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Investigation on Efficient Cooling Methods for Cryogenic Fluid Pipelines

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1.Introduction

2.Modeling

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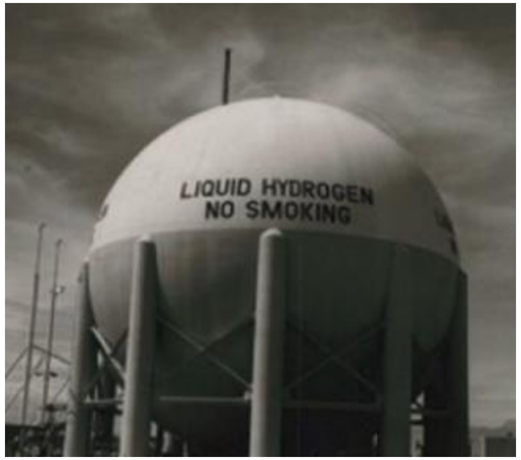
1 Hydrogen energy

- Hydrogen energy offers broad sources, high energy density, and environmental friendliness
- LH2 (0.1 MPa) exhibits 1.8 times the density of gaseous hydrogen (70 MPa)

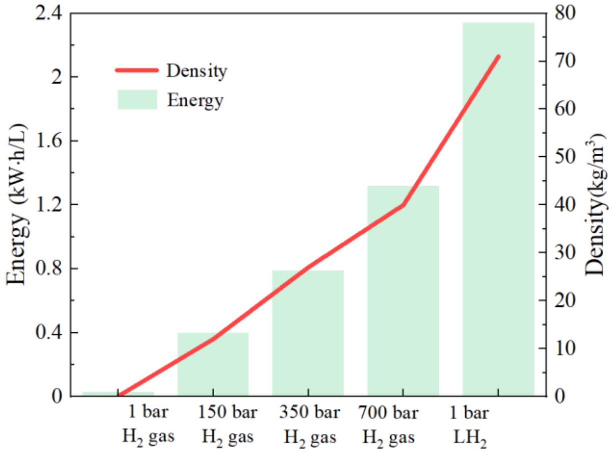
LH2 industry



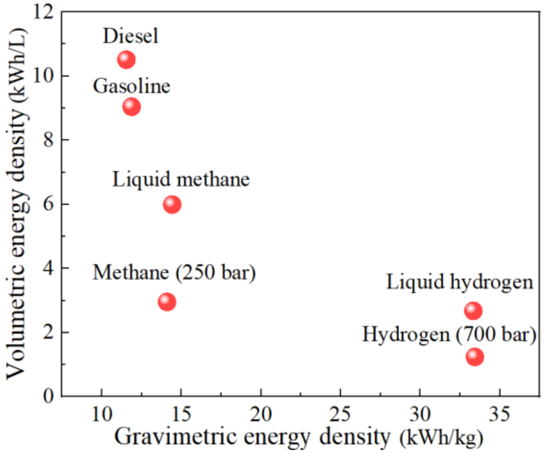
Kennedy Space Center (NASA)

Kobe LH2 terminal in Japan (Kawasaki Heavy Industries)

Energy density



Energy density of different hydrogen states



Energy density of different fluids

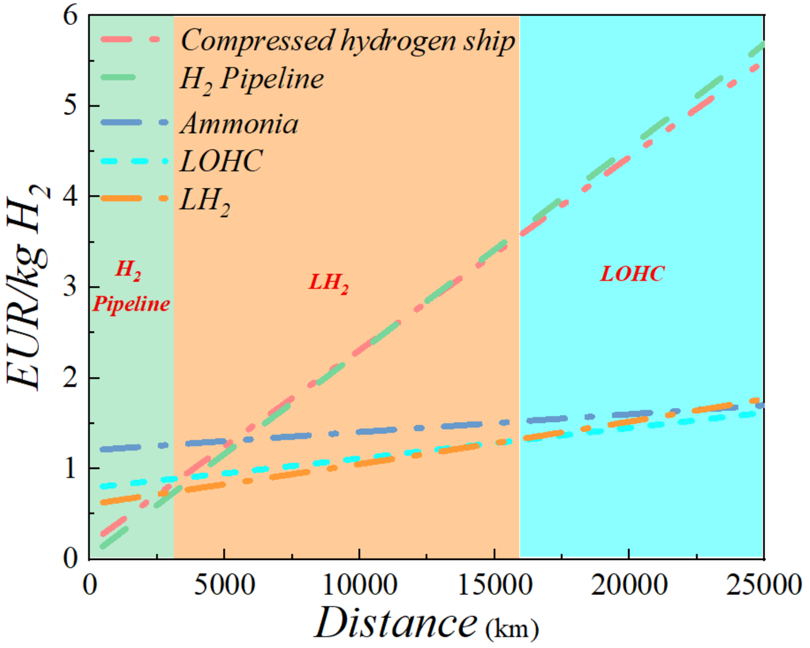
LH2 becomes a promising alternative energy source

Renewable and Sustainable Energy Reviews 182 (2023): 113360.

1 Storage and transportation of hydrogen

- LH2 offers excellent flexibility in storage and transportation compared to other hydrogen storage methods
- LH2 has a cost advantage for long-distance transport, especially for distances over 3000 km

Storage medium state	**Storage method**	**Volume**	**storage density ($g H_2/L$)**	**Cycling**	**Geographical constraints**
Gaseous state	Salt caverns	Large	~10 g/L (50–200 bar)	Month-weeks	Limited
	Pressurized containers	Small	~40 g/L (at 700 bar)	Daily	Not limited
Liquid state	Liquid hydrogen	Small-medium	~66 g/L (at 1 bar)	Days-weeks	Not limited
	Ammonia	Large	107 g/L (at 1 bar)	Month-weeks	Not limited
	LOHCs	Large	55 g/L (at 1 bar)	Month-weeks	Not limited



Transportation costs of different hydrogen storage methods

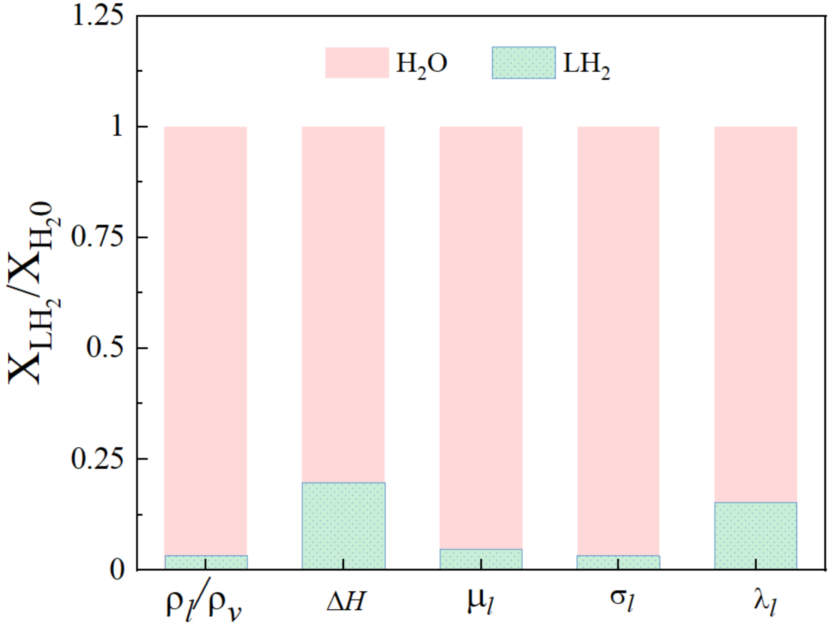
LH2 plays a crucial role in the long-distance transportation of hydrogen

Renewable and Sustainable Energy Reviews 182 (2023): 113360.

