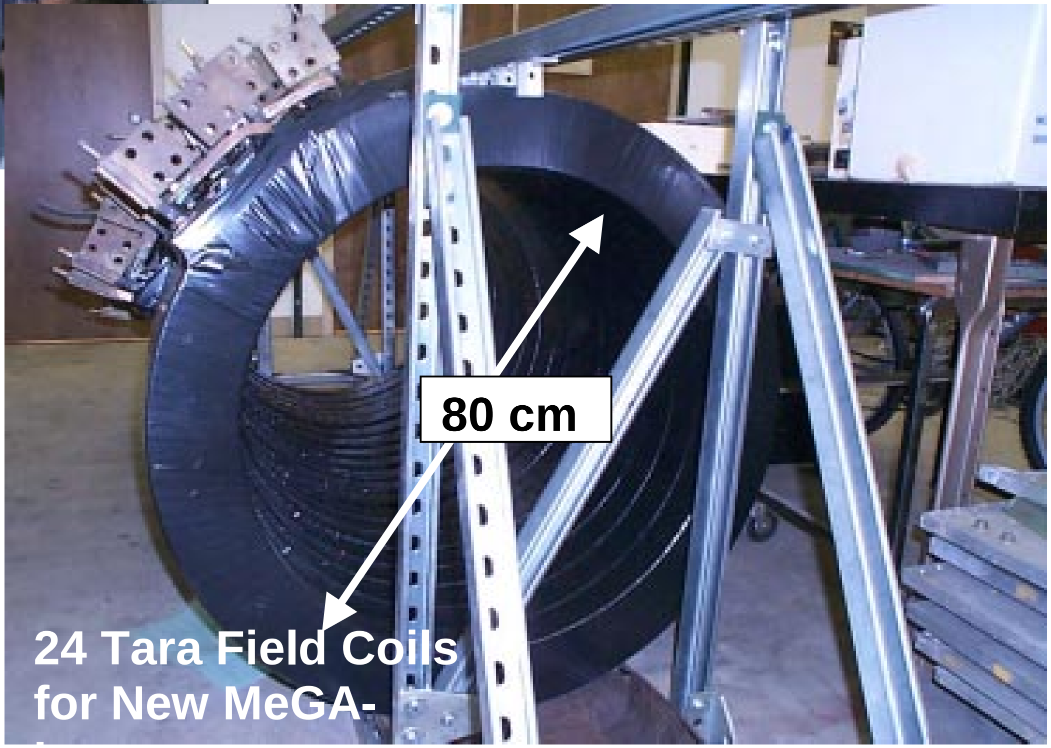
UCLA Fusion Science and Technology Group experience
- Magnet design and construction
- Thermofluid/MHD experimentation
- MHD/free surface modeling

Interested UCLA faculty with worldwide reputations

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

Major ExistingMagnet Facilities at UCLA





Plans for the MeGA-Loop

- Upgrade magnet set to moderate field solenoid or torus (20 additional coils and high current power supply acquired)
- Investigate effect of field gradients and orientation on free surface liquid metal flows (feasibility of passive flow MFE liquid wall concepts)
- Investigate effect of short pulsed toroidal and poloidal fields on free surface liquid metal flow (liquid motion in present large plasma test devices, e.g. NSTX)
- Investigate potential for in-situ control of free surface flows with applied electric currents (feasibility of actively controlled MFE liquid wall concepts)

