飽和プール沸騰の限界熱流束向上に関する研究

森　昌司（九州大学）

講演内容

1. 沸騰・蒸発冷却限界と工学的ニーズ

2. 飽和プール沸騰のCHF向上の現状

3. 従来のCHFメカニズムをベースとしたCHF向上

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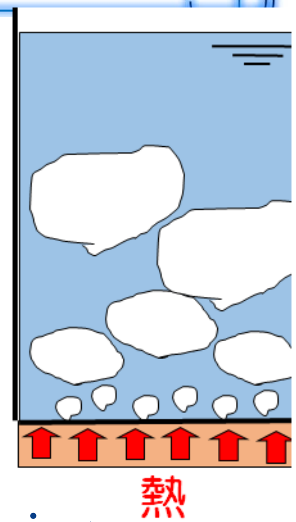
Cooling limitations of boiling and evaporation

1. Cooling limitation of a saturated pool boiling (CHF)(exp.)



$$q''_{CHF} = 0.156 \cdot \rho_v h_{fg} \left[\frac{\sigma g (\rho_l - \rho_v)}{\rho_v^{\,2}} \right]^{0.25}$$

100 W/cm² @0.1 Mpa, water

2. Cooling limitation of evaporation(theory)

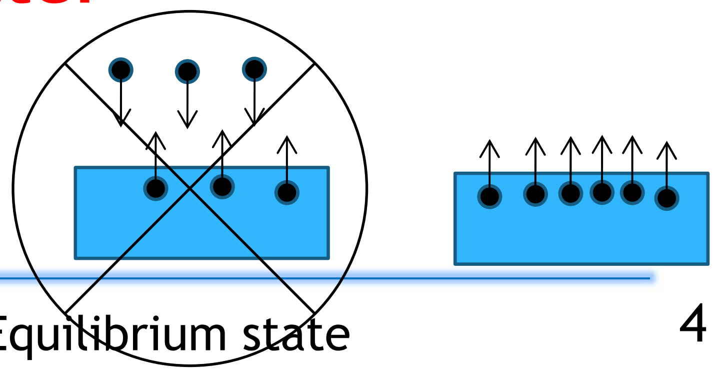
From kinetic theory, maximum heat flux is obtained in the following

$$q''_{\max} = \rho_v h_{lg} \sqrt{\frac{RT_{sat}}{2\pi M}}$$

where ρ_v: the density of the vapor, h_{lg}: the latent heat of evaporation , *R*: the universal gas constant, T_{sat}: the saturation temperature, and *M* : the molecular mass , respectively.

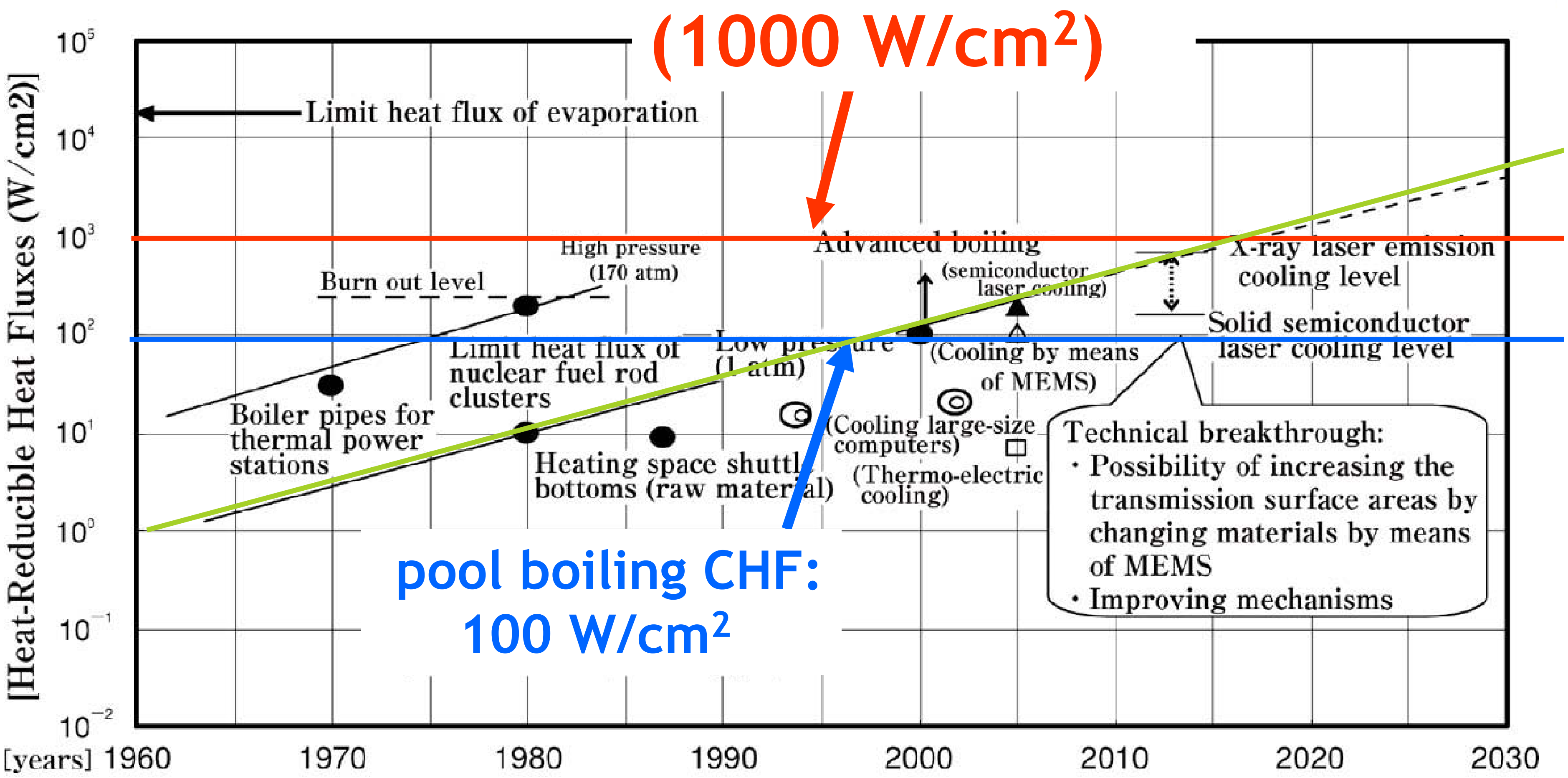
22,300 W/cm² @ 0.1 Mpa, water

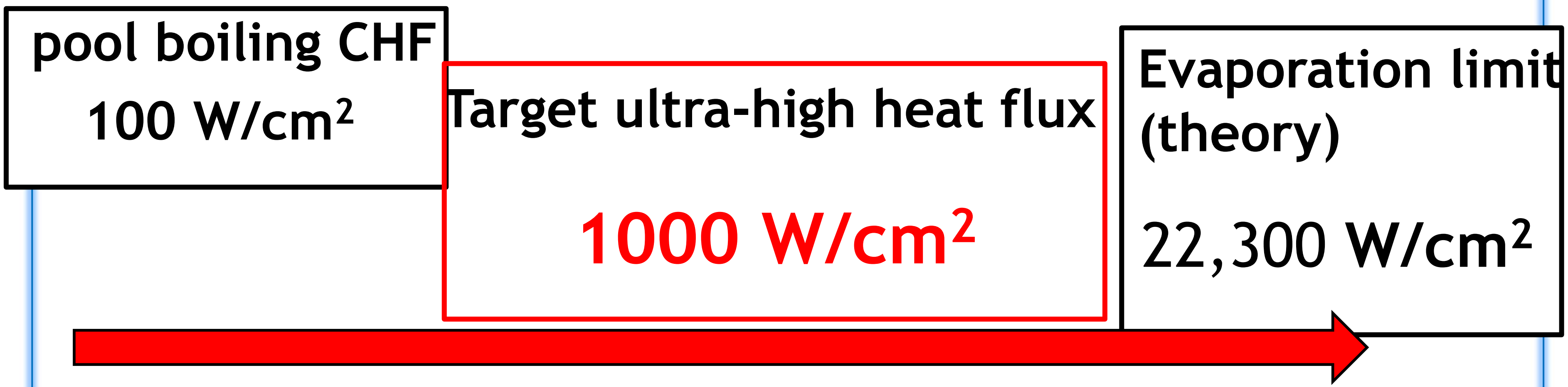
蒸発冷却限界にどこまで迫れる？



Equilibrium state

Roadmap of high heat flux removal technology (JSME,2016)





パッシブな手法で、超高熱流束除熱（1000 W/cm^2）は可能か？

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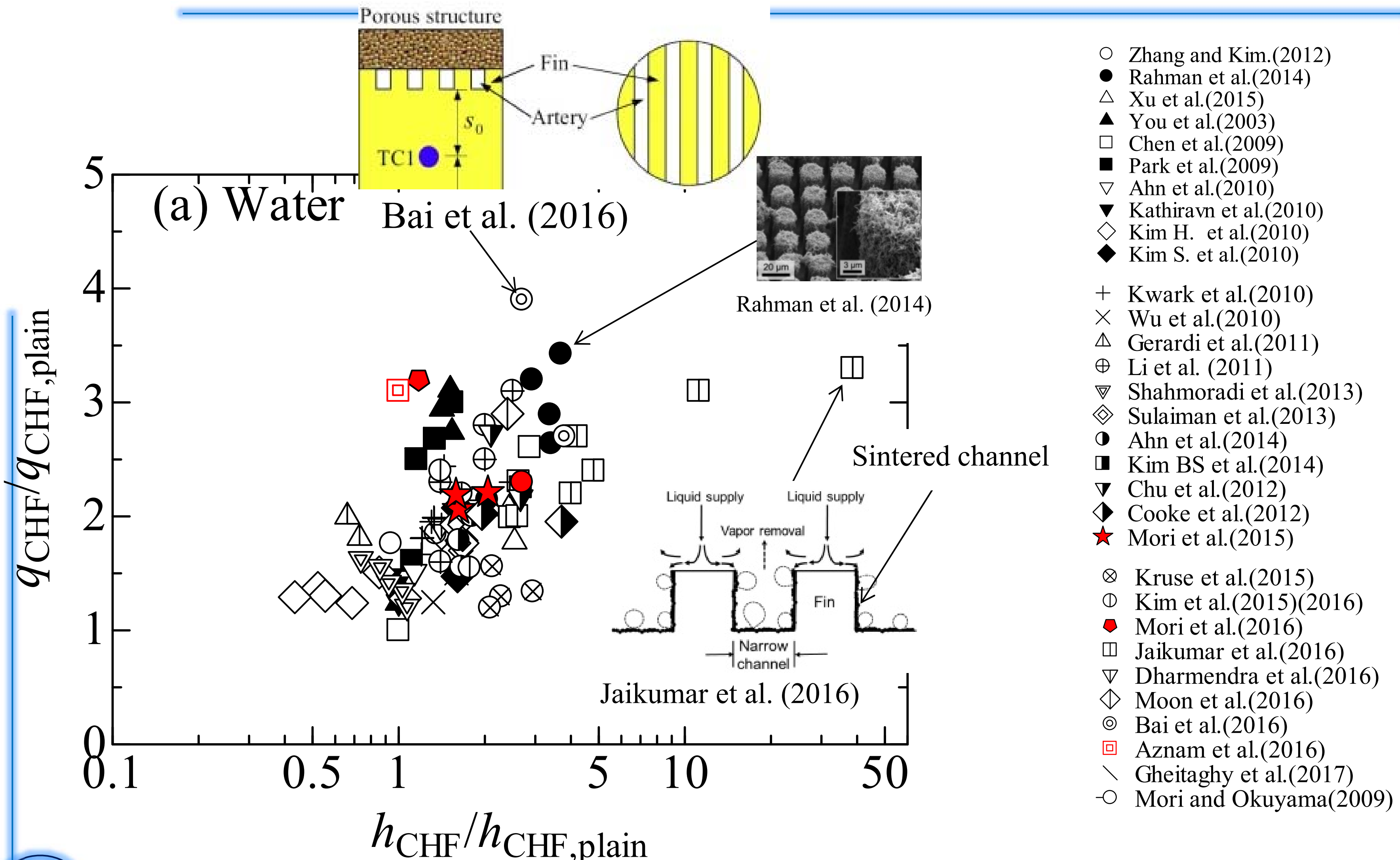
CHF Enhancement Mechanisms

1. Extended surface area
2. Capillary wicking
3. Nucleation site density
4. Wettability
5. Hydrodynamic limit.

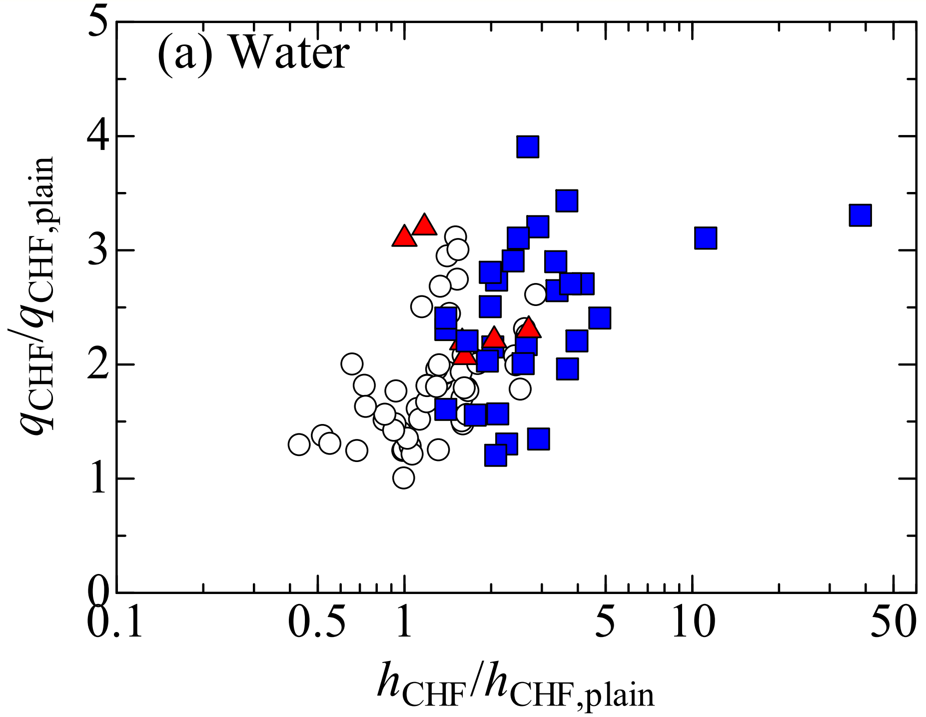
The exact relevance between each effect has not been well clarified yet.

Previous studies for CHF enhancement



S. Mori, Y. Utaka, Critical heat flux enhancement by surface modification in a saturated pool boiling: A review, International Journal of Heat and Mass Transfer, 108 (2017) 2534-2557.

Previous studies for CHF enhancement

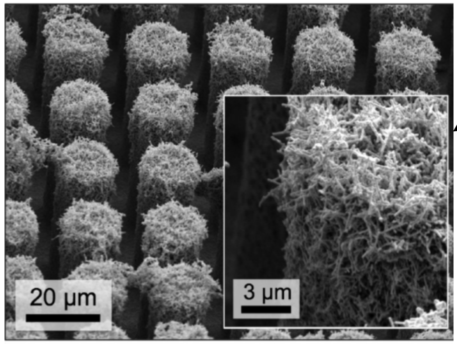


○ Uniform porous coating
▲ Modulated porous coatiing
■ Fin (microchannel or micro-pin)+Modulated/uniform porous coating

フィン 構造：性能高い

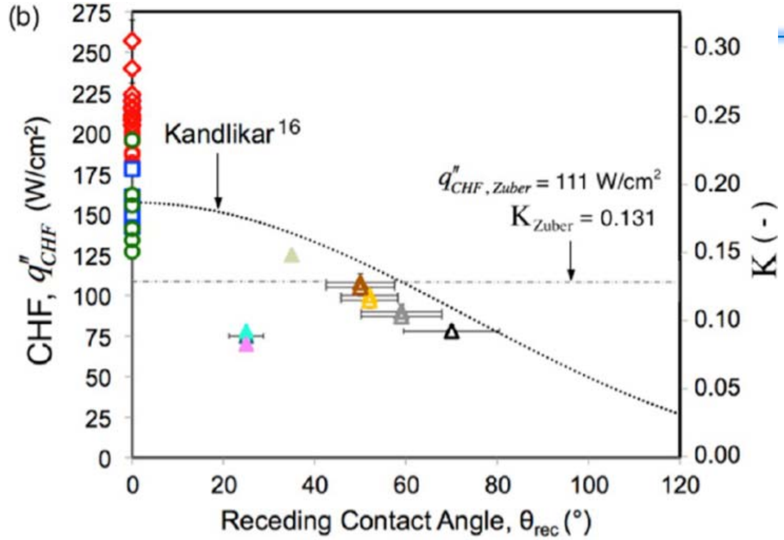
S. Mori, Y. Utaka, Critical heat flux enhancement by surface modification in a saturated pool boiling: A review, International Journal of Heat and Mass Transfer, 108 (2017) 2534-2557.

