Liquefaction Study of Gaseous Oxygen Inside Mars Ascent Vehicle Propellant Tank

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Thermal & Fluids Analysis Workshop
TFAWS 2017
August 21-25, 2017
NASA Marshall Space Flight Center
Huntsville, AL

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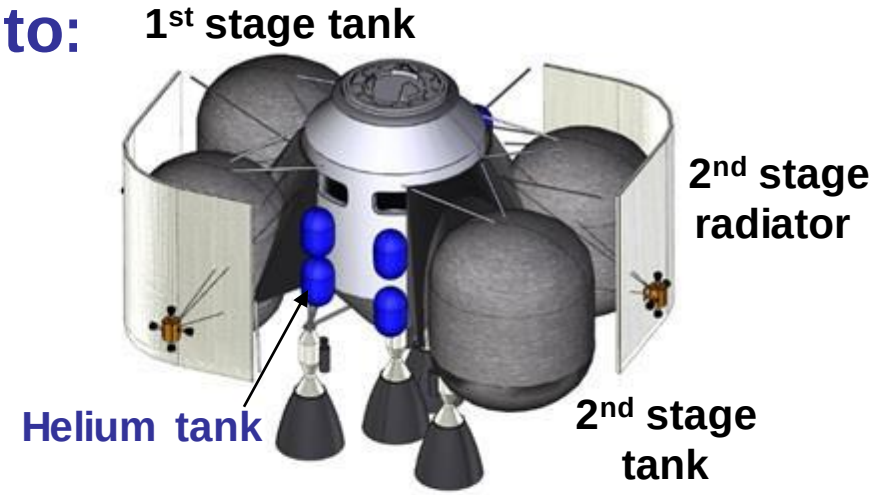
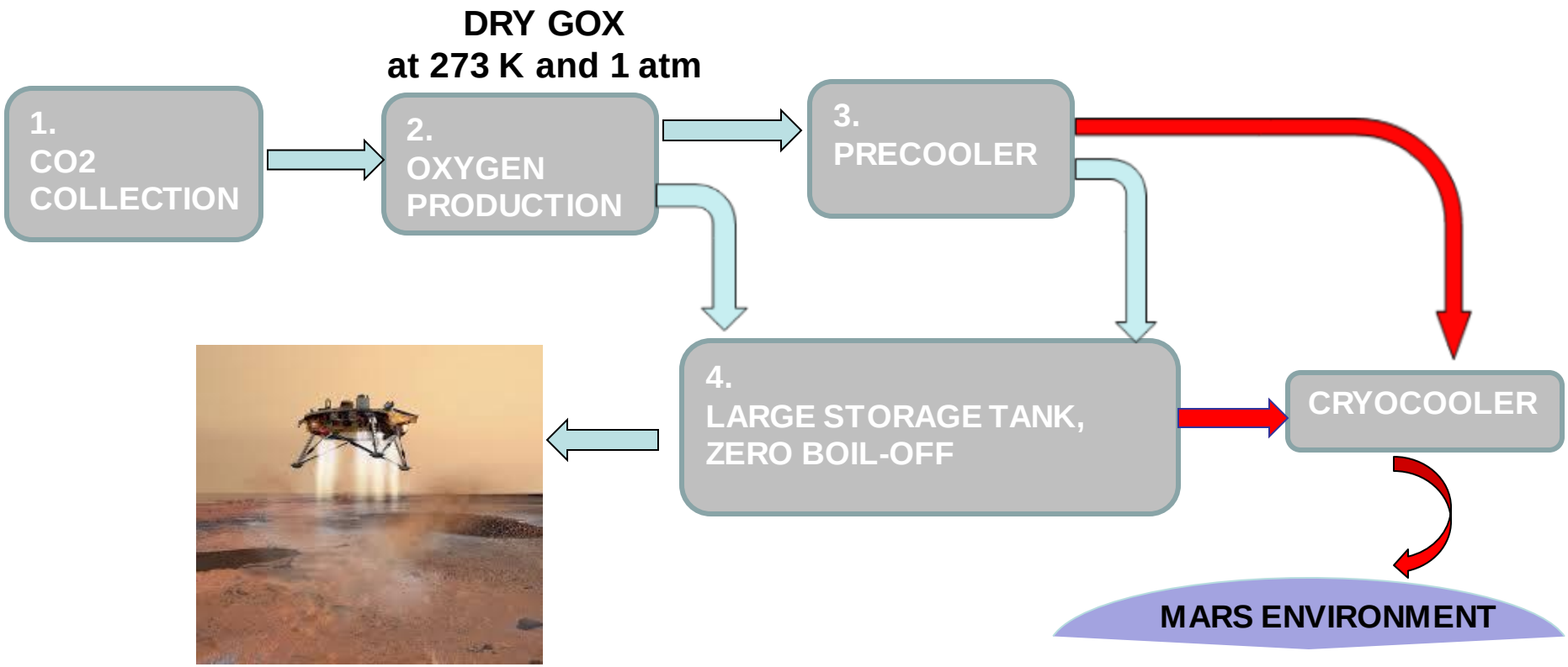
Introduction

- The in-situ production of propellants for Mars missions will utilize Mars atmospheric carbon dioxide (CO_2) to produce oxygen.
- The oxygen is then cooled, liquefied, and stored to be available for Mars ascent propulsion system, which could be up to 2 years after liquefaction starts.
- Recent investigations have demonstrated the feasibility of using high-efficiency <u>reverse turbo-Brayton-cycle cryocoolers</u> to:
  - Cool the oxygen gas
  - Liquefy the oxygen gas
  - Achieve zero boil-off
  - Control the pressure of oxygen within a tank



