Evaporation of A Liquid Nitrogen Droplet in Superheated Immiscible Liquids

<u>Neville Rebelo</u>, Huayong Zhao*, Francois Nadal, Colin Garner

Wolfson School of Mechanical, Electrical and Manufacturing Engineering

Loughborough University, United Kingdom, LE11 3TU

Email: H.Zhao2@lboro.ac.uk

Outline

- ❑ Background and Motivation
- ❑ Experimental Methodology
- ❑ Results
- ❑ Conclusion and future work

Cryogenic Energy System

Motivation：more sustainable and clean energy system for transportation

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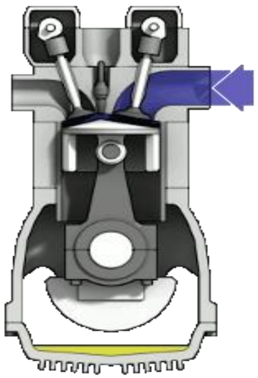
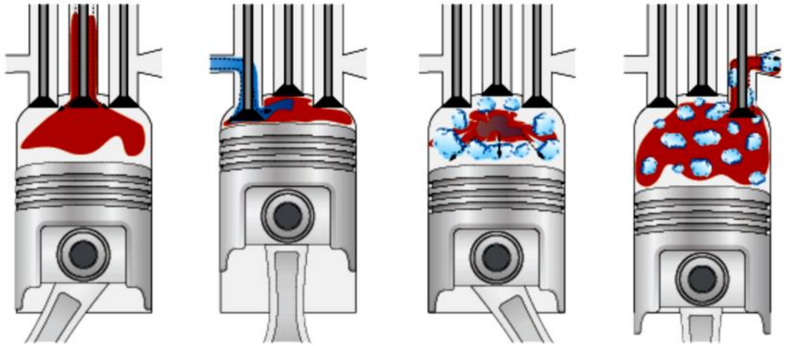




Chemical → Mechanical

Gasoline/Diesel：42-46 MJ/kg

Liquified Natural Gas： 50 MJ/kg

Electrical → Mechanical

Lithium-ion battery: 0.32-1.07 MJ/kg

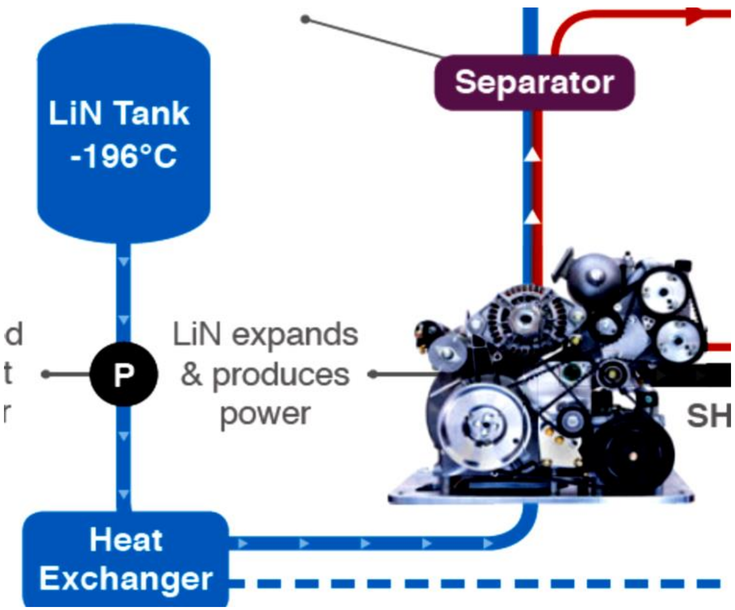
Heat → Mechanical

Liquid nitrogen (77K – 300K): 0.74 MJ/kg

Advantage：1. zero-emission；2. efficient in recovering low-grade heat or refrigeration；

