

Numerical Simulation Modeling of Transport Phenomena in Zero Boil-Off Cryogenic Storage Systems

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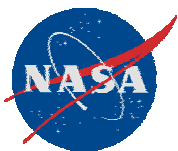
University of South Florida

Graduate Students:

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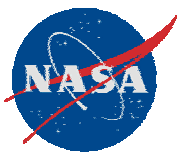
Start Date = June 1, 2002

Planned Completion = December 31, 2006



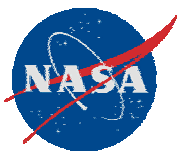
Research Goals and Objectives

- **Problem Addressed:**
 - A working numerical simulation model is needed to efficiently design future zero boil-off (ZBO) cryogenic storage systems for NASA applications.
- **Solution:**
 - Developing a finite element based numerical simulation model for fluid flow and heat transfer in zero boil-off cryogenic storage systems.
- **Innovation:**
 - A practical numerical prediction tool for thermo-fluid behavior within a cryogenic storage tank.



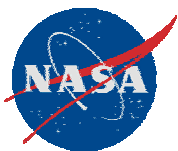
Relevance to Current State-of-the-Art

- Design of cryogenic storage tanks for space and automotive applications.
- Optimization of operation of active boil-off control systems under different operating conditions.
- Establishment of methodology of using numerical simulation modeling by means of Computational Fluid Dynamics (CFD) in designing industrial equipment and processes.



Relevance to NASA

- **With passive storage, the storage tank size and insulation weight increase with days in orbit, whereas in the ZBO storage system mass remains constant.**
- **A validated modeling and simulation tool will be needed to support ongoing experimental studies at NASA.**
- **The code will help the design of future experiments and mission applications.**
- **The ZBO concept and the computer model can be used for storage vessel design for any liquid hydrogen storage and transportation.**



Budget, Schedule and Deliverables

- **Budget & Schedule**

Year 1 (June 2002 – June 2003): \$ 91,278

- *Developed Basic Numerical Simulation Model – Single Phase (Liquid).*

Year 2 (July 2003 – December 2004): \$85,069

- *Advanced Model for Two Phase (Liquid and Vapor) in the Tank.*

Year 3 (January 2005 – December 2005): \$ 90,000

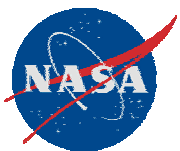
- *Developed Three-Dimensional Simulation Model for the Storage Tank.*

Year 4 (Proposed, January 2006 – December 2006): \$90,000

- *Advancements for Transient Heat Transfer under Periodic Heat Loads.*
- *Development of Post-Processing Programs (MATLAB-based) for Converting Massive CFD Results into a Ready-to-Use Engineering Tool.*

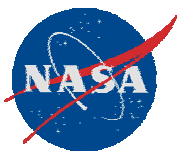
- **Deliverables**

- *Technical Reports.*
- *Computer Simulation Programs (in electronic files).*



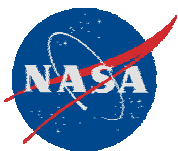
Anticipated Technology End Use

- **Effective storage technology for liquid hydrogen as fuel for space applications and for general transportation.**
- **Extension to storage technology for other liquefied gases (LO_2 , LN_2 , natural gas...) used in industry.**
- **Methodology of modeling fluid flow and heat and mass transfer phenomena in liquefied-gas storage systems.**
- **Optimize structural design based on pressure simulation.**

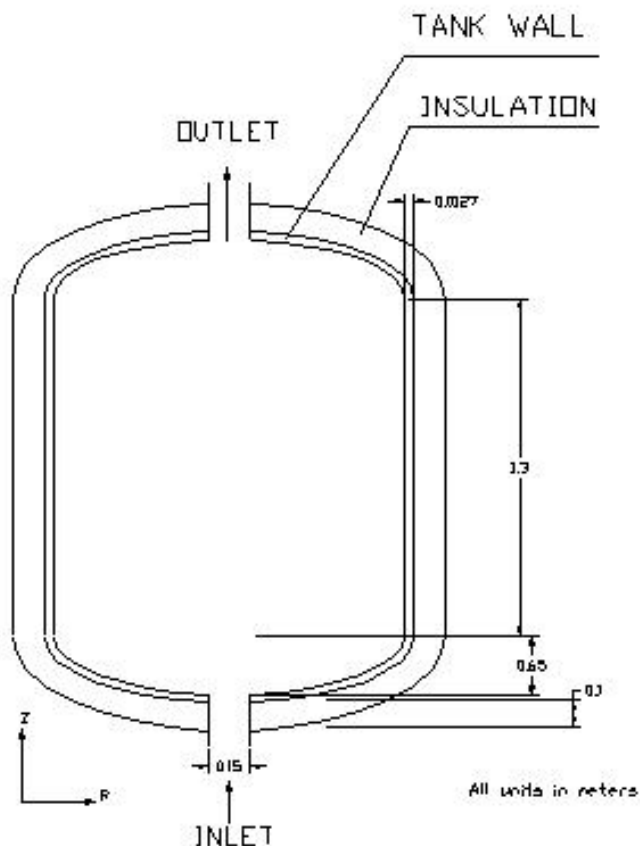


Accomplishments To Date

- Enhancement of fluid mixing within the tank by using liquid spray.
 - *Analysis for completely filled tank, various inlet opening shapes.*
 - *Analysis for partially filled (liquid + vapor) tank.*
 - *Analysis for completely filled tank with axial spraying nozzle.*
- Analysis for heat dissipation to the cryo-cooler using a heat pipe.
 - *Analysis for nitrogen storage in a spherical vessel.*
 - *Analysis for hydrogen storage in a cylindrical vessel with elliptical top and bottom with array of nozzles using axi-symmetric model.*
 - *Analysis for hydrogen storage in a cylindrical vessel with elliptical top and bottom with single nozzle using three-dimensional model.*
- Comparison with NASA experimental data.
- Four technical papers published.

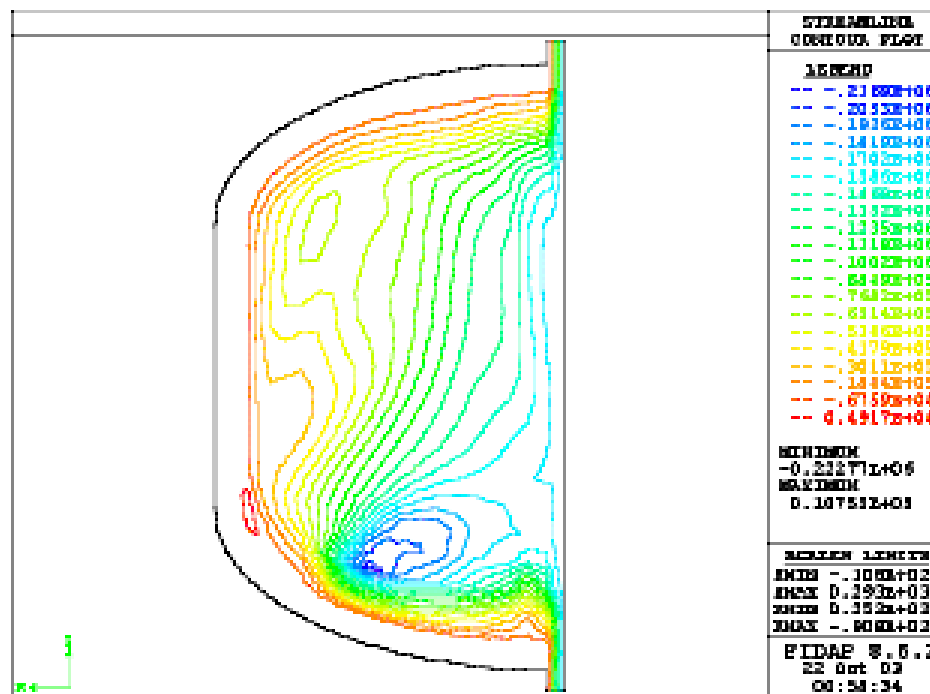


LH2 Completely Filled Tank – Single Phase Analysis

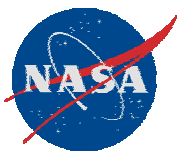


Schematic of LH2 filled tank.