In-situ Production – Liquefaction - Storage

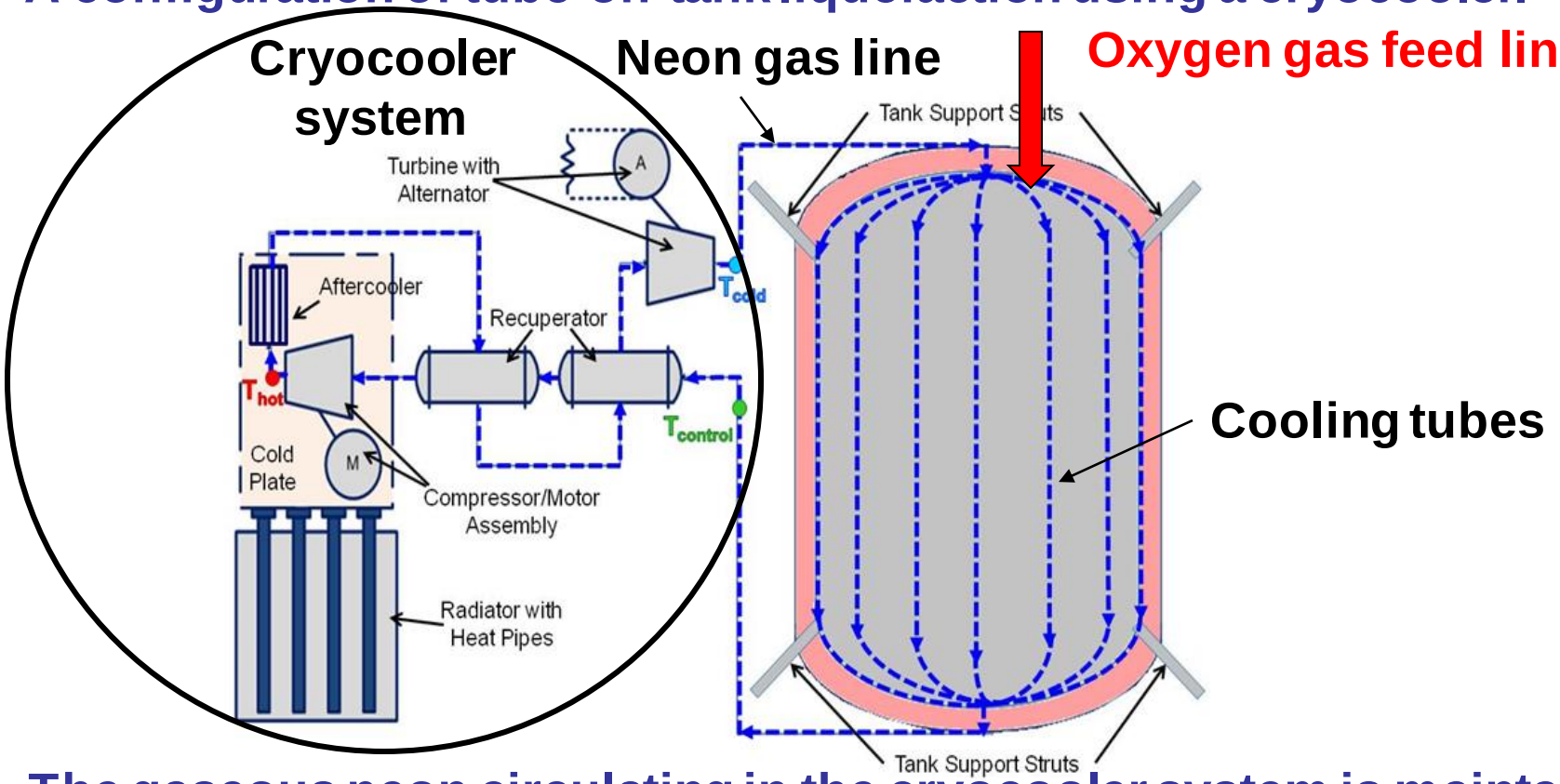


Reference:

1. "Mars Ascent Vehicle Design for Human Exploration", Tara Polsgrove, AIAA SPACE 2015.
2. "MAV Deep Dive: ISRU to MAV Propulsion Interface, Update on LOX Production, Liquefaction and Transfer v2.0", Bill Studak, Aug. 15 2015.

Concept Schematic of Tube-on-Tank

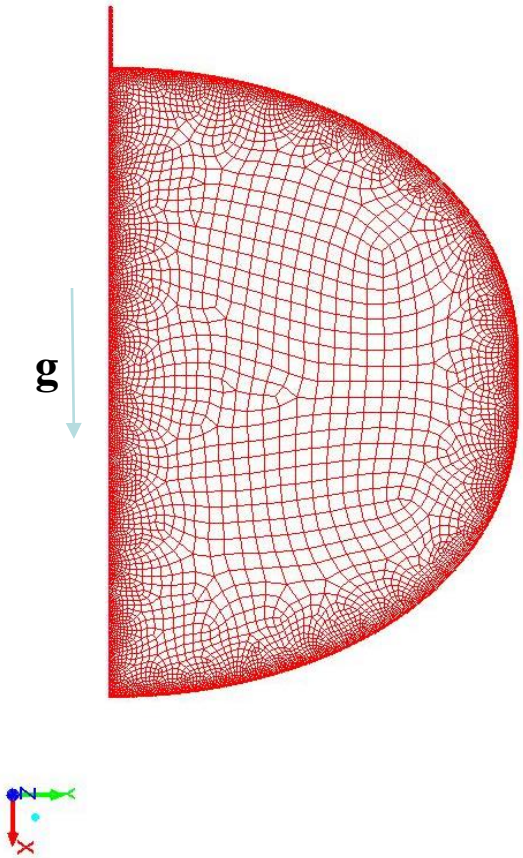
A configuration of tube-on-tank liquefaction using a cryocooler.



- The gaseous neon circulating in the cryocooler system is maintained slightly below liquid oxygen saturation temperature and is routed through a network of cooling tubes epoxied to the tank wall.
- The oxygen gas produced from the in-situ production process is introduced into the chilled tank.

CFD Model in ANSYS Fluent

- 2D axisymmetric, transient analysis
  - Multiphase model: Mixture/slip velocity/implicit body force
  - Turbulence model: shear stress transport (SST) k-ω (2 eqns)
- No conjugate heat transfer (Tank wall and neon tubes are not modeled)
  - Simplify Fluent CFD model to save computational time
  - Define tank wall boundary condition (constant T at 90 K or heat flux at - 12 W/m^2 = - 243.6 W/20.3 m^2 based on lift of cryocooler)
  - Investigate uncertainty of decoupling neon cooling tube and tank wall



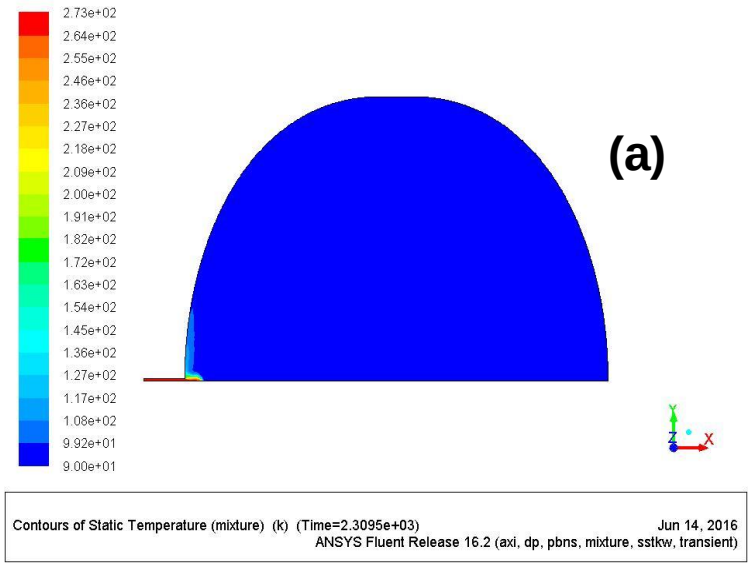
ANSYS Fluent Model Results Summary

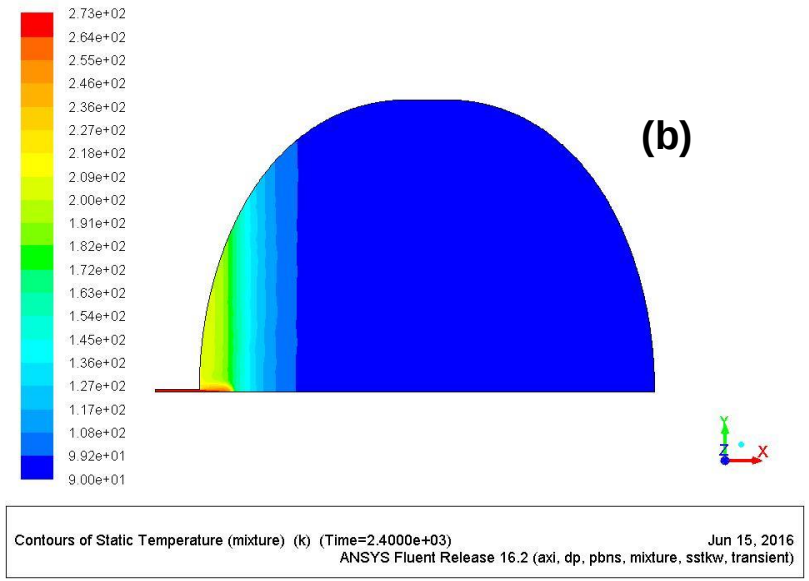
- Fluent model results will be shown for
  - Fill level: 0% and 95%
  - Incoming warm GOX at the mass flow rate of 2.2 kg/hr
  - Incoming pre-chilling GOX at the mass flow rate of 2.2 kg/hr
  - Wall boundary conditions:
    (a) constant tank wall temperature
    (b) constant tank wall heat flux

