Analysis of cryogenic liquid propellant densification with ejector

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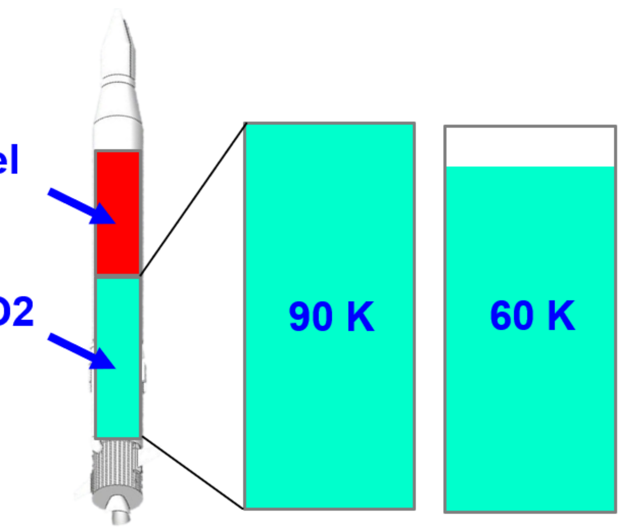
Abstract

A method for densification of cryogenic propellants by cooling down the temperature of liquid propellants is performed with ejector. LN2 and LO2 are subcooled by decreasing the vapor pressure of fluid under the atmospheric pressure. A single ejector showed low entrainment ratio due to the low suction pressure. Hens, a multiple ejector is proposed to increase the process entrainment ratio. The entrainment ratio which is directly connected with system efficiency significantly increased with the addition of ejector stages.

Introduction of propellant densification

- Subcooled cryogenic propellants such as LO2, LH2 is successfully applied in launch vehicles to increase density of propellants.
- Increase of density is advantageous for smaller propellant tanks and components which leads to reduction of lift-off weight of launch vehicle.
- Subcooling of propellants could be done by using independent refrigerators or by lowering the vapor pressure of fluid.



