Design Constraints for Liquid-Protected Divertors

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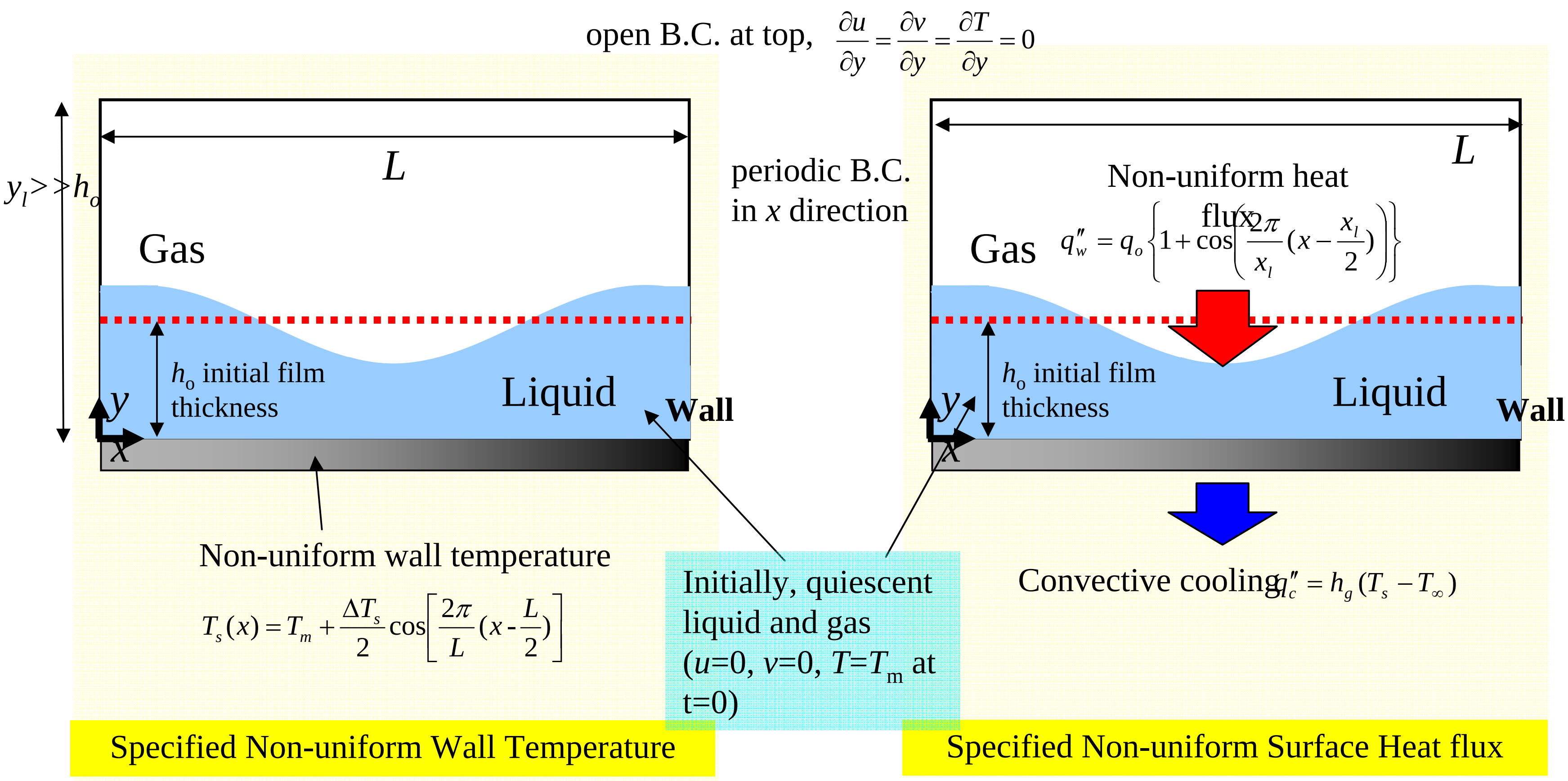
Problem Definition

