Simulations of Fluid Dynamics and Heat Transfer in LH_2 Absorbers

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Introduction: Approaches to Heat Removal

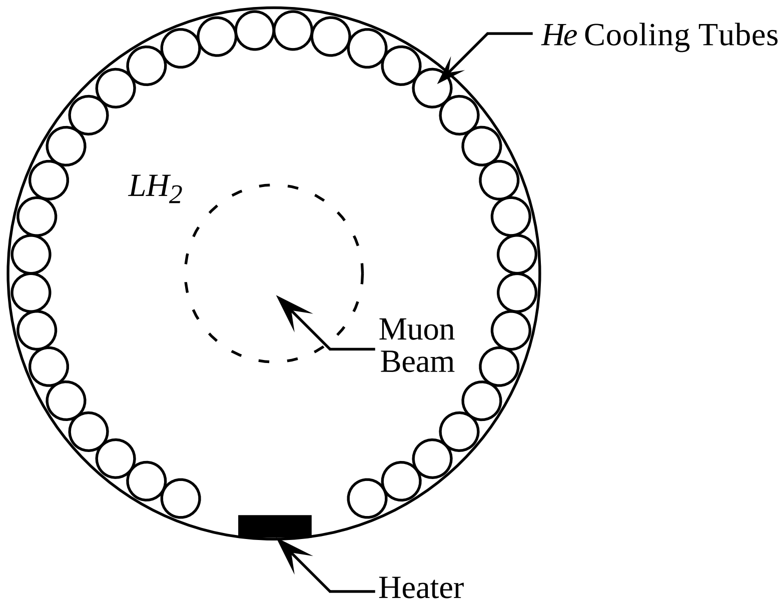
Two approaches under consideration:

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).



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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.

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):

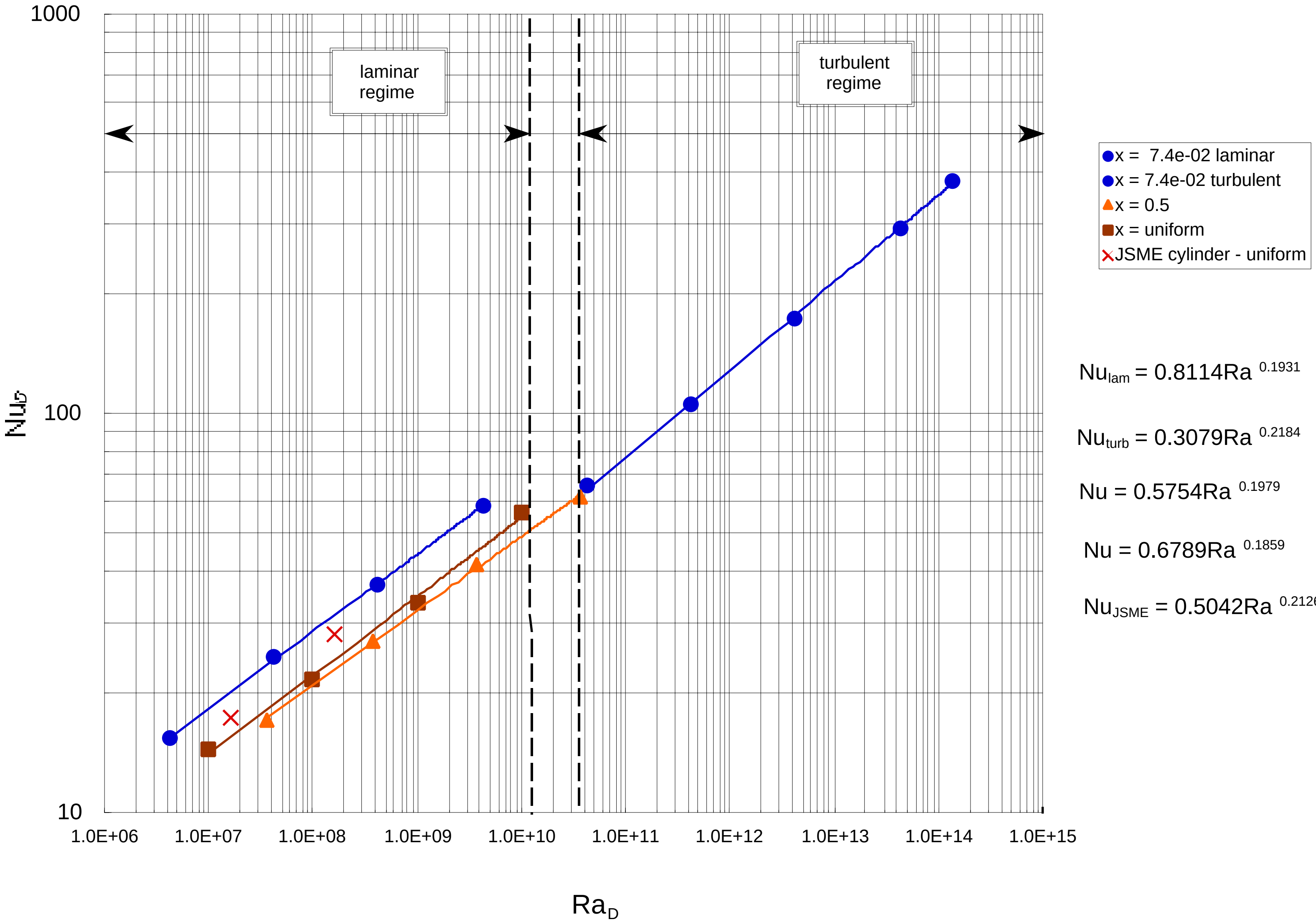
- ✓ Simulate one half of symmetric domain.
- ✓ Steady flow calculations.
- ✓ Heat generation via *steady* Gaussian distribution.
- ✓ Turbulence modeling (RANS) used for $Ra_R \geq 4 \times 10^8$.