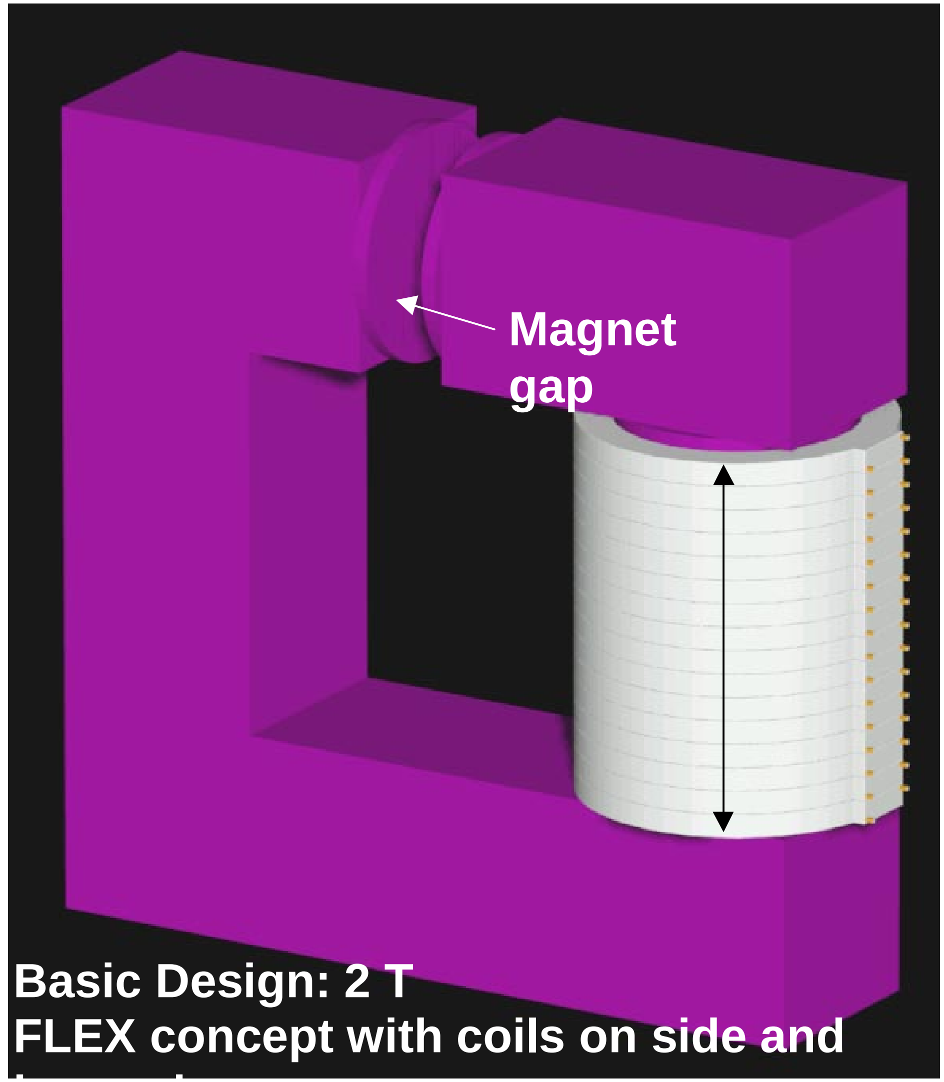
FLEX: Flexible Geometry Magnetic Field Facility

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, and Fli-Hy

If higher fields are needed for relevant heat transfer tests, then

- B > 4T possible with high-current air-core solenoid (US-Monbusho)
- Design of small, low cost 4T test coil is underway in collaboration with PPPL.



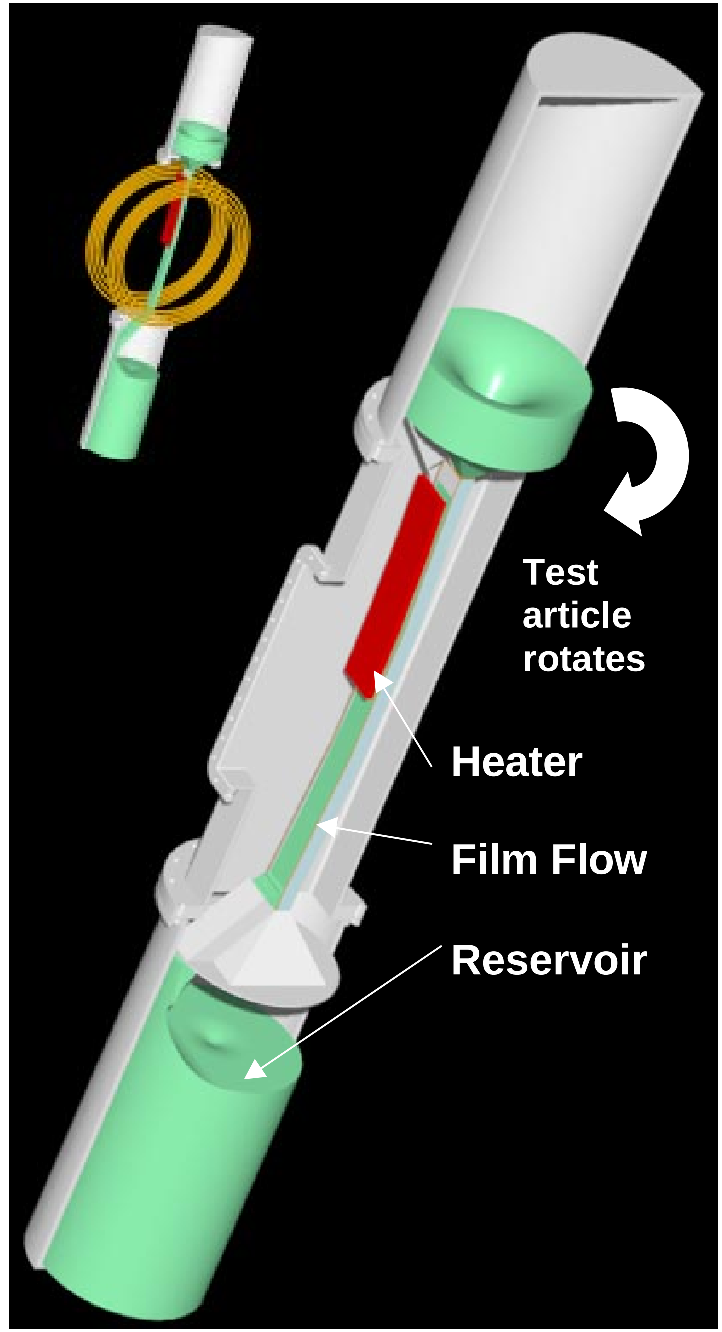
Basic Design: 2 T
FLEX concept with coils on side and

