Yamagata University Faculty of Engineering

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SUBCOOLED FLOW BOILING OF HFE-7000 UNDER ELECTRIC FIELD

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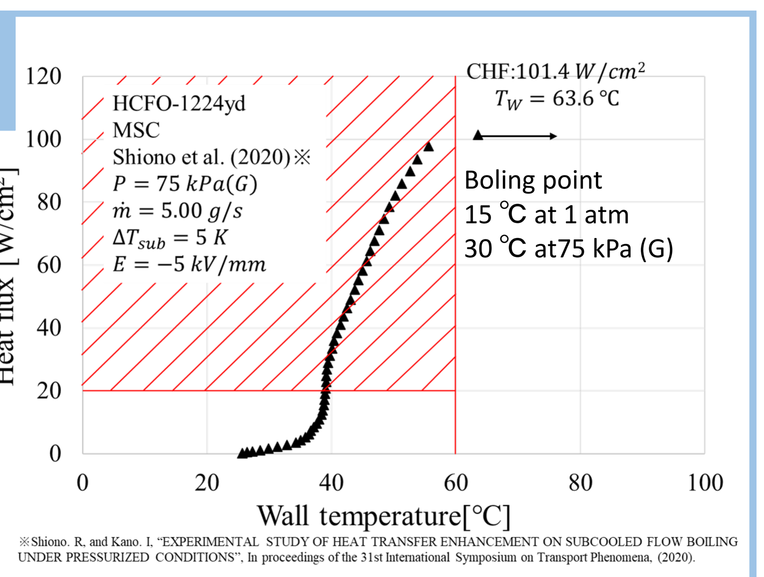
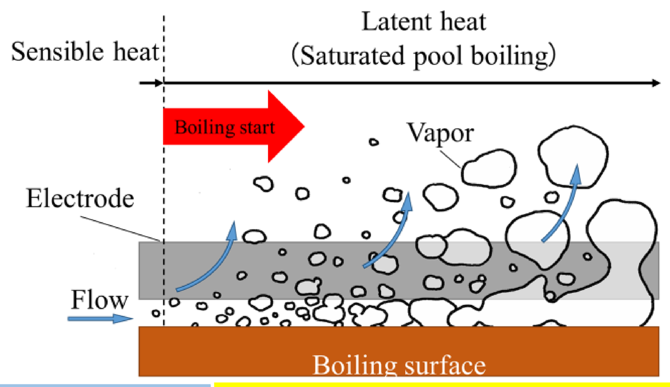
Flow boiling

1 Enhanced by electric field
2 Increasing in CHF
 20 W/cm² → 100 W/cm²
3 Removing high heat flux
 at Low wall temperature
 T_w < 60 °C

Prediction: no permittivity and surface tension of HCFO-1224yd (Low boiling point)



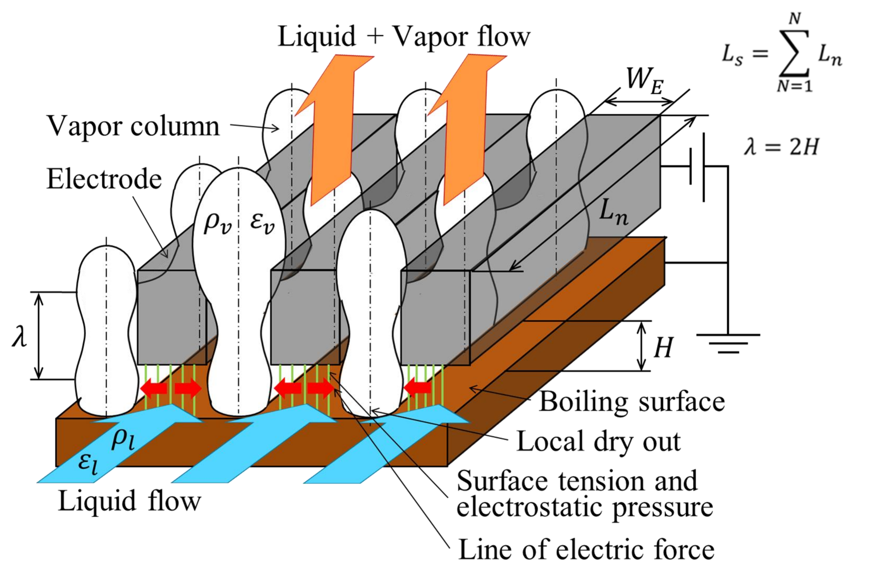
※Shiono, R. and Kano, I. "EXPERIMENTAL STUDY OF HEAT TRANSFER ENHANCEMENT ON SUBCOOLED FLOW BOILING UNDER PRESSURIZED CONDITIONS", In proceedings of the 31st International Symposium on Transport Phenomena, (2020).