- Work on Liquid Surface Plasma Facing Components and Plasma Surface Interactions has been performed by the ALPS and APEX Programs
- Operating Temperature Windows have been established for different liquids based on allowable limits for Plasma impurities and Power Cycle efficiency requirements
- This work is aimed at establishing limits for the maximum allowable temperature gradients (i.e. heat flux gradients) to prevent film rupture due to thermocapillary effects
- Spatial Variations in the wall and Liquid Surface Temperatures are expected due to variations in the wall loading
- Thermocapillary forces created by such temperature gradients can lead to film rupture and dry spot formation in regions of elevated local temperatures
- Initial Attention focused on Plasma Facing Components protected by a “non-flowing” thin liquid film (e.g. porous wetted wall)

Problem Definition



- Two Dimensional Cartesian (x-y) Model (assume no variations in toroidal direction)
- Two Dimensional Cylindrical (r-z) Model has also been developed (local “hot spot” modeling)

Governing Equations

- Conservation of Mass $\frac{\partial u'}{\partial x'} + \frac{\partial v'}{\partial y'} = 0$

$\sigma' = 1/\mathrm{We} - (\mathrm{M}/\mathrm{Pr})T'$

- Momentum

$$a^2\rho^+\left[\frac{\partial u'}{\partial t'} + u'\frac{\partial u'}{\partial x'} + v'\frac{\partial u'}{\partial y'}\right] = -\frac{\partial p'}{\partial x'} + a^2\frac{\partial}{\partial x'}\left(2\mu^+\frac{\partial u'}{\partial x'}\right) + \frac{\partial}{\partial y'}\left(\mu^+\frac{\partial u'}{\partial y'}\right) + a^2\frac{\partial}{\partial y'}\left(\mu^+\frac{\partial v'}{\partial x'}\right) + \int\left(\sigma'\kappa\mathbf{n} + \frac{\partial\sigma'}{\partial s}\mathbf{t}\right)\delta ds\cdot\hat{\mathbf{i}}$$

$$a^4\rho^+\left[\frac{\partial v'}{\partial t'} + u'\frac{\partial v'}{\partial x'} + v'\frac{\partial v'}{\partial y'}\right] = -\frac{\partial p'}{\partial y'} + \frac{\rho^+}{\mathrm{Fr}} + a^4\frac{\partial}{\partial x'}\left(\mu^+\frac{\partial v'}{\partial x'}\right) + a^2\frac{\partial}{\partial x'}\left(\mu^+\frac{\partial u'}{\partial y'}\right) + a^2\frac{\partial}{\partial y'}\left(2\mu^+\frac{\partial v'}{\partial y'}\right) + a\int\left(\sigma'\kappa\mathbf{n} + \frac{\partial\sigma'}{\partial s}\mathbf{t}\right)\delta ds\cdot\hat{\mathbf{j}}$$

- Energy

$$a^2\rho^+\left[\frac{\partial c^+T'}{\partial t'} + u'\frac{\partial c^+T'}{\partial x'} + v'\frac{\partial c^+T'}{\partial y'}\right] = \frac{a^2}{\mathrm{Pr}}\frac{\partial}{\partial x'}\left(k^+\frac{\partial T'}{\partial x'}\right) + \frac{1}{\mathrm{Pr}}\frac{\partial}{\partial y'}\left(k^+\frac{\partial T'}{\partial y'}\right)$$

- Non-dimensional variables

$$a = \frac{h_o}{L} \quad y' = \frac{y}{h_o} \quad x' = \frac{x}{L} = \frac{ax}{h_o}$$

$$u' = \frac{u}{(\mu_L/\rho_L L)} \quad v' = \frac{v}{(a\mu_L/\rho_L L)} \quad t' = \frac{t}{(\rho_L L^2/\mu_L)}$$

$$T' = \frac{T - T_m}{\Delta T_s} \quad V_g = \frac{\mu_L}{\rho_L h_o}$$

$$\mathrm{We} = \frac{\rho_L V_g^2 h_o}{\sigma_o} = \frac{\mu_L^2}{\rho_L\sigma_o h_o}$$

