Onboard Cryogenic Propellant Subcooler for Launch Vehicles Using Joule-Thomson Device

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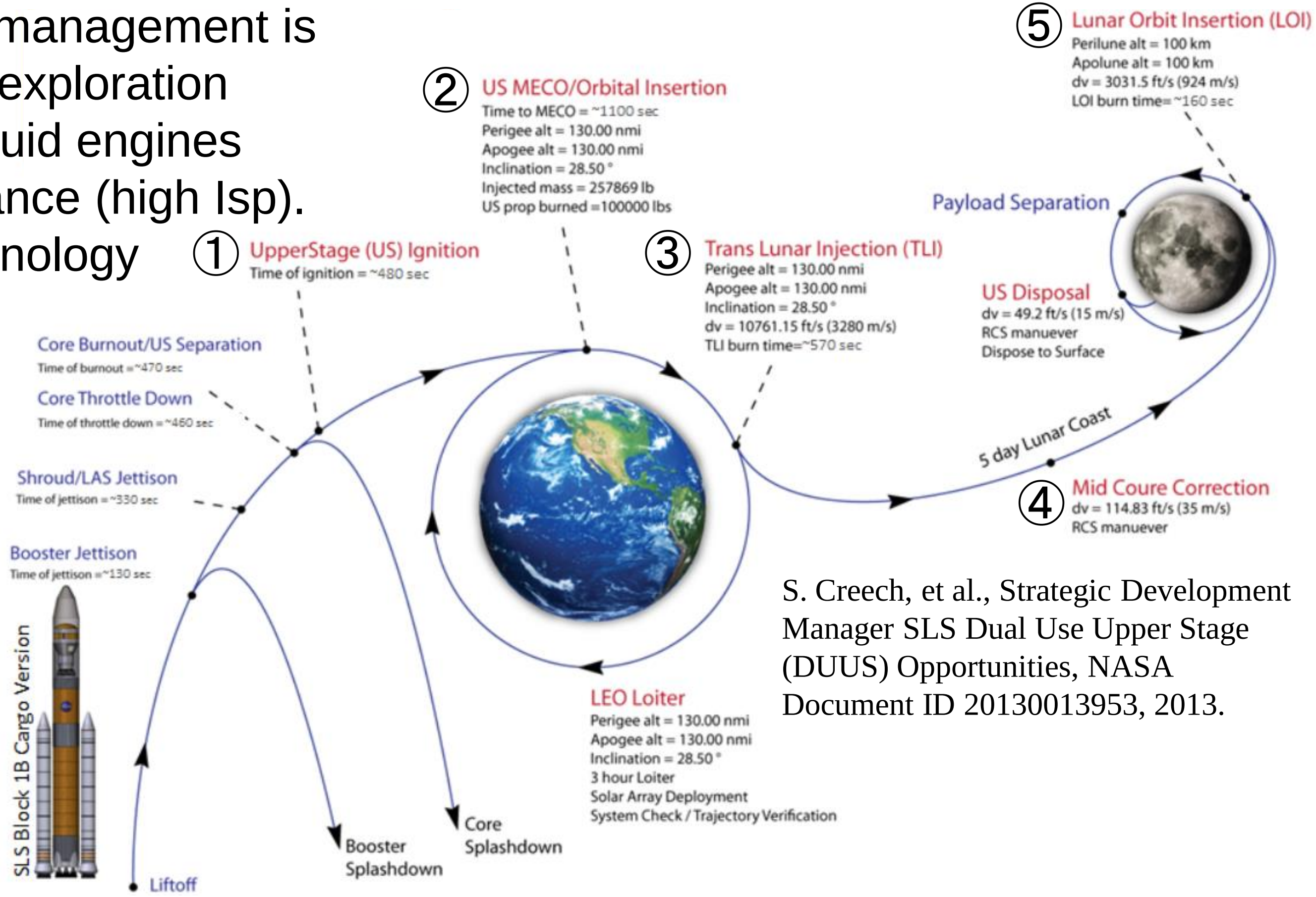
Introduction: Cryogenic Upper Stage for Space Exploration

- Cryogenic propellant management is a key for deep space exploration because cryogenic liquid engines provide high performance (high Isp).
- One of important technology is multiple cryogenic engine ignition.