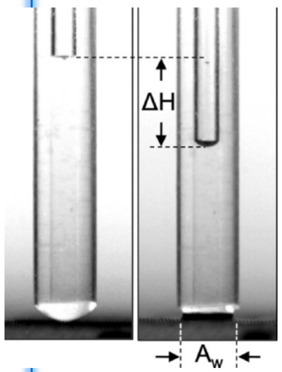
Rahman et al., Langumir (2014)

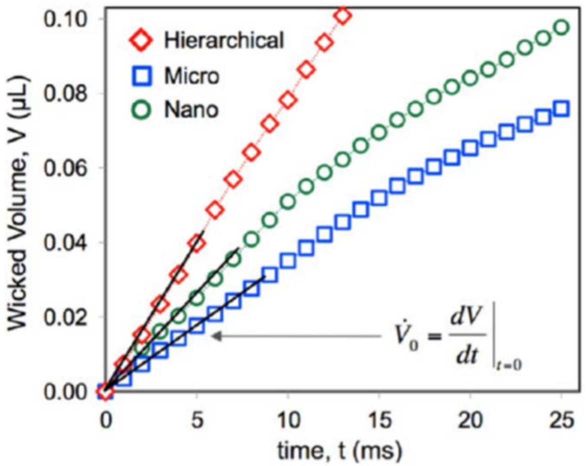


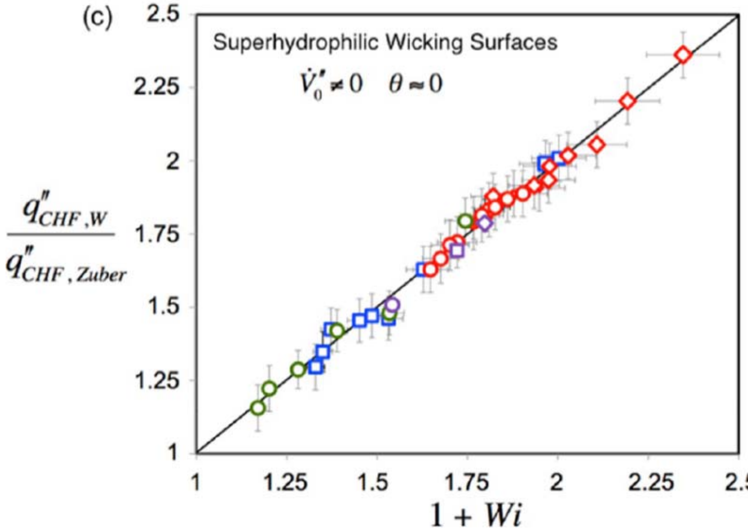
Tobacco mosaic virus

$$\frac{q_{CHF}}{q_{CHF,Plain}} \approx 3$$







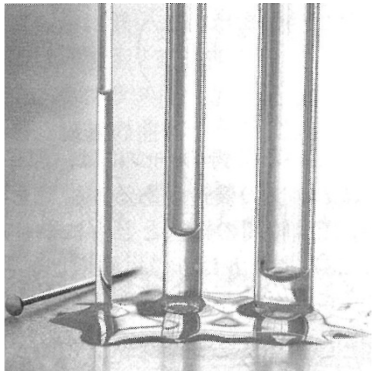


$$Wi^2 = \frac{\rho_l \left(\dot{V}''_0\right)^2 \sqrt{\frac{\sigma}{g(\rho_l - \rho_v)}}}{\sigma}$$

M.M. Rahman, E. Olceroglu, M. McCarthy, Role of wicka
superhydrophilic surfaces, Langmuir : the ACS journal o ... 4.

CHF向上する*Wi* の上限は？

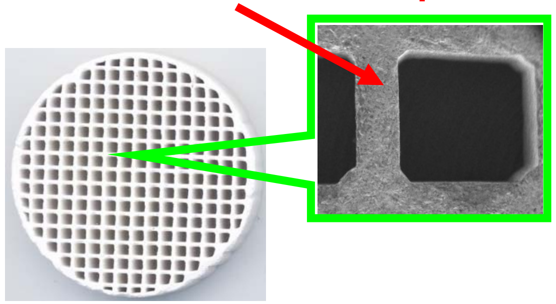
CHF enhancement technique using Honeycomb Porous Plate(HPP)



Capillarity

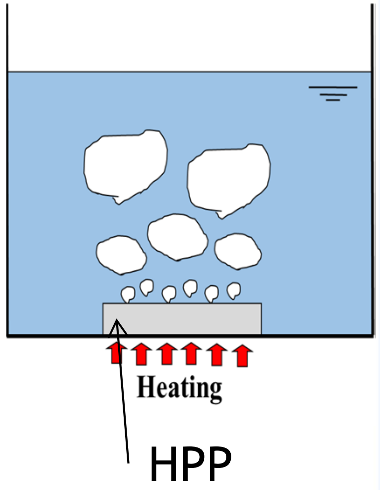
（$P_{c,max}$=2.4 MPa for a pore diameter of 0.1 μm)

HPP
Pore diameter：0.1μm

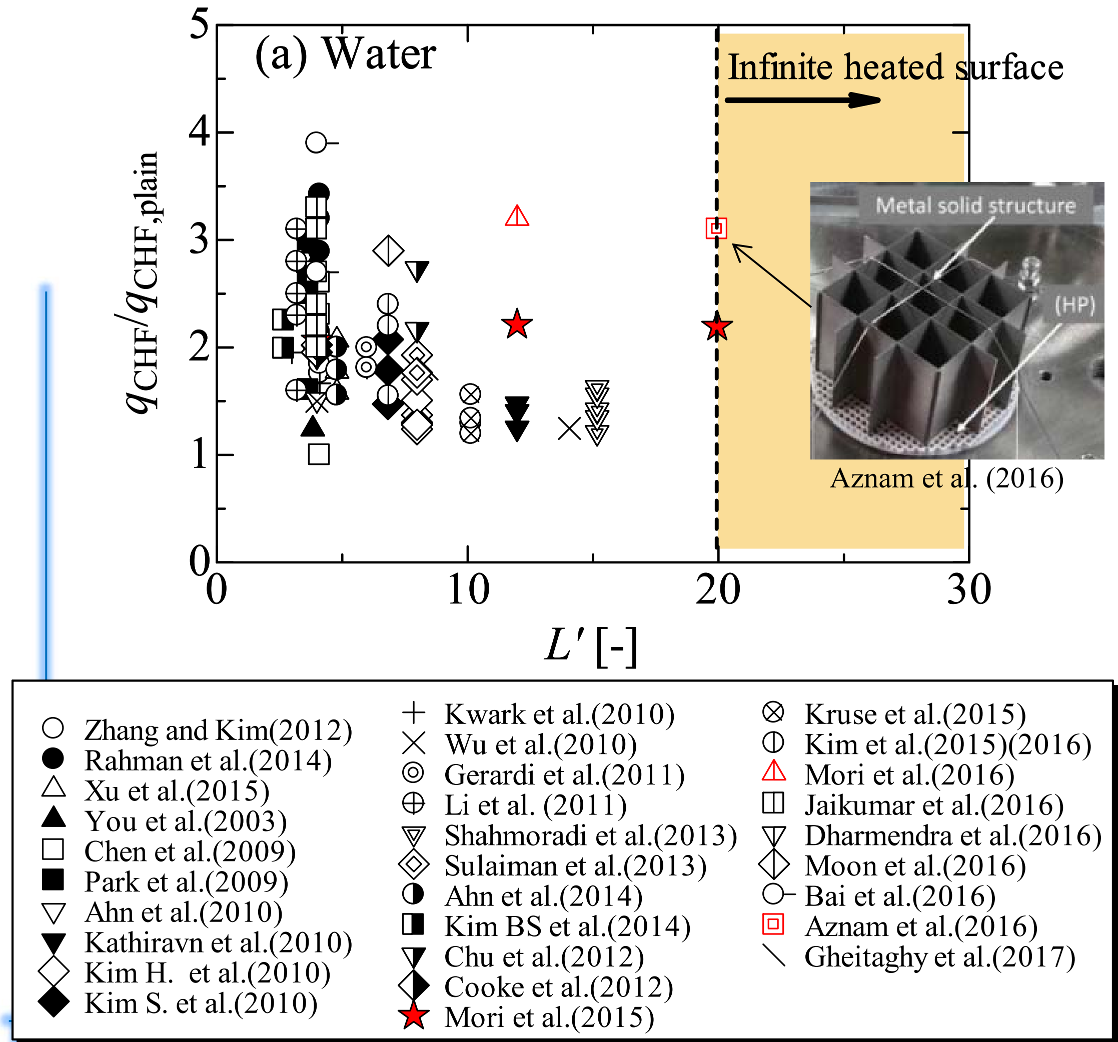


CHF of saturated pool boiling is enhanced by more than three times (320 W/cm²) at the maximum that of a plain surface (100 W/cm²).

q = 47 W/cm², ΔT_{sub} = 0 K



Review of studies on CHF enhancement (Effect of heater size on the CHF)



Decrease with the increase of heated size

This region can be regarded as an infinite heated surface by Arik & Bar-Cohen(2003)

L’ >20

$$L' = \frac{L}{\left(\frac{\sigma}{g(\rho_l - \rho_v)}\right)^{1/2}}$$

Background

Under severe accident conditions

Melt-through of RV must be prevented

IVR (In-Vessel Retention) is needed

Heat removal is limited by the CHF

CHF enhancement is needed

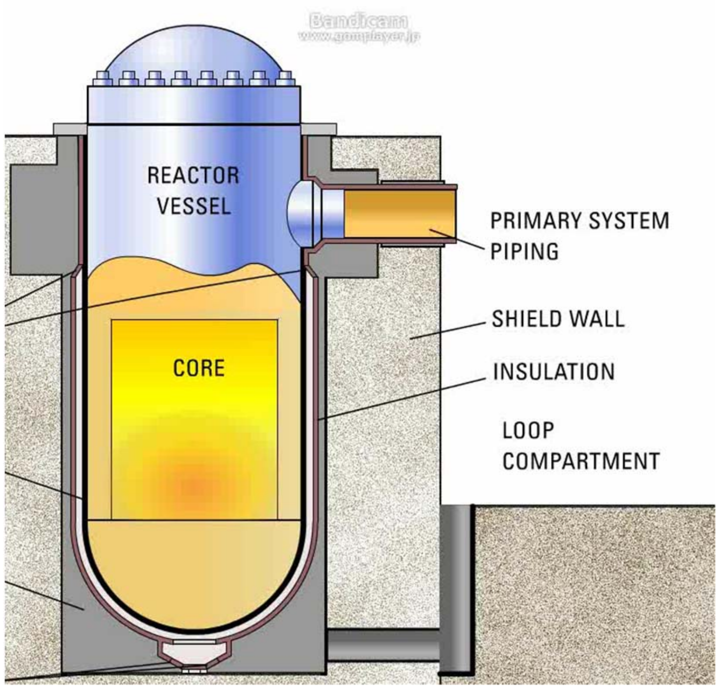
Important points for IVR

1.High heat flux must be removed from large heated surface under atmospheric pressure conditions.
2. Systems for IVR should be simple and installable at low cost.

超大伝熱面の高熱流束除熱

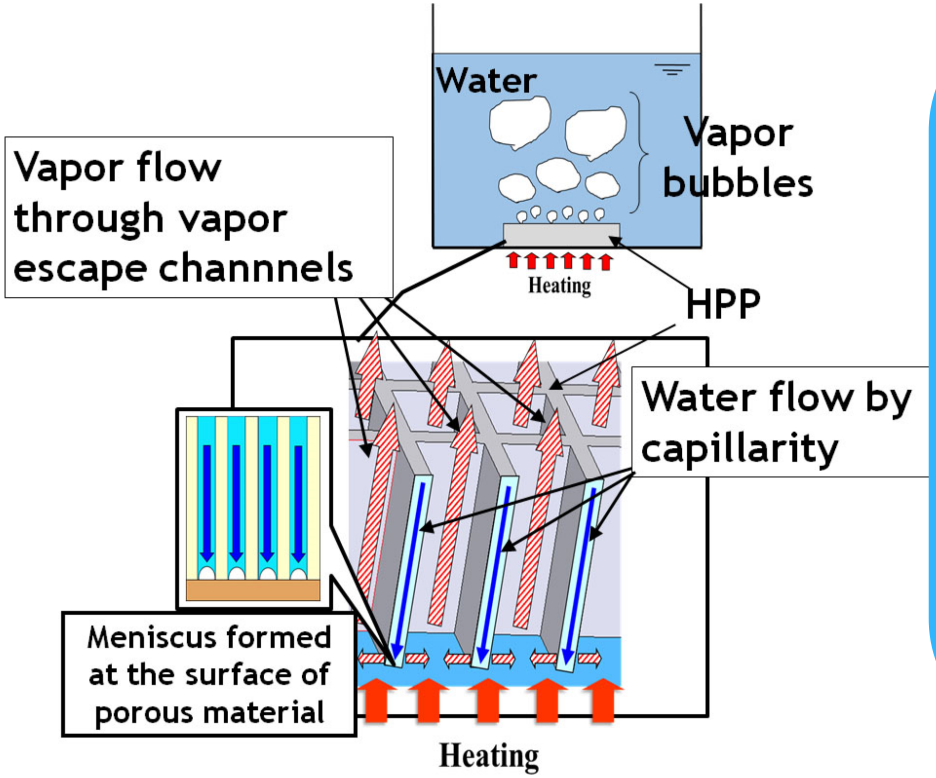
下向き伝熱面冷却

極めて困難



In-Vessel Retention (IVR)
Cooling system at nuclear power plant

CHF enhancement technique using Honeycomb Porous Plate(HPP)



Main mechanisms of CHF enhancement

1. Liquid is supplied by strong capillary force.
2. Vapor generated in close vicinity to the heated surface escapes upward through the vapor channels.