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.

FLUENT CFD Results

Average Nusselt Number vs. Rayleigh Number:



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COA 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

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:

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

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

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:

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

Nusselt number:

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

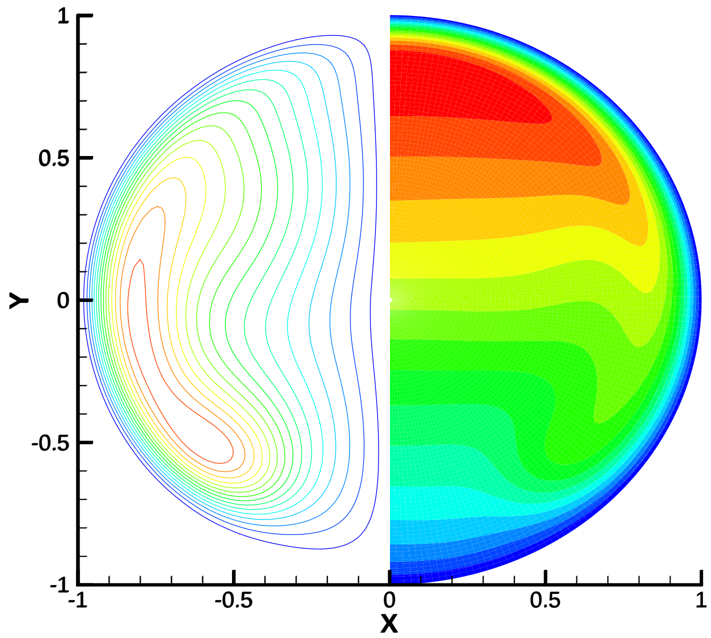
Results – Flow Regimes

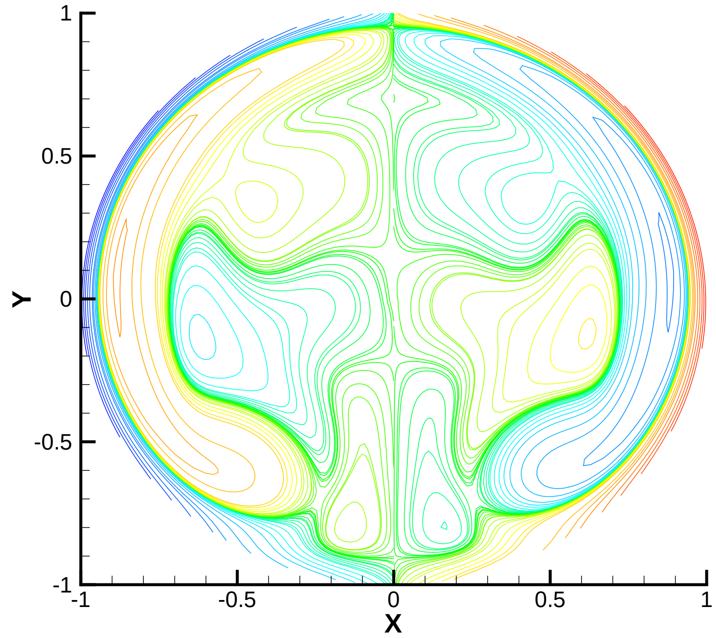
The following flow regimes are observed:

- ☞ 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:

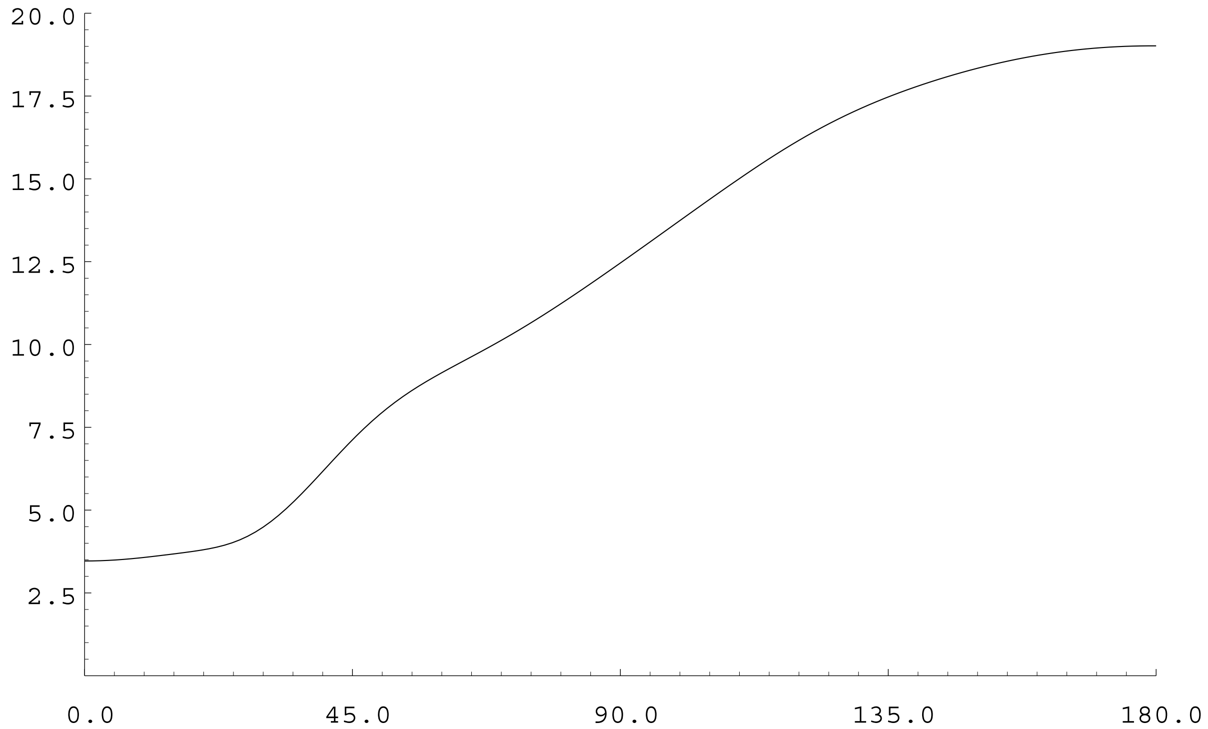




Steady, Symmetric Results (cont'd)

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

Nu vs. θ:



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

Uniform heat generation ($\sigma \to \infty$) 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.* $\bar{N}u_{MB} = 0.7041 \cdot Ra_{MB}^{0.1864}$.

