PROGRESS ON FLIBE HYDRODYNAMICS SIMULATION FACILITY AND HEAT TRANSFER ENHANCEMENT TECHNIQUES EVALUATION

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Free-surface temperature is a key feasibility issue for the utilization of a Flibe liquid layer as a First-Wall/Blanket in a fusion reactor system.

FLI-HY EXPERIMENTAL GOALS

1. **Understand underlying science and phenomena for Flibe flow and heat transfer issues through conducting experiments using Flibe simulant.**

2. **Compare experimental and modeling results to provide guidance and design database for liquid wall concepts that uses Flibe.**

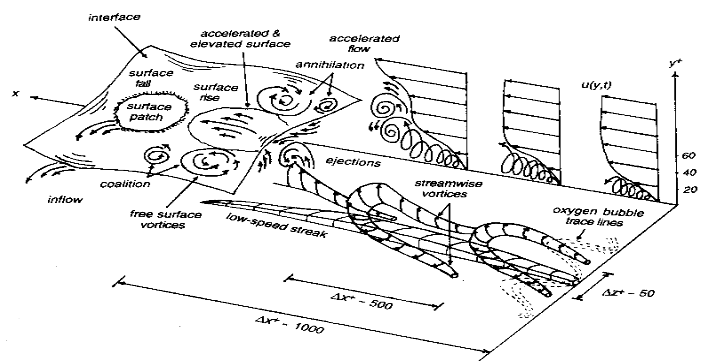
3. **Utilize Innovative secondary flow generating mechanisms that may change the hydrodynamics and enhance the heat transfer characteristics of various liquid first-wall and divertor concepts for their ability to quickly renew the liquid surface.**

FLI-HY EXPERIMENTS FOR APEX

Understanding & Modelling the Free Surface Heat Transfer using Electrically Low Conducting High Prandtl Number Fluid

I Turbulence at and near the free (deformable and wavy) surface
- turbulence intensity and hydrodynamic boundary condition
- heat transfer mechanism at the free surface w/wo heat transfer enhancement

II MHD effect in free surface flows
- on turbulence intensity
- on the turbulent and viscous sub-layers
- heat transfer rate



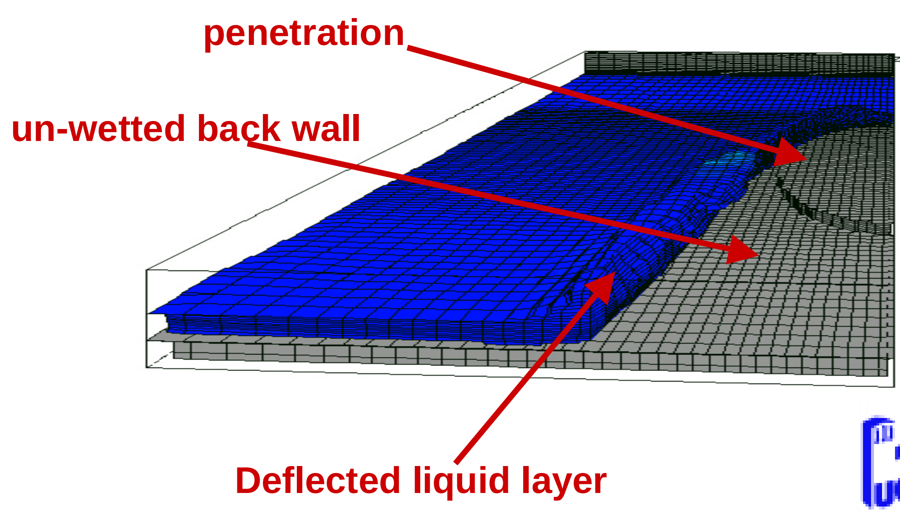
Turbulence structures generated at the liquid-solid interface govern heat transfer and impurity flux at liquid-plasma interface

Understanding The Basic Hydraulic Phenomena For Liquid Wall Design

I Demonstration of liquid wall concepts using hydrodynamically scaled experiments

II Accommodation of penetrations
- Different penetration size shape and positioning
- Back wall topology tailoring

III Flow recovery system design
- flow divertors with minimum kinematics energy losses.



EXPERIMENTAL HYDRODYNAMIC SIMULANTION ANALYSIS

CLIFF Operation Fluid

	ρ (kg/m^3)	μ N/m· s	σ N/m	C_p J/kg· K	k W/m· K	σ_{el} 1/Ω· m	Pr
Flibe 500 ^{o}C 34 % Be_2F 66 % LiF	2035	0.0155	0.193	2380	1.06	155	33.2

In selecting Candidate Operating Fluid

- optically transparency (use of wide range diagnostic systems)
- low operating temperatures (low cost easy operation)
- material compatibility
- minimum time requirement for experimental facility construction
- easy upgradebility

are taken into account.

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

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

* 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, AQUEOUS KOH PLAY DIFFERENT ROLES AS FLIBE SIMULANTS

Candidate operation fluids for experimental simulation study

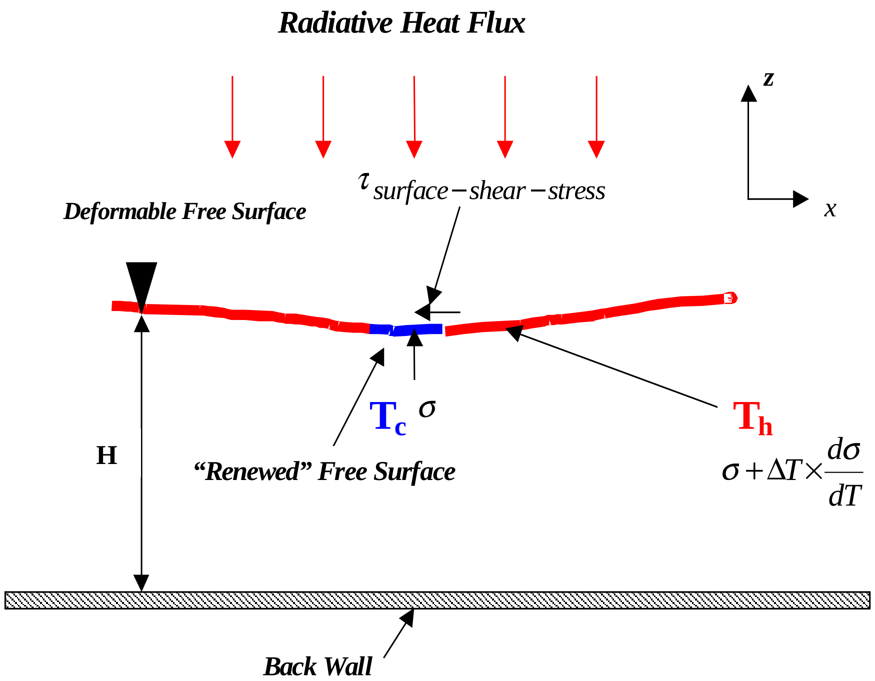
		ρ	μ	σ	C_p	k	σ_{el}	Pr	α
	Flibe	2036	0.015	0.193	2380	1.06	155	33.68	2.25 E-07
1	Water 5 C	1000	0.00155	0.073	4200	0.56	10^{-6}	11.55	1.34 E-07
2	Water 25 C	997	0.0009	0.072	4190	0.56	10^{-6}	6.69	1.36 E-07
3	Water 50 C	988	0.00055	0.068	4180	0.56	10^{-6}	4.07	1.38 E-07
4	KOH 35% wt 5 C	1340	0.0043	0.116	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

