Heat transfer during bubble shrinking in saturated He II under microgravity condition

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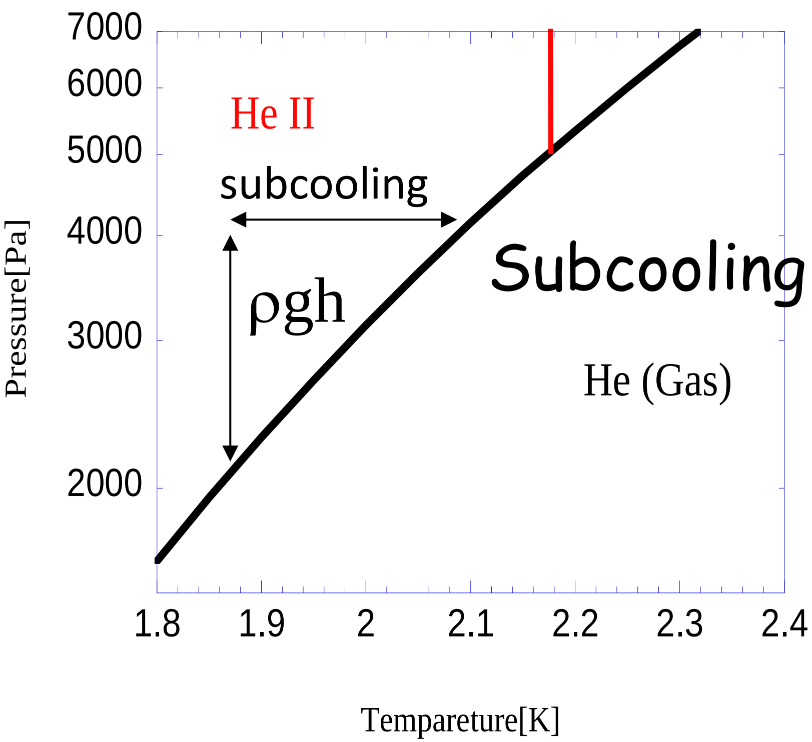
Contents

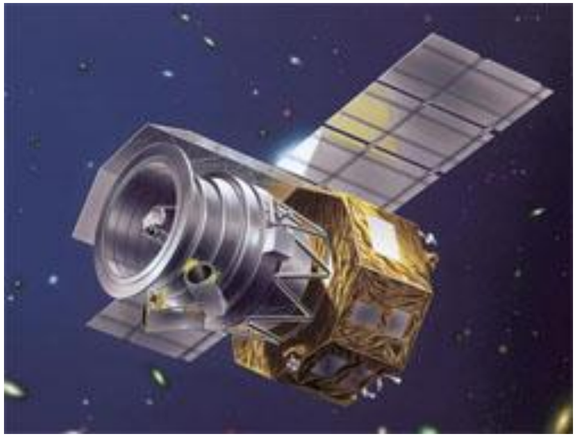
Background of this "μ-g" experiment

He II is utilized as a Coolant for space applications.



Subcooling becomes zero

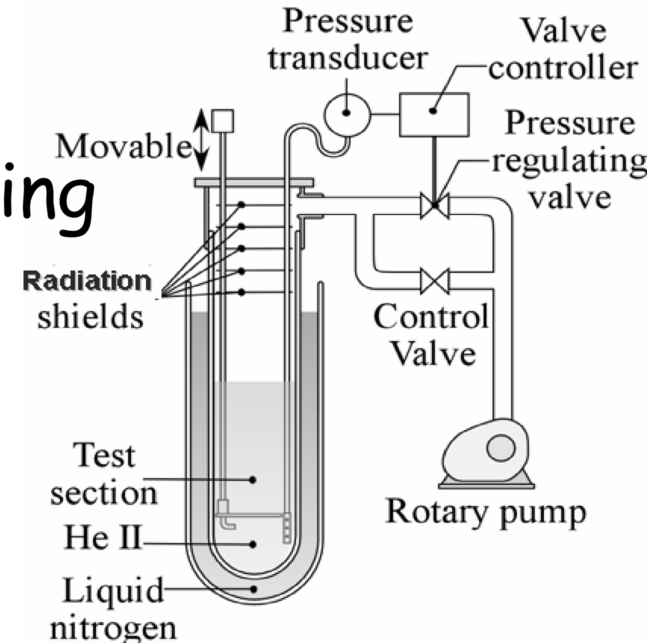
X-ray telescope
ASTRO-H @ JAXA



Infrared telescope
AKARI (ASTRO-F) @ JAXA

Study of Heat transfer in μ-g is required
Critical heat flux of onset boiling must be small.

Previous experiments
: Critical heat flux for onset of boiling



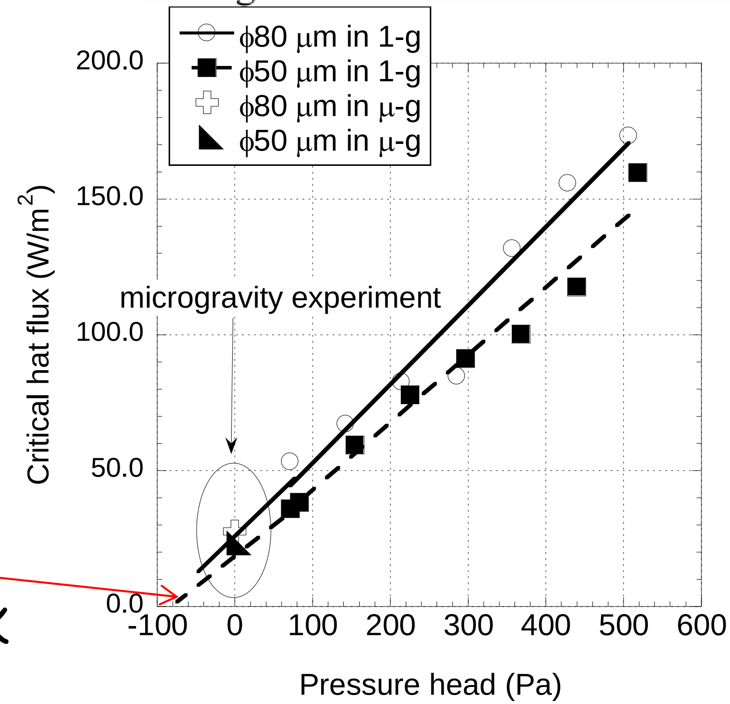
Gorter-Millink equation for cylindrical cordinate

$$q_{cr} = \left(\frac{(m-1)\varphi}{r} \int_{T_b}^{T_i} \frac{dT}{f(T)} \right)^{1/m}$$

Rewritten using with Clausius-Clapeyron equation

$$q_{cr} = \left(\frac{(m-1)\varphi}{r} \cdot \frac{T_b}{\rho_v L} \cdot \frac{\Delta p_A}{f(T)} \right)^{1/m}$$