Circulation of liquid and vapor flows is enhanced one dimensionally

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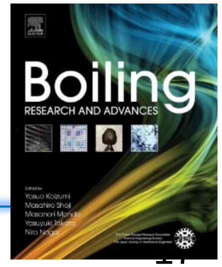
Models for Critical heat flux

1. Far-field model
(Hydrodynamic instability model, Zuber,1959)

2. Near-surface model
(Macrolayer dry-out model, Haramura and Katto,1984)

3. On-surface model
(Microlayer model, Zhao and Tsuruta, 2002)



3.2 Takaharu Tsuruta
(Kyushu Institute of Technology)

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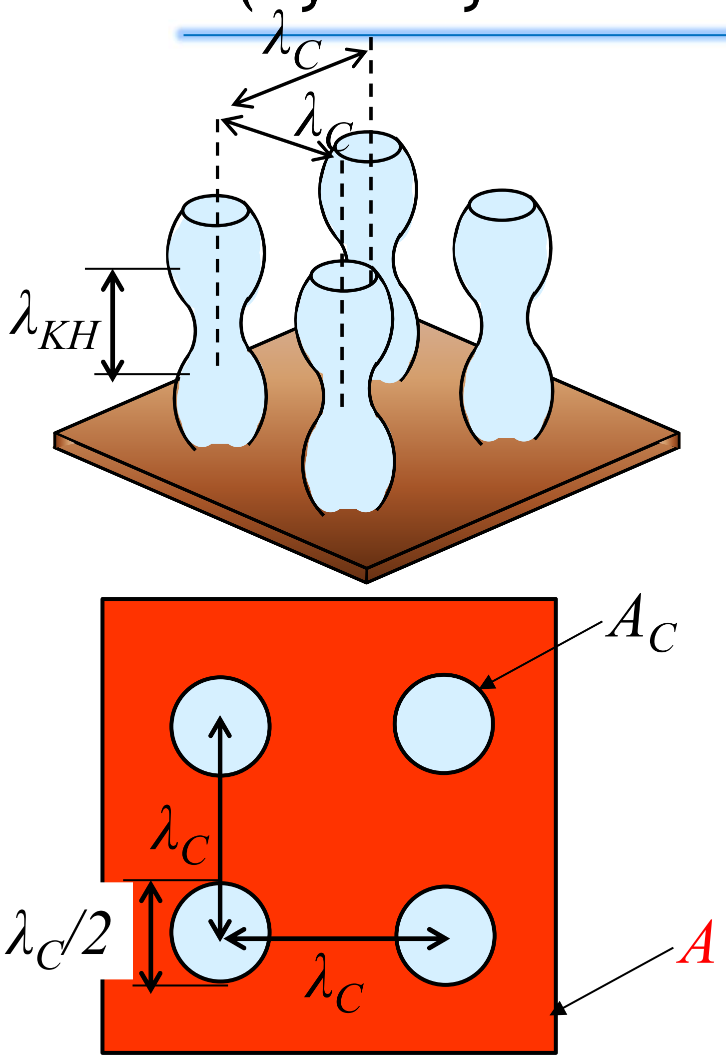
Far-field model
(Hydrodynamic instability model,Zuber(1959))



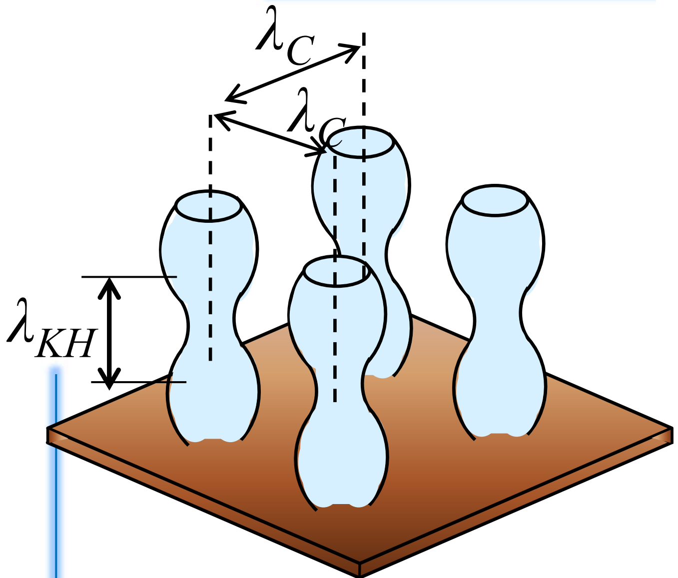
CHF occurrence condition is assumed as follows:

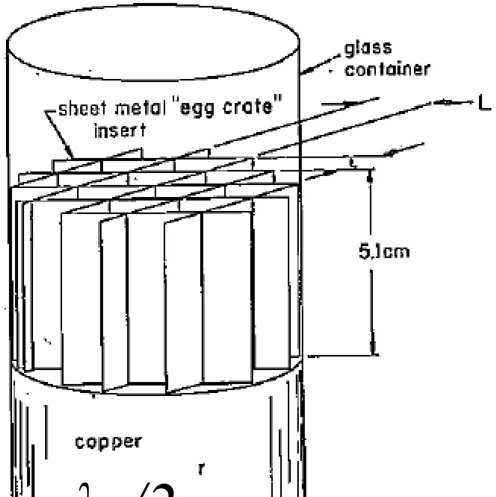
When the velocity of the steam column reaches the critical velocity obtained by KH instability

λ_c: RT unstable wave length

λ_{KH}: KH unstable wave length

Lienhard, Dhir, and Riherd, JHT(1973)



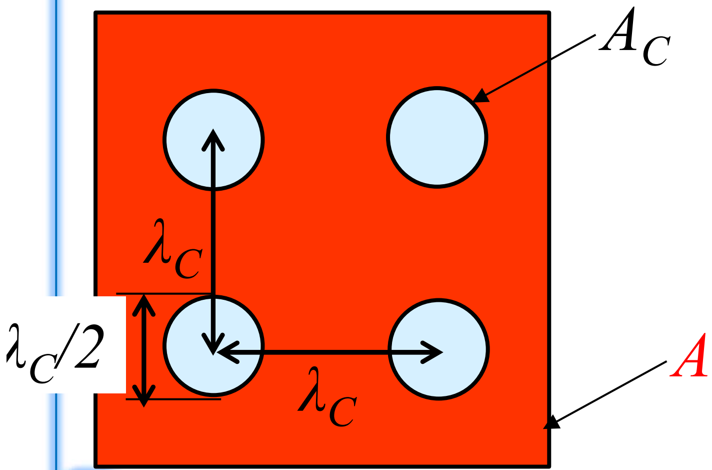


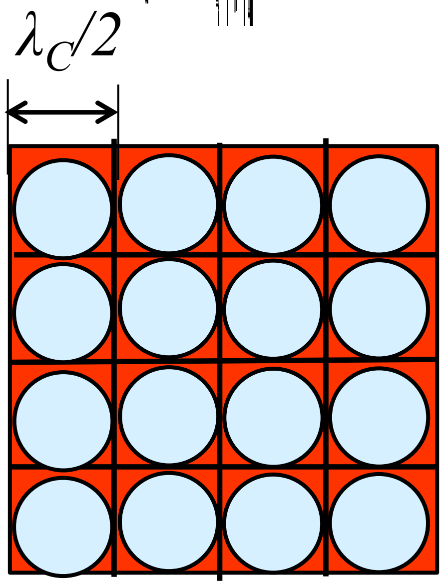
Limit flow rate at which Kelvin Helmholtz instability occurs

$$u_v = \sqrt{\frac{2\pi\sigma}{\rho_v \lambda_{KH}}} \qquad \lambda_{KH} = \pi \frac{\lambda_C}{2}$$

$$q'' = \frac{\rho_v u_v A_C h_{fg} \times N_i}{A}$$

$$\frac{q_{\max, finite}}{q_{\max, zuber}} = 1.14 \frac{N_i}{A_H / \lambda_C^2} \leq 4$$





原理的には裸面に比して
最大4倍までCHF向上可能

実験的には2倍程度のCHF向上

J.H. Lienhard, V.K. Dhir, D.M. Riherd, Peak pool boiling heat-flux measurements on finite horizontal flat plates, Journal of Heat Transfer, 95(4) (1973) 477-482.

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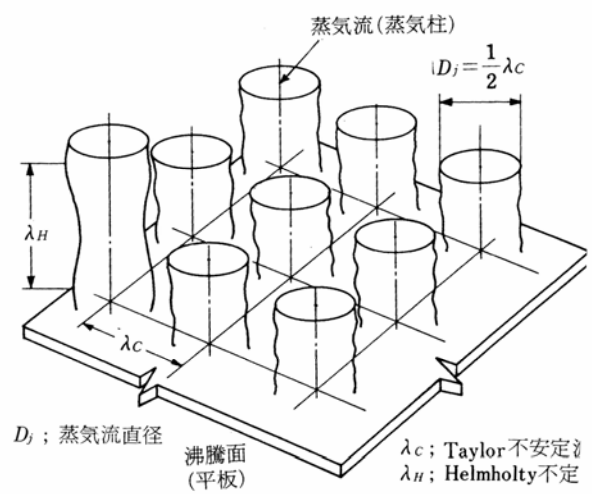
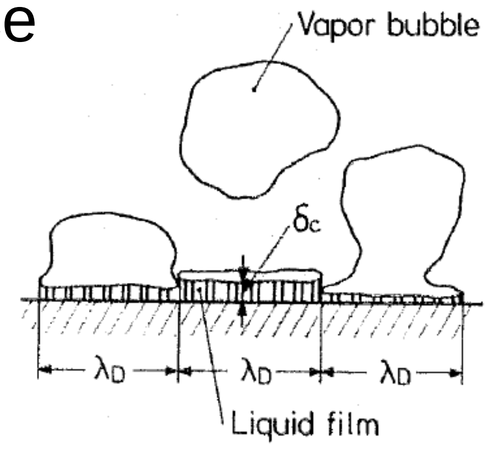
Near-surface model

(Macrolayer dry-out model, Haramura and Katto,1984)

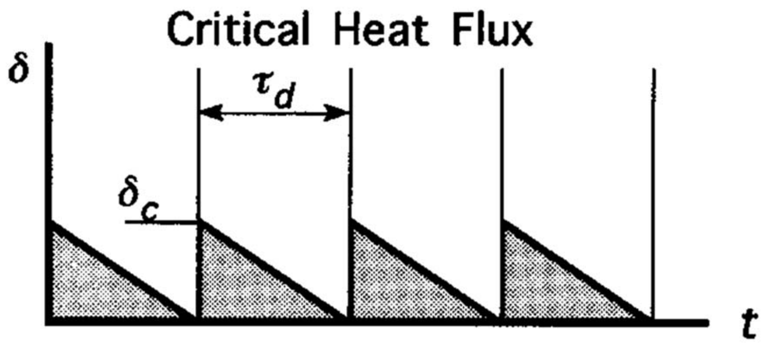
A hydrodynamic model consistent with the fluid behavior near the heated surface



Zuberの限界熱流束における蒸気流のモデル



水平無限平板加熱面上の
高熱流束プール沸騰



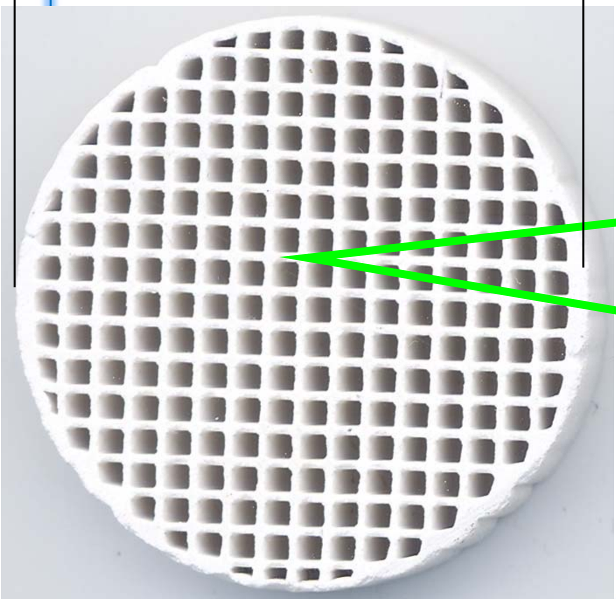
Time history of microlayer consumption at CHF

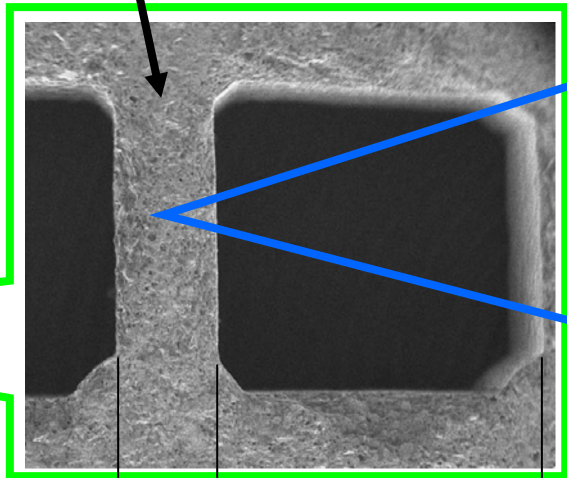
Shape of honeycomb porous medium

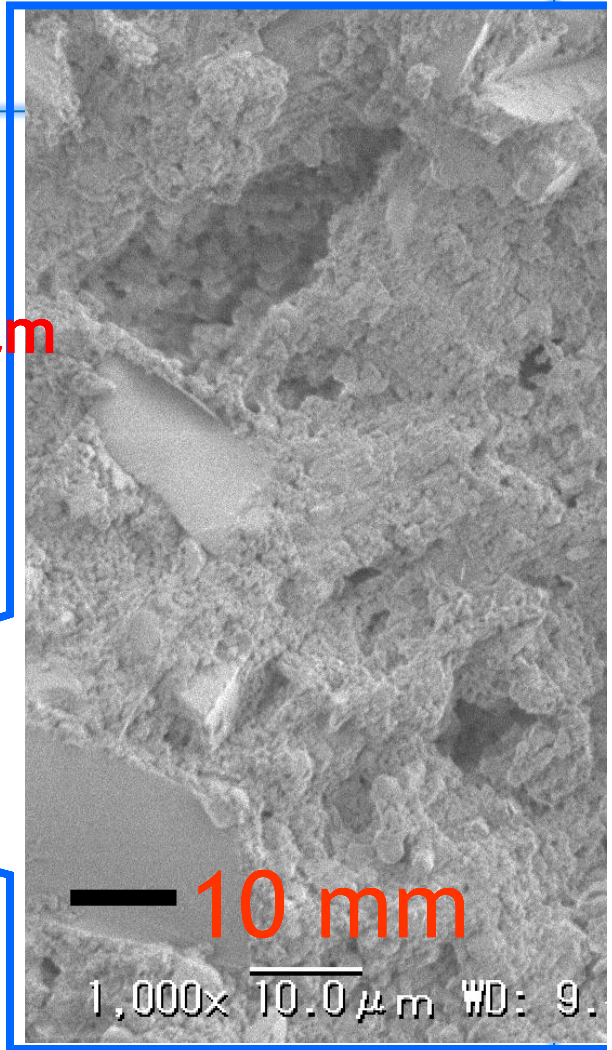
Constituent: Calcium aluminates ($CaO \cdot Al_2O_3$)
Fused silica (Fused SiO_2)
Titanium dioxide (TiO_2)