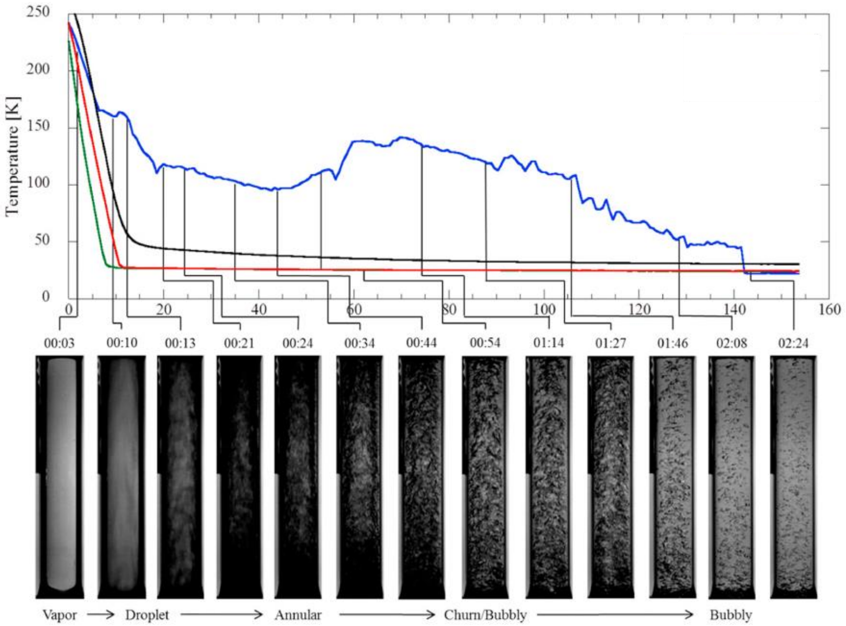
1 Unique properties of LH2

- LH2 exhibits more intense boiling processes due to its lower latent heat of vaporization
- The two-phase flow state of LH2 in pipelines is mainly stratified flow and bubbly flow

Properties of water and LH2



LH2 pipeline chilldown

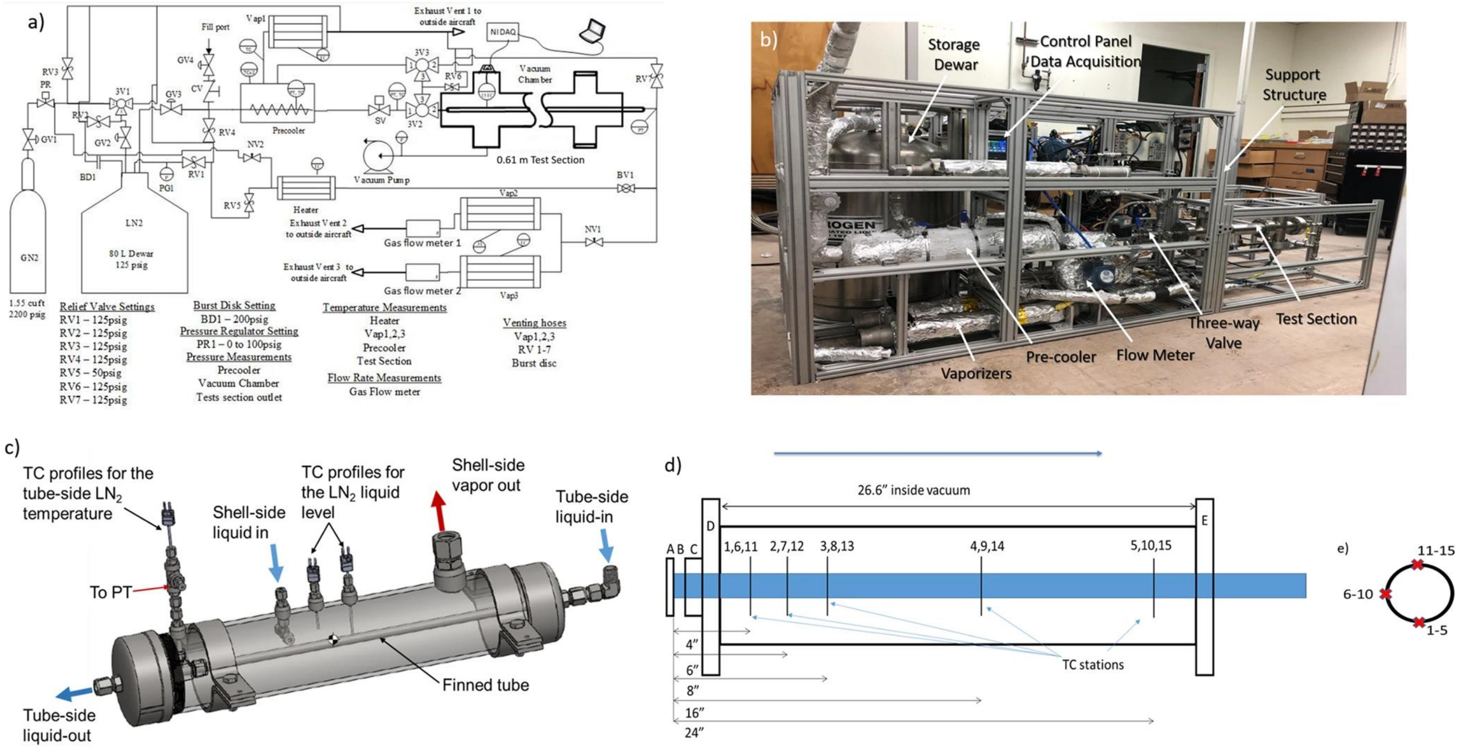


LH2's two-phase flow exhibits significant characteristics due to its distinct properties

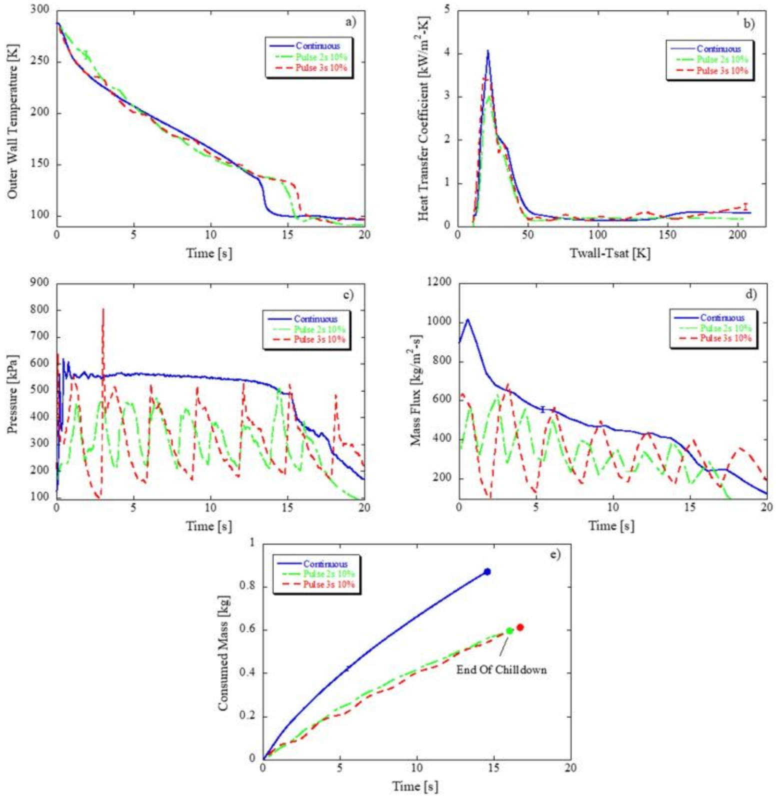
International Journal of Heat and Mass Transfer 156 (2020): 119805.

1 LH2 pipeline chilldown

- NASA evaluates two methods to reduce propellant consumption during chilldown (low thermally conductive coatings and pulse flow), and experiments show these methods can cut consumed mass by up to 75%



Experimental platform for efficient cooling of LN2 pipelines (NASA)



npj Micrography 8, no. 1 (2022): 33

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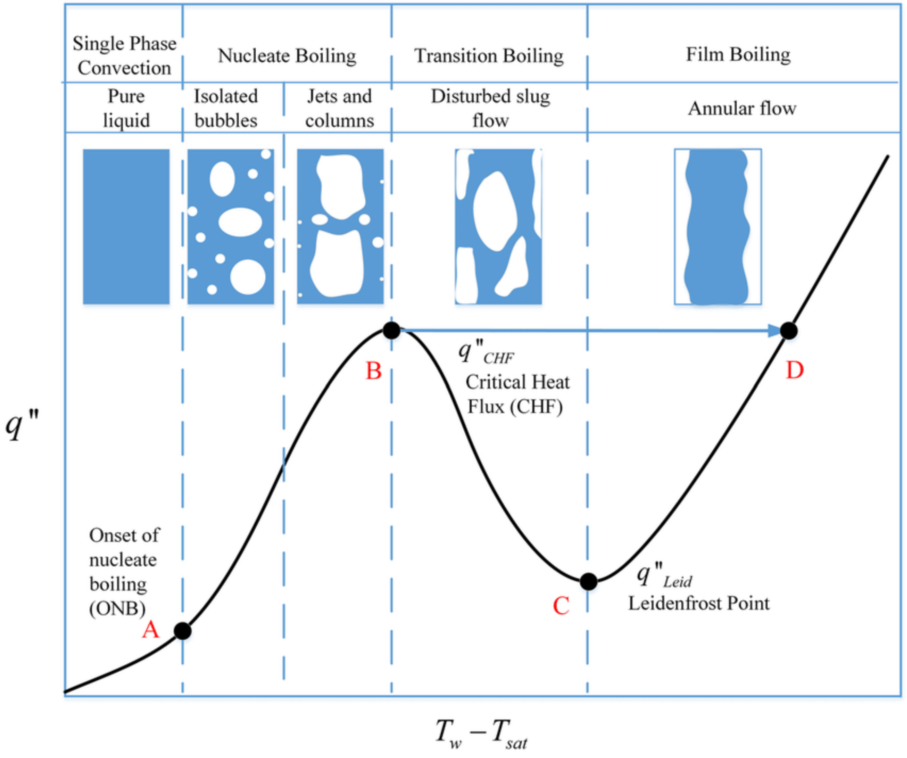
Heat transfer correlation

