Simulations of Fluid Dynamics and Heat Transfer in LH_2 Absorbers

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Introduction: Approaches to Heat Removal

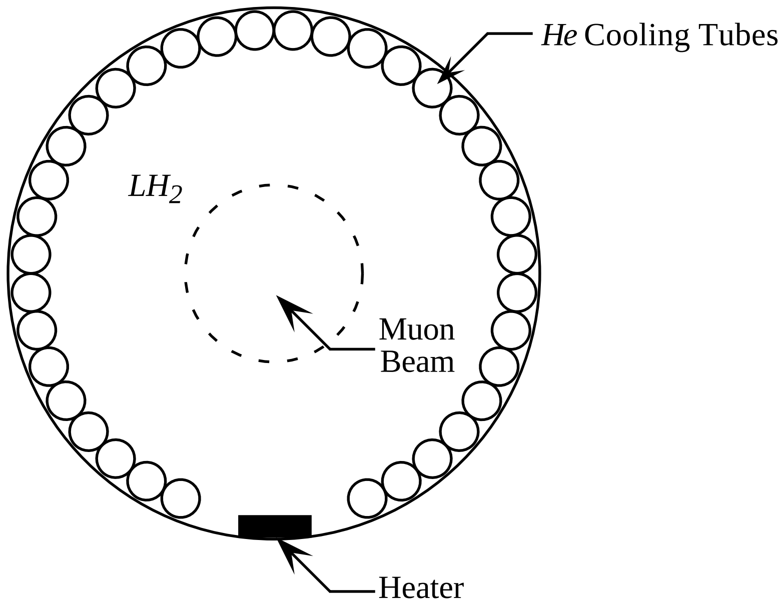
Two approaches under consideration:

① External cooling loop (traditional approach).

☞ Bring the LH_2 to the coolant (heat removed in an external heat exchanger).

② Combined absorber and heat exchanger.

☞ Bring the coolant, i.e. He, to the LH_2 (remove heat directly within absorber).



Introduction (cont'd)

Advantages/disadvantages of an external cooling loop:

+ Has been used for several LH_2 targets (e.g. SLAC E158).
+ Easy to regulate bulk temperature of LH_2.
+ Is likely to work best for small aspect ratio (L/R) absorbers.
− May be difficult to maintain uniform vertical flow through the absorber.

Advantages/disadvantages of a combined absorber/heat exchanger:

+ Takes advantage of natural convection transverse to the beam path.
+ Flow in absorber is self regulating, *i.e.* larger heat input $\Rightarrow$ more turbulence $\Rightarrow$ enhanced thermal mixing.
+ Is likely to work best for large aspect ratio (L/R) absorbers.
− More difficult to ensure against boiling at very high Rayleigh numbers.

Heat Exchanger Analysis

Energy balance between LH_2 and coolant (He).

✓ Parameters:

T_i	=	coolant inlet temperature
T_o	=	coolant outlet temperature
T_{LH_2}	=	bulk temperature of LH_2
A	=	surface area of cooling tubes
h_{LH_2}	=	convective heat transfer coefficient of LH_2
h_{He}	=	convective heat transfer coefficient of He
Δx	=	thickness of cooling tube walls
k_w	=	thermal conductivity of cooling tube walls
c_p	=	specific heat capacity of He

Heat Exchanger Analysis (cont'd)

✓ Rate of heat transfer:

$$\dot{q} = -\frac{A(T_o - T_i)}{\left(\frac{1}{h_{LH_2}} + \frac{\Delta x}{k_w} + \frac{1}{h_{He}}\right) \ln\left(\frac{T_{LH_2} - T_o}{T_{LH_2} - T_i}\right)}$$

✓ Mass flow rate of He:

$$\dot{m}_{He} = \frac{\dot{q}}{c_p\,(T_o - T_i)}.$$

$h_{He} \Rightarrow$ from appropriate correlation (flow through a tube).

h_{LH_2} and $T_{LH_2} \Rightarrow$ from CFD simulations (no correlations for natural convection with heat generation).

Computational Fluid Dynamics (CFD)

Features of the CFD Simulations:

✓ Provides average convective heat transfer coefficient and average LH_2 temperature for heat exchanger analysis.