Previous prediction model
- Verified using HFE-7000 known liquid characteristics (Permittivity, Surface tension)
- Verified with open circuit (at atmospheric pressure)
- Small boiling area (17 × 17 mm²)

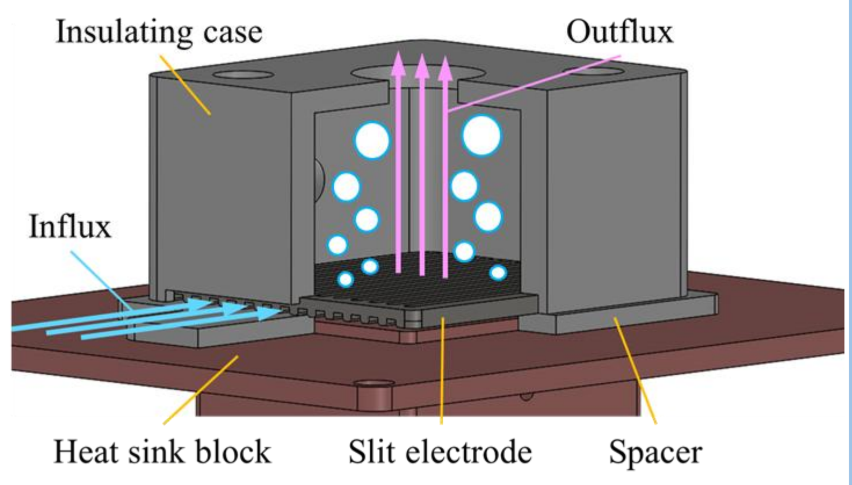
Aim of the study
To predict CHF with previous prediction model using HFE-7000 at various system pressure (20, 70 128 kPaG) and a large boiling area (28 × 24.5 mm²).

Flow boiling model and CHF prediction



$L_s = \sum_{N=1}^{N} L_n$

- A : Boiling area [m²]
- E_t : Electric field [V/m]
- H : Distance between electrode and surface [m]
- L : Latent heat [J/kg]
- L_n : Slit length [m]
- L_s : Total slits length [m]
- $\dot{m}$: Mass flux [kg/s]
- V : Voltage [V]
- W_E : Electrode width [m]
- ε_l : Liquid Permittivity [F/m]
- ε_v : Vapor Permittivity [F/m]
- λ : Wave length [m]
- ρ_l : Liquid density [kg/m³]
- ρ_v : Vapor density [kg/m³]
- σ : Surface tension [N/m]



Latent heat (CHF prediction of saturated pool boiling), Kano et al. (2022)

$$CHF_{ESP} = \frac{\pi\lambda}{48} L\rho_v \frac{L_s}{A}\left[\frac{\rho_l+\rho_v}{\rho_l\rho_v}\left\{\frac{2\pi\sigma}{\lambda} + E_t^2(\varepsilon_l-\varepsilon_v)\tanh\left(\frac{\pi W_E}{\lambda}\right)\right\}\right]^{\frac{1}{2}} \quad \cdots (1)$$

Sensible Heat flux and maximum heat flux

$$q_s = \frac{\dot{m}C_p\Delta T_l}{A},\quad q_{s,max} = \frac{\dot{m}C_p\Delta T_{l,max}}{A} \qquad \Delta T_l = \frac{T_{in}-T_{out}}{2},\quad \Delta T_{l,max} = \frac{T_{in}-T_{sat}}{2} \quad \cdots (2)$$