$$\boxed{\Delta p_A = \left(\frac{\rho_v}{m_{He4}} \right)^2 \cdot a}$$



Offset pressure = van der Waals pressure

～80Pa at 1.9K

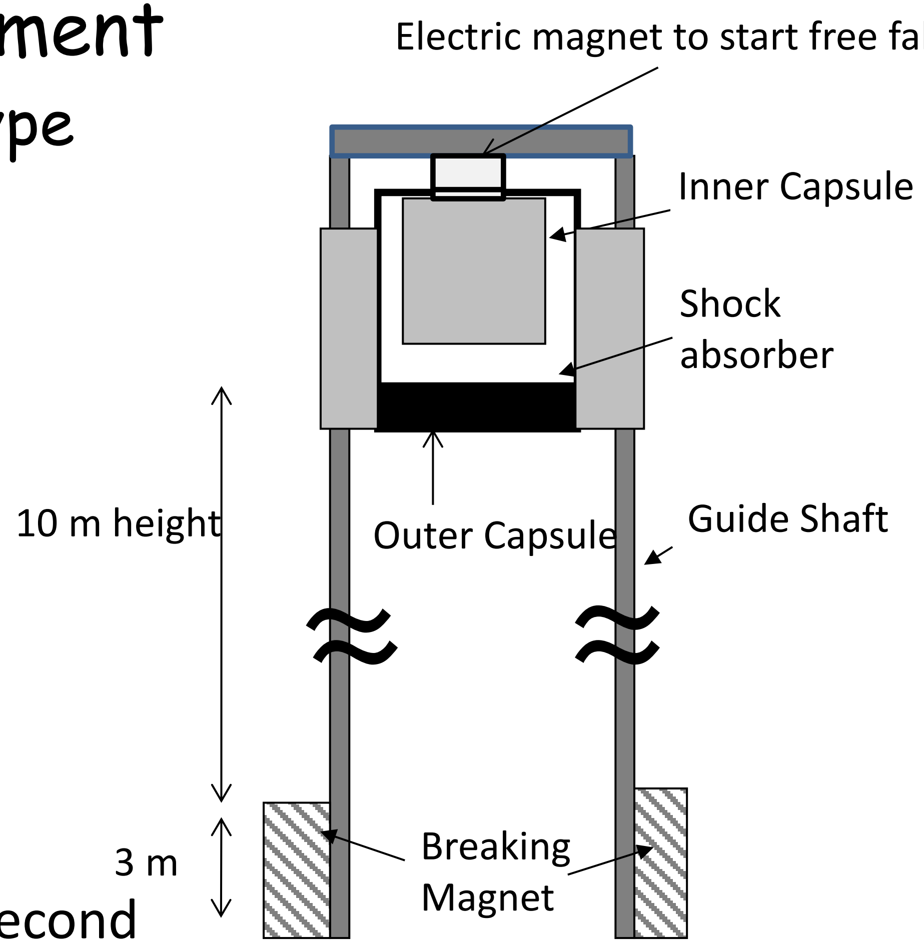
(Not surface tension: ～20 Pa)

Remaining problem is after onset of boiling

How to express the heat transfer across vapor-liquid interface under μ-g condition.

3. Experimental setup

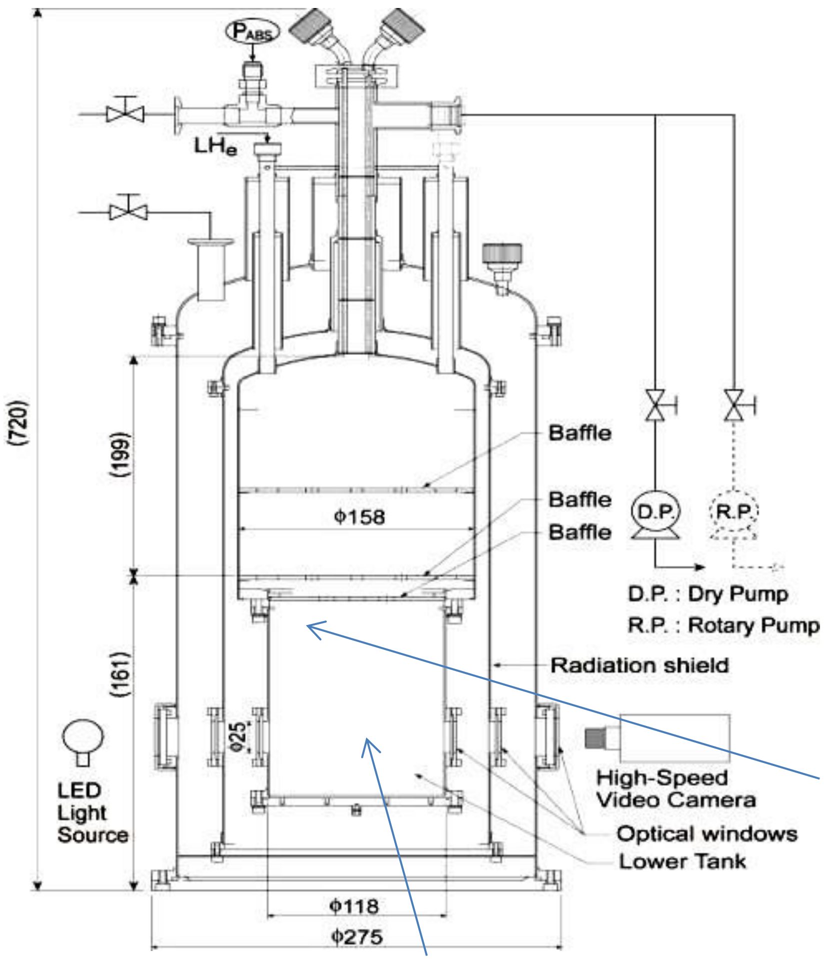
Drop tower Experiment
: Double capsule type



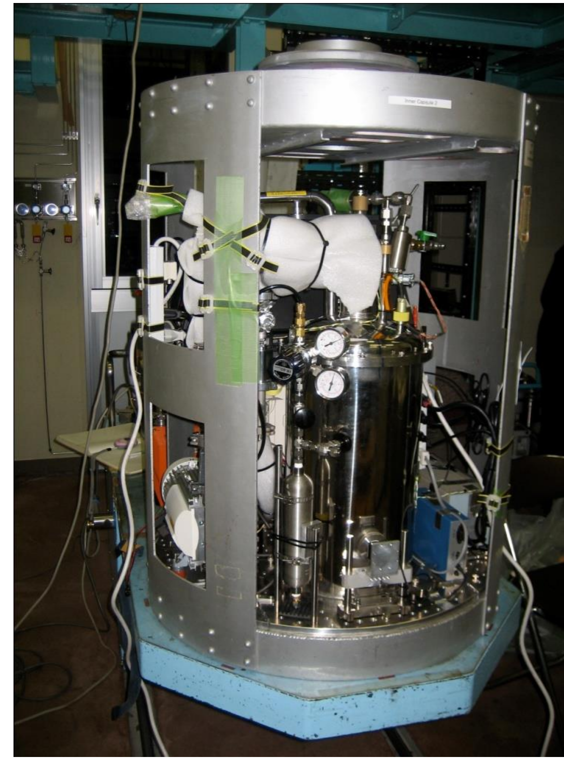
- AIST* Hokkaido, Japan
- Below 1 milli g_{earth} : for 1.27 second
- Limit : <100 kg, <ϕ720 x 820 (size of inner capsule)
- Brake: 4～6 g_{earth}
- Turn around: 15 min
- Timing signal synchronized with Electro magnet