- LH2 pipeline cooling process involves various boiling states, including film, transition, and nucleate boiling
- Accurate prediction of the chilldown process relies on selecting the appropriate correlations for each stage



Boiling curve and two-phase flow pattern

Boiling regime	Correlation
Film boiling	$Nu_{fb} = 1.09 * 10^{-3}\left\{Re_g\left[x + \frac{\rho_g}{\rho_l}(1-x)\right]\right\}^{0.989} Pr_g^{1.41}Y$
	$Y = \left[1 - 0.1\left(\frac{\rho_l - \rho_g}{\rho_g}\right)^{0.4}(1-x)^{0.4}\right]^{-1.15}$
Transition boiling	$h_{tb} = 1.1Pr_l^{-0.9}X_{darr}h_{nb}$
	$X_{darr} = 10.37 - 36.93\phi + 47.49\phi^2 - 20.82\phi^3$
	$\phi = \frac{T_w - T_{sat}}{T_{wet} - T_{sat}}$
Nucleate boiling	$h_{nb} = 22.8Re_l^{-0.332}Ja_l^{-0.254}\left\{0.023Re_l^{0.8}Pr_l^{0.4}\frac{k_l}{D}\right\}$
Rewetting temperature	$T_{wet} = \frac{27}{32}T_{critical}(1 + 0.322We_l^{0.01}Re_l^{0.007Ja_l})$
Critical heat flux	$(Q/A)_{chf} = 0.64Gh_{lg}We_l^{-0.5}\left(\frac{\rho_l}{\rho_g}\right)^{-0.91}\left(\frac{L}{D}\right)^{0.48}\left(1 + 0.07We_l^{0.35}\frac{\Delta h_{sub}}{h_{lg}}\right)$

Cryogenics 118 (2021): 103324.

2

Governing equations

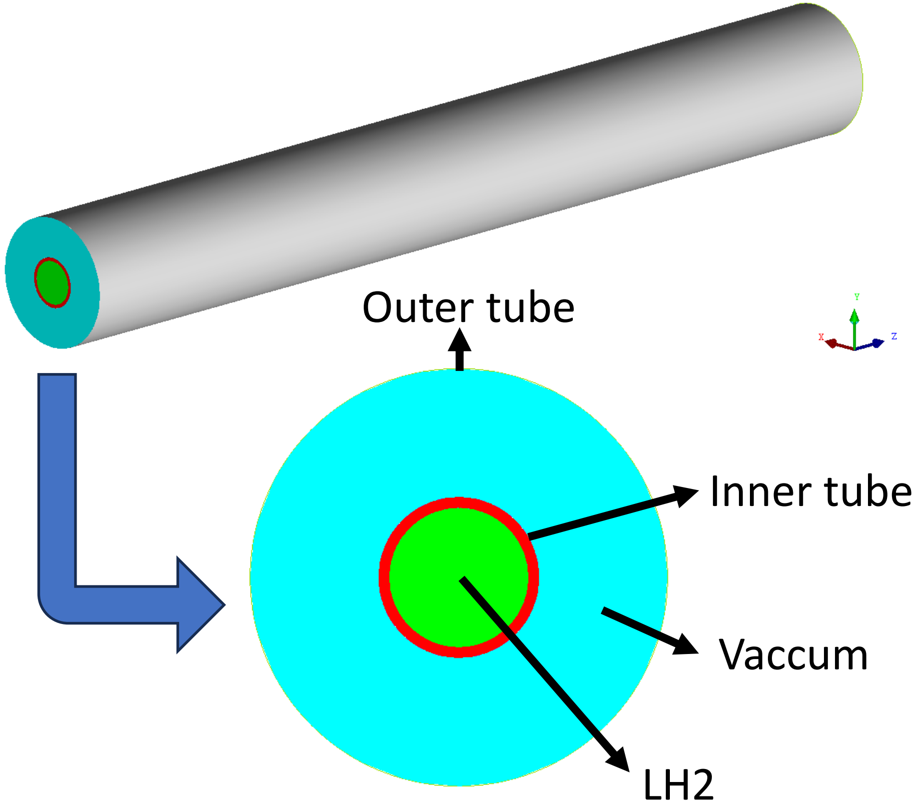
- ➢ Eulerian-Eulerian two-phase flow model is employed, where each phase has its respective governing equations.
- ➢ The two sets of equations are coupled through mass, momentum, and heat transfer between phases.

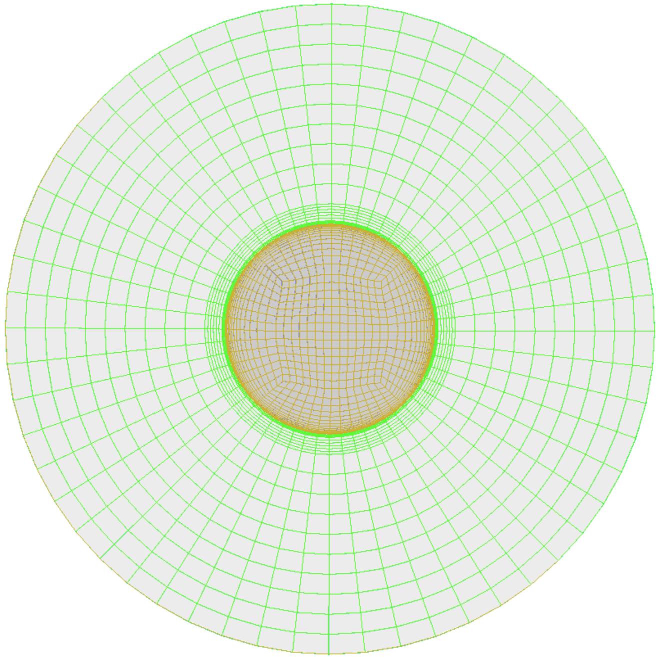
Governing equation	**Formulation**
Mass conservation	$\frac{\partial}{\partial t}(\alpha_q \rho_q) + \nabla \cdot (\alpha_q \rho_q \boldsymbol{v}_q) = \sum_{p=1}^{2} (\dot{m}_{pq} - \dot{m}_{qp})$
Momentum conservation	$\frac{\partial}{\partial t}(\alpha_q \rho_q \boldsymbol{v}_q) + \nabla \cdot (\alpha_q \rho_q \boldsymbol{v}_q \boldsymbol{v}_q) = -\alpha_q \nabla p + \alpha_q \rho_q \boldsymbol{g} + \sum_{p=1}^{2} \left(\boldsymbol{R}_{pq} + \dot{m}_{pq} \boldsymbol{v}_{pq} - \dot{m}_{qp} \boldsymbol{v}_{qp}\right) + \left(\boldsymbol{F}_{\mathrm{vm},q} + \boldsymbol{F}_{\mathrm{lift},q}\right)$
Energy conservation	$\frac{\partial}{\partial t}(\alpha_q \rho_q h_q) + \nabla \cdot (\alpha_q \rho_q w_q h_q) = \alpha_q \frac{\partial p_q}{\partial t} - \nabla \cdot \boldsymbol{q}_q + \sum_{p=1}^{2} \left(Q_{pq} + \dot{m}_{pq} h_{pq} - \dot{m}_{qp} h_{qp}\right)$

2

Physical model

- A 3D model was established, consisting of an inner tube, an outer tube, and a vacuum layer.
- The geometric dimensions of this model are derived from Sakamoto 's experimental data for validation.





Parameters	size
Length	1600 mm
Inner diameter	15 mm
Inner tube wall thickness	2 mm
Outer diameter	45 mm

Grid model and geometric dimensions

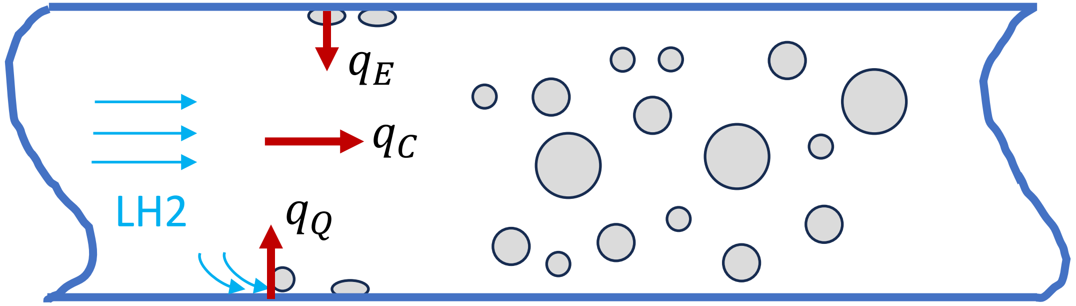
Cryogenics 131 (2023): 103652.