✓ Track maximum LH_2 temperature (*cf.* boiling point).

✓ Determine details of fluid flow and heat transfer in absorber.

$\Rightarrow$ *Better understanding leads to better design!*

CFD (cont'd)

Take 1: Results using FLUENT (M. Boghosian):

- ✓ Simulate one half of symmetric domain.
- ✓ Steady flow calculations.
- ✓ Heat generation via *steady* Gaussian distribution.
- ✓ Turbulence modeling (RANS) used for $Ra \geq 4 \times 10^9$.

Take 2: Results using COA code (A. Obabko and E. Almasri):

- ✓ Simulate full domain.
- ✓ Unsteady flow calculations.
- ✓ All scales computed for all Rayleigh numbers.
  - ➥ Investigate startup behavior, *e.g.* startup overshoot in T_{max}.
  - ➥ Investigate possibility of asymmetric flow oscillations.
  - ➥ Investigate influence of beam pulsing.

Formulation

Properties and parameters:

R	=	radius of absorber
T_w	=	wall temperature of absorber
$\dot{q}'''(r)$	=	rate of volumetric heat generation (Gaussian distribution)
$\dot{q}'$	=	rate of heat generation per unit length
ν	=	kinematic viscosity of LH_2
α	=	thermal diffusivity of LH_2
k	=	thermal conductivity of LH_2
β	=	coefficient of thermal expansion of LH_2

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Governing Equations (T - ω - ψ formulation)

Energy equation:

$$\frac{\partial T}{\partial t} + v_r \frac{\partial T}{\partial r} + \frac{v_\theta}{r}\frac{\partial T}{\partial \theta} = \frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} + \frac{1}{r^2}\frac{\partial^2 T}{\partial \theta^2} + q(r)$$

Vorticity-transport equation:

$$\begin{aligned}\frac{\partial \omega}{\partial t} + v_r \frac{\partial \omega}{\partial r} + \frac{v_\theta}{r}\frac{\partial \omega}{\partial \theta} \quad &= \quad Pr\left[\frac{\partial^2 \omega}{\partial r^2} + \frac{1}{r}\frac{\partial \omega}{\partial r} + \frac{1}{r^2}\frac{\partial^2 \omega}{\partial \theta^2}\right] \\ &\quad + Ra_R Pr\left[\sin\theta\frac{\partial T}{\partial r} + \frac{\cos\theta}{r}\frac{\partial T}{\partial \theta}\right]\end{aligned}$$

Streamfunction equation:

$$\frac{\partial^2 \psi}{\partial r^2} + \frac{1}{r}\frac{\partial \psi}{\partial r} + \frac{1}{r^2}\frac{\partial^2 \psi}{\partial \theta^2} = -\omega$$

$$v_r = \frac{1}{r}\frac{\partial \psi}{\partial \theta}, \quad v_\theta = -\frac{\partial \psi}{\partial r}$$

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Formulation (cont'd)

Initial and boundary conditions:

$$T = \omega = \psi = v_r = v_\theta = 0 \quad \text{at} \quad t = 0,$$

$$T = \psi = v_r = v_\theta = 0 \quad \text{at} \quad r = 1.$$

Non-dimensional variables:

$$r = \frac{r^*}{R}, \quad v_r = \frac{v_r^*}{R/\alpha}, \quad v_\theta = \frac{v_\theta^*}{R/\alpha}, \quad t = \frac{t^*}{R^2/\alpha},$$

$$T = \frac{T^* - T_w}{\dot{q}'/k}, \quad \psi = \frac{\psi^*}{\alpha}, \quad \omega = \frac{\omega^*}{\alpha/R^2},$$

$$q(r) = \frac{\dot{q}'''(r)}{\dot{q}'/R^2} = \frac{1}{2\pi\sigma^2} e^{-\frac{r^2}{2\sigma^2}}, \quad \sigma = \frac{\sigma^*}{R}.$$

Formulation – Non-Dimensional Parameters

Prandtl Number:

$$Pr = \frac{\nu}{\alpha}$$

Rayleigh Number:

$$Ra_R = Gr\,Pr = \frac{gR^3\beta\dot{q}'/k}{\nu\alpha}\left(= \frac{\pi}{32}Ra_{MB}\right)$$