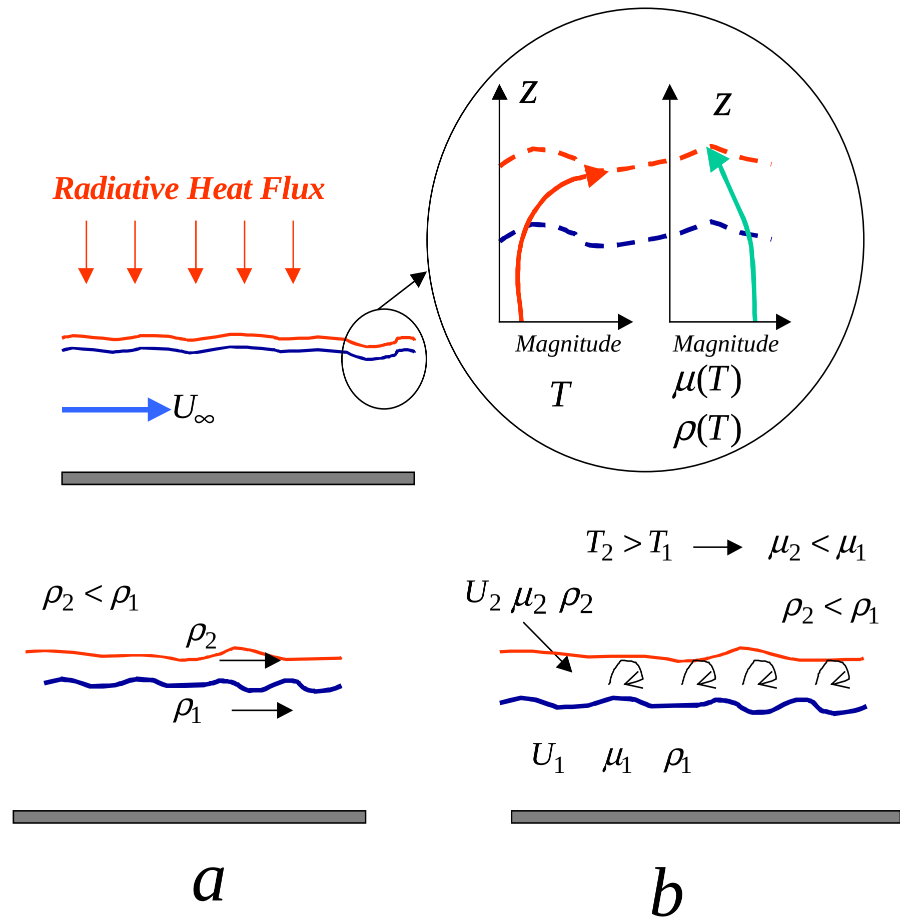
SCALING (Re+Fr)	1	2	3	4	5	6
U_{base}/U_{exp}	1.68	2.01	2.36	1.31	1.12	1.91
L_{base}/L_{exp}	2.82	4.05	5.6	1.73	1.25	3.66

Note: KOH case give closer match to We number as well

PHYSICAL MECHANISMS THAT ARE EFFECTED BY THE TEMPERATURE GRADIENT OF THERMOPHYSICAL PROPERTIES OF OPERATING FLUID



$$\tau = \frac{d\sigma}{dT}\frac{dT}{dx} \qquad Ma = \frac{\frac{d\sigma}{dT}\Delta T \times H}{\mu\alpha} \qquad S = \frac{1}{\Pr}\frac{\frac{d\sigma}{dT}\Delta T}{\sigma}$$



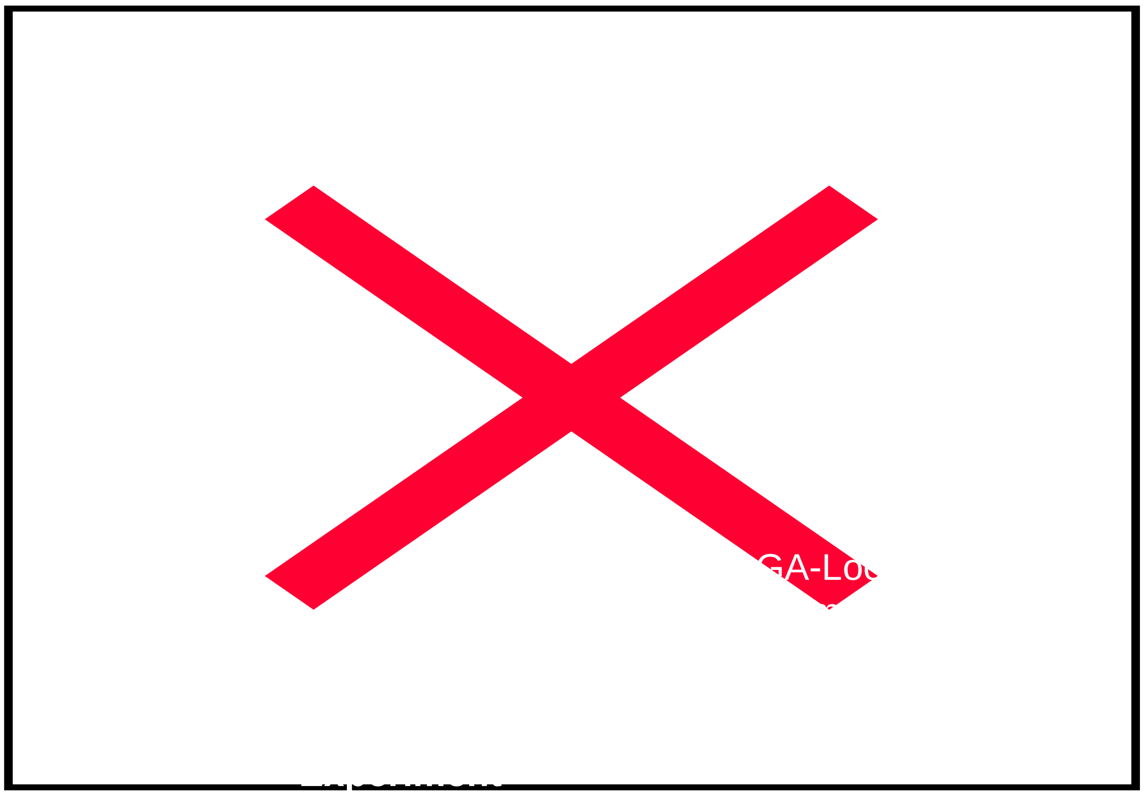
Surface tension gradients on the free surface as a result of free surface renewal by cold bulk liquid as the eddies impinges on the free surface.