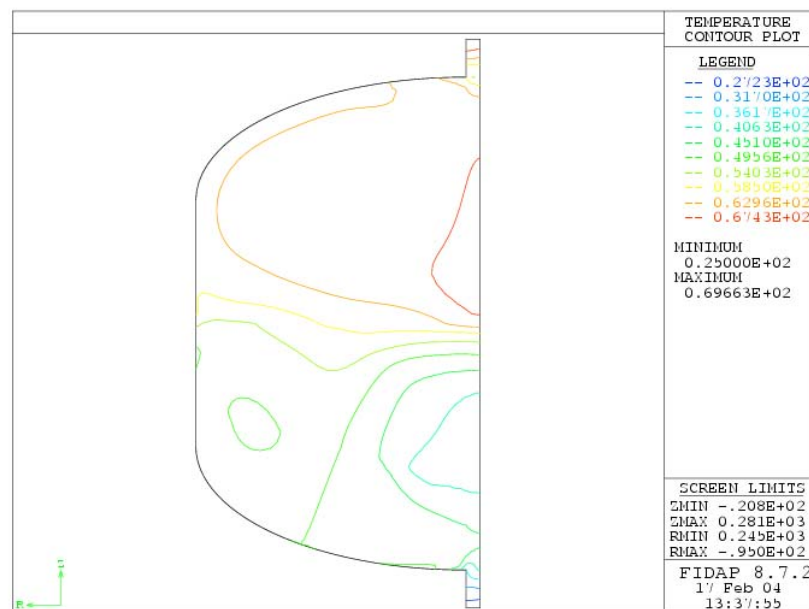
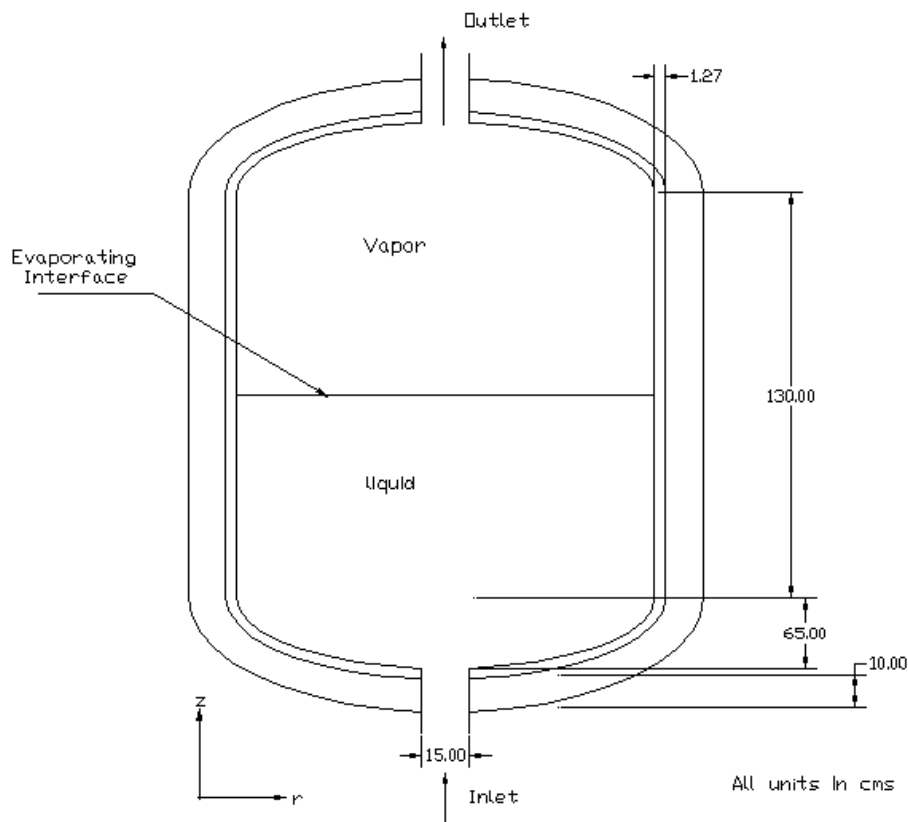
– Cold fluid from inlet continuously replaced heated up fluid inside the tank.



Numerical solution – Streamlines



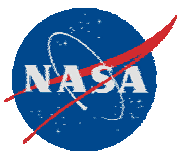
LH2 Partially Filled Tank – Two Phase Analysis



**Numerical solution –
Temperature distribution**

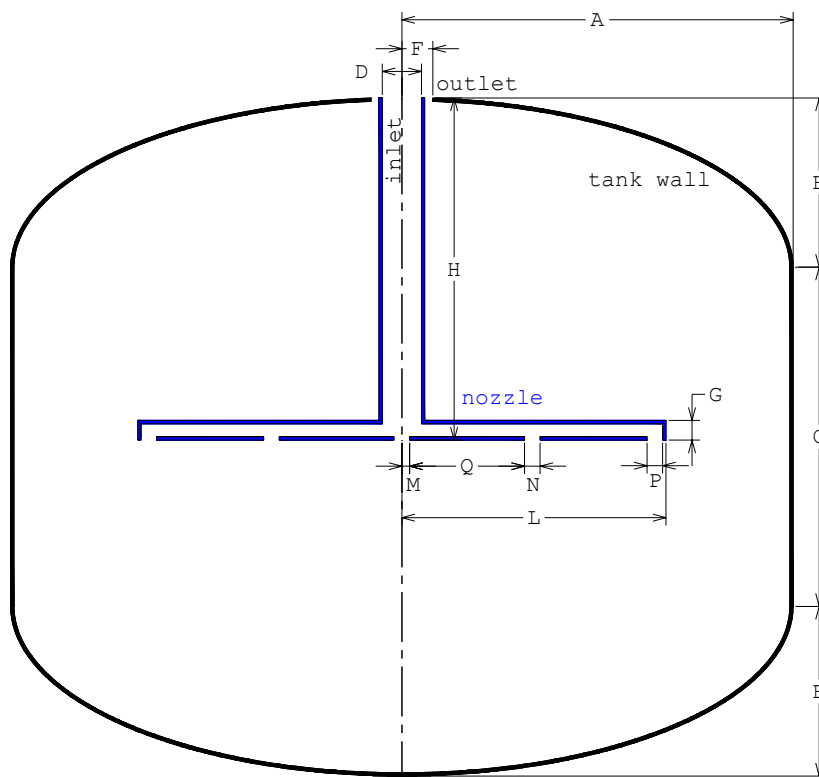
Schematic of LH2 tank, two phase.

– Cold fluid from inlet continuously replaced heated up fluid inside the tank.

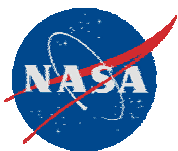


LH2 Tank with Axial Spray Nozzle - Model

Varying Dimensions	
D	0.10 m
	0.15 m
	0.20 m
H	0.80 m
	1.30 m
	1.80 m
L	0.90 m
	1.00 m
	1.20 m
	1.30 m



Constant Dimensions	
A	1.50 m
B	0.65 m
C	1.30 m
G	0.05 m
M	0.01 m
N	0.02 m
P	0.02 m