Nusselt number:

$$Nu_R = \frac{h_{LH_2}R}{k}\left(= \frac{Nu_{MB}}{2}\right)$$

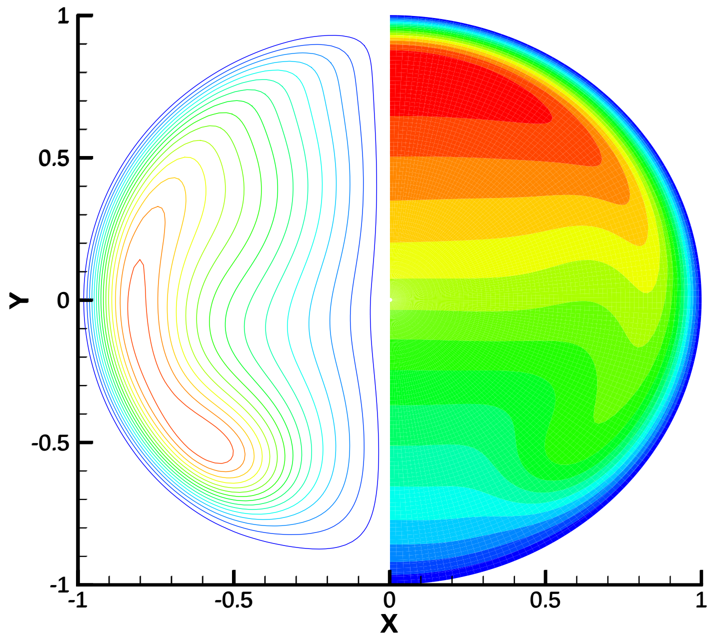
Results – Flow Regimes

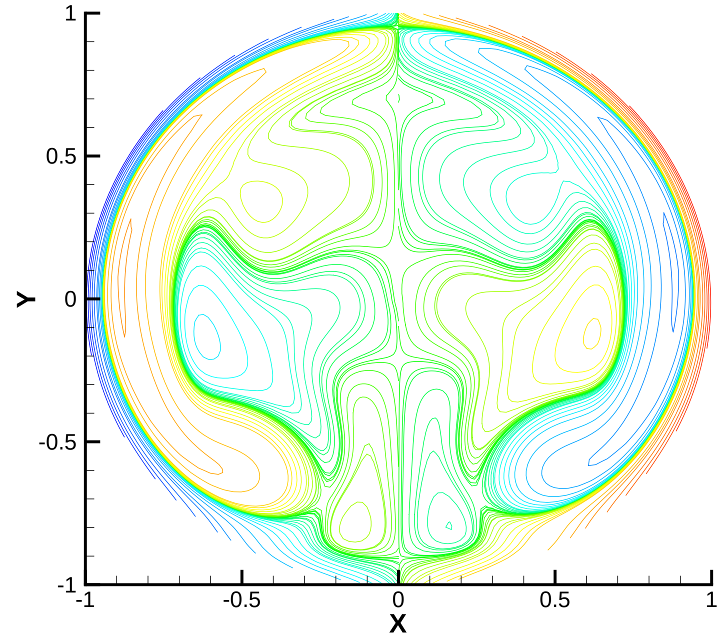
Based on preliminary results, the following flow regimes are observed:

- ☞ Steady, symmetric solutions: $Ra_R \leq 1 \times 10^8$
- ☞ Unsteady, asymmetric solutions: $Ra_R \geq 1 \times 10^9$

Steady, symmetric results for $Ra_R = 1.57 \times 10^7$ (uniform heat generation):

Streamfunction: Temperature: Vorticity:





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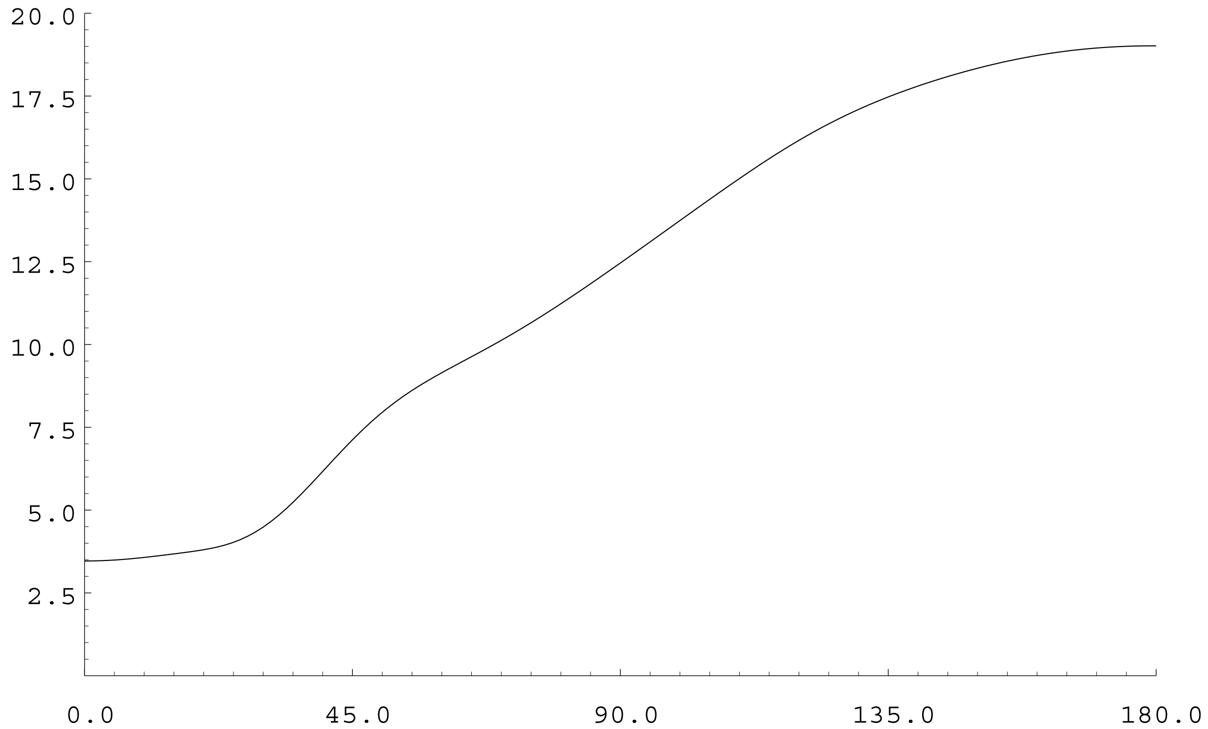
Steady, Symmetric Results (cont'd)

Nusselt number versus θ for $Ra_R = 1.57 \times 10^7$ (uniform heat generation):

Nu vs. θ:



Code Comparisons – Average Nusselt Number ($\bar{N}u$)

Uniform heat generation ($\sigma \longrightarrow \infty$) with $Pr = 1$:

Ra_R	Mitachi *et al.* [1]	FLUENT[2]	COA Code
1.57×10^6	8.58	7.7	8.2
1.57×10^7	14.0	11.9	12.0

[1] Mitachi *et al.* (1986, 1987) - Results shown are from numerical simulations which compared favorably with experiments.

[2] From M. Boghosian's correlation for $Pr = 1.4$, *i.e.* $\bar{N}u_{MB} = 0.7041 \cdot Ra_{MB}^{0.1864}$.

