Heat Flux Gradient Limits for Liquid-Protected Divertors

S. I. Abdel-Khalik, S. Shin, and M. Yoda

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Georgia Institute of Technology

G. W. Woodruff School of Mechanical Engineering
Atlanta, GA 30332–0405 USA

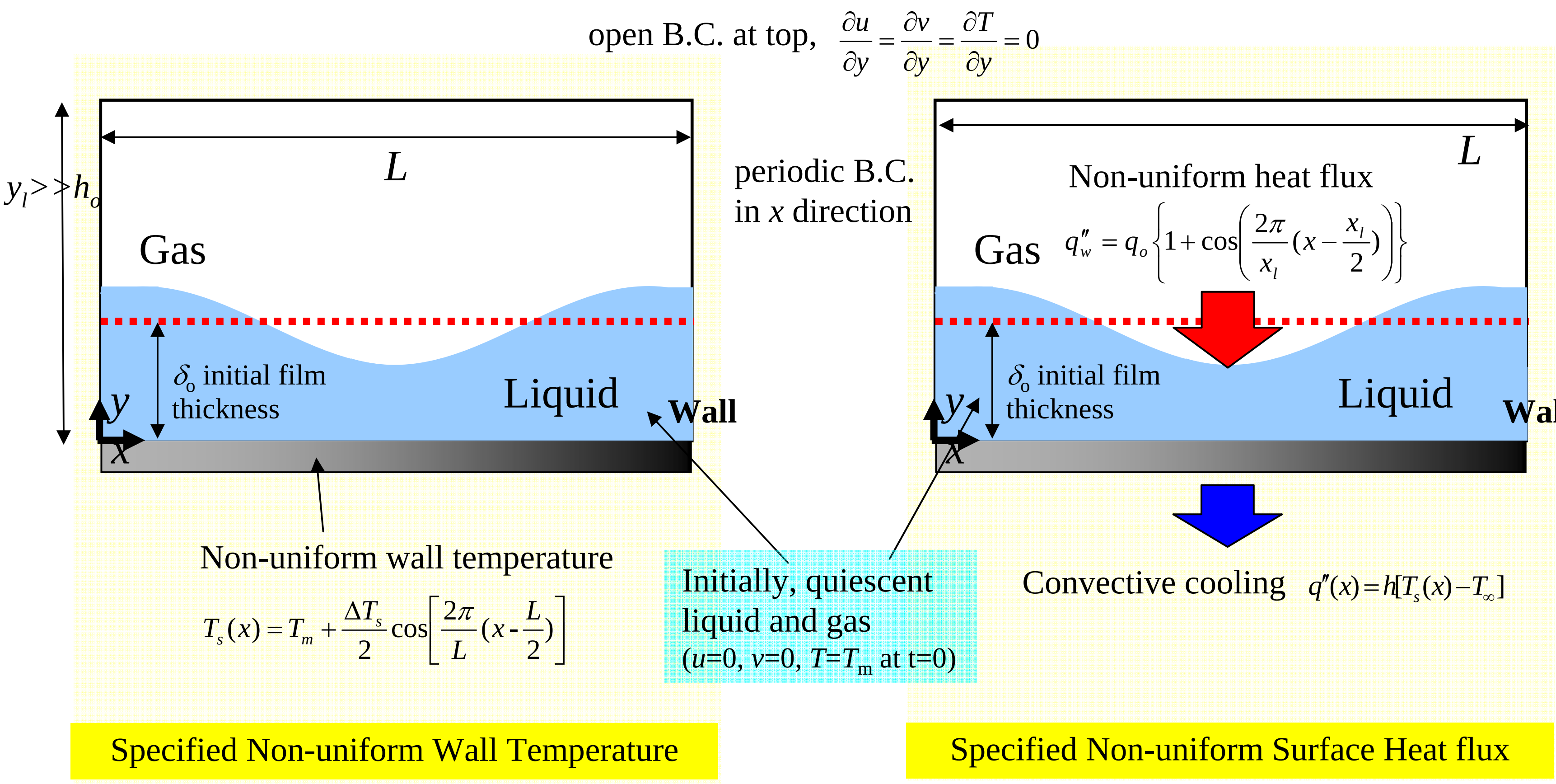
Problem Definition

- 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 heat flux gradients (i.e. temperature gradients) to prevent film rupture due to thermocapillary effects

Problem Definition

- Maximum Temperature gradients to prevent film rupture were previously established -- Analysis was extended to determine the maximum allowable heat flux gradients (based on comment made by Don Steiner)
- 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)

