Modeling of Gaseous Oxygen Liquefaction Inside Mars Ascent Vehicle Propellant Tank

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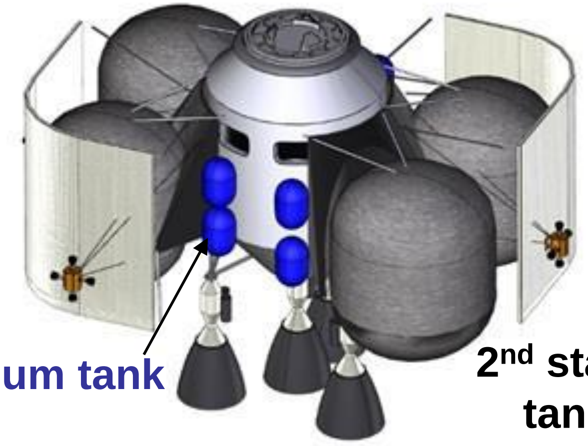
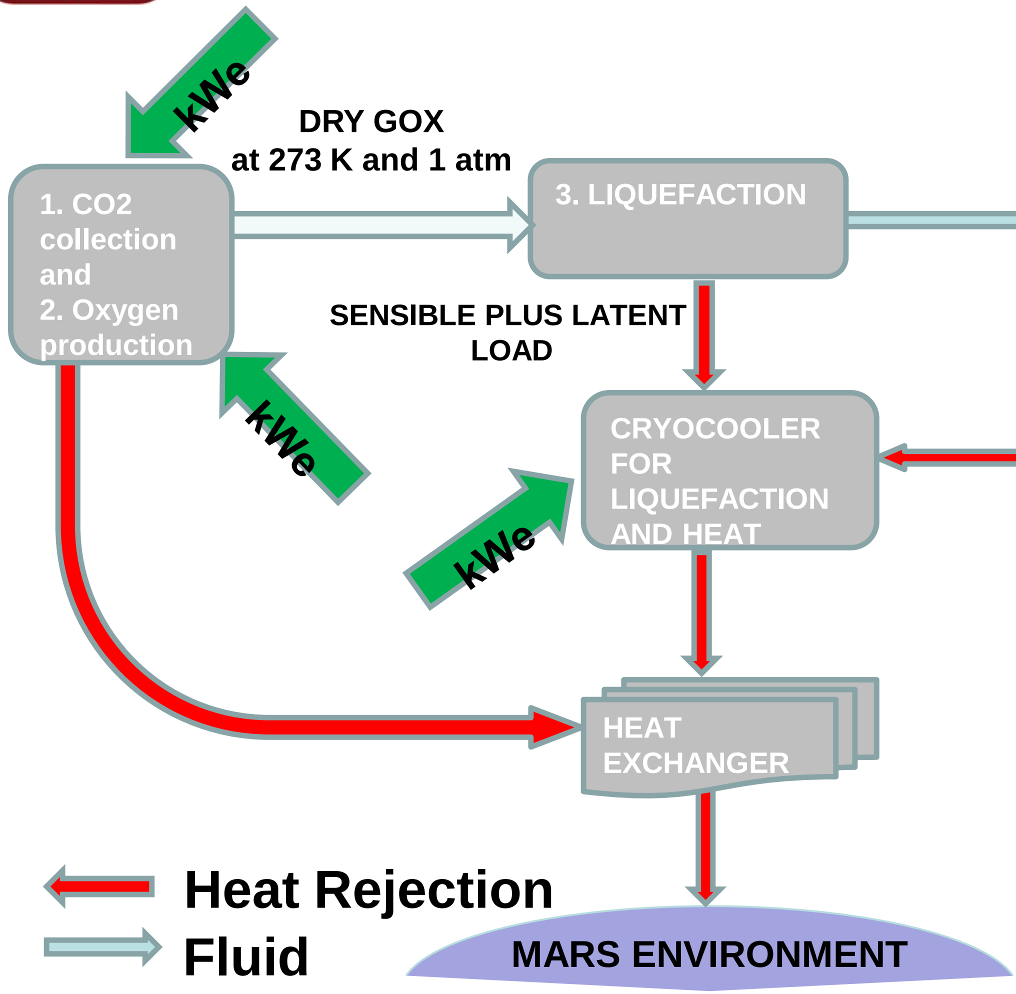
Contents

- Introduction
- Concept Schematic of tube-on-tank concept
- Objectives of the CFD analysis
- Details of the CFD model
- CFD model results:
  - Incoming gas with temperature:
    - 273 K (warm case, baseline)
    - 100 K (cold case)
  - Tank wall boundary condition:
    a) Define wall temperature at 90 K
    b) Define the heat flux as 12 W/m^2
- Conclusions
- Forward works

- 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 **reverse turbo-Brayton-cycle** cryocoolers to:
  - Cool the oxygen gas
  - Liquefy the oxygen gas
  - Achieve zero boil-off
  - Control the pressure of oxygen within a tank