ANSYS Fluent Results (I): 0% Fill Level

Temperature contour of mixture of GOX and LOX

- Incoming gas: 273 K
  - (a) wall temperature fixed at 90 K
  - (b) wall heat flux fixed at -12 W/m^2



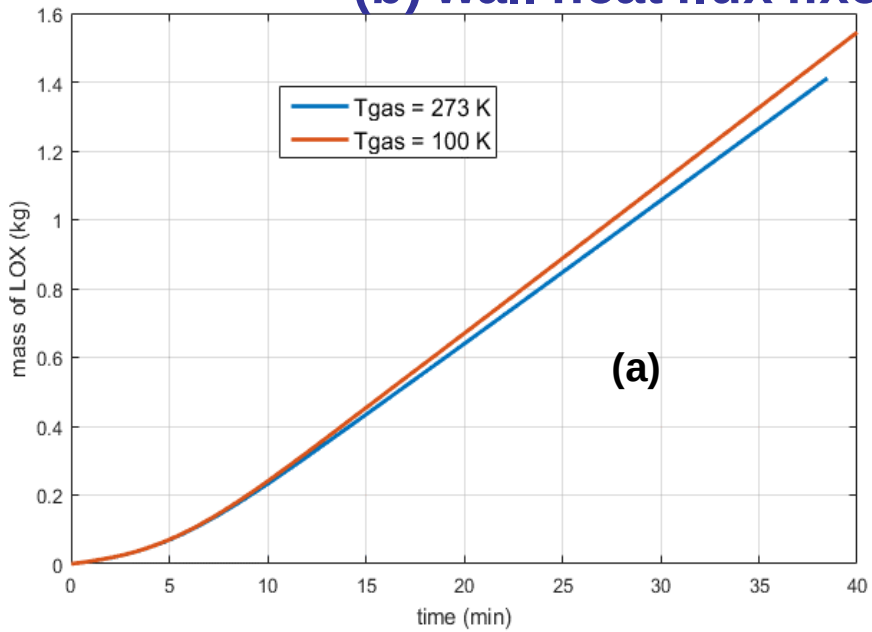


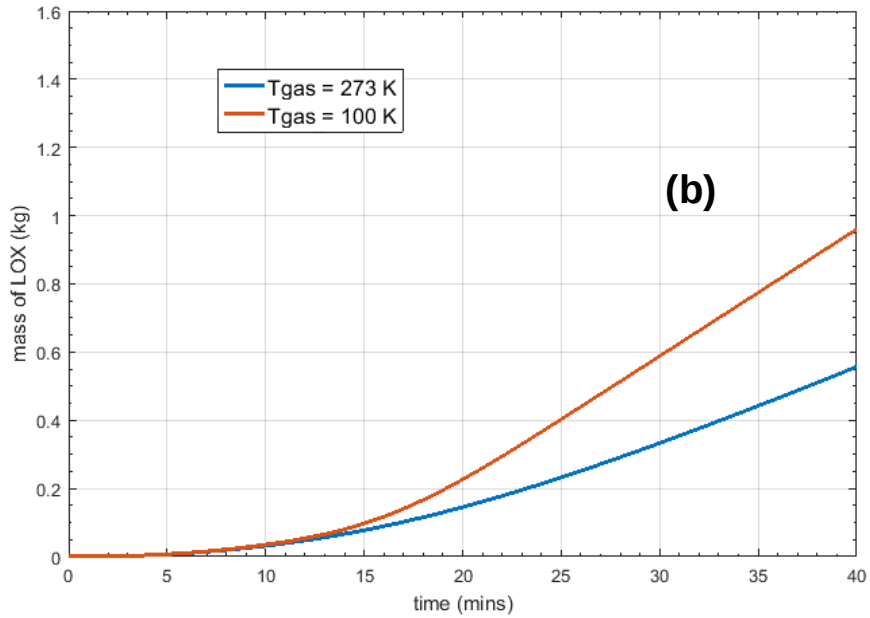
- **The warm gaseous O_2 chills down within smaller volume with a cold wall as shown in case (a).**

ANSYS Fluent Results (II): 0% Fill Level

Time history of the mass of LOX:

- **Incoming gas: 273 K and 100 K**
  - **(a) wall temperature fixed at 90 K**
  - **(b) wall heat flux fixed at -12 W/m^2**



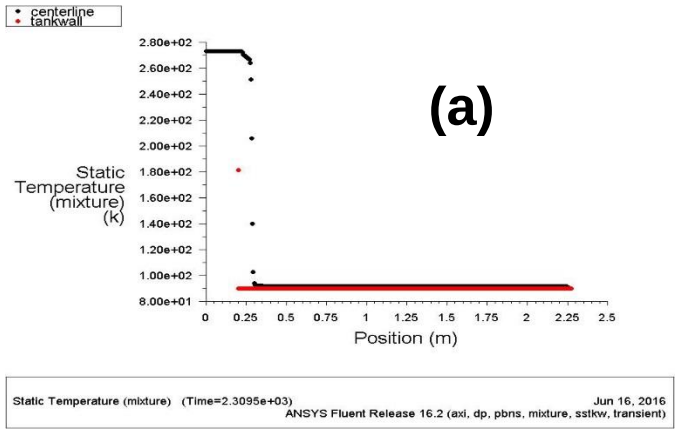


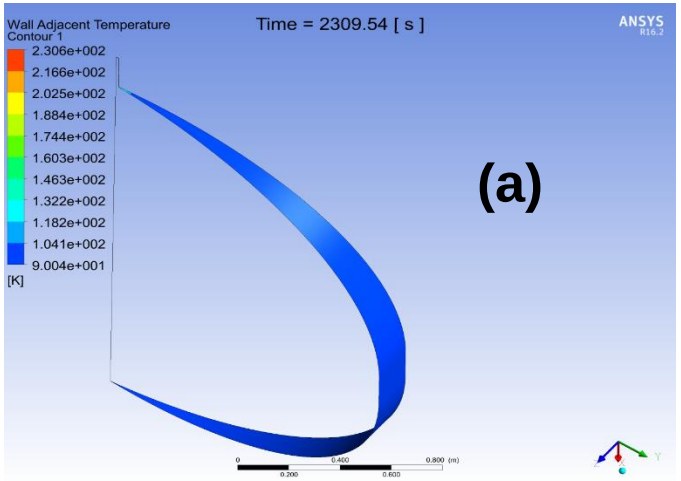
- **The LOX mass produced inside the tank at t = 40 minutes is**
  - **For incoming gas of 273 K:**
    - **1.48 kg in case (a), 0.55 kg in case (b), a ratio of 2.7.**
  - **For incoming gas of 100 K:**
    - **1.52 kg in case (a), 0.95 in case (b), a ratio of 1.6.**