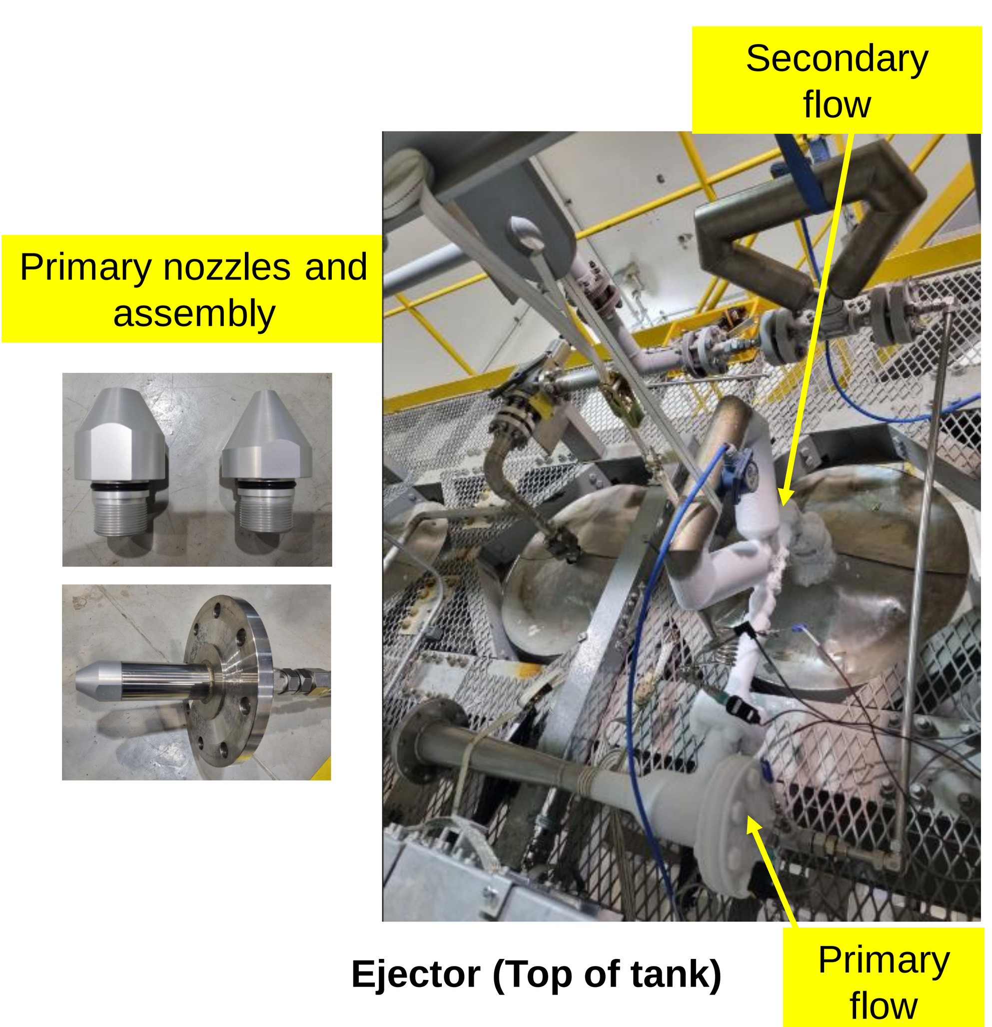
same mass of LO2

Temperature(K)	Density(kg/m³) at 1 atm
90	1142.1
80	1190.6
70	1237.1
60	1282.1

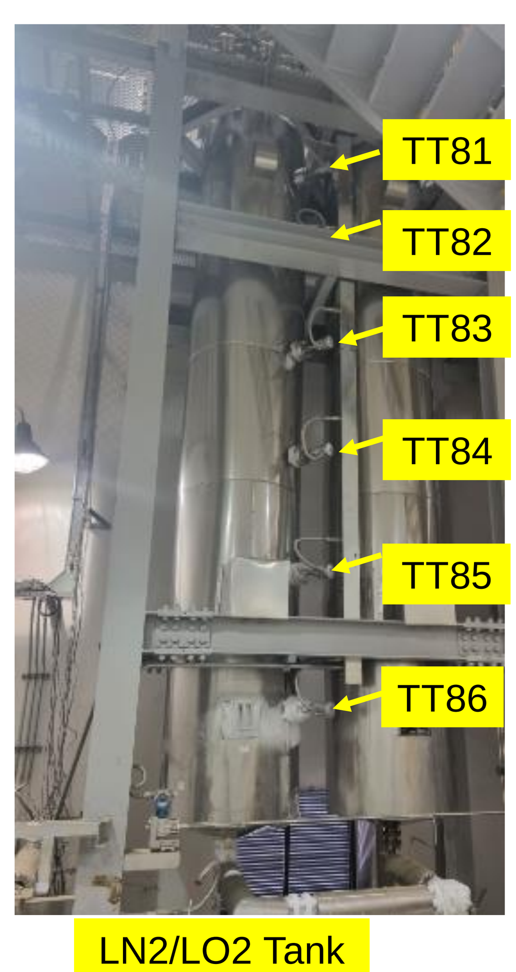
- LO2 density varies with temperature
- LO2 volume can be reduced 89.1% at 60 K

Ejector and Test Facility

- Ejector is fabricated with three types of nozzles, and the ejector is installed at the top of LN2/LO2 tank (internal volume: 600 Liter).



