Indian Institute of Technology Kharagpur
भारतीय प्रौद्योगिकी संस्थान खड़गपुर

Lumped Multi-Bubble Analysis of Injection Cooling System for Storage of Cryogenic Liquids

by
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Injection Cooling

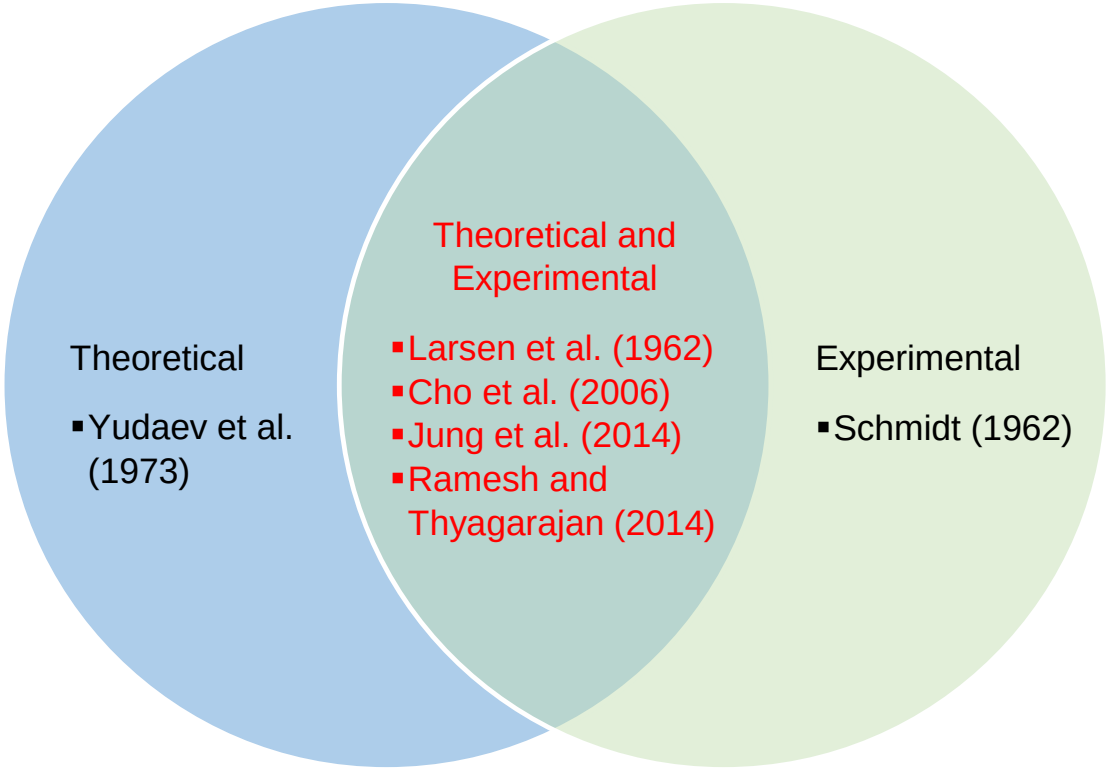
- Proposed for storing cryogenic liquids.
- Useful when
  - Space is at premium.
  - Vibrations (In the conventional cooling techniques) are unacceptable.
  - Payload should be reduced.
- Applied for storing cryogenic propellants (LOX and LH2).

Working Principle

- Evaporation rate $\propto \left(P^{Sat} - p\right)$
  P^{Sat} = Saturation pressure of evaporating component.
  p = Partial pressure of the evaporating component in the gas phase.

- Temperature change of stored liquid depends on
  - **Latent heat** transfer during evaporation.
  - Sensible heat transfer between gas and liquid.
  - Ambient heat inleak.

Earlier Works



Systems Used: LOX-GHe, LOX-GN2, LN2-GHe, LH2-GHe and Water-Air.

Lumped Parameter Approach

1. Quick performance evaluation.
2. Quick identification of operating range and critical operating variables.
3. Preliminary process design.

Reported Theoretical Approaches

1. Thermodynamic models (energy balance).
2. Single bubble analysis.
3. Instantaneous heat and mass transfer.
4. Evaporation modeling based on boiling heat transfer.

Technological Gaps

1. No considerations of two-phase bubble hydrodynamics
   - Rise velocity.
   - Flow trajectory.
   - Bubble interaction (coalescence, break up etc.).
   - Bubble deformation.
2. No accounting for the pressure driving force for mass transfer.
3. No consideration of heat and mass transfer transients.