2 Boiling model

- RPI model has been widely used in simulating various boiling processes, achieving good predictions.
- Three types of heat flux (q_E、 q_Q、 q_C) are defined when considering bubble behavior.

Boiling model	**Formulation**
RPI	$q = q_E + q_Q + q_C$ $\begin{cases} q_E = \frac{\pi}{6} d_{\mathrm{b}}^3 \rho_{\mathrm{V}} n f h_{\mathrm{fg}} \\ q_Q = \frac{2k_l}{\sqrt{\pi \tau a_l}} A_{\mathrm{b}} (T_{\mathrm{W}} - T_l) \\ q_C = h_C (T_{\mathrm{W}} - T_l)(1 - A_{\mathrm{b}}) \end{cases}$ $A_{\mathrm{b}} = min\left(1, K \frac{n \pi d_{\mathrm{b}}^2}{4}\right)$

RPI model

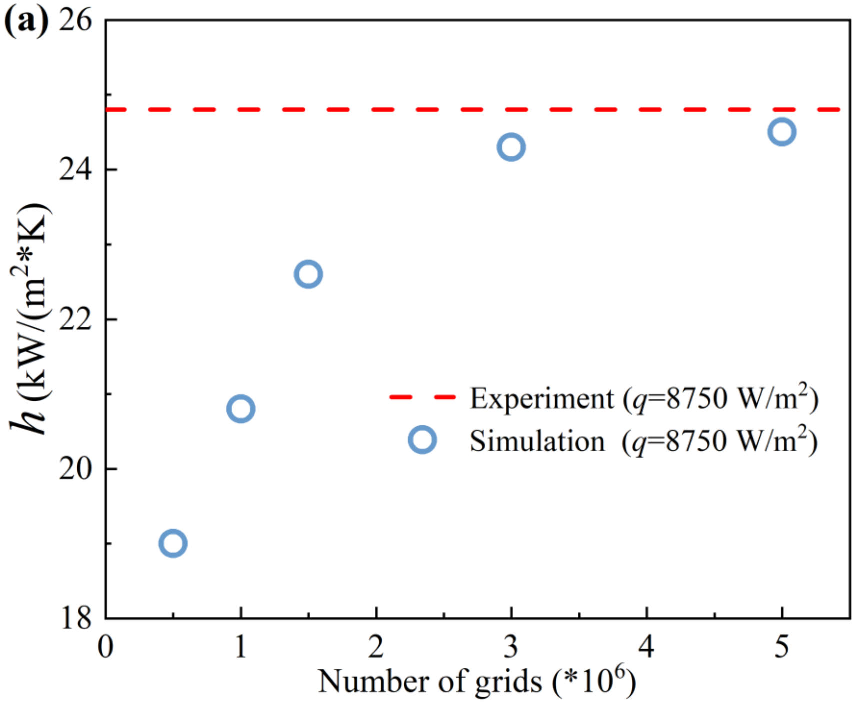


Heat flux	**Definition**
q_E	Boiling heat flux due to bubble nucleation and detachment
q_Q	Quenching heat flux caused by the sudden cooling from liquid impacting bubble detachment points
q_C	Convective heat flux due to single-phase liquid flow

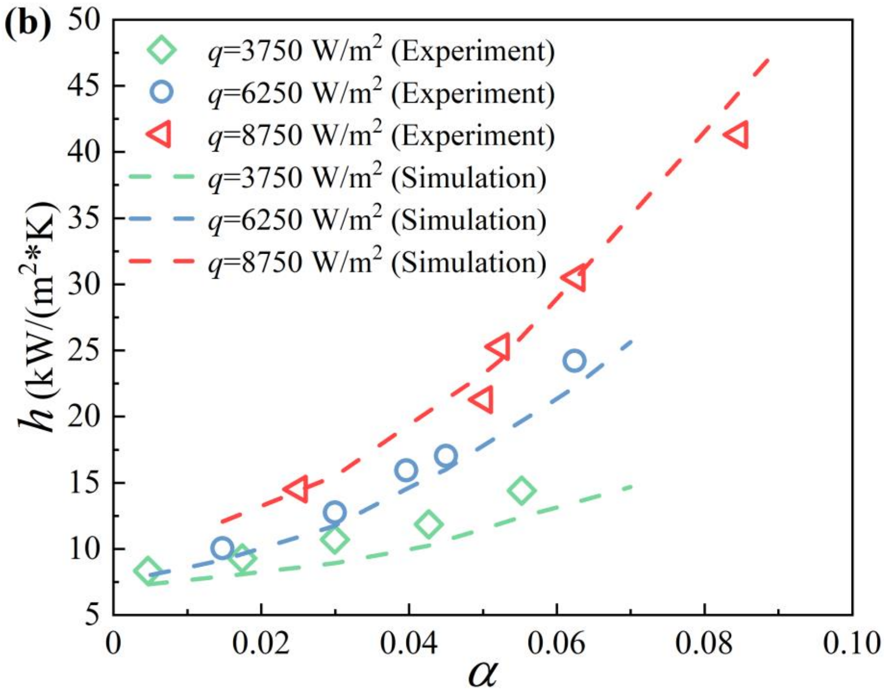
2 Model validation

- A 3-million-grid model was adopted when considering both calculation time and accuracy
- The calculated heat transfer coefficient matches well with experimental data from Sakamoto

Grid independence



Model validation



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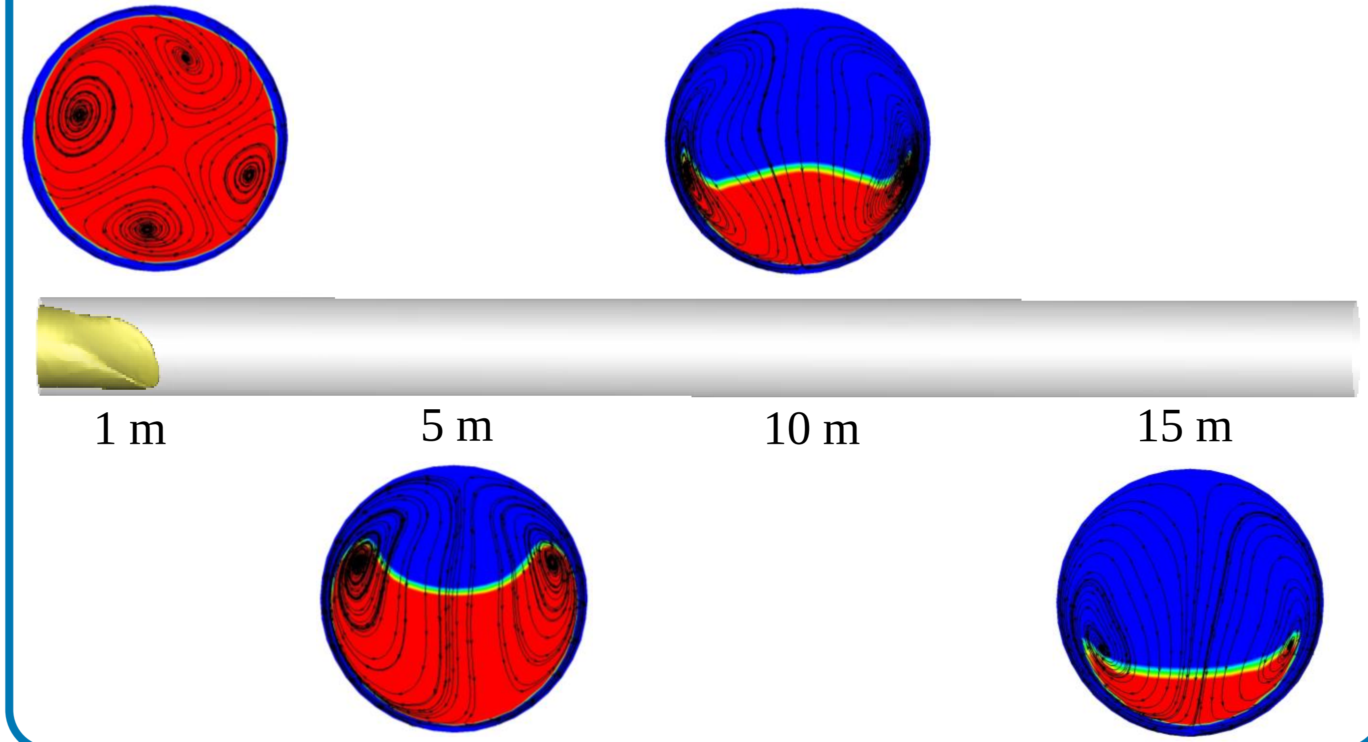
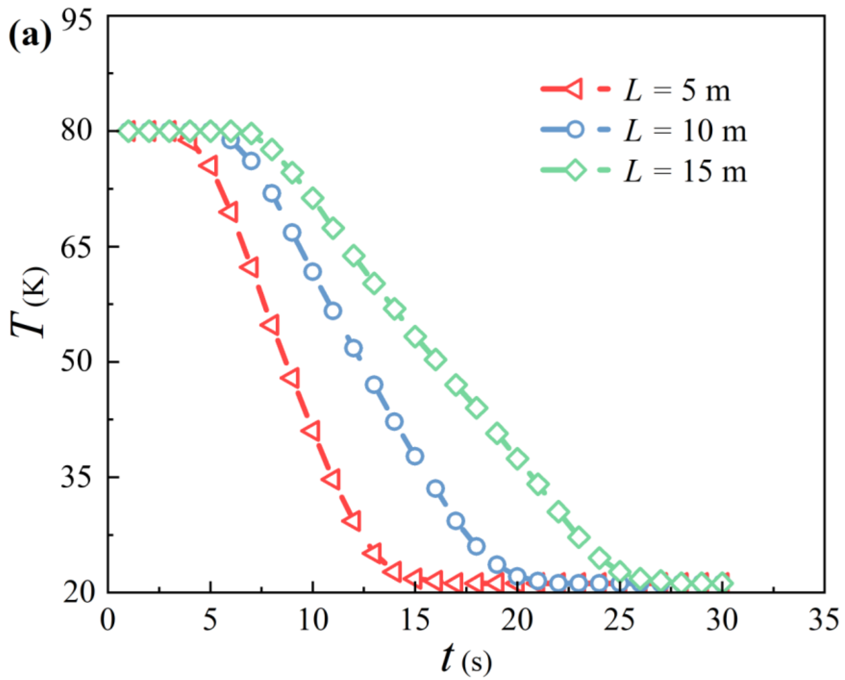
Pipeline chilldown

