Hydrodynamics and MHD Modeling for the
CLIFF - Convective Liquid Flow First Wall Concept

Presented by Neil Morley

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Convective Liquid Flow Firstwall (CLiFF) Concepts

- First Structural Wall protected by a fast moving layer of liquid, typically 1 to 2 cm thick at 10 m/s.
- Flibe, Lithium, and Sn-Li considered
- The liquid layer:
  - is injected at (or near) the top of the reactor chamber with an independently removable nozzle assembly
  - adheres to curved structural wall by means of centrifugal force
  - serves as an integrated divertor, either film or droplet type
  - is collected and drained at the bottom of the reactor through combination vacuum/drain port
- Liquid recirculated to breeder blanket based on ARIES-RS located behind the CLiFF-wall
Potential and Issues of CLIFF Concepts

- **Potential:** Removal of surface heat loads (greater than 2 MW/m² possible). Local peaking and transients can be tolerated.

- **Potential:** FW surface protected from sputtering erosion and possibly disruption damage

- **Potential:** Elimination of high thermal stresses and pressures in solid FW components, having a potentially positive impact of FW/Blanket failure rates

- **Potential:** Possible reduction of structure-to-breeder material ratio in FW area, with breeder material facing virgin neutron flux

- **Potential:** Integrated divertor surface possible where CLiFF removes all α heat

- **Potential:** Complex tokamak D-shape and port penetration can be accommodated, implementation is straight-forward

- **Issue:** Hydrodynamics and heat transfer involve complicated MHD interaction between flow, geometry, and the magnetic field:
  - suppression of turbulence and waves
  - LM-MHD drag thickening the flow and inhibiting drainage from chamber
  - effects of spatially and temporally varying fields on LM surface stability

- **Issue:** Evaporated liquid can pollute core plasma, surface temperature limits unknown

- **Issue:** High mass flowrate requirement can result in low coolant ΔT or two coolant streams

- **Issue:** Effect of liquid choice on edge plasma gettering, tritium through-put, and tritium breeding

- **Issue:** Neutron damage in structure is only slightly reduced compared to standard blankets, frequent blanket change-out required for high power density operation
• ARIES-RS size and plasma shape taken as design base
  – fusion power scaled to 4500 MW
  – 75% $\alpha$-heat radiated to FW
  – Average NWL = 8 MW/m²
  – Average FW-SHF = 2.1 MW/m²
  – Average D-SHF = 7.6 MW/m²
  – converted to single null at bottom of plasma

• Material Choices
  – Li/V
  – Flibe/ODS Ferritic Steel
  – Sn-Li/Ferritic Steel??
Blanket for CLiFF Design

- Segmented box blanket with simple poloidal flow paths
- Organized into layers having different lifetime and replacement schedules
- Insulator coating required for low pressure for Li and Sn-Li

ARIES-RS Layered Lithium Blanket/Reflector/Shield
# CLIFF Thermal-hydraulics with ARIES-like Blanket

<table>
<thead>
<tr>
<th></th>
<th>Lithium</th>
<th>Sn-Li(^a)</th>
<th>Flibe</th>
<th>Units</th>
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<tbody>
<tr>
<td>Fusion Power (scaled from ARIES)</td>
<td>4500</td>
<td>4500</td>
<td>4500</td>
<td>MW</td>
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<tr>
<td>FW Flow Inlet Depth (in/outboard)</td>
<td>2/2</td>
<td>2/2</td>
<td>2/2</td>
<td>cm</td>
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<tr>
<td>FW Flow Inlet Velocity (in/outboard)</td>
<td>15/15</td>
<td>10/8</td>
<td>10/8</td>
<td>m/s</td>
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<td>FW Volumetric Flowrate per Sector</td>
<td>1.11</td>
<td>0.66</td>
<td>0.66</td>
<td>m(^3)/s</td>
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<td>FW Mass Flowrate per Sector</td>
<td>543</td>
<td>4492</td>
<td>1316</td>
<td>kg/s</td>
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<td>FW Pumping Power Estimate</td>
<td>2.01</td>
<td>8.83</td>
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<td>Peak Surface Temperature</td>
<td>464</td>
<td>750</td>
<td>564</td>
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<td>Number of Outlet Streams</td>
<td>2</td>
<td>1</td>
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<td>% Recycled to Blanket</td>
<td>41</td>
<td>100</td>
<td>100</td>
<td>%</td>
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<td>FW Flow Inlet Temperature</td>
<td>325</td>
<td>400</td>
<td>500</td>
<td>C</td>
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<tr>
<td>Stream Temperature</td>
<td>364/603</td>
<td>665</td>
<td>599</td>
<td>C</td>
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<td>Stream Mass Flow</td>
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<td>72</td>
<td>21</td>
<td>ton/s</td>
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<td>Stream Volume Flow</td>
<td>10.5/7.3</td>
<td>10.6</td>
<td>10.6</td>
<td>m(^3)/s</td>
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<td>Stream Thermal Power</td>
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<td>5006</td>
<td>5006</td>
<td>MW</td>
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<td>Estimated Thermal Efficiency</td>
<td>33/39</td>
<td>43</td>
<td>39</td>
<td>%</td>
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<td>Gross Electric Power (w/ M=1.15)</td>
<td>1902</td>
<td>2152</td>
<td>1952</td>
<td>MW</td>
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\(^a\) assumes thermophysical properties of Tin
# CLiFF Hydrodynamic Parameters