ANSYS Fluent Results (III): 0% Fill Level

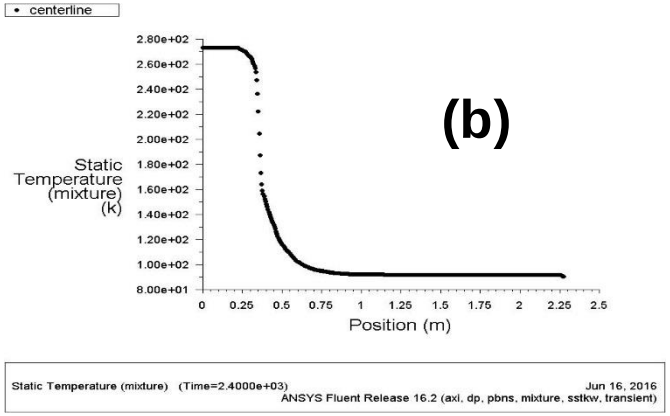
Incoming GOX temperature distribution

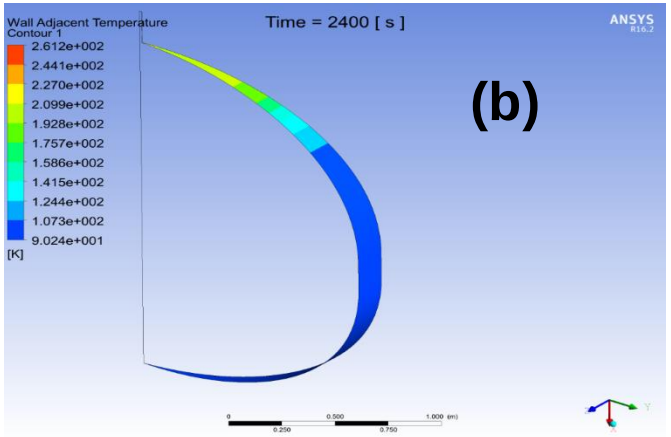
(a) Wall temperature fixed at 90 K





(b) Wall heat flux fixed at -12 W/m²

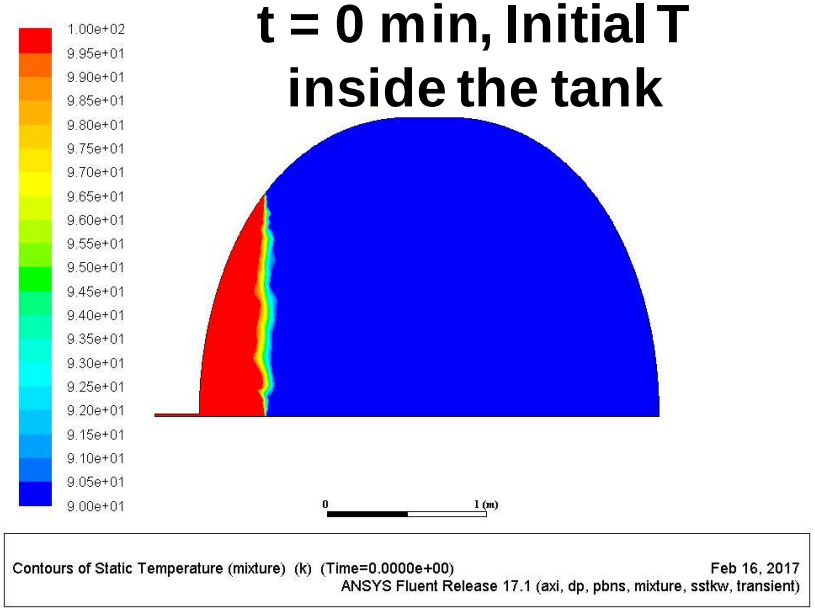




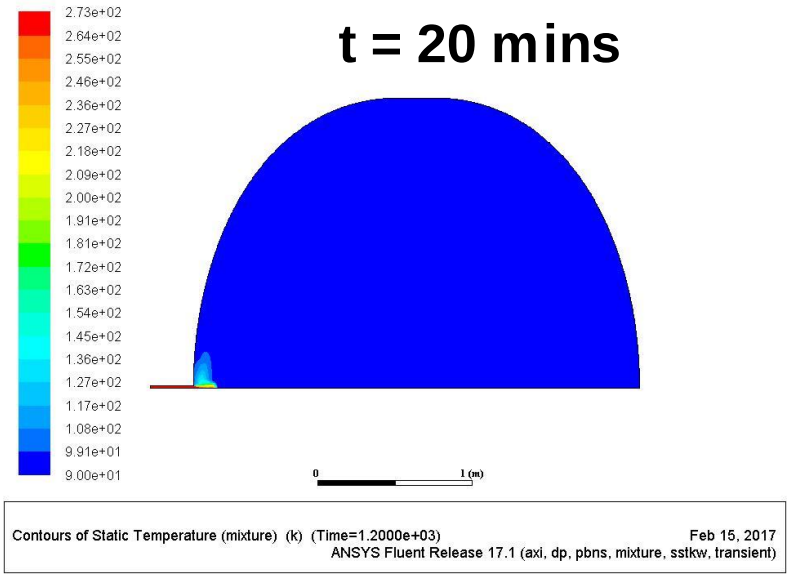
ANSYS Fluent Results: 95% Fill Level

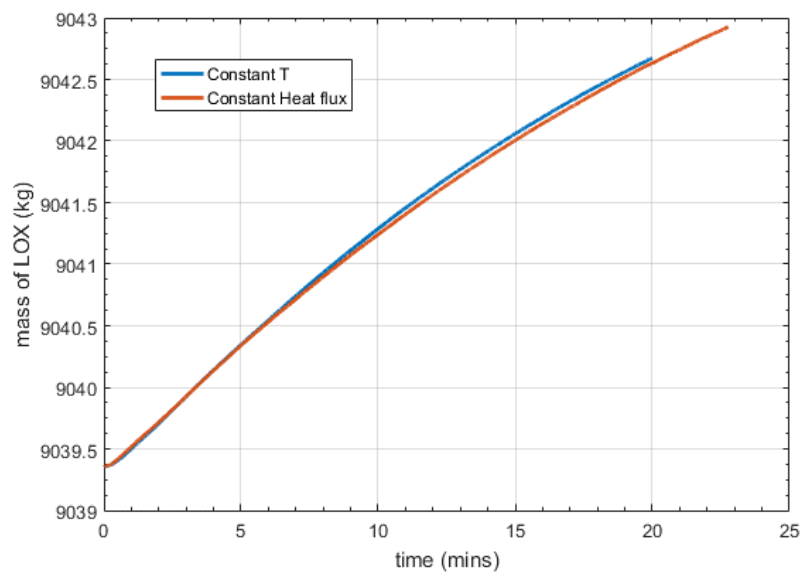
Temperature contour of the mixture of GOX and LOX for incoming gas at 273 K