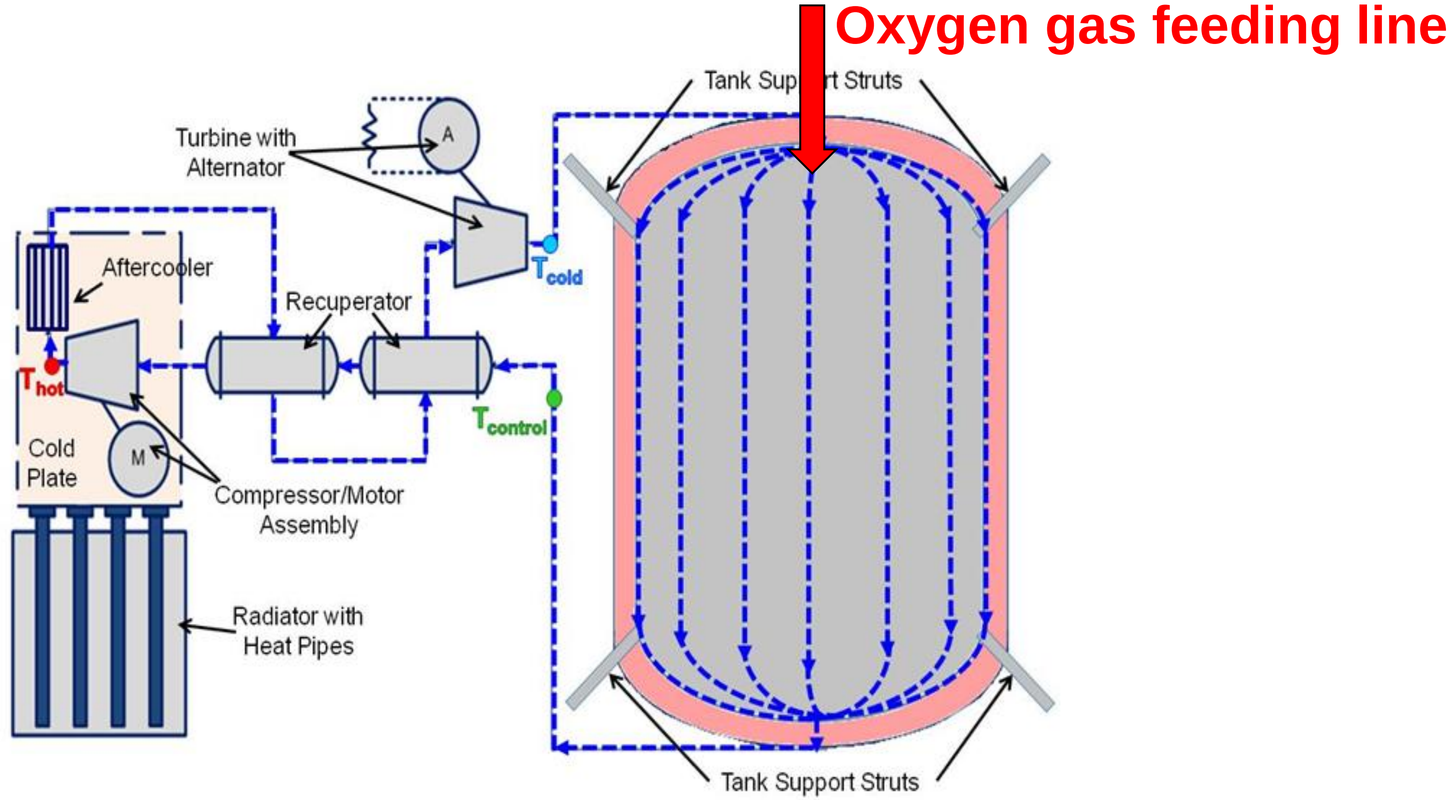


In-situ Production – Liquefaction - Storage



Concept Schematic of tube-on-tank

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



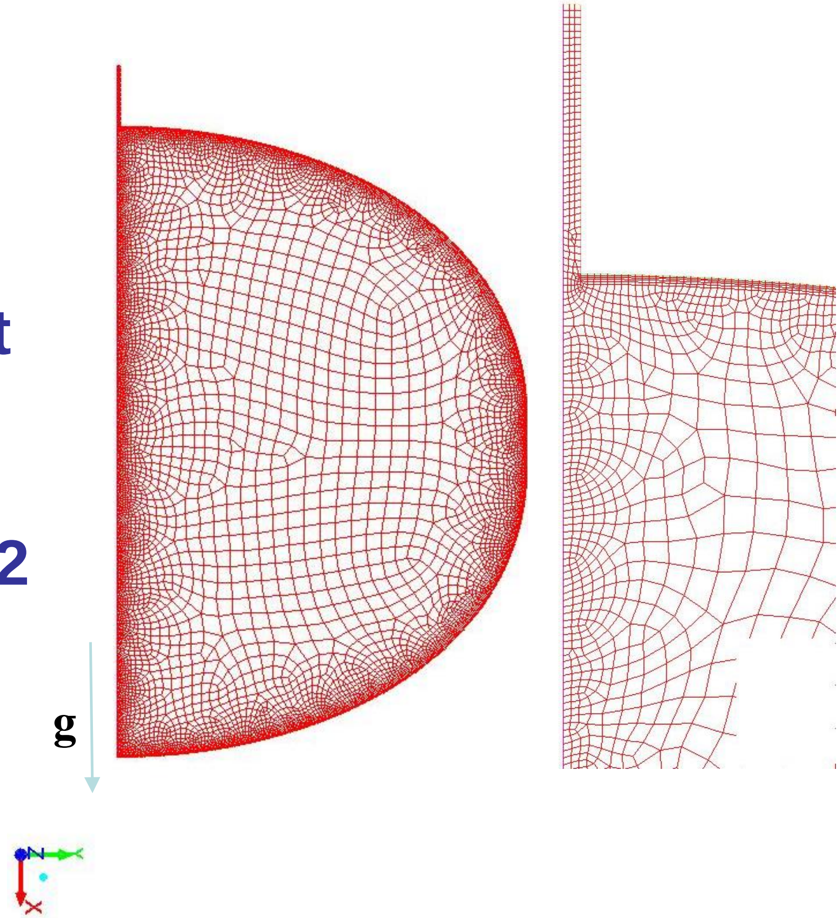
- **The gaseous Neon circulating in the cryocooler system is maintained slightly below liquid oxygen saturation temperature and is routed through a network of cooling tubes.**
- **The oxygen gas produced from the in-situ production process is introduced into the chilled tank.**

Objectives of the CFD analysis

- Model the proposed active thermal liquefier design (tube-on-tank) to reduce the uncertainty of the heat transfer coefficient inside the tank
- Model liquefier configuration options to create an efficient system
  - Meet the **requirement** of the liquefaction time
  - Minimize the **mass and power** for the active thermal liquefier system
- Understand the relationship between the incoming gaseous O_2 temperature versus **tank surface area** and **condensation rate** of the gas inside the tank
- Investigate the advantage of pre-chilling gaseous O_2