CHF of subcooled flow boiling affected by contact angle

$$CHF_{sfb} = q_{s,max} + \left(C_A\frac{\cos\phi}{\sin^2\phi} + C_B\frac{1}{\sin\phi}\right)CHF_{ESP} \quad \cdots (3)$$

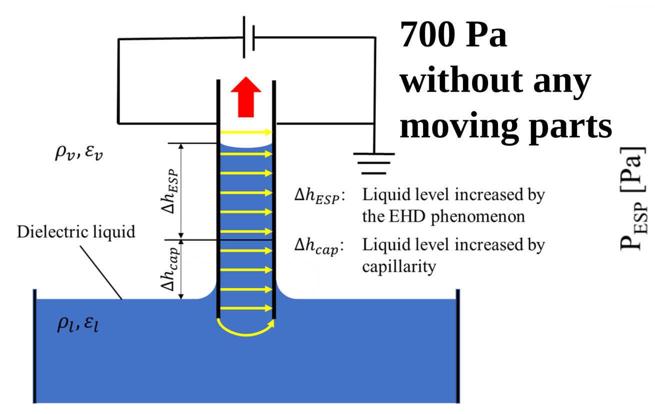
Upper limit of heat flux

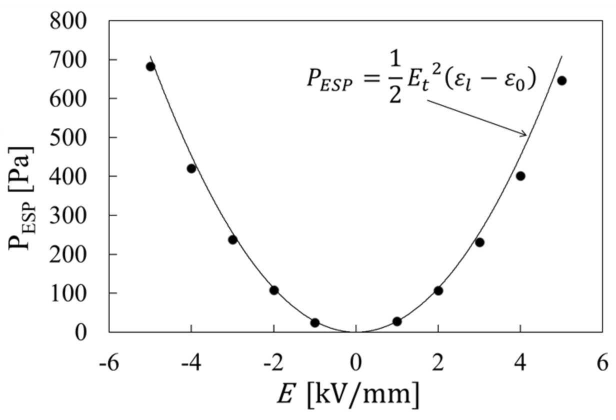
$$CHF_{lim} = \frac{\dot{m}L}{A} + q_{s,max} \quad \cdots (4)$$

Vapor quality

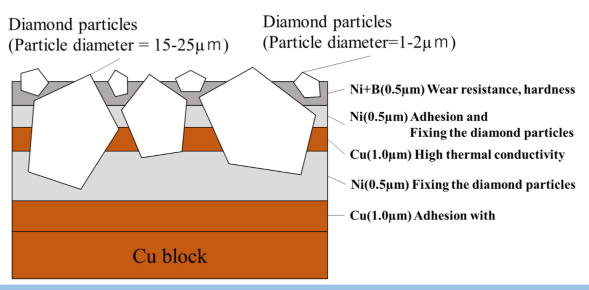
$$\chi = \frac{(q-q_s)A}{\dot{m}L} \quad \cdots (5)$$