<table>
<thead>
<tr>
<th>Properties</th>
<th>Flibe (500C)</th>
<th>Lithium (400C)</th>
<th>Lithium-Tin</th>
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<tbody>
<tr>
<td><strong>Composition</strong></td>
<td>Mole %</td>
<td>66% LiF, 34% BeF₂</td>
<td>100% Li</td>
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<tr>
<td>Melting Point, Tₘ</td>
<td>K</td>
<td>733</td>
<td>459</td>
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<td>Density, ρ</td>
<td>Kg/m³</td>
<td>2036</td>
<td>490</td>
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<td>Dynamic Viscosity, μ</td>
<td>Kg/m/s</td>
<td>0.015</td>
<td>4.02 × 10⁻⁰⁴</td>
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<td>Electrical Cond., σ</td>
<td>1/Ω.m</td>
<td>155</td>
<td>3.19 × 10⁺⁰⁶</td>
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<td>Thermal Cond., k</td>
<td>W/m.K</td>
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<td>Specific Heat, Cₚ</td>
<td>J/kg.K</td>
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<td>4209.76</td>
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<td>Surface Tension, γ</td>
<td>N/m</td>
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<td>0.366</td>
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<tr>
<td><strong>CLiFF Parameters</strong></td>
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<tr>
<td>Film Depth, h</td>
<td>m</td>
<td>0.02</td>
<td>0.02</td>
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<tr>
<td>Film Velocity, V</td>
<td>m/s</td>
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<td>Channel ½ Width, w</td>
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<td>Flow Length, L</td>
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<td>Toroidal Field, Bₜ</td>
<td>T</td>
<td>8</td>
<td>8</td>
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<tr>
<td>Radial Field, Bᵣ</td>
<td>T</td>
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<td>0.2</td>
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<td>Radius of Curvature, R</td>
<td>m</td>
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<td><strong>Dimensionless Numbers</strong></td>
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<tr>
<td>Aspect ratio, β</td>
<td>h/w</td>
<td>0.02</td>
<td>0.02</td>
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<tr>
<td>Reynolds No., Re</td>
<td>h.V.ρ/μ</td>
<td>2.71 × 10⁺⁰⁴</td>
<td>2.44 × 10⁺⁰⁵</td>
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<tr>
<td>Hartmann No., Haₜ</td>
<td>Bₜ.w.(σ/μ)⁴</td>
<td>8.13 × 10⁻⁰²</td>
<td>7.13 × 10⁺⁰⁵</td>
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<tr>
<td>Radial Hartmann, Haᵣ</td>
<td>Bᵣ.h.(σ/μ)⁴</td>
<td>4.07 × 10⁻⁰¹</td>
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<td>Interaction parameter, N</td>
<td>B².σ.h/ρ.V</td>
<td>0.01</td>
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<td>Vert. Froude No., Frᵥ</td>
<td>V²/gL</td>
<td>1.28</td>
<td>1.28</td>
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<td>Cent. Froude No., Frᵣ</td>
<td>R/h</td>
<td>150</td>
<td>150</td>
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<tr>
<td>Thermal Diffusivity, α</td>
<td>k/Cₚ.ρ</td>
<td>2.19 × 10⁻⁰⁷</td>
<td>2.44 × 10⁻⁰⁵</td>
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<td>Prandtl No., Pr</td>
<td>Cp.μ/k</td>
<td>33</td>
<td>0.034</td>
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<tr>
<td>Modified Hartmann</td>
<td>Haₜ.β²</td>
<td>0.33</td>
<td>285</td>
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<tr>
<td>Modified Reynolds</td>
<td>Re/Haₜ.β</td>
<td>1667</td>
<td>17</td>
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<tr>
<td>Force Ratio, Fc/Fgrav</td>
<td>V²/gR</td>
<td>3.40</td>
<td>3.40</td>
</tr>
</tbody>
</table>