* National institute of advanced industrial science and technology , Japan

Small cryostat



Only Liquid helium

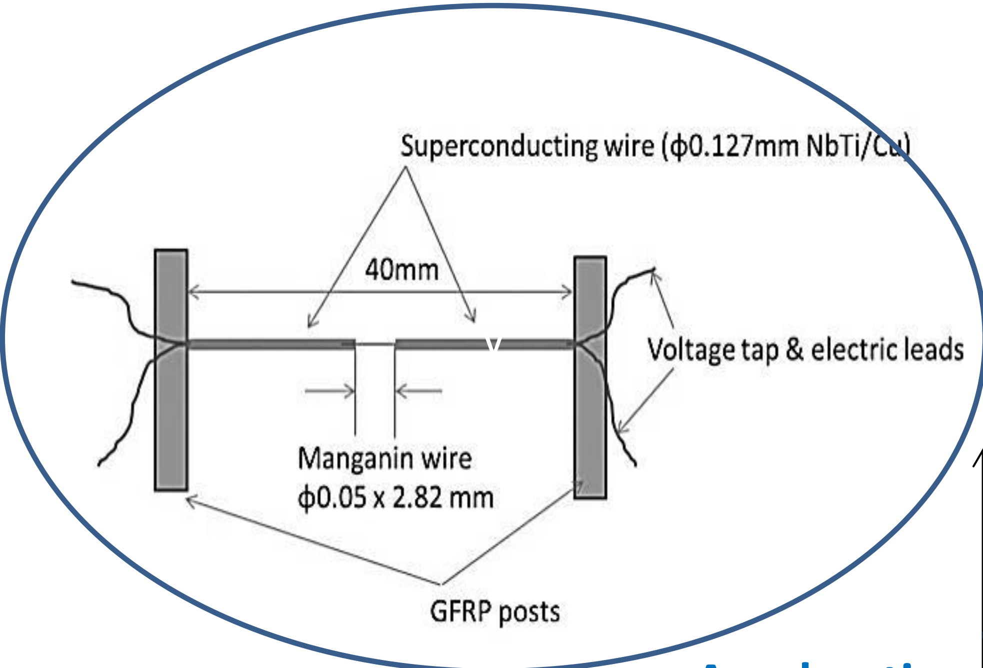


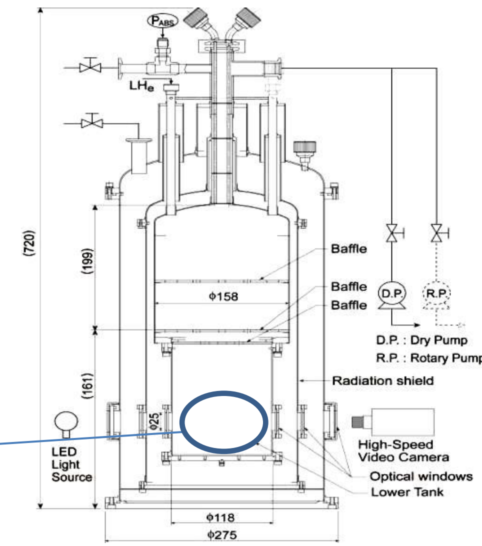
All devices were set in inner capsule
(ϕ720 x 800 mm)

Baffle : porous metal to avoid initial flow
due to capillary force

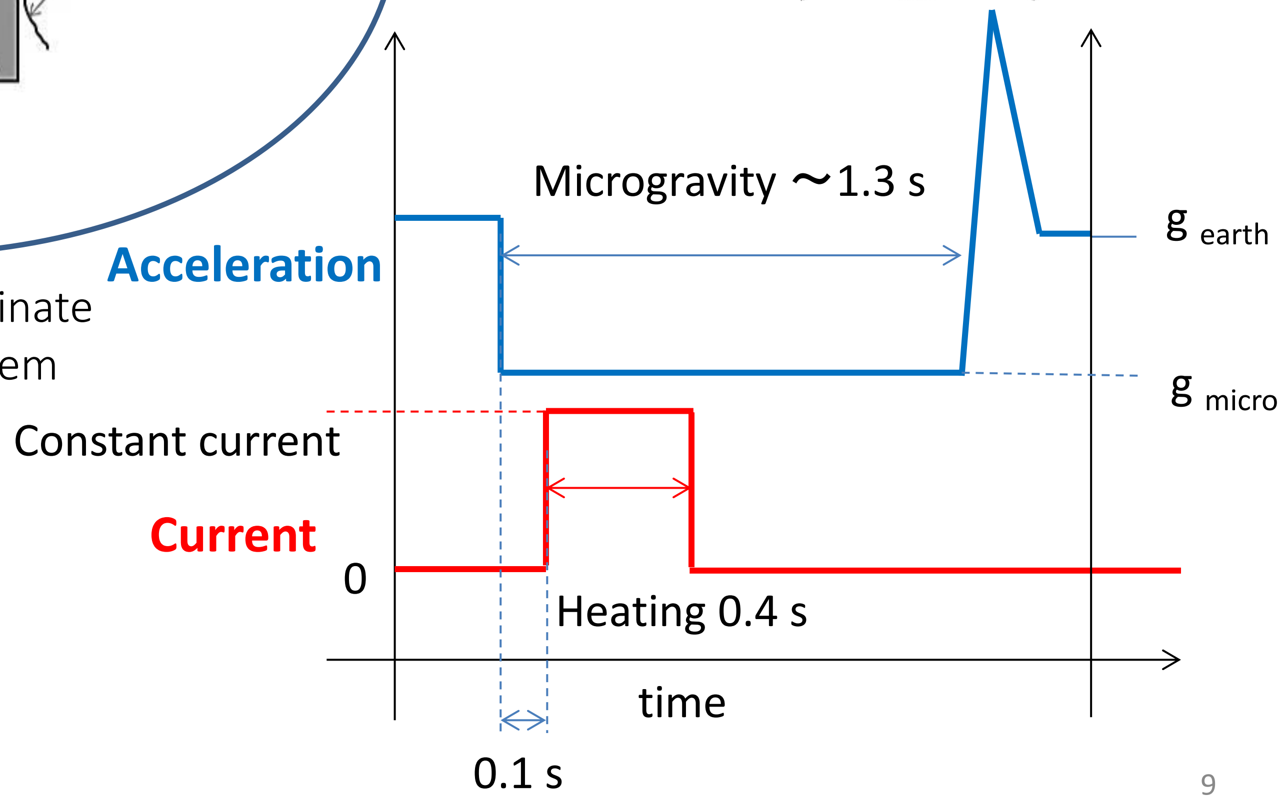
“Mitsubishi materials corporation”

Small heater unit was set in test vessel



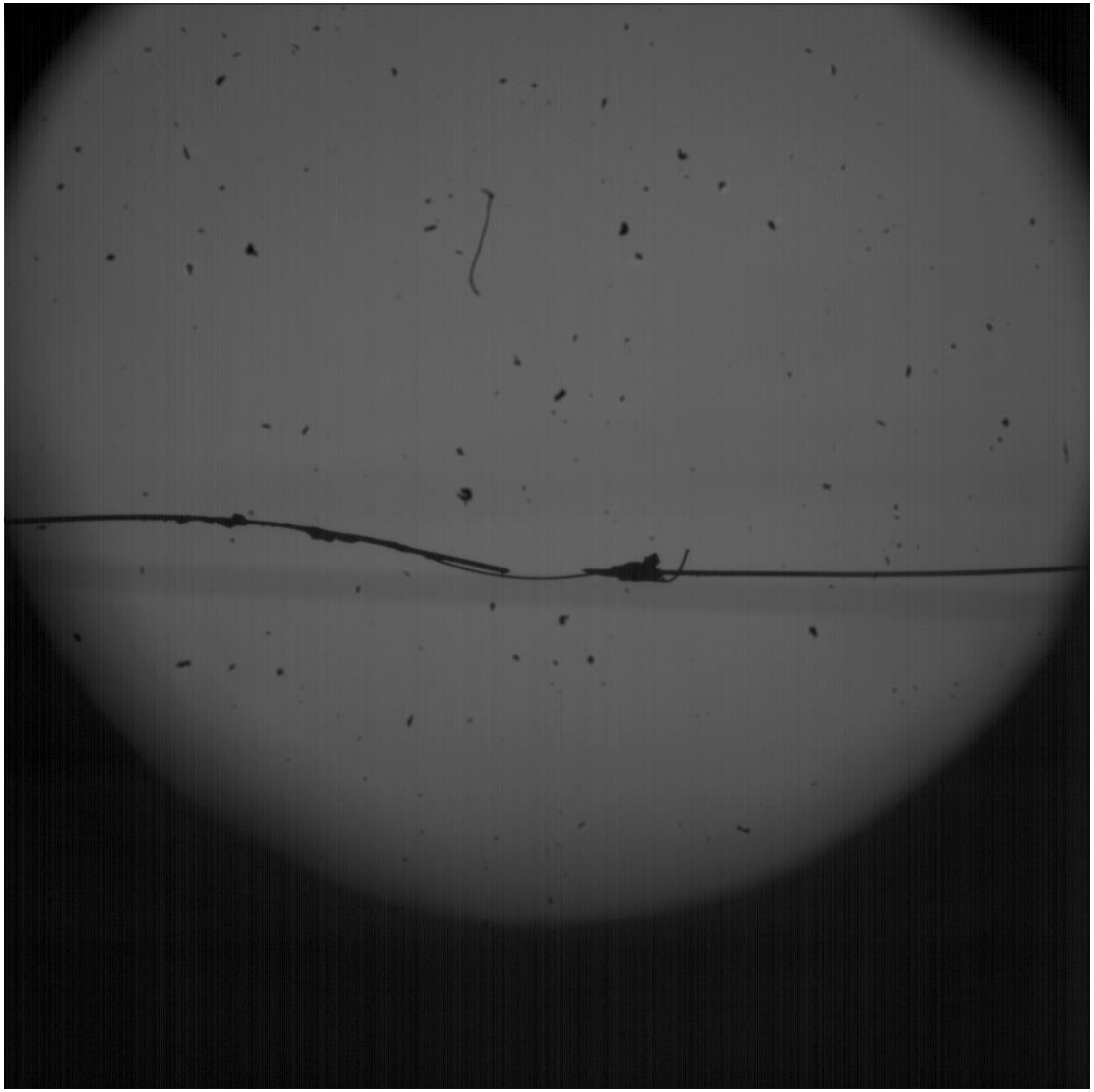


We tried make sphere coordinate to be realized simple system



4. Results & Discussion

Visualization results (movie)