$$\mathrm{Fr} = \frac{V_g^2}{g h_o} = \frac{\mu_L^2}{g\rho_L^2 h_o^3}$$

$$\mathrm{Pr} = \frac{\mu_L c_L}{k_L} \quad \mathrm{M} = \frac{\gamma_o \Delta T_s h_o}{\mu_L \alpha_L}$$

$$q'' = -k_L\frac{\partial T}{\partial y} \quad q_o \sim k_L\frac{\Delta T}{h_o} \quad \Delta T \sim \frac{h_o q_0}{k_L}$$

$$aNu = \left(\frac{h_o}{L}\right)\left(\frac{h_g L}{k_L}\right) = \frac{h_o h_g}{k_L} \quad T' = \frac{T - T_\infty}{(h_o q_o/k_L)}$$

$$Q = 1 + \cos\left[2\pi\left(x - \frac{1}{2}\right)\right]$$

Specified Non-uniform Wall Temperature

Specified Non-uniform Surface Heat flux

Asymptotic Solution (Low Aspect Ratio Cases)

- Long wave theory with surface tension effect (a<<1). Govering Equations reduce to :

$$\frac{a^2 \mathrm{Fr}}{\mathrm{We}}\frac{\partial^3 h}{\partial x^3}h+\frac{\partial h}{\partial x}h+\frac{3}{2}(\mathrm{M}/\mathrm{Pr})\cdot \mathrm{Fr}\frac{\partial T_s}{\partial x}=0 \qquad \frac{\sigma_o}{\rho_{\mathrm{L}} g L^2}\frac{\partial^3 h}{\partial x^3}h+\frac{\partial h}{\partial x}h+\frac{3}{2}\frac{(Q/L)}{a(\rho_{\mathrm{L}} gk/\gamma_o)}\left[\frac{\partial hQ}{\partial x}+\frac{1}{B}\frac{\partial Q}{\partial x}\right]=0$$

Specified Non-uniform Wall Temperature * | Specified Non-uniform Surface Heat flux

* [Bankoff, et al. Phys. Fluids (1990)]

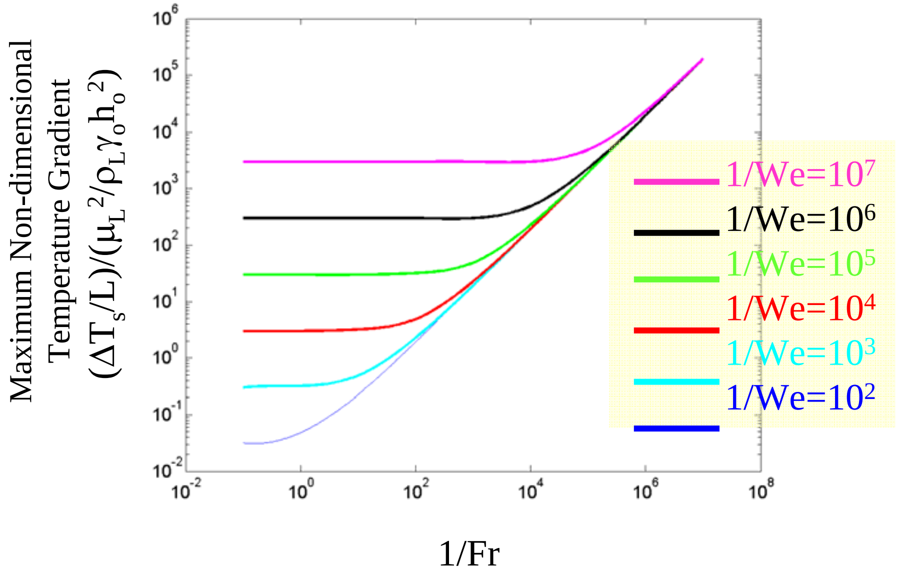
- Asymptotic solution used to analyze cases for Lithium, Lithium-lead, Flibe, Tin, and Gallium with different mean temperature and film thickness