Vortices may form between stratified Layer and bulk layer
a: temperature gradient of density
b: temperature gradient of gradient

FLI-HY FACILITY

Current Facility Design Specifications

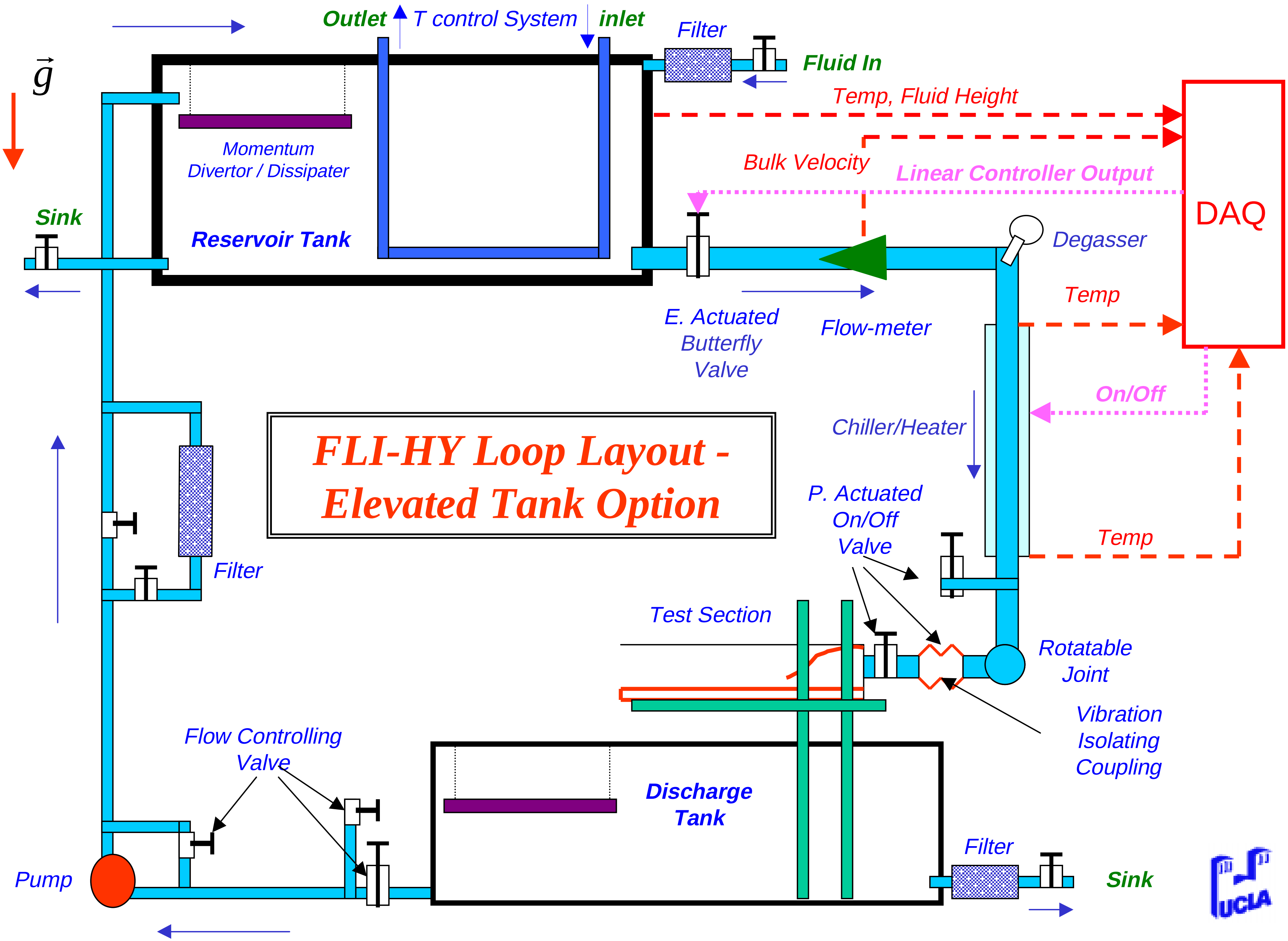
- Switchable water or water/electrolyte working liquid
- Discharge or continuos operating modes
- 316SS and CPVC components for electrolyte compatibility
- >2 m^3 working volume
- >100 l/s maximum flow rate capability (in discharge mode)
- >10 m/s flow velocity
- Temperature control from 4 to 50C



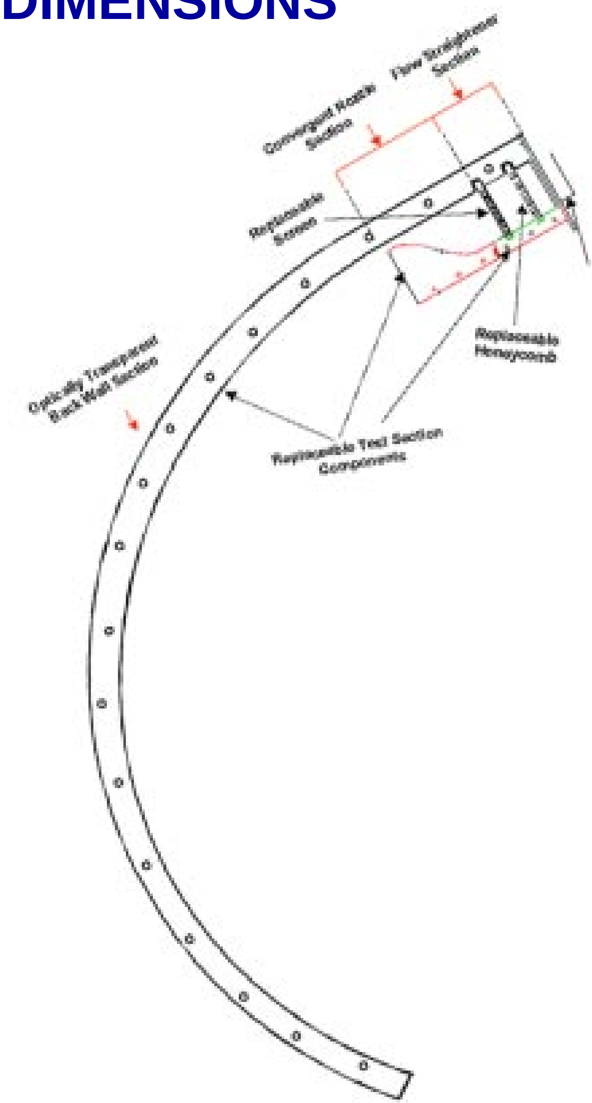
Status

- **Design phase is concluding**
- **Construction phase is awaiting design review at UCLA.**

FLI-HY Loop Layout - Elevated Tank Option



EXPERIMENTAL TEST SECTION DIMENSIONS



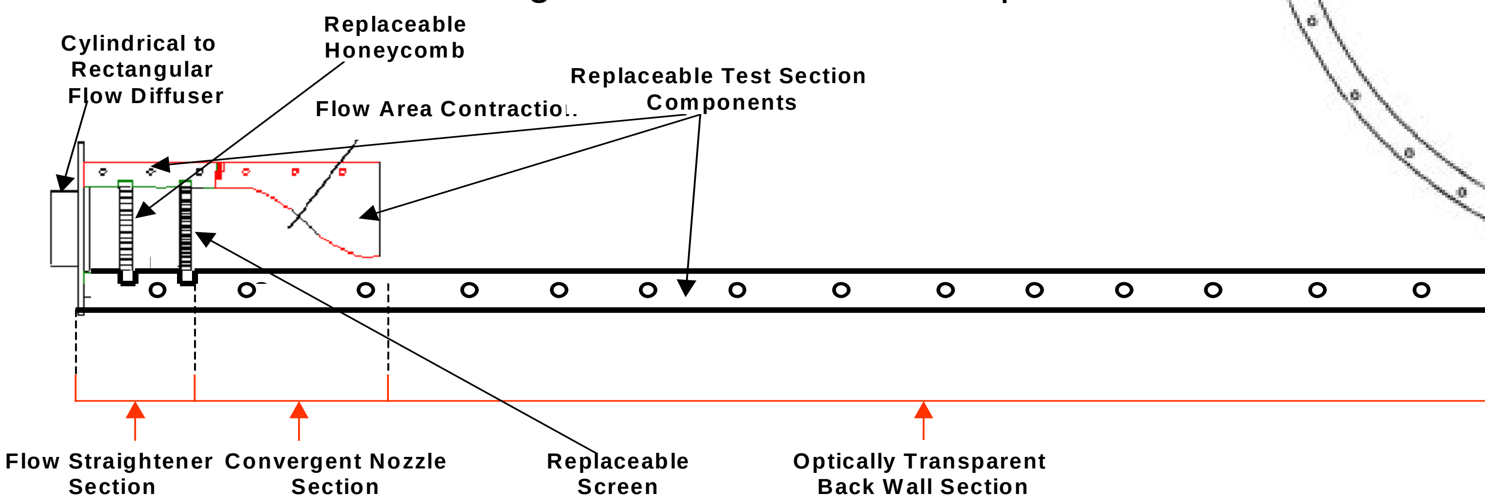
Deliver similar hydrodynamic conditions of the CLiFF base case

