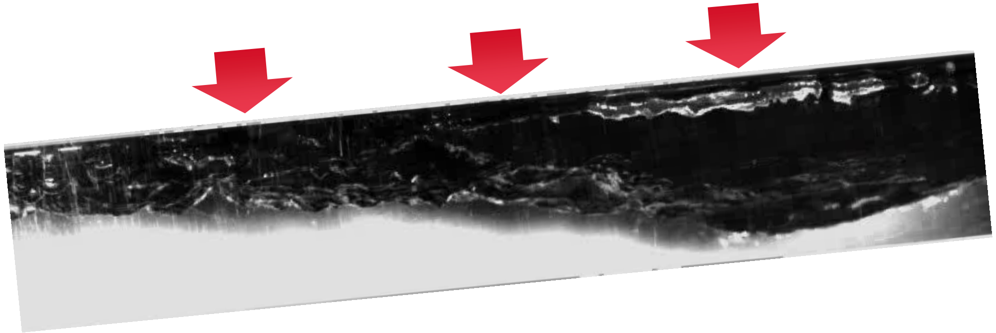
# Analysis of the Mechanistic Critical Heat Flux Models for Downward Facing Boiling Heat Transfer

Heat Flow through downward facing Heating Wall



*Side View*

*Bottom View*

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- Experimental description
- Results and analysis: Models VS Exp. (present)
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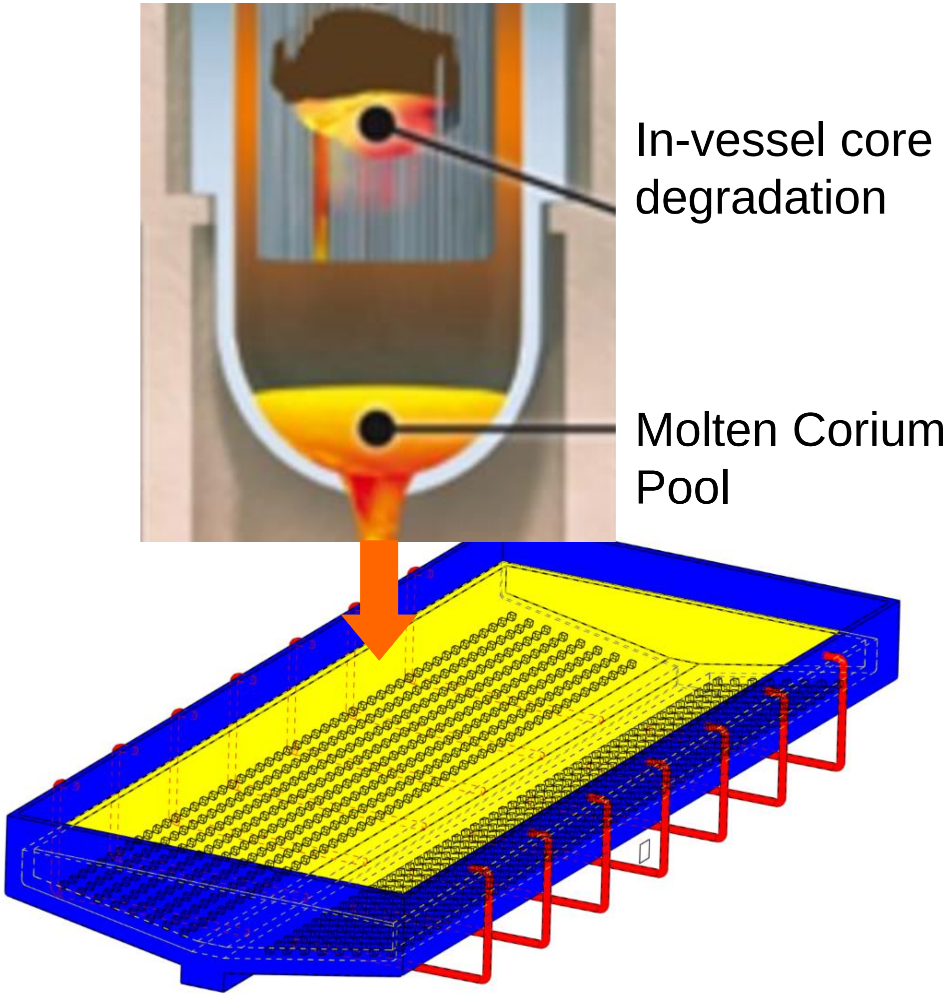
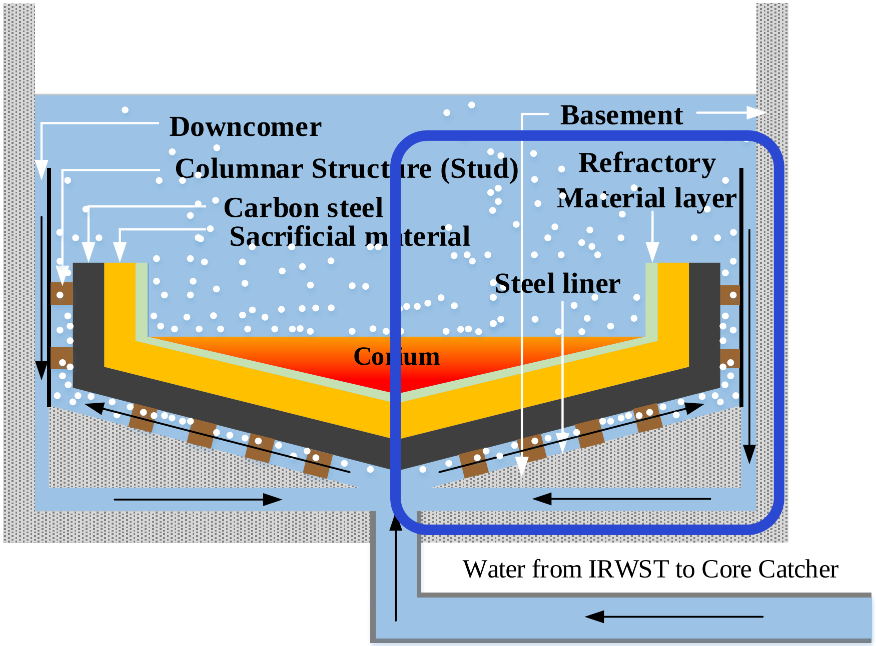
# Background