Median pore radius: 0.13 μm
Porosity: 25 %

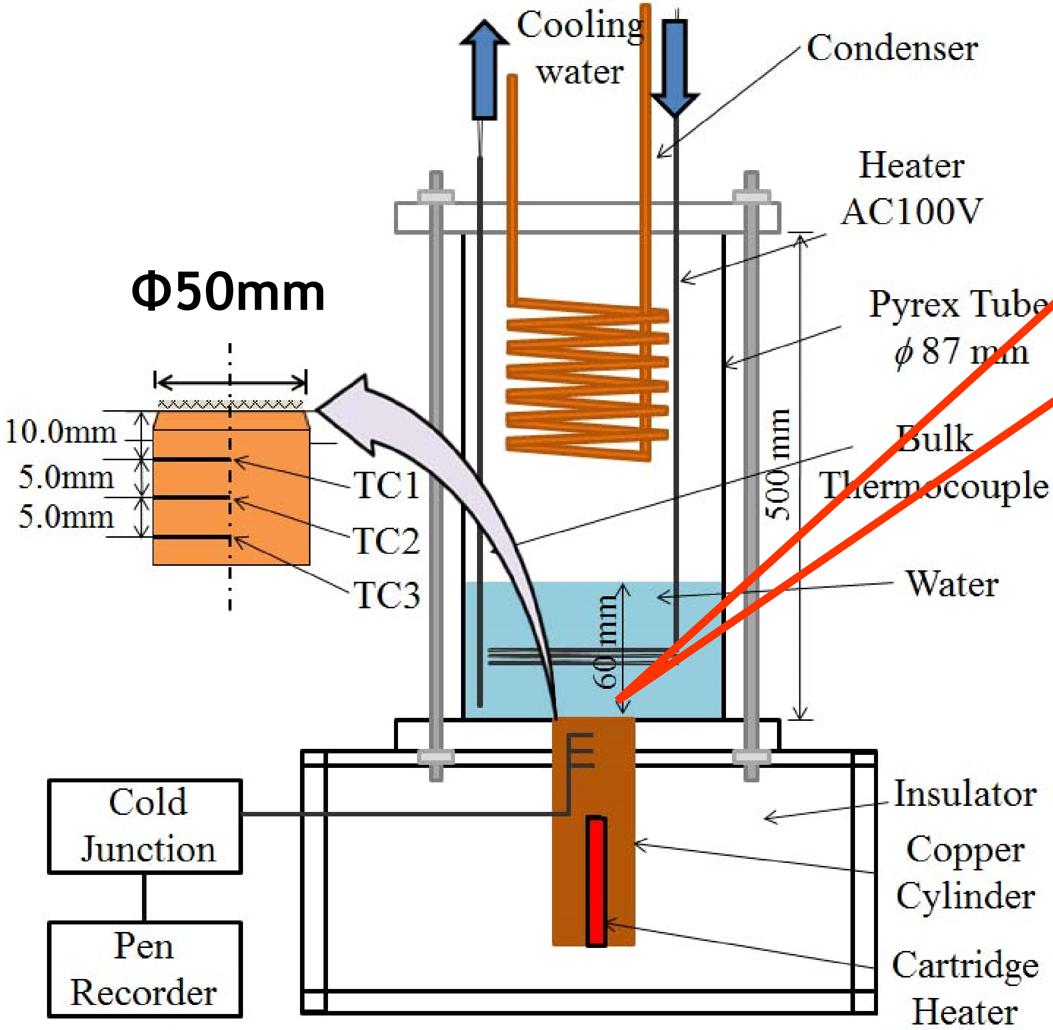
φ30

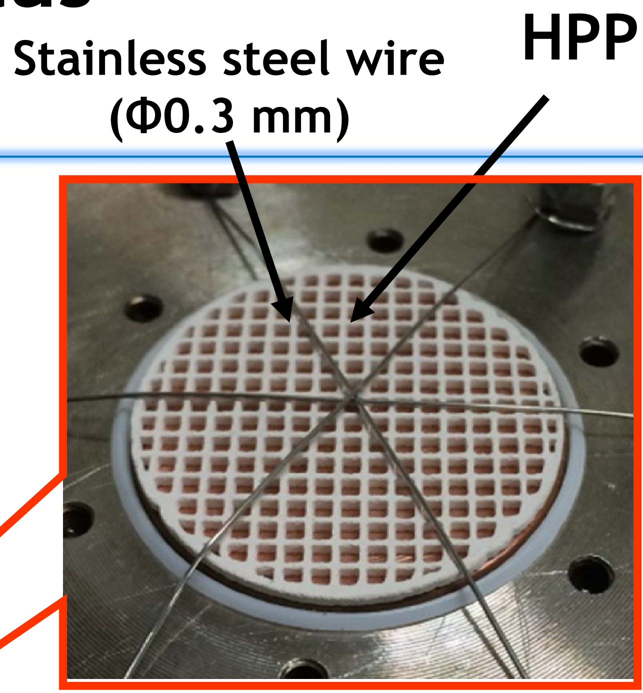






Experimental apparatus





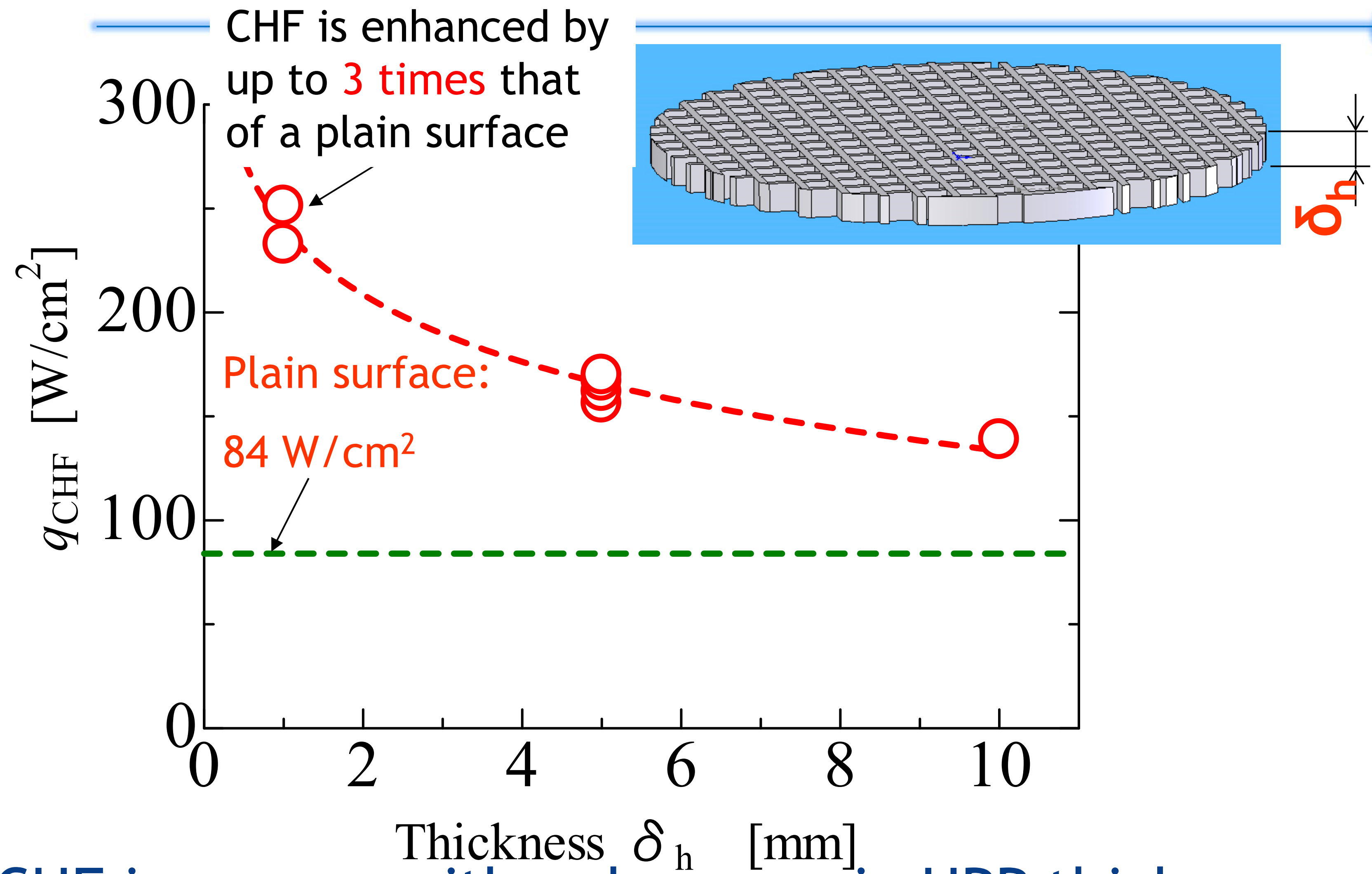
Working fluid: Water

System pressure: 0.1MPa

Copper cylinder diameter: 50 mm

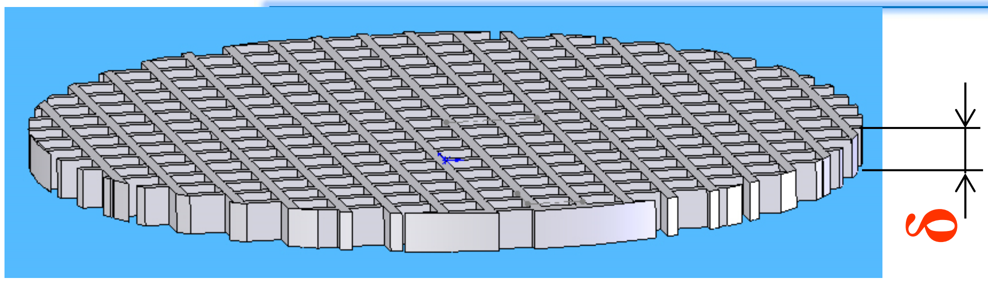
ΔT_{SUB} = 0 K

Relationship between q_{CHF} and HPP thickness.



CHF increases with a decrease in HPP thickness

Capillary limit model(Mori and Okuyama(2009))



$$p_c = \Delta p_l + \Delta p_v$$

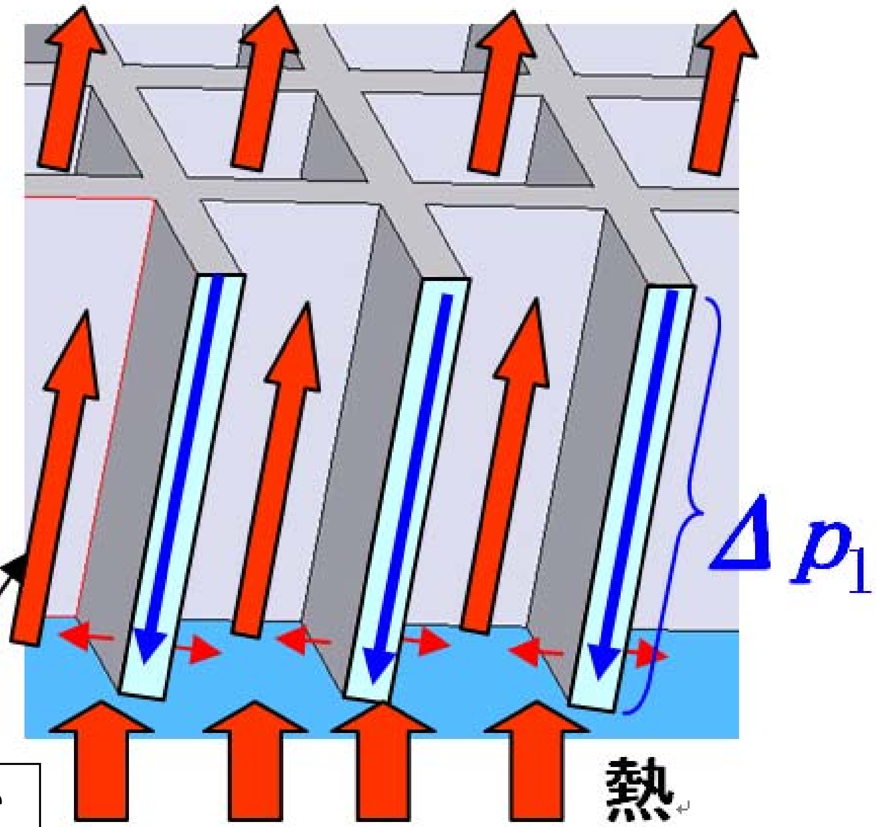
$$\frac{2\sigma}{r_{eff}} = \frac{\mu_l Q_{\max}\delta}{K A_W \rho_l h_{fg}} + \frac{\mu_v Q_{\max}\delta}{2n\pi\rho_v d_v^4 h_{fg}}$$

Δp_v

Maximum capillary pressure

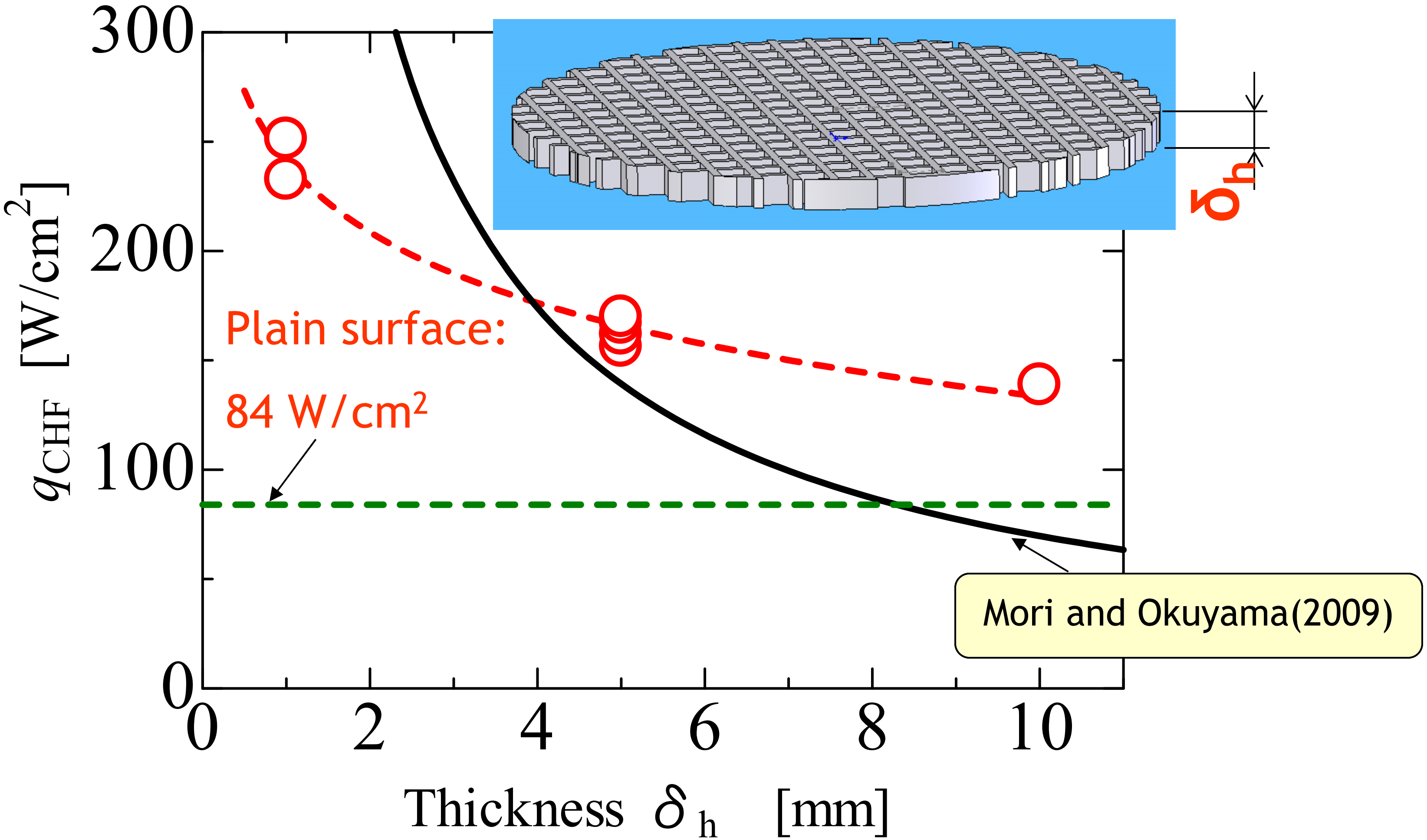
the frictional pressure drops caused by the liquid flow in the porous medium

the frictional pressure drops caused by the vapor flow through the channels



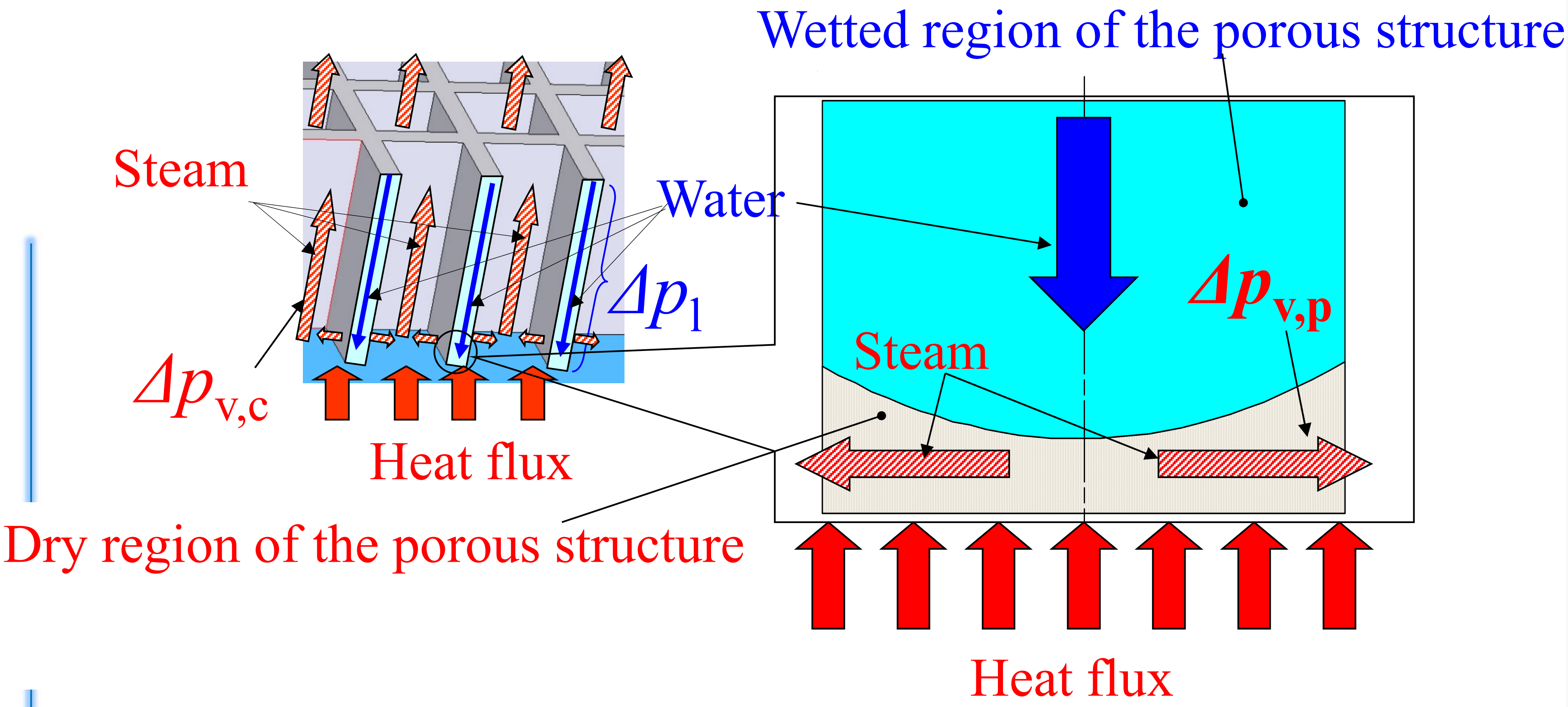
$$q_{CHF} = \frac{2\sigma\rho_l h_{fg}}{\mu_l}\frac{K A_W}{r_{eff}\delta}$$

Relationship between q_{CHF} and HPP thickness.