Enhancement techniques





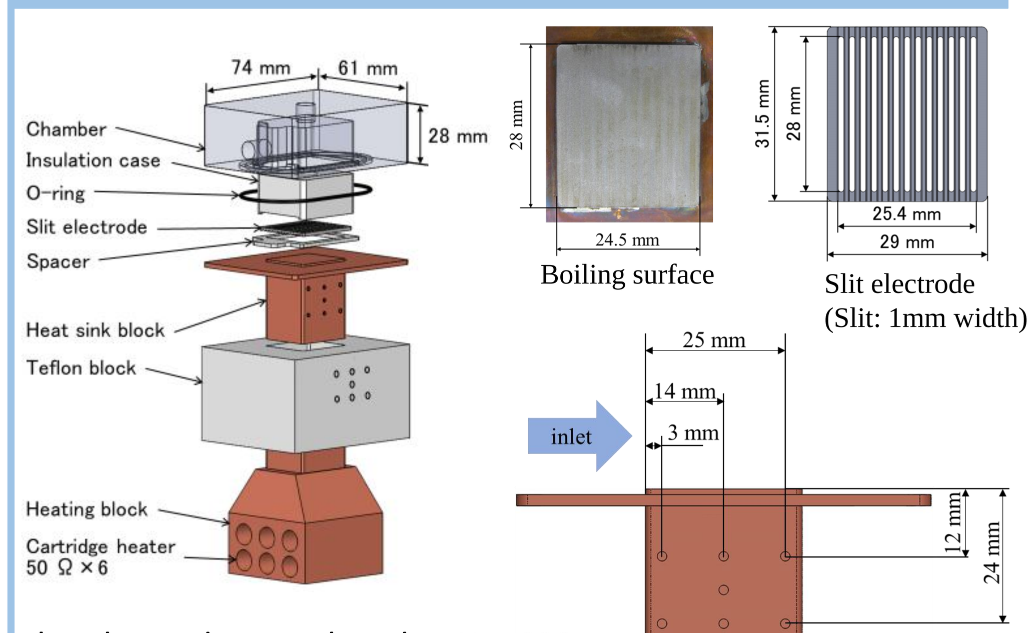
- **Electrostatic pressure**
 Behaves like a pump without any moving parts
- **Low contact angle (θ = 13.5 - 15.1°)**
 Electroplating with fine diamond particles (Polished Cu: θ = 18°)



Experimental setup

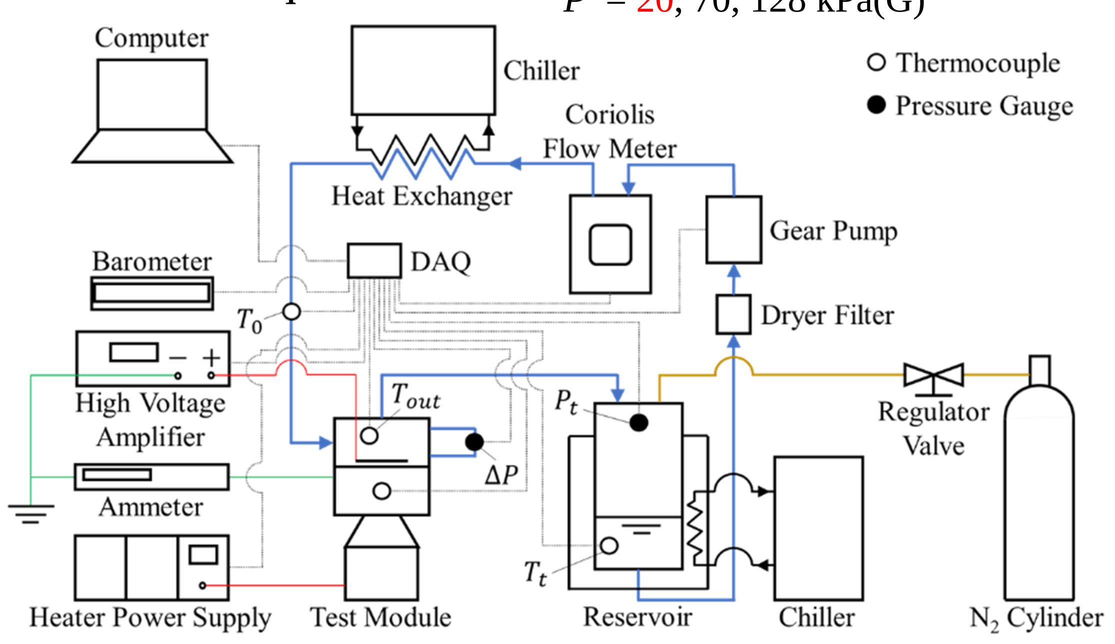
Refrigerant : HFE-7000
Boiling point at 1atm : 34 °C

Experimental condition
E = 0, -1, -2, -3, -4, -5 kV/mm
$\dot{m}$ = 1.66, 3.33, 5.00 g/s
Δt_{sub} = 5, 10, 15 K at P = 20 kPa(G)
P = 20, 70, 128 kPa(G)



