CFD Simulations of Fluid Dynamics and Heat Transfer in Liquid-Hydrogen Absorbers

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Where We Fit In

- Part of the Absorber Group of MuCool and the Neutrino Factory and Muon Collider Collaboration since 1999.
- Collaborating with IIT (Physics), NIU (Physics), Fermi NAL, Argonne NL, KEK Japan and Oxford University.
- Personnel (Mechanical, Materials and Aerospace Engineering Dept.):

Name	Role
Kevin Cassel	Associate Professor
Aleksandr Obabko	Postdoc
Michael Boghosian	M.S. (2001)
Eyad Almasri	M.S. (2003)
Danny Bockenfeld	M.S. (2004)

- Performing CFD analysis required to design strategies for removal of heat from LH_2 absorbers.

Introduction: Approaches to Heat Removal

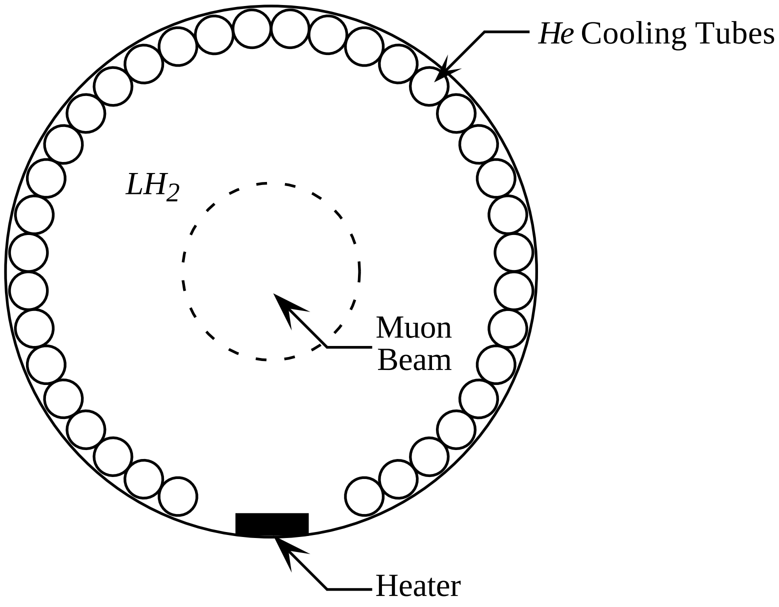
Two approaches under consideration:

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.

$+$ Can apply for large heat load configurations.

$-$ May be difficult to maintain uniform vertical flow through the absorber.

Introduction (cont'd)

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.
- $+$ Conceptually simpler and less expensive to build and maintain than flow-through design.
- $-$ More difficult to ensure against boiling at very high Rayleigh numbers.
- $-$ Can only apply to moderate heat load configurations, i.e. 100s of watts.

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 $Ra_R \geq 4 \times 10^8$.

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.