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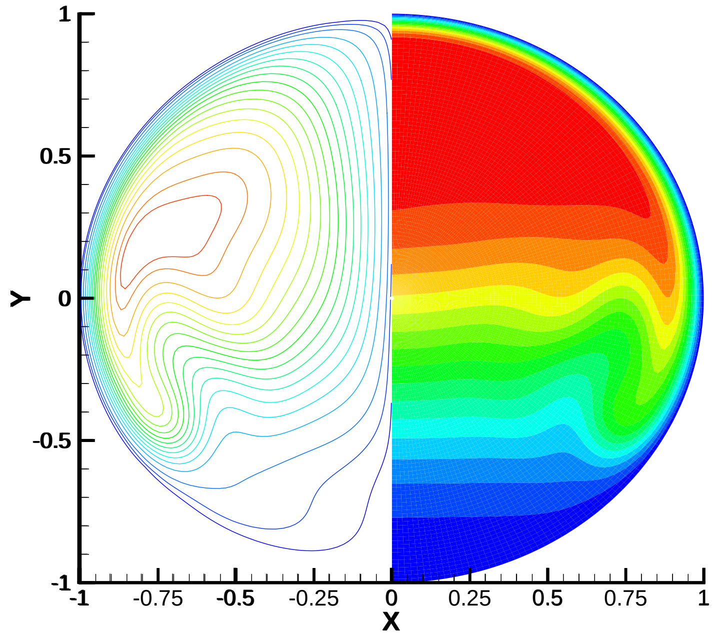
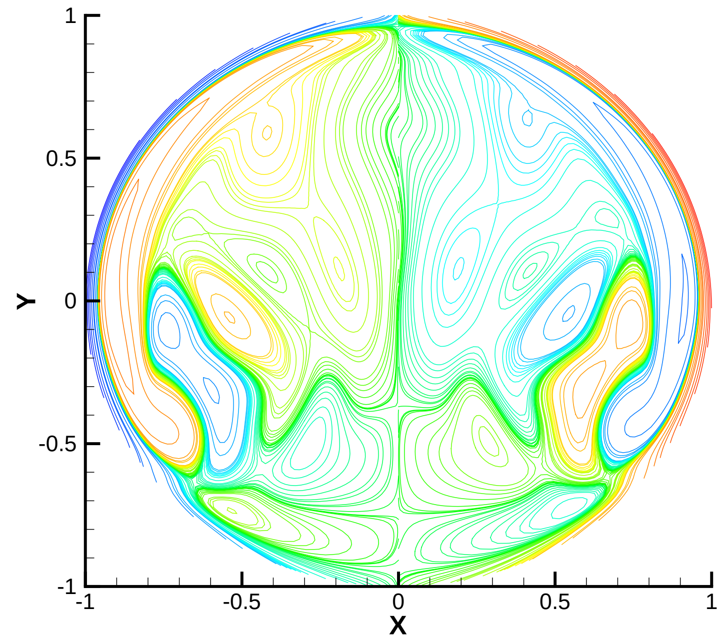
Steady, Symmetric Results: $Ra_R = 1 \times 10^8, \sigma = 0.25$

Streamfunction: Temperature:



Vorticity:



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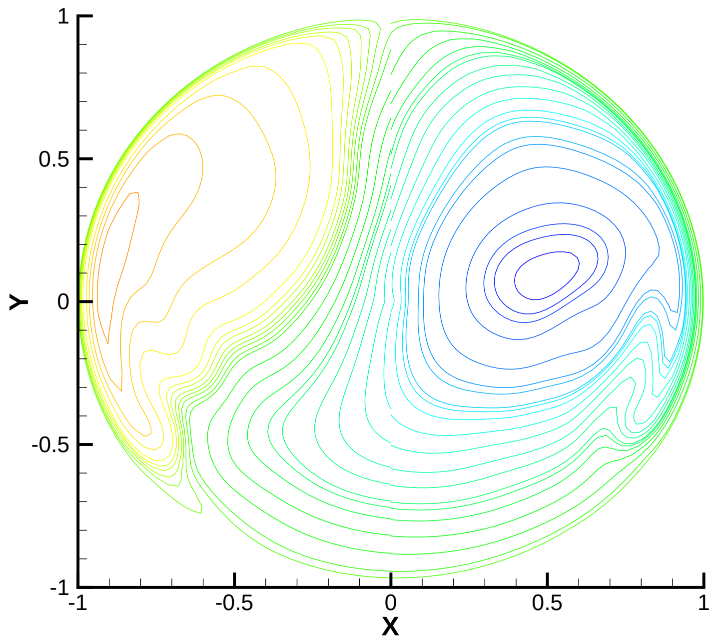
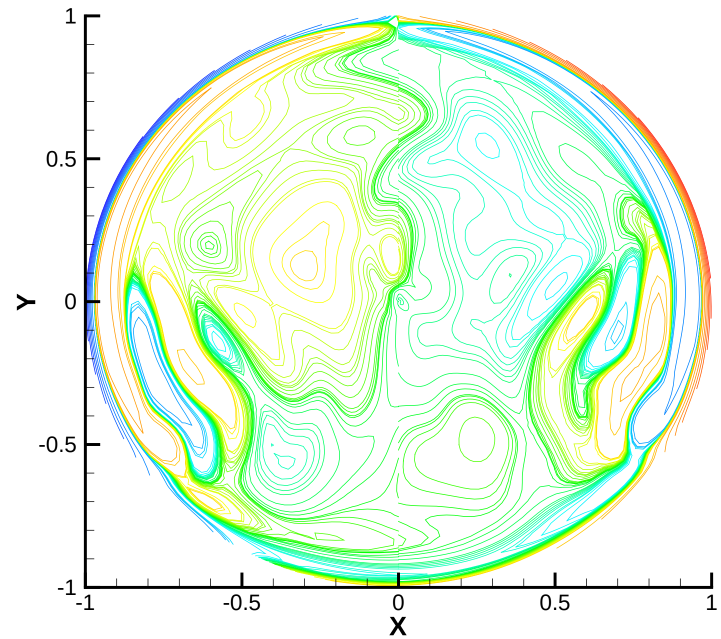
Unsteady, Asymmetric Results: $Ra_R = 1 \times 10^9, \sigma = 0.25$