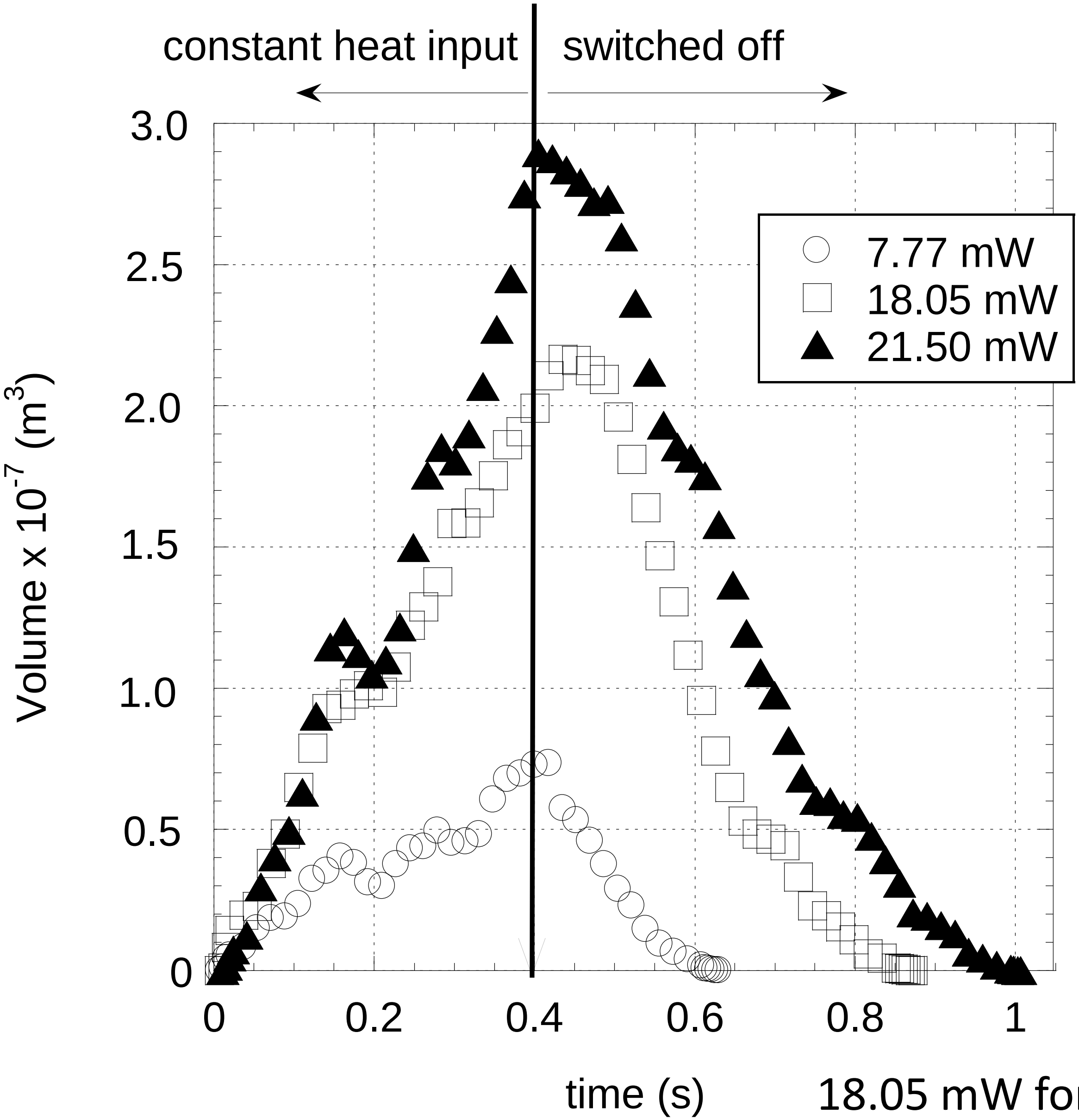


20 mm

20 mm

18.05 mW for 0.4 s at 1.9 K
Playback speed is 15 times longer

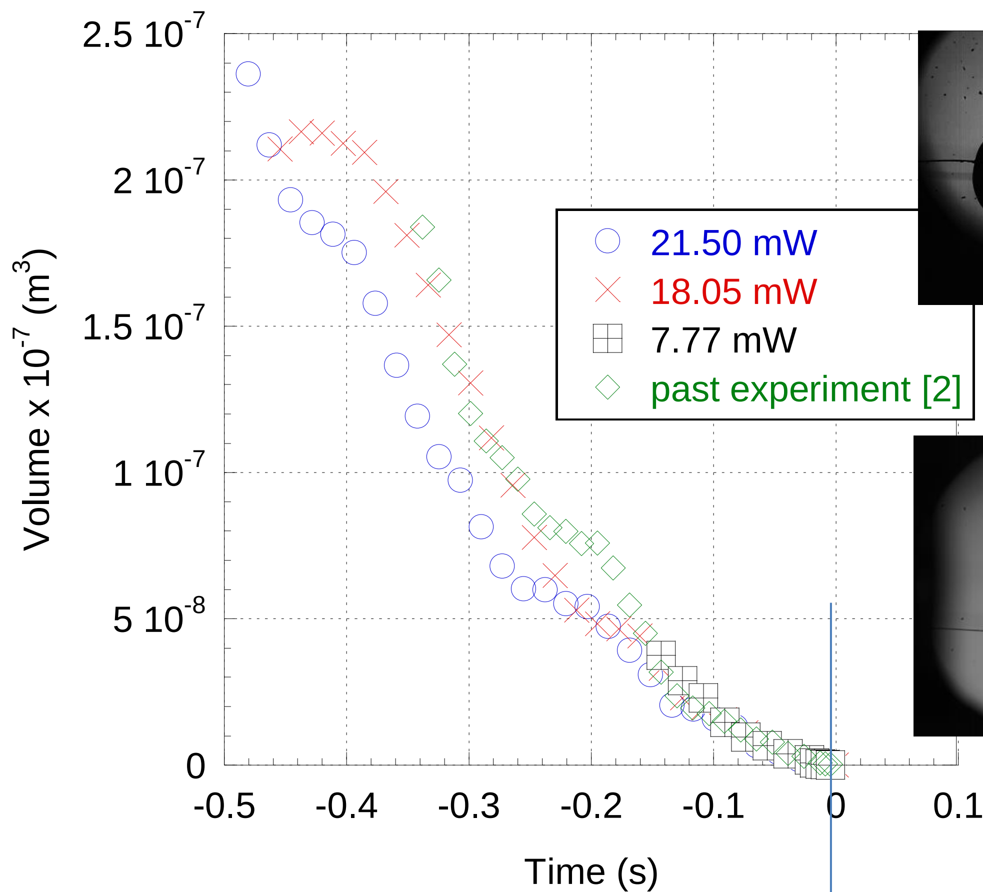
Time variation of vapor volume by image analysis