- During the chilldown process of LH2 pipelines, it mainly occurs in the form of stratified wave flow
- Different locations exhibit varied cooling rates, correlating with the two-phase flow pattern of the boiling process

Evolution of gas-liquid interface



Cooling curve



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3 Comparison of Various Cooling Methods

- Three flow control methods are adopted for pipeline chilldown: trickle flow, CHV, and pulse flow
- Efficient cooling of pipelines involves considerations of cooling time, LH2 consumption, and system complexity

Method	Principle	Advantage	Disadvantage
Trickle flow	It provides a constant flow of liquid cryogen through the transfer line	Easy to operate, achieving fast cooling	Consuming more propellant
CHV (Charge-hold-vent)	It introduces a fluid slug into a closed transfer line, where it heats and evaporates until pressure reaches a critical value, then vents and repeats.	A controlled amount of liquid hydrogen with minimal loss	Relying on multi valve control and posing a safety risk of overpressure
Pulse flow	It involves intermittently opening and closing the upstream flow valve while keeping the downstream valve open, resulting in liquid pulses.	Requiring less fluid mass for chilldown	Complex valve control system

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3 Method 1: Trickle flow

- Stratified flow is more pronounced at low flow rates, and the wall surface wets faster at high flow rates.
- When doubling and tripling the flow rate, the maximum heat transfer coefficient increases by 70% and 125%

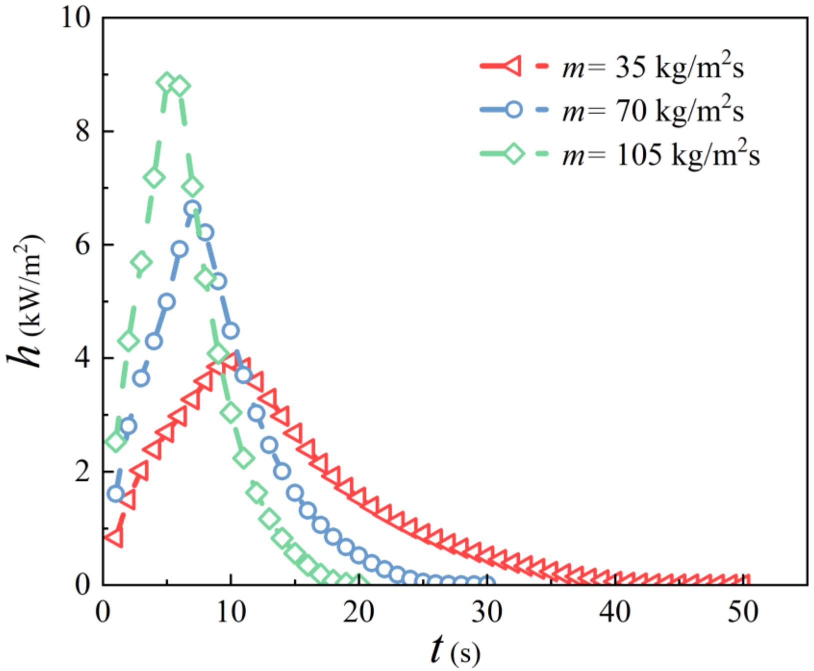
Evolution of gas-liquid interface

m = 35 kg/(m^2·s)

m = 70 kg/(m^2·s)

m = 105 kg/(m^2·s)

Heat transfer coefficient



3 Method 1: Trickle flow

- As the flow rate of the trickle increases, the cooling rate of the pipeline accelerates
- When doubling and tripling the flow rate, cooling time decreases by 41% and 58%

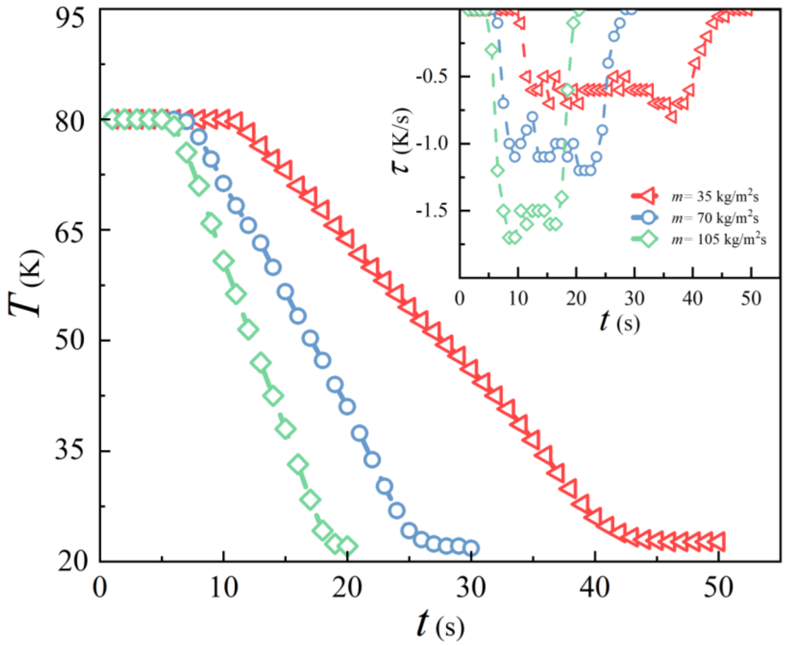
Temperature change

m = 35 kg/(m^2·s)

m = 70 kg/(m^2·s)

m = 105 kg/(m^2·s)