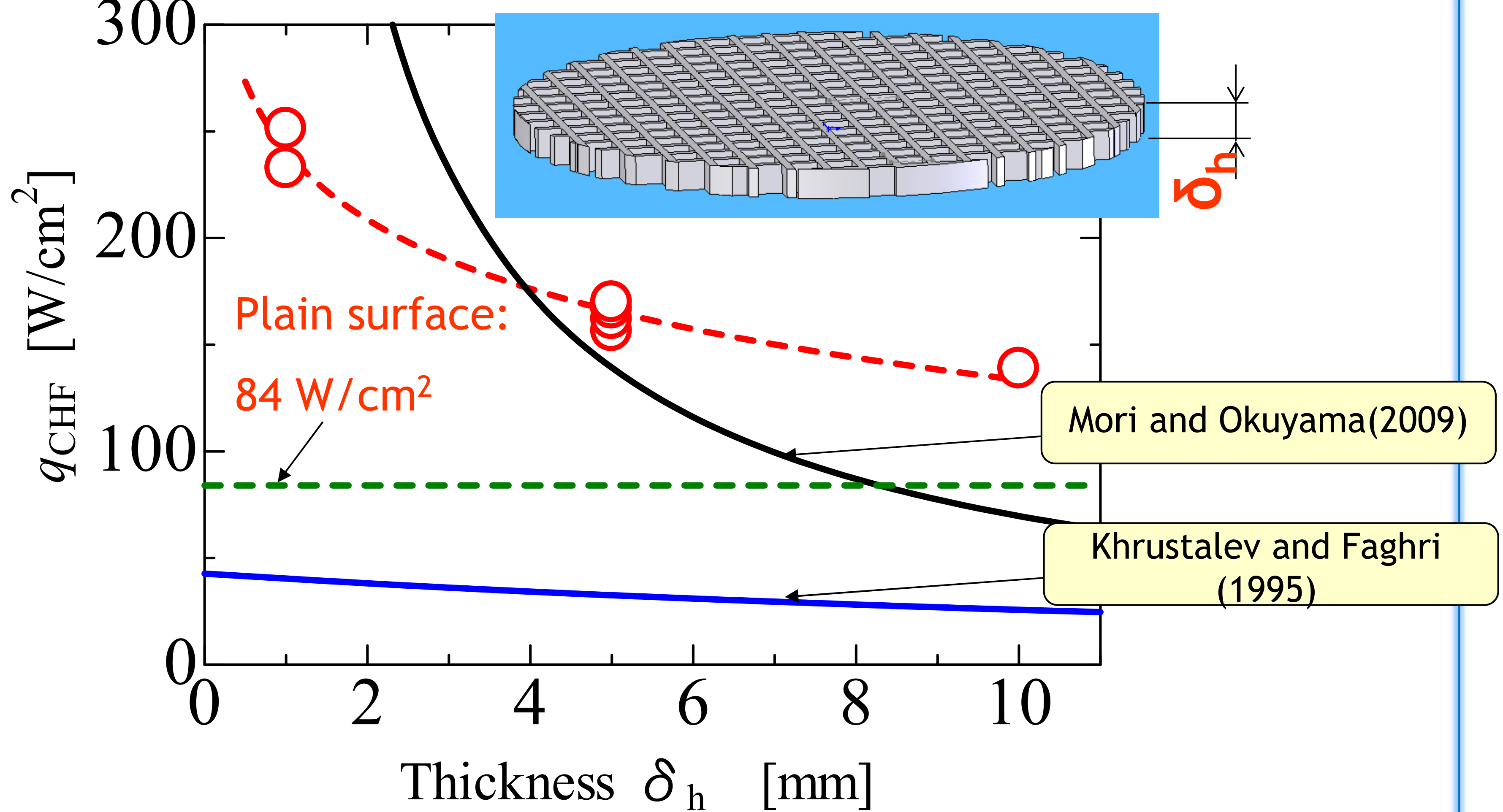
This model is roughly agreement with experimental results.

Khrustalev and Faghri model(1995)



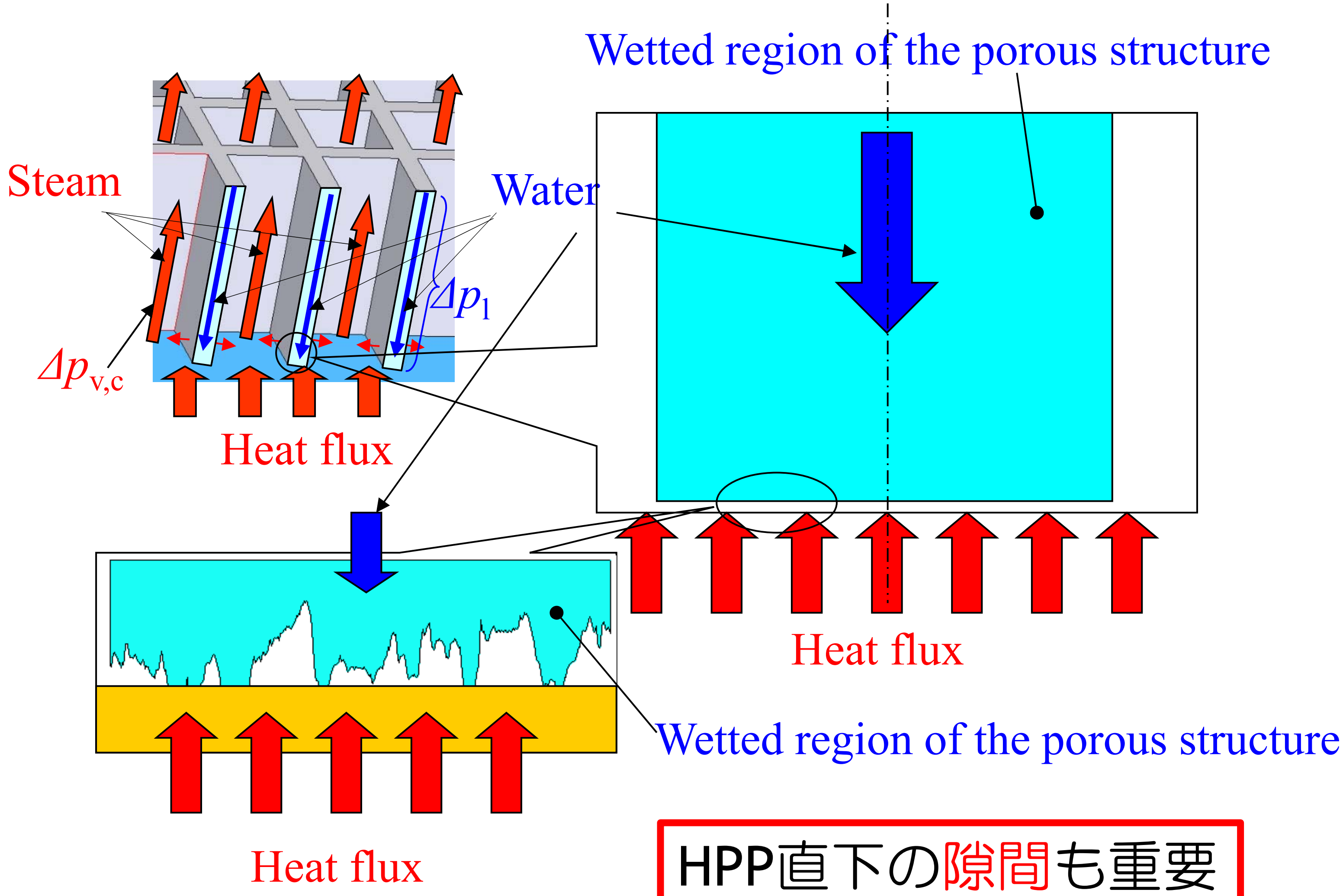
$$\Delta p_{c,\max} = \Delta p_l + \Delta p_{v,c} + \Delta p_{v,p}$$

Relationship between q_{CHF} and HPP thickness.



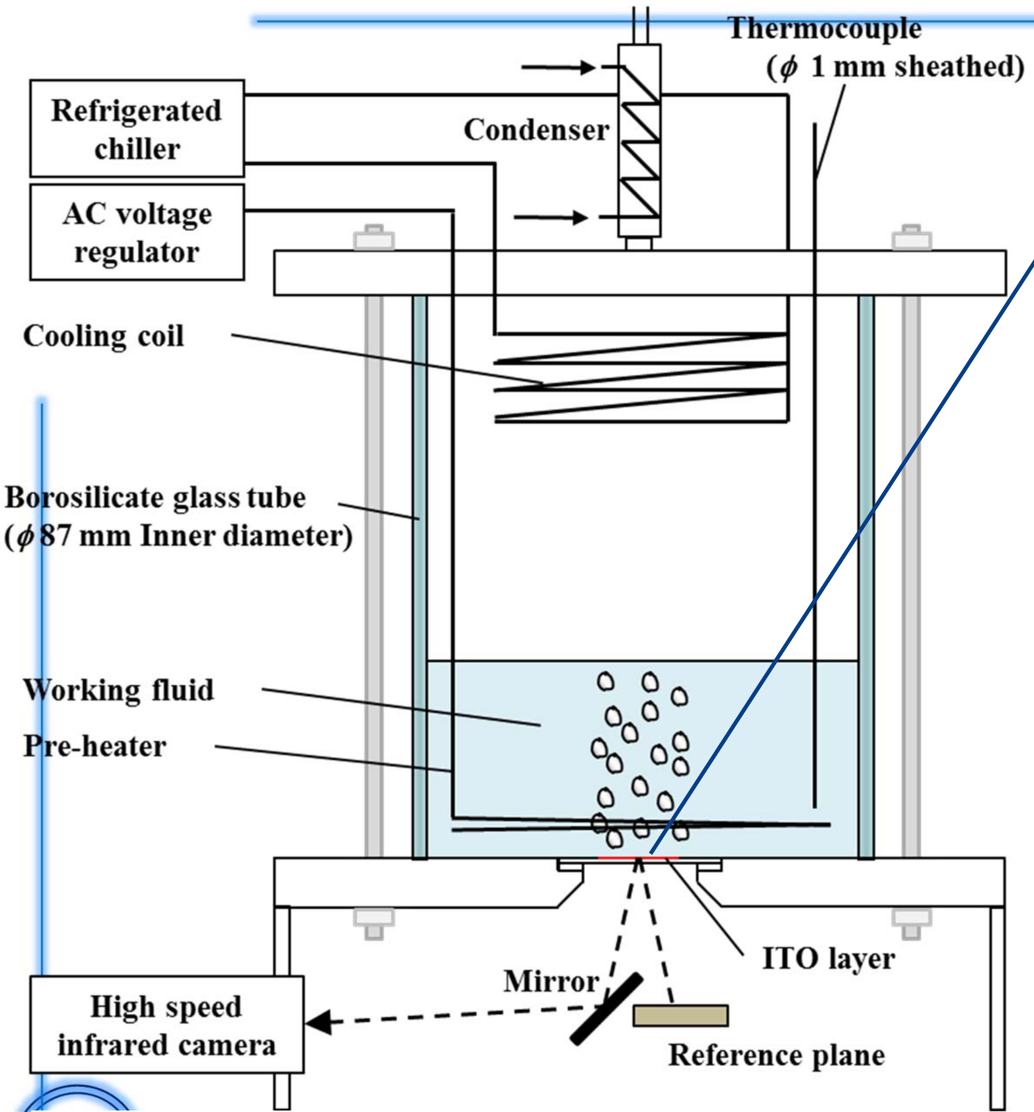
実験値よりかなり低く予測 → ドライアウトが発生していないことを実験的にも確認

HPP直下部での様相



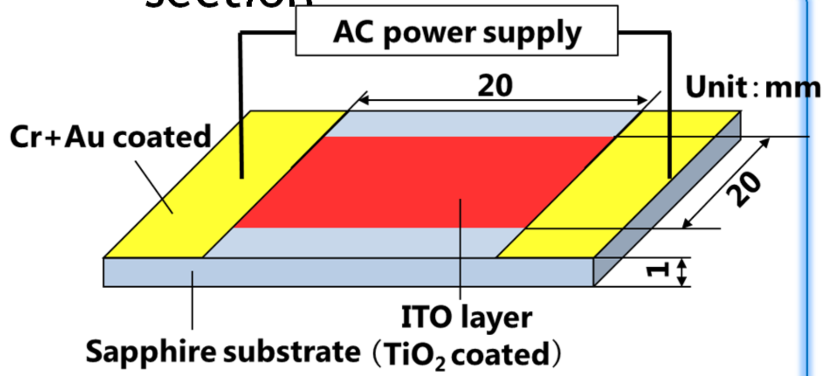
HPP直下の隙間も重要

ITOヒータを用いた温度分布変化の測定



Detection wavelength 3~5 μm

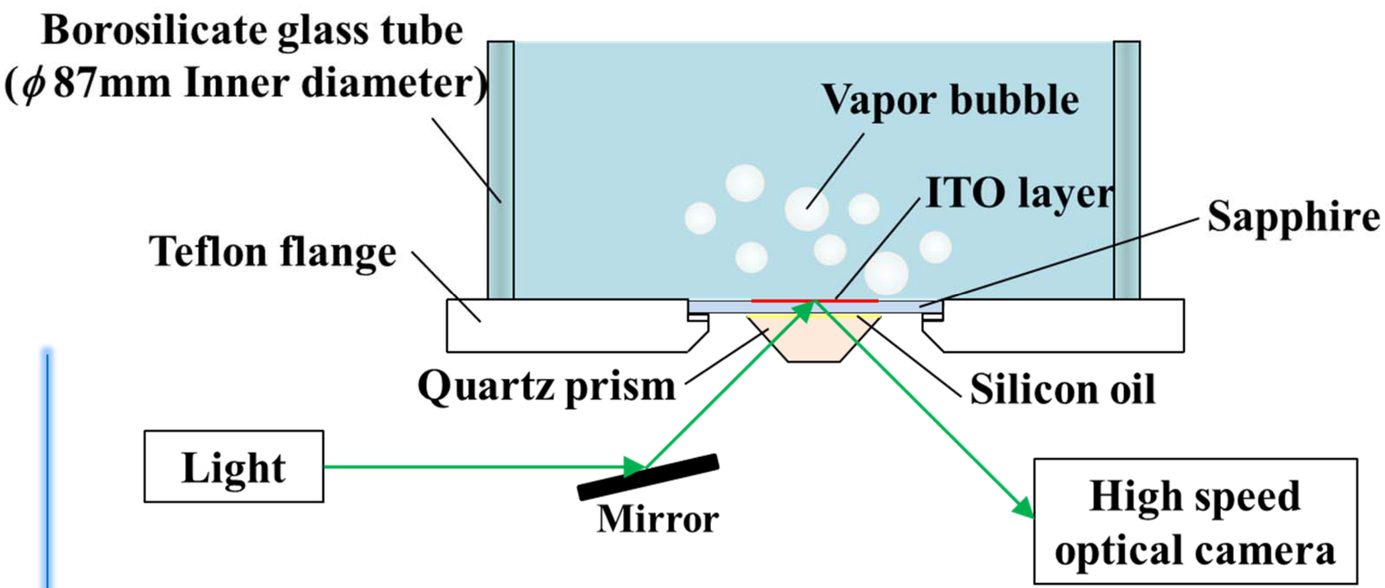
Heating section



Experimental condition

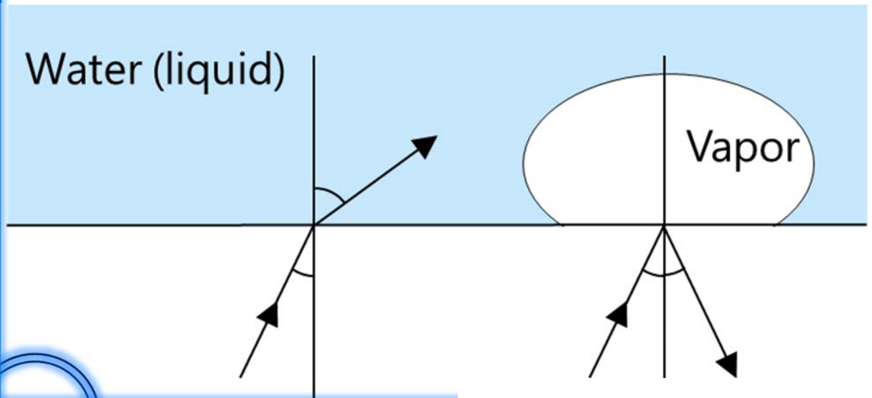
- Saturated pool boiling
- System pressure ： 1 atm
- Energization method ： 1 kHz AC
- Working fluid ： Distilled water