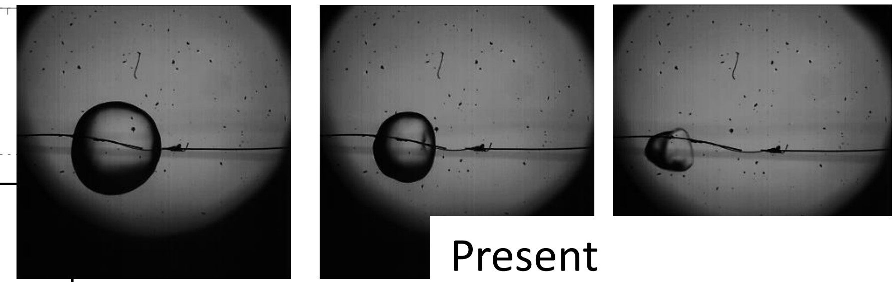


18.05 mW for 0.4 s at 1.9 K

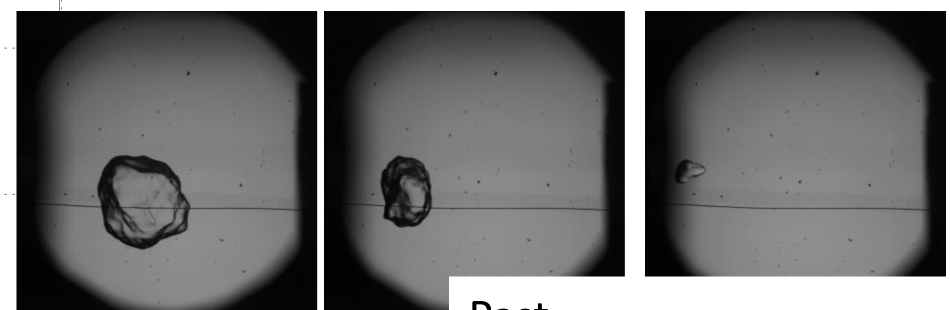
Playback speed is 15 times longer

Replot of Time variation of vapor volume in shrinking stage





Present
Small heater experiment

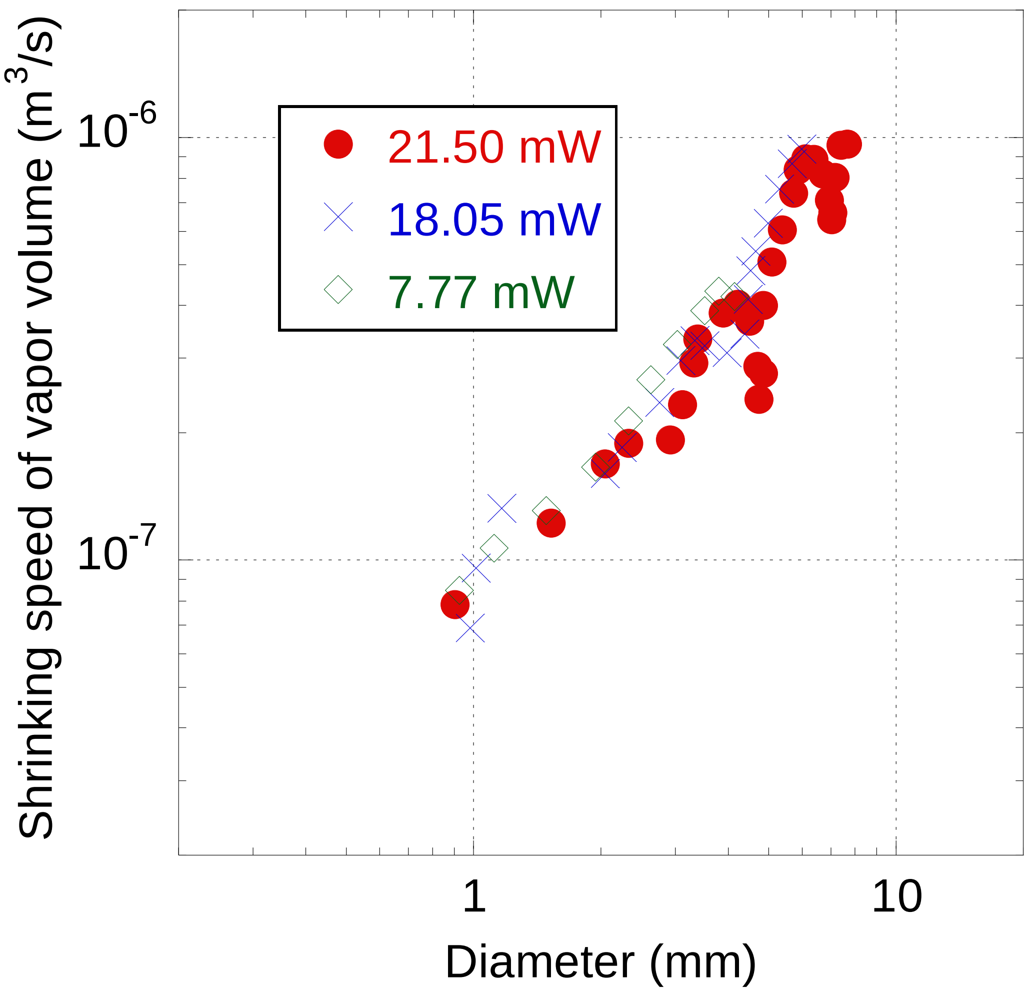


Past
Long heater experiment

t=0 redefined the moment of vanishing a vapor bubble

Shrinking speed depends on size dominantly. The vapor motion and gas condition inside a bubble has no significant effect to the bubble shrinking

Derivation *dV/dt* results from time variation of volume



The shrinking speed is roughly proportional to the diameter

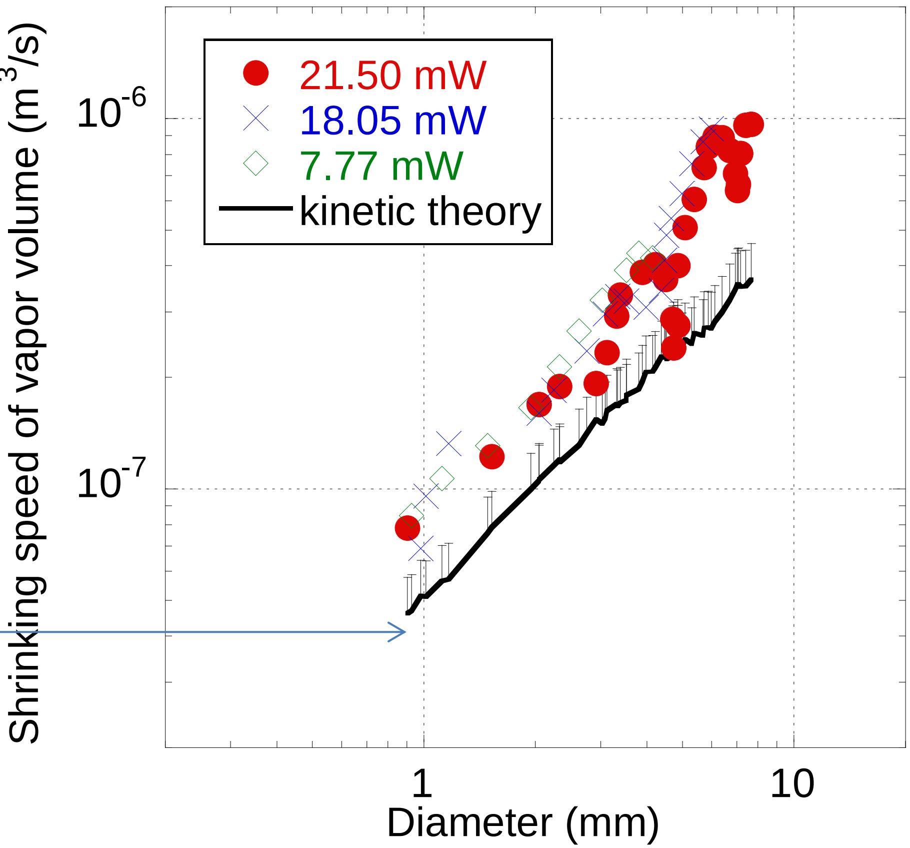
The equation of energy balance on the interface based on kinetic theory

$$2\sqrt{\pi}\left(\frac{1-0.4\beta}{\beta}\right)j-\frac{2\sigma}{r}\sqrt{2RT_i}+\frac{\sqrt{\pi}}{4}q_i=0$$

j is mass flux across interface, (measured)
β is thermal expansion ratio, 0.72 *
q_i is heat flux across interface