Objectives

1. Development of lumped parameter modeling based on
   - Two phase bubble hydrodynamics.
   - Finite heat and mass transfer.
2. Parametric and sensitivity study
   - Gas flow rate.
   - Gas Injection temperature.

Schematic of Injection Cooling Process

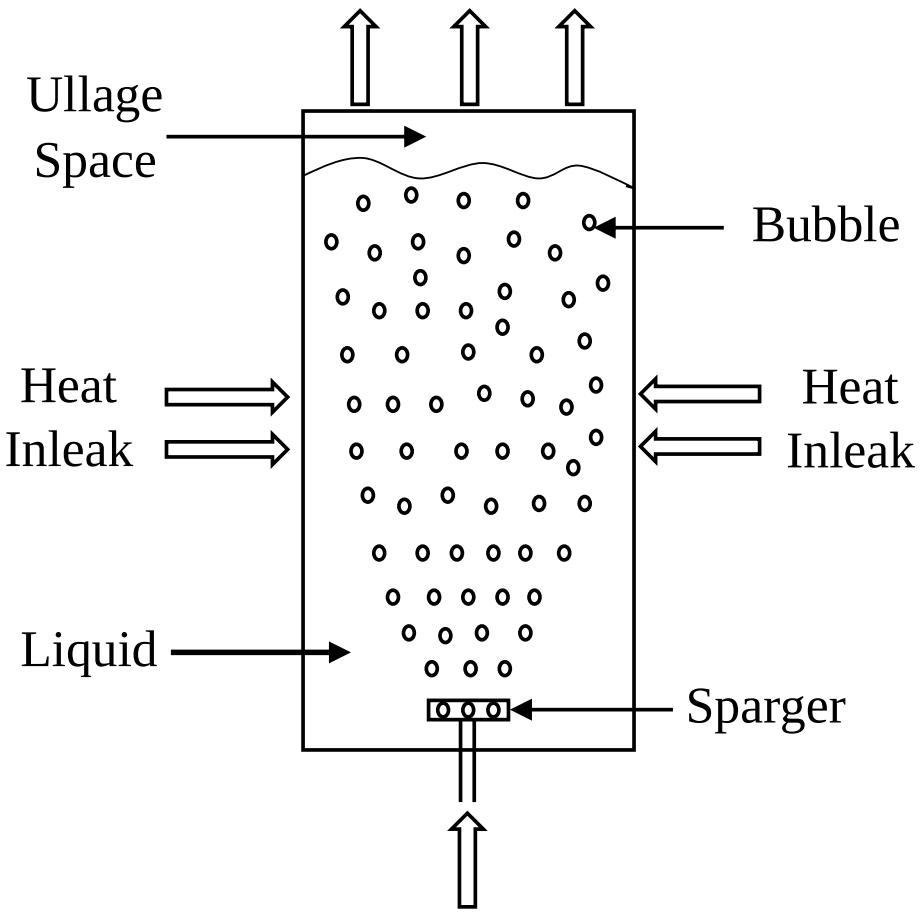


Figure: Schematic of Injection cooling system.

Mechanism of Heat and Mass Interactions

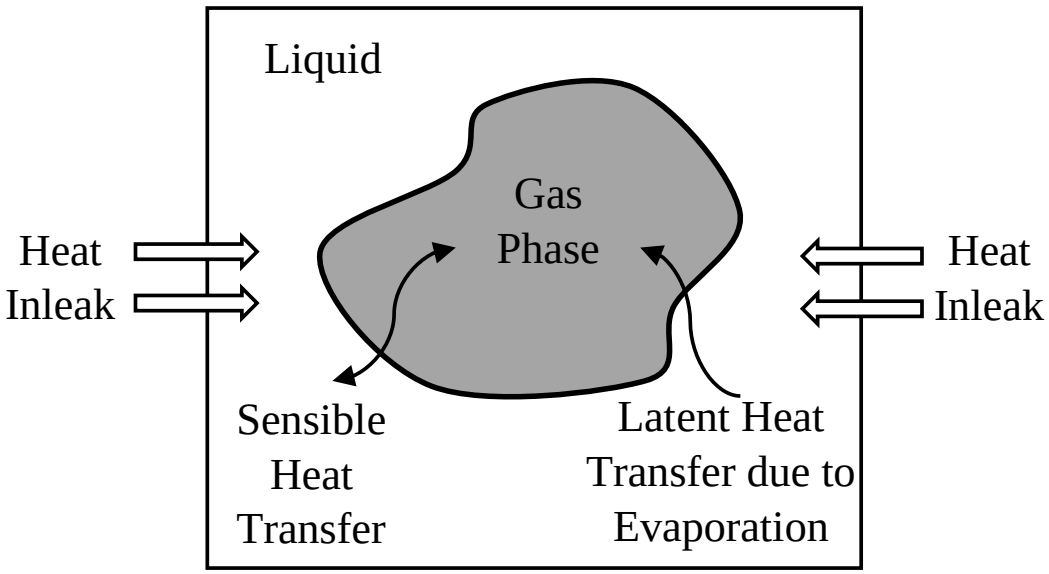


Figure: Heat and mass interactions between gas phase and surrounding liquid.