CFD model approach using ANSYS Fluent

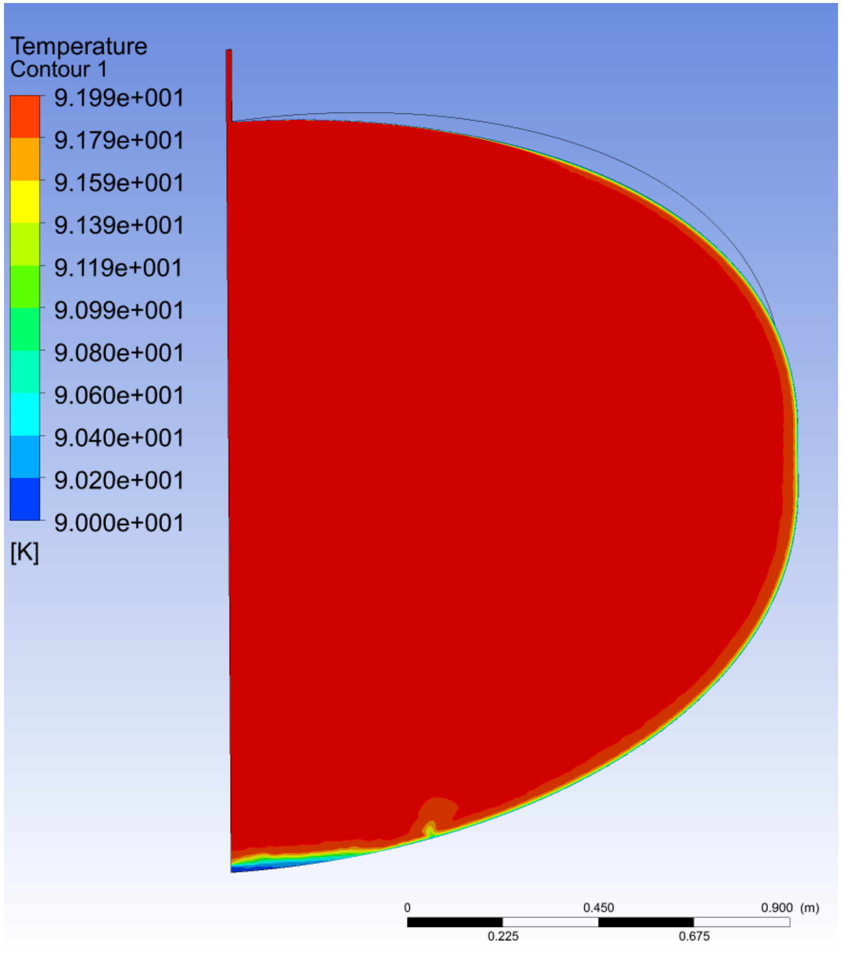
- 2D axisymmetric, nc = 11201, nv = 11785, dt = 0.01 s
  - Solver: Pressure-based, transient, coupled
  - Multiphase model: Mixture/slip Velocity/Implicit Body force
  - Turbulence model: shear stress transport (SST) k-ω (2 eqns)
- Tank wall boundary condition
  a) Set temperature: 90 K
  b) Set heat flux: 243.6 W/20.3 m^2 = 12 W/m^2 (based on the lift of the cryocooler)

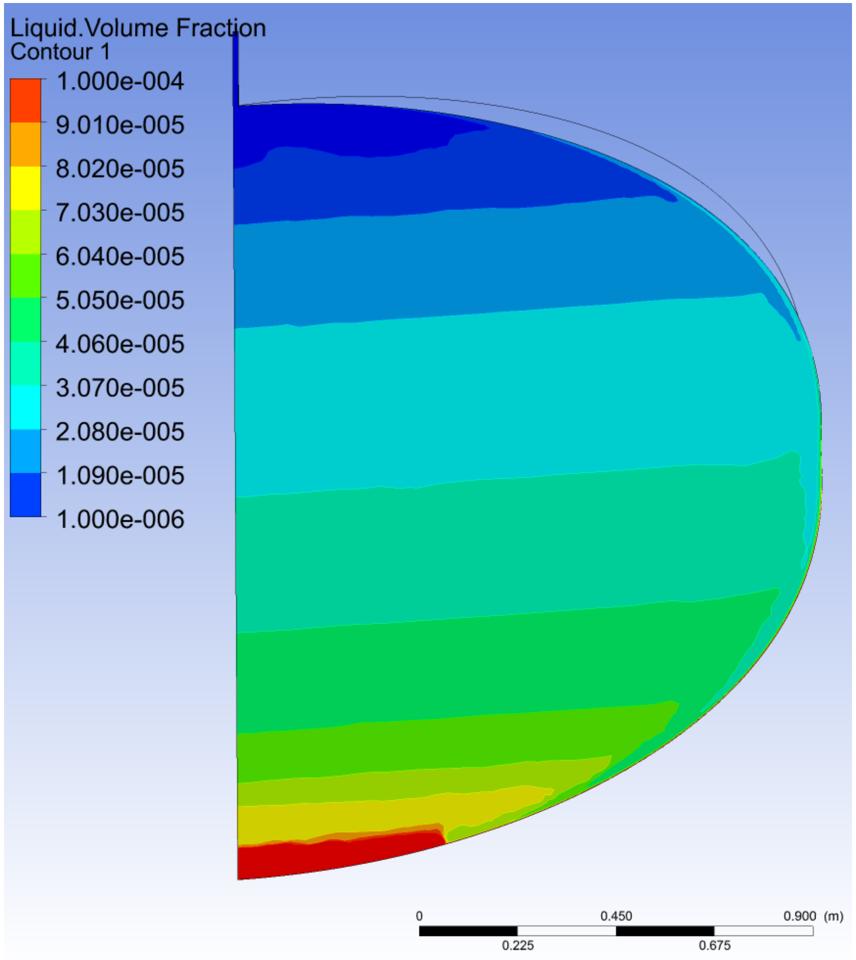


CFD model chilled GOX assumptions

- Inlet gaseous O_2:
  - Warm gas at 273 K (baseline)
  - Cool gas at 100 K
- Mass flow rate:
  - 2.2 kg/hr = 6.11 g/s (baseline)
- Initial conditions:
  - T = 100 K
  - VOF of the liquid oxygen: 0
- Inlet tube:
  - 1” diameter at the top of the tank