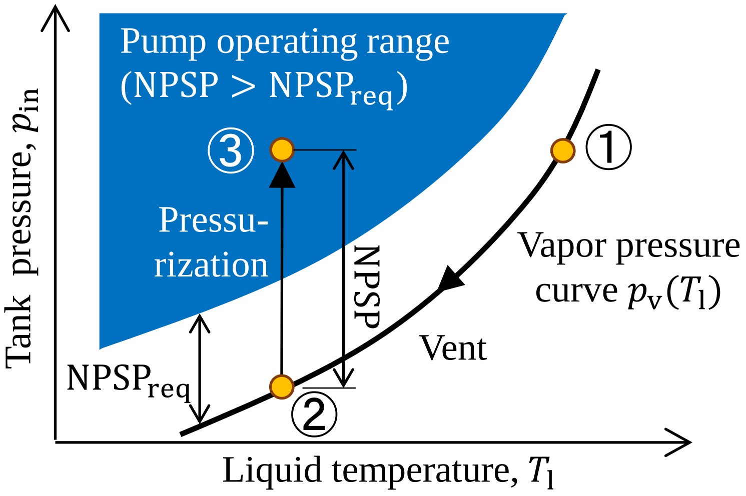


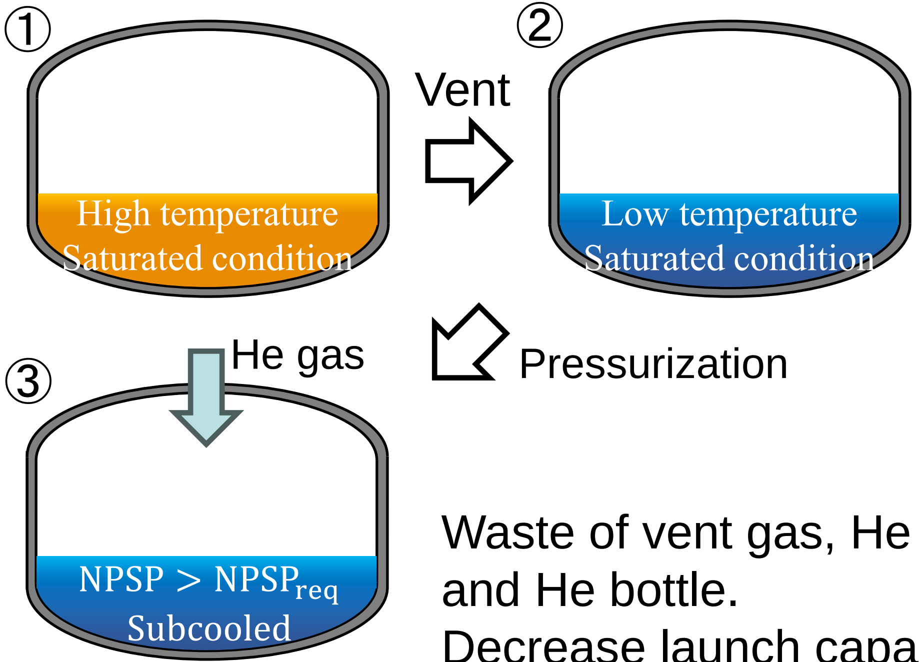
S. Creech, et al., Strategic Development Manager SLS Dual Use Upper Stage (DUUS) Opportunities, NASA Document ID 20130013953, 2013.

Conventional Sequence Before Engine Ignition

Subcooled liquid or sufficient NPSP is required to avoid cavitation instability in the pump:

$$\mathrm{NPSP} = p_{\mathrm{in}} + \frac{1}{2}\rho_{\mathrm{l}} u^2 - p_{\mathrm{v}}(T_{\mathrm{l}})$$





Waste of vent gas, He gas and He bottle.
Decrease launch capability.