Observation of “dry out” using Total reflection method



q=0.14 MW/m^2

Total reflection method



Difference of refractive index between liquid and gas

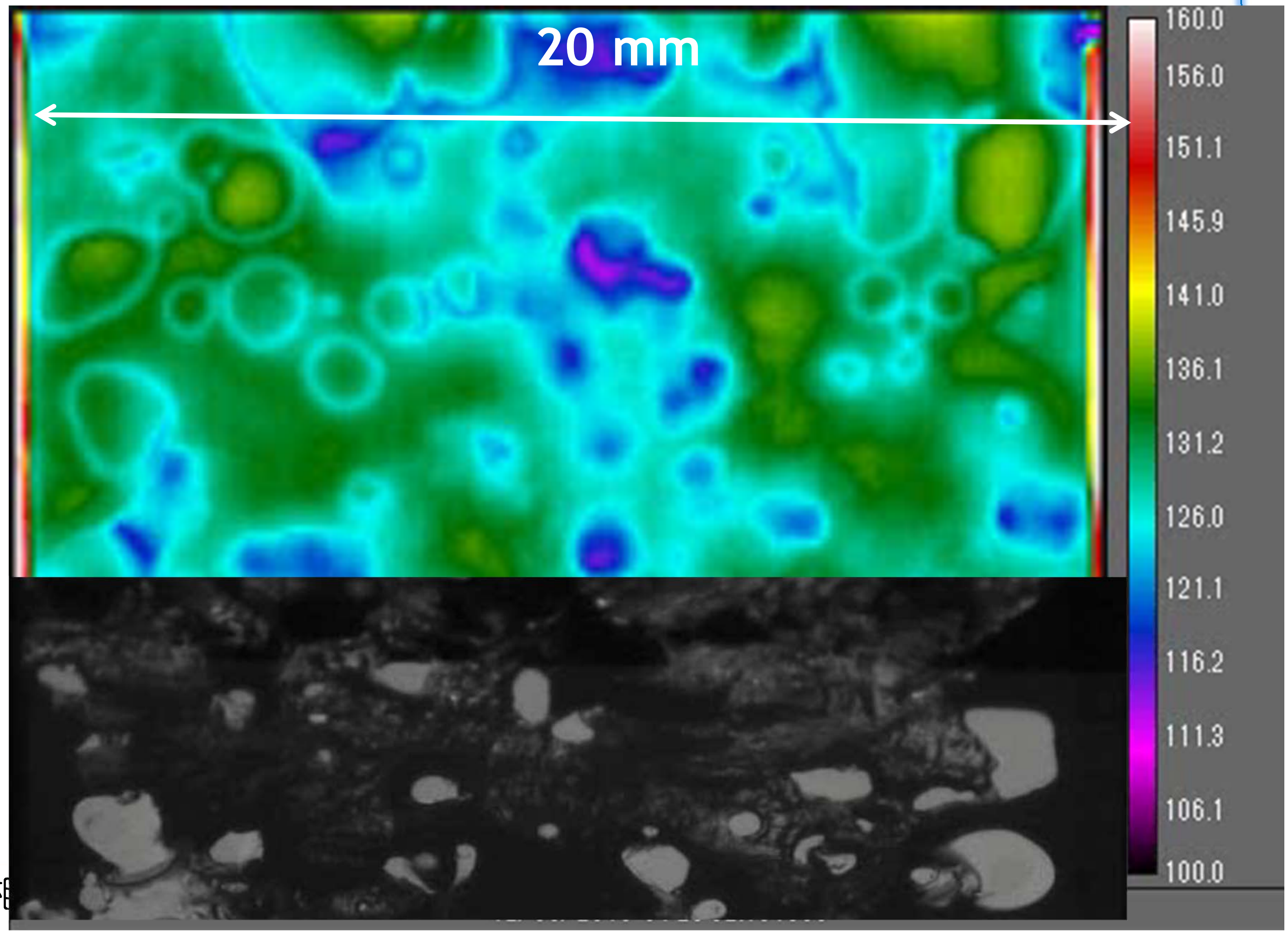
Liquid ➡ **Dark**

Gas ➡ **Light**

Determine “dry area” from brightness

Change of wall temperature and dry out
（*plain surface*, *CHF condition*, $q \fallingdotseq 120\ W/cm^2$）

Record rate:
480fps
Play rate:
10 fps



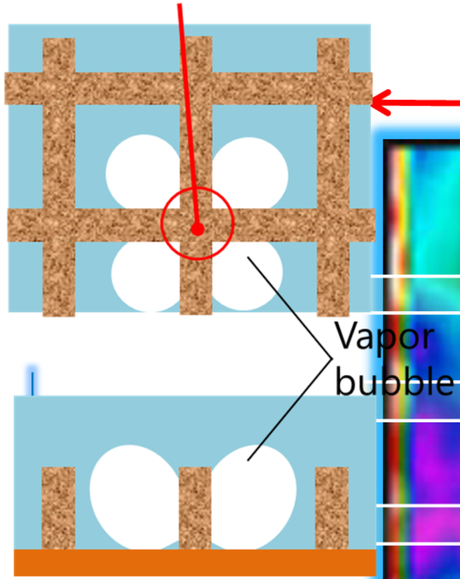
Record rate:
6000 fps
Play rate:
10 fps

Change of wall temperature and dry out

($q \fallingdotseq 120\ \mathrm{W/cm^2}$)

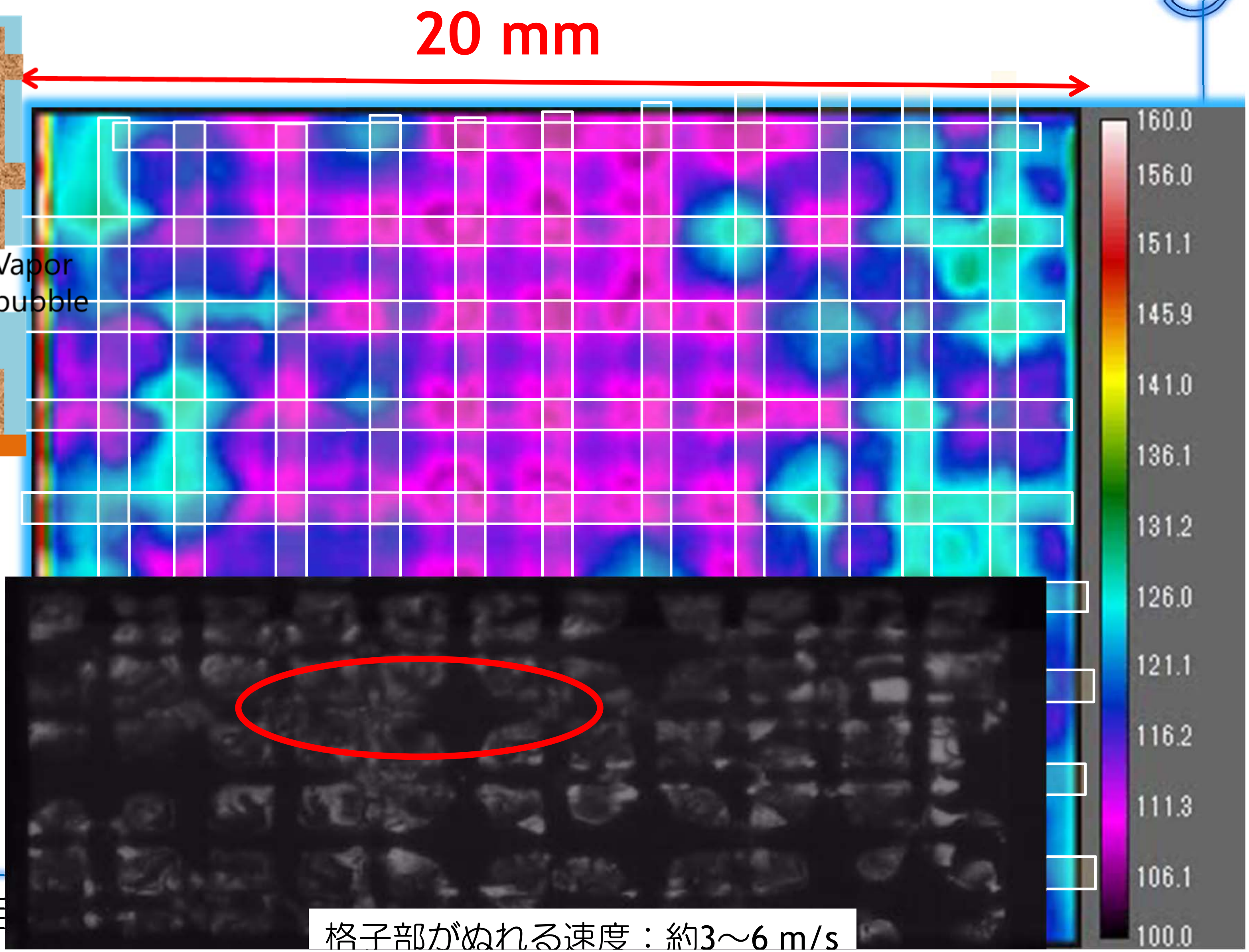
HPP • Distilled water

Boiling under the **intersection of HPP**



Record rate: 480fps
Play rate: 10 fps

Record rate: 6000 fps
Play rate: 10 fps

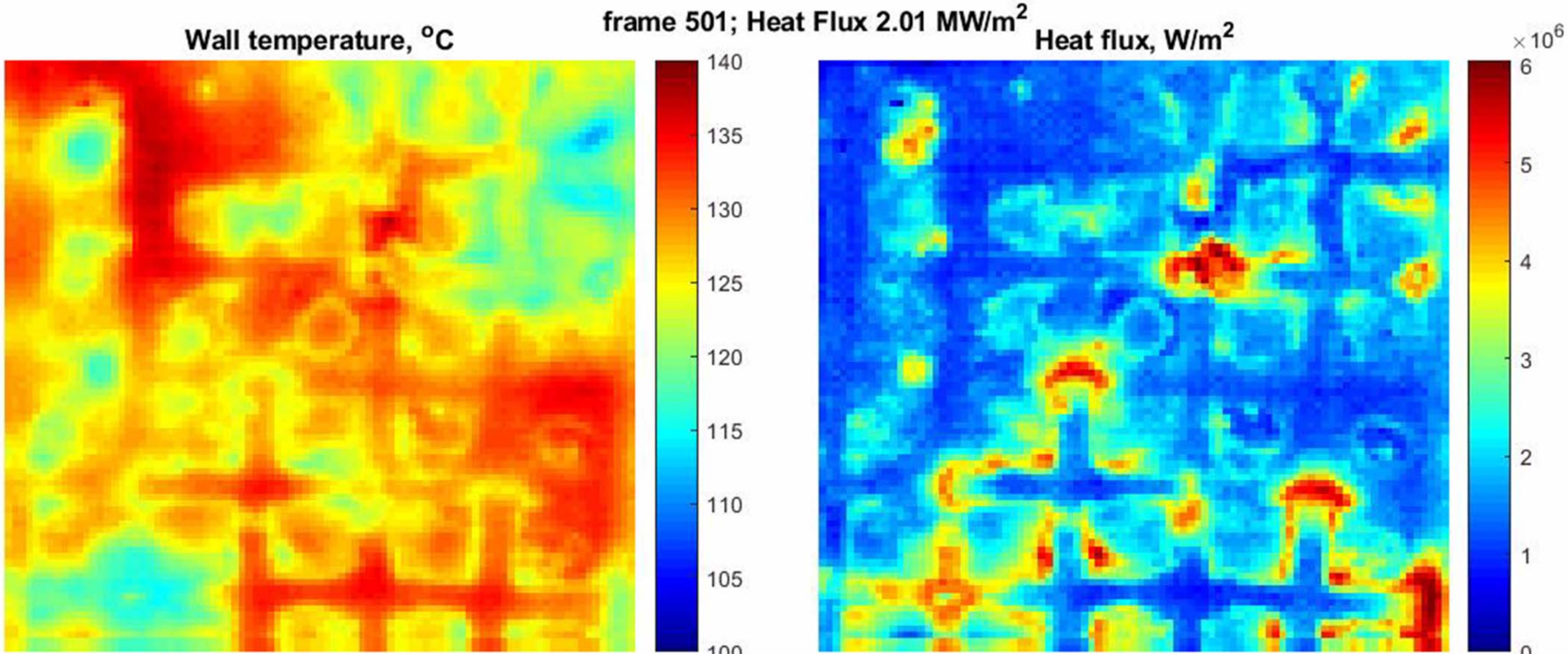


Change of surface wall temperature with time
（ CHF condition, $q \fallingdotseq 200\ \mathrm{W/cm^2}$ ）

Prof . Matteo Bucci
(MIT)

With HPP

Record rate: **2,500fps**



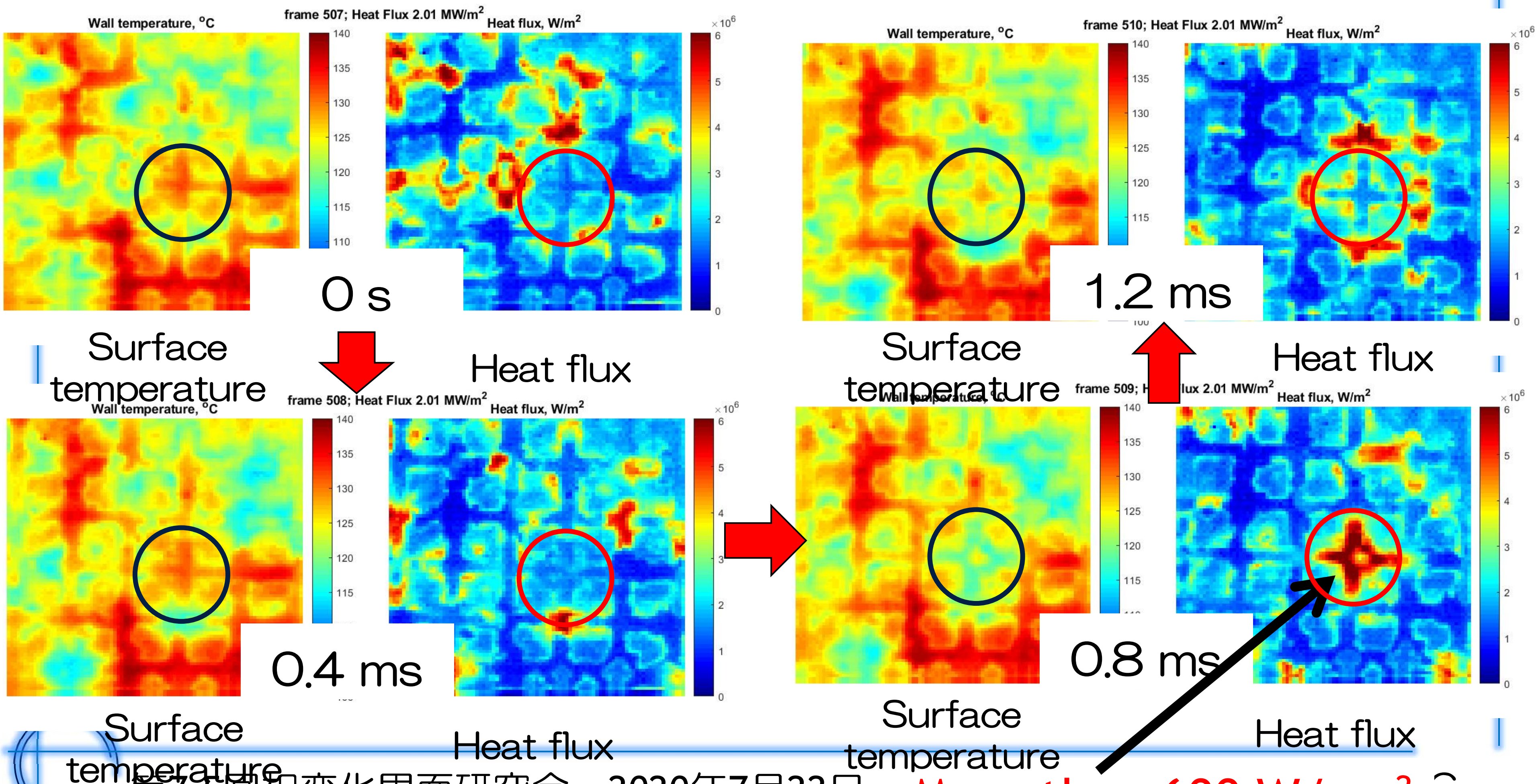
Wall temperature

Surface heat flux

Change of surface wall temperature with time
（ CHF condition, $q ≒ 200\ W/cm^2$ ）