Variables definition

- Non-dimensional variables

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

$$u' = \frac{u}{(\mu_L / \rho_L L)}$$

$$v' = \frac{v}{(a\mu_L / \rho_L L)}$$

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

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

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

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

$$\mathrm{Pr} = \frac{\mu_L c_L}{k_L}$$

$$\mathrm{M} = \frac{\gamma_o \Delta T_s \delta_o}{\mu_L \alpha_L}$$

Specified Non-uniform Wall Temperature

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

$$\Delta T \sim \frac{\delta_o q_0}{k_L} \quad T' = \frac{T - T_\infty}{(\delta_o q_o / k_L)}$$

$$aNu = \left(\frac{\delta_o}{L}\right)\left(\frac{hL}{k_L}\right) = \frac{\delta_o h}{k_L}$$

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

Specified Non-uniform Surface Heat flux

Governing Equations

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

- Momentum

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

$$a^2\rho^+\left[\frac{\partial u'}{\partial t'}+u'\frac{\partial u'}{\partial x'}+v'\frac{\partial u'}{\partial y'}\right]$$

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

$$a^4\rho^+\left[\frac{\partial v'}{\partial t'}+u'\frac{\partial v'}{\partial x'}+v'\frac{\partial v'}{\partial y'}\right]$$

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

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

Asymptotic Solution

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

$$\frac{a^2\mathrm{Fr}}{\mathrm{We}}\frac{\partial^3\delta}{\partial x^3}\delta+\frac{\partial\delta}{\partial x}\delta+\frac{3}{2}(\mathrm{M}/\mathrm{Pr})\cdot\mathrm{Fr}\frac{\partial T_s}{\partial x}=0$$

Specified Non-uniform Wall Temperature *

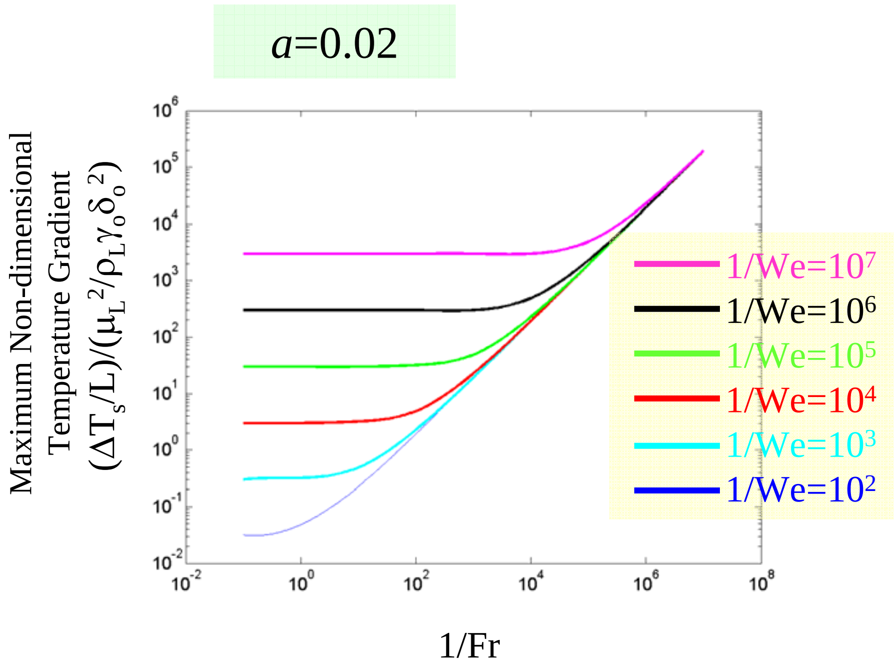
$$\frac{\sigma_o}{\rho_{\mathrm{L}}gL^2}\frac{\partial^3\delta}{\partial x^3}\delta+\frac{\partial\delta}{\partial x}\delta+\frac{3}{2}\frac{(Q/L)}{a(\rho_{\mathrm{L}}gk/\gamma_o)}\left[\frac{\partial\delta Q}{\partial x}+\frac{1}{(aNu)}\frac{\partial Q}{\partial x}\right]=0$$