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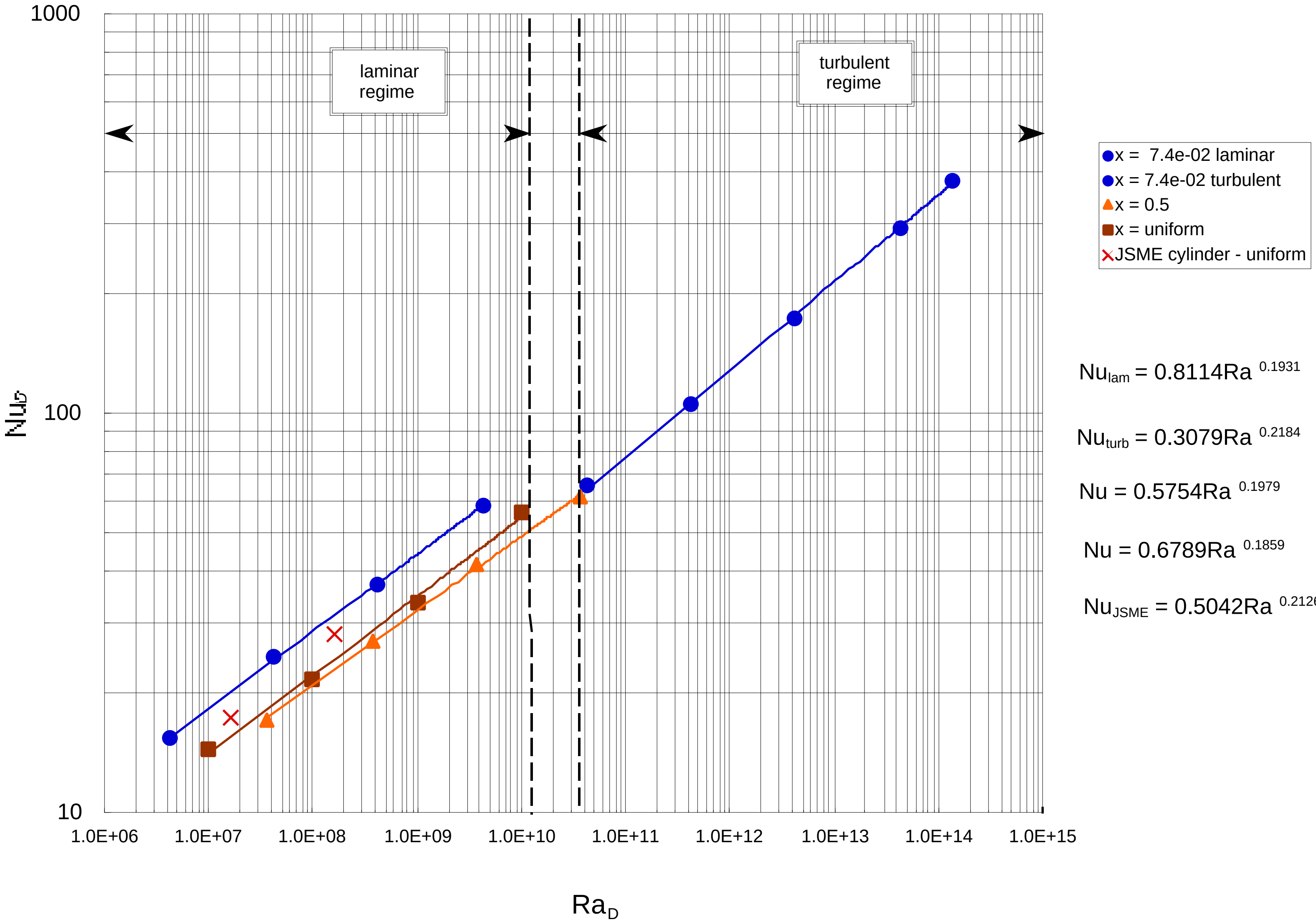
FLUENT CFD Results

Average Nusselt Number vs. Rayleigh Number:



$Nu_{lam} = 0.8114Ra^{0.1931}$

$Nu_{turb} = 0.3079Ra^{0.2184}$

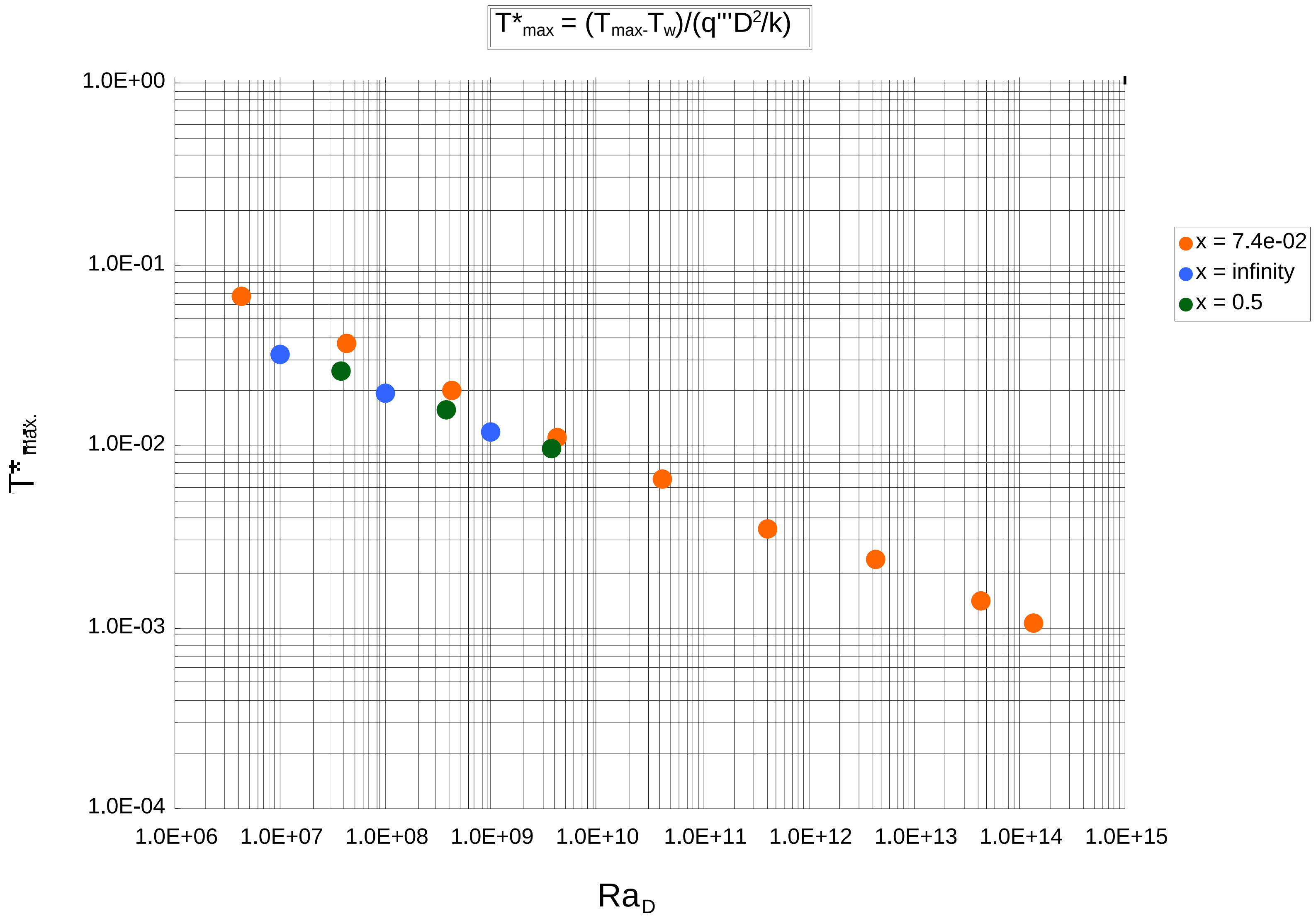
$Nu = 0.5754Ra^{0.1979}$

$Nu = 0.6789Ra^{0.1859}$

$Nu_{JSME} = 0.5042Ra^{0.2126}$

FLUENT CFD Results (cont'd)

Non-Dimensional Maximum Temperature vs. Rayleigh Number:



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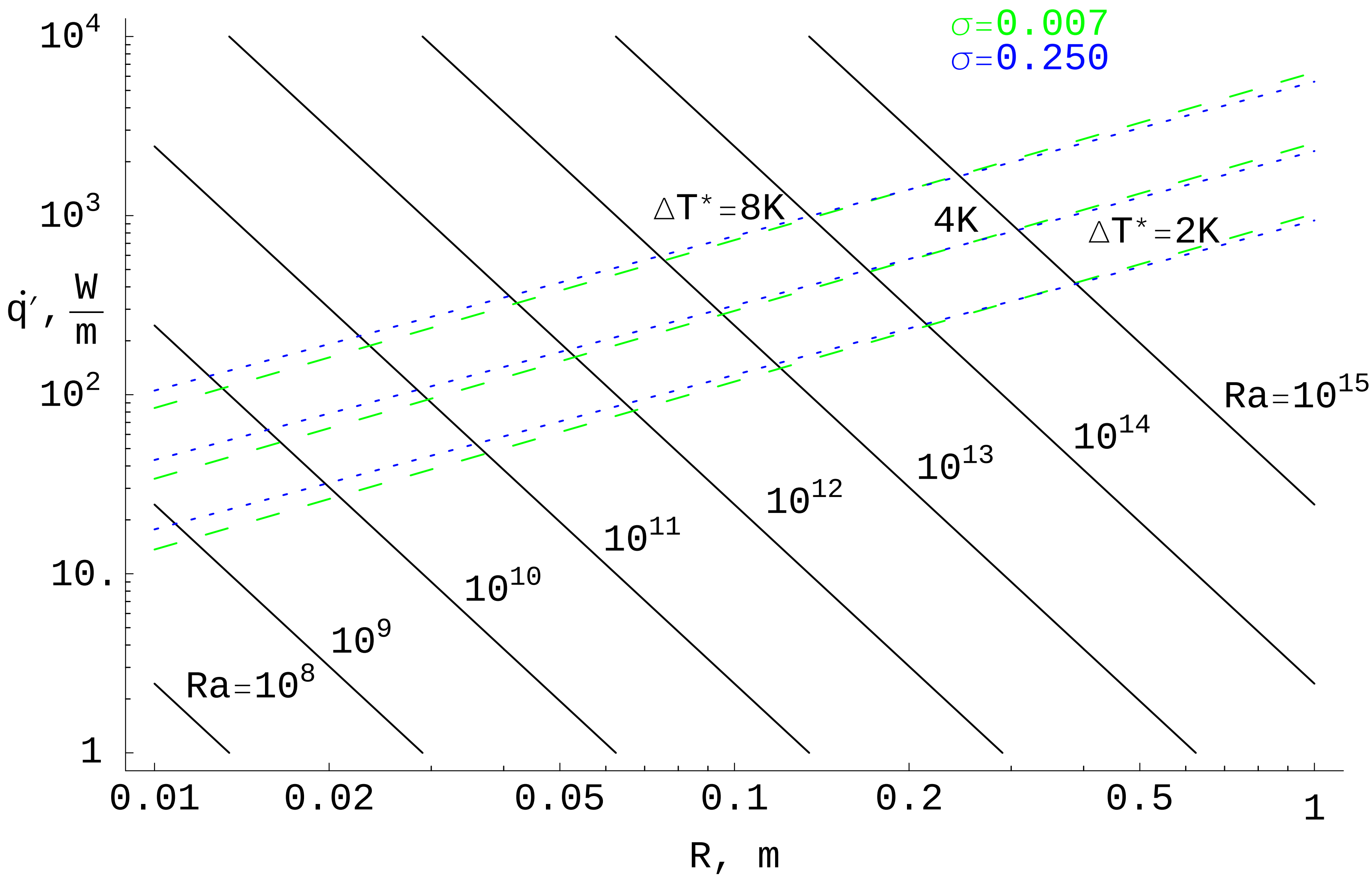
Parameter Map for LH_2



Note: Properties taken at 18 K, 2 atm.

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Sample Heat Exchanger Analysis

Absorber parameters (single-flip lattice):

$$L = 0.3\,\text{m}, \quad R = 0.2\,\text{m}, \quad \dot{q} = 150\,\text{W} \quad \Rightarrow \quad Ra_R = 1.64 \times 10^{14}$$

Heat exchanger parameters (LH_2 and He at 2 atm):

$$\begin{aligned} T_i^* &= 14\text{ K} \\ T_o^* &= 15\text{ K} \\ T_{LH_2}^* &= 18.5\text{ K (from CFD results)} \\ T_{max}^* &= 18.9\text{ K (from CFD results)} \\ h_{He} &= 1{,}580\text{ W}/\text{m}^2\text{K} \\ h_{LH_2} &= 210\text{ W}/\text{m}^2\text{K (from CFD results)} \end{aligned}$$

Results:

Required heat transfer area: $A = 0.20\text{m}^2$

Mass flow rate of He: $\dot{m}_{He} = 0.028$ kg/s (3.9 l/s)

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Accomplishments

- ✓ Proposed convection absorber concept.
- ✓ Provided CFD data as proof-of-concept for convection absorber.
- ✓ Produced CFD data required for heat exchanger analysis of absorber.
- ✓ KEK has built two prototypes of the convection absorber, one of which will be tested at Fermi this summer.
- ✓ Graduated/ing three M.S. students.
- ✓ Papers and presentations:

  Papers:

  M. M. ALSHARO'A *et al.* , "Recent Progress in Neutrino Factory and Muon Collider Research within the Muon Collaboration," *Physical Review Special Topics – Accelerators and Beams*, (2003), Vol. **6**, pp. 081001-1–52.

  D. M. KAPLAN, E. L. BLACK, K. W. CASSEL AND M. A. CUMMINGS, "Energy Absorber R&D," *Nuclear Instruments and Methods in Physics Research, Section A* (2001), Vol. **472**, pp. 632–638.

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Accomplishments

A. V. OBABKO, E. A. ALMASRI AND K. W. CASSEL "Unsteady Natural Convection in a Horizontal Cylinder with Internal Heat Generation," *Proceedings of the 2003 ASME Fluids Engineering Division Summer Meeting*, Honolulu, Hawaii, July 6–10, 2003.

R. P. JOHNSON *et al.* , "Gaseous Hydrogen and Muon Accelerators," *AIP Conference Proceedings* (2003), Vol. **671**, Issue 1, pp. 328-336.

M. A. CUMMINGS *et al.* , "Current LH_2 Absorber R&D in MuCool," *Proceedings of the NuFact '02 Workshop*, London, England, July 1–6, 2002.

D. M. KAPLAN *et al.* , "Progress in Energy Absorber R&D 2: Windows," *Proceedings of the 2001 Particle Accelerator Conference*, Chicago, Illinois, June 18–22, 2001.

S. ISHIMOTO *et al.* , "Convection-Type LH_2 Absorber R&D for Muon Ionization Cooling," *Proceedings of the NuFact '01 Workshop*, Tsukuba, Japan, May 24–29, 2001.

D. M. KAPLAN *et al.* , "Progress in Absorber R&D for Muon Cooling," *Proceedings of the NuFact '01 Workshop*, Tsukuba, Japan, May 24–29, 2001.

D. M. KAPLAN, E. L. BLACK, K. W. CASSEL AND M. A. CUMMINGS, "Energy Absorber R&D," *Proceedings of the NuFact '00 Workshop*, Monterey, California, May 22–26, 2000.

Accomplishments

Presentations:

K. W. CASSEL AND D. BOCKENFELD, "Absorber Simulations Update" Absorber Review Meeting, Fermi National Accelerator Laboratory, Batavia, Illinois, May 17, 2004.

K. W. CASSEL, A. V. OBABKO AND E. A. ALMASRI, "Symmetry-Breaking Instability in Natural Convection Flow with Internal Heat Generation," 56^{th} Annual Meeting of the Division of Fluid Dynamics of the American Physical Society, Meadowlands, New Jersey, November 23–25, 2003.

K. W. CASSEL,"Unsteady Phenomena in High-Reynolds-Number and Rayleigh-Number Flows," Department of Mathematics, University of Manchester, July 29, 2003 (Invited Seminar).

K. W. CASSEL,"Unsteady Phenomena in High-Reynolds-Number and Rayleigh-Number Flows," Department of Mathematics, Imperial College London, July 25, 2003 (Invited Seminar).

K. W. CASSEL,"Unsteady Phenomena in High-Reynolds-Number and Rayleigh-Number Flows," Department of Mathematics, University College London, July 24, 2003 (Invited Seminar).

K. W. CASSEL,"Unsteady Phenomena in High-Reynolds-Number and Rayleigh-Number Flows," Department of Applied Mathematics and Theoretical Physics, Cambridge University, July 21, 2003 (Invited Seminar).