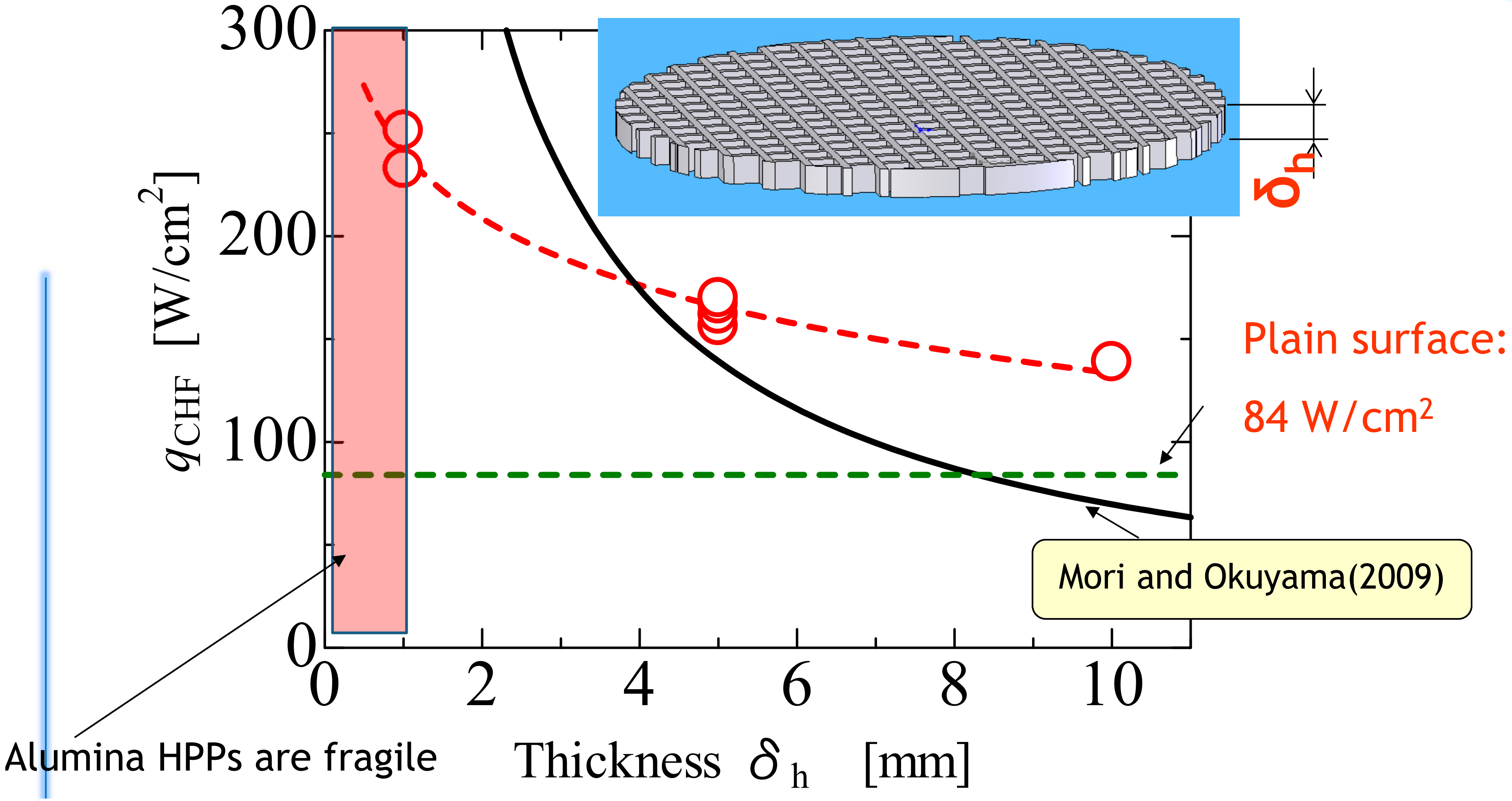
With HPP

Record rate: 2,500fps



More than 600 W/cm²

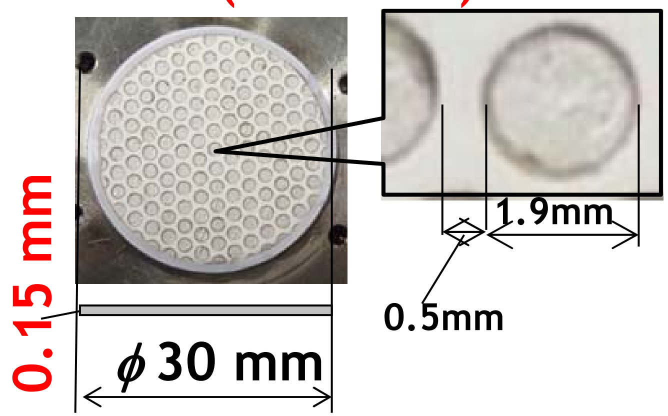
Can we improve the CHF by thinning the HPP thickness?



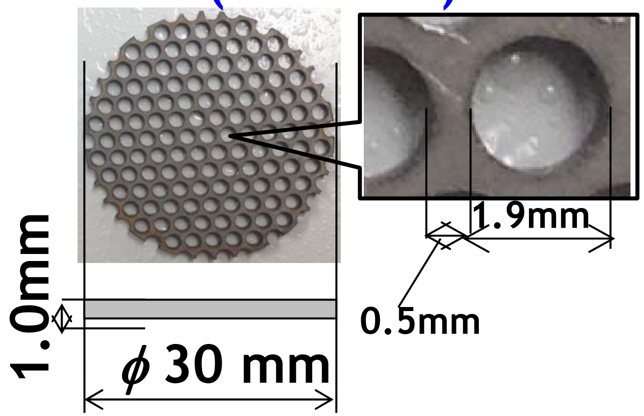
What happens when the HPP thickness is decreased to less than 1 mm?
Is the CHF increased?

Test porous materials

MF-millipore HPP (cellulose)

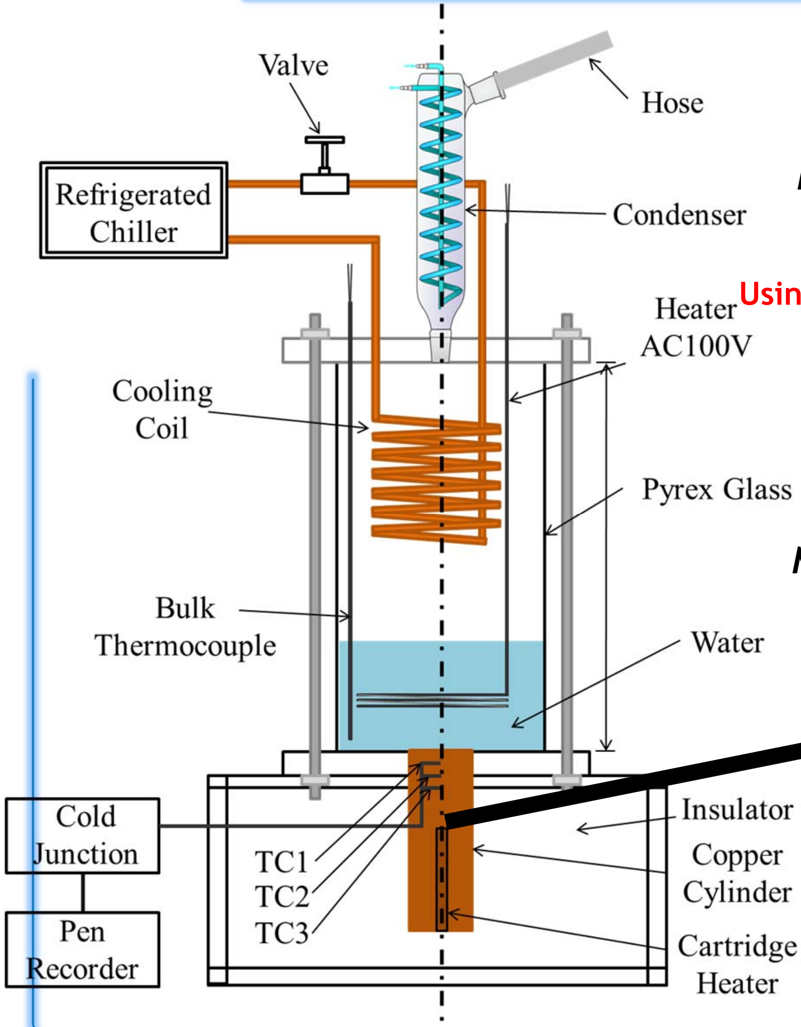


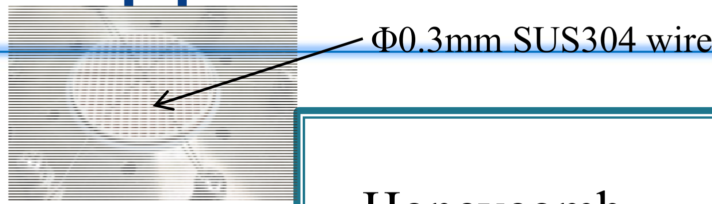
Metal HPP (SUS316L)



	MF-millipore HPP	Metal HPP
Effective pore radius: r_{eff} [μm]	1.6	18
Porosity: ε [-]	0.82	0.7
Permeability: $K[\times 10^{-14} m^2]$	6.9	66
Aperture ratio (ratio of the open area to total area)	0.55	0.55