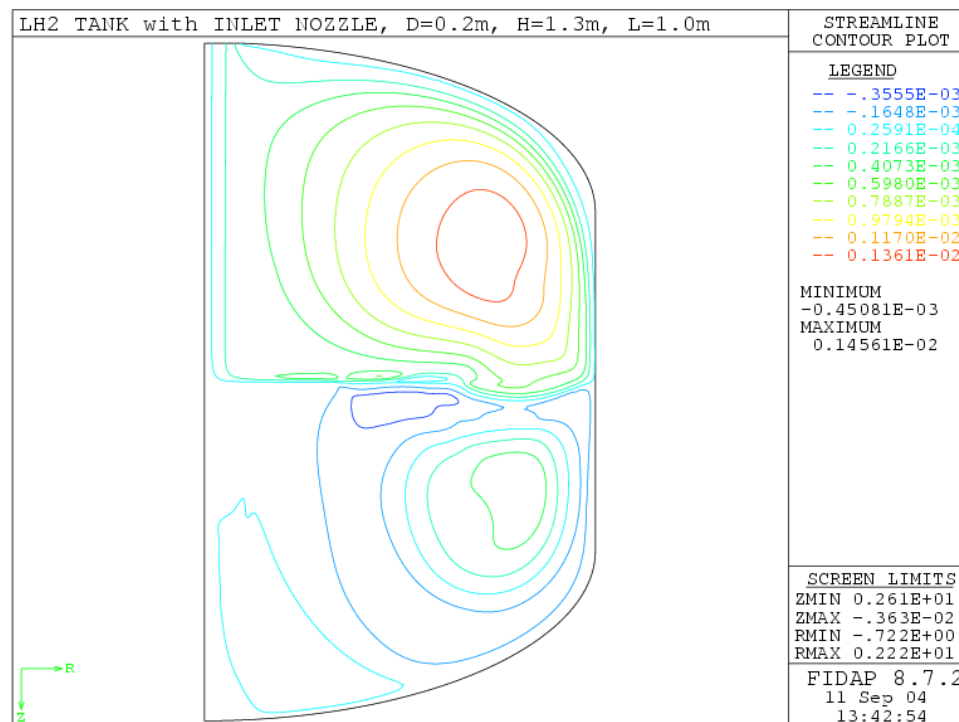


LH2 Tank with Spray Nozzle – Simulation

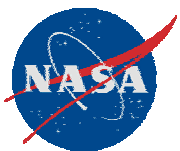
• $V_{\text{inlet}} = 0.01 \text{ m/s}$

• $T_{\text{inlet}} = 15 \text{ K}$

D	0.20 m
H	1.30 m
L	1.00 m

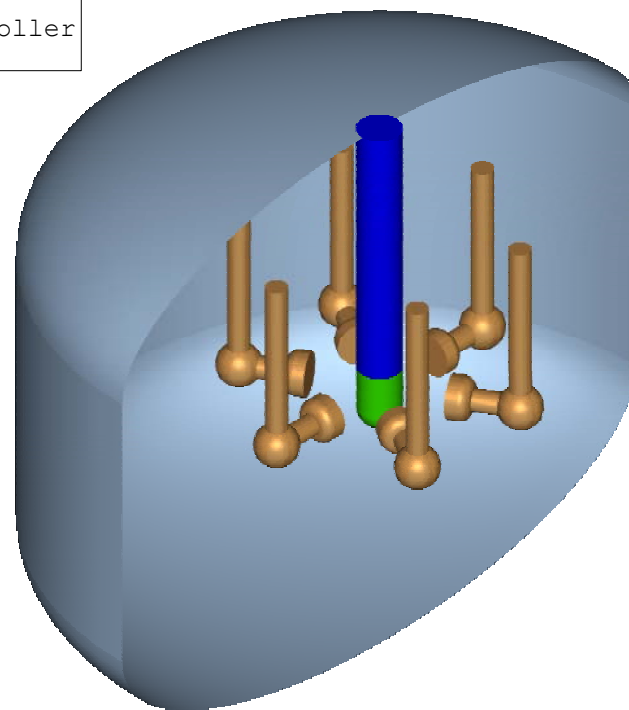
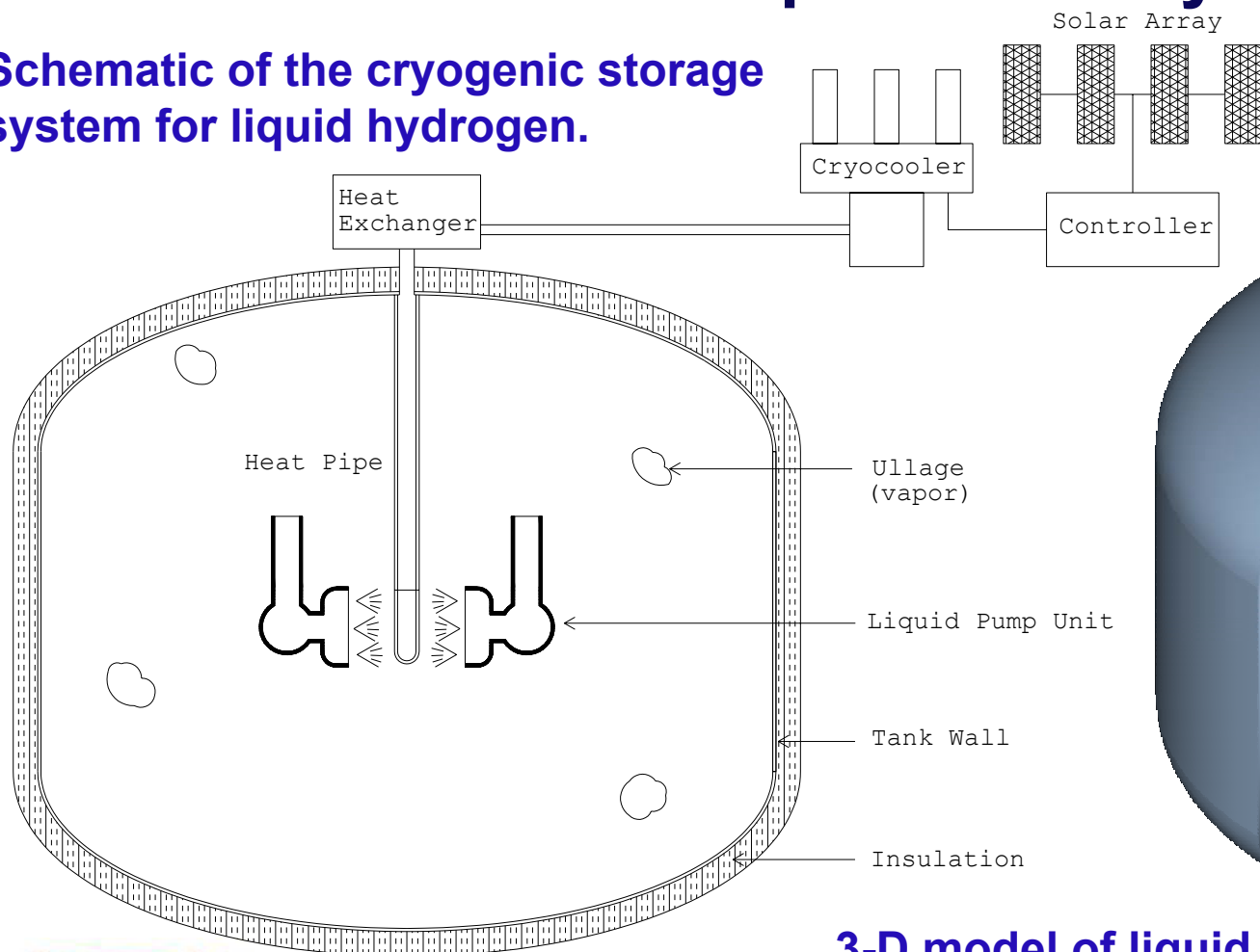


Numerical solution – Streamlines

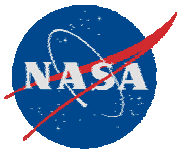


Tank with Heat Pipe and Array of Nozzles

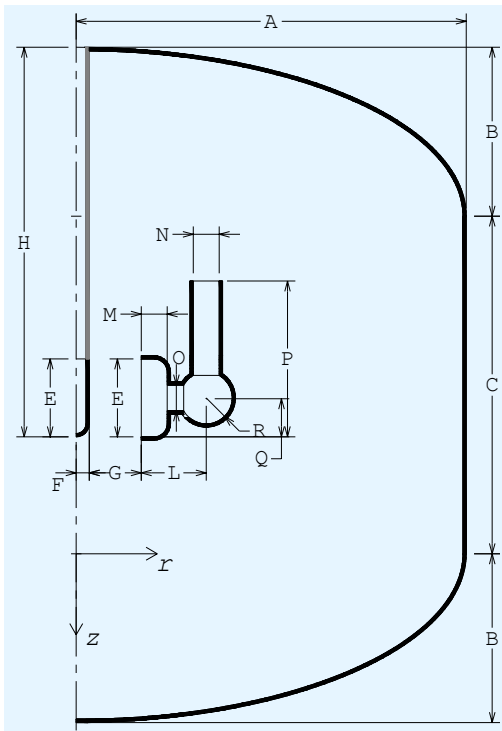
Schematic of the cryogenic storage system for liquid hydrogen.



3-D model of liquid hydrogen tank with heat pipe and array of pump-nozzle units.