$$T_i \approx T_b$$

$$\frac{dV}{dt}=\frac{\pi D^2 q_i}{\rho_{sat} h_{fg}}$$

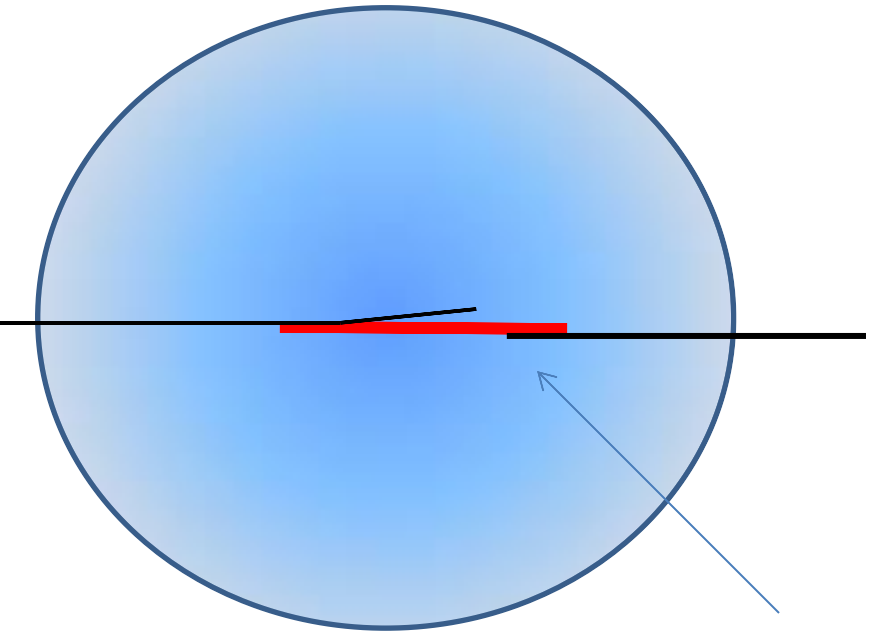


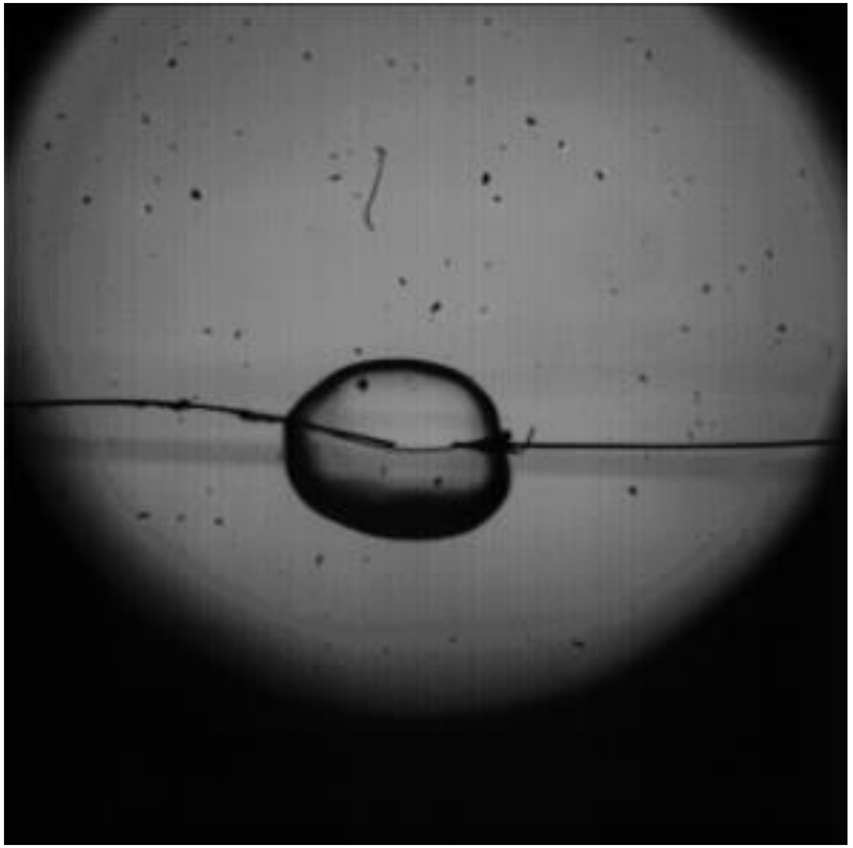
The error bars were drawn with +25%
of the maximum ratio between the shadow area of the bubble and peripheral length.

Actually gas density is smaller than ρ_{sat}
so that calculation result is smaller than the measured data.

*Murakami M., Furukawa T., Maki M., Fujiyama J., 2002 Experimental Thermal and Fluid Science, Volume 26 p 229-235

Rough Estimation of gas density inside a bubble.





Known values:

Heater temperature (resistance of Manganin) : 50 ～80 K

Bubble size

Temperature on Liquid-vapor interface

Thermal conduction of through a sphere from a point heat source

$$Q = 4\pi r^2 \kappa \frac{dT}{dr}$$

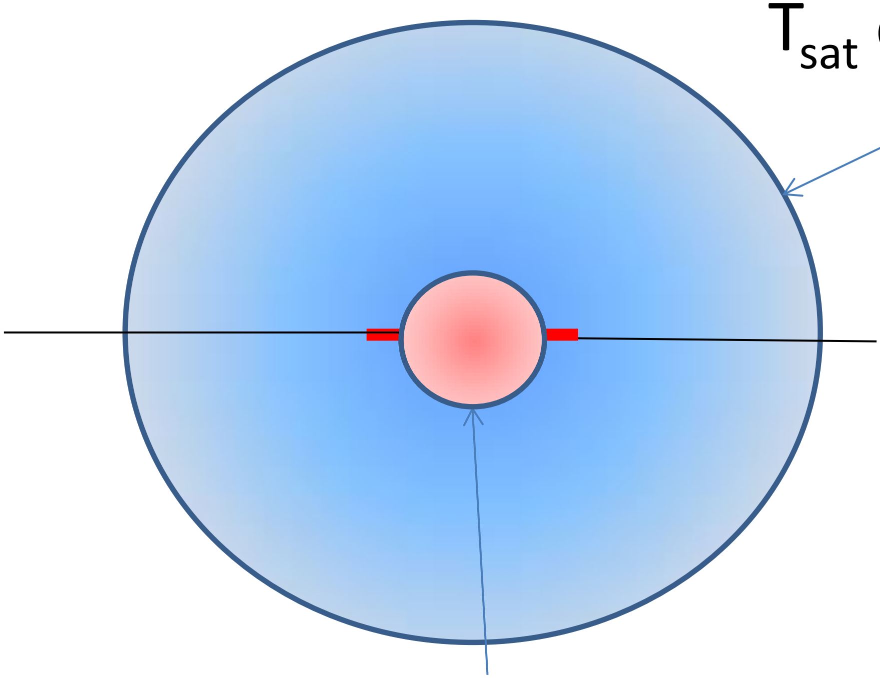
Boundary Condition
r =ε, T= Tc (ε is micro element)

$$T_r = T_c + \frac{Q}{4\pi k}\left(\frac{1}{r} - \frac{1}{\varepsilon}\right)$$

$$T_{ave} = \frac{\int_0^{r_i}\left(T_c + \frac{Q}{4\pi\kappa}\left(\frac{1}{r} - \frac{1}{\varepsilon}\right)\right)\cdot 4\pi r^2 dr}{\frac{4}{3}\pi r^3} = T_c + \frac{Q}{4\pi\kappa}\left(\frac{1}{(2/3)\cdot r} - \frac{1}{\varepsilon}\right)$$

Heater temperature is represent on the surface temperature of sphere in the 2/3 diameter of heater length.