## Application: Ex-Vessel Core Catcher Cooling System





▭ Boiling induced natural circulation

<Conceptual design proposed by KAERI&KHNP>

# Motivation

## Thermal Hydraulic Features in the NC cooling channel

Natural Circulation (low mass vel.)

- Passive device
- Low turbulence level

Thick Heating Wall (Carbon steel ~150mm)

- High thermal inertia
- Non-uniform heat flux distribution formation due to non uniform HTC

Slightly and constantly inclined downward facing large heating surface

- Two phase boundary layer flow
- Easily merged large bubble in the vicinity of heating surface

***Lack of***

- ***Experimental Data on CHF***
- ***Mechanistic CHF Model***

Low pressure & large hydraulic diameter

- Relatively large bubble size
- Two-phase boundary layer flow

Many aligned Columnar Structures (STUD)

- Hydraulic resistance
- Distortion of flow field
- Locally degraded HTC
- Stagnant region induced hot spot

Changing Flow Boiling Regime: subcooled to saturated

- Subcooling effect on CHF
- Changing mass velocity in the channel

# Major Objective

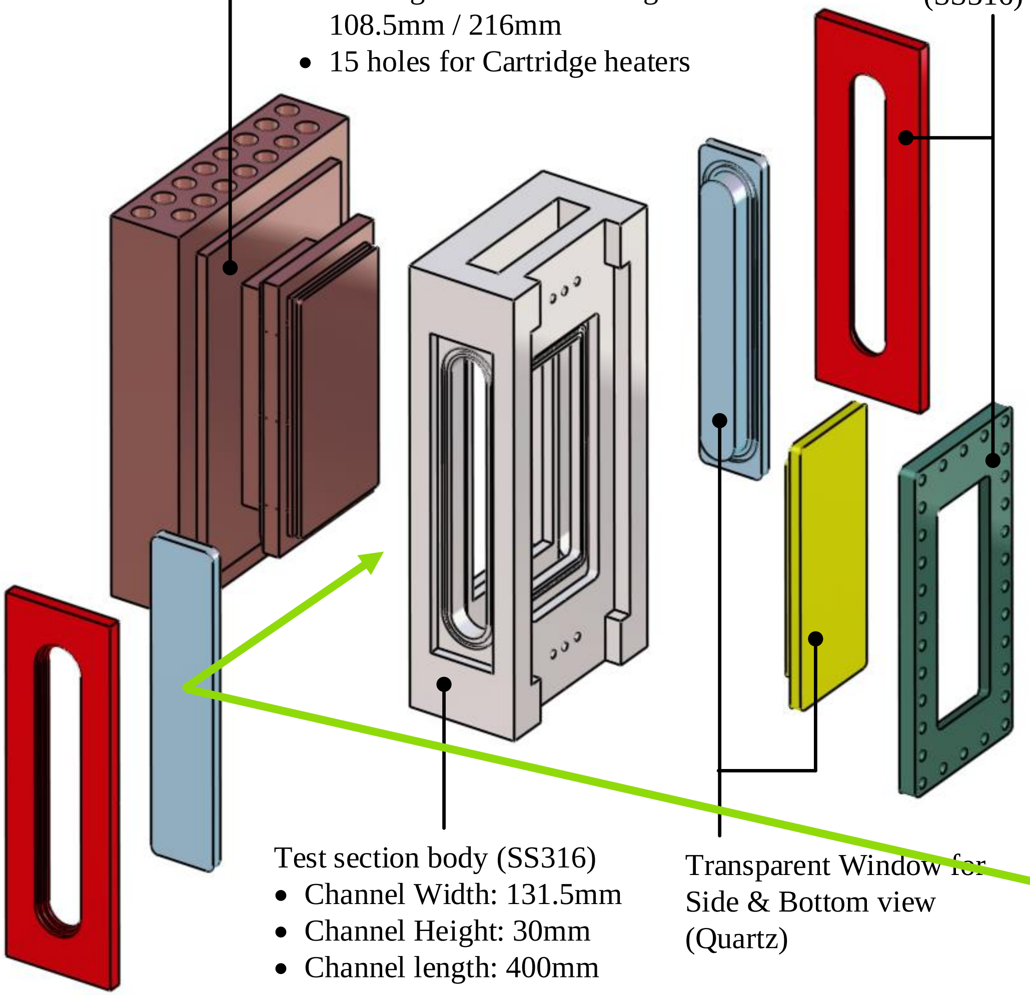
Comparison and analysis between
existing CHF Models and experimental data