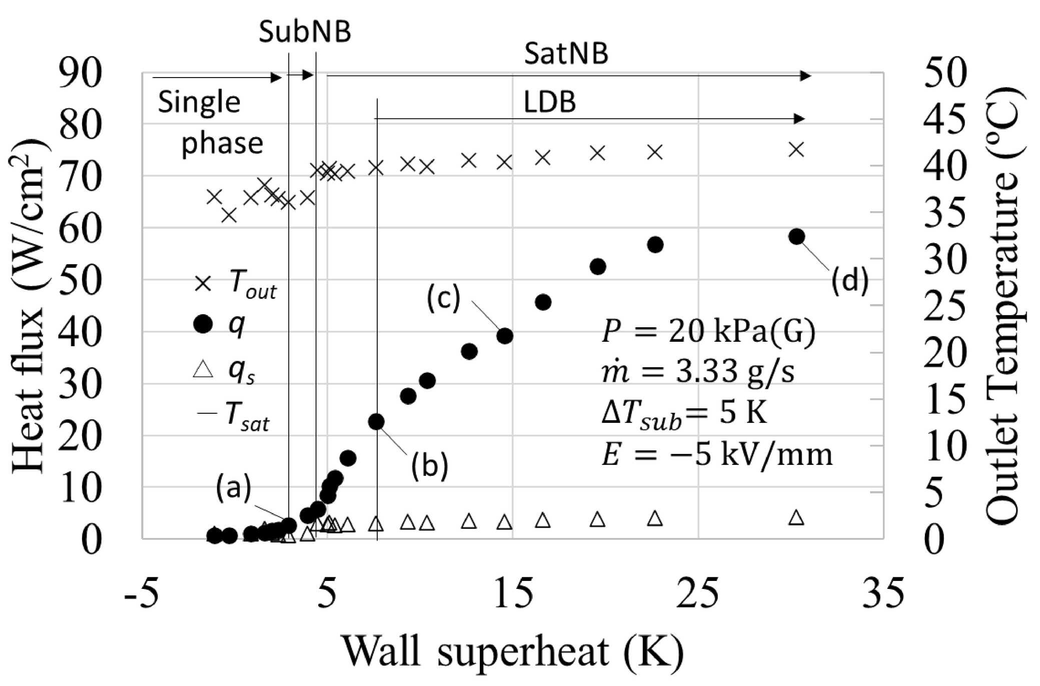
The electrode was placed at H = 600 μm

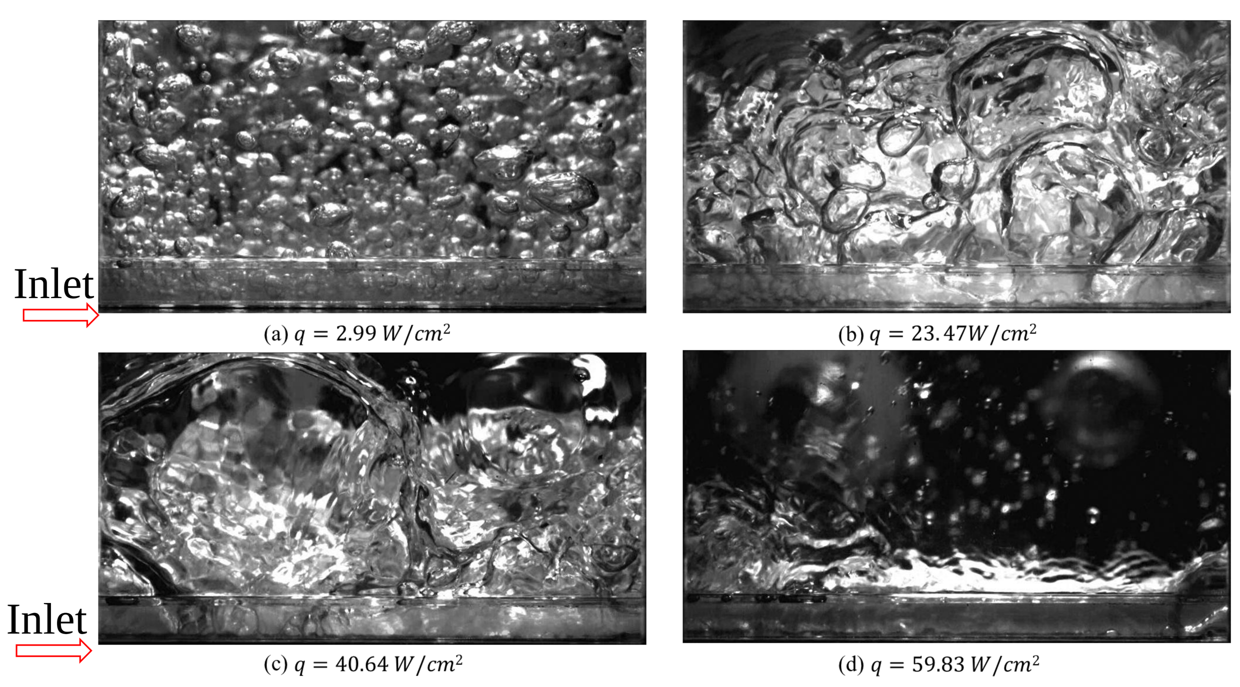
Liquid Circuit

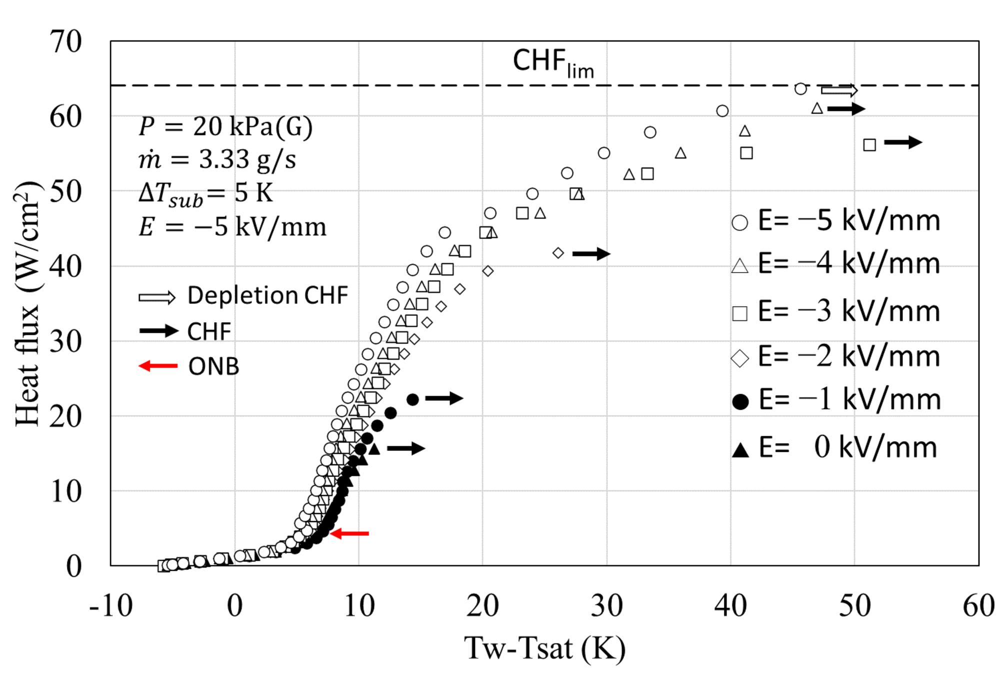


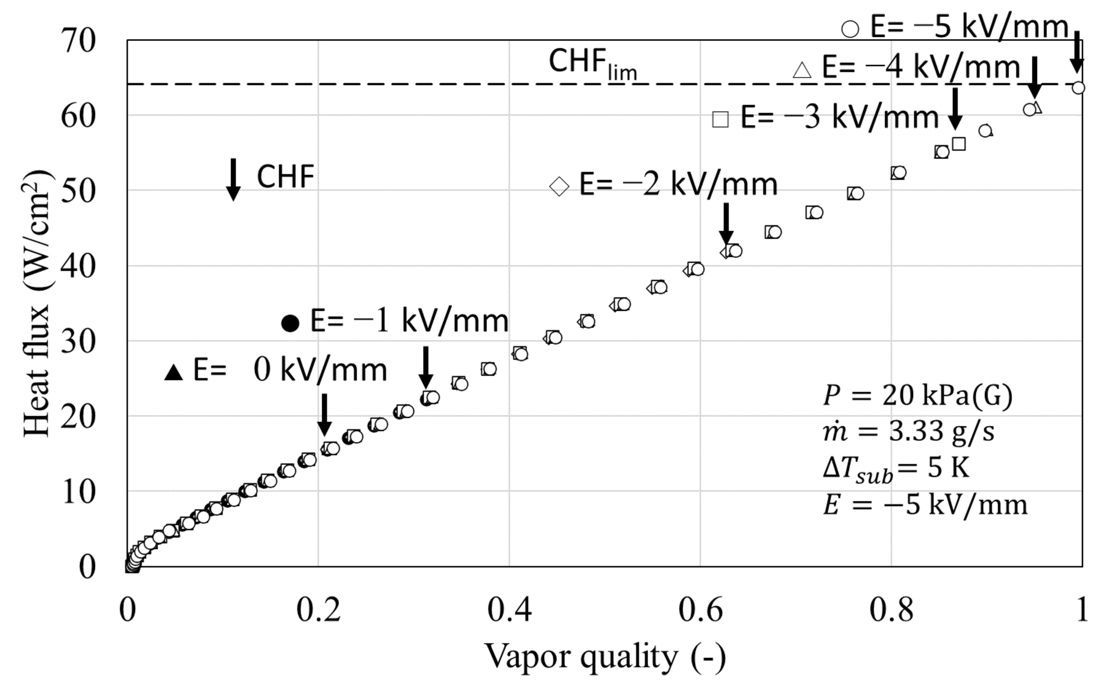
Results

- Sub : Subcooled
- Sat : Saturated
- NB : Nucleate Boiling