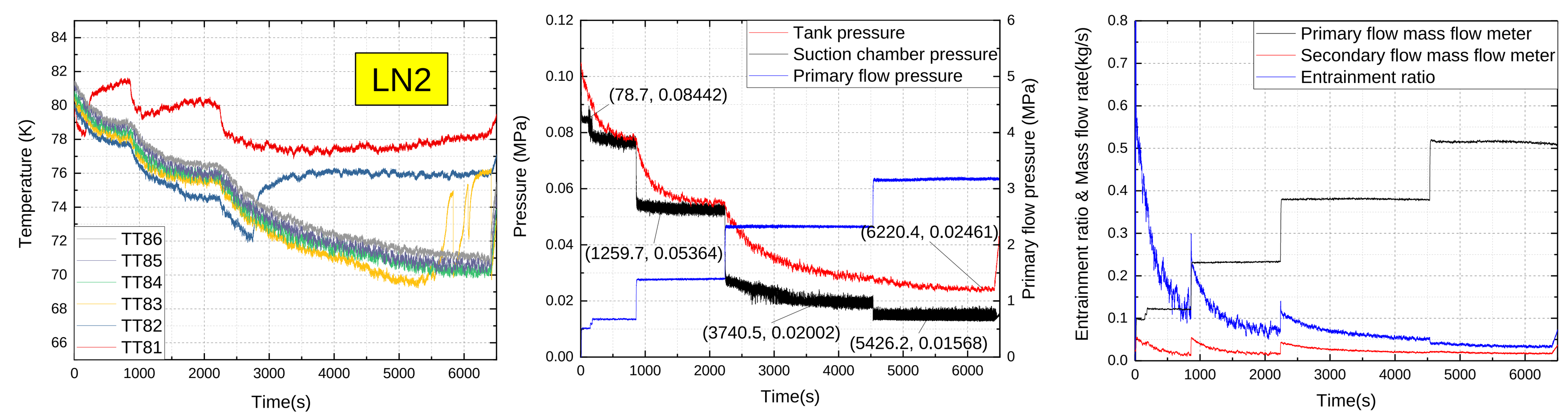
Ejector (Top of tank)

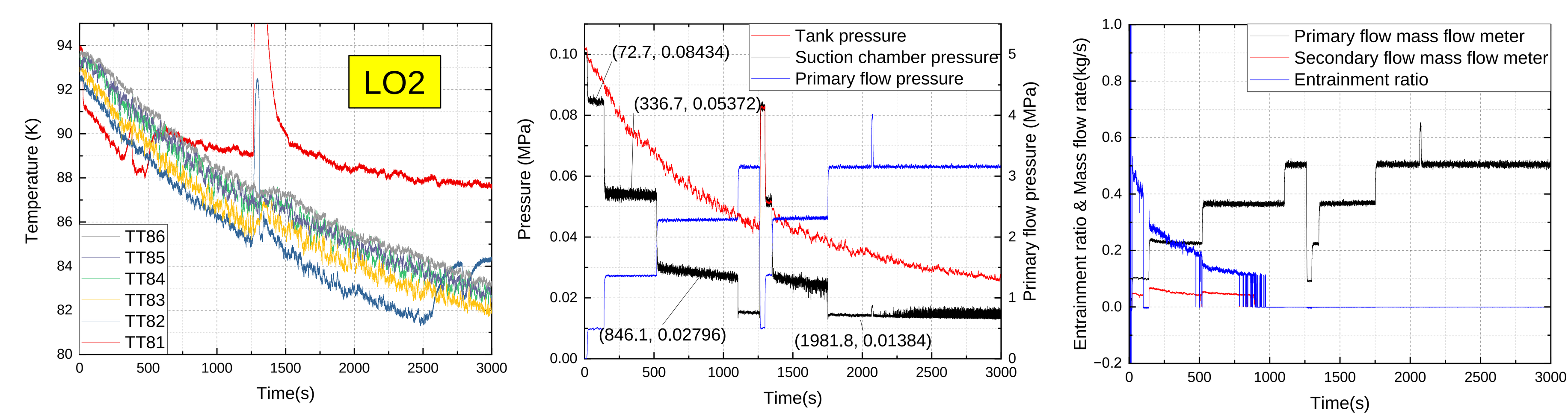


LN2/LO2 Tank

Densification test results with LN2 and LO2

- LN2 is subcooled to 70 K, and LO2 is subcooled to 82 K by the ejector.
- Tank pressure follows the ejector suction chamber pressure.
- Fluid is subcooled by evaporation cooling, so the temperature from the top position of fluid is lower than others, and top position temperature starts to rise when the sensor is exposed to the vapor state of fluid.
- Entrainment ratio decreases rapidly along the time because both of the secondary flow rate and the tank pressure decrease.