Cooling curve

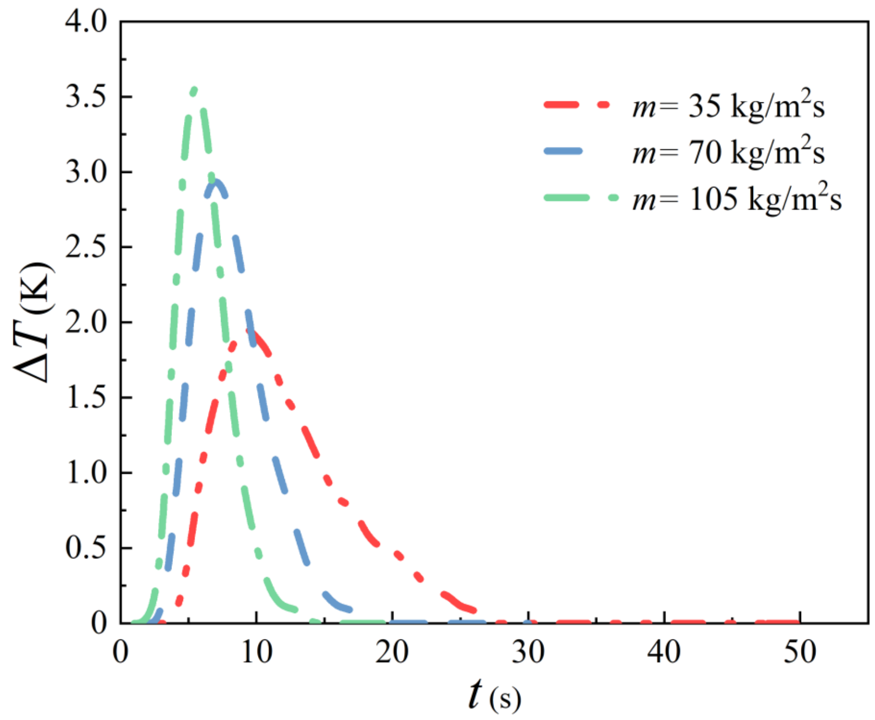


3

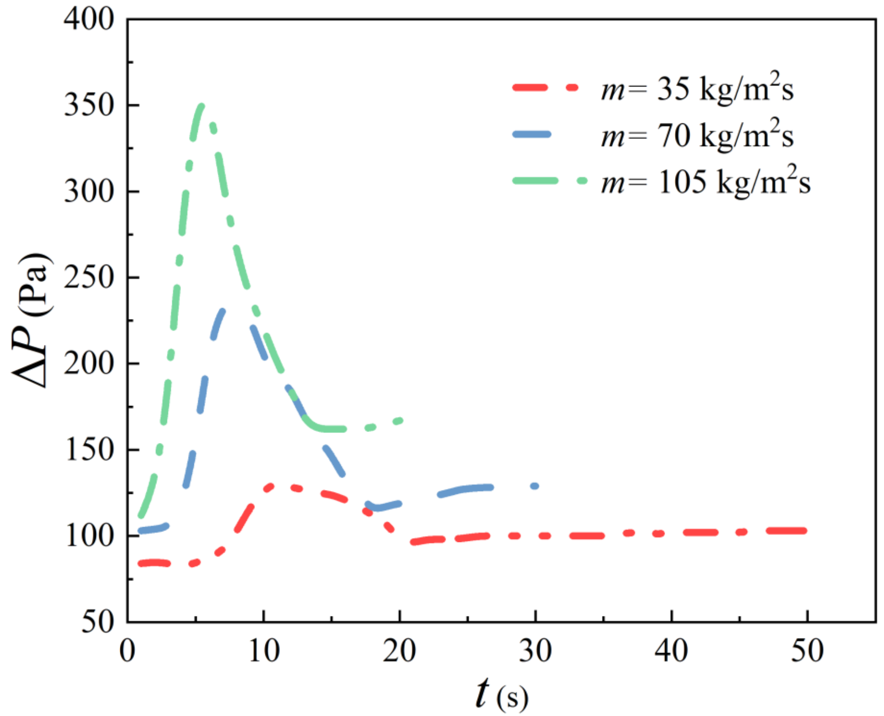
Method 1: Trickle flow

- When doubling and tripling the flow rate, the pipeline local temperature difference increases by 70% and 125%
- When doubling and tripling the flow rate, the pipeline pressure drops increases by 80% and 180%

Pipeline local temperature difference



Pressure drop



3 Method 2: Variable flow

- According to the varying cooling demands during different stages, variable flow cooling method is employed
- Higher initial flow rates wets most areas of the pipeline faster and achieve the higher heat transfer coefficient

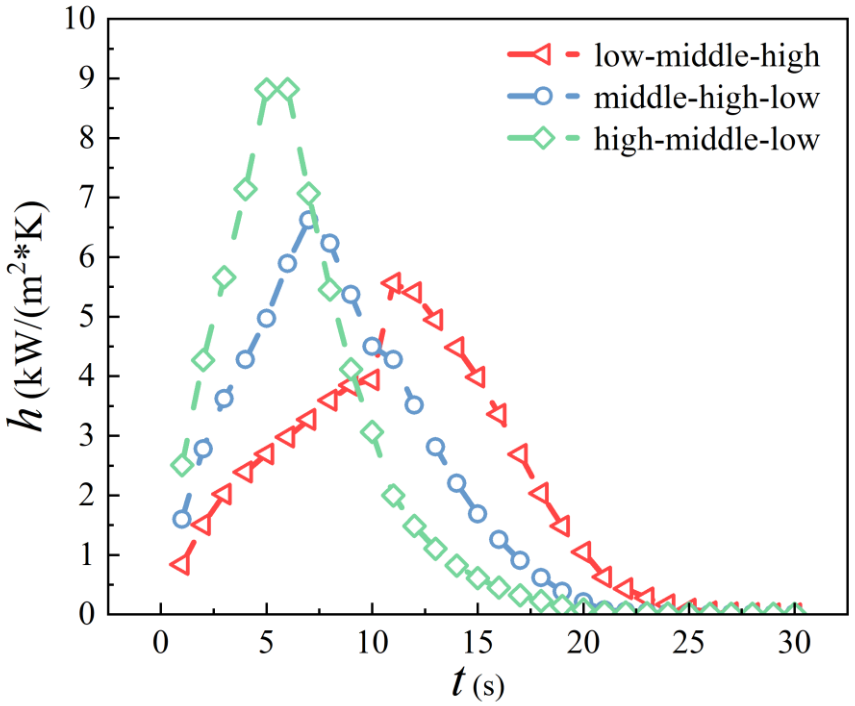
Evolution of gas-liquid interface

1. m = 35~70~105 kg/(m^2·s) **< 10 s for each flow rate >**

2. m = 70~105~35 kg/(m^2·s) **< 10 s for each flow rate >**

3. m = 105~70~35 kg/(m^2·s) **< 10 s for each flow rate >**

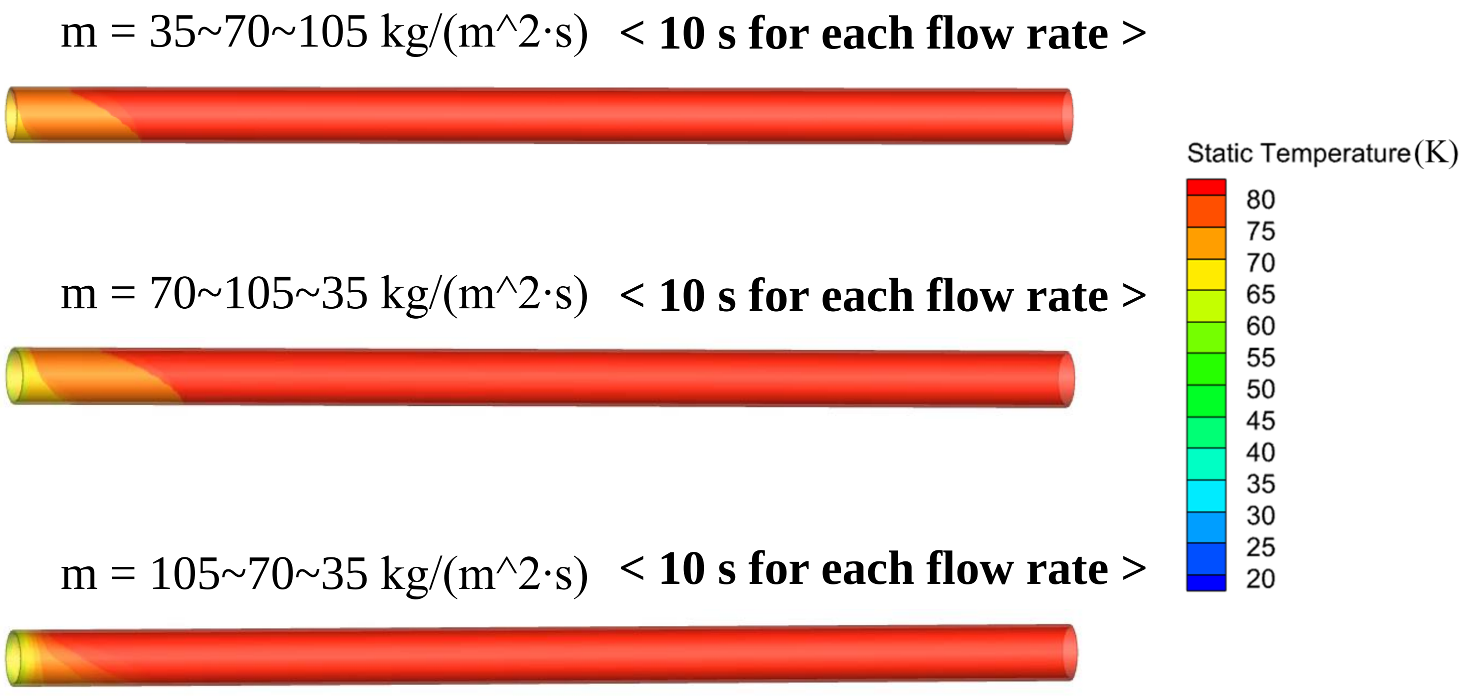
Heat transfer coefficient



3 Method 2: Variable flow

- The initial low-flow-rate cooling mode shows a significant lag in the pipeline chilldown.
- Comparing to the increasing flow mode, the decreasing flow mode can shorten pipe cooling time by 20%.