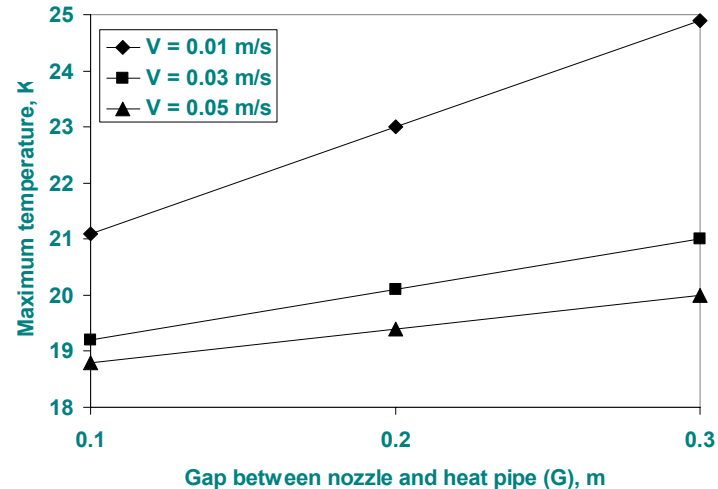
Axi-symmetric Model – Parametric Study



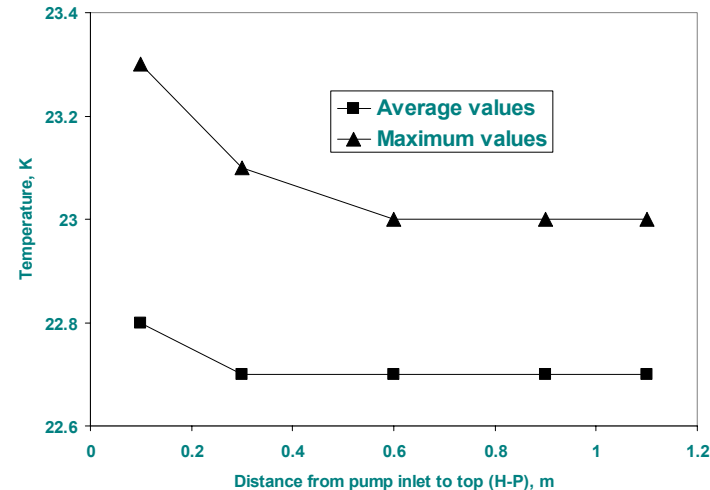
Geometric Parameters.

For better cooling:

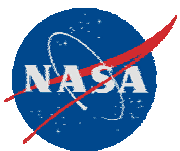
- Increase fluid speed at nozzle
- Decrease gap between nozzle and heat pipe
- Increase distance from top of tank to inlet of pump



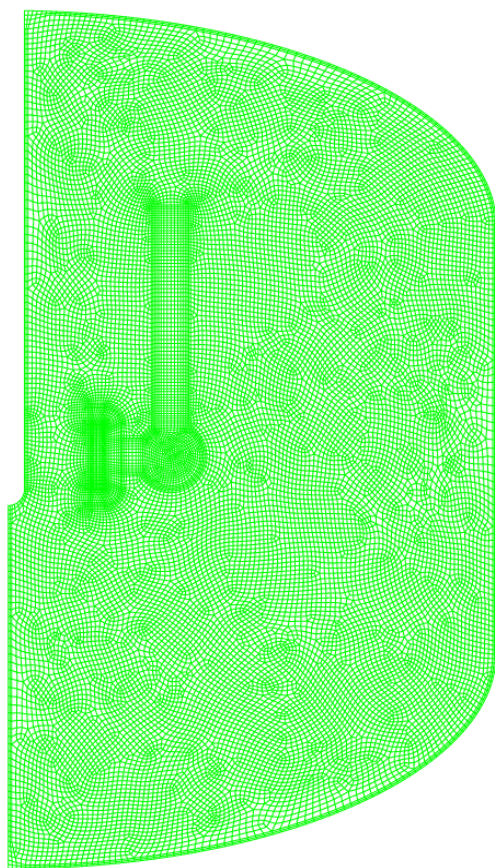
Effect of spraying gap between nozzle and heat pipe.



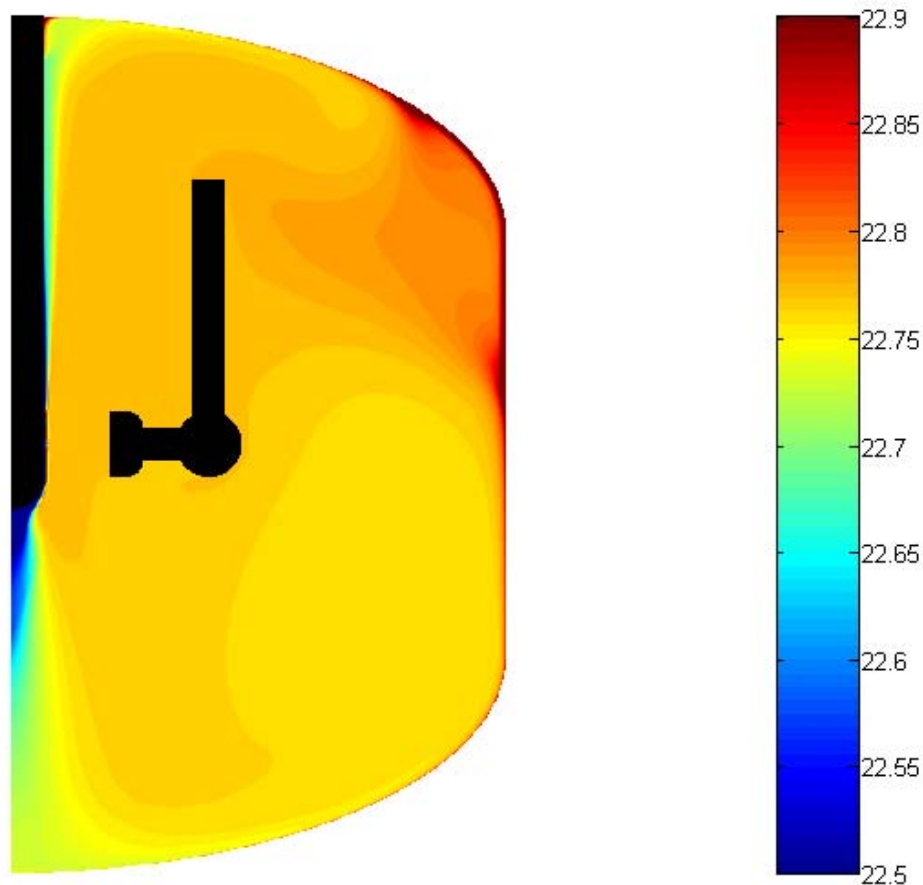
Effect of distance from inlet location to top of tank.



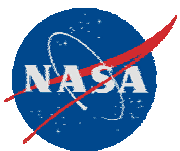
Axi-symmetric Model – Numerical Solution