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[^a]: Prandtl Number scales importance of convective motion on heat transfer
[^b]: Modified Hartmann Number scales amount of MHD drag (< 1 indicates little drag)
[^c]: Modified Reynolds Number scales amount of Turbulence (> 500 indicates turbulence)
[^d]: Force Ratio scales amount of centrifugal adhesive force (> 1 indicates adhered flow)
Magneto-Hydrodynamic Issues
for CLiFF with Flibe

Expectations
• Turbulent fluctuations remain: Modified Reynolds Number > 500
• Little MHD drag: Modified Hartmann Number < 1

Critical hydrodynamic issues under investigation
• Accurate determination of equilibrium velocity/film height profiles as a function of flow length
  1. Appropriate model for turbulence effect on hydrodynamic drag
  2. Effect of flow area variation with major radius
• Flow stability
• Free surface renewal by turbulent motion and effect of magnetic field (for heat and mass transfer, talk by Smolentsev/Ying tomorrow)

Hydrodynamic issues in need of future investigation
• Formation of divertor droplet screen and associated heat transfer
• Drainage of flow from vacuum chamber
Magneto-Hydrodynamic Issues for CLiFF with Liquid Metals

Expectations
- Highly laminarized, possible 2D turbulence: Modified Reynolds Number < 500
- Significant MHD drag by walls or penetrations: Modified Hartmann Number > 100

Critical hydrodynamic issues under investigation
- Accurate determination of equilibrium velocity/film height
  1. Fully-developed flow model
  2. Effect of developing flow currents
  3. Effect of variation of flow area with major radius
  4. Effect of variation of the toroidal magnetic field with major radius
- Surface stability
- Time dependent fluctuations of the magnetic field

Hydrodynamic Issues in need of further investigation
- Formation of divertor droplet screen and associated heat transfer
- Drainage of flow from vacuum chamber
- Pressure drops in supply piping, film former, and blanket channels
Accurate determination of equilibrium velocity/film height profiles as a function of flow distance

- CLiFF requires sufficient velocity to ensure adherence to backing structure
  - \( V^2/R > g \) gives \( V \approx 6 \) m/s (assuming radius of curvature \( R \approx 4 \) m)

- CLiFF requires a sufficient liquid velocity to keep surface temperature low
  - estimates of at least 10 m/s for laminarized lithium and tin-lithium
  - possibly lower for turbulent Flibe, still under investigation
  - surface temperature limits still unknown for candidate liquids

- CLiFF requires all surfaces to remain covered and protected
  - Initial depth great enough to allow spreading out for full toroidal coverage
  - Velocity and depth (for quasi-steady flow) are related by continuity,
    \( Q = v(\theta) \cdot h(\theta) \cdot w(\theta) \) is constant
  - Penetrations designed so to not significantly disturb the flow
Design Model Formulation for Turbulent Flibe Flow

Simplest case, friction factor extrapolation from duct flow

• Assume a cylindrically-shaped surface

• Replace viscous Navier-Stokes terms with a simple loss term of the form

\[
\Delta \text{head}_f = \frac{fL}{4R_H} \frac{V^2}{2g} \Rightarrow \frac{\partial p_{\text{loss}}}{\partial \theta} = \frac{fR \rho V^2}{4h} \frac{1}{2}
\]

where \( f \) is the turbulent friction factor (darcy-weisbach) \( f = 4 C_f \)

\( h \) is flow depth, and

\( R \) is radius of curvature

• Account for toroidal spreading via the continuity equation

  □ Outboard: \( w(\theta) = w_o \cdot \frac{(R_o + R_c \cdot \sin[\theta])}{(R_o + R_c \cdot \sin[\theta_o])} \)

  □ inboard: \( w(\theta) = w_o \)

  □ no energy loss in flow re-distribution
Outboard Sector Width

Outboard CLiFF sector width as a function of flow distance
CLiFF Exploration: Outboard Flibe Flows with $R_c = 3.8$ m

Various initial depths at $V_0 = 10$ m/s

CLiFF depth/velocity profiles for various initial depths

Flow Distance (m) vs.