t = 0 min, Initial T inside the tank



t = 20 mins





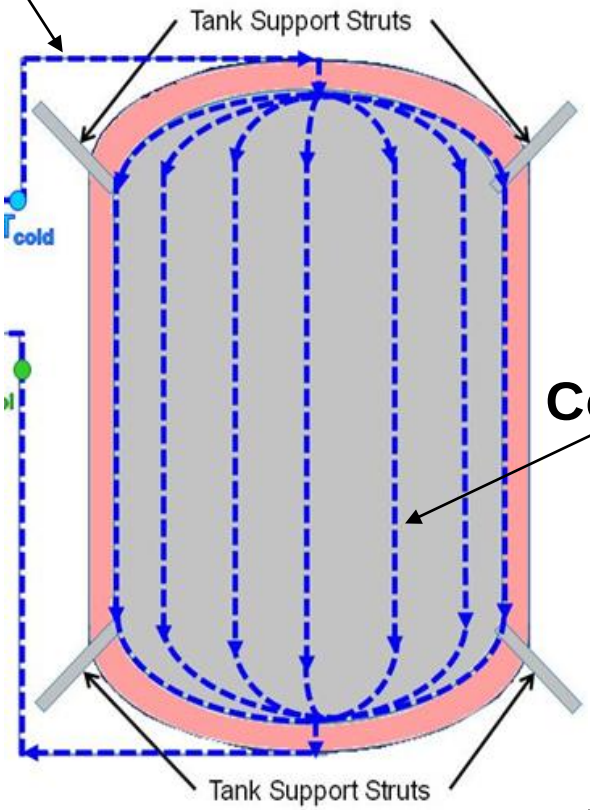
Tank wall boundary condition doesn't change the liquefaction rate for 95% fill level case.

Observation from Fluent Results

- Fluent model results show the mixing of the warm incoming GOX with the gas inside the tank.
- Fluent results provide temperature distribution of incoming warm gas.
- Tank wall boundary conditions show significant difference of liquefaction rate for 0% fill level, but very little difference for 95% fill level.
- The entire picture of heat transfer from neon gas to the tank wall then fluids is not shown in Fluent analysis. It will be interesting to know temperature changes of the neon fluid along the tube and the temperature gradient near the top of the tank.
- 1D thermal circuit is built to understand more of the tube-on-tank configuration.

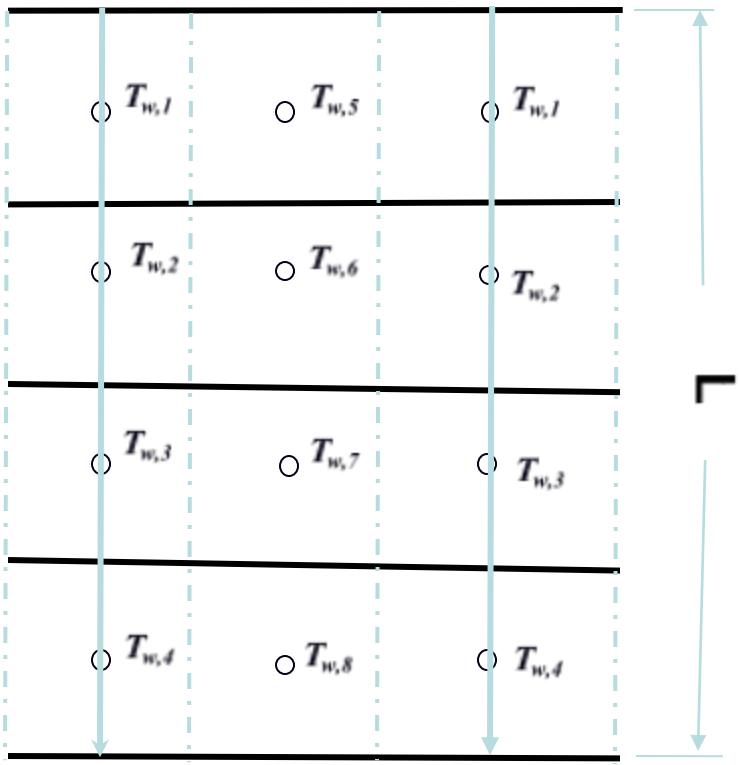
1D thermal model of Tube-on-tank (I)