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

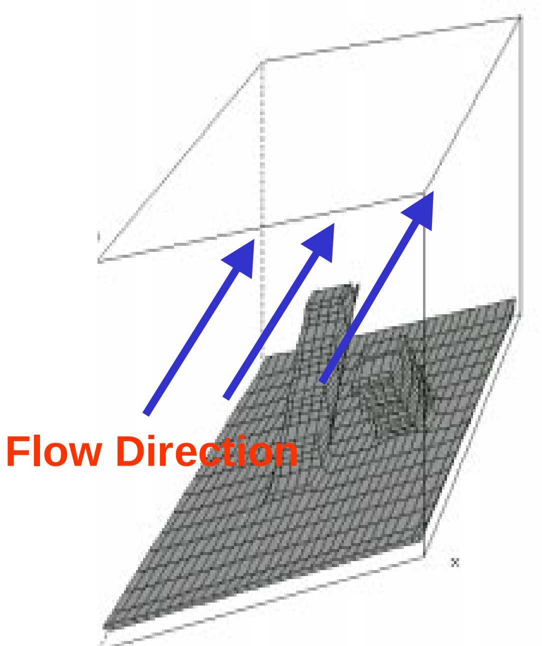
- High Speed Camera 1000 frame/s, 512*256 pixel
- Strobe with variable frequency

Measure flow rate and fluid depth for comparison to numerical models

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

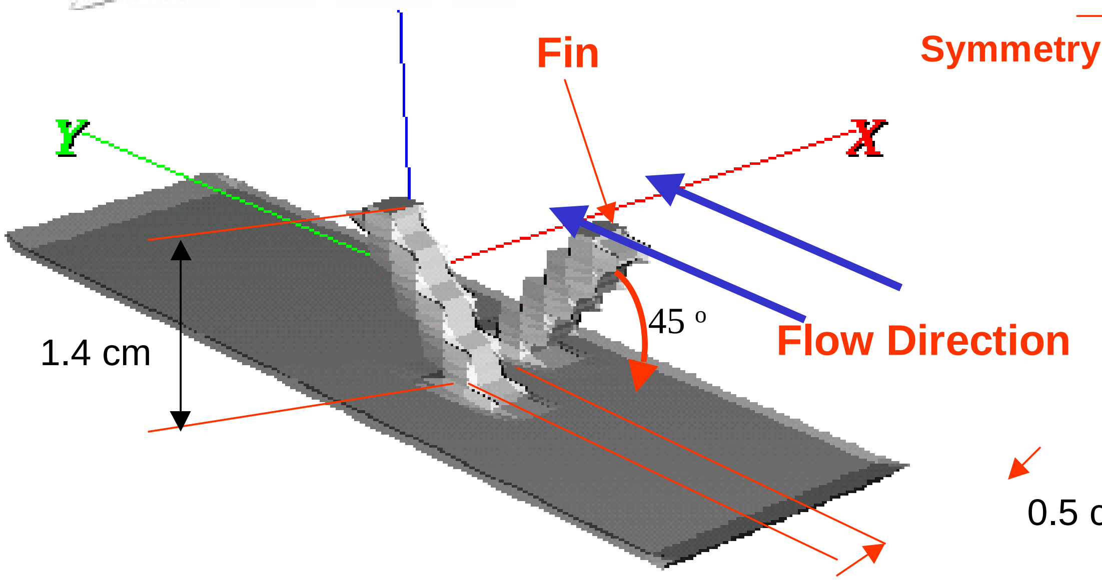


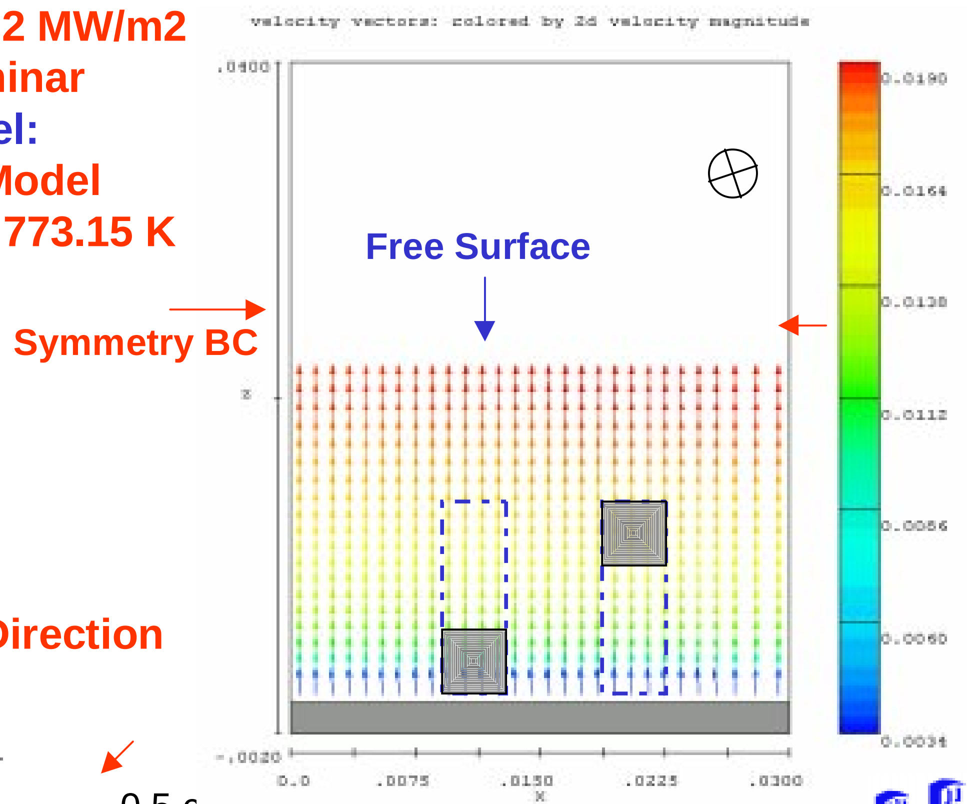
STREAMWISE VORTICES GENERATION MECHANISM
3-D TIME DEPENDENT FLUID FLOW & HEAT TRANSFER CALCULATIONS



Liquid Layer Velocity	: 1.5 m/s
Liquid Layer Height	: 2.0 cm
Fin Height	: 1.4 cm
Fin Width	: 0.5 cm
Spacing Between Fins	: 0.5 cm

Surface Heat Flux 2 MW/m2
Flow Regime: Laminar
Surface Heat Model:
Stefan-Boltzman Model
Initial Flow temp: 773.15 K