Specified Non-uniform Surface Heat flux

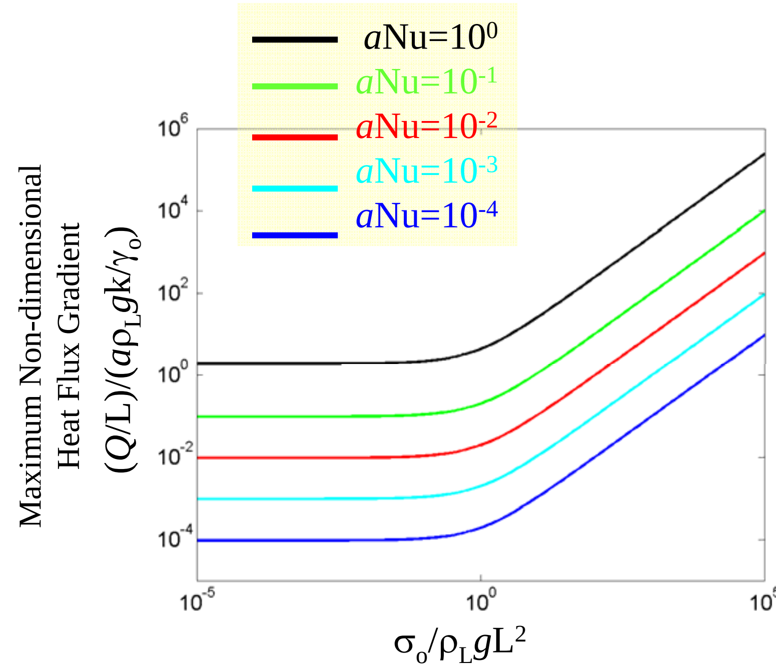
* [Bankoff, et al. Phys. Fluids (1990)]

- 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



Specified Non-uniform Wall Temperature



Specified Non-uniform Surface Heat flux

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

Results -- Asymptotic Solution
– Specified Non-uniform Wall Temp (δ_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
$\frac{\mu_L^2}{\rho_L \gamma_o \delta_o^2}$ **[K/m]**	2.8	1.5	4.4	1.3	140	4.3	0.72	0.55	1.6	1.1

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

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

Results -- Asymptotic Solution
– Specified Non-uniform surface heat flux

- δ_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/m^2)/cm]		
			*a*Nu=1.0	*a*Nu=0.1	*a*Nu=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}

- δ_o=1 mm, *aNu*=1.0

Coolant	Mean Temperature [K]	Max. Heat Flux. Gradient : $(Q''/L)_{max}$ [(MW/m^2)/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}

Conclusions

- Limiting values for the heat flux gradients (i.e. temperature gradients) to prevent film rupture can be determined
- Generalized charts have been developed to determine the 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 limit
- Experimental Validation of Theoretical Model has been initiated

Extra Slides

Results -- Asymptotic Solution (δ_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/m^2)/cm]**		
			aNu=1.0	aNu=0.1	aNu=0.1
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}

Results -- Asymptotic Solution (δ_o=1 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=0.1
Lithium	573	2.54×10^{-2}	0.63	3.2×10^{-2}	3.1×10^{-3}
Lithium-Lead	673	2.04×10^{-3}	4.9	0.24	2.4×10^{-2}
Flibe	673	4.35×10^{-3}	6.5×10^{-2}	3.3×10^{-3}	3.2×10^{-4}
Tin	1273	3.04×10^{-3}	6.8	0.34	3.3×10^{-2}
Ga	1073	4.81×10^{-3}	19	0.98	9.6×10^{-2}

Results -- Asymptotic Solution (δ_o=0.1 mm, a=0.02)

Coolant	**Mean Temperature [K]**	$\sigma_o/\rho_L g L^2$	**Max. Heat Flux. Gradient $(Q''/L)_{max}$ [(MW/m^2)/cm]**		
			aNu=1.0	aNu=0.1	aNu=0.1
Lithium	573	2.54×10^{0}	2.6	0.11	1.1×10^{-2}
Lithium-Lead	673	2.04×10^{-1}	6.2	0.3	2.9×10^{-2}
Flibe	673	4.35×10^{-1}	0.1	4.8×10^{-3}	4.7×10^{-4}
Tin	1273	3.04×10^{-1}	9.5	0.46	4.4×10^{-2}
Ga	1073	4.81×10^{-1}	31	1.5	0.14

Results -- Asymptotic Solution (δ_o=1 mm, aNu=1.0)

Coolant	Mean Temperature [K]	Max. Heat Flux. Gradient $(Q''/L)_{max}$ [(MW/m^2)/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}

Results -- Asymptotic Solution (δ_o=1 mm, aNu=0.1)