Neon gas line



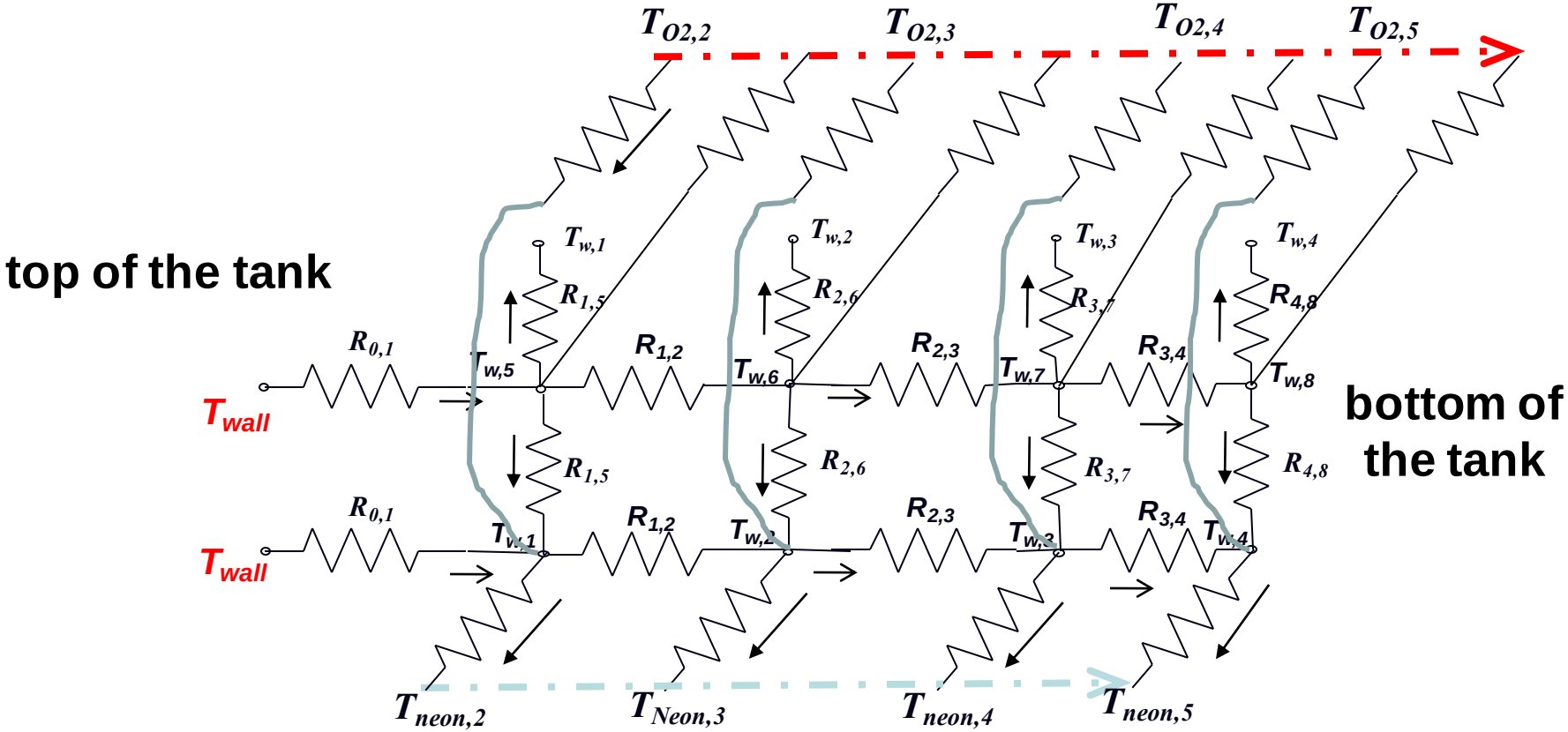
Top of the tank

Cooling tubes



Bottom of the tank

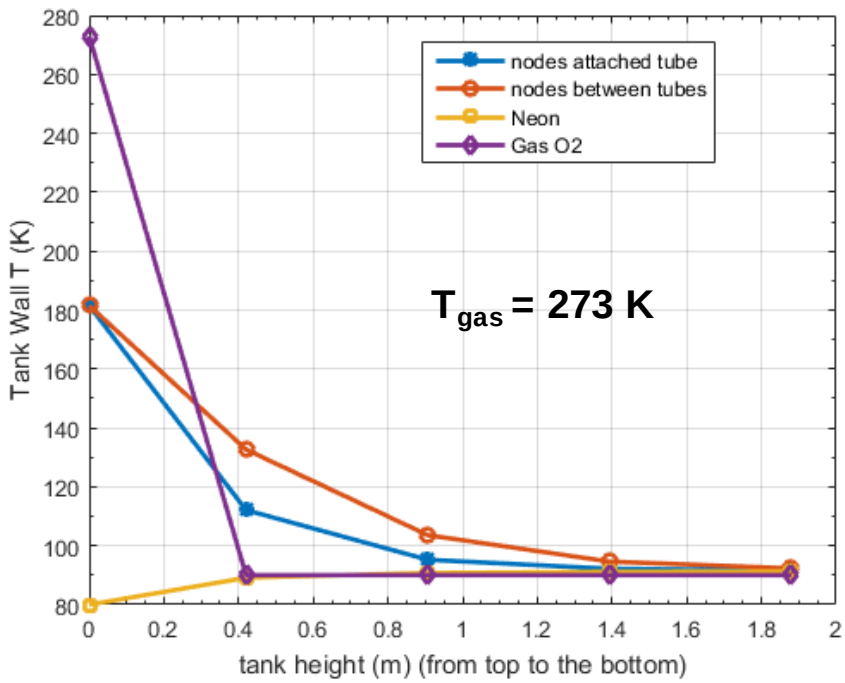
1D Thermal Circuit For The Concept Of Tube-on-tank:

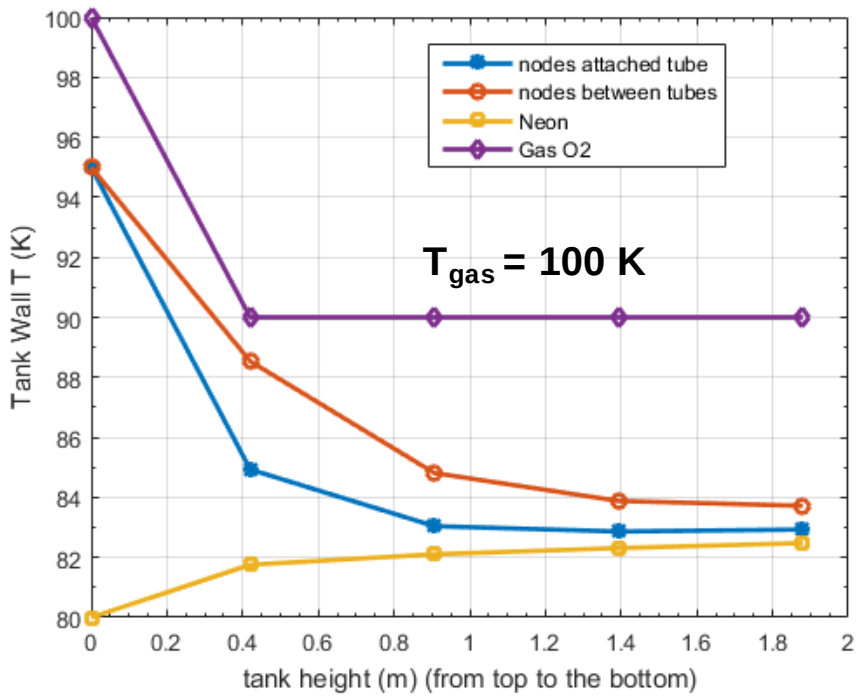


- Conduction resistance between the wall nodes along the axial/circumferential directions
- Convection resistance between the cooling tube wall and neon fluid
- Convection resistance between the tank wall and gaseous O2
- Contact resistance between the cooling tube and tank wall
- T_{wall} and T_{O2} distribution are needed to specify as BC
- Inlet temperature of neon gas and mass flow rate need to be defined

1D Model Results (I)

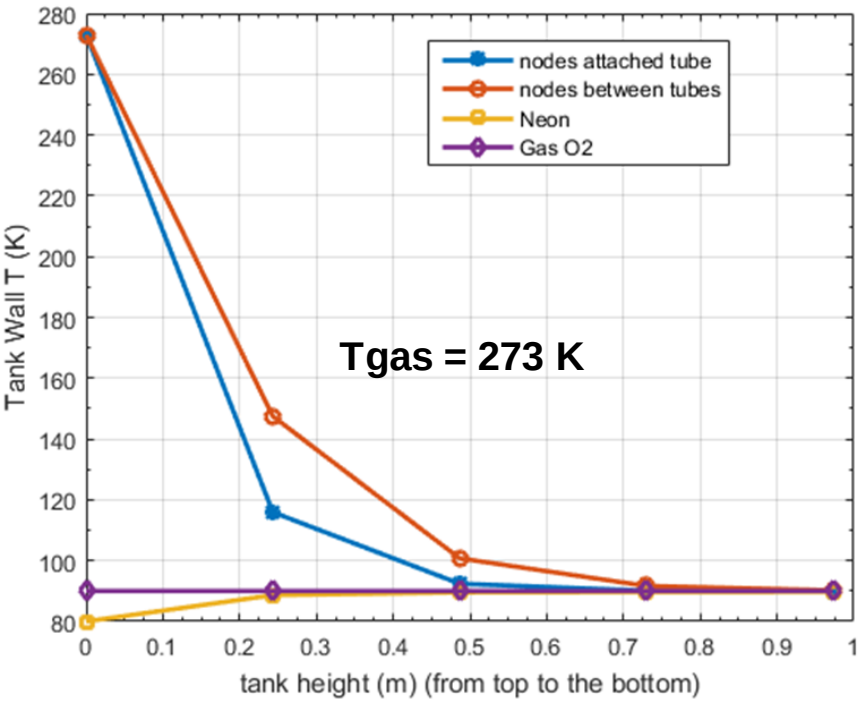
- $T_{wall} = (T_{gas}+T_{sv})/2.0$ at the top is used, T_{sv} is the saturated vapor temperature
- Neon gas inlet temp is assumed to be 80 K
- Estimate the tank surface area *A* needed to cool the warm gas (T_{gas}) to the saturated temperature using $m_{dot}C_p(T_{gas}-T_{sv}) = h\,A\,(T_{gas}-T_{wall})$, then compute the tank height (= 0.42 m) based on A, which is at 94% fill level assuming h = 0.5 W/m^2-k