- LDB : Local Dry-out Boiling









Boiling curve and Bubble behavior in MSC

- Single phase, Subcooled nucleate boiling, Saturated nucleate boiling regions
- Boiling starts in the subcooling condition
- Size of bubbles are not changed
- Heat flux suddenly increases due to latent heat
- Bubbles are coalesced and growth
- Local dry out occurred under the slits
- Almost inflow liquid is vaporized at the CHF

Effect of Electric field

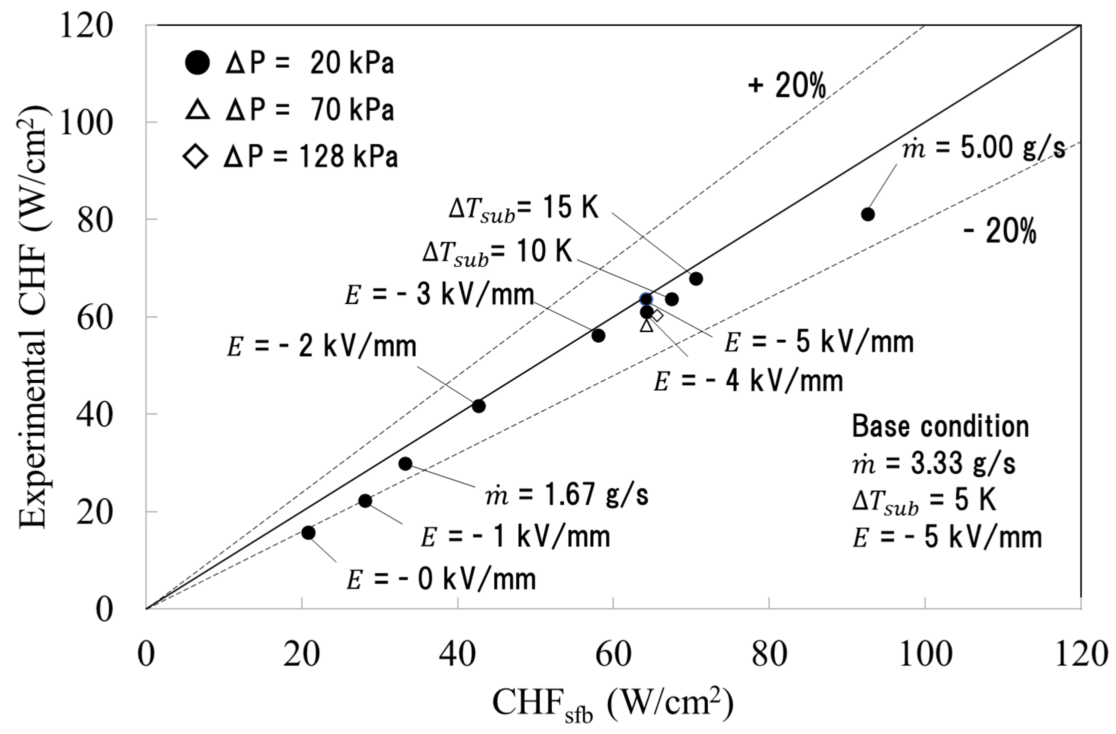
- 16 → 64 W/cm² (4 times greater)
- Heat flux reaches to a upper limit of heat flux at E = - 5 kV/mm