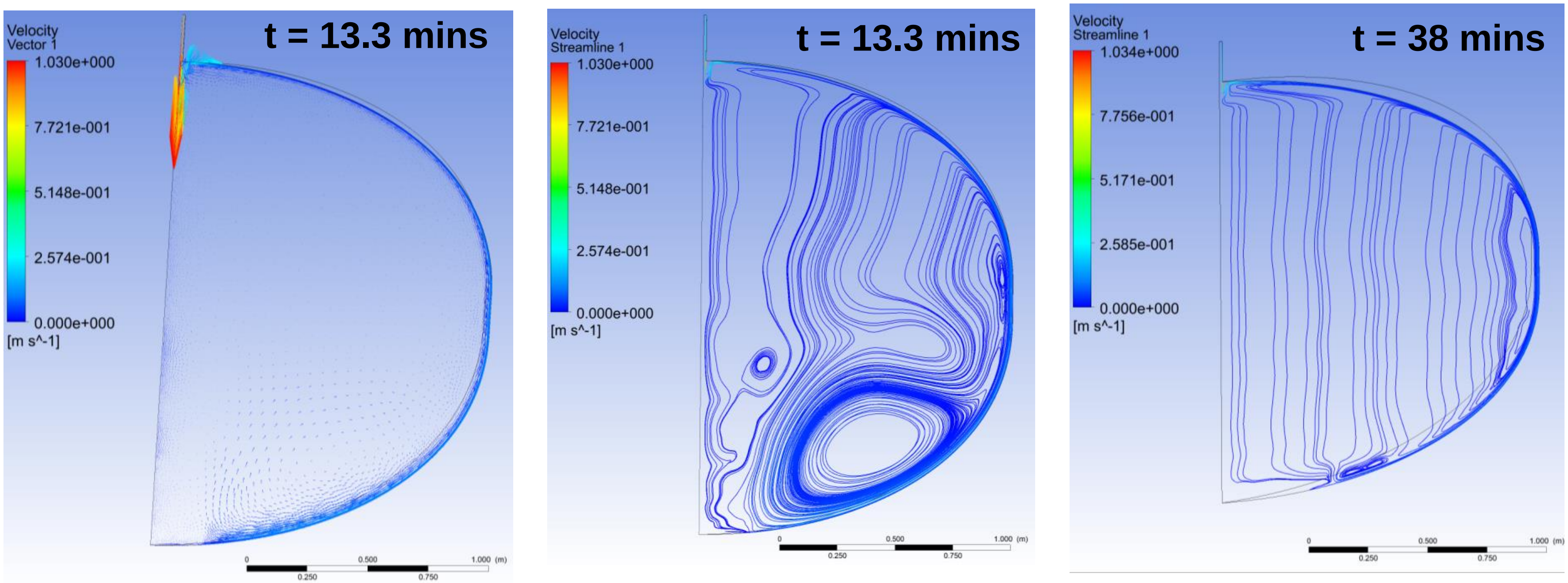
ANSYS Fluent results: t = 38 mins, case (a)





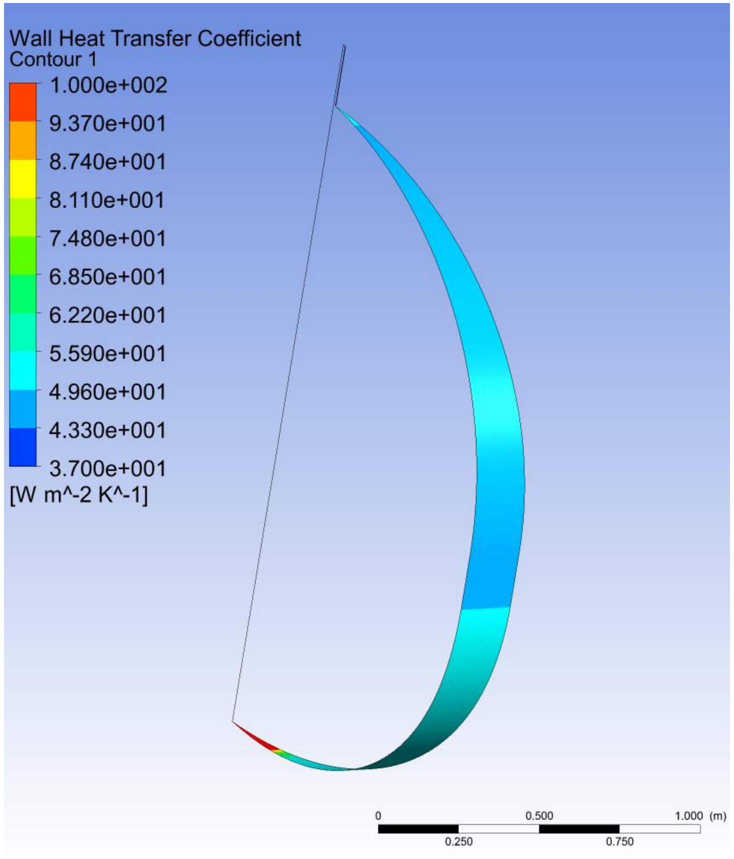
- **Liquefaction occurs at the bottom of the tank**

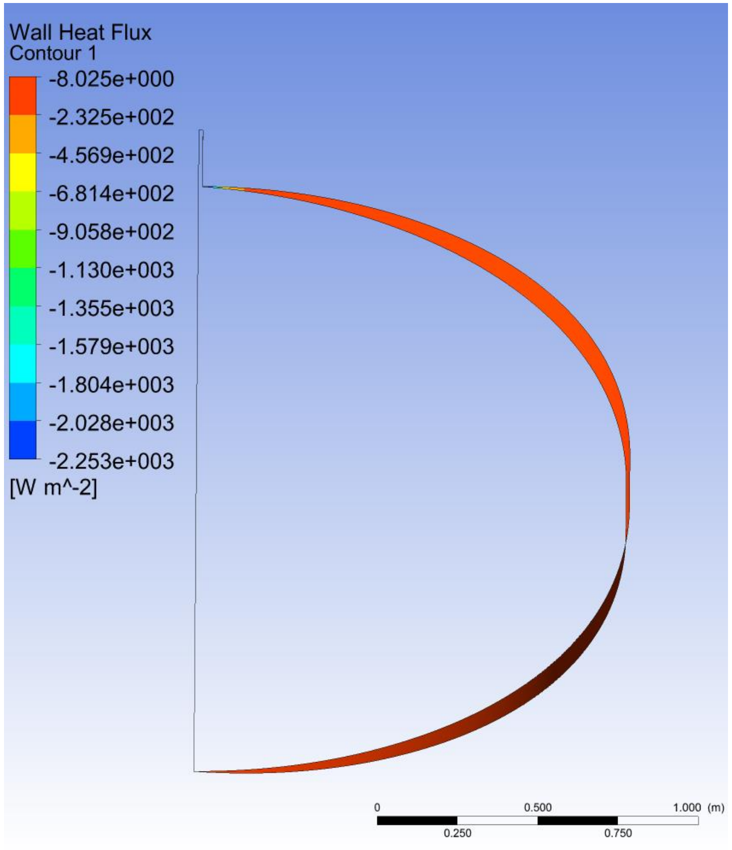
ANSYS Fluent results: t = 13.3 & 38 mins, case (a)