Liquid nitrogen system – heat and mass transfer

Approach 1: Indirect Injection



Technical requirement: effective systematic thermal management

Approach 2: Direct Injection

H. Clarke et. al (2010)

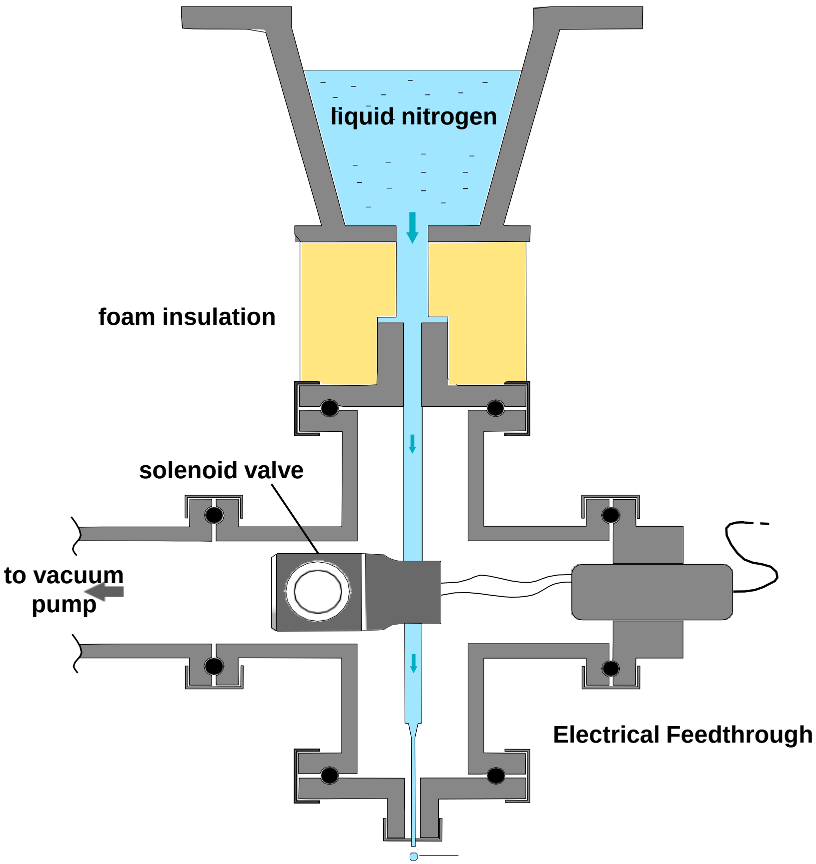
Technical requirement:

Fast evaporation process

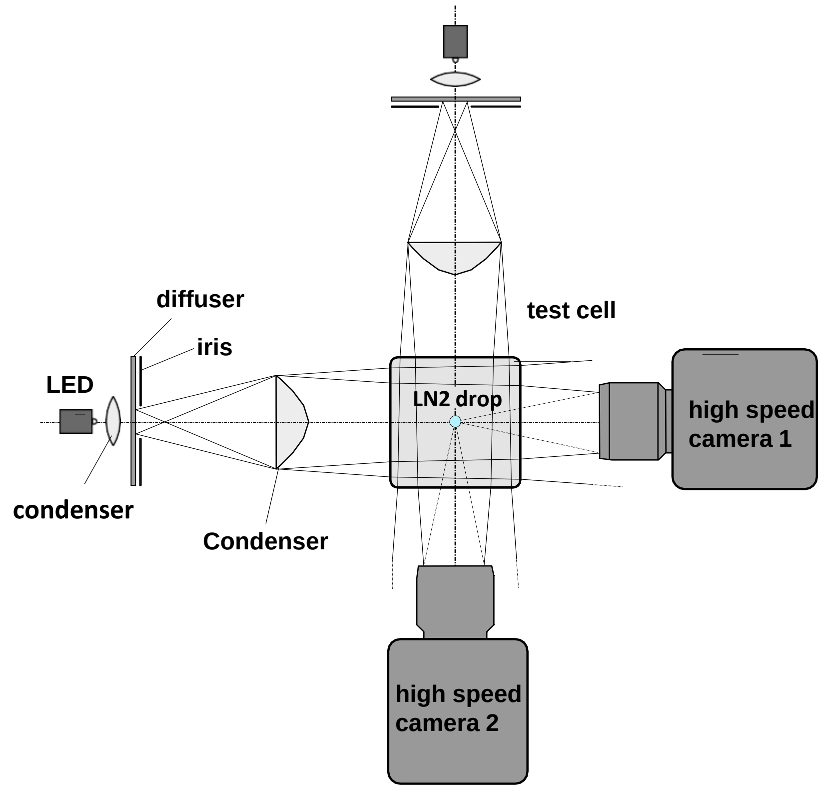
How?