Coolant	Mean Temperature [K]	Max. Heat Flux. Gradient $(Q''/L)_{max}$ [(MW/m^2)/cm]				
		a=0.05	a=0.02	a=0.01	a=0.005	a=0.002
Lithium	573	9.2×10^{-2}	3.2×10^{-2}	1.5×10^{-2}	7.7×10^{-3}	3.0×10^{-3}
Lithium-Lead	673	6.2×10^{-1}	2.4×10^{-1}	1.2×10^{-1}	6.1×10^{-2}	2.4×10^{-2}
Flibe	673	8.4×10^{-3}	3.3×10^{-3}	1.6×10^{-3}	8.1×10^{-4}	3.2×10^{-4}
Tin	1273	8.7×10^{-1}	3.4×10^{-1}	1.7×10^{-1}	8.5×10^{-2}	3.4×10^{-2}
Ga	1073	2.5×10^{0}	9.8×10^{-1}	4.9×10^{-1}	2.4×10^{-1}	9.7×10^{-2}

Results -- Asymptotic Solution (δ_o=1 mm, aNu=0.01)

Coolant	**Mean Temperature [K]**	**Max. Heat Flux. Gradient $(Q''/L)_{max}$ [(MW/m^2)/cm]**				
		a=0.05	a=0.02	a=0.01	a=0.005	a=0.002
Lithium	573	8.9×10^{-3}	3.1×10^{-3}	1.5×10^{-3}	7.5×10^{-4}	3.0×10^{-4}
Lithium-Lead	673	6.1×10^{-2}	2.4×10^{-2}	1.2×10^{-2}	6.0×10^{-3}	2.4×10^{-3}
Flibe	673	8.2×10^{-4}	3.2×10^{-4}	1.6×10^{-4}	8.0×10^{-5}	3.2×10^{-5}
Tin	1273	8.5×10^{-2}	3.3×10^{-2}	1.7×10^{-2}	8.3×10^{-3}	3.3×10^{-3}
Ga	1073	2.5×10^{-1}	9.6×10^{-2}	4.8×10^{-2}	2.4×10^{-2}	9.5×10^{-3}

Results -- Asymptotic Solution (L=5 cm, 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	1.6×10^{0}	6.3×10^{-1}	3.2×10^{-1}	1.6×10^{-1}	6.4×10^{-2}
Lithium-Lead	673	1.2×10^{1}	4.9×10^{0}	2.5×10^{0}	1.3×10^{0}	5.2×10^{-1}
Flibe	673	1.6×10^{-1}	6.5×10^{-2}	3.3×10^{-2}	1.7×10^{-2}	8.5×10^{-3}
Tin	1273	1.4×10^{1}	6.8×10^{0}	3.4×10^{0}	1.7×10^{0}	6.8×10^{-1}
Ga	1073	4.8×10^{1}	1.9×10^{1}	9.5×10^{0}	4.8×10^{0}	1.9×10^{0}

Results -- Asymptotic Solution (L=5 cm, aNu=0.1)

Coolant	Mean Temperature [K]	Max. Heat Flux. Gradient $(Q''/L)_{max}$ [(MW/m^2)/cm]				
		a=0.05	a=0.02	a=0.01	a=0.005	a=0.002
Lithium	573	8.0×10^{-2}	3.2×10^{-2}	1.6×10^{-2}	8.0×10^{-3}	3.2×10^{-3}
Lithium-Lead	673	6.0×10^{-1}	2.4×10^{-1}	1.2×10^{-1}	6.0×10^{-2}	2.4×10^{-2}
Flibe	673	8.3×10^{-3}	3.3×10^{-3}	1.7×10^{-3}	8.5×10^{-4}	3.4×10^{-4}
Tin	1273	8.5×10^{-1}	3.4×10^{-1}	1.7×10^{-1}	8.5×10^{-2}	3.4×10^{-2}
Ga	1073	2.5×10^{0}	9.8×10^{-1}	4.9×10^{-1}	2.5×10^{-1}	1.0×10^{-1}

Results -- Asymptotic Solution (L=5 cm, aNu=0.01)

Coolant	**Mean Temperature [K]**	**Max. Heat Flux. Gradient $(Q''/L)_{max}$ [(MW/m^2)/cm]**				
		a=0.05	a=0.02	a=0.01	a=0.005	a=0.002
Lithium	573	7.8×10^{-3}	3.1×10^{-3}	1.6×10^{-3}	8.0×10^{-4}	3.2×10^{-4}
Lithium-Lead	673	6.0×10^{-2}	2.4×10^{-2}	1.2×10^{-2}	6.0×10^{-3}	2.4×10^{-3}
Flibe	673	8.0×10^{-4}	3.2×10^{-4}	1.6×10^{-4}	8.0×10^{-5}	3.2×10^{-5}
Tin	1273	8.3×10^{-2}	3.3×10^{-2}	1.7×10^{-2}	8.5×10^{-3}	3.4×10^{-3}
Ga	1073	2.4×10^{-1}	9.6×10^{-2}	4.8×10^{-2}	2.4×10^{-2}	9.6×10^{-3}