- **Free convection inside the tank and near the interface of liquid and gaseous O_2**
- **Flow streamline contours shown**

ANSYS Fluent results: t = 38 mins, case (a)



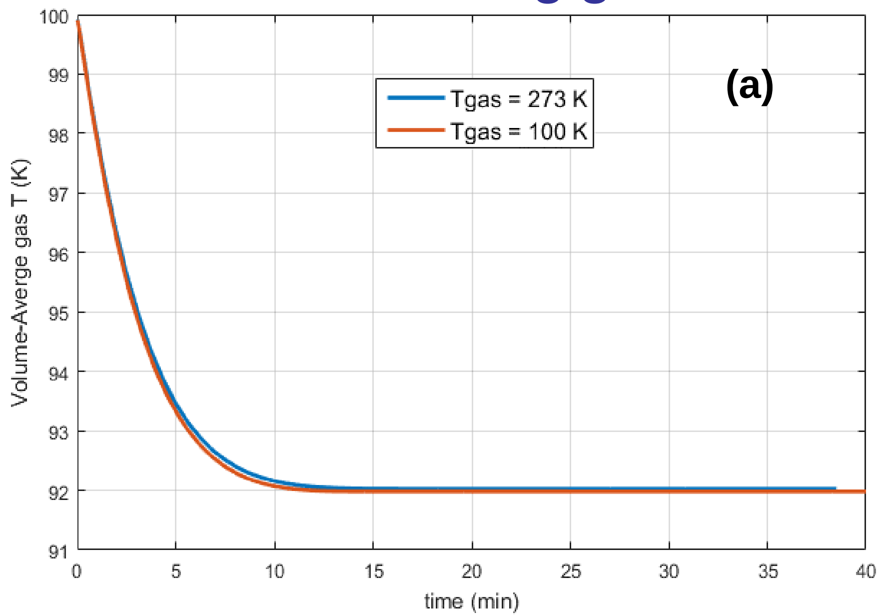


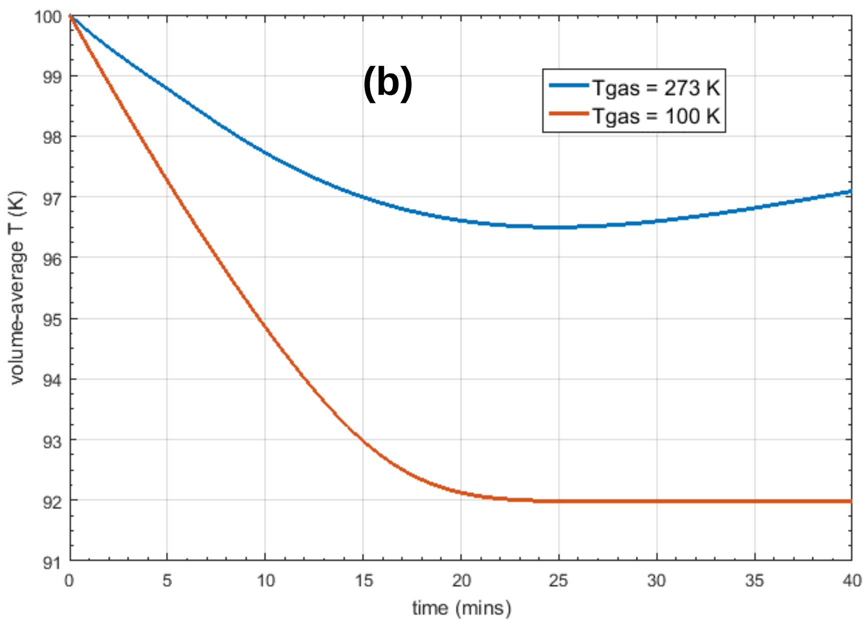
- **Heat transfer coefficient near the dry wall is around 50 W/m^2-K.**
- **Natural convection calculated from CFD model is an order of magnitude (50 W/m^2-K) larger than hand calculations using Grashof numbers (0.3 – 1.85 W/m^2-K)**