Modeling Assumptions

1. Spherical and non-deformable bubbles.
2. Constant bubble formation frequency.
3. Ideal gas.
4. Completely submerged orifice.

Energy Balance Equations

- Liquid side

$$\frac{d}{dt}\left(m_l C_{p,l} \Delta T_l\right) = \left(\dot{q}_{g-l} + \dot{q}_{amb} - \dot{q}_{evp}\right)$$

- Gas side

$$\frac{d}{dt}\left(m_g C_{p,g} \Delta T_g\right) = \left(\dot{q}_{evp} - \dot{q}_{g-l}\right)$$

Rate Equations and Transfer Coefficients

Rate Equations

The sensible heat transfer rate	$\dot{q}_{g-l} = h_l a_s \varepsilon_g V_t \left(T_g - T_l\right)$
The heat inleak from ambient	$\dot{q}_{amb} = 2\pi K_{ins} L_c \frac{T_{amb} - T_l}{\ln\left(\frac{r_{ins,o}}{r_{ins,i}}\right)}$
The latent heat transfer rate	$\dot{q}_{evp} = \dot{m}_{evp} h_{fg}$
The liquid mass evaporation rate	$\dot{m}_{evp} = k_g a_s \varepsilon_g V_t \left({P_A}^{Sat} - p_{A,g}\right)$

Transfer Coefficients

Heat transfer coefficient (Deckwer, 1980)	$\mathrm{St} = 0.1\left(\mathrm{Re}_c \mathrm{Fr} \mathrm{Pr}^2\right)^{-0.25}$
Mass transfer coefficient (Saboni et al., 2016)	$\mathrm{Sh} = 6.57 + \left(\frac{\mathrm{Re}_d \mathrm{Sc}}{8.35 + 0.0125\left(\mathrm{Re}_d \mathrm{Sc}\right)^{1.66}}\right)^2$

Bubble Hydrodynamics

The Gas-Liquid specific surface area	$a_s = \frac{6\varepsilon_g}{d_{vs}}$
the Gas phase holdup (Viswanathan and Rao, 1984)	$\varepsilon_g = 0.5{v_g}^{0.8}{v_t}^{-0.4}(0.5gd_c)^{-0.2}$
The Sauter mean diameter (Akita and Yoshida, 1974)	$d_{vs} = 26d_c\mathrm{Bo}^{-0.50}\mathrm{Ga}^{-0.12}\mathrm{Fr}^{-0.12}$

Bubble Hydrodynamics

The terminal rise velocity of bubble (Clift et al., 2005)

$$v_t = \frac{\mu_l}{\rho_l d_{vs}} \mathrm{Mo}^{-0.149} \left(0.94 {H_0}^{0.747} - 0.857\right)$$

$$\text{when } (2 < H_0 \leq 59.3)$$

$$v_t = \frac{\mu_l}{\rho_l d_{vs}} \mathrm{Mo}^{-0.149} \left(3.42 {H_0}^{0.441} - 0.857\right)$$