Finding a point for **improvement**
in the existing CHF models

# Existing Downward Facing CHF models

| No. | Authors (Year) | Base CHF model | Key characteristics |
|---|---|---|---|
| *[1]* | *M. J. Brusstar and H. M. Jr. (1994)* | *Sublayer dryout model* | • Based on Zuber’s model of CHF<br>• Subcooling effect based on Jacob number<br>• CHF ~ vapor terminal velocity<br>• Applicable small heater and pool condition |
| *[2]* | *F. B. Cheung and K. H. Haddad (1997)* | *Sublayer dryout model* | • Hydrodynamic CHF model for saturated pool boiling at the downward facing curved wall<br>• Critical Void fraction = 0.915, CHF ~ liquid velocity<br>• Two-phase boundary flow analysis – Drift flux model<br>• Spatial variation of the CHF along the curved vessel |
| *[3]* | *Hui He et al. (2015)* | *Sublayer dryout model* | • For subcooled pool boiling at the downward facing curved wall<br>• $q''_{CHF}=q''$(evaporation) + $q''$(liquid replenishment, subcooling using Jacob No.)<br>• CHF ~ vapor velocity in two phase boundary layer<br>• The others are similar with Cheung and Haddad model |
| *[4]* | *Azin Behdadi et al. (2017)* | *Sublayer dryout model* | • Similar with Cheung and Haddad model<br>• Tried Separated flow model and Drift flux model<br>• Subcooling effect → single phase & quenching HT<br>• Needs on bubble influence area, $HTC_{quenching}$ → Difficult.. |
| *[5]* | *R. Guo et al. (2014)* | *Near wall bubble crowding* | • Extension of Weisman and Pei’s model from vertical to inclined flow<br>• Using wall heat flux partitioning model to calculate accurate flow quality in bubbly layer and bulk liquid layer separately<br>• Subcooling effect:<br>→ $q_{CHF} = f\left(x_1, x_2\right)$, 1: in bubbly layer, 2 : bulk liquid layer |

# Lab. scaled test section assembly



Heating Block (Oxygen Free Copper)

- Heating surface width/length: 108.5mm / 216mm
- 15 holes for Cartridge heaters

Cover Plate (SS316)

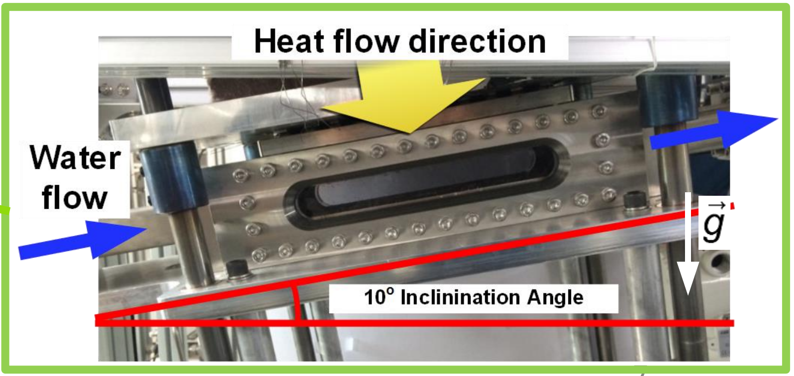
Test section body (SS316)