- Velocity (m/s)
- Depth (cm)

velocity curves
depth curves
CLiFF Exploration: Outboard Flibe Flows with $R_c = 3.8$ m

Various initial velocities at $h_o = 2$ cm

CLiFF depth/velocity profiles for various initial velocities
Is the flow adhered to the backwall?

Pressure profiles for various initial conditions:

- $V_o=7 \text{ m/s, } h_o=1\text{ cm}$
- $V_o=10 \text{ m/s, } h_o=1\text{ cm}$
- $V_o=10 \text{ m/s, } h_o=2\text{ cm}$
- $V_o=7 \text{ m/s, } h_o=2\text{ cm}$
- $V_o=12 \text{ m/s, } h_o=2\text{ cm}$
More Sophisticated Modeling Needed for Heat Transfer

\( k-\varepsilon \) model of turbulence used to determine effective “turbulent viscosity”

1. Two-equation model ("k-\( \varepsilon \)" model extended to the MHD case)

\[
\nu_t = C_D f_D \, \text{Re}^2 \frac{k^2}{\varepsilon}
\]

"k" (turbulent kinetic energy) equation:

\[
\frac{\partial k}{\partial t} + U \frac{\partial k}{\partial x} + V \frac{\partial k}{\partial y} = \frac{1}{\text{Re} \, \frac{\partial}{\partial y}} \left[ (1 + \frac{\nu_t}{\sigma_k} \frac{\partial k}{\partial y} ) + \frac{1}{\text{Re}} \nu_t (\frac{\partial U}{\partial y})^2 - \frac{\varepsilon}{\text{Re}} - 2 \left( \frac{\partial \sqrt{k}}{\partial y} \right)^2 - C_3 \beta^2 Nk \right]
\]

"\( \varepsilon \)" (dissipation rate of the turbulent kinetic energy) equation:

\[
\frac{\partial \varepsilon}{\partial t} + U \frac{\partial \varepsilon}{\partial x} + V \frac{\partial \varepsilon}{\partial y} = \frac{1}{\text{Re} \, \frac{\partial}{\partial y}} \left[ (1 + \frac{\nu_t}{\sigma_\varepsilon} \frac{\partial \varepsilon}{\partial y} ) + \frac{f_1}{\text{Re}} C_1 \nu_t \varepsilon \frac{\partial U}{\partial y}^2 - \frac{f_2}{\text{Re}} C_2 \frac{\varepsilon^2}{k} + 2 \nu_t \left( \frac{\partial^2 U}{\partial y^2} \right)^2 - C_4 \beta^2 N\varepsilon \right]
\]
**k-ε Model Predicts Higher Turbulent Drag and Thickening of the Flow**

![Graph showing film thickness scaled by Ho versus distance from the inlet, m. Legend: 1. k-ε model, 2. ff model, 3. laminar model.](image-url)
First k-ε Benchmark Test Case Inconclusive

Comparison of model predictions with experimental data

Inclined Plate: 
Vo = 1.9 m/s, ho = 2 mm, angle = 10 deg
3D Modeling of CLiFF in Expanding/Contracting Channel

- 2 cm flow is not filling in space near the walls
- Computational errors prevented program completion
- More work to settle this issue is required, including flared nozzle design
Channel Filling of Expanding Channel

20 cm deep flow fills all space, in fact, overfills near side wall

But, still need modeling of CLiFF reference cases
Design Model Formulation for CLiFF LM Flow

Simplest case, average across toroidal direction

- Assume a cylindrically-shaped surface
- Several variant to account for MHD forces

\[
\frac{\partial p_{loss}}{\partial \ell} = 0.5 \beta^2 \left( \frac{h}{y} \right) \left( j_z \big|_{z=1} - j_z \big|_{z=-1} \right) + \\
+ \frac{0.5 \beta^2}{Re} \left( \frac{\partial f}{\partial z} \big|_{z=1} - \frac{\partial f}{\partial z} \big|_{z=-1} \right)
\]