Experimental Methodology - Setup

Vacuum Insulated Drop Injector



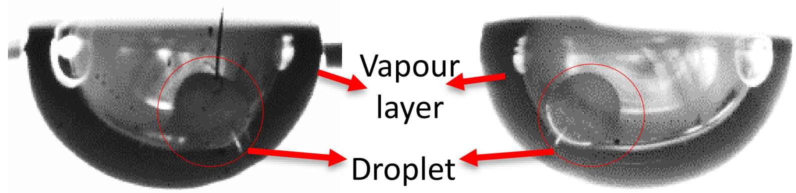
Optical system and Test section



Orthogonal-view high-speed backlit imaging system

N. Rebelo et al., Evaporation of liquid nitrogen droplets in superheated immiscible liquids, *Int. J. Heat Mass Trans.*, 143, 2019

Experimental Methodology – post-processing



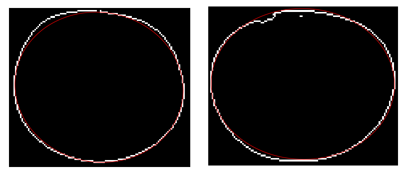
a) Front view **b) Side view**

Edge detection

Sobel / Canny filters

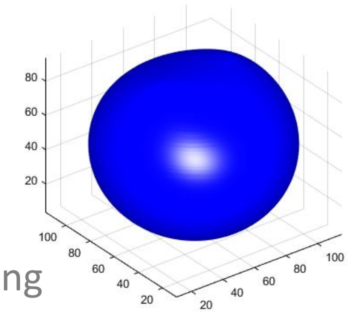
Ellipse detection

Randomized Hough Transform



3D reconstruction

Alpha Shape Fitting



<u>Measured</u> : $V_{drop}, V_{bubble}, A_{drop}$ & A_{bubble}

$\Rightarrow$ <u>Derived parameter</u> : Equivalent radius $r = \frac{3\times V}{A}$, heat flux $\dot{Q} = \frac{\rho_g \Delta V_{bubble} h_{fg}}{\Delta t . A_{drop}}$

Main assumption:

1. Smooth ellipsoid with aspect ratio close to unity (Bo $\leq$ 4 & $Re \leq 9$)
2. Increase in the sensible heat in the vapour layer << latent heat during evaporation