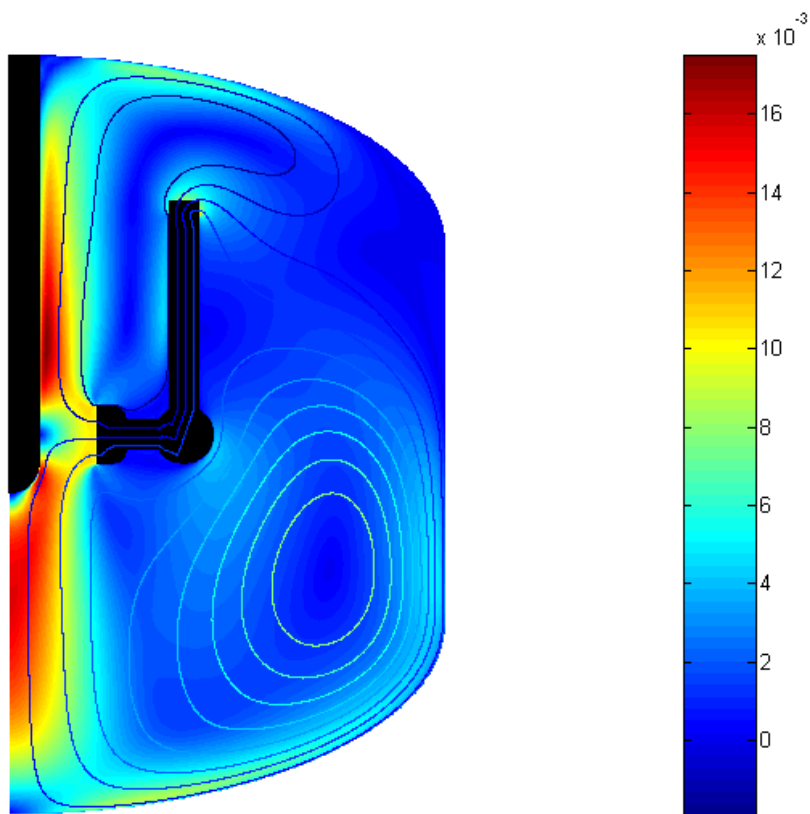
Mesh



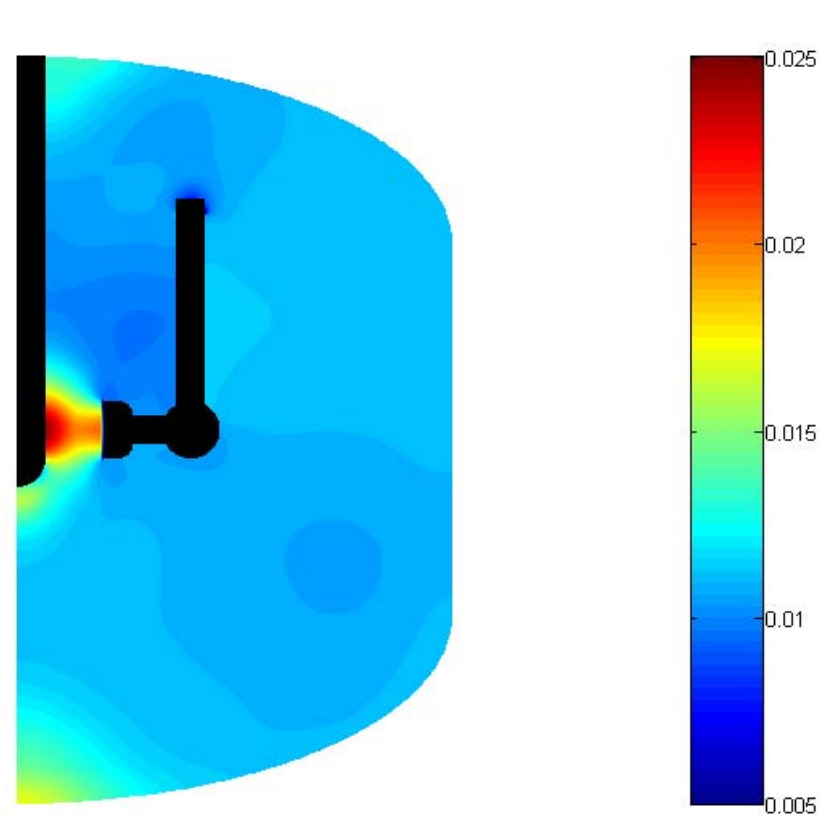
Temperature distribution



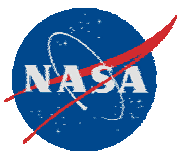
Axi-symmetric Model – Numerical Solution



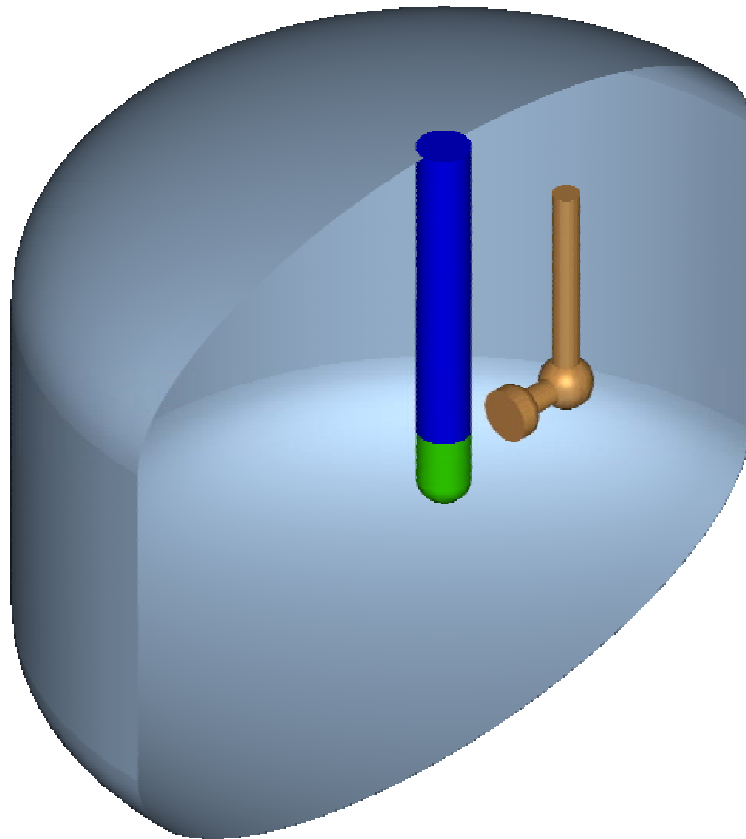
Streamlines/Speed distribution



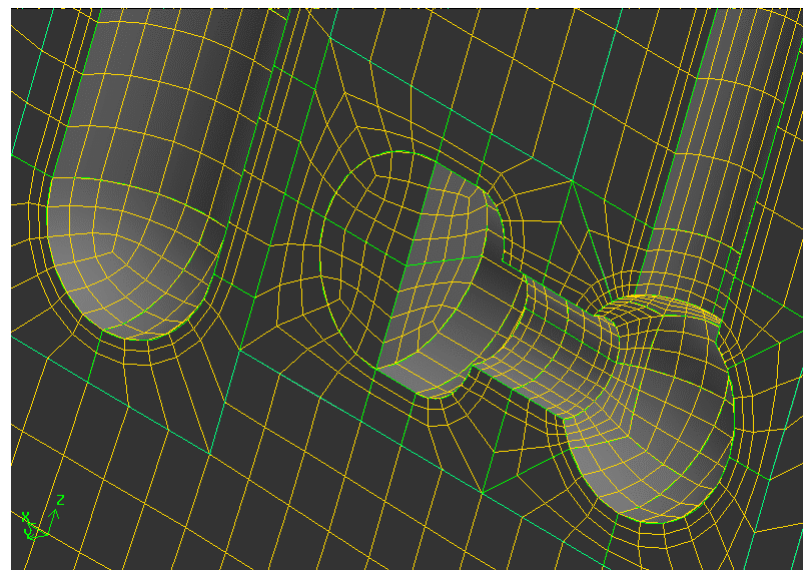
Pressure distribution



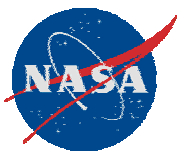
LH2 Tank with Heat Pipe & Single Nozzle – 3-D Model



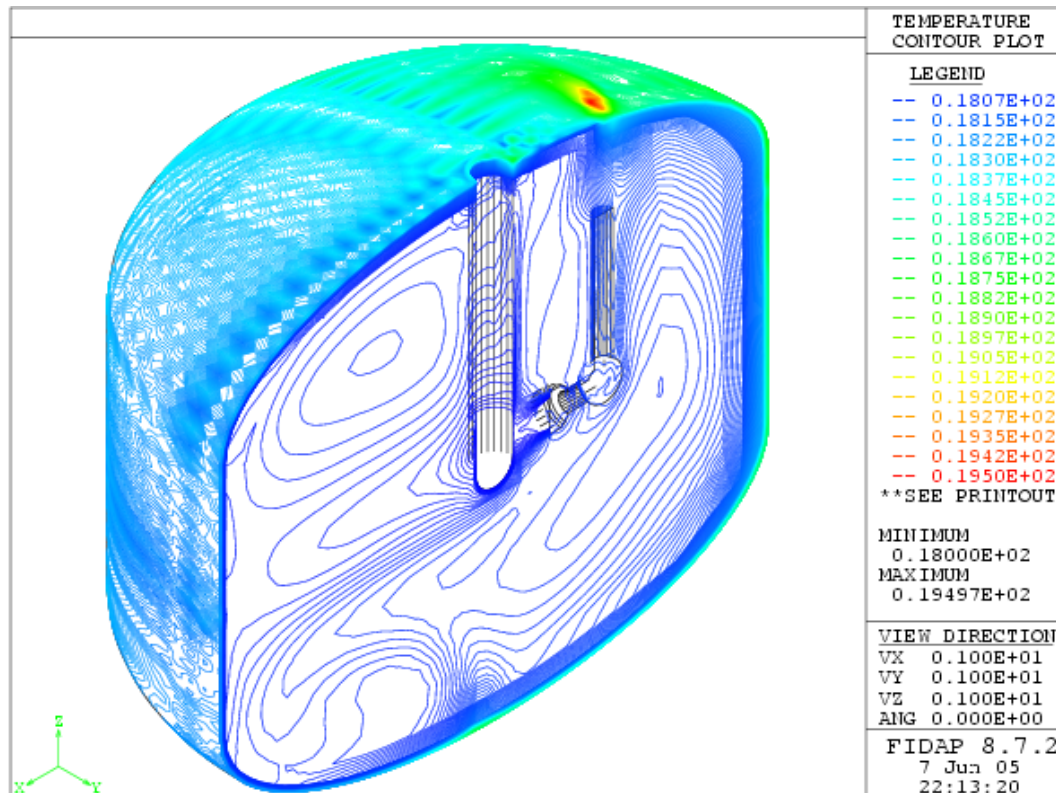
**3-D model of LH2 tank with heat pipe
& single pump-nozzle unit**



