# Analysis of Liquid Oxygen Feeding System for Pump-Fed Liquid Propulsion Rocket

*Nam-Kyung Cho*, Oh-Sung Kwon*, In-Hyun Cho*, Young-Mog Kim**
*Korea Aerospace Research Institute*
*45 Oun-Dong Yusung-Gu Daejeon 305-333 Korea*
*cho@kari.re.kr*

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## Abstract

**For design of cryogenic propellant feeding system, one of the main requirements is to meet temperature requirement for satisfying turbo-pump NPSH requirement. In this paper improved method of estimating the thermal stratification in liquid oxygen tank is presented to help design. In the case of liquid rocket using turbo-pump, the inner pressure of liquid oxygen tank is maintained low, so vaporization of liquid oxygen is generally occurred. In this paper, inner process of LOX tank is analyzed by two phase flow modeling. The vaporization rate and required helium mass is investigated.**

## Introduction

The primary objective of a liquid rocket propellant and pressurization system is to supply propellant to the engine at the required conditions. For a pump-fed engine, sufficient pressure is required to suppress cavitation in the pump. The rocket designer must provide the required margin between total pressure and vapor pressure at all times during flight. As NPSH(Net Positive Suction Head) depends strongly on propellant temperature, the avoidance of propellant temperature increment is important. Concerning LOX temperature in tank, temperature increase is usually occurred during pre-pressurization stage. At the pre-pressurization stage, LOX is usually pressurized by helium from ground source. In usual case, LOX tank is not thermally insulated from room temperature environment for the purpose of reducing system complexity and weight which makes LOX temperature gradually increase by wall heat flux and pressurant helium gas. In this paper the LOX temperature increment is simulated during pre-pressurization stage.

It is often advantageous to apply hot gas heat exchanger in the pressurization system to increase the specific volume of the pressurant[5] and thereby reduce overall system weight[1]. A significant improvement in pressurization can be achieved in a cryogenic system, where the gas is stored inside the cryogenic tank.

During flight the LOX is pressurized by high temperature helium. In addition the tank experiences aerodynamic heating. Although the operating time is short, it is thought that the high temperature helium inflow (about 550 K) may bring about the vaporization of LOX (93 K). The vaporized LOX mass may reduce needed helium inflow, whereas it may cool helium ullage, which leads to more helium inflow. So the estimation of the amount of LOX vaporized is considered to be important issue. In this paper the LOX vaporization effect on required helium mass is investigated.

## Modeling of Propulsion System

Fig. 1 shows the schematic of LOX (liquid oxygen) feeding system to be analyzed. The system is assumed to be applied for 1st stage launcher propulsion system for LEO(low earth orbit) satellite. The pressurization is performed by helium. Helium bottle is installed in the LOX tank for densification. The cryogenic helium(about 91 K) is entered into heat exchanger where it is heated up to 550 K. The feeding system consists of liquid oxygen and kerosene supply lines. The mass flow rate of liquid oxygen is set at 256 kg/s. and kerosene is at 109 kg/s.(The flow rate is controlled by turbo-pump)

Liquid oxygen (90K) are supplied at 0.43 Mpa and kerosene(290 K) are at 0.33 Mpa.

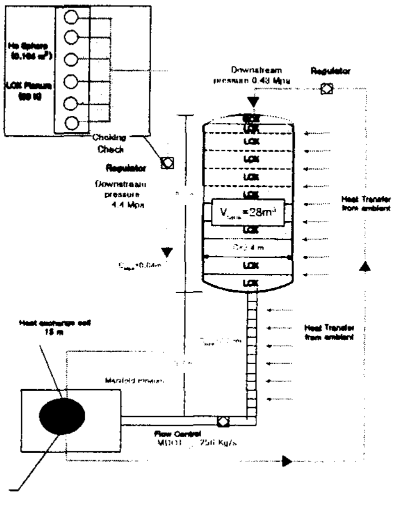

Fig. 1 Schematic of LOX feeding system

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## Modeling Method

### Modeling Program

For the analysis of propulsion system, SINDA/FLUINT program is used. SINDA/FLUINT is a comprehensive finite-difference, lumped parameter (circuit or network analogy) tool for heat transfer design analysis and fluid flow analysis in complex systems.