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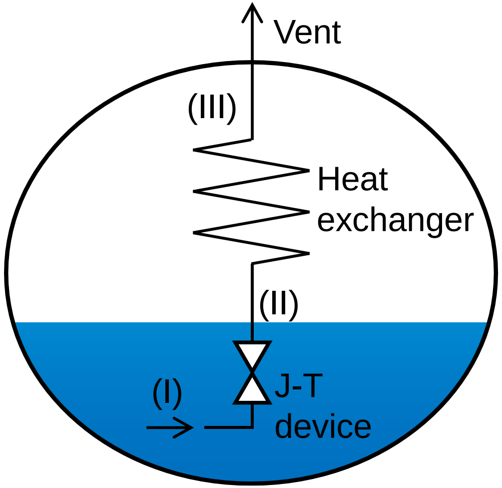
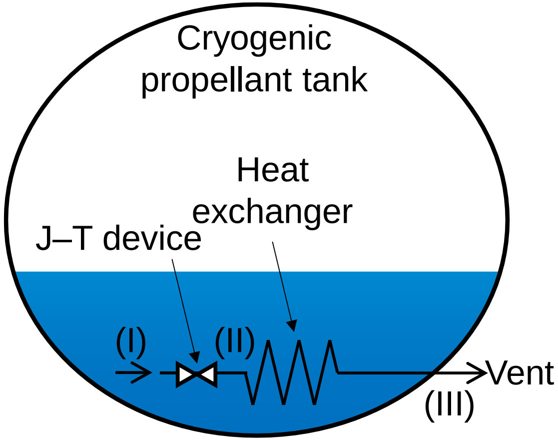
Proposed Method: TVS-based Liquid Subcooler

Onboard liquid subcooler based on TVS (Thermodynamic Vent System) using J-T (Joule-Thomson) expansion.



Normal TVS

Ullage cooling and pressure control



Proposed subcooler

Liquid subcooling

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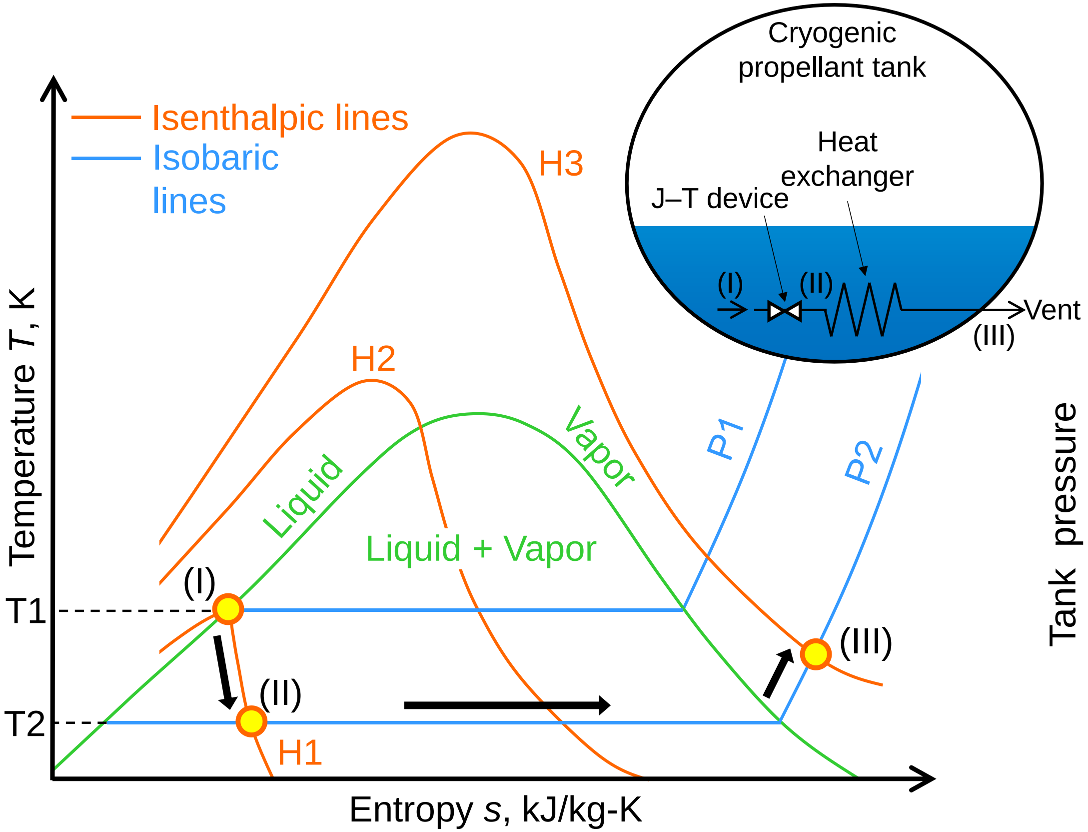
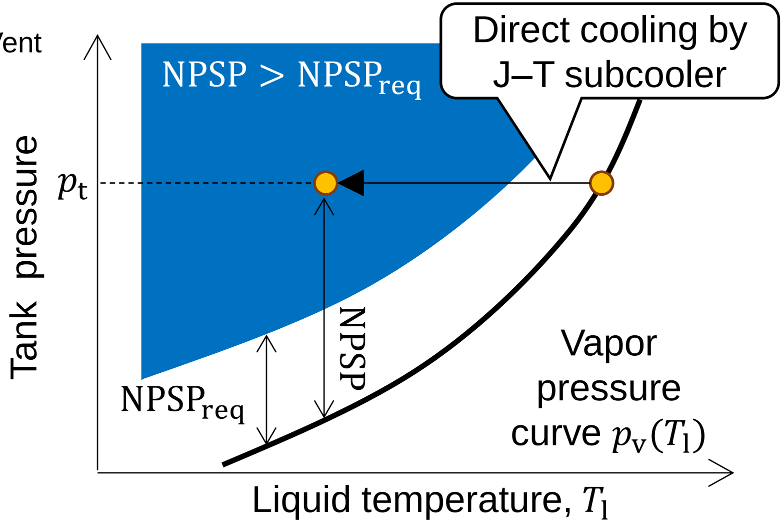
Thermodynamic Diagram of the Subcooler