- Channel Width: 131.5mm
- Channel Height: 30mm
- Channel length: 400mm

Transparent Window for Side & Bottom view (Quartz)

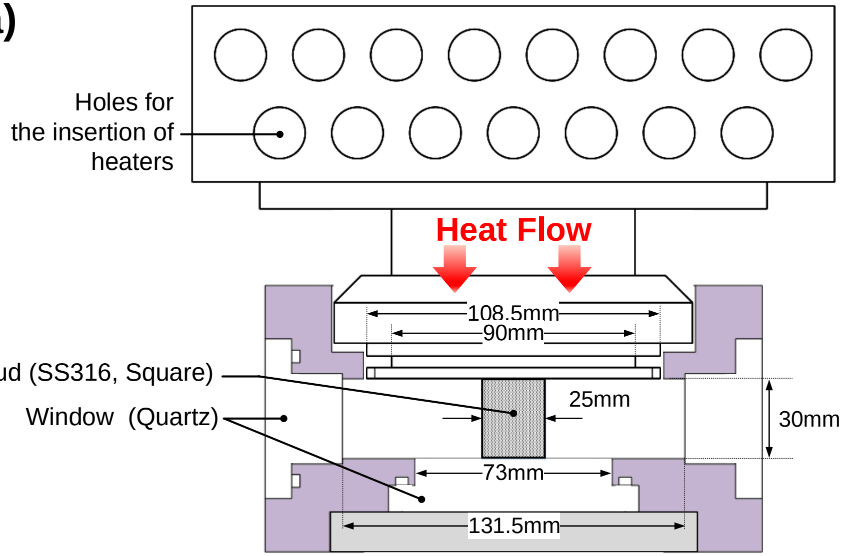
## Features for the similarity of CHF mechanism

- 10deg Slightly inclined downward facing heater
- Sufficient heating surface area (width, length)
- High thermal inertia of heater
- Large hydraulic diameter



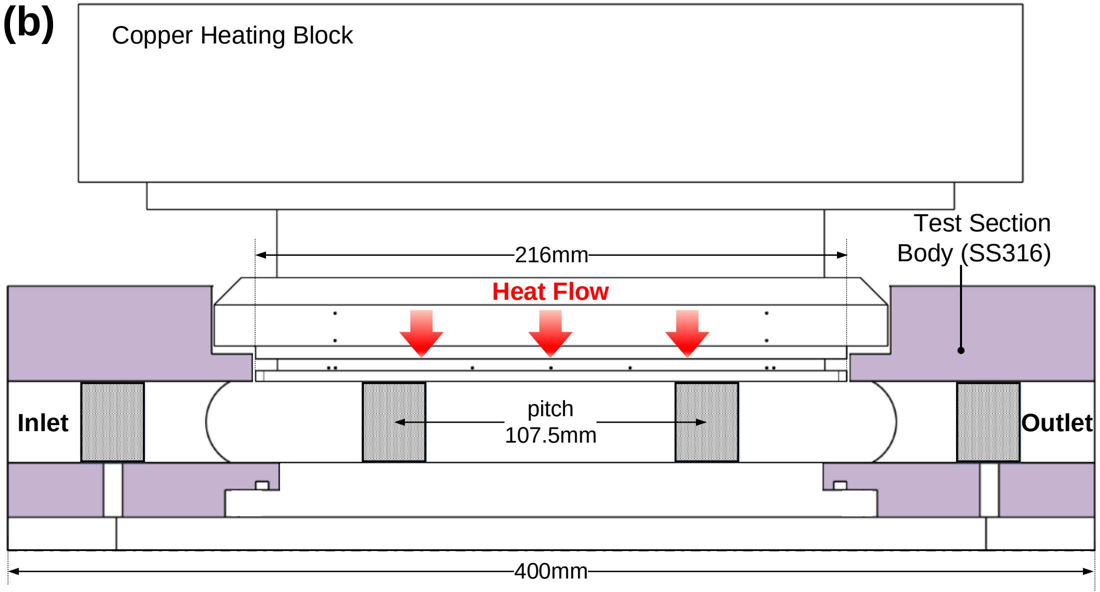
# Detailed view of the test section

(a)