ANSYS Fluent results

Time history of the volume-average gas temperature

- Incoming gas: 273 K and 100 K



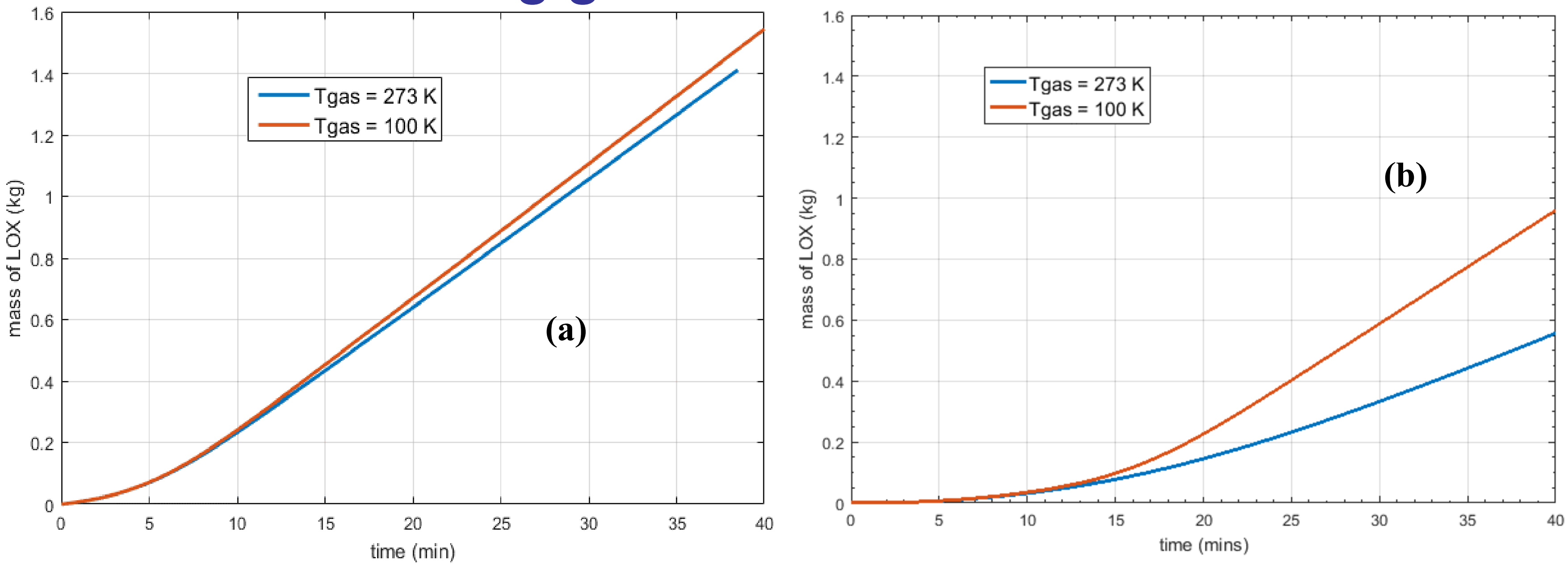


- **In graph (a), with tank wall at 90 K, GOX chills down very quickly, within 10 minutes for both cases - incoming gas at 273 K and 100 K. This is the optimal case.**
- **In graph (b), the tank wall heat flux is fixed. This is the worse case.**
  - **With the incoming gas of 273 K, it takes much longer to cool the gas down and the gas is much warmer.**
  - **With the incoming gas of 100 K, it takes 20 minutes to chill down.**

ANSYS Fluent results

Time history of the mass of Lox

- Incoming gas: 273 K and 100 K

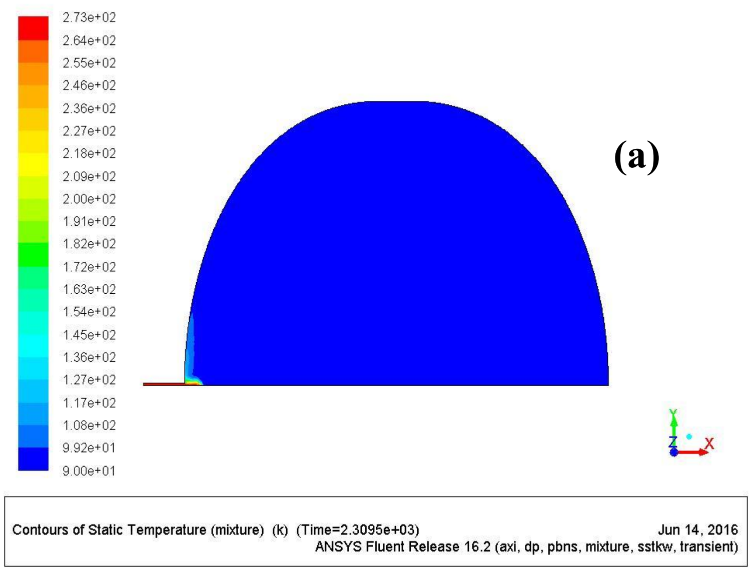


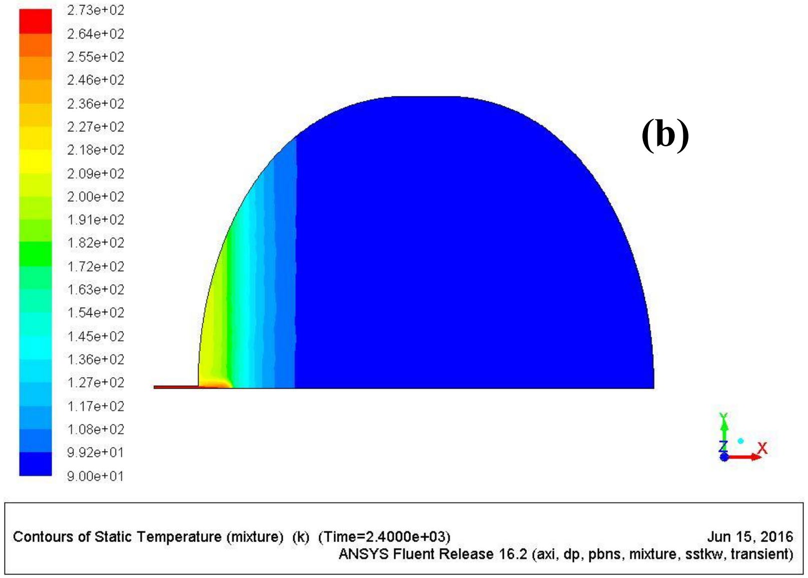
- **Graph (a) wall temperature fixed at 90K; graph (b) heat flux is fixed.**
- **The liquid oxygen inside the tank at t = 40 minutes is**
  - **For incoming gas of 273 K:**
    - **1.48 kg in case (a), 0.55 kg in case (b), a factor of 2.7.**
  - **For incoming gas of 100 K:**
    - **1.52 kg in case (a), 0.95 in case (b), a factor of 1.6.**