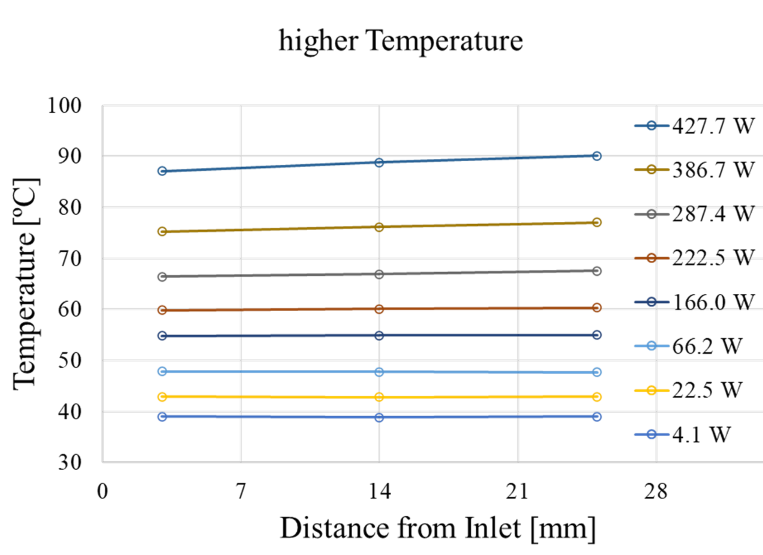
Vapor quality

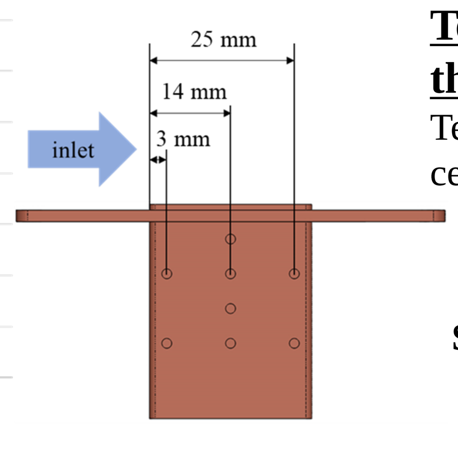
- Electric field effectively enhances the boiling until 100 % of inflowed liquid is evaporated

Comparing with CHF prediction

- Effects of electric fields, additional system pressures, and mass flow rates were considered.
- Predicting CHF within ±20 %







Temperature distribution on the boiling surface

Temperature difference with the center is 1.9 %

Surface temperature is uniform

Conclusion

Subcooled flow boiling CHF in closed and pressurized circuit was predicted within ±20 %

Future study

R_T : Thermal Resistance

Heat transfer coefficient is very high, however, the thermal resistance (R_T = 0.06 K/W) is need to improve because of small boiling surface

We need to study the electric field enhancement technique over the additional boiling surface erea like a plate-fin surface

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