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

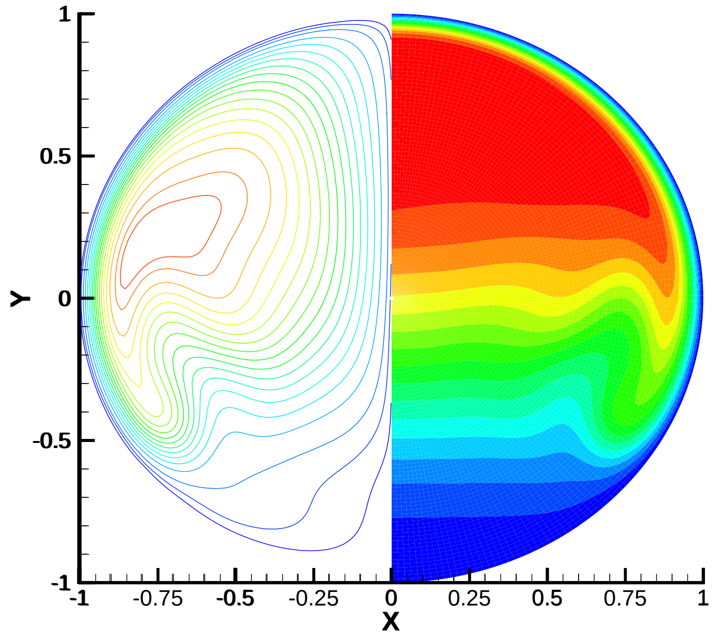
Gaussian heat generation: $\sigma = 0.25$

Ra_R	FLUENT[1]	COA Code
1×10^8	16.4	15.6
1×10^9	25.1	25.4

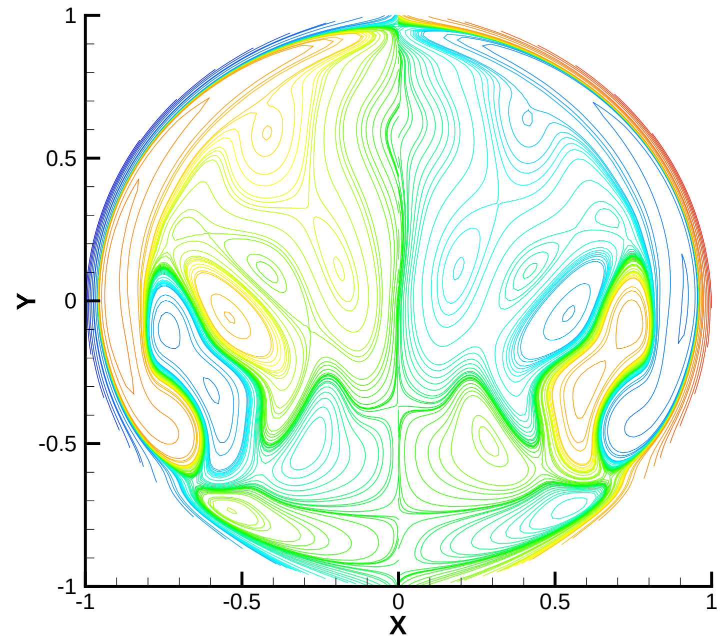
[1] From M. Boghosian's correlation, *i.e.* $\bar{N}u_{MB} = 0.7041 \cdot Ra_{MB}^{0.1852}$.