*<u>Transversal cross sectional view</u>*

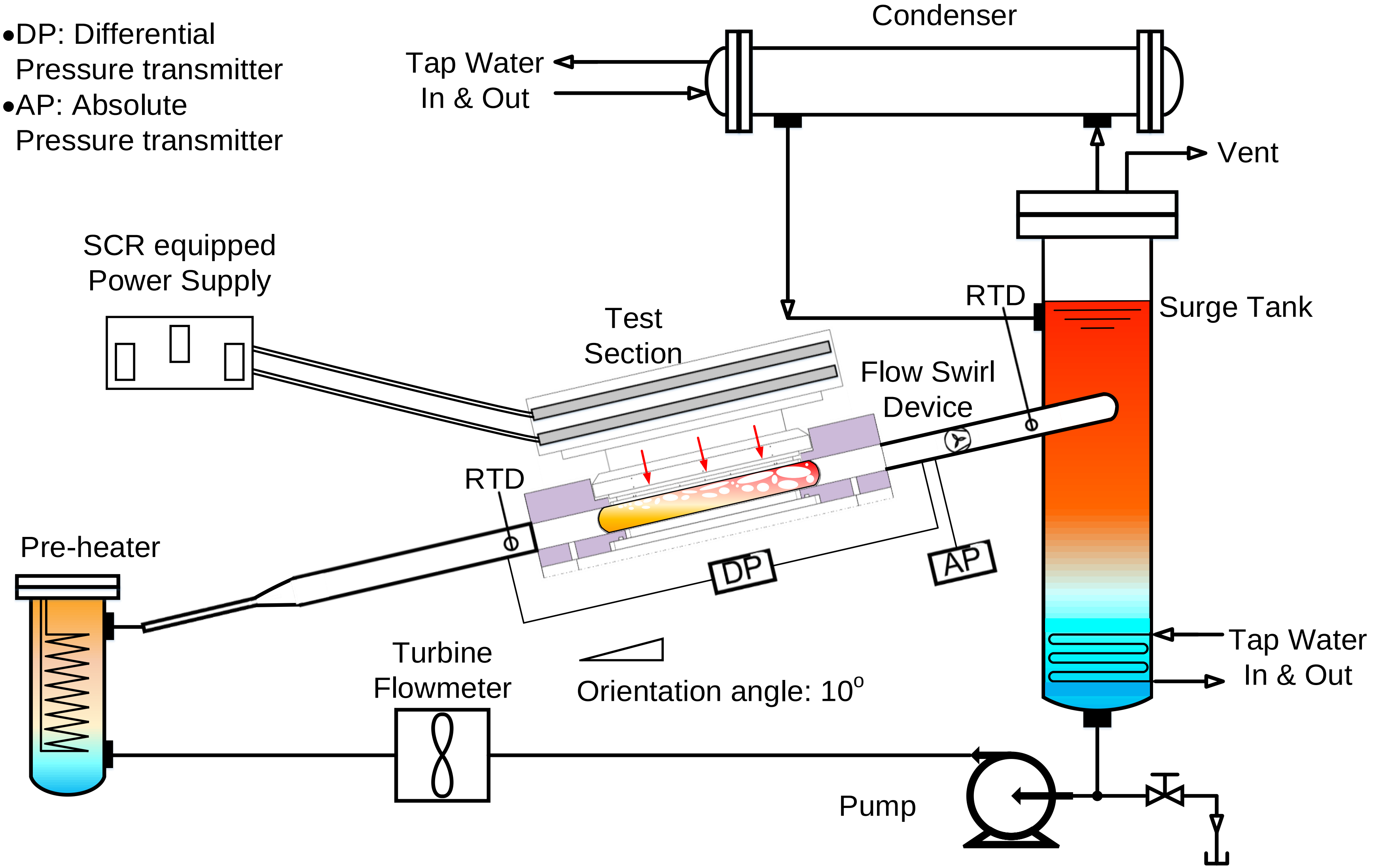
(b)



*<u>Longitudinal cross sectional view</u>*

# Flow Boiling Water Loop in Lab.

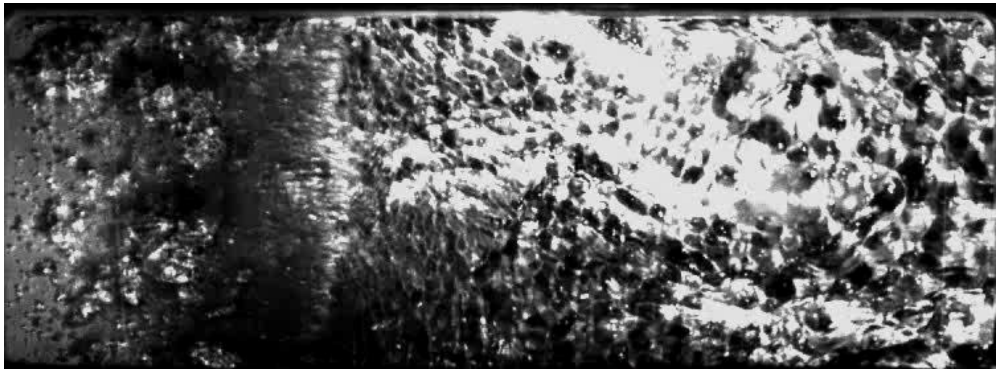
- DP: Differential Pressure transmitter
- AP: Absolute Pressure transmitter