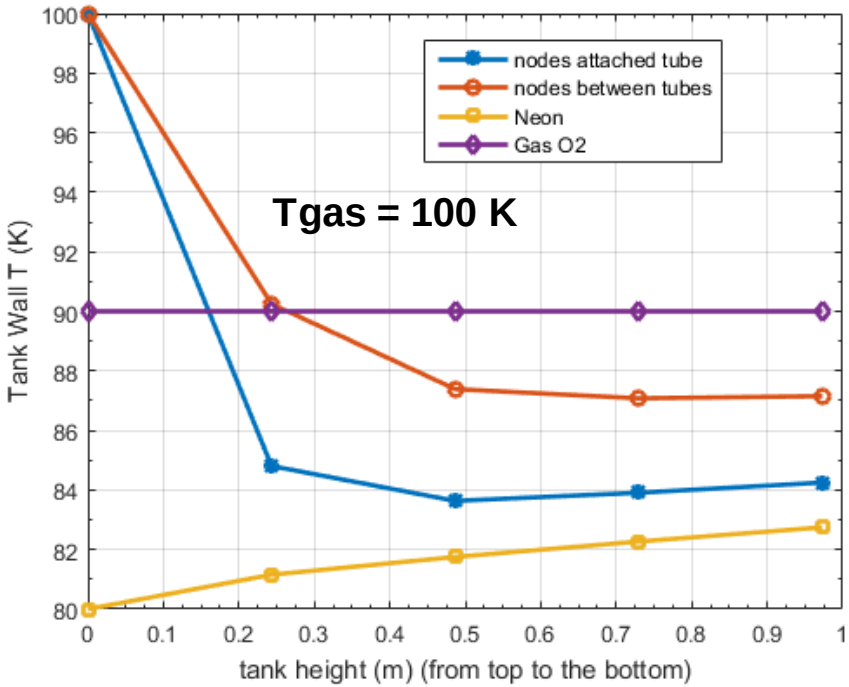




1D Model Results (II)

- $T_{wall} = T_{gas}$, same as the incoming T_{gas}.
- Inside the tank, assume the temperature of $T_{gas} = T_{sv}$.

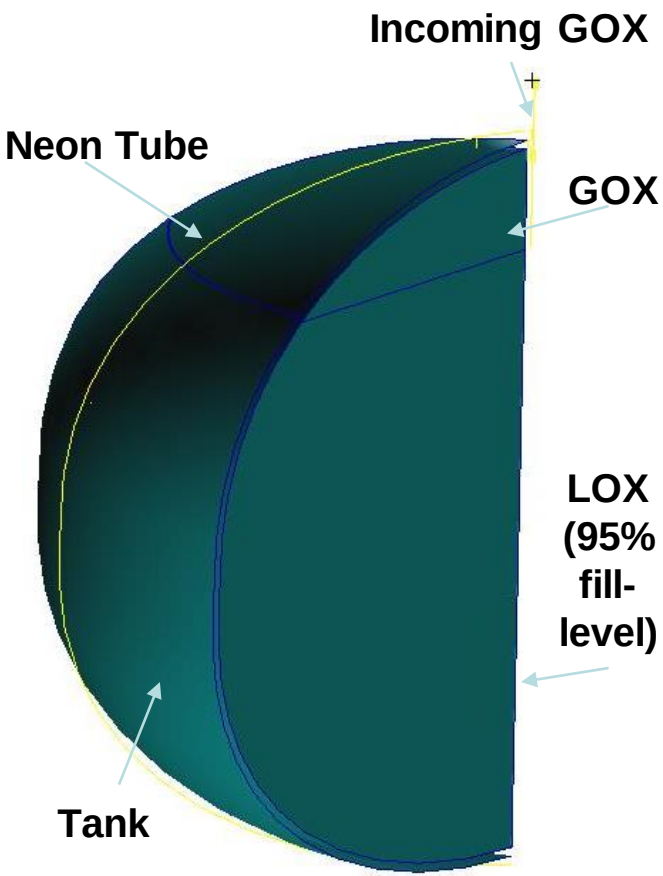




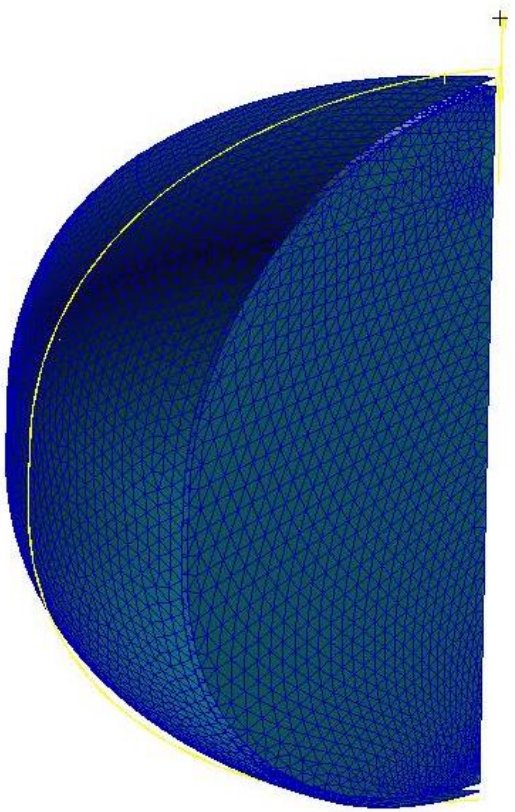
Summary Of 1D Tube-on-tank Model Results

- There are uncertainties on how to define the incoming GOX temperature distribution inside the tank and the tank wall temperature near the top of the tank.
- 1D model can not accurately show the gradient since the mesh size is limited.
- 1D thermal circuit model shows the major BCs and assumptions that need to be considered for the modeling.
- 3D tube-on-tank model in MSC Patran/pthermal is built to investigate the temperature gradient on the top of the tank.