Results – $T_{bulk} = 294\ K$

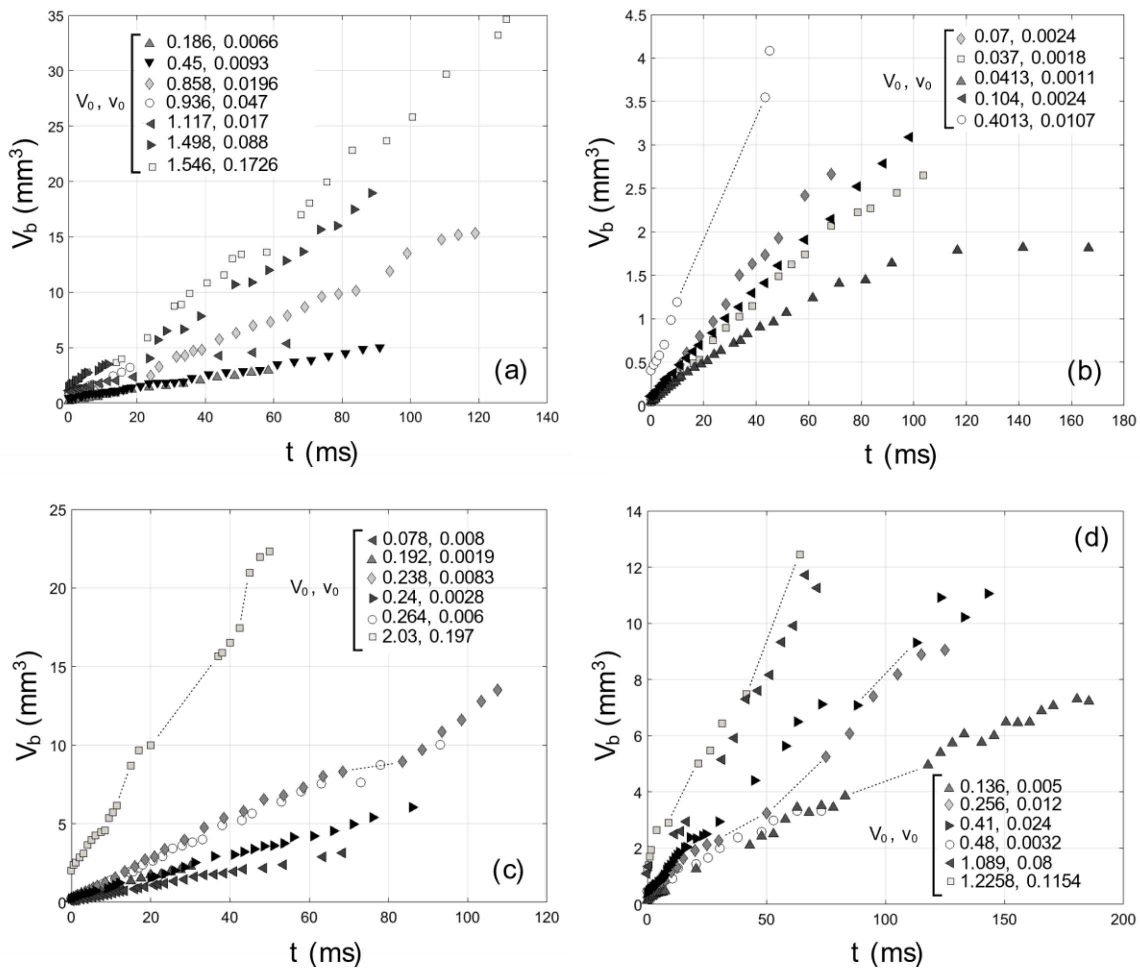


Fig. Bubble volume (V_b) growth for a nitrogen droplet in (a) Propanol; (b) methanol; (c) Pentane; (d) hexane

- The initial droplet size (v_0) has the dominant effect – larger droplet lead to more rapid growth
- Other fluid properties, e.g. viscosity and surface tension could have minor but noticeable effect

Results – Scaling analysis

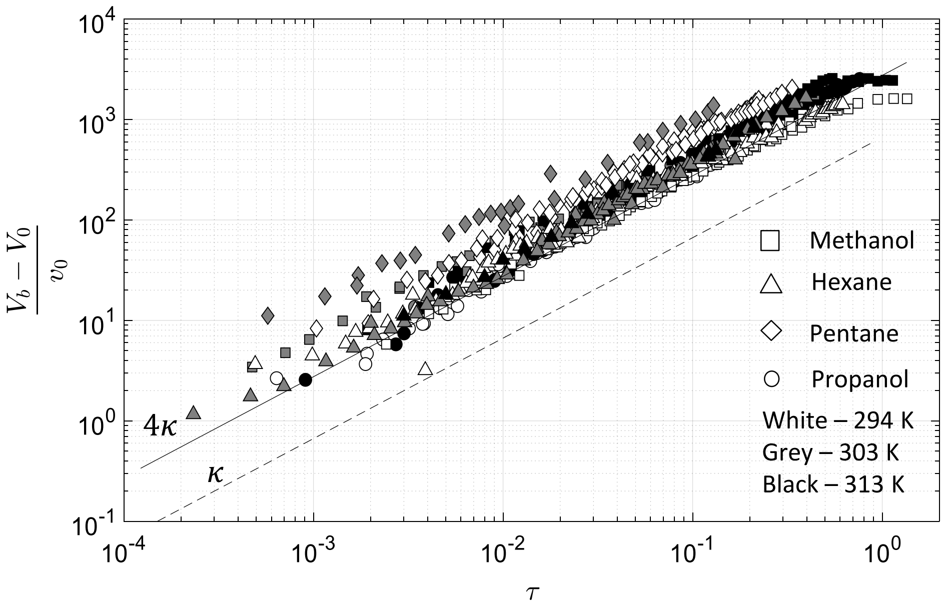


Fig. Rescaled experimental data based on Eq. (1)

Eq. (1) with $\kappa' = 4\kappa$ fits experimental data well, except for the pentane data

Assume 1) diffusion-controlled evaporation of the droplet and negligible droplet heating:

$$r_d^2 = r_0^2 - \alpha t \qquad D^2\text{-law}$$

Where r_d - radius of the droplet at time t; r_0 is the initial radius;

Further assume 2) quasi-steady vapour phase;
3) vapour phase behaves as ideal gas;
4) vapour pressure and temperature are uniform
5) Negligible effect of vapour confinement

$$\Rightarrow \boldsymbol{v_o^{-1} \frac{dV_b}{d\tau} = \kappa}; \qquad \text{Eq. (1)}^1$$

$$\text{Where } \kappa = \frac{3}{2}\frac{\rho_d R\bar{T}}{M_{N_2} P_a}; \tau = \frac{\alpha t}{r_o^2};$$

$$\alpha = \frac{2k_b}{\rho_d c_p} \ln\left[1 + \frac{c_p(T_b - T_d)}{h_{fg}}\right]$$