Where electric currents and toroidal velocity dependence are taken from solutions of the equivalent fully developed problem ⇒

- No accounting for toroidal spreading

Fully developed cross-sections considered
Unsteady Stability Results for Lithium

- Lithium with $h_0 = 2$ cm and $V_0 = 10$ m/s

- Initial disturbances are specified as perturbations of the mean velocity in the initial cross-section without perturbation of the flow-rate: $U/U_0 = 1+\varepsilon\sin(\omega t)$.

  1 - $\varepsilon=5\%; \omega=0.02 (\lambda\approx4.5 \text{ m})$
  2 - $\varepsilon=5\%; \omega=0.05 (\lambda\approx2.0 \text{ m})$
  3 - $\varepsilon=5\%; \omega=0.10 (\lambda\approx1.0 \text{ m})$
  4 - $\varepsilon=5\%; \omega=0.50 (\lambda\approx0.2 \text{ m})$
Conclusion from Simple MHD Model

• For thin CLiFF flow in 8 T Toroidal Field, sidewalls and penetrations have a critical allowable spacing in the toroidal direction

  1. Electrically Insulated walls: \( w = 1 \, \text{m} \)
  2. SiC walls (assumed thickness = 1 cm, \( \sigma = 10^3 \, \Omega^{-1}\text{m}^{-1} \)): \( w = 8 \, \text{m} \)
  3. Bare Metal Walls (assumed thickness = 2 mm, \( \sigma = 10^6 \, \Omega^{-1}\text{m}^{-1} \)): \( w = 110 \, \text{m} \)

• For infinite CLiFF flow with Field in Radial Direction

  1. Electrically Insulated Backing structure: \( B_r < 0.5 \, \text{T} \)
  2. SiC Backing Structure (thickness = 1 cm, \( \sigma = 10^3 \, \Omega^{-1}\text{m}^{-1} \)): \( B_r < 0.4 \, \text{T} \)
  3. Bare Metal Backing Structure (thickness = 2 mm, \( \sigma = 10^6 \, \Omega^{-1}\text{m}^{-1} \)): \( B_r < 0.15 \, \text{T} \)

Acceptability criteria is defined as less than a factor of 2 increase in initial flow height due to MHD drag
MHD Modeling of Spatial and Temporal Field Variations

Problem Description

- Infinitely wide film in z-direction
- Applied and induced magnetic field in z-direction with spatial and temporal variations
- Change from nozzle to free surface at x=0
- Backplate and nozzle surfaces range from electrically insulated to thin conducting walls
- Planar or cylindrical geometry with arbitrarily oriented gravity vector

Governing Equations

\[
\frac{\partial B_i}{\partial t} + (\vec{u} \cdot \nabla)B_i = \frac{1}{\sigma \mu} \nabla^2 B_i + \frac{1}{\mu} (\nabla \times B_i) \times \nabla \frac{1}{\sigma} - (u \cdot \nabla)B_a - \frac{\partial B_a}{\partial t}
\]

\[
\frac{\partial \vec{u}}{\partial t} + (\vec{u} \cdot \nabla)\vec{u} = -\frac{1}{\rho} \nabla \left( p + \frac{B_i^2}{2\mu} \right) + \nabla^2 \vec{u} + \vec{g} + \frac{1}{\rho \mu} (\nabla \times B_i \hat{z}) \times B_a \hat{z}
\]

\[
\frac{\partial \vec{F}}{\partial t} + (\vec{u} \cdot \nabla)\vec{F} = 0, \quad \nabla \cdot \vec{F} = 0
\]
FREE2D Development Progress

- Coupled induction equation backward Euler solver with 2D Navier-Stokes projection method solver successfully tested on closed duct flow
- VOF free surface tracking with linear surface reconstruction successfully tested
- Still to do:
  1. Optimize outflow boundary to reduce impact on upstream flow
  2. Test induction equation solver with free surface flows
  3. Improve user interface for running various test problems

Test Results – Film Flow on Inclined Plate, B=0

- surface height profile
- u-velocity contours