Direct Experience with Flibe

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 EH&S Office**



Features of Flibe Simulation with Aqueous KOH Solution

Advantages:

- Low cost for working liquid
- Low operating temperature
- Wide material compatibility and low material cost
- Large flow volumes and flow rates possible for free surface flow tests
- Transparent medium for optical flow measurements
- Scaling favors reduced size and flow velocity tests
- Relatively high electromagnetic parameters for simulation of MHD/turbulence interactions

Concerns:

- Some health hazard and corrosive characteristics, but good materials and safety procedures have already been identified.
- High vapor pressure at elevated temperatures

HYDRODYNAMIC SIMILARITY CONDITIONS

For Re and Fr Number Equality

$$\frac{U_{\exp}}{U_{base}} = \left(\frac{\rho_{base}\mu_{\exp}}{\rho_{\exp}\mu_{base}} \right)^{1/3} \qquad \frac{L_{\exp}}{L_{base}} = \left(\frac{\rho_{base}\mu_{\exp}}{\rho_{\exp}\mu_{base}} \right)^{2/3}$$

For Re and We Number Equality

$$\frac{U_{\exp}}{U_{base}} = \frac{\mu_{base}\rho_{\exp}}{\mu_{\exp}\rho_{base}} \qquad \frac{L_{\exp}}{L_{base}} = \left(\frac{\mu_{\exp}}{\mu_{base}} \right)^{2} \frac{\rho_{base}}{\rho_{\exp}} \frac{\sigma_{base}}{\sigma_{\exp}}$$

Re and Froude number similarity should be taken into account.

* The effect of back wall curvature on the hydrodynamic characteristics of the flow is taken into account by modifying the Froude number using acceleration due to centrifugal force

$$Fr = \frac{U^2}{gL} \rightarrow Fr_c = \frac{U^2}{a_c h} = \frac{R}{h} \qquad a_c = \frac{U^2}{R}$$

Similarity condition for the modified Froude number is geometric, and independent of thermophysical properties of the operating fluid.

WATER AND AQUEOUS KOH ARE GOOD FLIBE SIMULANTS

Candidate operation fluids for experimental simulation study

		ρ	μ	σ	C_p	k	σ_{el}	Pr	α
	Flibe	2036	0.015	0.193	2380	1.06	155	33.68	2.25 E-07
1	Water 5 C	1000	0.00155	0.073	4200	0.56	10^{-6}	11.55	1.34 E-07
2	Water 25 C	997	0.0009	0.072	4190	0.56	10^{-6}	6.69	1.36 E-07
3	Water 50 C	988	0.00055	0.068	4180	0.56	10^{-6}	4.07	1.38 E-07
4	KOH 35% wt 5 C	1340	0.0043	0.116	2926	0.68	39.2	18.45	1.75 E-07
5	KOH 43% wt 5 C	1421	0.0075	0.124	2800	0.716	30.1	29.33	1.79 E-07
6	KOH 35% wt, 50C	1330	0.0014	0.112	2926	0.711	96	5.76	1.83 E-07

Hydrodynamic scaling of Candidate Fluids for Cliff operating fluid

SCALING (Re+Fr)	1	2	3	4	5	6
U_{base}/U_{exp}	1.68	2.01	2.36	1.31	1.12	1.91
L_{base}/L_{exp}	2.82	4.05	5.6	1.73	1.25	3.66

Note: KOH cases give a closer match to We number as well

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Key MHD Physical Properties & Scaling Parameters of Interest

Properties		Flibe	KOH+Water	HTS[2]
Working Temperature	*C 500*	*50*	*200*	
Density	ρ *(kg/m³)*	*2035*	*1346*	*1930*
Electrical Conductivity	σ *(1/Ωm)*	*155*	*96*	*59*
Dynamics Viscosity	μ*(Kg/ms)*	*0.0148*	*0.0016*	*0.0076*
Important Factors for Heat Transfer and MHD Effect Considerations				
Prandtl Number	$C_p\mu/k$	*33.2*	*6.1*	*19.5*
Hartmann Factor	$(\sigma/\mu)^{1/2}$	*101*	*245*	*88*
Interaction Factor[1]	(σ/ρ)	*0.078*	*0.071*	*0.031*