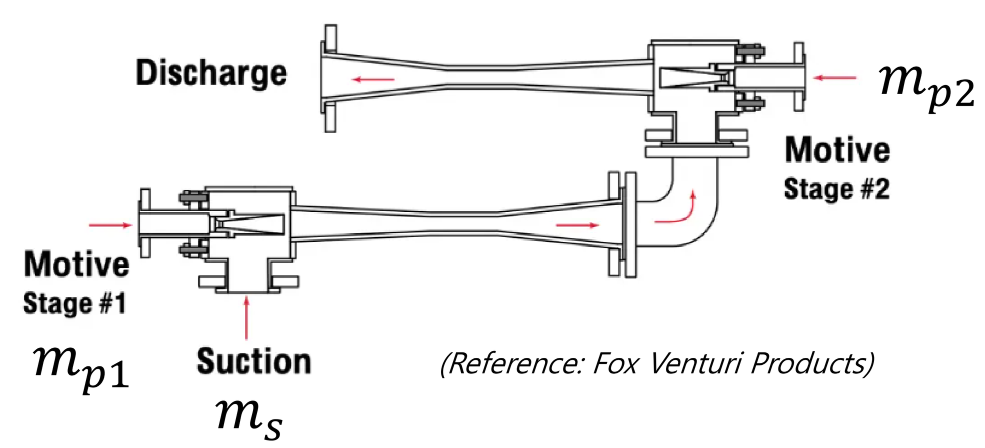




Application of multiple stage ejectors

- Usually multiple ejectors are used to achieve a lower vacuum pressure.
- If the secondary flow inlet pressure and the diffuser outlet pressure is constant, the secondary flow rate can be increased with multiple ejectors.
- This means entrainment ratio and cooling capacity of the ejector densification system can be increased.

Example of two-stage ejector



(Reference: Fox Venturi Products)

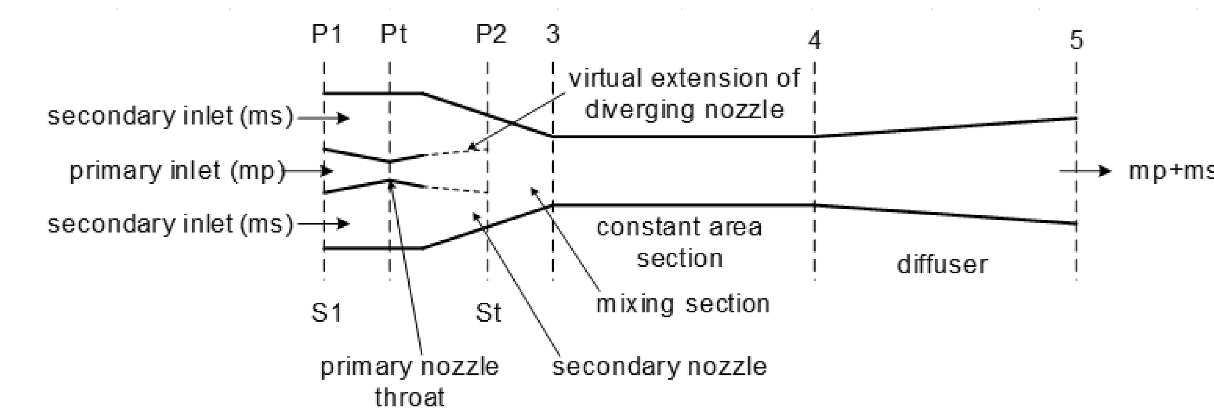
$$\mu = \frac{\dot{m}_s}{\dot{m}_p} \qquad P_r = \frac{P_{out}}{P_s} \qquad \mu \propto \frac{1}{P_r}$$