1 - N. Rebelo et al., Evaporation of liquid nitrogen droplets in superheated immiscible liquids, *Int. J. Heat Mass Trans.*, 143, 2019

Simplified 1D Model

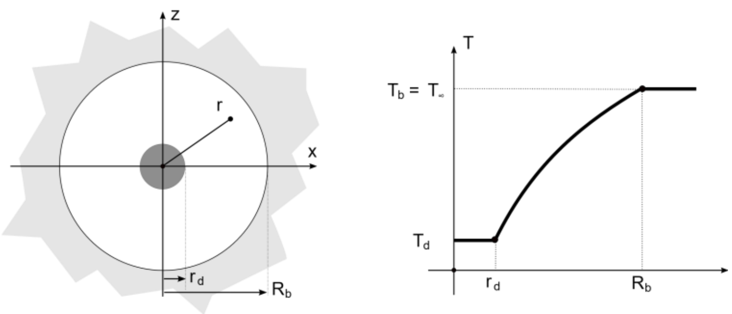


Fig. Geometrical configuration used for the model

Other main assumptions:

1. Negligible droplet heating
2. Inviscid vapour phase
3. Quasi-steady temperature profile at each time step ($\mathrm{Pe} = \frac{R_0}{D}\frac{dR_b}{dt} \in [0.2, 1.1]$ so not fully justified)
4. Negligible convection

Each time step (δt):

$$\nabla^2 T = 0 \;\rightarrow T(r) \rightarrow q = k_b \frac{dT}{dr} \rightarrow dn = \frac{4\pi r_d^2 q}{h_{fg} M_{N_2}} dt$$

$$P_b = P_l + \frac{2\sigma_l}{R_b}; \rho_b(r) = \frac{P_b M_{N_2}}{RT(r)} \rightarrow n = \frac{4\pi}{R} P_b \int_{r_d}^{R_b} \frac{r^2}{T(r)} dr$$

$$\Rightarrow dR_b = \left[\frac{R}{4\pi} dn + \left(P_l + \frac{2\sigma_l}{R_b}\right)\frac{r_d^2}{T_d} dr_d\right] / \left[\left(P_l + \frac{2\sigma_l}{R_b}\right)\frac{R_b^2}{T_b} - \frac{2\sigma_l}{R_b^2}\int_{r_d}^{R_b} \frac{r^2}{T(r)} dr\right]$$