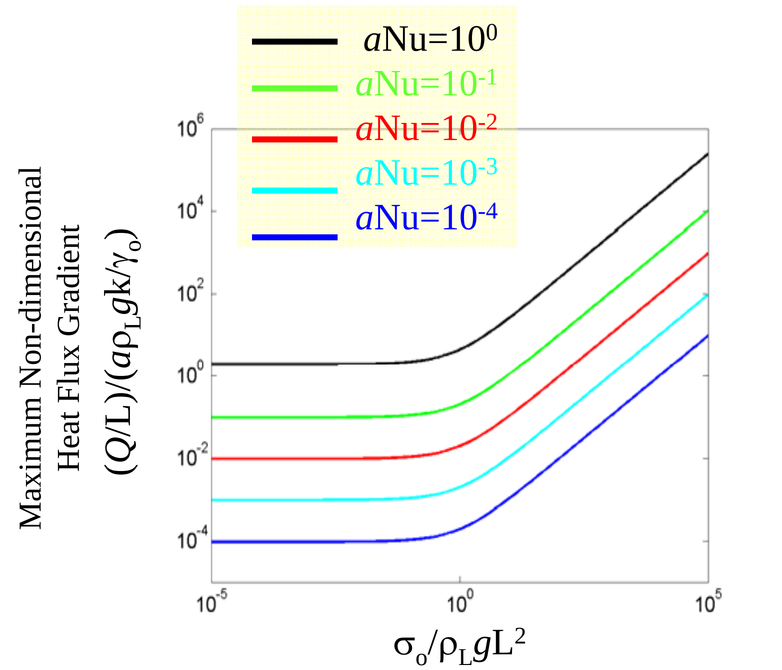
- Asymptotic solution produces conservative (i.e. low) temperature gradient limits

- Limits for “High Aspect Ratio” cases analyzed by numerically solving the full set of conservation equations using Level Contour Reconstruction Method

Asymptotic Solution (*Low Aspect Ratio Cases*)

a=0.02





Specified Non-uniform Wall Temperature

Specified Non-uniform Surface Heat flux

- Similar Plots have been obtained for other aspect ratios $(M/Pr)_{crit} = \frac{\pi^2}{12}\frac{1}{Fr}$
- In the limit of zero aspect ratio

Asymptotic Solution (Low Aspect Ratio Cases) *– Specified Non-uniform Wall Temp (h_o=1mm)*

- Property ranges

Parameter	Lithium		Lithium-Lead		Flibe		Tin		Gallium	
	573K	773K	573K	773K	573K	773K	1073K	1473K	873K	1273K
Pr	0.042	0.026	0.031	0.013	14	2.4	0.0047	0.0035	0.0058	0.0029
1/Fr	1.2×10^4	2.2×10^5	1.9×10^5	6.3×10^5	1.2×10^3	3.8×10^4	5.3×10^5	6.7×10^5	5.7×10^5	8.2×10^5
1/We	7.8×10^5	1.3×10^6	9.4×10^5	3.0×10^6	1.3×10^4	4.0×10^5	4.2×10^6	4.8×10^6	6.9×10^6	1.0×10^7
$\frac{\mu_L^2}{\rho_L \gamma_o h_o^2}$ **[K/m]**	2.8	1.5	4.4	1.3	140	4.3	0.72	0.55	1.6	1.1

* $1/We \propto h_o$, $1/Fr \propto h_o^3$

Coolant	Mean Temperature [K]	Max. Temp. Gradient : $(\Delta T_s/L)_{max}$ [K/cm]	
		Asymptotic Solution	**Numerical Solution**
Lithium	573	13	30
Lithium-Lead	673	173	570
Flibe	673	38	76
Tin	1273	80	113
Ga	1073	211	600

Asymptotic Solution (Low Aspect Ratio Cases) – Specified Non-uniform Surface Heat Flux