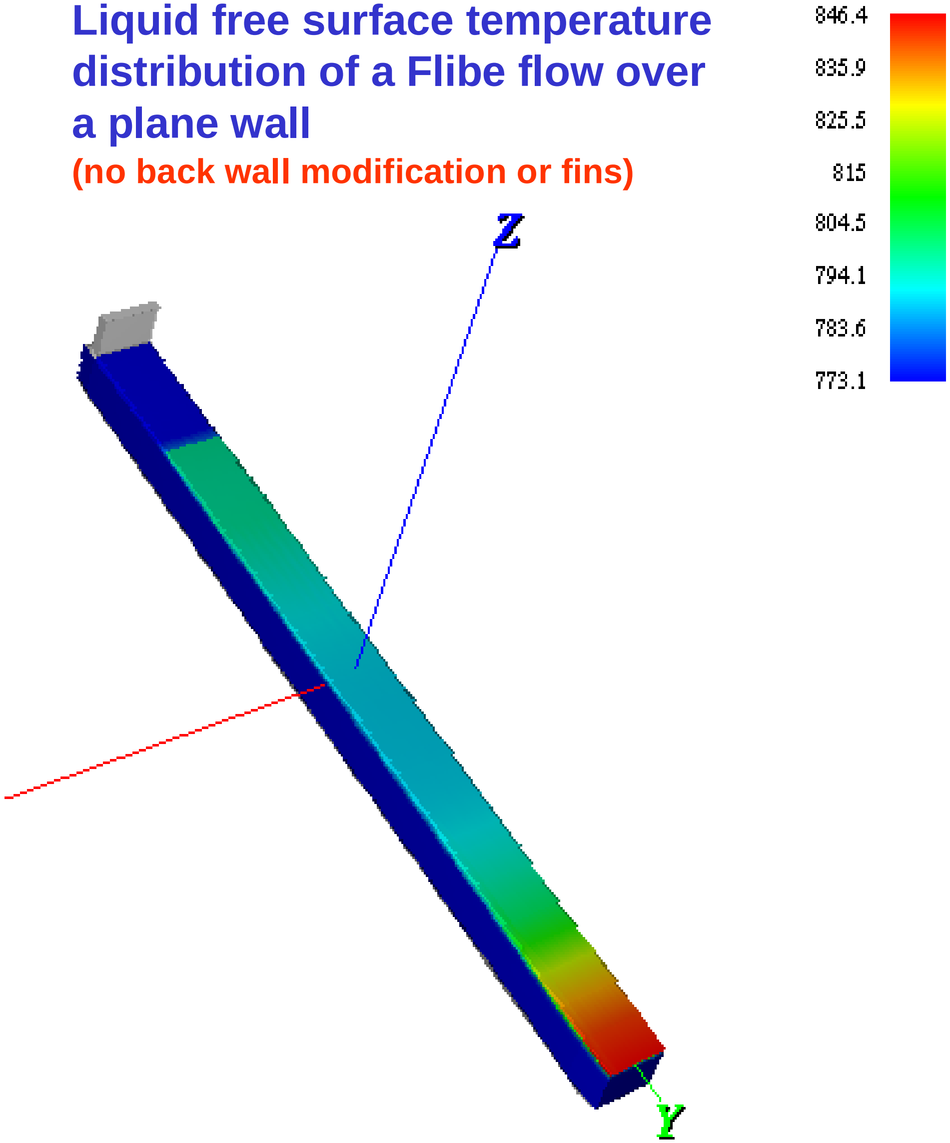
2-D Velocity magnitude
3.4 cm away from inlet (units are in cm)

UCLA

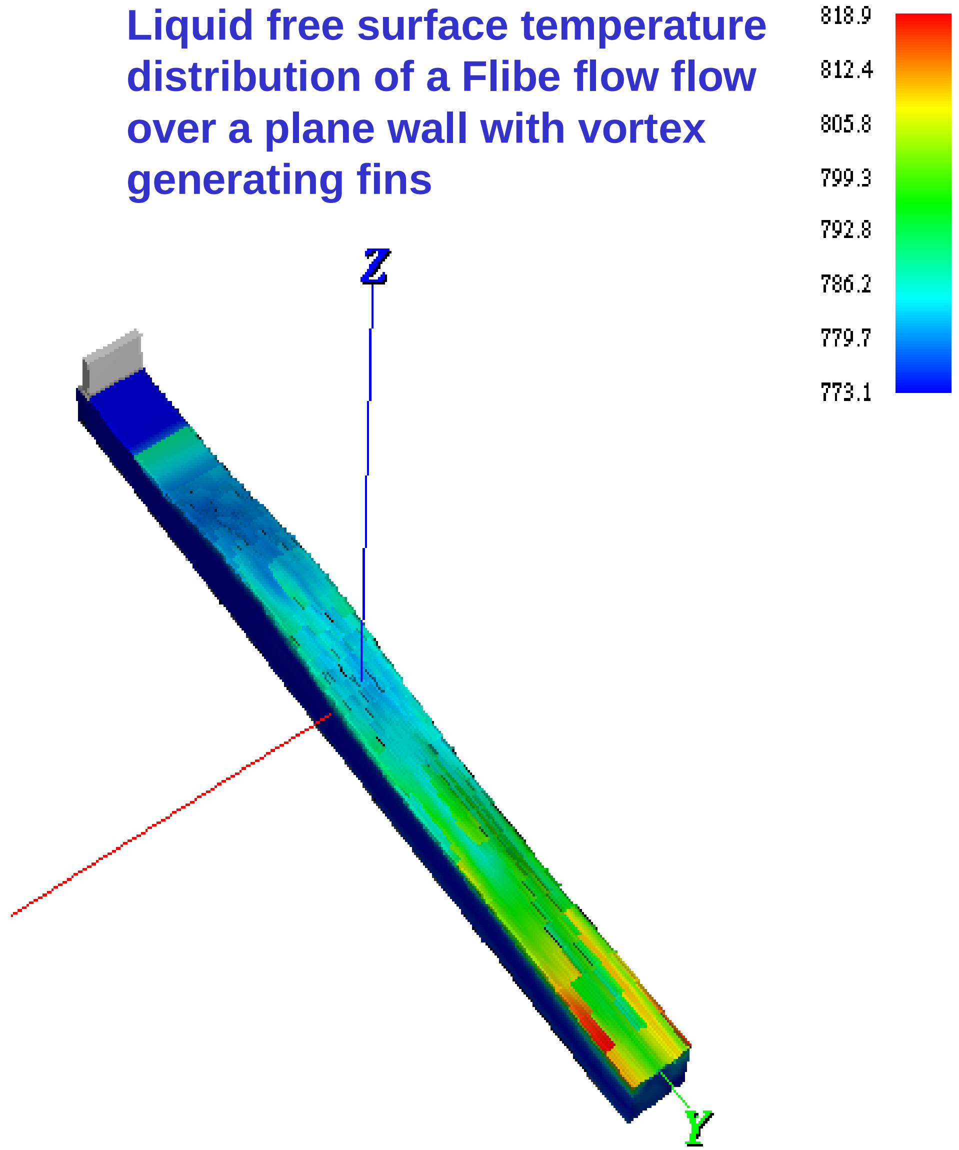
SURFACE RENEWAL MECHANISMS MAY ENHANCE THE FEASIBILITY OF ELECTRICALLY LOW CONDUCTING HIGH PRANDTL NUMBER FLUIDS

Same hydrodynamic and heat transfer operating conditions were applied for a case with a plane wall only and with a plane wall with fins.