### Thermal Modeling

In applying SINDA/FLUINT model, for dealing with solid or stationary fluid, thermal model is used[2]. Thermal model can be summarized as capacitance and conductance modeling. $\rho CV$ term in eq. (1) is capacitance (control volume concept) and, if heat generation is ignored, right side of eq. (1) corresponds to conductance.

$$\rho CV\frac{dT}{dt} = \dot{Q}_{generation} + \dot{Q}_{transfer} \tag{1}$$

In the model of LOX feeding system, helium bottle wall, pipe wall, LOX tank wall, ambient are modeled as thermal model with temperature varying specific heats. Heat transfer between LOX and helium bottle wall , between pipe wall and ambient, and between LOX tank wall and ambient are modeled as conductance with appropriate natural convection coefficient which depends on temperature varying properties.

### Flow Modeling

Capacitance/Conductance concept can be applied to fluid model. But the conductor in the flow model is diverse comparing with thermal model as in eq. (2). The control volume at which energy and mass are conserved are described as lump in flow model[2]. Each lump has a single characteristic thermodynamic state.

$$\rho CV\frac{dT}{dt} = \sum h_{in}\dot{m}_{in} - \sum h_{out}\dot{m}_{out} + \dot{Q}_{generation} + \dot{Q}_{transfer} - P\frac{dV}{dt} \tag{2}$$

In LOX feeding system model, helium gas in the bottle and LOX, model interfaces, joining points (e.g. tees), dead ends, intermediate pipe flow are described as lump. The mass flow through lump is described as path as in eq. (3).

$$\frac{d\dot{m}}{dt} = \frac{A}{L}(P_{up} - P_{down} + HC + FC\cdot\dot{m}|\dot{m}|^{FPOW} + AC\cdot\dot{m}^2 - \frac{FK\cdot\dot{m}\cdot|\dot{m}|}{2\cdot\rho\cdot A^2}) \tag{3}$$

In eq. (3) HC is body force term, FC is pipe loss coefficient ($f$ in $\Delta P = f(L/D)\times\rho V^2/2$), FK is device loss coefficient ( $K$ in $\Delta P = K\times\rho V^2/2$ ), AC is recoverable loss coefficient due to area and density change. In applying SINDA/FLUINT model, various path elements which describe pipe, regulator, pump suction, orifice etc. are used.

### LOX sub-volume interface

As in Fig.1, LOX tank is subdivided into 10 sub-volumes to examine thermal stratification phenomena. The sub-volume interface is described by 'iface' in SINDA/FLUINT. Unlike a path, no mass flows through an 'iface'. Rather, an iface describes the interface attribute between the two LOX sub-volumes and how they behave. That is, iface interface means that two adjacent control volumes (LOX sub-volumes) share a common boundary and their pressures and volumes are interrelated. During LOX supply to engine, the calculation method is Lagrangian approach. The properties for a given sub-volume are tracked as it is subjected to the processes within the tank. Each sub-volume lose mass during LOX supply to engine ( $\dot{m} = 256 kg/s$ ), gain heat or lose entanlphy depending upon what is happening. In initial period, LOX is supplied from the lowest sub-volume and in some time it is depleted. If the lower sub-volume gets too small it is collapsed and LOX is supplied from adjoining sub-volume until all LOX sub-volumes are depleted. During the process pressure is same among all sub-volumes and total volume is conserved as in eq. (4) and (5)

$$P_k = P_{k-1} + \rho gh \tag{4}$$

$$V_{total} = \sum \Delta V_k \tag{5}$$

Among the LOX sub-volumes, conduction heat transfer is assumed.

### LOX vaporization and heat transfer with wall

Heat transfer to the LOX are schematically indicated in Fig. 2; heat transfer between liquid and wall adjacent to the liquid, heat transfer between liquid and liquid surface layer, heat transfer between gas and liquid surface layer, heat transfer between gas and wall adjacent to gas, heat transfer between external surroundings and wall adjacent to liquid.