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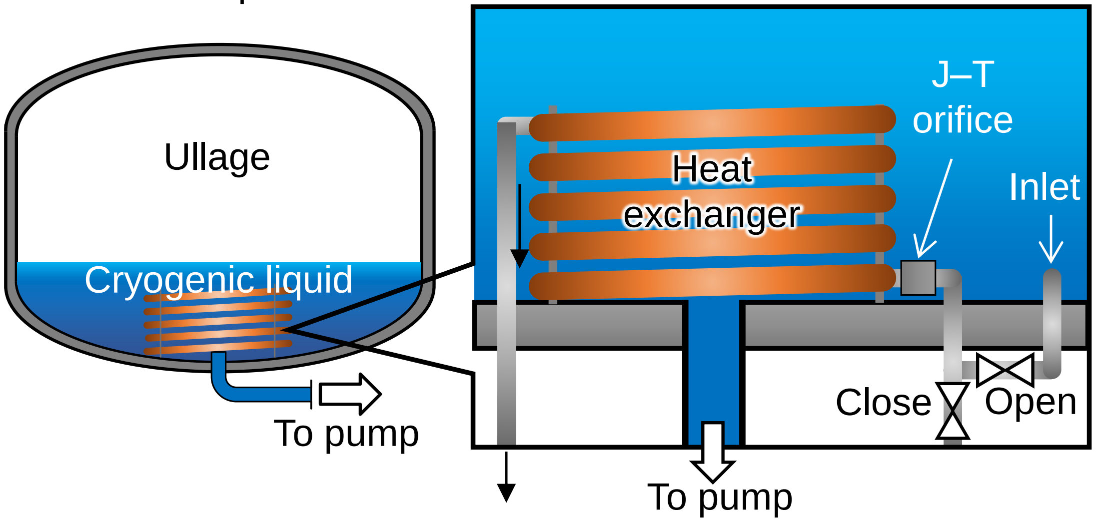
Subcooler Installation

Before reignition in orbit

To achieve required NPSP



Applying the subcooler to low liquid level situation because

- Small and light weight heat exchange at the bottom can be used.
- Conventional pressurization method requires a large amount of He gas due to large ullage.

The use of the subcooler is expected to provide 100 kg mass advantage per engine ignition.