Liquid free surface temperature distribution of a Flibe flow over a plane wall
(no back wall modification or fins)

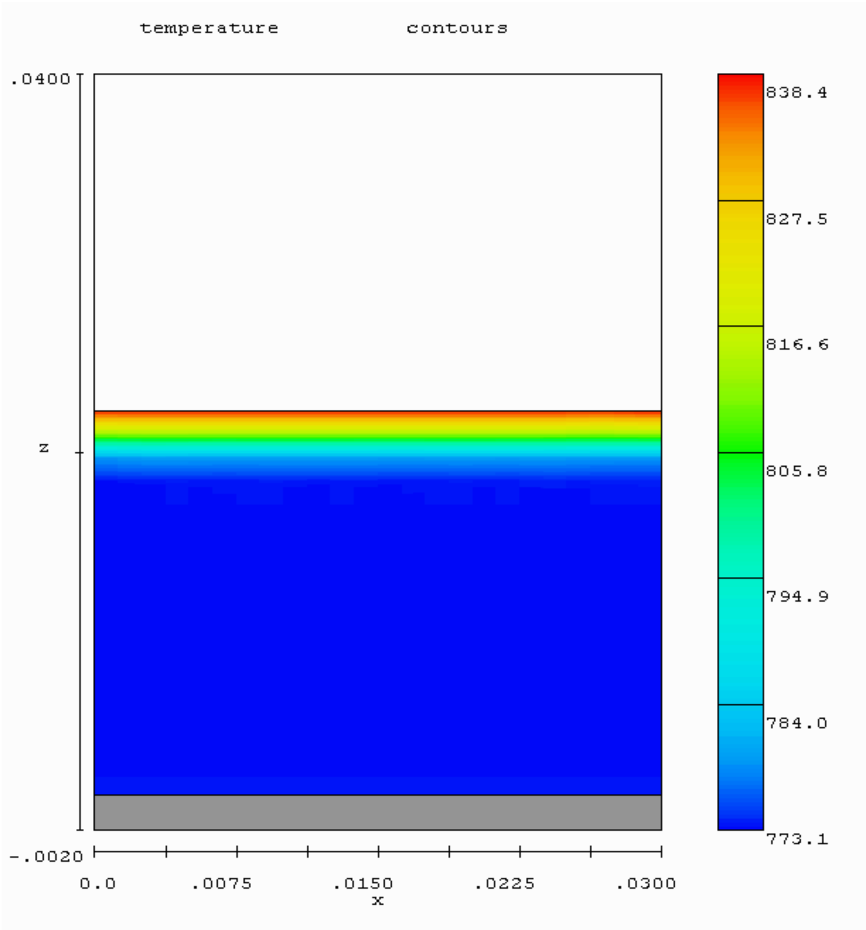


Liquid free surface temperature distribution of a Flibe flow flow over a plane wall with vortex generating fins

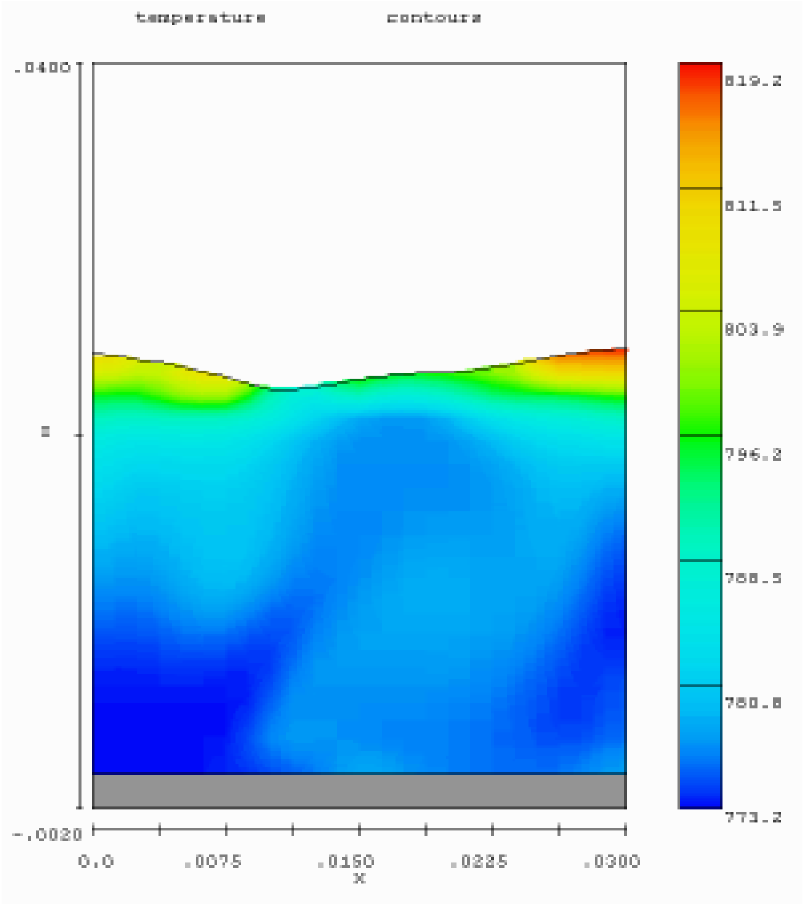


SURFACE RENEWAL MECHANISM DECREASES FREE SURFACE TEMPERATURE DISTRIBUTION OF HIGH PRANDTL NUMBER FLUIDS (I)

2-D Temperature distribution in planes perpendicular to the flow direction at 37.5 cm away from inlet.