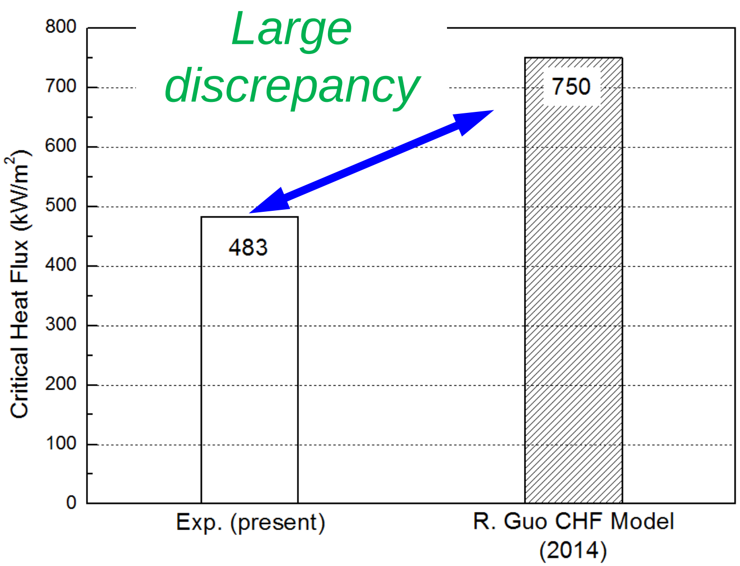


# **Results:** Natural Circulation condition

## G=210 kg/m$^2$-s, $\Delta T_{sub}$ = 10 K under near atmospheric P

*Visual characterization of CHF*



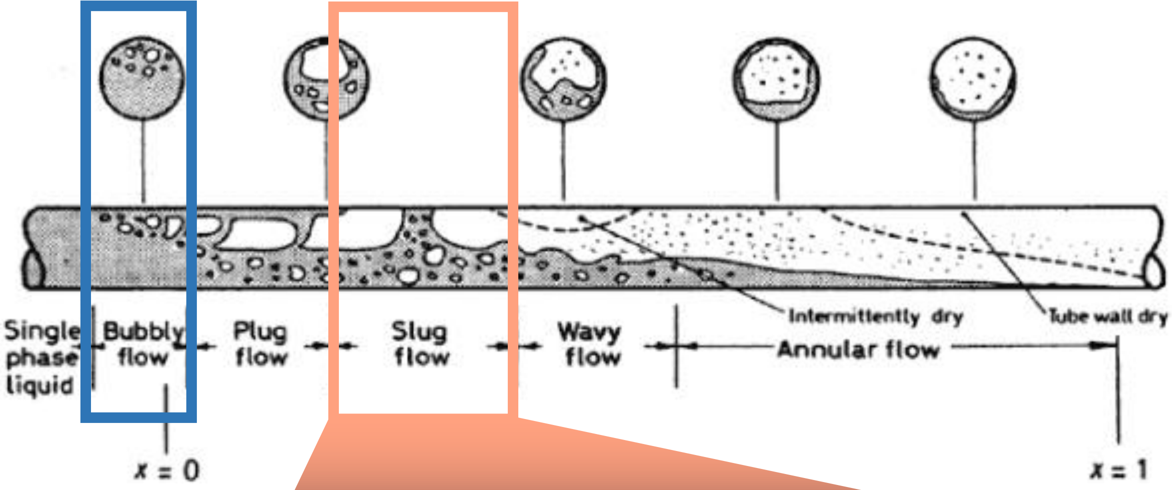


- R. Guo model: modeling of large curved channel → higher vapor velocity expected
- May be mainly due to difference: Bubbly flow (R. Guo model) VS. Slug flow (observed)
  - Model prediction: $u_1(\text{bulk liquid}) > u_2(\text{vapor layer})$ , Observation: $u_1 < u_2$
  - Steam-water mixture flow thickness: Model (<2mm), Observation (>8mm)
  - Critical void fraction =0.82 (in bubbly layer), =0.915 (in slug flow, Cheung and Haddad,1997)