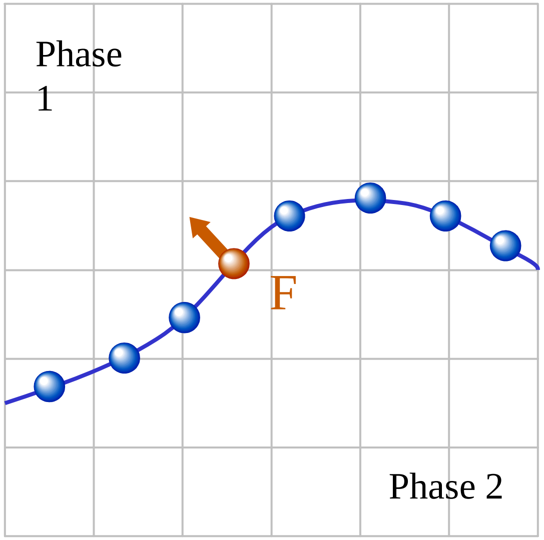
- h_o=10 mm, a=0.02

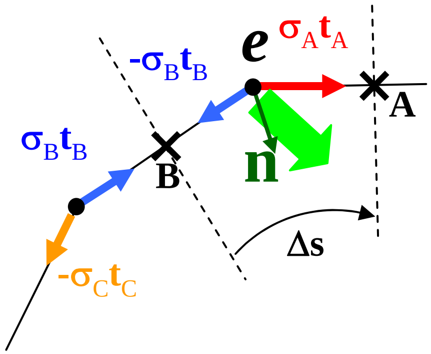
Coolant	**Mean Temperature [K]**	$\sigma_o/\rho_L g L^2$	**Max. Heat Flux. Gradient : $(Q''/L)_{max}$ [(MW/m²)/cm]**		
			aNu=1.0	aNu=0.1	aNu=0.01
Lithium	573	2.54×10^{-4}	0.61	3.1×10^{-2}	3.0×10^{-3}
Lithium-Lead	673	2.04×10^{-5}	4.9	0.24	2.4×10^{-2}
Flibe	673	4.35×10^{-5}	6.4×10^{-2}	3.2×10^{-3}	3.2×10^{-4}
Tin	1273	3.04×10^{-5}	6.8	0.34	3.3×10^{-2}
Ga	1073	4.81×10^{-5}	19	0.97	9.5×10^{-2}

- h_o=1 mm, aNu=1.0

Coolant	**Mean Temperature [K]**	**Max. Heat Flux. Gradient : $(Q''/L)_{max}$ [(MW/m²)/cm]**				
		a=0.05	a=0.02	a=0.01	a=0.005	a=0.002
Lithium	573	1.9×10^{0}	6.3×10^{-1}	3.1×10^{-1}	1.5×10^{-1}	6.1×10^{-2}
Lithium-Lead	673	1.2×10^{1}	4.9×10^{0}	2.4×10^{0}	1.2×10^{0}	4.9×10^{-1}
Flibe	673	1.7×10^{-1}	6.5×10^{-2}	3.2×10^{-2}	1.6×10^{-2}	6.4×10^{-3}
Tin	1273	1.7×10^{1}	6.8×10^{0}	3.4×10^{0}	1.7×10^{0}	6.8×10^{-1}
Ga	1073	5.0×10^{1}	1.9×10^{1}	9.7×10^{0}	4.8×10^{0}	1.9×10^{0}

Numerical Solution *(High Aspect Ratio Cases)*





n : unit vector in normal direction

t : unit vector in tangential direction

κ : curvature

- Evolution of the free surface is modeled using the Level Contour Reconstruction Method
- Two Grid Structures
  - Volume - entire computational domain (both phases) discretized by a standard, uniform, stationary, finite difference grid.
  - Phase Interface - discretized by Lagrangian points or elements whose motions are explicitly tracked.

- A single field formulation
- Constant but unequal material properties
- Surface tension included as local delta function sources
  - Variable surface tension : $\sigma = \sigma_o + \gamma_o (T - T_m)$
  - Force on a line element

$$\delta F_e = \int_{\Delta s} \left[\sigma \kappa \mathbf{n} + \frac{\partial \sigma}{\partial s} \mathbf{t} \right] ds = \int_B^A \frac{\partial (\sigma \mathbf{t})}{\partial s} ds = (\sigma_A \mathbf{t}_A - \sigma_B \mathbf{t}_B)$$