3D Tube-on-tank Thermal Model In MSC Patran/Pthermal



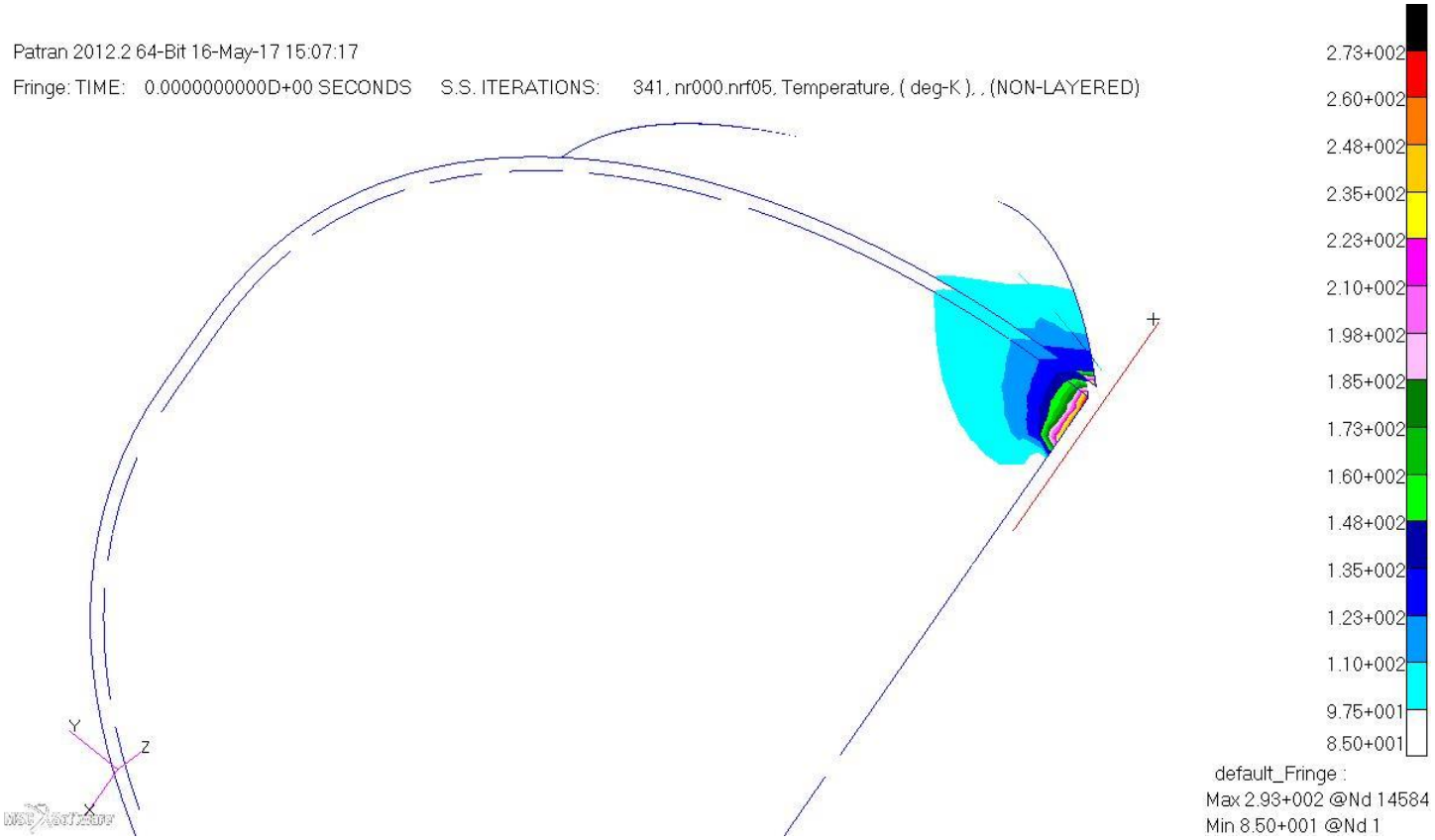
- Steady-state analysis
- Geometry: 60° wedge of the MAV tank (6 cooling tubes)
- FEM mesh for large temperature gradient on the top of the tank
- Conduction is modeled for both GOX and LOX
- Convection is not modeled, phase change is not modeled
- Temperature of incoming GOX from Fluent model is used as BC



FEM mesh

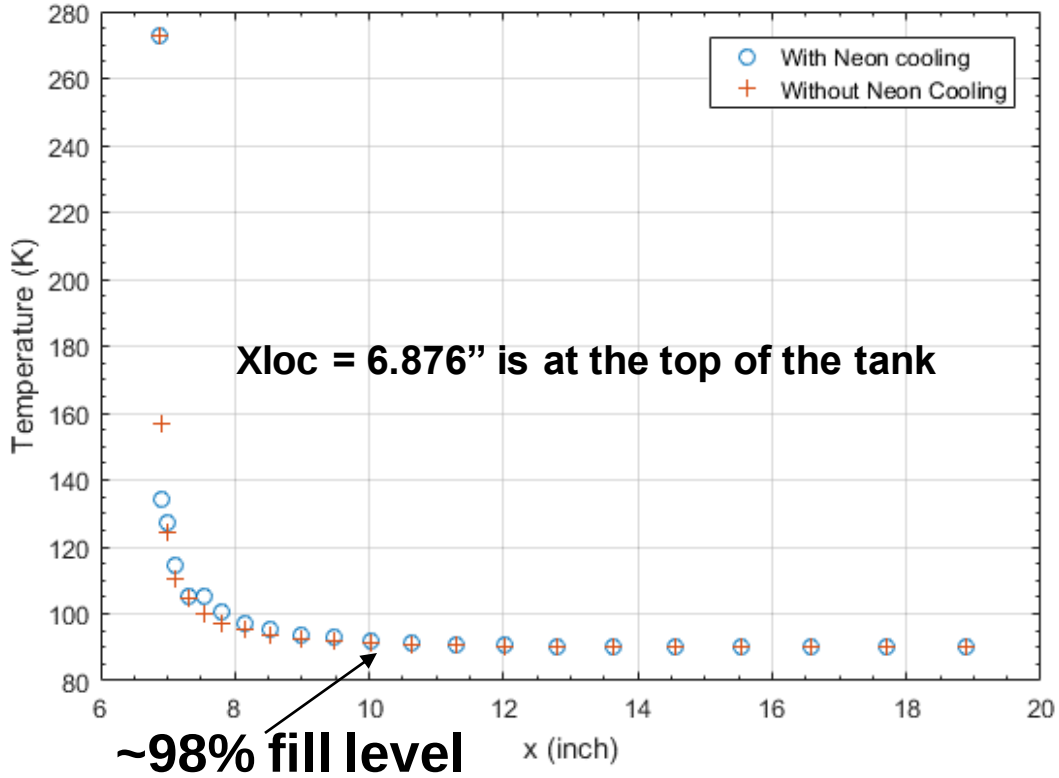
MSC Patran/Pthermal Tube-on-tank Model Results (I)

- **Apply the Fluent model results of the incoming GOX temperature along the center line of the tank**
- **Specify the tank wall temperature at the top equal to the incoming hot gas temperature**
- **Specify the neon gas inlet temperature and mass flow rate**



MSC Patran/Pthermal Tube-on-tank model Results (III)

- **Wall temperature distribution along the Xloc (height of the tank) with and without neon cooling (the worst case)**



Xloc (inch)	T (K) (with Neon)	T(K) (No Neon)
6.876	273.000	273.000
6.911	134.346	157.024
6.993	127.414	124.497
7.124	114.595	110.559
7.304	105.333	104.443
7.535	105.297	99.997
7.817	100.350	97.055
8.151	97.158	95.246
8.539	95.223	93.703
8.980	93.760	92.574
9.476	92.786	91.708
10.028	92.056	91.214
10.635	91.411	90.858
11.299	90.967	90.598
12.020	90.657	90.377
12.802	90.431	90.233
13.647	90.272	90.132
14.556	90.172	90.070
15.534	90.102	90.032
16.580	90.049	90.011
17.699	90.017	90.003
18.892	90.000	90.000

- **Results show the temperature near the top of the tank cools to 90 K within a short distance**

Observations From 3D Patran Thermal Model Results

- Patran/pthermal results show a clear picture of the temperature gradient near the top of the tank due to cold neon and incoming hot GOX.
- The tank wall temperature drops to 90 K from 273 K within a short distance, that is above the 97-98% fill level, even for the case of no neon cooling.
- Based on three model results, we can conclude that liquefying the warm GOX without pre-chill is feasible and no major concern near the top of the tank for the thermal gradient.
- The liquefaction rate over long time period (42+ days) was investigated using a separate thermal model in Thermal Desktop/Sinda-Fluint.

Acknowledgement

- **Great appreciation goes to Wesley Johnson, David Plachta and Daniel Hauser at GRC for valuable technical discussions and inputs.**
- **AES Lander Technology project's support for this work.**