# Results: Natural Circulation condition

## G=210 kg/m$^2$-s, $\Delta T_{sub}$ = 10 K under near atmospheric

***Difference in the flow pattern between physical observation and model***



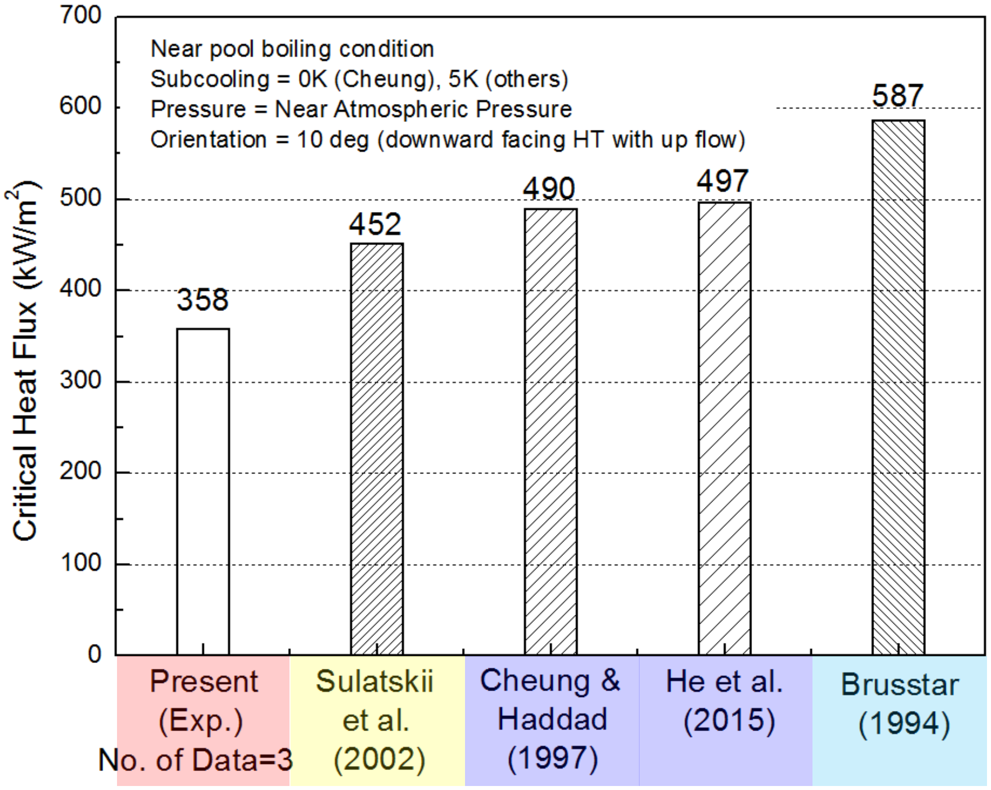
***Bubbly flow assumed in R. Guo CHF model***

***Physical observation at 0.7q”$_{CHF}$***

# Results: Pool Boiling condition

## Saturated Pool Boiling under near 1atm

### *Explanations on the discrepancy*



***Present*** : Flat downward facing heater

- Two phase boundary layer flow (TPBL)
- Very clean heating surface
- Gap boiling: having relatively small volume of bulk liquid region

***Brusstar***: small heater size is small (L19.1 mm)

- No TPBL flow → Easy supply of liquid to HS
- Achieve high CHF

***C&H and He et al***.: Modeling of RPV heating wall

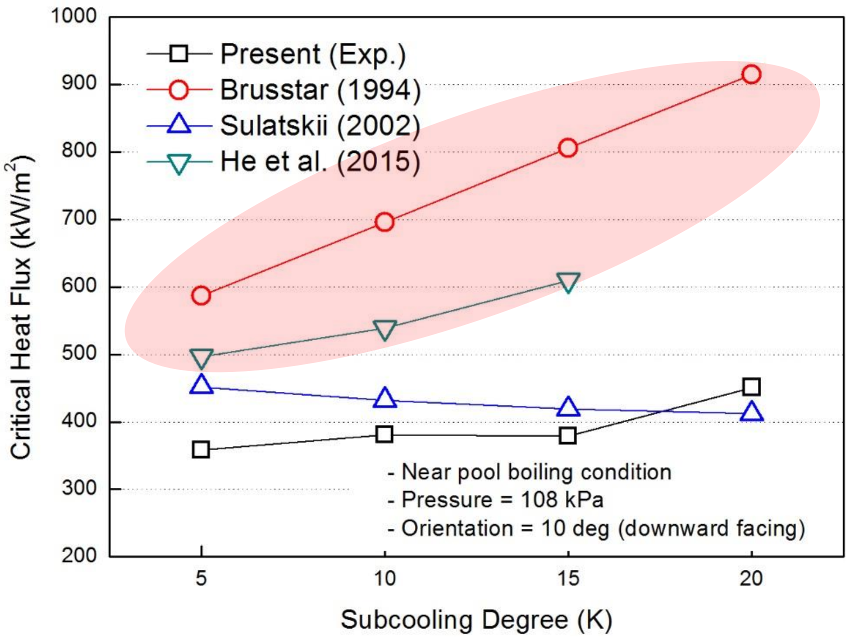
- Buoyancy force increase from 0 to vertical (90$^o$)
- Vapor accelerates along curved channel
- Achieve high CHF
- Additional contribution from significantly aged heating surface