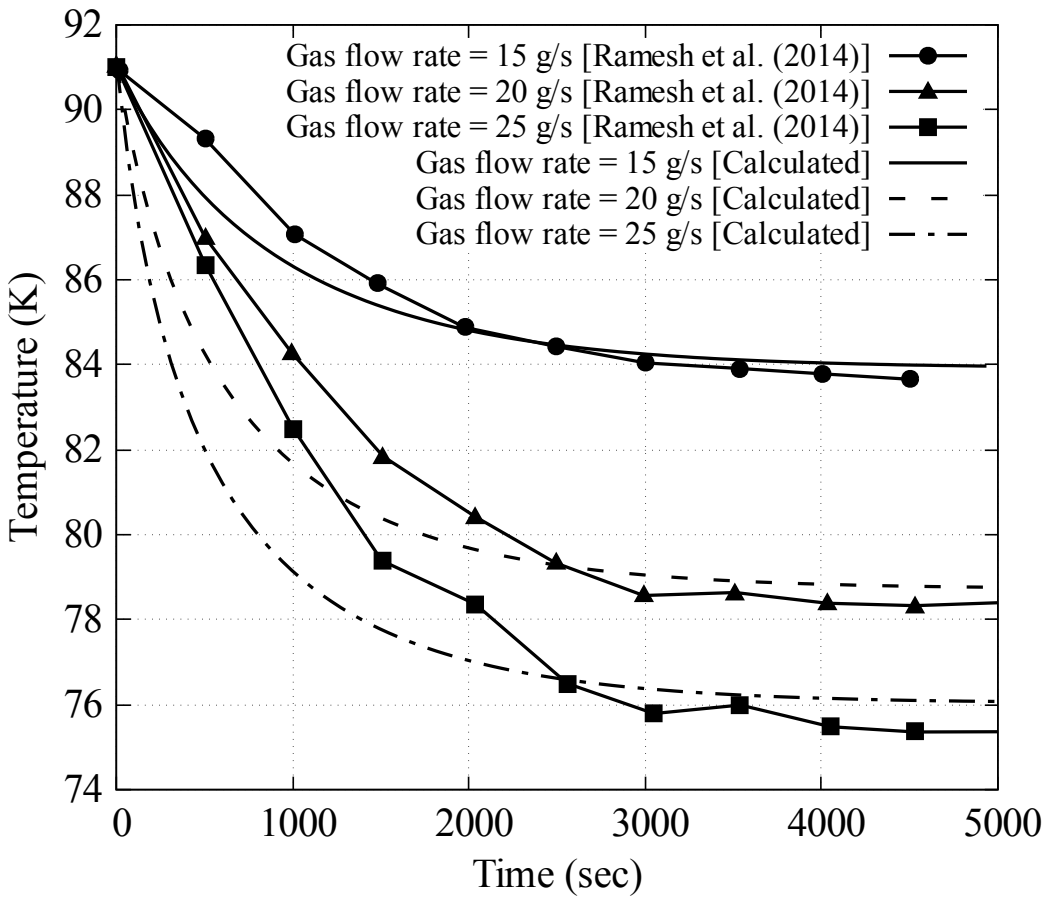
$$\text{when } (H_0 > 59.3)$$

System Configuration and Operating Variables

Table: System configuration and operating variables used for simulation and validation (Ramesh and Thyagarajan, 2014).

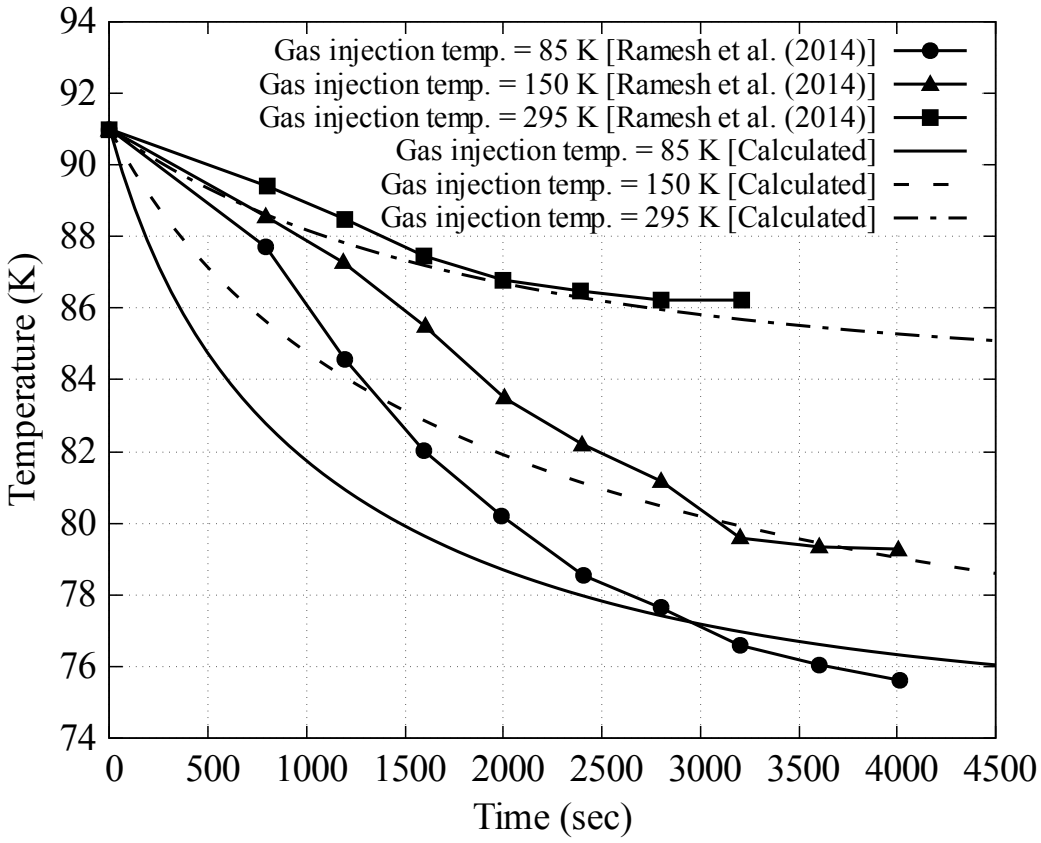
System configuration and operating variables	Values
Height of working liquid (m)	0.9
Column diameter (m)	0.9
Orifice diameter (m)	0.002
Number of orifices	40
Pressure (atm)	1.0
Mass flow rate of gas (g/s)	15, 20 and 25
Gas temperature (K)	85, 91, 150 and 295
Liquid temperature (K)	91 (LOX) and 78 (LN2)
Mass of liquid (kg)	650 (LOX) and 460 (LN2)
Heat inleak (W)	220.0