T_{sat} on the liquid-vapor



surface temperature on ϕ1.82
= heater temperature

Thermal conduction of symmetric sphere

$$Q = 4\pi r^2 \kappa \frac{dT}{dr}$$

Effective thermal conductivity can be calculated

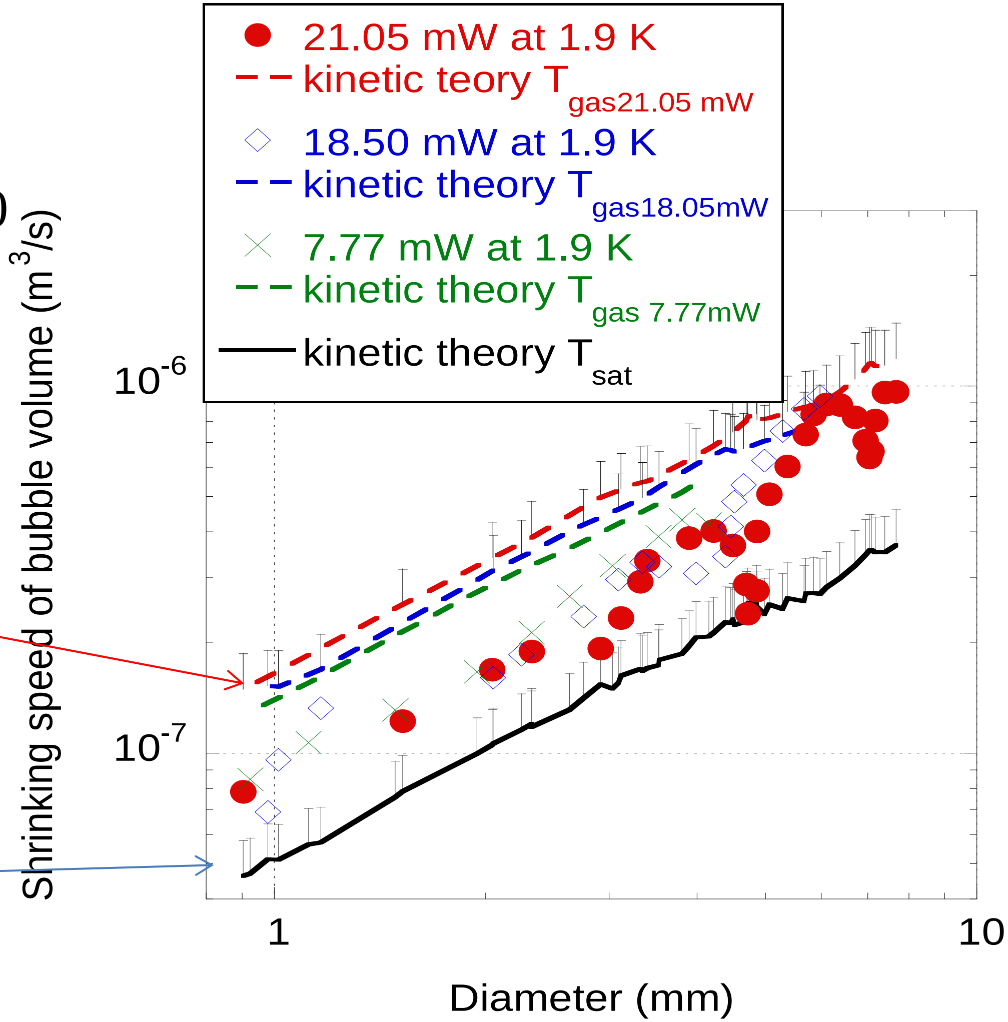
$$\kappa_{avg}\left(T_{avg}\right) = \frac{Q(r_i - r_w)}{4\pi r_i r_w (T_w - T_i)}$$

T_{gas} is estimated by κ-T relation of Helium property
the results are between 5～7K

$$2\sqrt{\pi}\left(\frac{1-0.4\beta}{\beta}\right)j-\frac{2\sigma}{r}\sqrt{2RT_i}+\frac{\sqrt{\pi}}{4}q_i=0$$

$$\frac{dV}{dt}=\frac{\pi D^2 q_i}{\rho_{avg}h_{fg}}$$

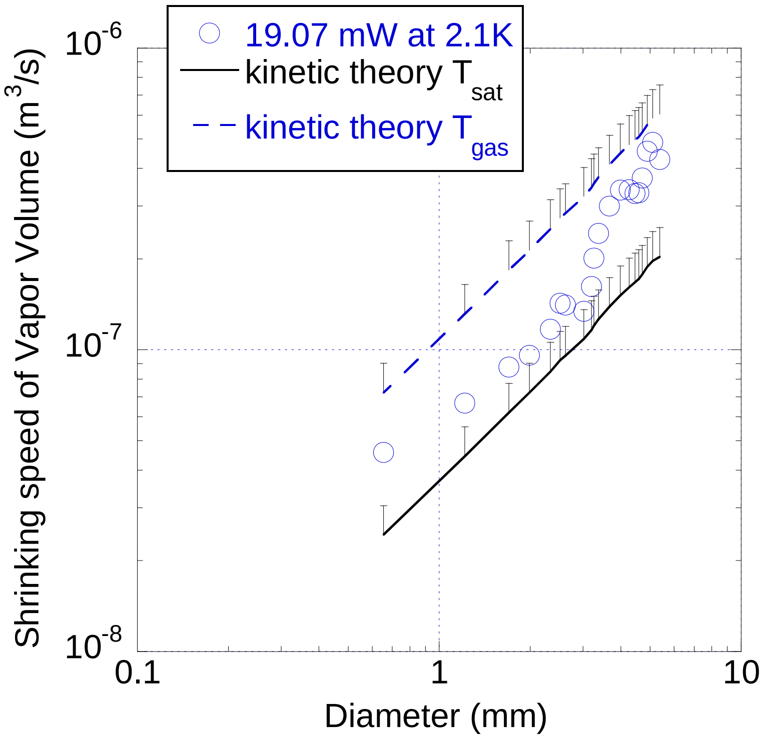
$$\frac{dV}{dt}=\frac{\pi D^2 q_i}{\rho_{sat}h_{fg}}$$



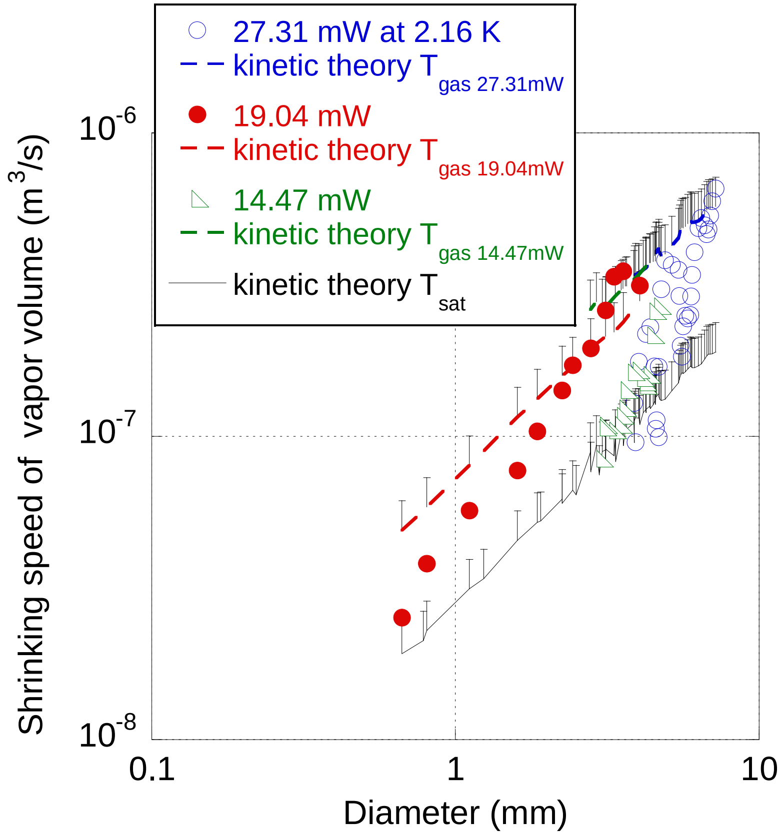
Shrinking speed of bubble is related to

the heat transport explained by the kinetic theory and the gas constriction

Bath Temperature dependence



2.1 K



2.16 K

This phenomenon is not depending on the temperature difference between T_b and T_λ.

Kinetic theory is “universal”.

But in other liquid this heat transport is hard to be observed because of ΔT in liquid phase, gas density, and ･･･.

Conclusion

To investigate the heat transfer across the liquid-vapor interface under microgravity condition, a visualization experiment using a single shrinking bubble was carried out with a drop tower. Image analyses of pictures taken by a high-speed video camera reveal that

Findings:

- The shrinking speed of the bubble under the microgravity condition is related to the heat transport across the vapor-liquid boundary as explained by the kinetic theory and gas constriction.