$$\therefore \sigma \kappa \mathbf{n} + \frac{\partial \sigma}{\partial s} \mathbf{t} = \sigma \frac{\partial \mathbf{t}}{\partial s} + \frac{\partial \sigma}{\partial s} \mathbf{t} = \frac{\partial (\sigma \mathbf{t})}{\partial s}$$

normal surface tension force

thermocapillary force

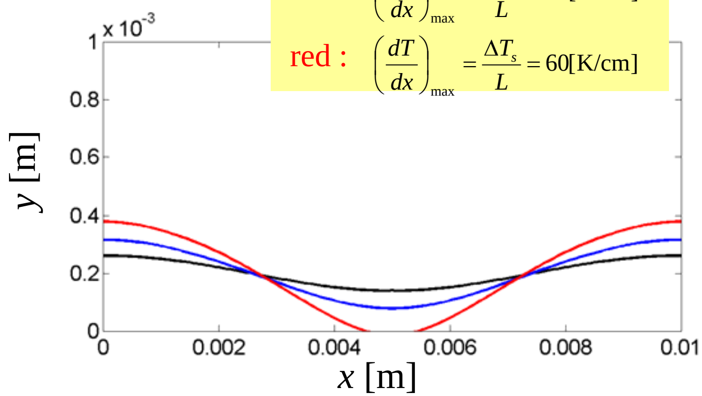
Numerical Solution (High Aspect Ratio Cases)
- Specified Non-uniform Wall Temperature case using Lithium

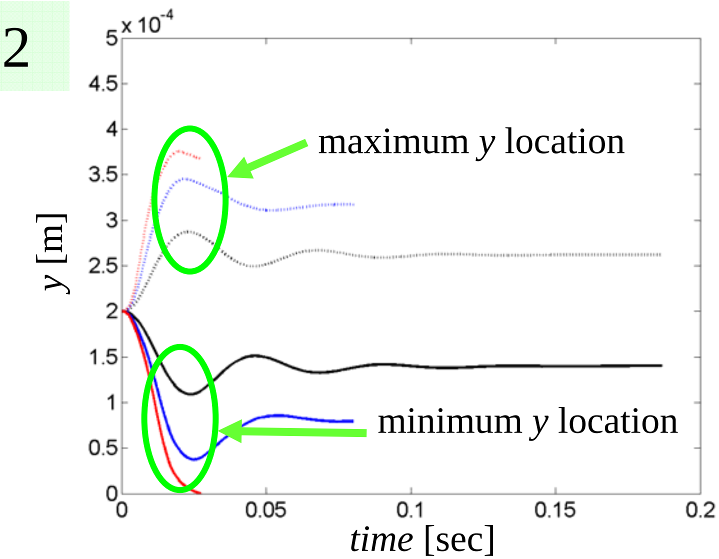
black : $\left(\frac{dT}{dx}\right)_{max} = \frac{\Delta T_s}{L} = 20[\mathrm{K/cm}]$

blue : $\left(\frac{dT}{dx}\right)_{max} = \frac{\Delta T_s}{L} = 40[\mathrm{K/cm}]$

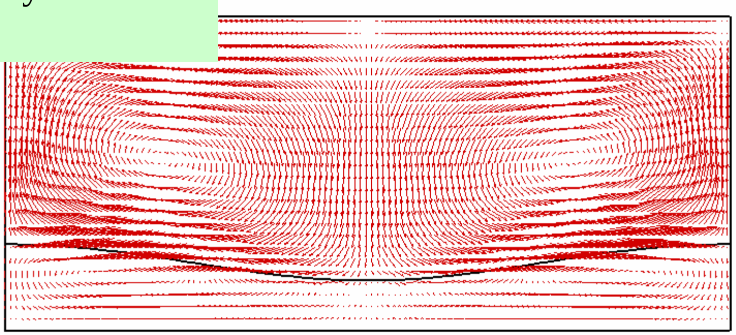
red : $\left(\frac{dT}{dx}\right)_{max} = \frac{\Delta T_s}{L} = 60[\mathrm{K/cm}]$