ANSYS Fluent results

Temperature contour of mixture

- Incoming gas: 273 K



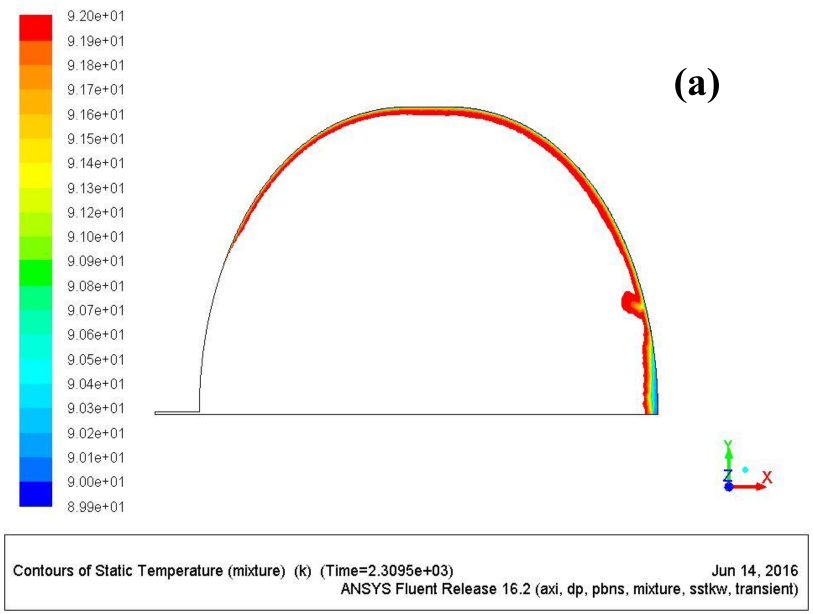


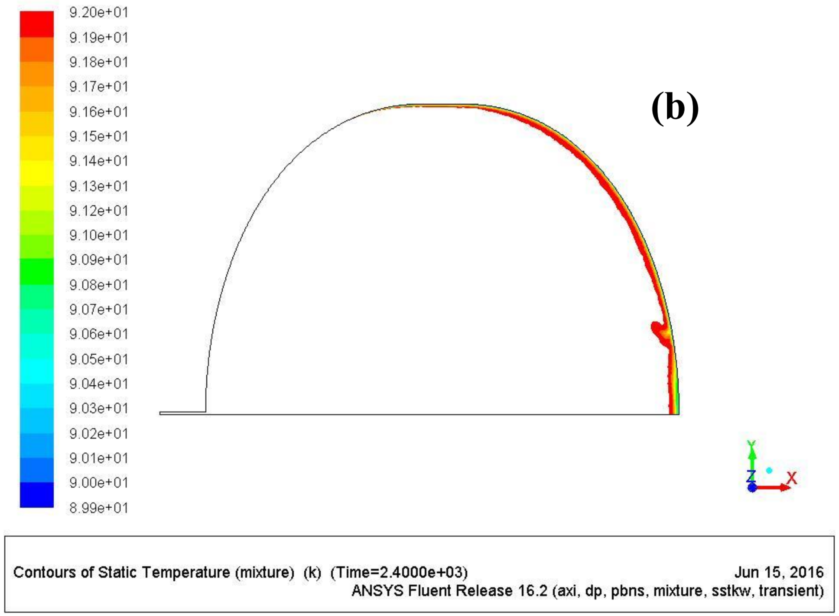
- **Graph (a) wall temperature fixed at 90 K; graph (b) heat flux is fixed.**
- **The warm gaseous O_2 chills down within smaller volume with a cold wall.**

ANSYS Fluent results

Temperature contour of the mixture

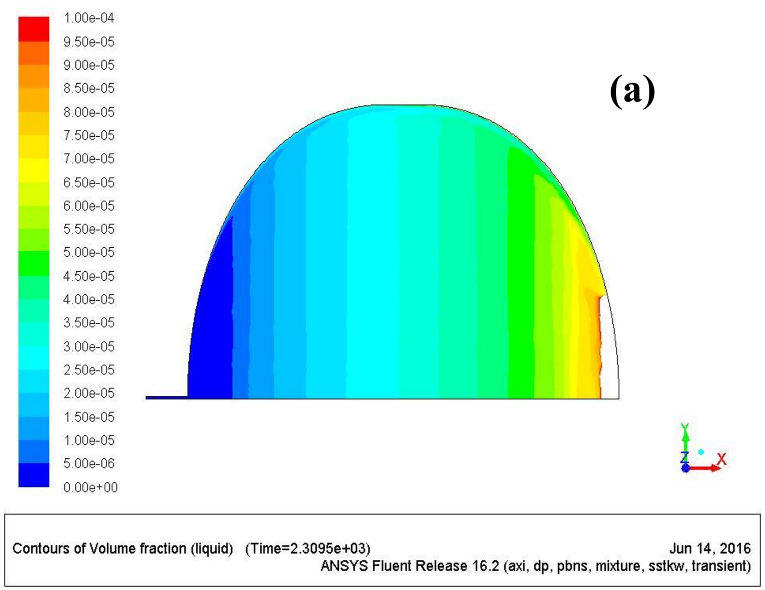
- Incoming gas: 273 K

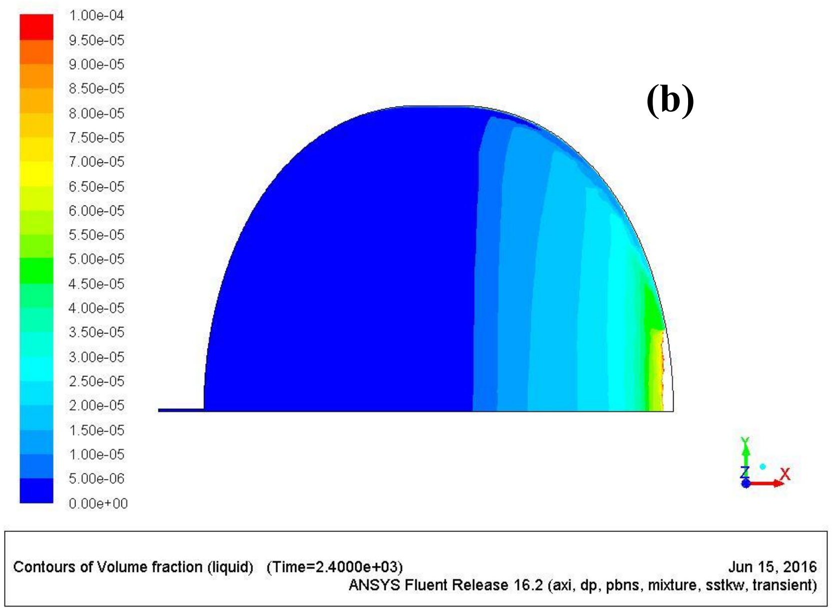




- **Graph (a) wall temperature fixed at 90 K; graph (b) heat flux is fixed.**
- **With a cold wall, condensation occurs more surface area of the tank.**