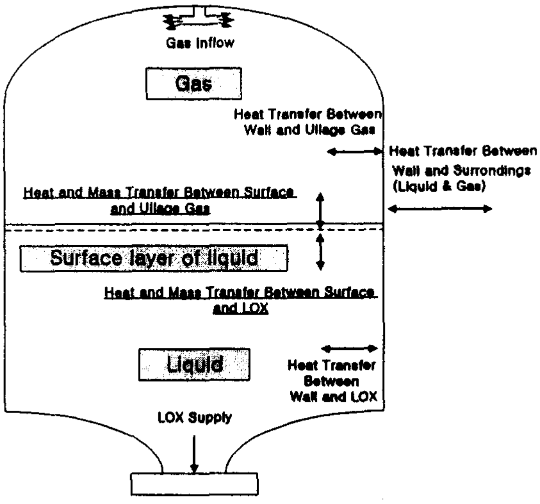

Fig 2. Schematic of LOX tank

It is assumed that initially the ullage space is filled with helium from ground source. As the warm helium enters the ullage space, it mixes with the cold ullage gas and the temperature of the ullage gas starts to increase due to mixing and compression. Initially, the walls of the tank are also at propellant temperature. Heat transfer from the ullage gas to the propellant and the tank wall and mass transfer from the propellant to the ullage start immediately after the helium begins flowing into the tank. LOX flows from the tank to the engine under the influence of ullage pressure and gravitational head in the tank. By heat transfer from warm gas to LOX surface, LOX is vaporized until the LOX surface temperature reaches saturation temperature according to the ullage pressure. Heat transfer between the liquid and the LOX surface takes the form of free convection from a horizontal surface. The heat transfer coefficient applied between the wall and LOX depends on wall temperature. If wall temperature is below saturation temperature, conventional natural convection is applied and if wall temperature is higher than saturation temperature, boiling heat transfer coefficient is applied. For waiting time with pre-pressurization, film boiling heat transfer coefficient is applied and for main LOX supply stage, nucleate boiling is applied$^{10)}$.

## Results

### Waiting Stage with pre--pressurization

Fig. 3 shows LOX temperature distribution with hydrostatic height during waiting time(No LOX is supplied to engine and pre-pressurized up to 4.3 bar). As the figure shows, the temperature of the layer adjacent to surface (H=5.5-6 m) is higher by 0.6 K than other layers. The temperature is almost uniform at layers below H=5.5 m. About 1.4 K is raised during 60 minutes waiting period.

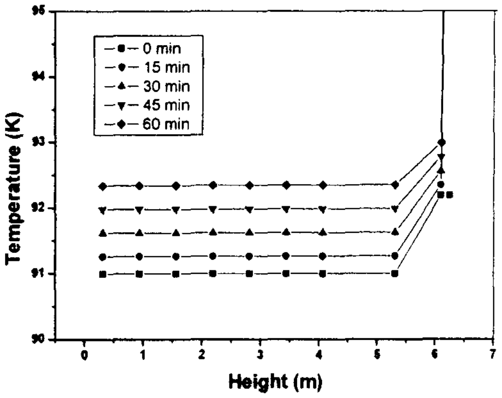

Fig 3. Temperature distribution during waiting period

Fig. 4 shows LOX temperature history during 60 minutes. The graph shows the temperature histories of top layer and layer adjacent to top layer. The relative high temperature of the top layer is caused from heat transfer from ullage gas. The temperature increment is about 0.8 K at top layer and 1.2 K at second layer. The relatively low temperature increment on the top layer is caused that vaporized LOX suppress temperature increment(heat of vaporization is removed from surface)$^{9)}$.

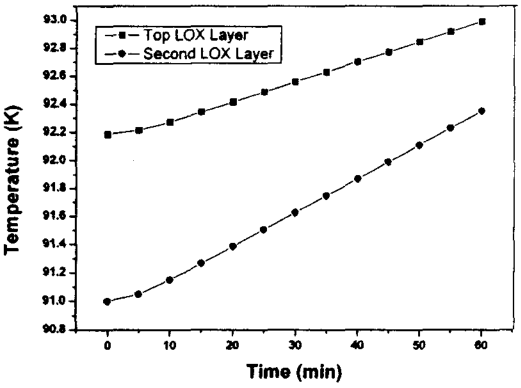

Fig. 4 LOX layer temperature history waiting during period

Fig 5. shows LOX ullage temperature and vaporized LOX flow history during waiting period. During waiting time LOX is pre-pressurized at 4.3 bar. As times goes on, some part of vaporized LOX is vented to atmosphere by vent valve and small amount of helium comes into ullage, The figure describes that in initial stage in waiting time, high rate of vaporization occurs. And after 20 minutes, ullage temperature and vaporized LOX mass flow is gradually increased.

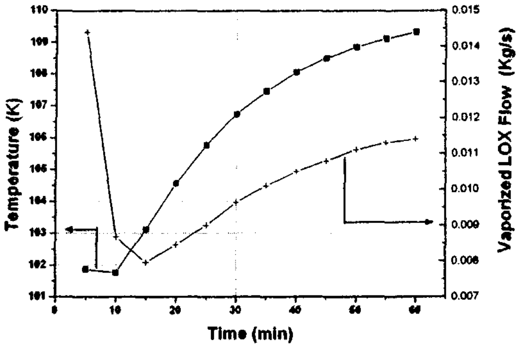

Fig. 5 LOX ullage temperature and vaporized LOX flow

### Main LOX supply stage

Fig. 6 shows LOX ullage temperature in case of LOX vaporization comparing with the case that vaporization is not considered. During main LOX supply stage high temperature helium gas(550 K) inflow to ullage. In case of vaporization is considered, the ullage temperature is about 40 K lower as vaporized LOX cools ullage.