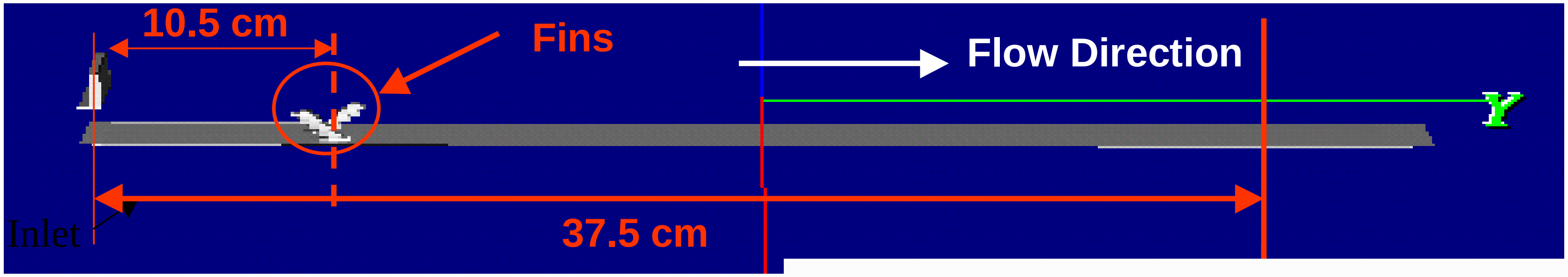


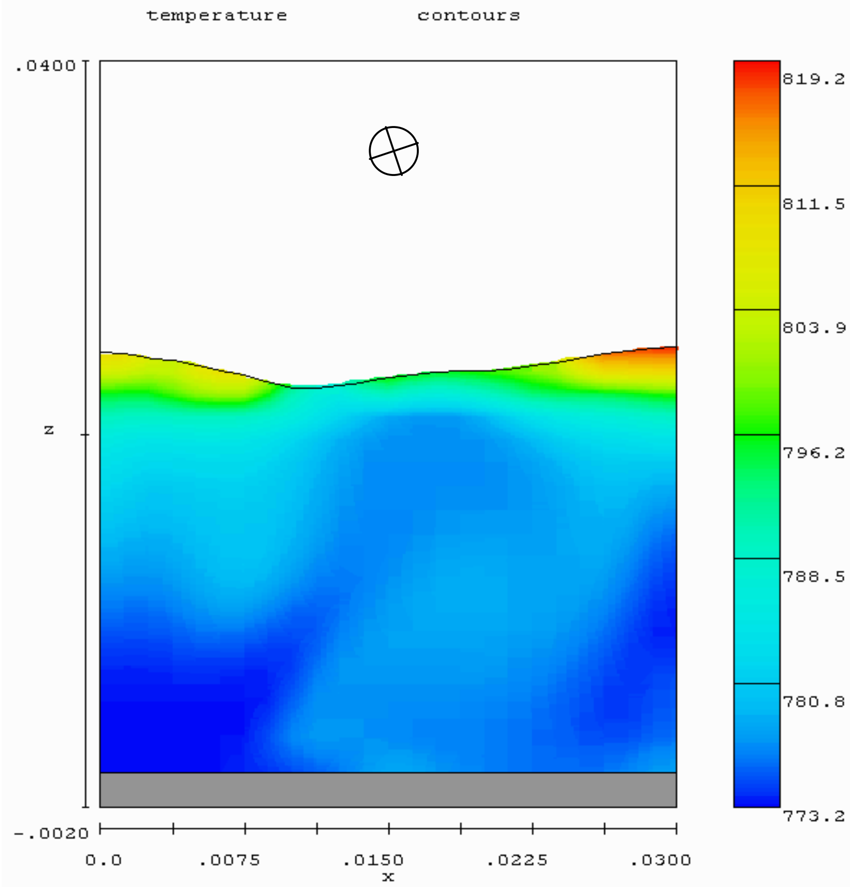
Flibe flow flow over a plane wall.

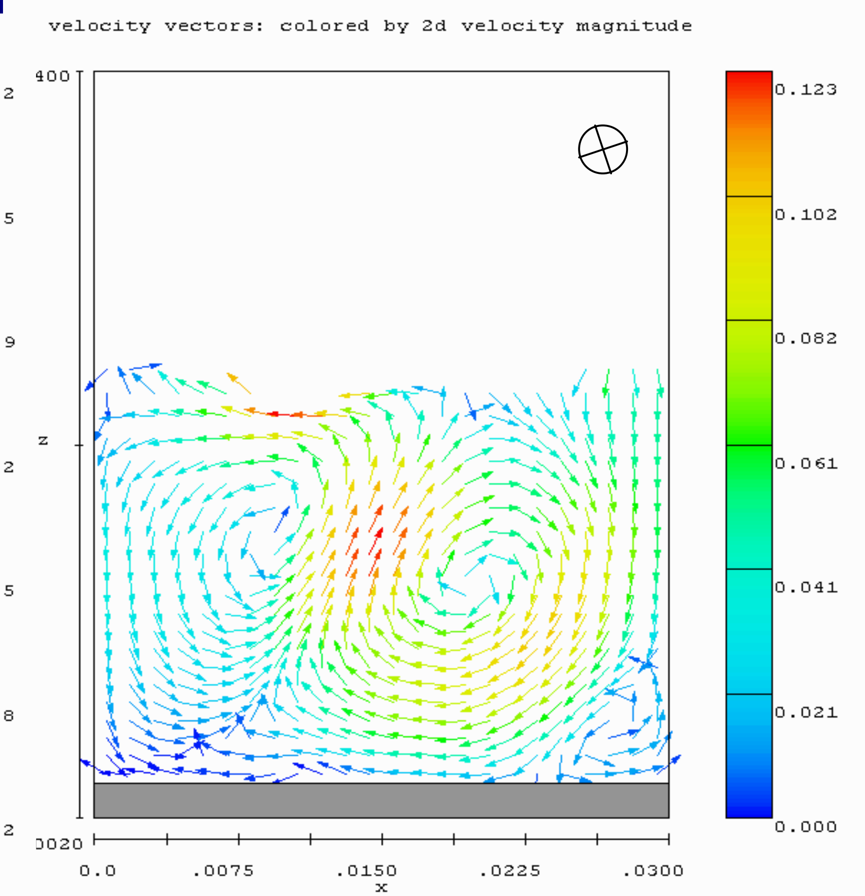


Flibe flow flow over a plane wall with vortex generating fins.
(27 cm away from fins)

SURFACE RENEWAL MECHANISM DECREASES FREE SURFACE TEMPERATURE DISTRIBUTION OF HIGH PRANDTL NUMBER FLUIDS (II)







2-D Temperature Distribution 37.5 cm away from inlet

2-D Velocity Magnitude Distribution 37.5 cm away from inlet

SURFACE RENEWAL MECHANISM DECREASES FREE SURFACE TEMPERATURE OF HIGH PRANDTL NUMBER FLUIDS (III)

- Heat transfer analysis of Flibe flow flow over a plane has been performed using laminar flow model for both flow over a plane wall with fins and without fins.

- Although large scale eddy formation may result

  - large local hot spots at the free surface (non-uniformity),

  - Longer time scale for surface renewal as compared the small scale eddies,

  It is shown that, large scale eddy formations downstream of the fins do enhance heat transfer rate at the free surface and mixing in the bulk.

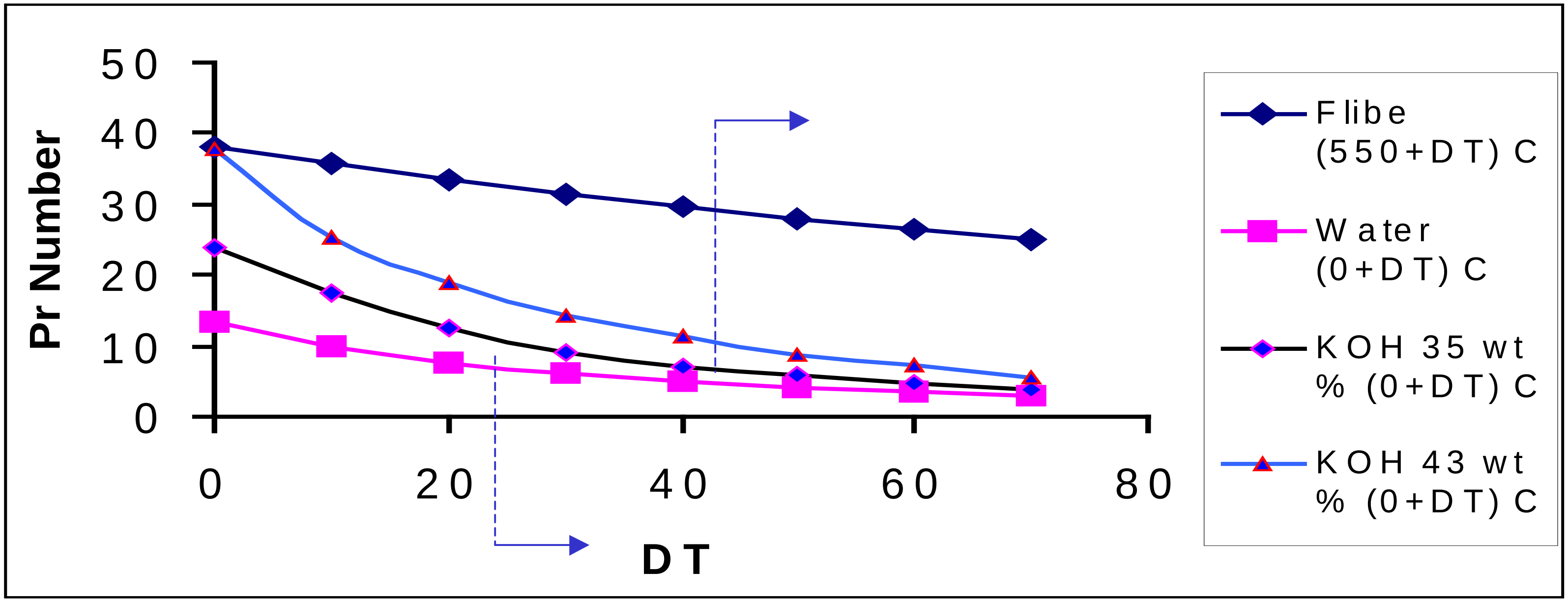
- More detailed analysis is required to quantitatively determine heat transfer enhancement using fin techniques presented in the current study.