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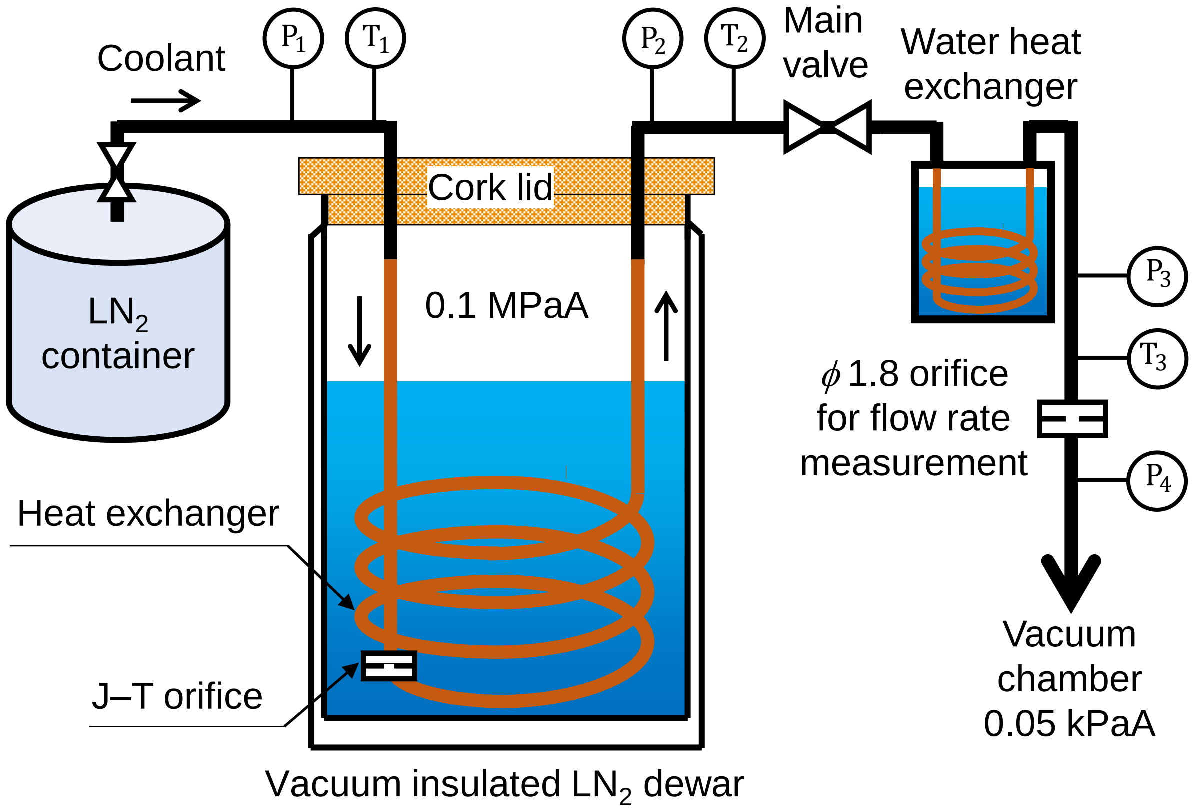
Experimental Setup



Experimental conditions:

- J-T orifice diameter

  ϕ0.3, 0.4, 0.5 mm

- Coolant Supply pressure (P1)

  0.17 ~ 0.27 MPaA

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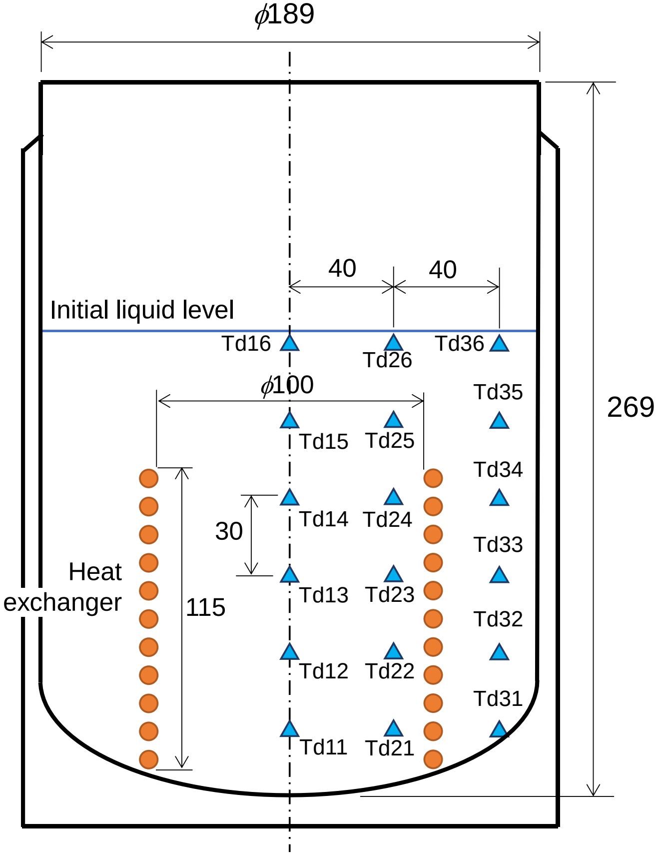
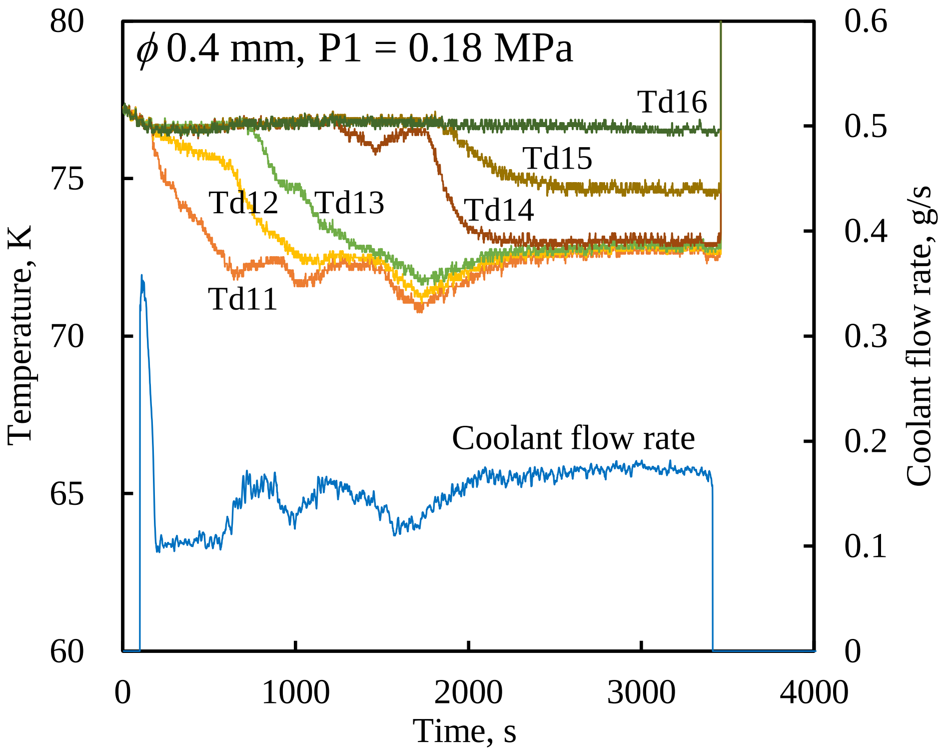
Typical Cooling History in the Dewar