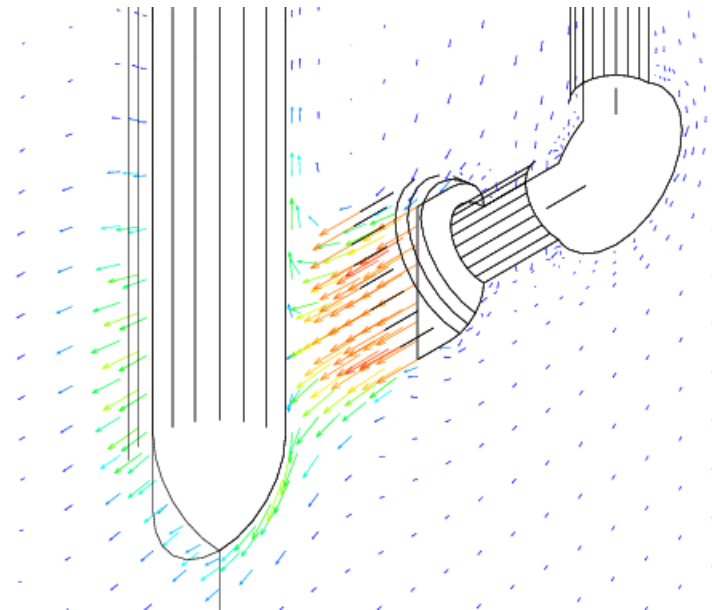
**3-D hexahedral-element mesh,
focused on pump-nozzle and heat pipe.**



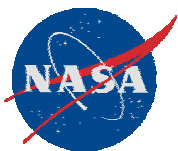
3-D Model – Numerical Solution



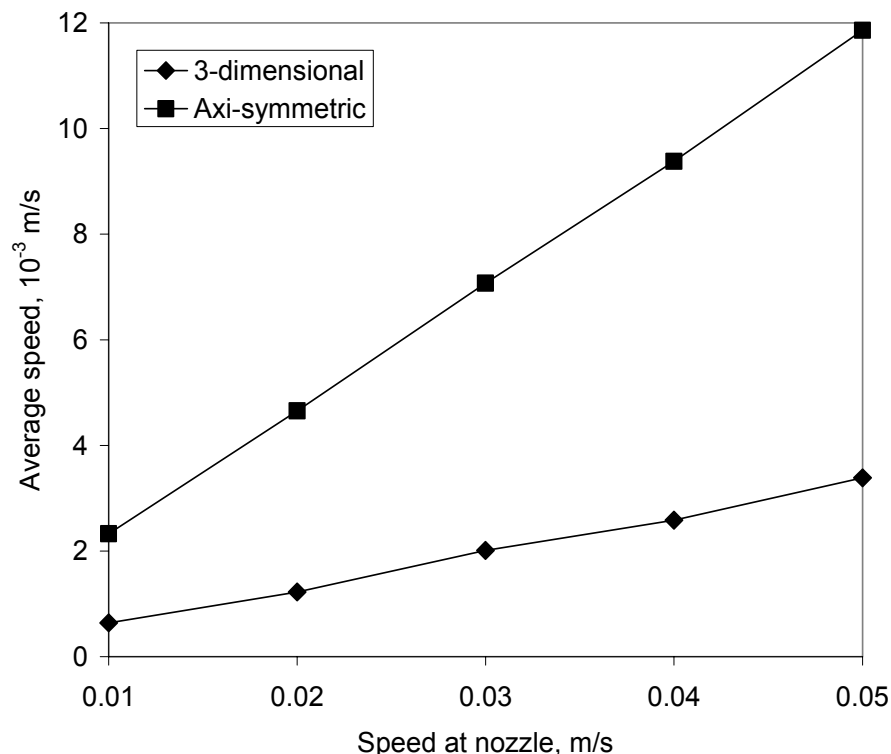
Temperature distribution



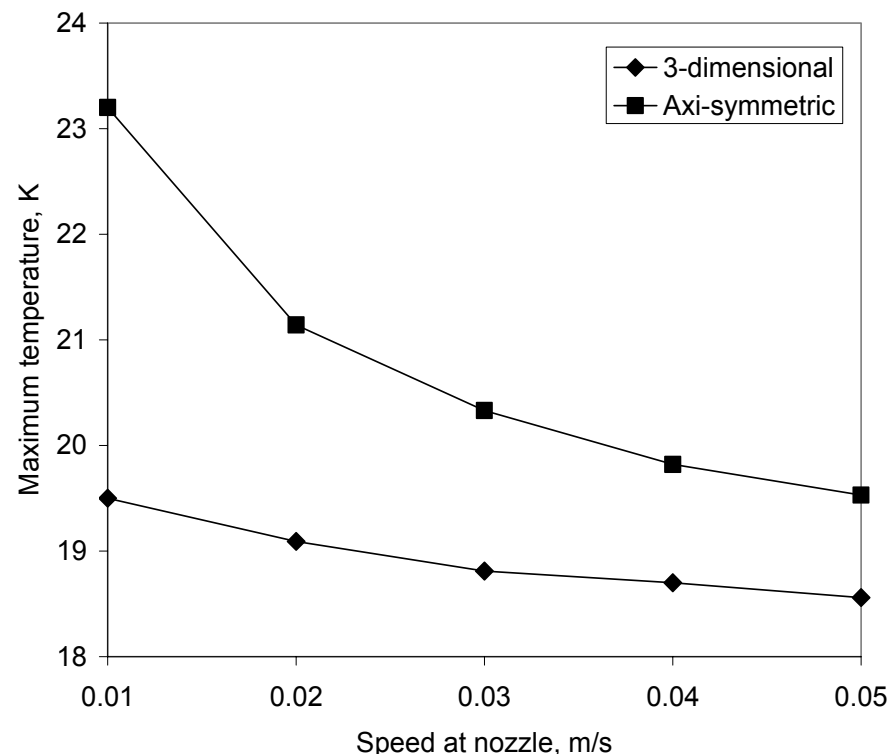
Velocity field, focused on pump-nozzle and heat pipe



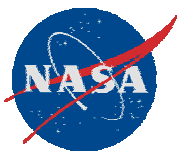
3-D Model & Axi-symmetric Model, Parametric Study