Accomplishments

A. V. OBABKO, K. W. CASSEL AND E. A. ALMASRI, "LH_2 Absorbers – Simulations and Proposed Flow Test" Absorber Review Meeting, Fermi National Accelerator Laboratory, Batavia, Illinois, February 21-22, 2003.

R. E. HARTLINE *et al.* , "Construction, Operation and Safety of the High-Pressure RF Test Cell to be used in Lab G," Muons, Inc. Note-001, December 2002.

K. W. CASSEL, E. A. ALMASRI AND A. V. OBABKO, "Natural Convection in a Horizontal Cylinder with Internal Heat Generation," 55^{th} Annual Meeting of the Division of Fluid Dynamics of the American Physical Society, Dallas, Texas, November 24–26, 2002.

K. W. CASSEL, A. V. OBABKO AND E. A. ALMASRI, "Simulations of Fluid Dynamics and Heat Transfer in LH_2 Absorbers," MuCool/MICE Collaboration Meeting, Lawrence Berkeley National Laboratory, Berkeley, California, October 22-26, 2002.

K. W. CASSEL, A. V. OBABKO AND E. A. ALMASRI, "Simulations of Fluid Dynamics and Heat Transfer in LH_2 Absorbers," Absorber Review Meeting, Fermi National Accelerator Laboratory, Batavia, Illinois, August 12-13, 2002.

M. M. ALSHARO'A, *et al.* "Status of Neutrino Factory and Muon Collider Research and Development and Future Plans," Neutrino Factory and Muon Collider Collaboration Report, May 2002.

Accomplishments

K. W. Cassel, M. E. Boghosian, A. V. Obabko and E. A. Almasri, "Computational Simulations of Liquid-Hydrogen Absorbers," MuCool/MICE Collaboration Meeting, Illinois Institute of Technology and Fermi National Accelerator Laboratory, Chicago, Illinois, February 5-8, 2002.

K. W. Cassel, M. E. Boghosian, E. A. Almasri, S. Ishimoto and K. Yoshimura, "Natural-Convection Liquid-Hydrogen Absorber R&D," Absorber Review Meeting, Illinois Institute of Technology, Chicago, Illinois, September 26, 2001.

K. W. Cassel, M. E. Boghosian and E. A. Almasri, "CFD of Liquid Hydrogen Absorbers," Absorber Review Meeting, Northern Illinois University, DeKalb, Illinois, March 15, 2001.

M. A. Cummings, D. M. Kaplan, E. L. Black and K. W. Cassel, "LH_2 Absorber R&D at Fermilab," Neutrino Factory and Muon Collider Collaboration Meeting, Brookhaven National Laboratory, Brookhaven, New York, February 1–2, 2001.

K. W. Cassel, "A Novel Approach to LH_2 Absorber Design," Absorber Review Meeting, Fermi National Accelerator Laboratory, Batavia, Illinois, August 9, 2000.

D. M. Kaplan, E. L. Black, K. W. Cassel, M. E. Boghosian and M. A. Cummings, "LH_2 Absorber Design Status," Neutrino Factory and Muon Collider Collaboration Meeting, Avalon, Catalina Island, California, May 17–19, 2000.

Accomplishments

D. M. Kaplan, E. L. Black, K. W. Cassel, M. E. Boghosian and M. A. Cummings, "LH_2 Absorber Design Status," Neutrino Factory and Muon Collider Collaboration Meeting, Lawrence Berkeley National Laboratory, Berkeley, California, December 13–15, 1999.

K. W. Cassel and M. E. Boghosian, "Liquid-Hydrogen Absorber: Fluid Dynamics and Heat Transfer Issues," MuCool Collaboration Meeting, Fermi National Accelerator Laboratory, Batavia, Illinois, November 11–12, 1999.

K. W. Cassel and M. E. Boghosian, "Liquid-Hydrogen Absorber Design for the Muon Cooling Experiment at Fermilab: Absorber as Heat Exchanger," MuCool Meeting, Fermi National Accelerator Laboratory, September 3, 1999.