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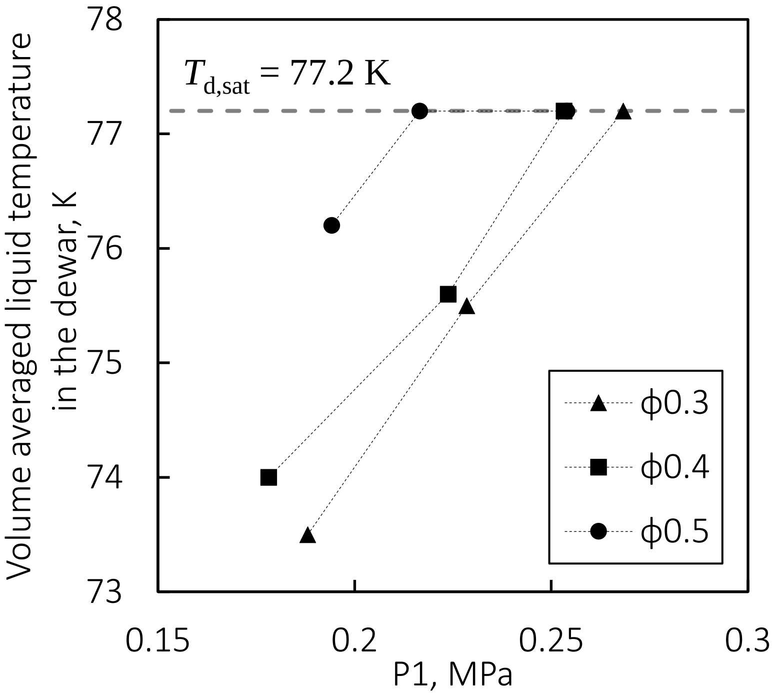
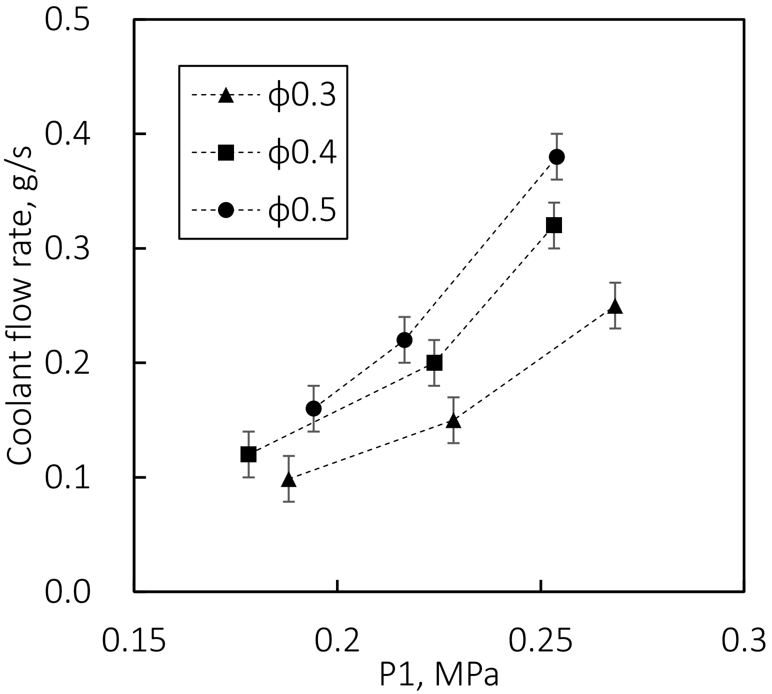
Degree of Subcooling and Coolant Flow Rate