$t = 0.2$

Streamfunction:



Vorticity:



Movies for streamfunction, temperature and vorticity ($0 \leq t \leq 0.25$).

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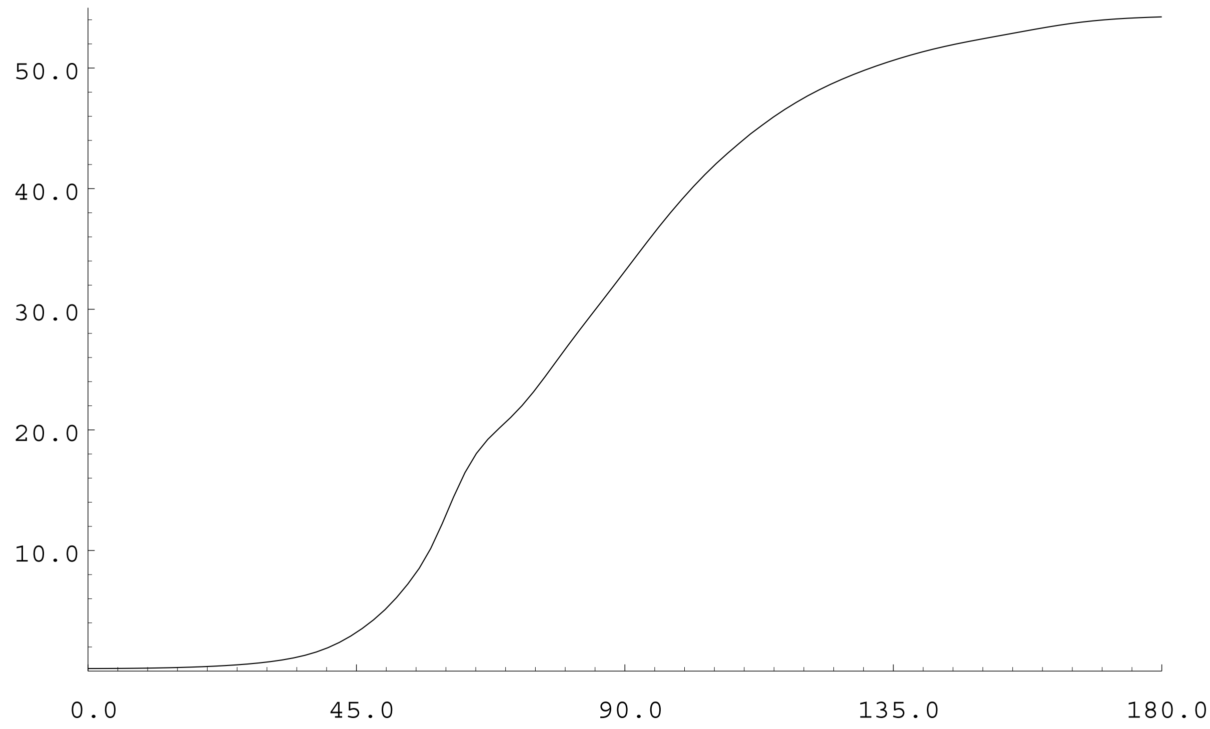
Unsteady, Asymmetric Results: $Ra_R = 1 \times 10^9, \sigma = 0.25$

Asymmetric oscillation does not significantly influence wall heat transfer (*e.g.* Nu for left and right walls superimposed).