a=0.02

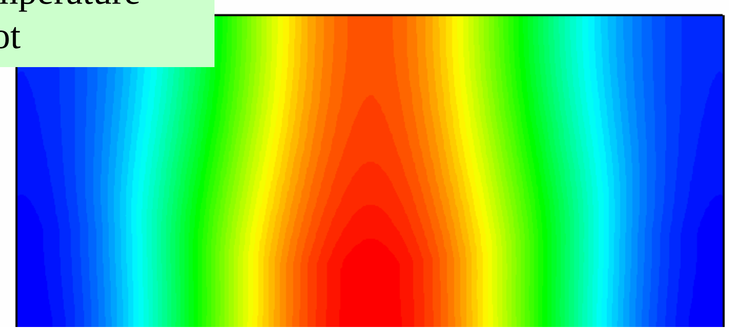




velocity vector plot



temperature plot

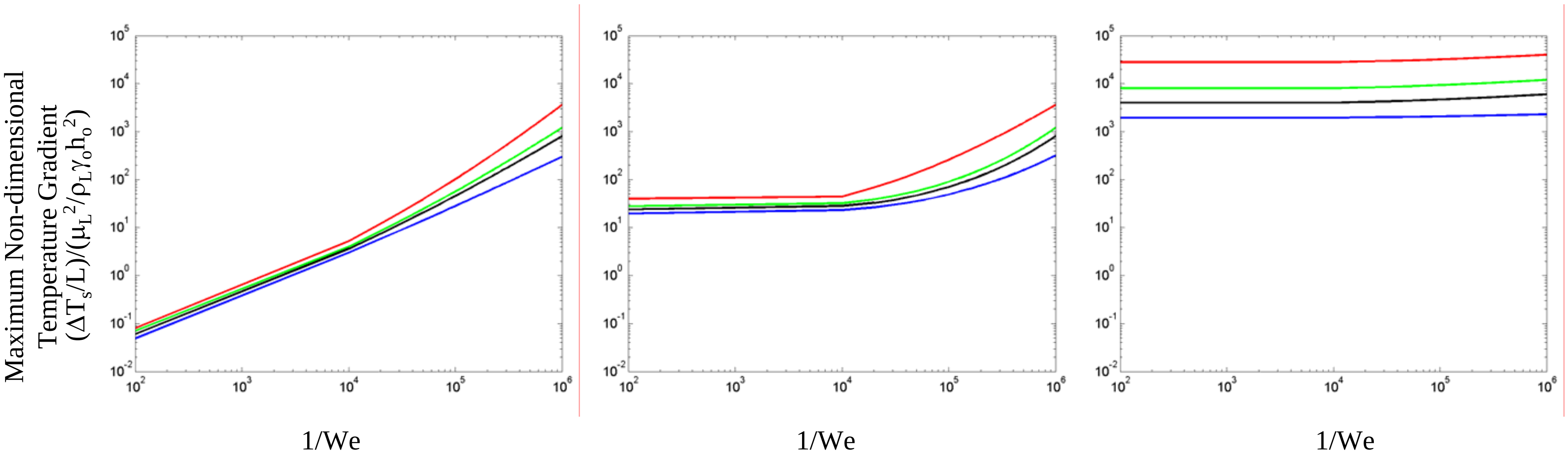


- Two-dimensional simulation with 1[cm]×0.1[cm] box size, 250×50 resolution, and h_o=0.2 mm

Numerical Solution (High Aspect Ratio Cases)
- Specified Non-uniform Wall Temperature case

a=0.02

1/Fr=10^1 1/Fr=10^3 1/Fr=10^5



Pr=40 Pr=0.4 Pr=0.004 Asymptotic Solution

Conclusions

- Limiting values for the temperature gradients (or heat flux gradients) to prevent film rupture can be determined
- Generalized charts have been developed to determine the temperature (or heat flux) gradient limits for different fluids, operating temperatures (i.e. properties), and film thickness values
- For thin liquid films, limits may be more restrictive than surface temperature limits based on Plasma impurities (evaporation) constraint
- Experimental Validation of Theoretical Model has been initiated
- Preliminary results for Axisymmetric geometry (hot spot model) produce more restrictive limits for temperature gradients