$$R_b(t+\delta t) = R_b(t) + dR_b; r_d(t+\delta t) = r_d(t) + dr_d$$

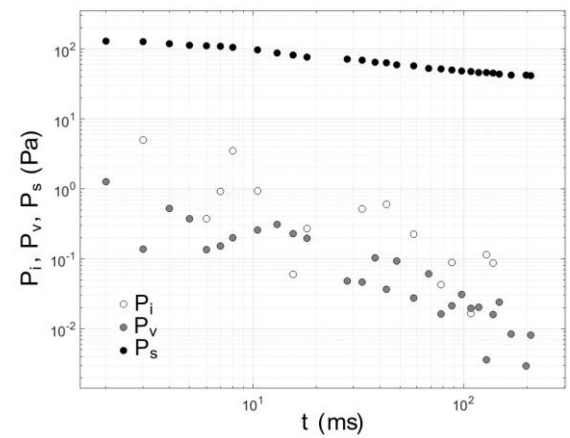
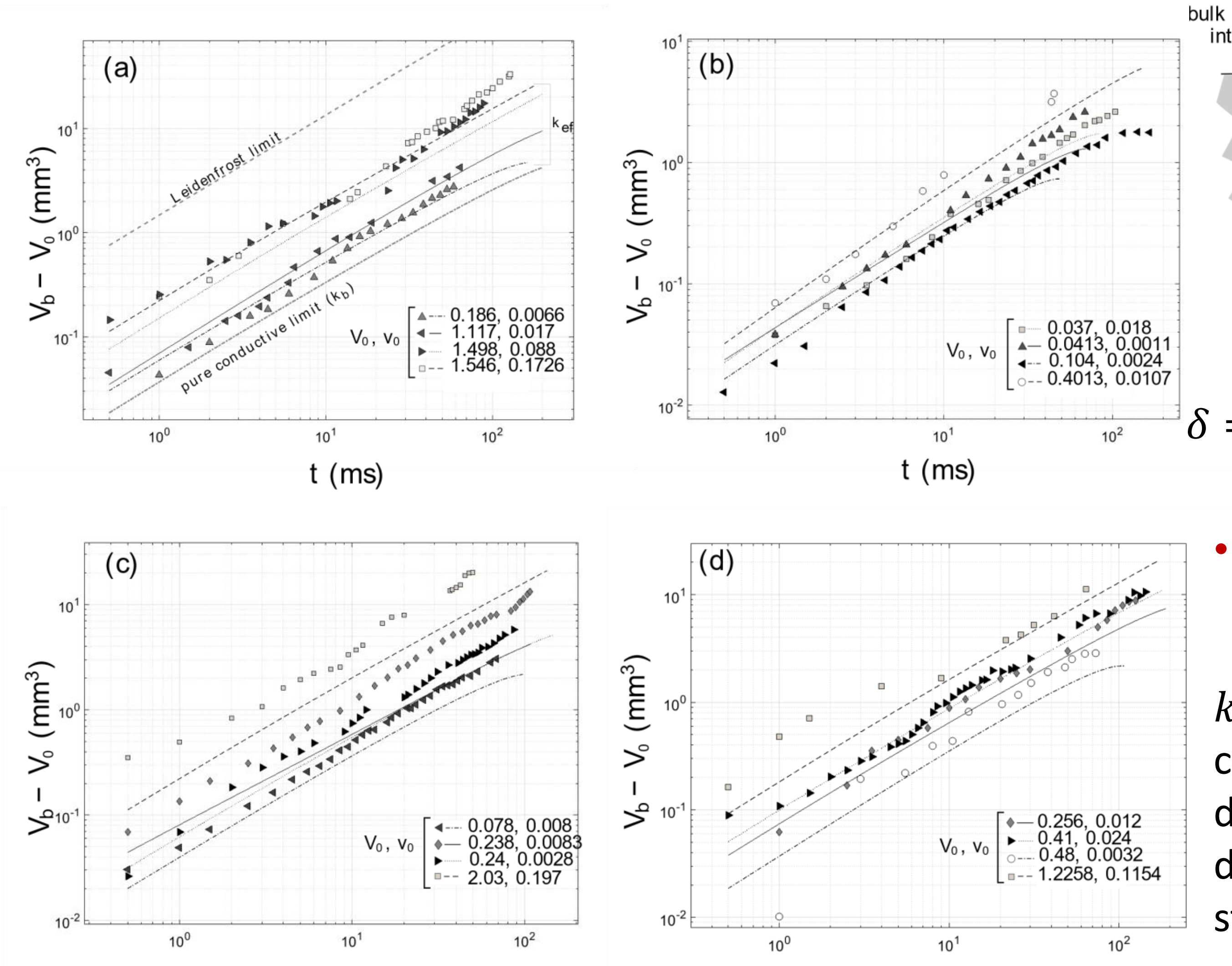
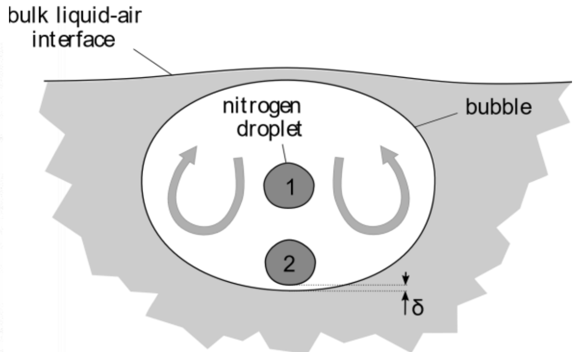


Fig. Pressure due to inertial (P_i), viscous (P_v) and capillary (P_s)