Volume fraction of liquid contour

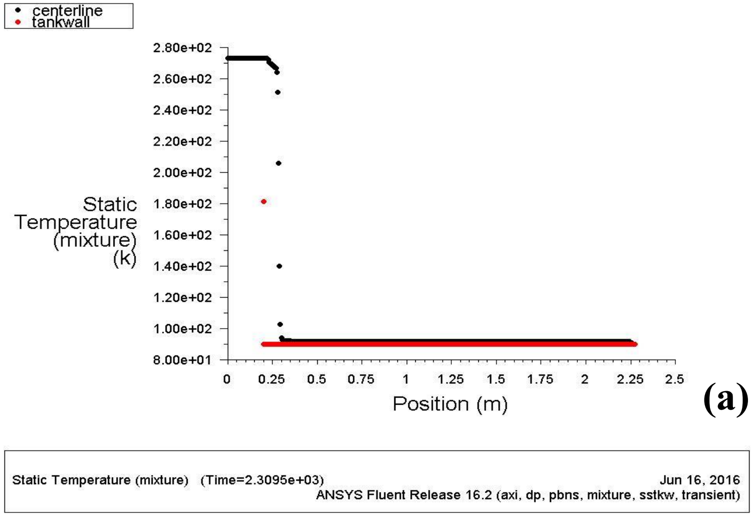


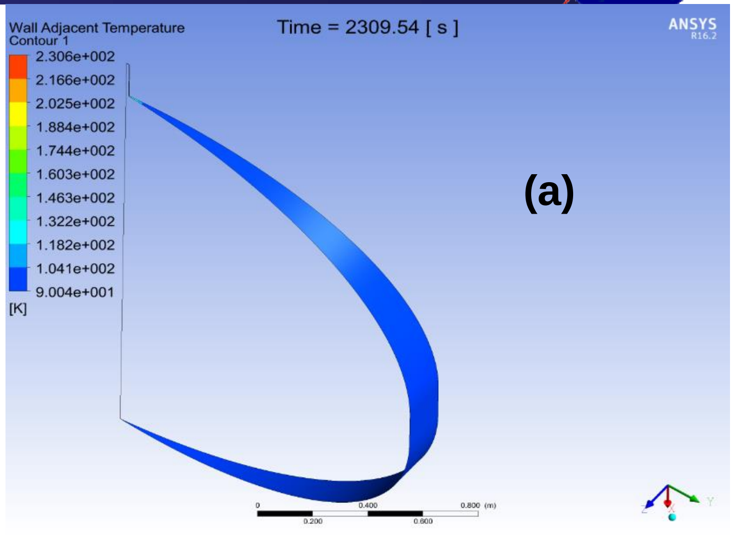


- **Graph (a) wall temperature fixed at 90 K; graph (b) heat flux is fixed.**
- **With a cold wall, more liquid O_2 is formed at the bottom of the tank.**

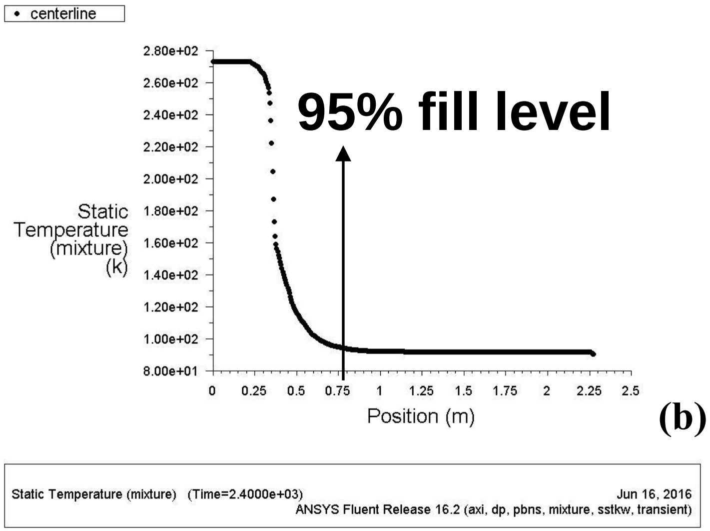
ANSYS Fluent results of gas temperature

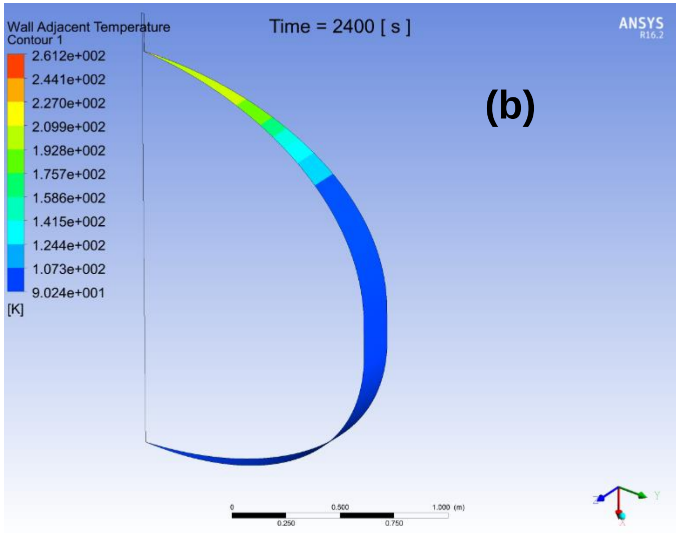
specify Twall
as 90 K
(optimal case)





Specify Heat flux
as BCs
(worst case)





Conclusions

- The condensation rate predicted by CFD analysis depends on the tank wall boundary condition. We presented two bounding cases.
  - For case (a), with an assumed 90K tank wall the gas chills down very quickly, within 10 minutes for both incoming gas of 273 K and 100 K. This is the optimal case.
  - For case (b), with a constant heat flux assumed, for the incoming gas of 273 K, the condensation rate is much smaller and larger portion of the tank area near the top stays warm. This is could be the worse case.
  - Heat transfer around the majority of tank is natural convection driven.
  - Incoming warm gas induces mixing currents and forced convection occurs near the inlet tube.
- Natural convection calculated from CFD model is an order of magnitude (50 W/m^2-K) larger than hand calculations (0.3 – 1.85 W/m^2-K)
- Tube-on-tank concept works for the baseline condition (warm case). MAV tank provides enough heat transfer area for liquefaction. There are some concerns near the top of the tank, however, it is beyond 95% fill level.
- Pre-chilling gaseous O_2 will speed up the liquefaction rate inside the tank as long as the lift of the cryocooler is allocated enough for the tank itself.

Future works

- 1D thermal model in Matlab and 3D thermal model in Thermal Desktop are on-going to include the cooling fluid in the model to get a more realistic tank wall boundary conditions.
- Test plans on the tube-on-tank concept are on-going. The objectives of the test plan are
  - To integrate the reverse turbo-Brayton-cycle cryocoolers system with the tank and control system (existing hardware)
  - To Investigate the performance of the active thermal liquefier system under
    - Different fill levels
    - Different feeding gaseous oxygen temperatures
    - Different control schemes
- Validations between the test results and model results will be performed.

Acknowledgement

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Back up charts