Low P1 (coolant supply pressure) and small orifice lead to high degree of subcooling owing to low P2 (J-T orifice downstream pressure).

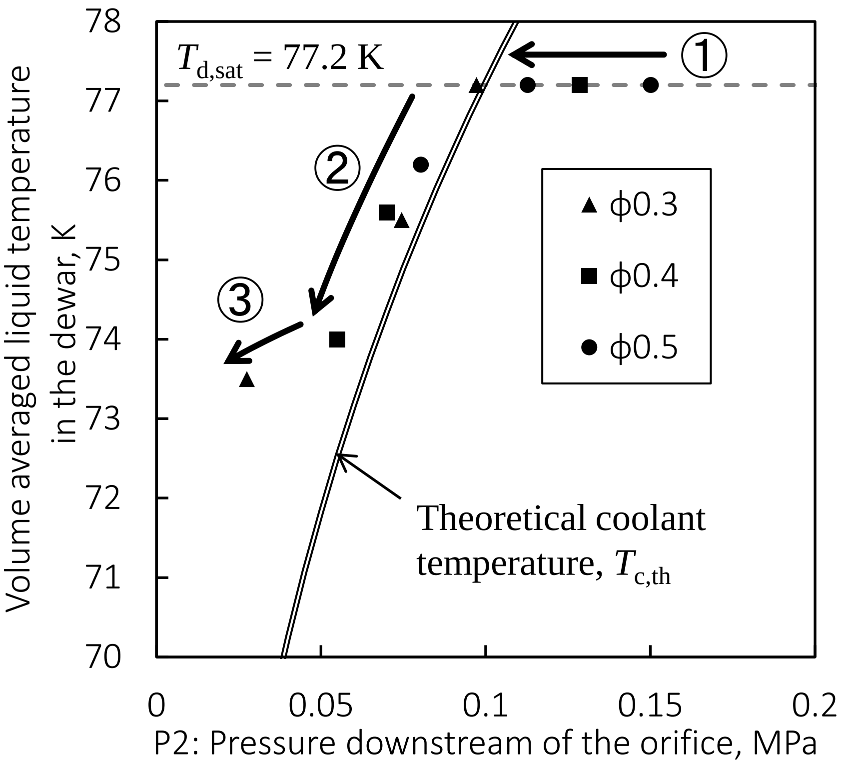


However, low P1 and small orifice caused low coolant mass flow rate $\dot{m}_c$.

⇨ Low coolant enthalpy capacity $\dot{m}_c L$



Effect of J-T Expansion Pressure on Subcooling



Effect of P2 (J-T orifice downstream pressure)

① P2 > 0.1 MPa

- No subcooling because of coolant temperature was over 77 K (Tsat at 0.1 MPa).

② 0.05 < P2 < 0.1 MPa

- Temperature in the dewar decreased along the theoretical coolant temperature.

③ P2 < 0.05 MPa

- The subcooling effect has diminished.
- Low P2 decreases coolant flow rate and cooling capacity. The coolant capacity is overwhelmed by the external heat input.