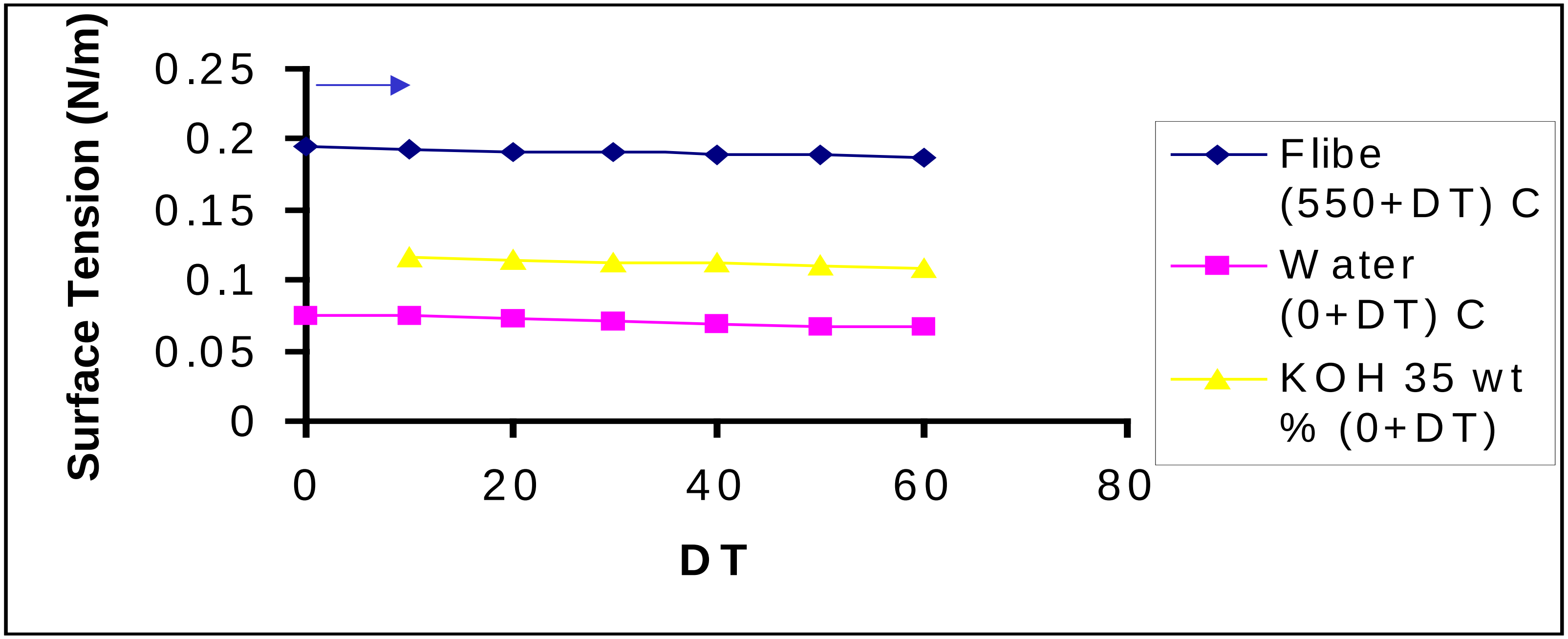
- Other heat transfer techniques such as modification of back wall topology to generate series of streamwise vortices (secondary flow) formations, delta wing should be analyzed computationally and experimentally.

- What is the difference between free surface temperatures with ***20 % area of 600 C 90 % 500 C*** from free a surface with ***100 % 550 C****? Surface evaporation rates of free surface with a temperature distribution should be evaluated in order to obtain a criteria to compare the effectiveness of surface renewal techniques.*

SUPPLEMENTARY VU-GRAPHS

TEMPERATURE GRADIENT OF THERMOPHYSICAL PROPERTIES OF FLIBE SIMULANT SHOULD BE SIMILAR TO FLIBE





FLI-HY FACILITY OPERATION PARAMETERS FOR CLIFF CONCEPT WHEN WATER IS USED AS A FLIBE SIMULANT

	CLIFF FLIBE 500 ^{o}C	FLI-HY WATER 5 ^{o}C	FLI-HY WATER 25 ^{o}C
Geometric Scale	1	0.35	0.246
Velocity Scale	1	0.595	0.496
Inlet Velocity U (m/s)	10.0	5.95	4.96
Dimensions D (m)	.02	0.007	.00492
Dimensions W (m)	1.0	1.0	1.0
Aspect Ratio β (D/W)	.02	0.007	0.00492
(W required for same β)(m)	1.0	.35	0.246
Radius (m)	3.0	1.05	0.738
Azimuthal flow distance (m) (150^{o})	7.85	2.74	1.93
Volumetric Flow Rate (m^3/s)	0.2	0.0416	0.0244
Strg Tank Size (m^3) (30 sec) (1 min)	4 (12)	1.25 (2.5)	0.732 (1.46)
Reynolds Number Re	35,000	35,000	35,000
Weber Number We	20,980	4,860	2350
Froude Number Fr_g	510	510	510
Modified Froude No Fr_c	150	150	150
Ohnesorge Number (10^{-3})	5.33	2.18	1.51
Temperature (°C)	500	5	25
Density ρ (kg/m^3)	2036	1000	997
Viscosity μ (kg/m s)	0.015	0.00155	0.0009
Surface Tension σ (N/m)	0.194	0.073	0.072

KEY PHYSICAL PROPERTIES & MHD PARAMETERS

Properties	Flibe	KOH+Water
Working Temperature C	*500*	*50*
Density ρ (kg/m^3)	*2035*	*1346*
Electrical Conductivity σ (1/Ωm)	*155*	*96*
Dynamics Viscosity μ(Kg/ms)	*0.0148*	*0.0016*

Important Factors for Heat Transfer and MHD Effect Considerations		
Prandtl Number $C_p\mu/k$	*33.2*	*6.1*
Hartman Factor $(\sigma/\mu)^{1/2}$	*101*	*245*
Interaction Factor[1] (σ/ρ)	*0.078*	*0.071*

Notes

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

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.)

DIAGNOSTIC SYSTEMS FOR CHARACTERIZATION OF VELOCITY & TEMPERATURE PROFILE, LIQUID LAYER HEIGHT AND SURFACE TOPOLOGY

Flibe simulant is chosen as an optically transparent fluid.

- **Flow visualization techniques**

  Using High speed digital camera (1000 frames/sec)

  - using strobe at varying frequencies to determine surface characteristic structures
  - determining temporal and spatial locations of O_2 bubbles (with constant generation frequency) in order to determine large scale turbulence structures in the flow.
  - determination of passive scalar transport in the flow using dye technique.

- **Temporal Fluid level measurement**

  Using Ultrasonic transducers or Using 5 mW He-Ne laser source, optics and 2-D photo-diode array configurations with high speed data acquisition card

  - to obtain information about the liquid layer height, surface wave angles at a single point along the flow direction.

- **Velocity profile and fluctuation measurements**

  Using high speed camera and O_2 bubbles.

  Using 2-D Laser Doppler Velocimetry system.

- **Temperature profile and fluctuation measurements**

  Using infra-red camera for free surface temperature distribution measurements.

  Using encapsulated thermo-chromic liquid crystal capsules.