Notes

1. ***All Flibe designs are not fully laminarized. The interaction number indicates the amount of turbulent modification and heat transfer degradation.***

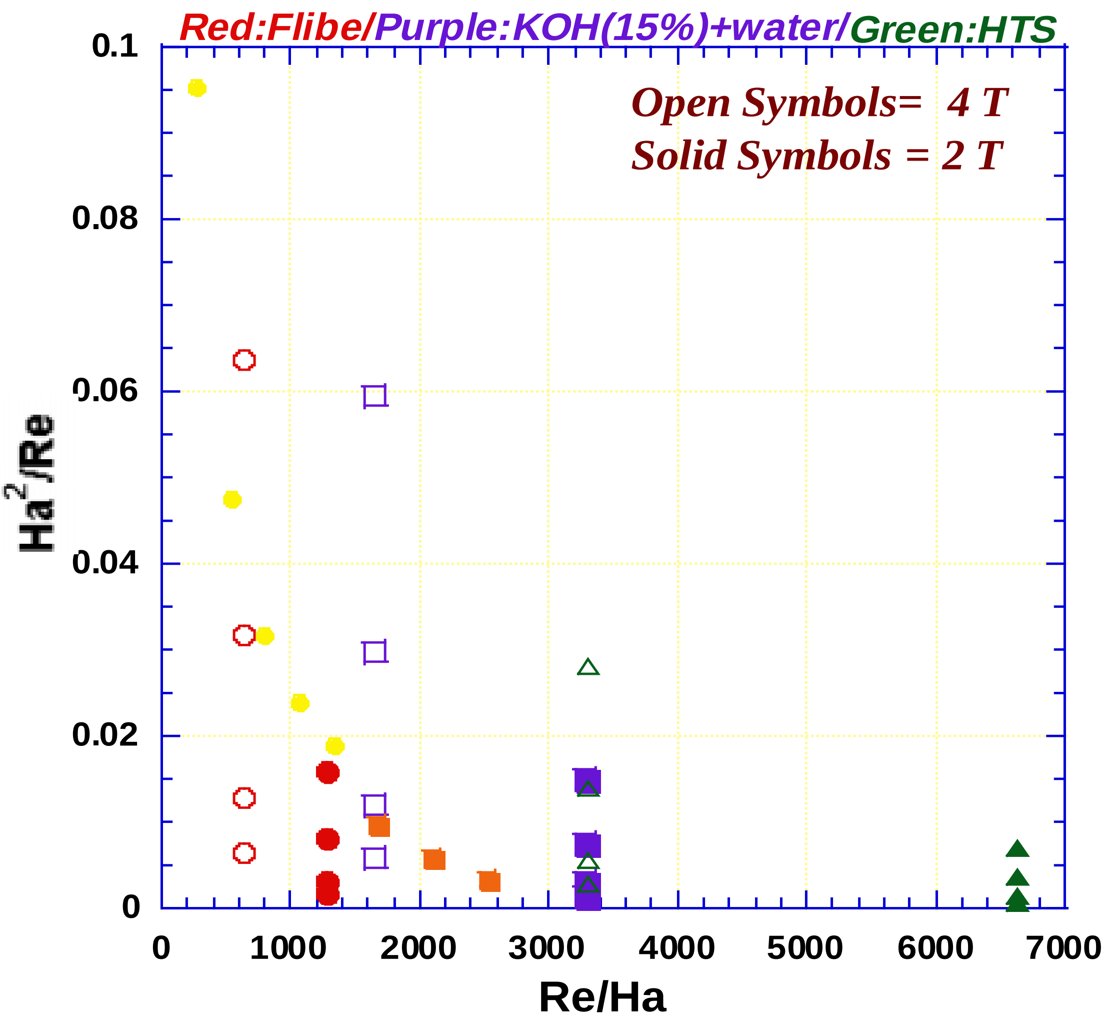
2. ***Based on data for 53 %*** KNO_3 ***, 40 %*** $NaNO_2$***, 7 %*** $NaNO_3$***, melting point =142 C (Electrical conductivity data is at 400 C, and should be considerably lower at 200 C)***

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



UCLA Experiments with KOH will complement HTS experiments in Japan

- Data from alternate simulant for comparison
- Enables high flowrate experiments
- Enables non-invasive optical measurements to quantify turbulence characteristics
- Flexible, low temperature facility for fast turnaround on multiple test sections
- High field magnet expertise and power supplies (developed for Liquid Metal MHD experiments at UCLA) can be used for Flibe simulant MHD/turbulence experiments