Energy Efficiency

- Definition of energy efficiency η_{E}

$$\eta_{\mathrm{E}} = \frac{\text{Heat removal from LN}_2\text{ in the dewar}}{\text{Decrease in coolant enthalpy}} = \frac{W_{\mathrm{d}} c_{pl} \left(\frac{d\hat{T}_{\mathrm{d}}}{dt}\right)}{\dot{m}_{\mathrm{c}}\left(h_{\mathrm{c}}|_{T_{\mathrm{d,sat}}} - h_{\mathrm{c,in}}\right)} \approx \frac{W_{\mathrm{d}} c_{pl} \left(\frac{\Delta\hat{T}_{\mathrm{d}}}{\Delta t}\right)}{\dot{m}_{\mathrm{c}} L}$$

$$\approx \frac{W_{\mathrm{d}} c_{pl}}{L} \frac{T_{\mathrm{d,sat}} - \hat{T}_{\mathrm{d}}}{\dot{m}_{\mathrm{c}} \Delta t}$$

$$\propto \frac{\text{Degree of subcooling of LN}_2\text{ in the dewar}}{\text{Coolant mass consumption}}$$

$=$ **Degree of subcooling of LN_2 per unit coolant mass consumption**

W_{d}: LN_2 mass in the dewar
c_{pl}: Specific heat of LN_2
$\dot{m}_{\mathrm{c}}$: Coolant flow rate
h_{c}: Coolant specific enthalpy
L: Latent heat of vaporization
Δt: Cooling duration until steady-state

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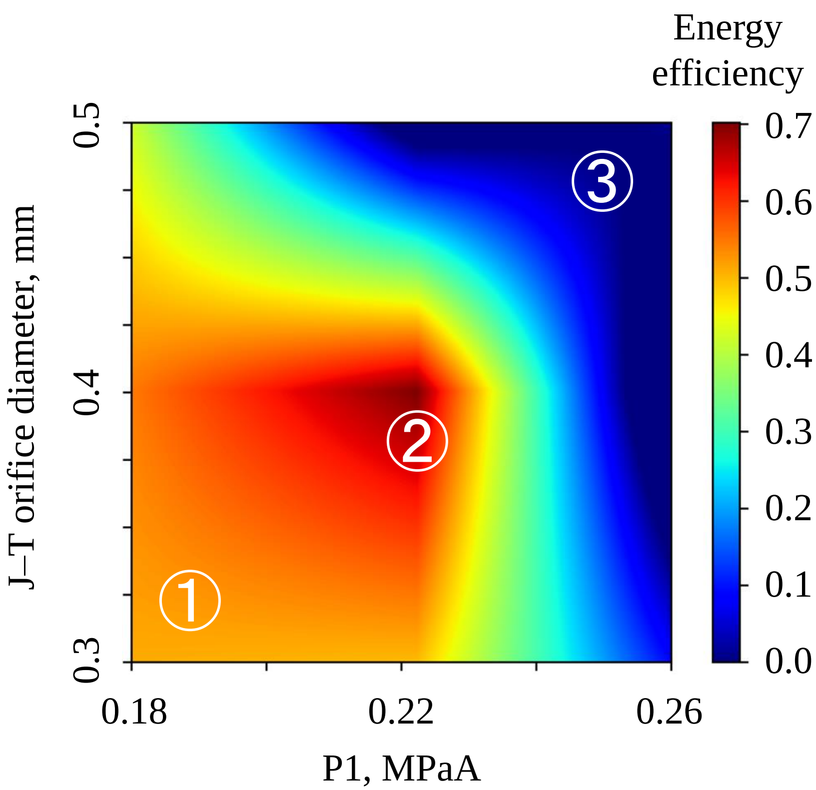
Optimization Based on Energy Efficiency



<u>① Low P1 and small orifice</u>

- Low temperature after J-T expansion
- Due to low coolant flow rate and its capacity, η_E decreases because the external heat input becomes relatively large.

<u>② Optimum point in this configuration</u>

<u>③ High P1 and large orifice</u>

- High temperature after J-T expansion
- Subcooler doesn't work when coolant is over the 77 K. Eeven less than 77 K, η_E decreases because the coolant does not completely evaporate in the HEX.

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Conclusion

- Onboard subcooler of cryogenic liquid propellants was proposed.
- The experiment showed a maximum degree of subcooling of 4 K.
- With low P1 (supply pressure) and small orifice, P2 (downstream pressure of the orifice) decreased, and the coolant temperature and flow rate also decreased. The flow rate is proportional to the coolant enthalpy capacity, thus, low P2 can result in lower energy efficiency.
- When using a high P1 and large orifice, the coolant flow rate and capacity increased, but the coolant temperature didn’t decrease. With the high coolant temperature, the subcooling effect diminishes, resulting in decreased efficiency.