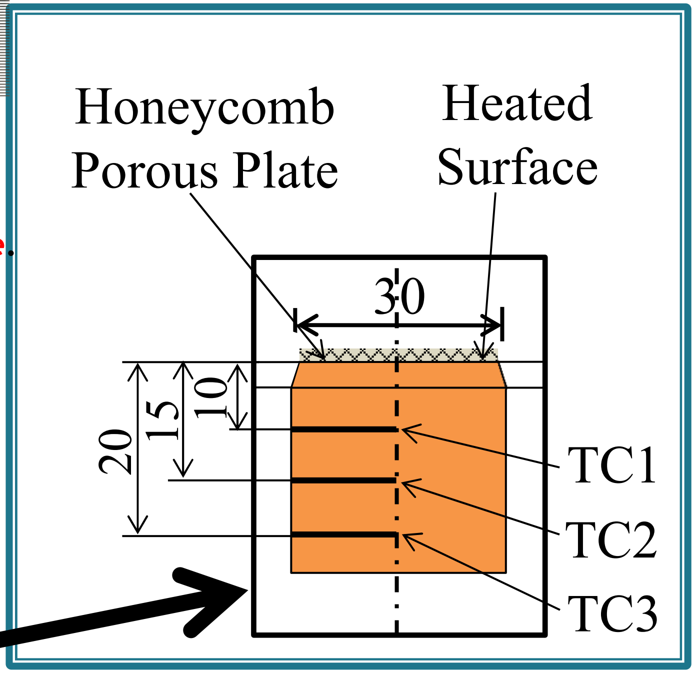
Experimental Apparatus





Metal porous HPP was fixed to heated surface **Using stainless steel wire.**

MF-millipore HPP was fixed to heated surface using adhesive



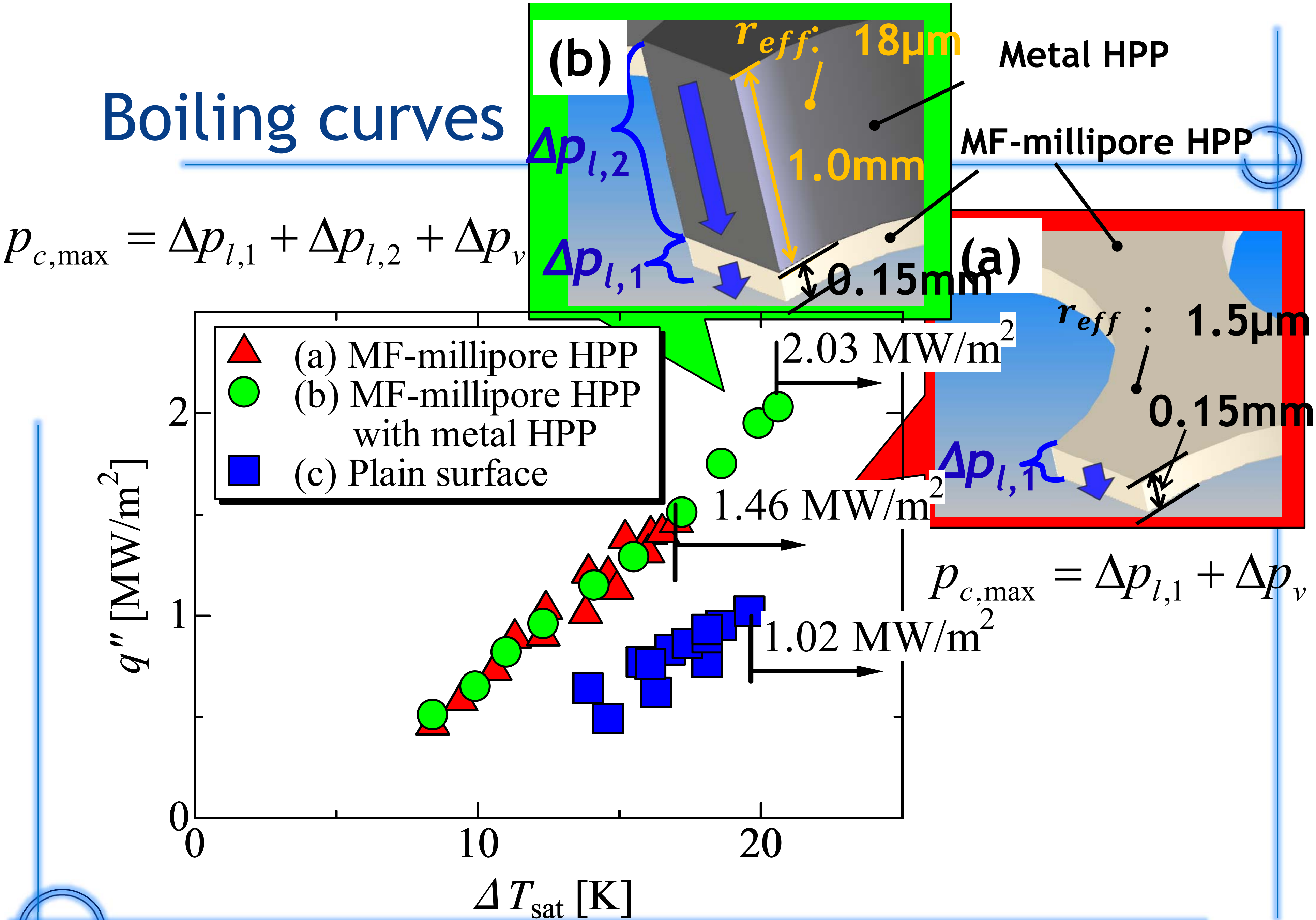
Experimental condition

Test fluid : Distilled Water

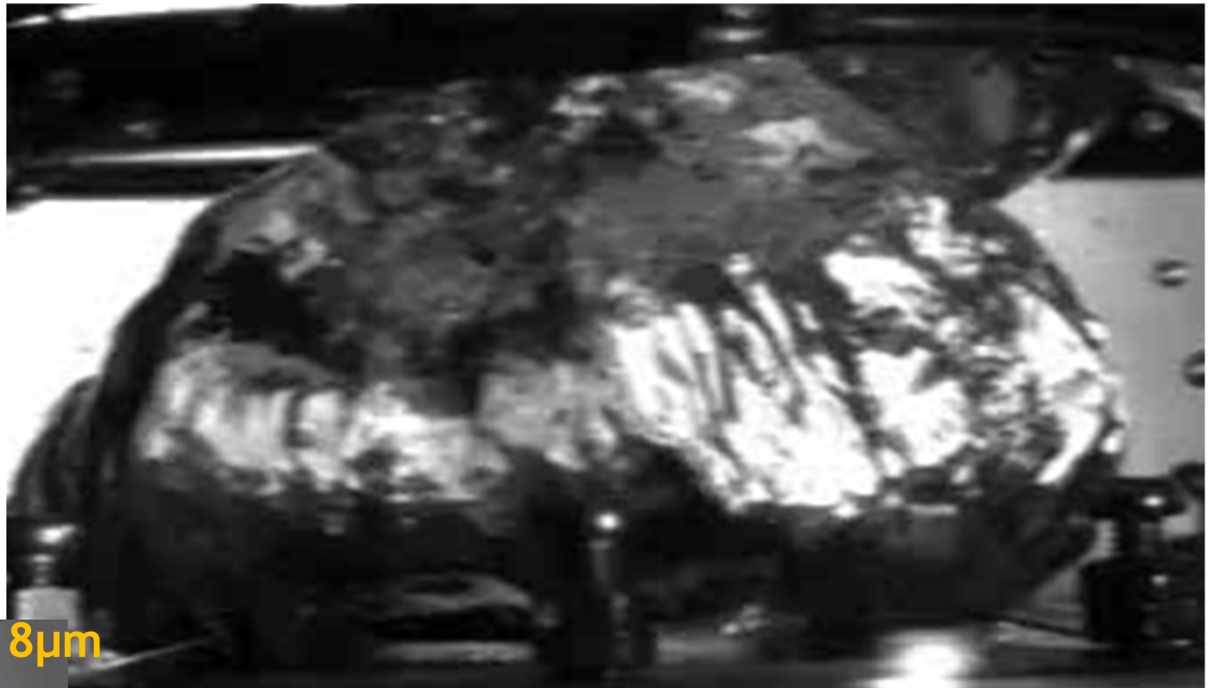
Pressure : 0.1 MPa

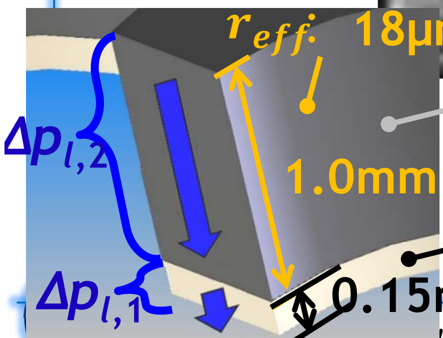
$\Delta T_{sub} = 0$ K

Boiling curves



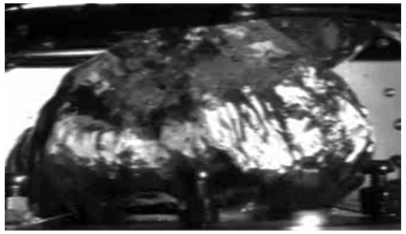
Boiling configuration near the CHF
(MF-millipore HPP with metal HPP, q_{CHF}=200 W/cm^2)

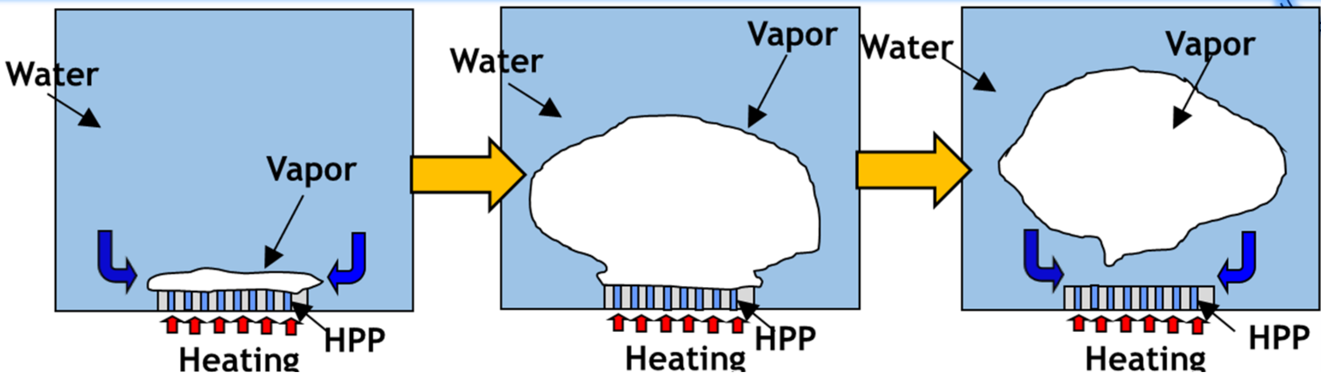




周期:約10 Hz

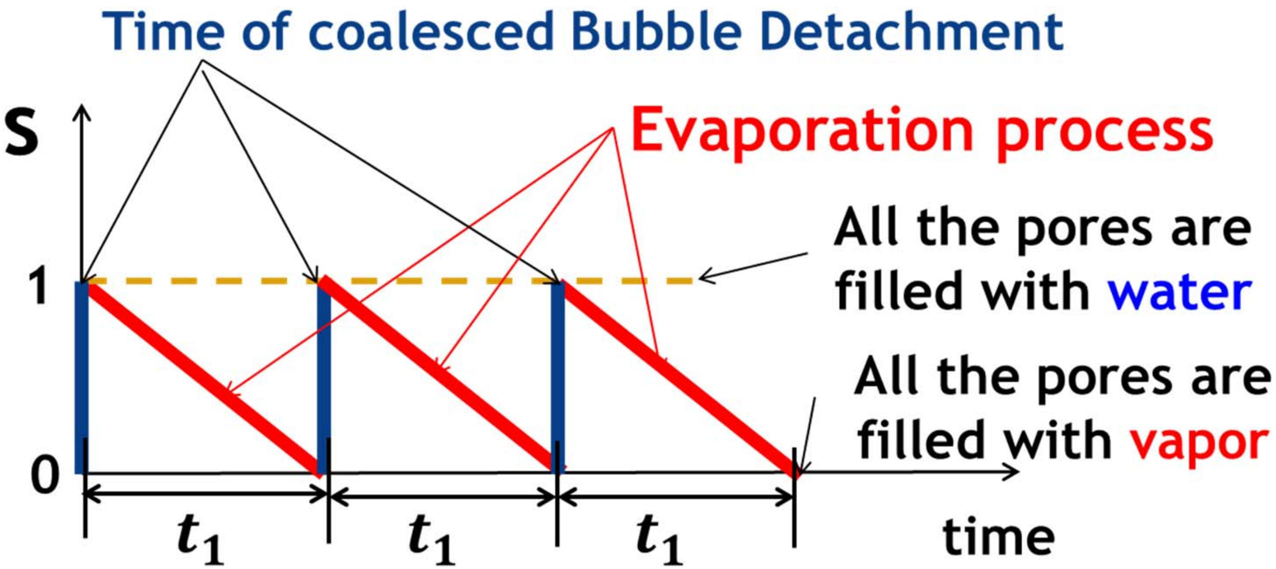
Growth processes of the coalesced bubbles on a HPP.



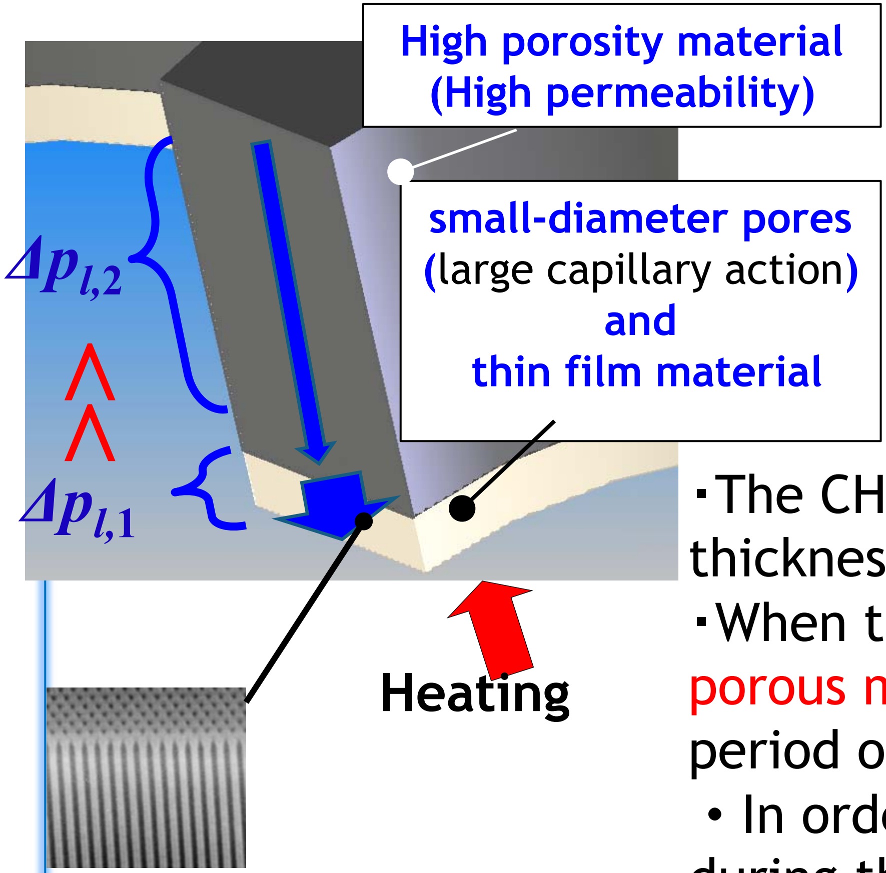


A stagnant large bubble restricts liquid supply from the bulk liquid to the HPP.

S: Liquid saturation
(volume fraction of pores occupied by the liquid phase)



CHF enhancement method using HPP with two-layer structure



Two-layer structured HPP can enhance CHF significantly in saturated pool boiling
The reasons and required conditions are summarized in the following .

・The CHF is increased with decreased in the thickness of HPP.

・When the HPP is too thin, dryout of liquid in a porous medium during the bubble-hovering period occurs.

・In order to prevent dry-out in a porous medium during the bubble-hovering period, a HPP with large permeability can be stacked on another HPP with a large capillary action.

$$q_{CHF} = \frac{2\sigma\rho_l h_{fg}}{\mu_l}\frac{KA_W}{r_{eff}\delta}$$

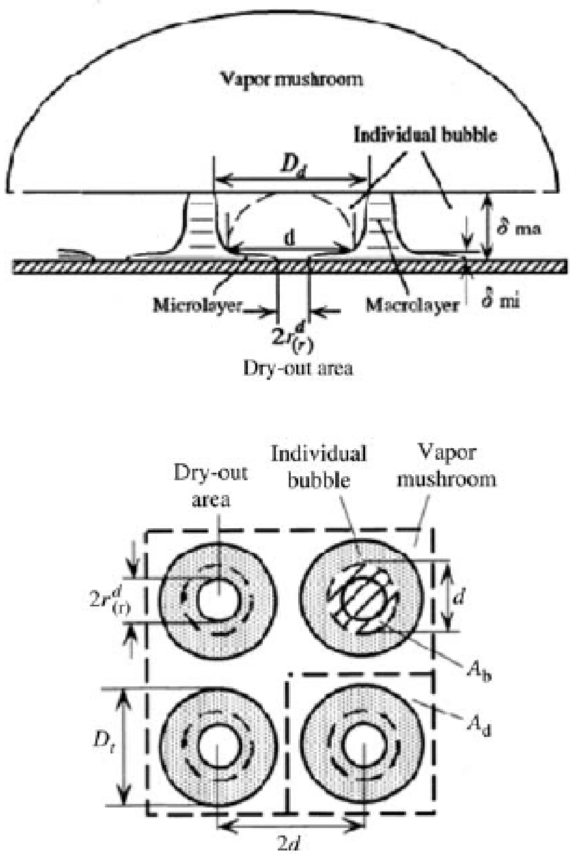
Models for Critical heat flux

1. Far-field model
(Hydrodynamic instability model, Zuber,1959)

2. Near-surface model
(Macrolayer dry-out model, Haramura and Katto,1984)

3. On-surface model
(Microlayer model, Zhao and Tsuruta, 2002)

On-surface model
(Microlayer model, Zhao and Tsuruta, 2002)



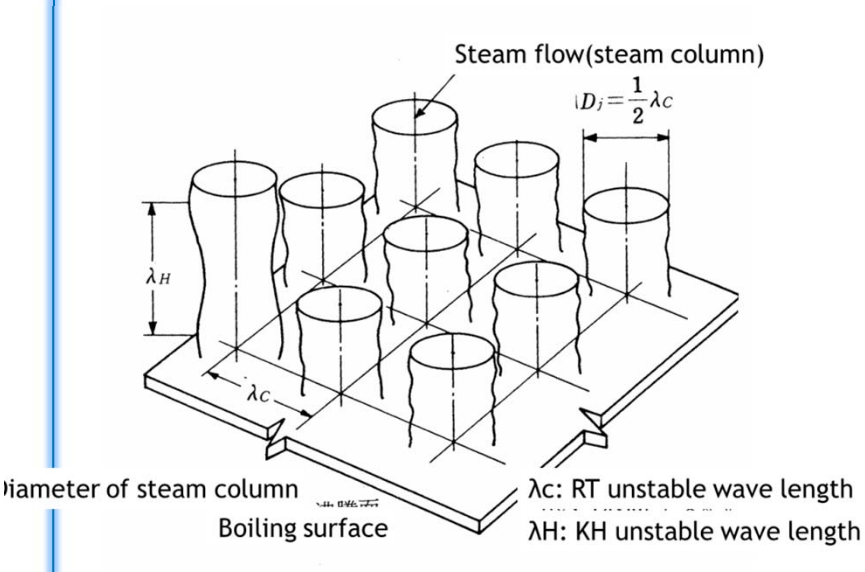
Microlayer model

何か良いアイディアありますか？

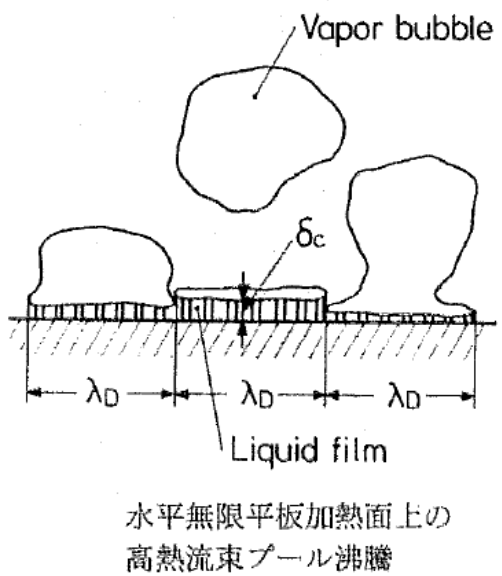
まとめ

1. 飽和プール沸騰CHF向上の最近の研究を紹介した。

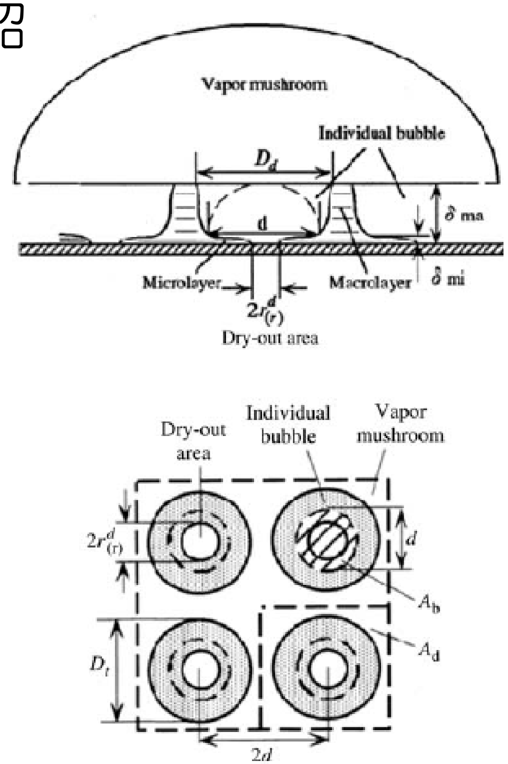
2. プール沸騰CHFモデルに基づいたCHF向上手法に関して、特にHPPを用いたCHF向上の研究について、ご紹介させて頂いた。



Hydrodynamic instability model



Macrolayer dry-out model



Microlayer model

ご清聴ありがとうございました！