Results – Model vs Experiments





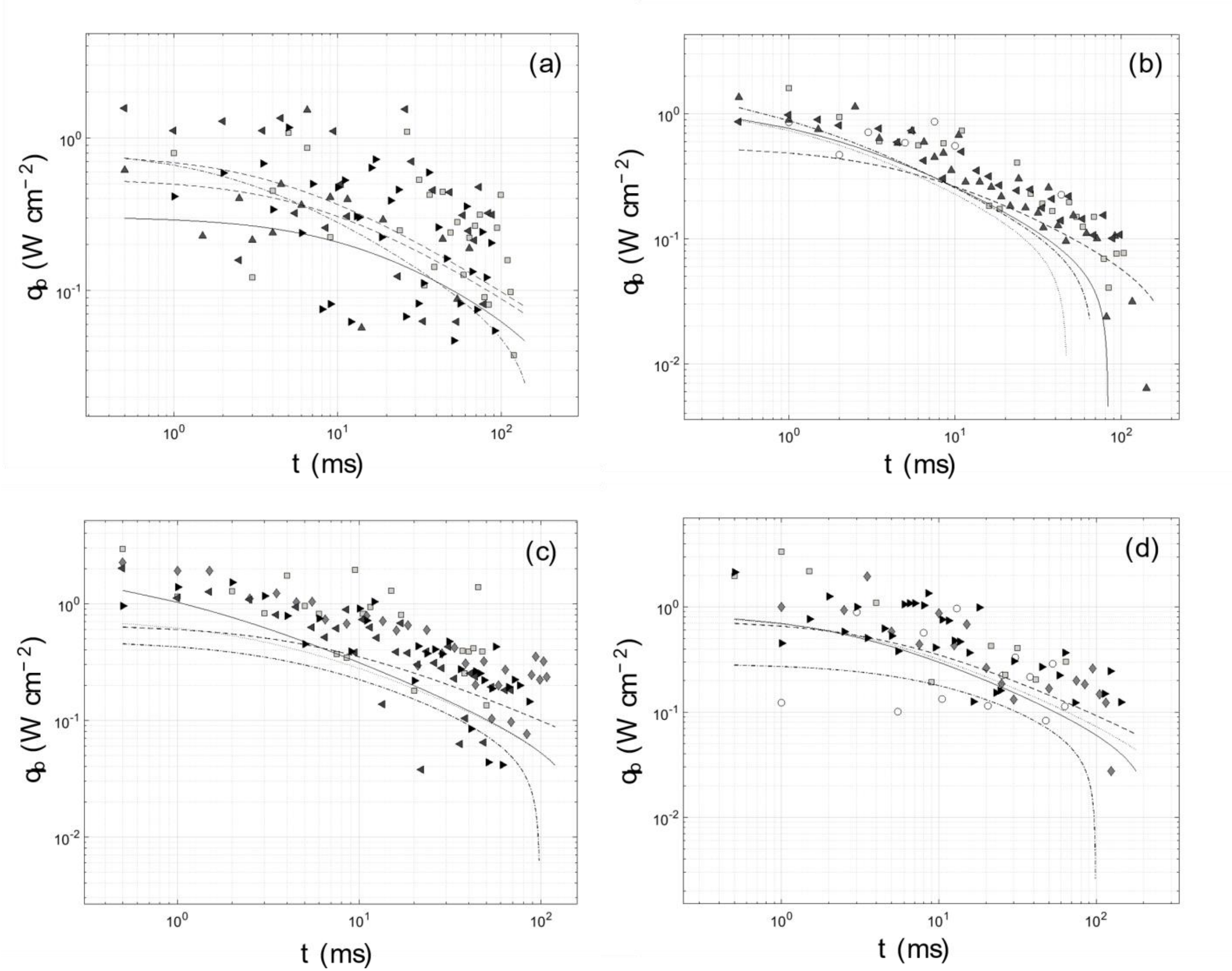
$$\delta = \left[\frac{3k_b(T_b - T_d)\mu_b}{4h_{fg}\rho_b\sigma_d a^2}\right]^{1/4} r_d^{5/4} \text{ [1]}$$

- $k_{\text{eff}} = 1.6 \times k_b$ fits experimental data well

k_{eff} - a simple way to compensate for the effects due to the mobilities of droplet and the quasi-steady state assumption

[1] Biance et al. Phys. Fluids, 15:1632-1637, 2003

Results – Heat flux during evaporation



$$q_b = \frac{\rho_b h_{fg}}{A_b}\frac{dV_b}{dt}$$

Normalised using the droplet surface area:

$$\overline{q_d} \sim 25 \text{ W cm}^{-2}$$

Pool boiling:
$\overline{q_s} \sim 6.5 \text{ W cm}^{-2}$

Key Conclusions

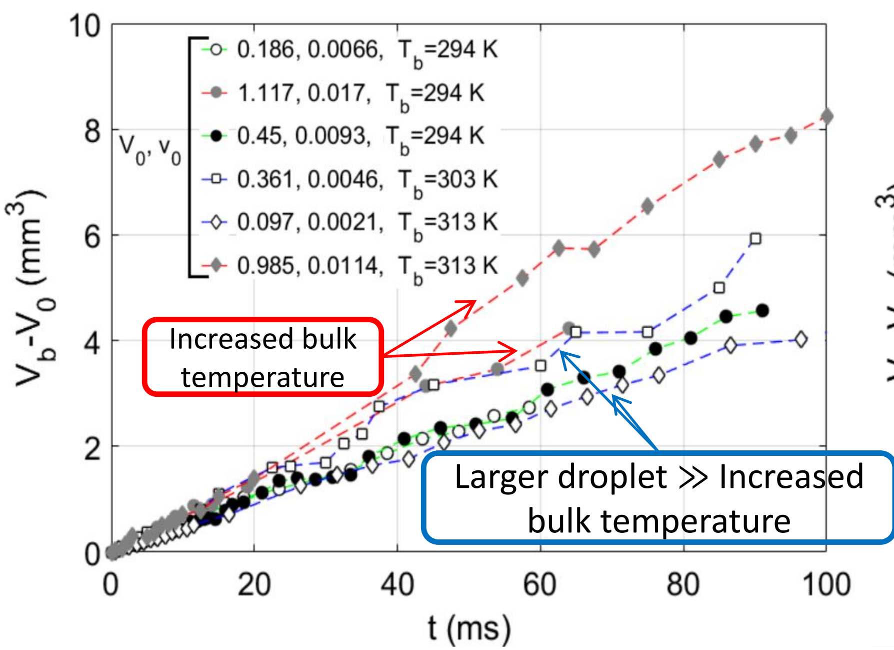
1. Evaporation rate of liquid nitrogen droplets in an immiscible superheated liquid can be scaled well by the D^2- law. The effect of droplet confinement and mobility requires a higher coefficient (4κ) compared to the classic quasi-steady state isothermal diffusive evaporation process.

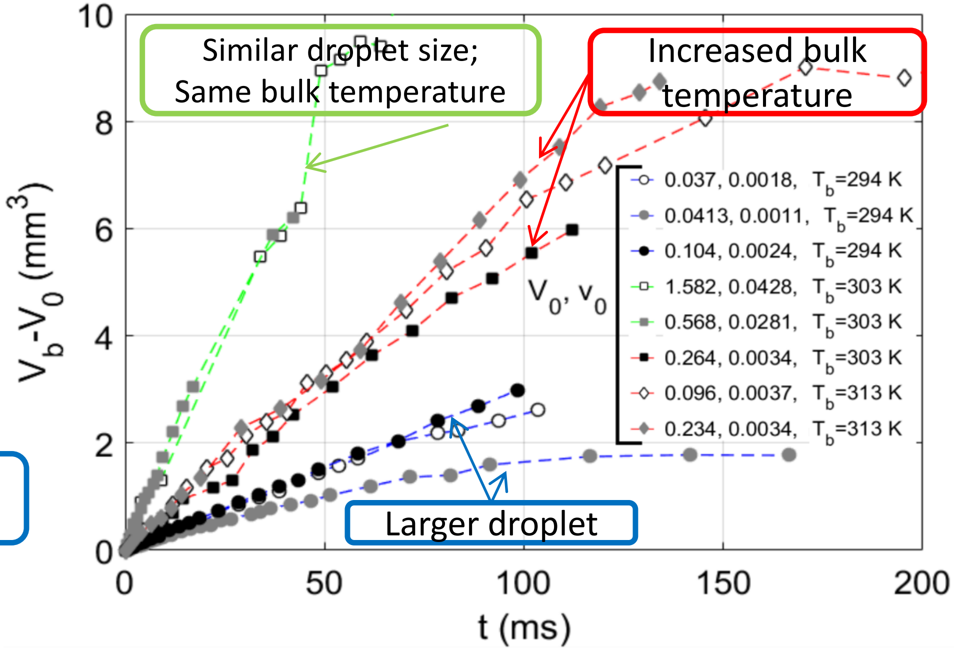
2. Correction for the effect of droplet confinement and mobility can be made by a simplified 1D quasi-steady state model with an 'effective thermal conductivity' $k_{\text{eff}} = 1.6k_b$

3. The assumption of quasi-steady state is not fully justified and further improvement of the model will require a transient multi-dimensional model, which could be difficult to implement in practical application.

4. The evaporation rate of the liquid nitrogen droplet in a superheated fluid is limited by the insulation vapour layer. More efficient practical application will require ways to destabilize the vapour layer.

Results – Effect of Bulk Liquid Temperature





- Higher growth rate in hotter bulk liquid, but the initial droplet size can still be important, or sometimes dominant, for the growth rate