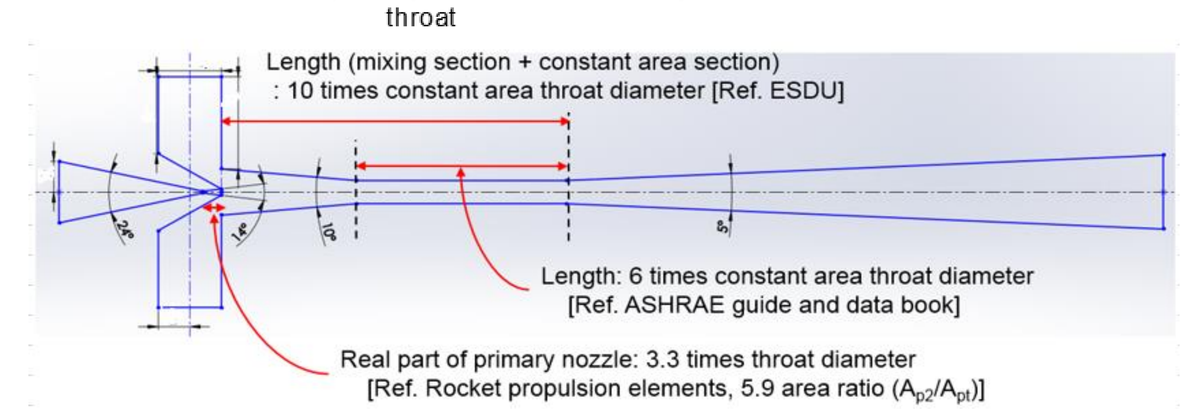
using multi-stage ejector

P_r ↓ μ ↑

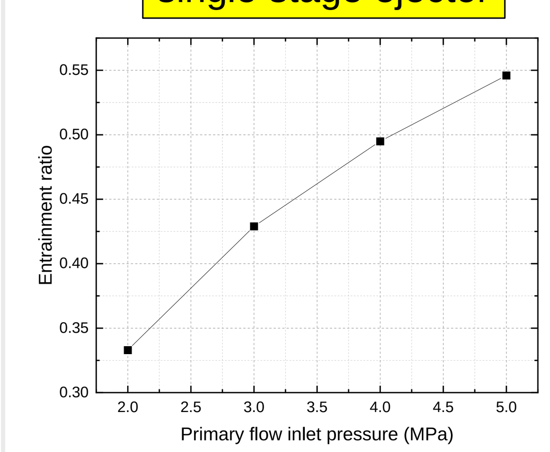
Performance prediction of multiple stage ejector with N2

- Ejector performance is calculated with 1-dimensional analytical ejector model.
- Secondary flow inlet condition is fixed at 30 kPa to avoid freezing point of nitrogen through the secondary flow acceleration.
- Secondary flow inlet temperature is assumed as saturated vapor at 30 kPa.
- Ejector outlet condition is fixed at atmospheric pressure.
- Primary flow inlet pressure is varied from 2 MPa to 5 MPa.
- Primary flow inlet temperature assumed as 300 K.

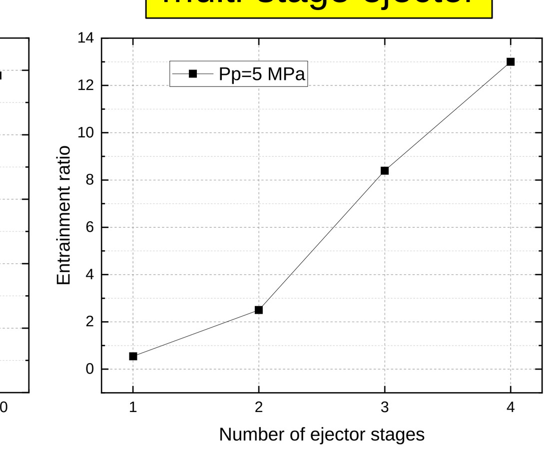




single stage ejector



multi-stage ejector



- Entrainment ratio increases with primary flow pressure.
- Entrainment ratio increases significantly with the addition of ejector stage.
- Calculation was not converged for high entrainment ratio with 5th addition of ejector.

Conclusion

- LN2 and LO2 are successfully subcooled by ejector.
- 300 liter of LN2 and LO2 are subcooled to 70 K and 82 K, respectively.
- Entrainment ratio was very low during cooling process especially with LO2.
- Multiple stage of ejector is proposed to increase the entrainment ratio.
- Entrainment ratio increases with higher primary flow pressure, however, the effect of multi-stage is more significant.
- Entrainment ratio increased more than 26 times with four-stage ejector.