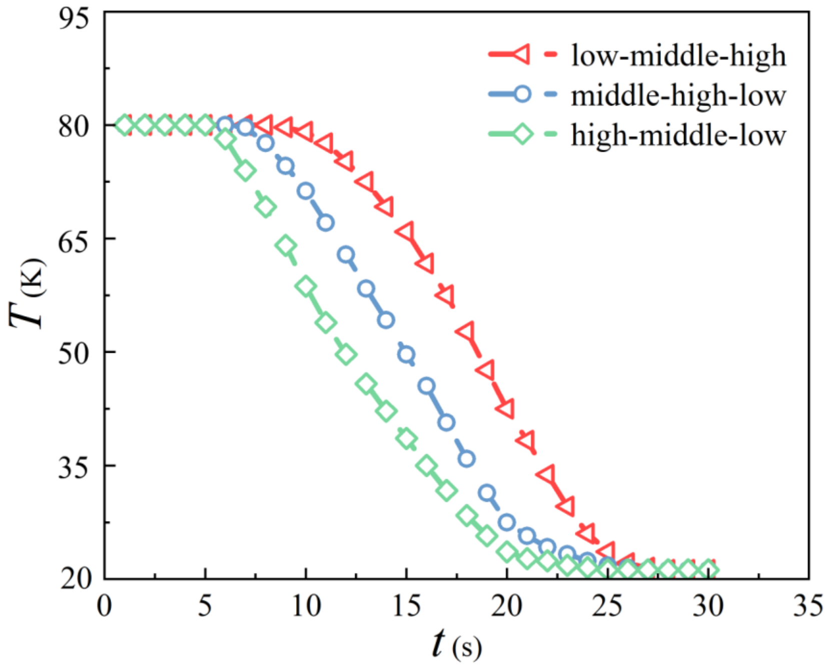
Temperature change


m = 35~70~105 kg/(m^2·s) **< 10 s for each flow rate >**

m = 70~105~35 kg/(m^2·s) **< 10 s for each flow rate >**

m = 105~70~35 kg/(m^2·s) **< 10 s for each flow rate >**

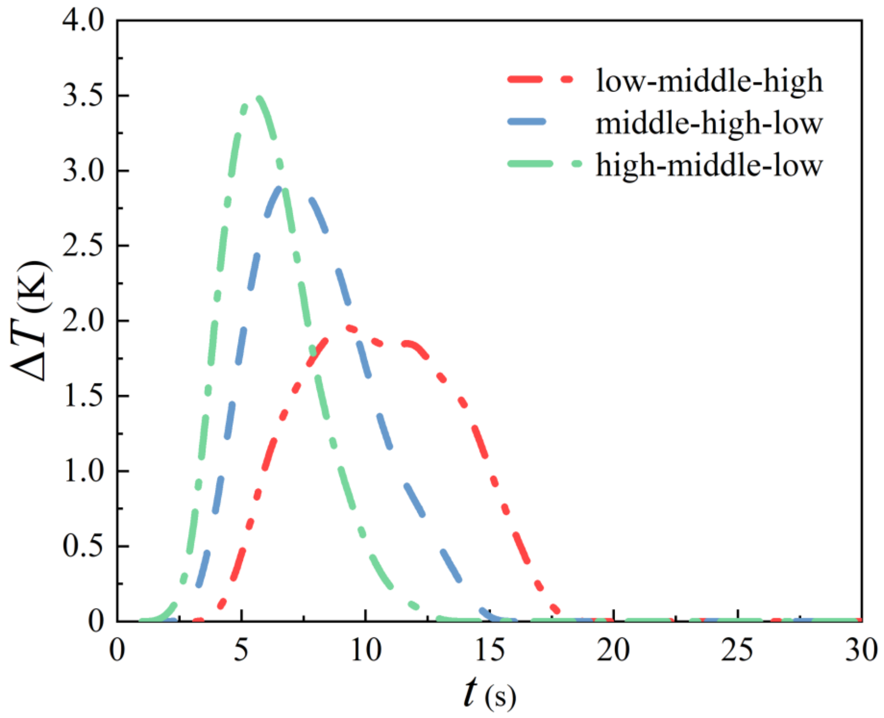
Cooling curve



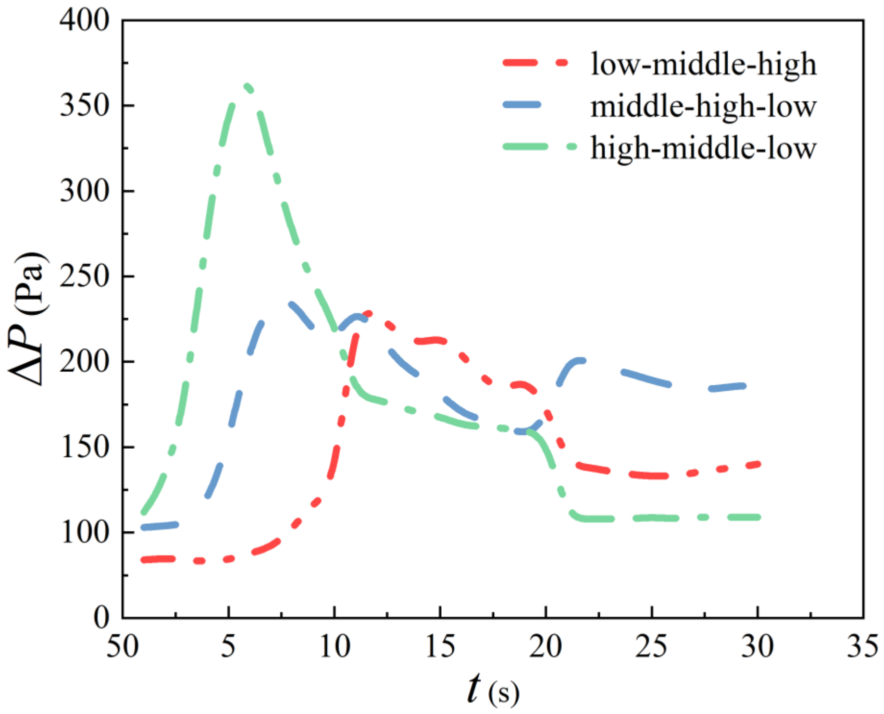
3 Method 2: Variable flow

- Comparing to the increasing flow mode, the decreasing flow mode increase local temperature differences by 75%.
- Comparing to the increasing flow mode, the decreasing flow mode increase pressure drop by 50%.

Pipeline local temperature difference



Heat transfer coefficient



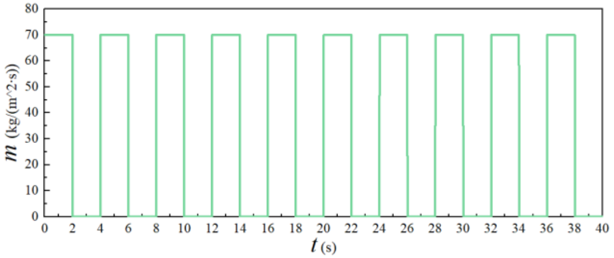
3 Method 3: Pulse flow

- In the late stages of pipeline cooling, much LH2 flowed out without evaporating, causing wasteful consumption.
- Pulse flow, as a type of intermittent flow, maximizes the utilization of the latent heat of phase change in LH2.