- The pressure difference due to **surface tension** plays a role for the heat transfer across the liquid-vapor interface in microgravity. The **van der Waals pressure** plays a role only **for the critical heat flux of onset boiling**.

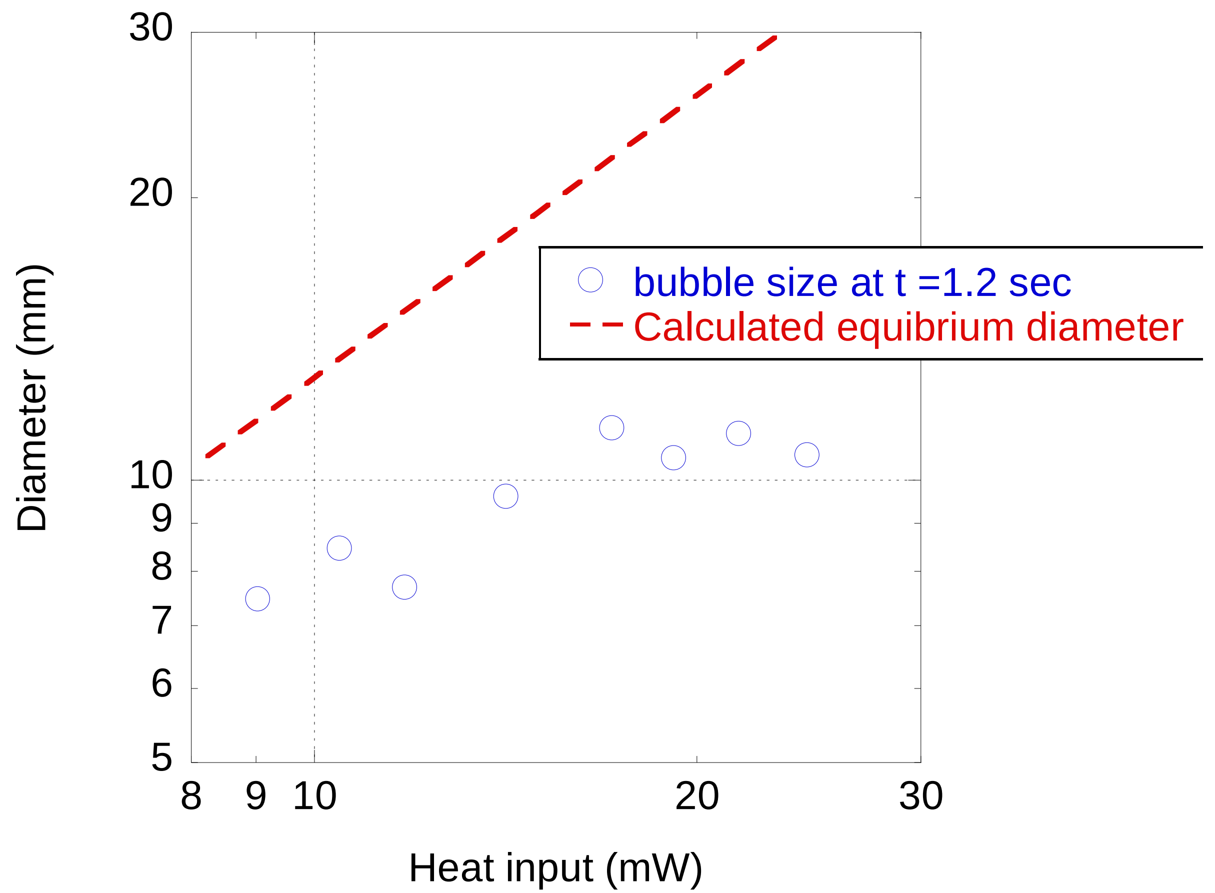
Thank you for your attention

"In addition"
Equilibrium diameter can be calculated

When dV/dt =0

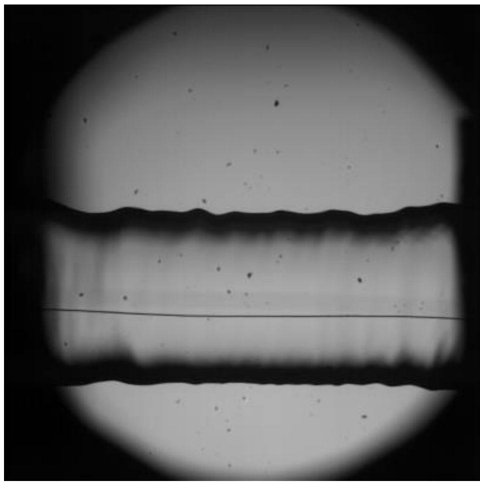
$$\begin{cases} q_i = \dfrac{4}{\sqrt{\pi}}\left(\dfrac{4\sigma}{D}\sqrt{2RT_i}\right) \\ Q = q_i D^2 \pi \end{cases}$$

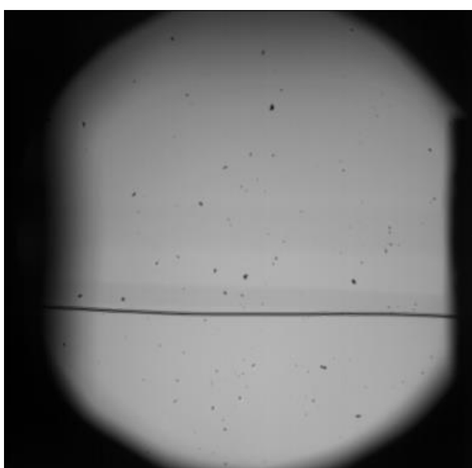
$$D = Q/16\sigma\sqrt{2RT_i\pi}$$

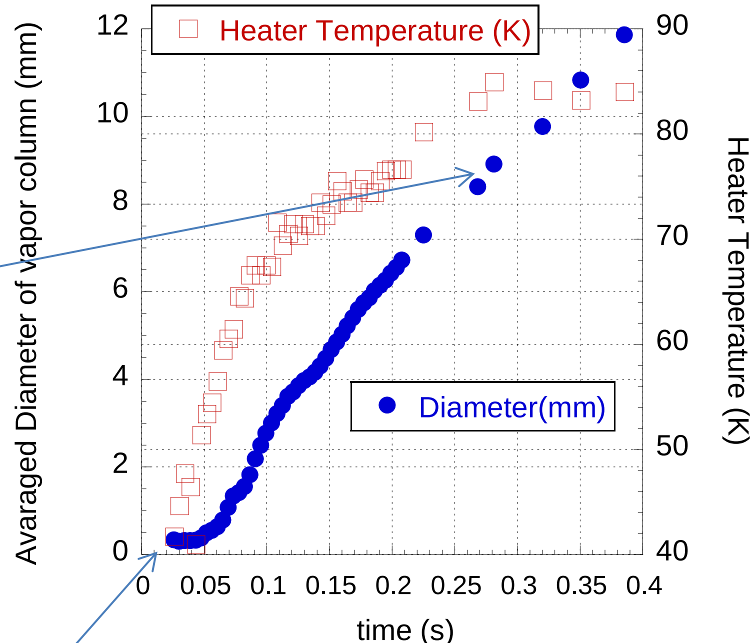


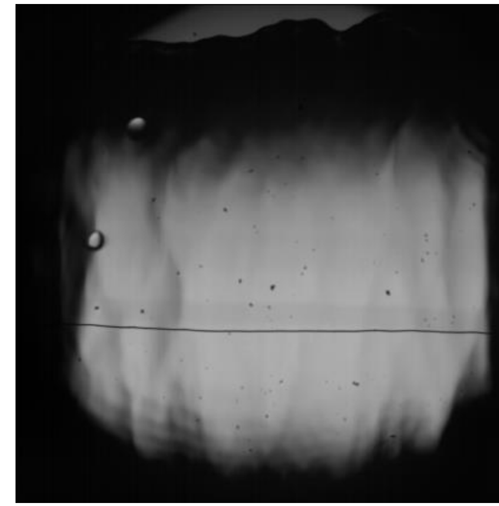
Why we don’t long wire heater.

previous study (Takada S., et al, ICEC24)









Larger than the window

The vapor bubble grew larger
than the size of the optical window