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

Streamfunction: Temperature:



Vorticity:



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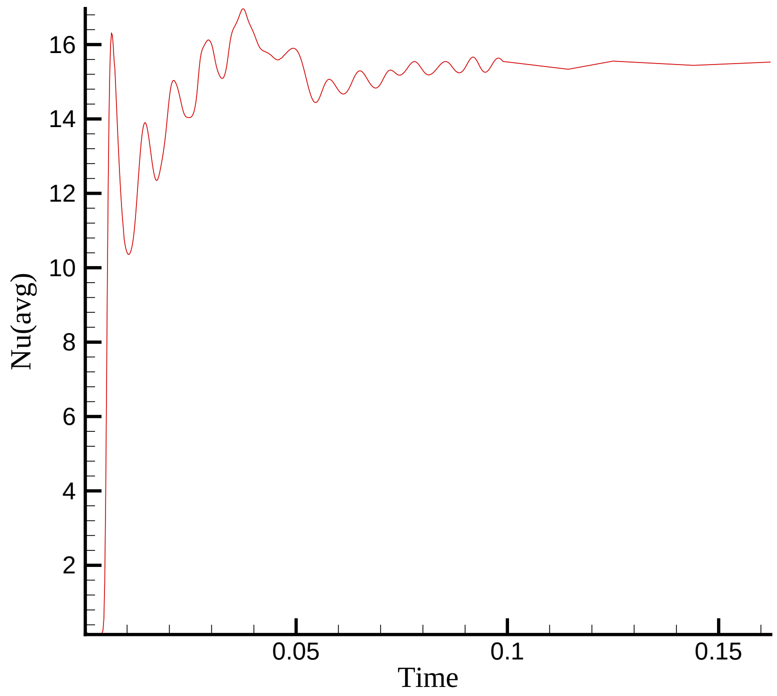
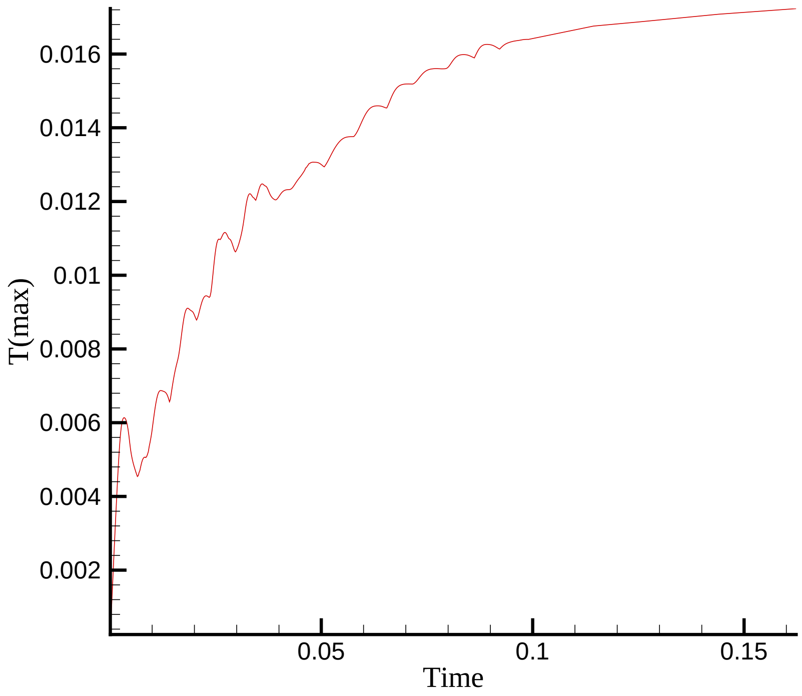
Steady, Symmetric Results: $Ra_R = 1 \times 10^8, \sigma = 0.25$

$\bar{Nu}$ vs. t:



T_{max} vs. t:



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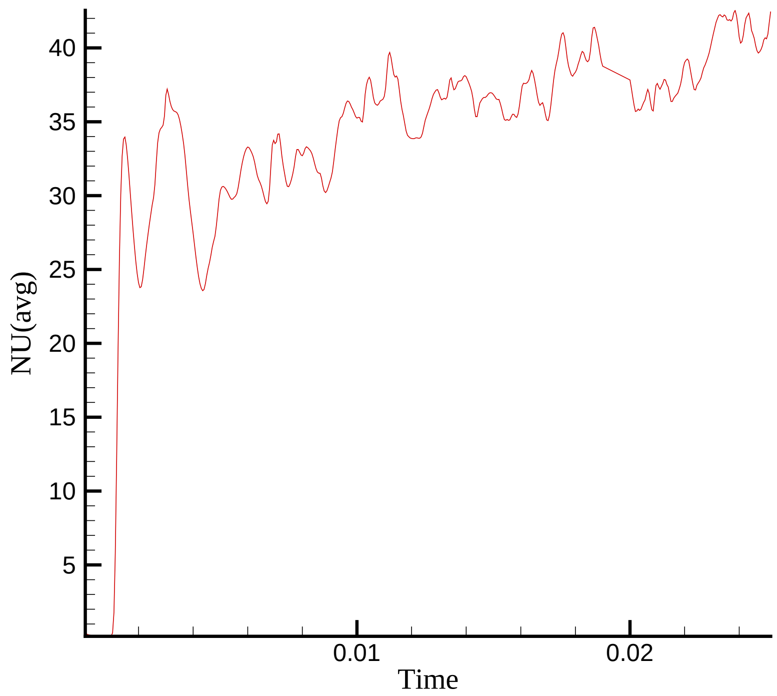
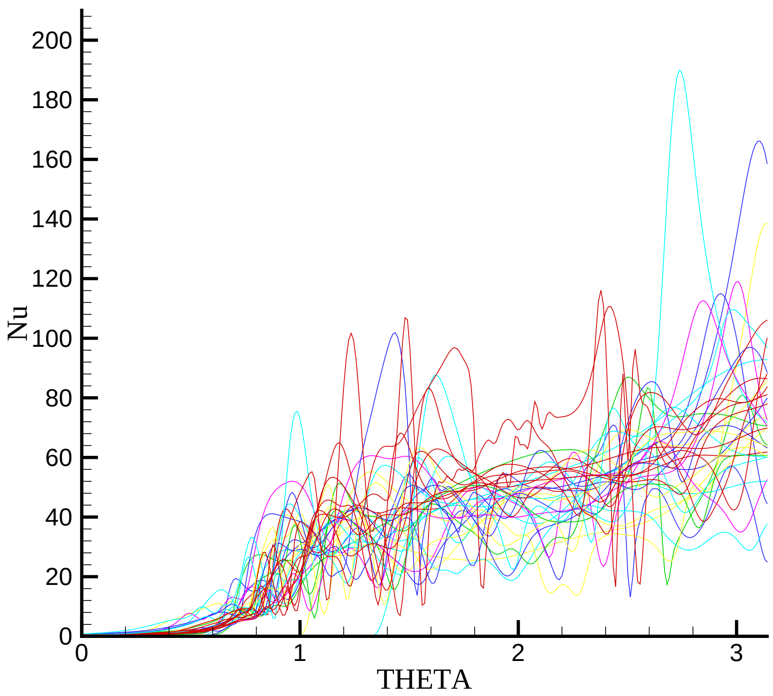
Unsteady, Asymmetric Results: $Ra_R = 1 \times 10^{10}, \sigma = 0.25$

$\bar{Nu}$ vs. t:



Nu vs. θ:



Movies for streamfunction, temperature and vorticity.

Conclusions

- Current COA results compare very well with FLUENT results and limited experimental data.
- Critical Rayleigh number for unsteady, asymmetric behavior is $Ra_R > 1 \times 10^8$.
- No start-up overshoot in temperature at high $Ra \Rightarrow$ Heater not necessary to improve performance of absorber as heat exchanger.

Current and Future Efforts

- Obtain solutions at higher Rayleigh numbers (target $Ra_R \sim 10^{14}$).
- Compare high-Rayleigh number COA solutions (unsteady) with FLUENT results (steady RANS).
- Evaluate influence of σ, *i.e.* ratio of beam size to absorber size, on heat transfer.
- 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.* $\Delta t = 10^{-8}$).