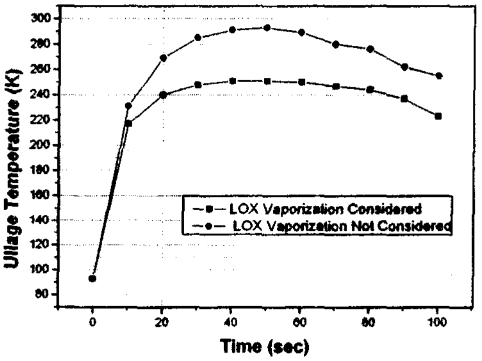

Fig 6. LOX ullage temperature comparison

Fig 7. shows vaporized LOX flow history. Due to high temperature helium inflow during pressurization , the vaporized mass flow rate is high. The vaporized mass increases rapidly in initial supply period. And at about 30 seconds, the vaporization rate decreases as the ullage is cooled by vaporized LOX.

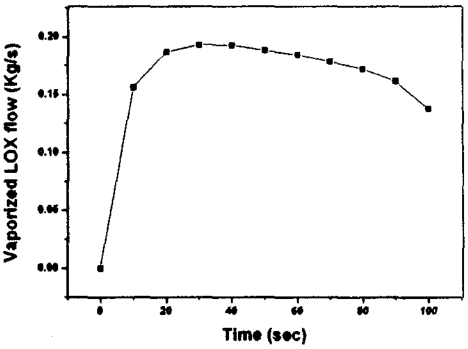

Fig 7. Vaporized LOX flow history (during main supply)

Fig 8. shows the comparison of helium mass per bottle during main supply period. As in Fig 6. The vaporized LOX cools helium ullage, which leads to be in need of more helium. Whereas the vaporized LOX mass may reduce helium inflow as it functions as pressurant gas in the ullage. Fig 8 shows the net effect of these two phenomena. The result shows 7.3% helium mass is increased in case of vaporization considered, which means cooling effect of vaporized LOX is dominant.

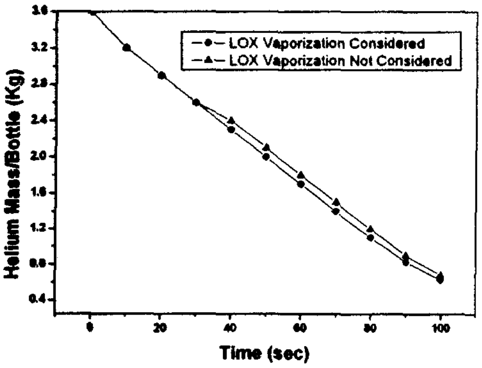

Fig. 8 Comparison of helium mass/bottle (during main supply period)

## Conclusion

In this paper improved method of estimating the thermal stratification in liquid oxygen tank is presented. At top LOX layer, the temperature is 0.8 K higher than other layers. As the rocket engine designer may have interested in maximum temperature encountered at the pump inlet, the LOX temperature of top layer should be carefully examined.

The temperature rise during pre-pressurization stage is about 1.4K. The vaporization rate and required helium mass is investigated. The vaporization of LOX at the surface increased required helium mass about 7.3%.

## Acknowledgement

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**Nomenclature**

| | |
|---|---|
| $\rho$ | density |
| $C$ | specific heat |
| $V$ | volume |
| $T$ | temperature |
| $\dot{Q}_{generation}$ | heat generation rate |
| $\dot{Q}_{transfer}$ | heat transfer rate |
| $\dot{m}$ | mass flow rate |
| $P$ | pressure |
| $A$ | area |
| $L$ | distance, length |
| $HC$ | body force term |
| $FC$ | pipe loss coefficient |
| $FK$ | device loss coefficient |
| $AC$ | recoverable loss coefficient due to area and density change |
| $h$ | hydrostatic head |

**Superscript/Subscript**

| | |
|---|---|
| $FPOW$ | flow rate exponent index |
| $up$ | upstream |
| $down$ | downstream |
| $k$ | order index |