$t = 2.0$:

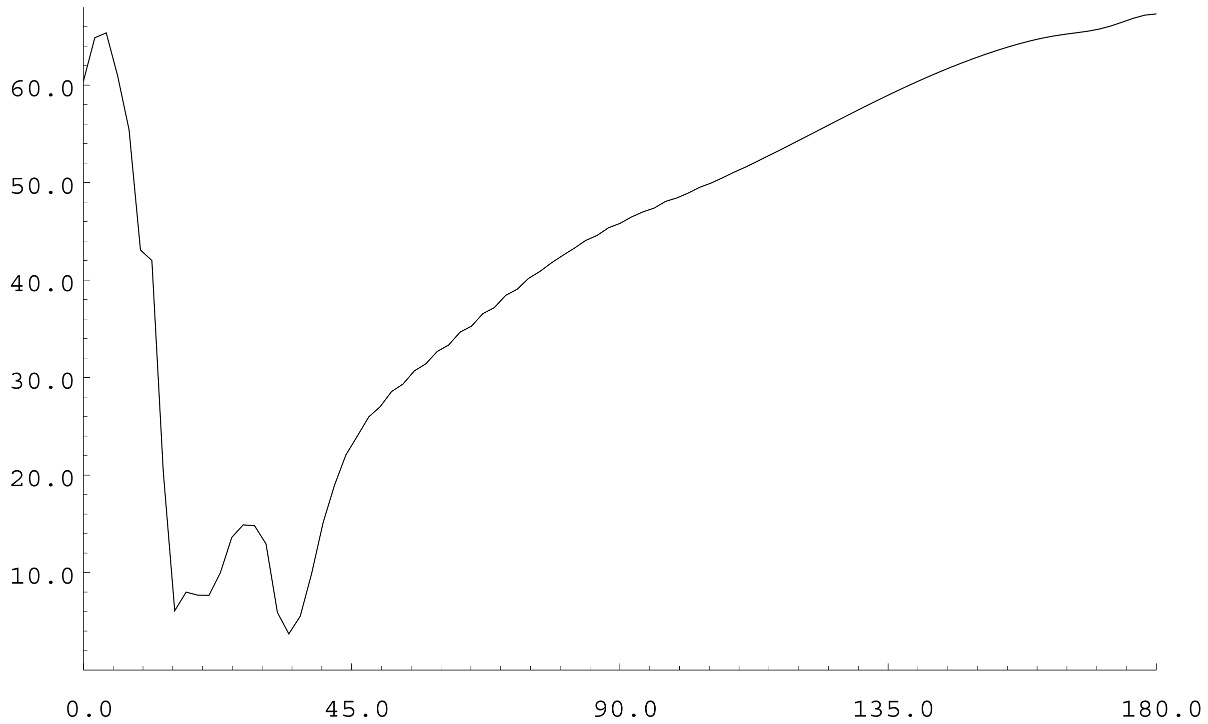


Unsteady Results – High-Ra Startup

Movie for $Ra_R = 1 \times 10^{11}$ ($\sigma = 0.25$).

Nu vs. θ:

$$t = 0.0015$$



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Current and Future Efforts

Current and future work:

- Simulate Argonne test case and compare results.
- Determine critical Rayleigh number above which solutions are unsteady and asymmetric.
- Evaluate influence of σ, *i.e.* ratio of beam size to absorber size, on heat transfer.
- Obtain solutions at higher Rayleigh numbers (target $Ra_R \sim 10^{14}$).
- Compare high-Rayleigh number COA solutions (unsteady) with FLUENT results (steady RANS).
- Examine need for heater, *e.g.* to combat start-up overshoot.
- Investigate influence of pulsed beam on fluid dynamics and heat transfer.

  Note that at 15 Hz, one pulse corresponds to 2.4×10^{-7} non-dimensional time units (*cf.* $\Delta t = 10^{-8}$).

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