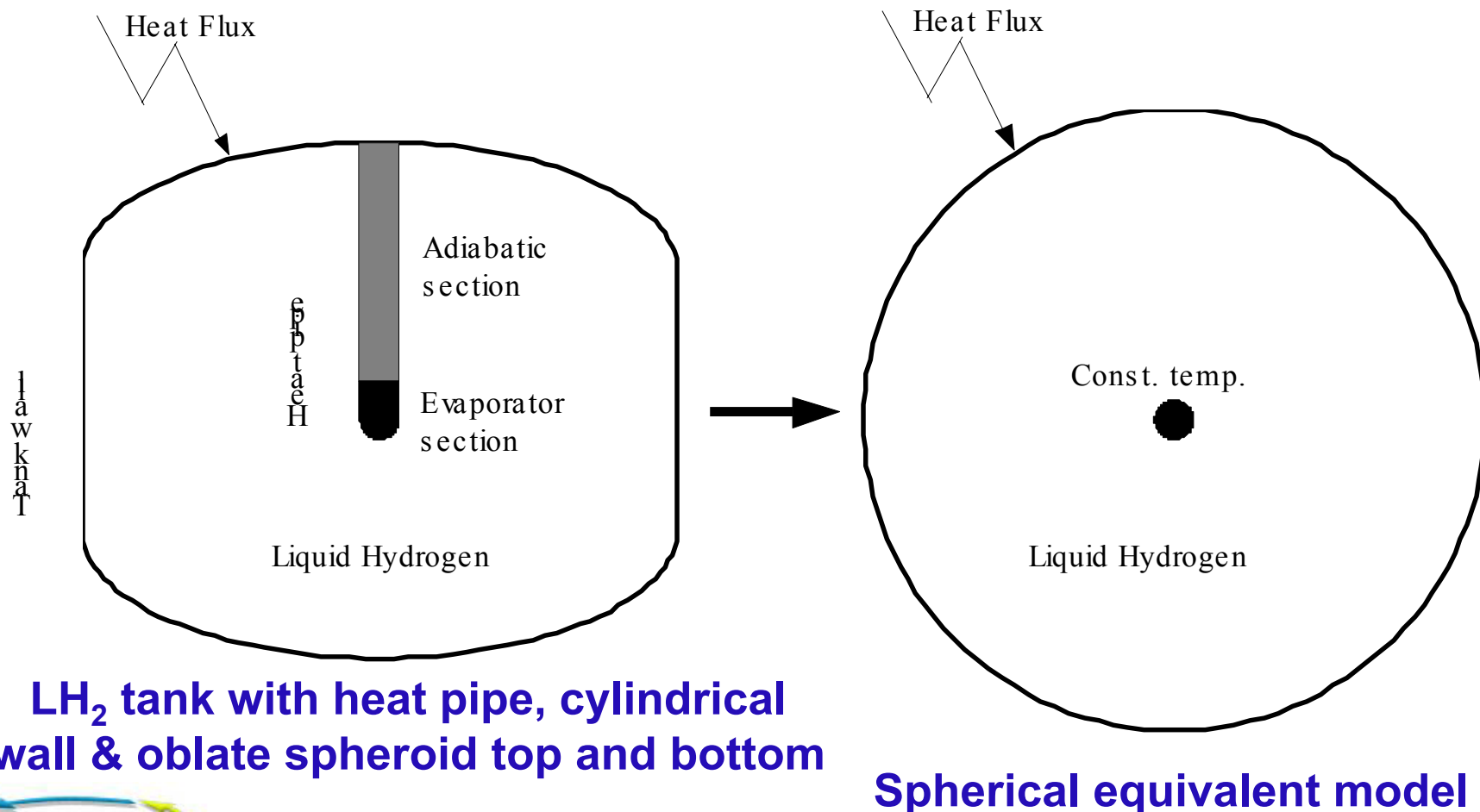
**Effect of fluid speed at nozzle
on average fluid speed (mixing)**

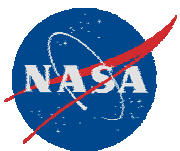


**Effect of fluid speed at nozzle
on maximum temperature (boiling)**



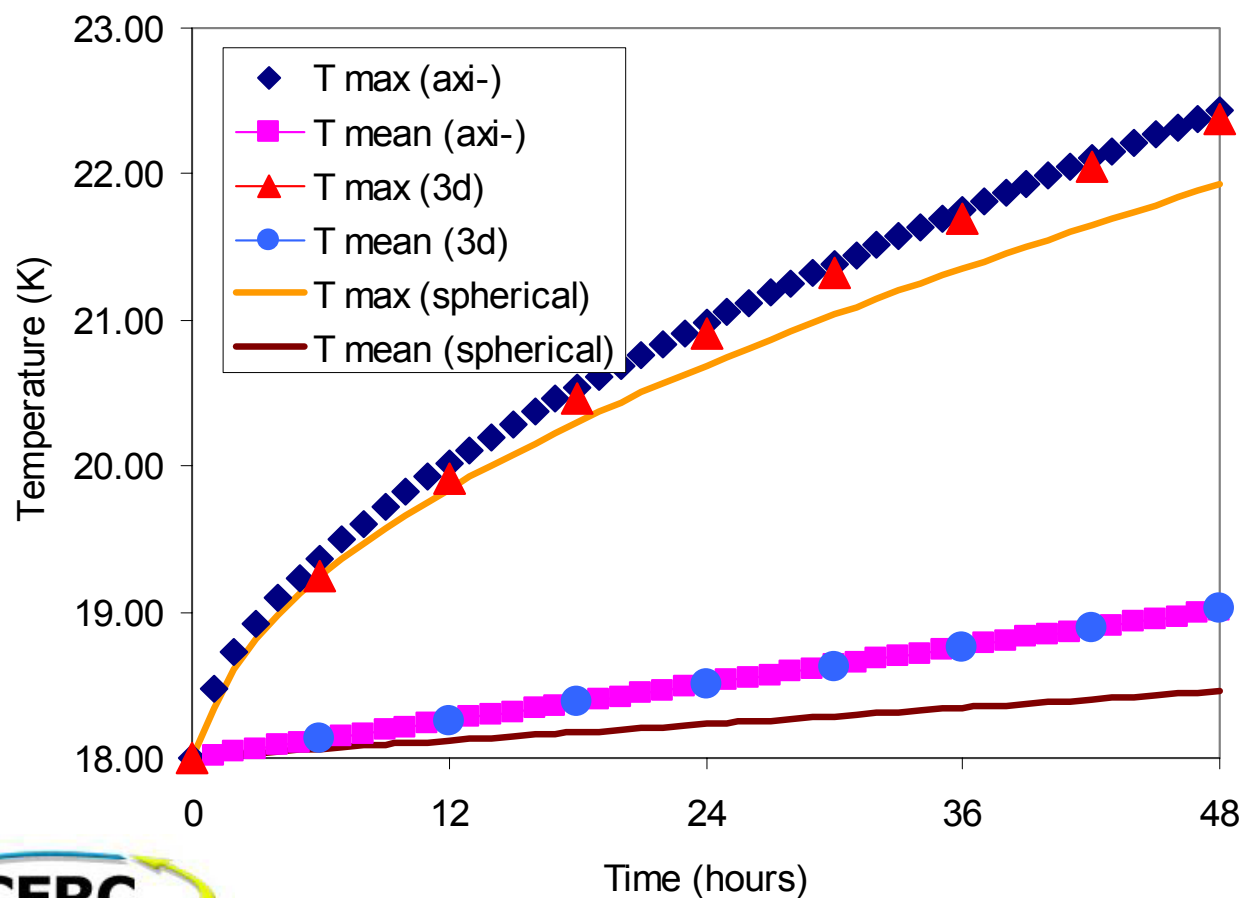
LH₂ Tank with Heat Pipe – Spherical Model



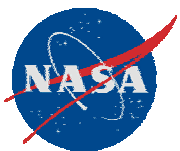


Transient Solution – Comparison of Temperature between Models (Axi-symmetric, 3-D, and Spherical)