Evolution of gas-liquid interface

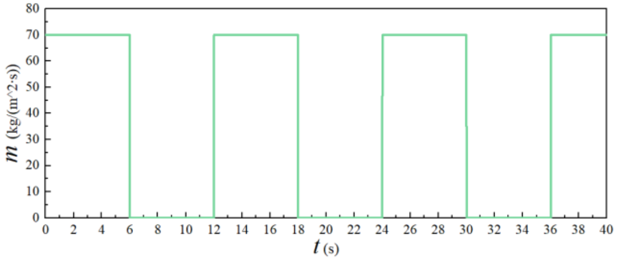
Pulse 2-2

Cycle: 2 s for m = 70 kg/(m^2·s)
2 s for m = 0



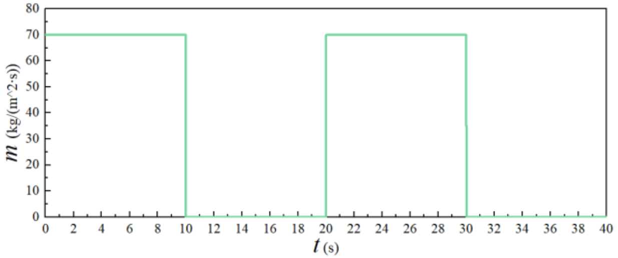
Pulse 6-6

Cycle: 6 s for m = 70 kg/(m^2·s)
6 s for m = 0



Pulse 10-10

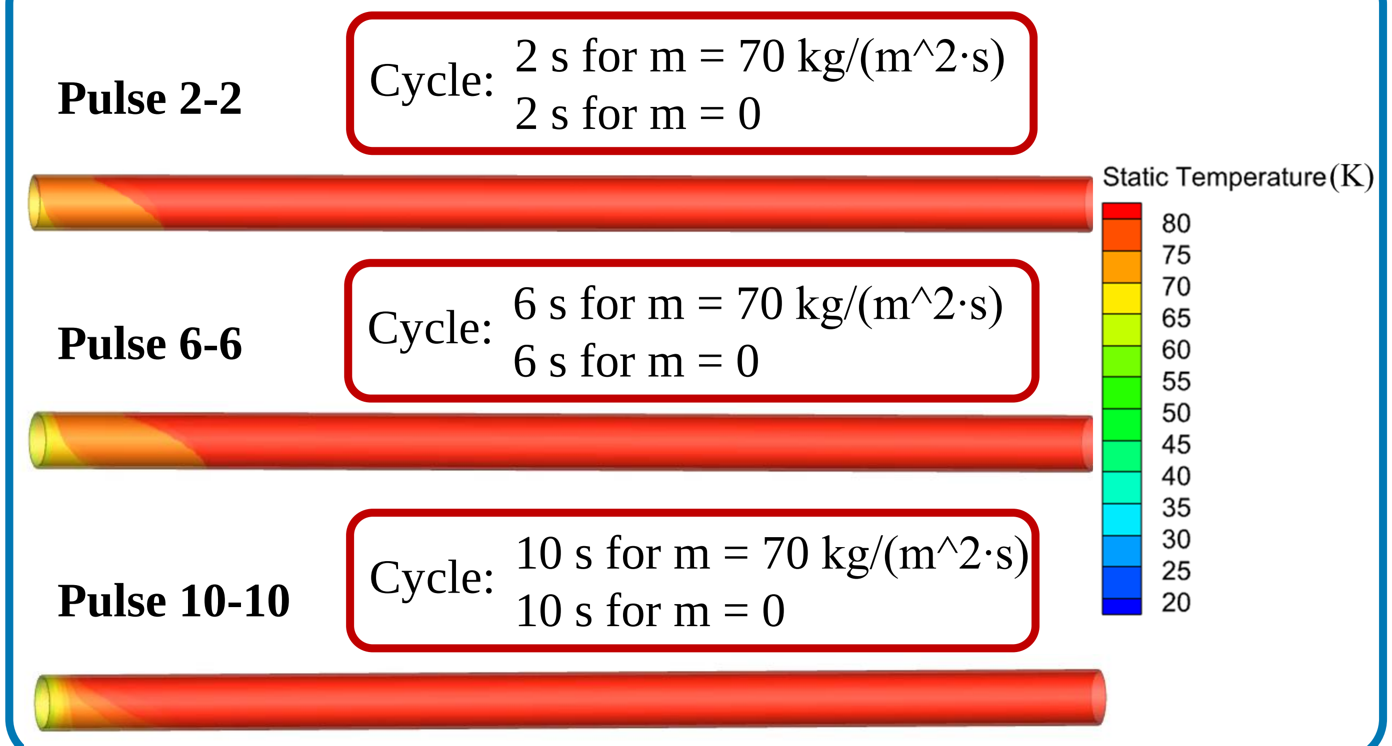
Cycle: 10 s for m = 70 kg/(m^2·s)
10 s for m = 0



3 Method 3: Pulse flow

- ➢ High frequency pulse flow (2 s) is not conducive to saving both cooling time and LH2 consumption.
- ➢ The best pulse flow cooling mode (8 s) can save 20% of LH2, but increase cooling time by 42%.

Evolution of gas-liquid interface



Pulse 2-2

Cycle: 2 s for m = 70 kg/(m^2·s)
2 s for m = 0

Pulse 6-6

Cycle: 6 s for m = 70 kg/(m^2·s)
6 s for m = 0

Pulse 10-10

Cycle: 10 s for m = 70 kg/(m^2·s)
10 s for m = 0

Cooling method	Cooling time (s)	LH2 consumption (kg)
Without pulse	26.0	32.54
Pulse 2-2	42.0	27.53
Pulse 4-4	41.1	26.41
Pulse 6-6	39.2	26.53
Pulse 8-8	**37.0**	**26.28**
Pulse 10-10	41.5	26.91

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4 Conclusion

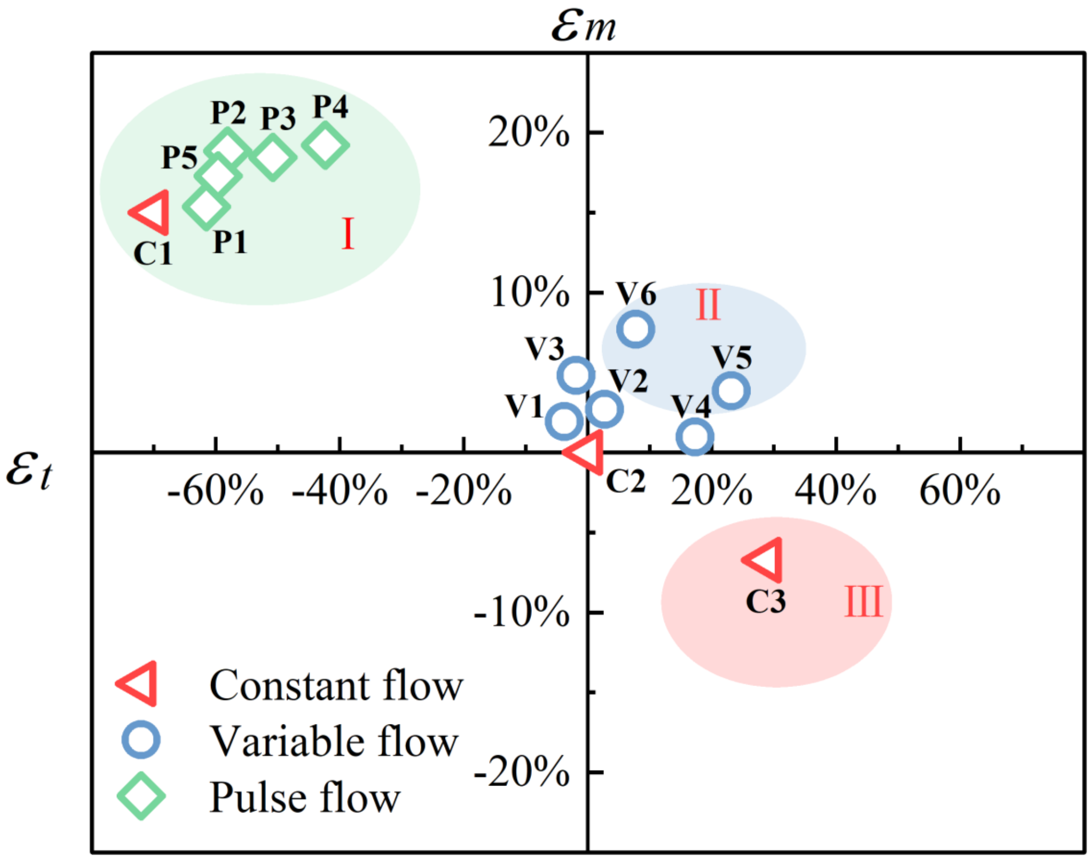
- Optimizing variable flow can reduce both cooling time and LH2 consumption, though the effect is limited (**II**).
- Pulse flow can significantly cut down on LH2 consumption, but it may slightly increase cooling time (**I**).

Efficiency in saving cooling time

$$\varepsilon_t = (t_{C2} - t_i)/t_{C2}$$

Efficiency in saving LH2 consumption

$$\varepsilon_m = (m_{C2} - m_i)/m_{C2}$$



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