Effects of Flow Rate



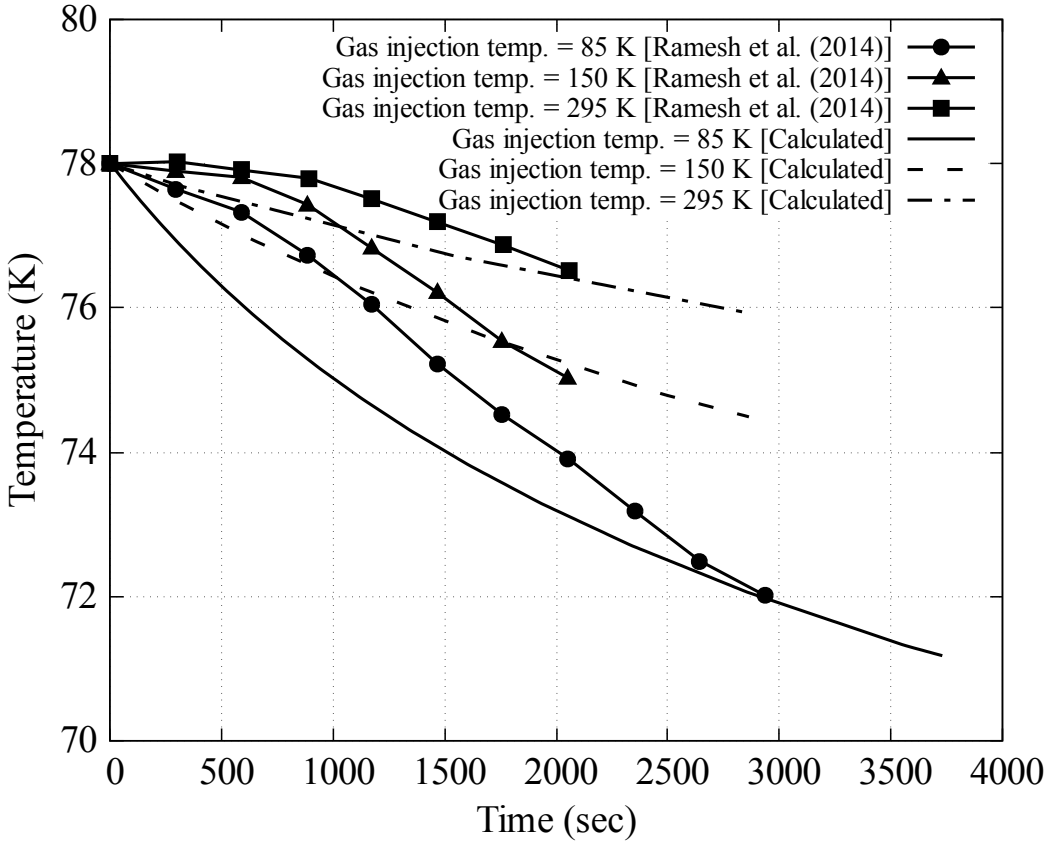
System: LOX-GHe
Gas injection Temperature: 91 K

Effects of Injection Temperature



System: LOX-GHe
Gas flow rate: 2.5 g/s

Effects of Injection Temperature



System: LN2-GHe
Gas flow rate: 2.5 g/s

Conclusion

- A novel lumped parameter model has been developed for injection cooling.
- The model is more realistic as it considers two phase bubble hydrodynamics and finite heat and mass transfer.
- Effects of gas flow rate and gas injection temperature can be predicted correctly.
- Model enables quick estimation of the cooling performance.

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Thank You!