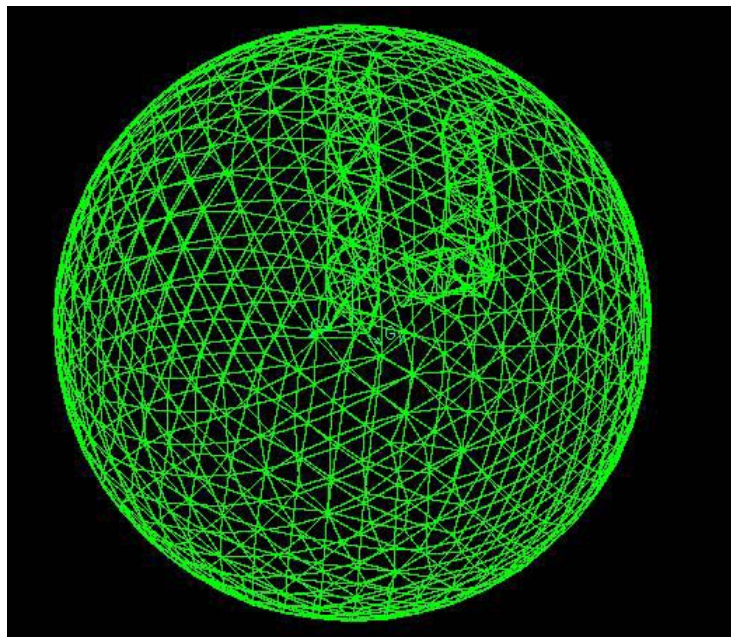
Temperature vs. Time



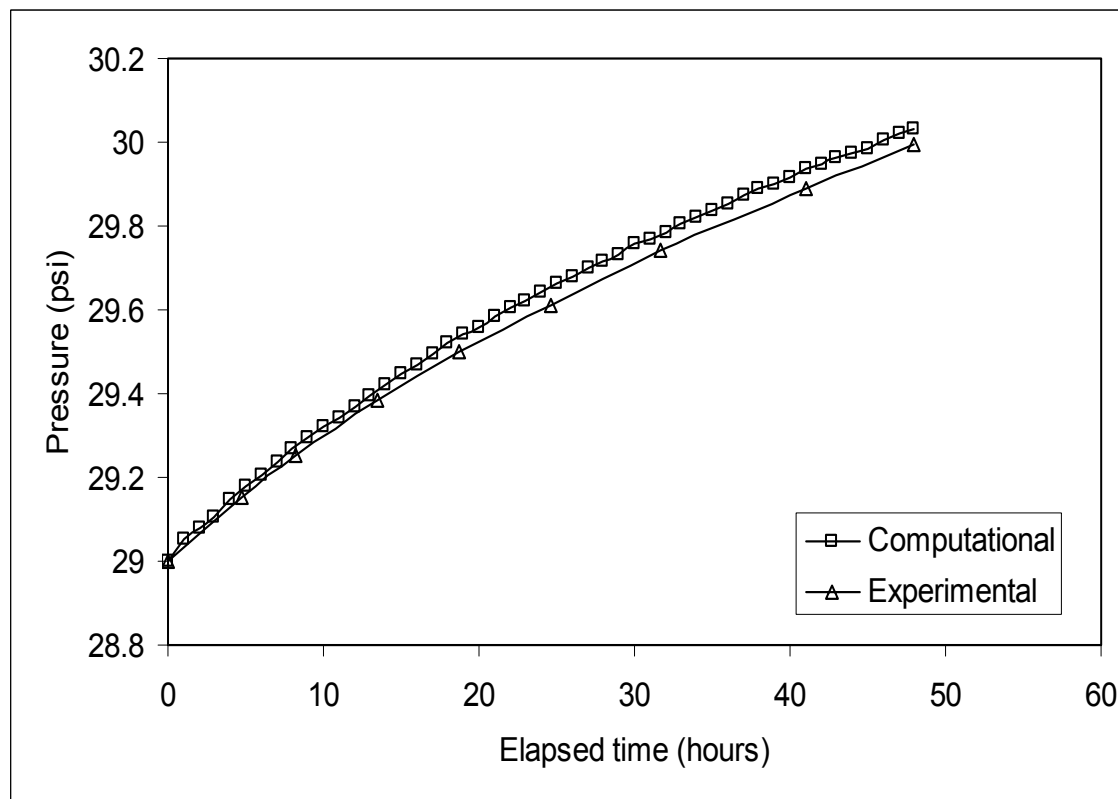
Solution for spherical model has the same form as that for axi-symmetric and 3-D models. A simple coefficient can make the spherical model match a better equivalent model for the real problem.



Comparison of Pressure in Spherical Nitrogen Tank

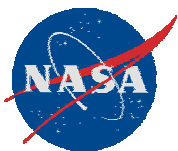


3-D tetrahedral-element mesh for spherical tank with heat pipe and pump-nozzle.

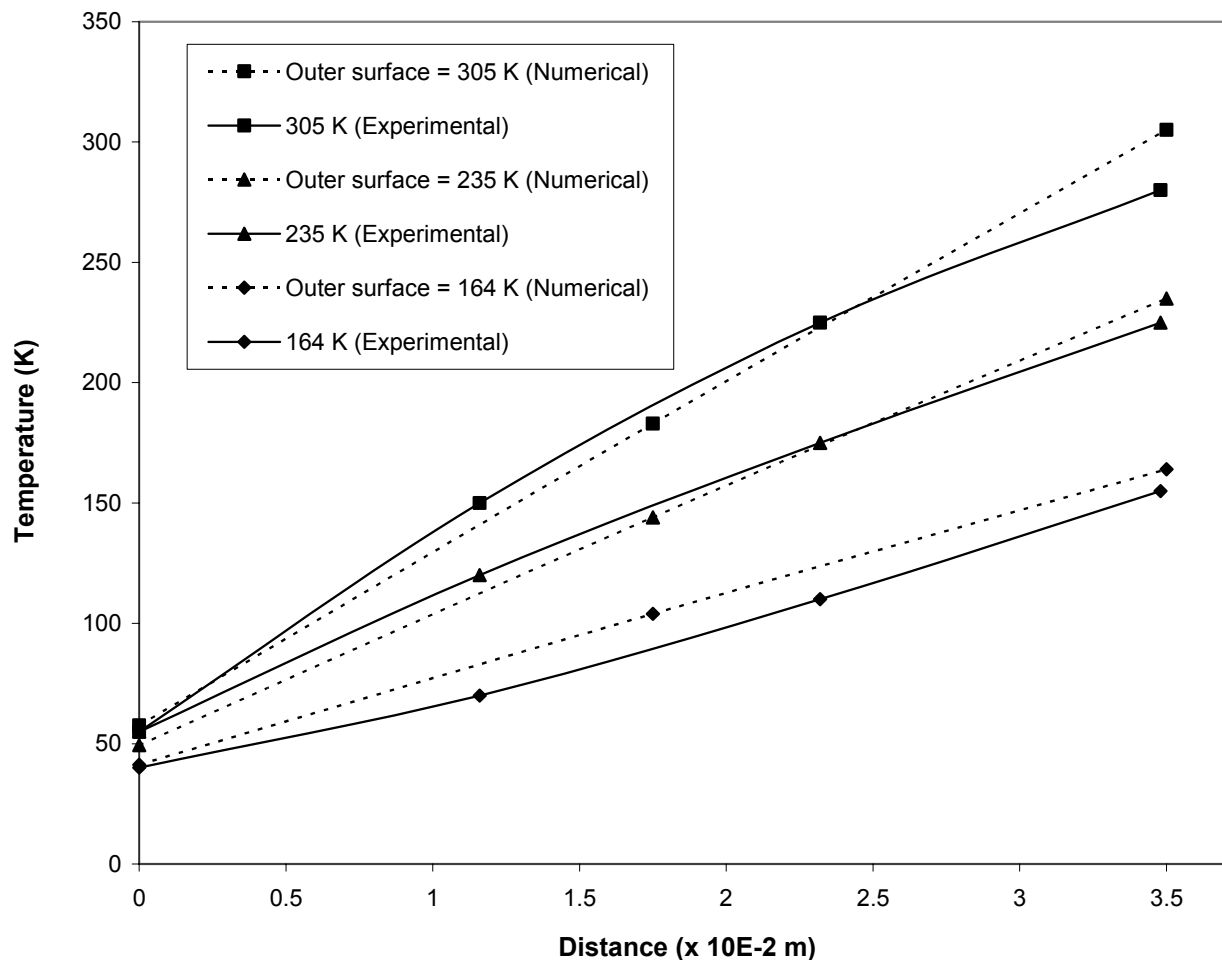


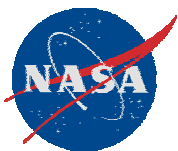
Comparison with NASA experiment data on nitrogen storage in spherical tank.

Computational results show good agreement with experimental data.



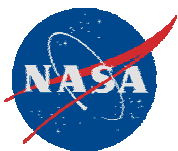
Comparison of Temperature Profile with NASA Test Data for Hydrogen Storage





Publications

1. **S.K. Mukka and M.M. Rahman, “Analysis of Fluid Flow and Heat Transfer in a Liquid Hydrogen Storage Vessel for Space Applications,” Space Technology and Applications International Forum, Albuquerque, New Mexico, February 2004.**
2. **S.K. Mukka and M.M. Rahman, “Computation of Fluid Circulation in a Cryogenic Storage Vessel,” AIAA 2nd International Energy Conversion Engineering Conference, Providence, Rhode Island, August 2004.**
3. **M. Rahman and S. Ho, “Zero Boil-Off Cryogenic Storage of Hydrogen,” NHA Hydrogen Conference 2005, Washington, D.C., March 2005.**
4. **S. Ho and M. Rahman, “Three-Dimensional Analysis of Liquid Hydrogen Cryogenic Storage Tank,” 3rd International Energy Conversion Engineering Conference and Exhibit, San Francisco, California, August 2005.**



Future Plans

- **Three-dimensional modeling for liquid hydrogen tank with auxiliary equipment inside the tank.**
- **Bubble formation and boiling in closed tank and resulting pressure profile.**
- **Transient solutions for periodic heat transfer and fluid flow.**
- **Development of a MATLAB-based design program using CFD numerical results as input.**