Implementation of Sub-Cooling of Cryogenic Propellants by Injection of Non-condensing Gas to the Generalized Fluid Systems Simulation Program (GFSSP)

Daniel J. Huggett[1] , Dr. Alok Majumdar[2]

[1]Department of Mechanical Engineering, Louisiana State University, Baton Rouge, LA

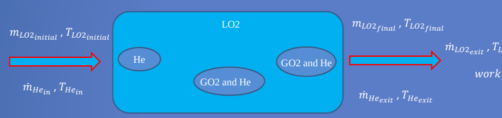
[2]ER43, NASA Marshall Space Flight Center, Huntsville, AL

ABSTRACT

Cryogenic propellants are readily heated when used. This poses a problem for rocket engine efficiency and effective boot-strapping of the engine, as seen in the "hot" LOX (Liquid Oxygen) problem on the S-1 stage of the Saturn vehicle. In order to remedy this issue, cryogenic fluids were found to be sub-cooled by injection of a warm non-condensing gas. Experimental results show that the mechanism behind the sub-cooling is evaporative cooling. It has been shown that a sub-cooled temperature difference of ≈ 13 °F below saturation temperature [1]. The phenomenon of sub-cooling of cryogenic propellants by a non-condensing gas is not readily available with the General Fluid System Simulation Program (GFSSP) [2]. GFSSP is a thermal-fluid program used to analyze a wide variety of systems that are directly impacted by thermodynamics and fluid mechanics. In order to model this phenomenon, additional capabilities had to be added to GFSSP in the form of a FORTRAN coded sub-routine to calculate the temperature of the sub-cooled fluid. Once this was accomplished, the sub-routine was implemented to a GFSSP model that was created to replicate an experiment that was conducted to validate the GFSSP results.

EVAPORATIVE COOLING

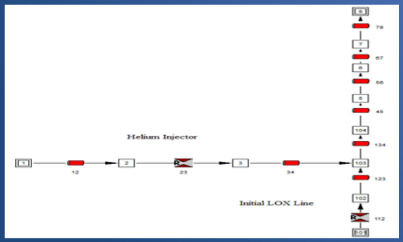
Figure 1 (right). Evaporative cooling mechanism. Initially, a LOX tank to saturation. After, gaseous Helium is injected. Evaporation of LOX occurs at the gas-liquid interface which transfers a portion of the oxygen to the Helium bubble (mechanical diffusion). This Evaporation of LOX lowers the energy of the surrounding fluid which consequently causes the temperature decrease of the bulk liquid.



METHODS

1. Analyze GFSSP mixing capabilities and compare with steady-state energy equation formulation
2. Create static LOX tank model with GFSSP
3. Implement He Injector to the model
4. Create FORTRAN subroutine to add new physics to the model
5. Implement subroutine to model to calculate new fluid temperatures.
6. Compare results to Vaniman's experimental results

ANALYSIS AND RESULTS



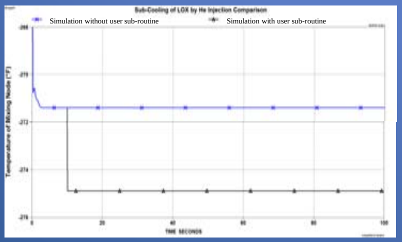


Figure 2. Seen above is a comparison of two simulations to analyze how GFSSP handles the mixing of LOX and Helium. The GFSSP GUI model (left) illustrates a LOX line with He injector. The first step was too analyze mixing by running a simulation with the current GFSSP mixing calculations. It can be seen that there is no sub-cooling of LOX. Next, a steady-state model was created to alter the current mixing calculations to accommodate evaporative cooling. The results (right) of the user sub-routine show sub-cooling of LOX.

$$\left(\dot{m}C_pT_{in}\right)_{LO2} + \left(\dot{m}C_pT_{in}\right)_{He} = \left(\dot{m}C_pT_{exit}\right)_{LO2} + \left(\dot{m}C_pT_{exit}\right)_{He} + \left(\dot{m}h_{fg}\right)_{GO2} + (work) \qquad (1)$$

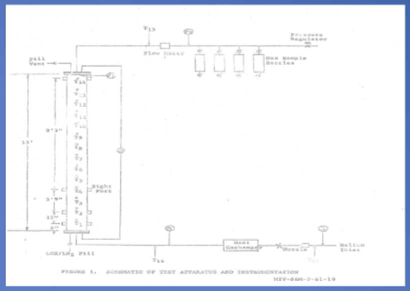


Figure 3. Schematic of LOX tank used in the Vaniman experiment [1].

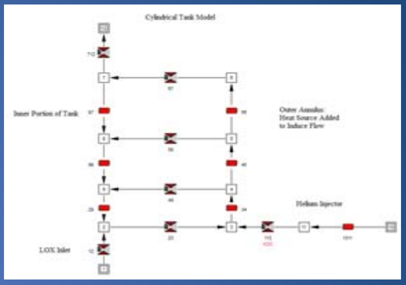


Figure 4. GFSSP GUI model representing the Vaniman tank experiment [2].

$$\frac{d}{dt}\left(mC_pT\right)_{LO2} = \left(\dot{m}C_pT\right)_{He} - \left(\dot{m}h_{fg}\right)_{GO2} - (work) \qquad (2)$$

$$T_{exit_{\tau+\Delta\tau}} = \frac{\left(mC_pT_{exit}\right)_{LO2_\tau} + \left[\left(\dot{m}C_pT_{in}\right)_{LO2_\tau} + \left(\dot{m}C_pT_{in}\right)_{He_\tau} - \left(\dot{m}h_{fg}\right)_{GO2} - (work)\right]\cdot\Delta\tau}{\left(mC_p\right)_{LO2_{\tau+\Delta\tau}} + \left[\left(\dot{m}C_p\right)_{LO2_{\tau+\Delta\tau}} + \left(\dot{m}C_p\right)_{He_{\tau+\Delta\tau}}\right]\cdot\Delta\tau} \qquad (3)$$

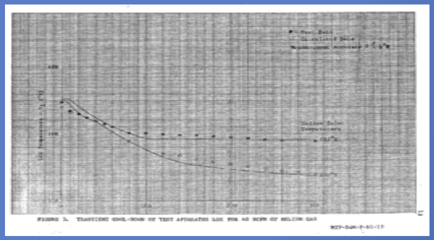


Figure 5. Vaniman experimental results of LOX sub-cooling [1].

LOX			He	
Initial Temp. (°F)	-307		Initial Temp. (°F)	55.33
Initial Pressure (psia)	12.56		Initial Pressure (psia)	400

Table 1. Initial values used in the GFSSP simulations for LOX and Helium

CONCLUSION

- It was found that normal modeling procedures with GFSSP could not be utilized and therefore an unconventional tank model was created.
- GFSSP mixture options were analyzed and determination of which calculation package produced most accurate results.
- A new derivation of the energy equation of mixing of fluids was created to simulate evaporative cooling.

REFERENCES

[1] Randolf, Wilburm, and Vaniman, Jerold, "Sub-Cooling of Cryogenic Liquids by Injection of Non-Condensing Gas", NASA TM-X-50062, 1961

[2] GFSSP, Generalized Fluid Systems Simulation Program, Ver. 6, NASA Marshall Space Flight Center, 2013

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