***Sulatskii et al***.: Flat large downward facing heater

- Most similar CHF value with Exp. Data
- Contribution from significantly aged heating surface significantly aged
- Achieve high CHF

# **Results:** Subcooling effect

## Subcooled Pool Boiling under near 1atm



- Subcooling effect: Jacob No. with a constant
- **Clear positive linearity**: CHF VS. Subcooling
- Brusstar: Short heater length → Easy liquid replenishment → most strong positive effect

- CHF model (He et al.): curved heater wall, use Jacob No. with $C_m$, empirical constant
- $C_m$ : Actual subcooling of liquid entering the sublayer
- Experimental condition at which $C_m$ is determined

: Vertical flow boiling at high pressure and mass velocity

***In consideration of downward facing boiling condition, the constant should be modified***

**Brusstar**

$$0.102\left(\frac{\rho_l}{\rho_v}\right)^{0.75}\boxed{\frac{c_{pl}\Delta T_{sub}}{h_{fg}}}$$

**He et al.**

$$q''_{replenishment} = \frac{G_r \delta_m h_{fg}}{L_m}\left[1+\boxed{\frac{c_{pf} c_m \Delta T_{sub}}{h_{fg}}}\right]$$

$$c_m \Delta T_{sub} = T_{sat} - T_{sublayer}$$

# Results: Subcooling effect

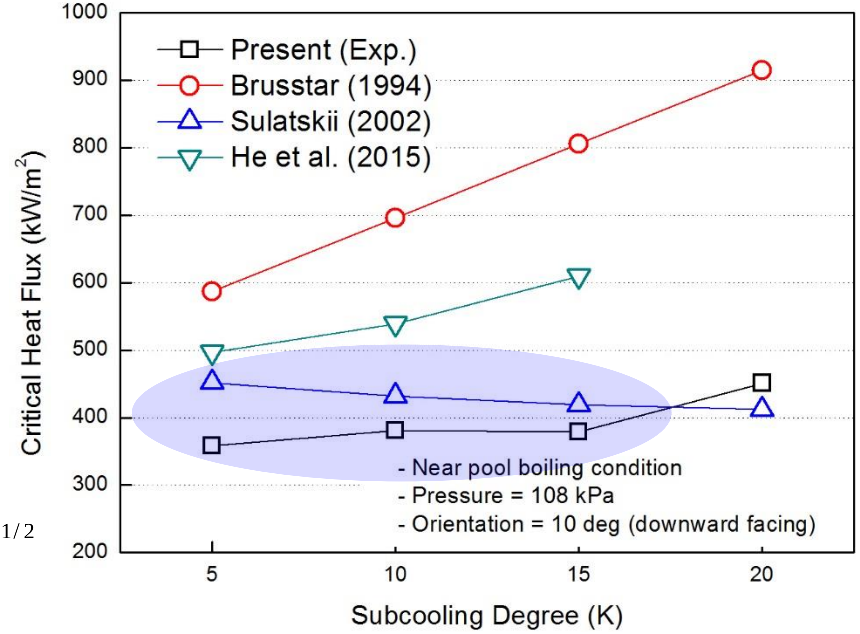
## Subcooled Pool Boiling under near 1atm at 10 degree

- Common feature: Weak or even negative subcooling effect observed: CHF VS. Subcooling
- Sulatskii et al. (2002): Pool boiling CHF correlation
- Large flat downward facing heater, 10 deg inclined
- Most similar experimental condition with core catcher cooling channel

$$\overset{\text{Normalized one}}{Q_{CHF,sub}(\theta)} = \left[\boxed{\overset{\text{Saturated CHF}}{Q^2_{CHF,sat}(\theta)}} + \boxed{\underset{\text{steam layer motion}}{C_1 Fr_*^2}} + \boxed{\overset{\text{Bulk liquid subcooling}}{C_2\left(c_{pl}\frac{(T_{sat}-T_l)}{h_{fg}}\sqrt{\frac{\rho_l}{\rho_v}}\right)^2}}\right]^{1/2}$$

$$\text{where}\quad Fr_* = \frac{\rho_v u_v}{\sqrt{\rho_l}\sqrt[4]{\sigma g \sin\theta(\rho_l-\rho_v)}}$$

$$Fr_*^2 = \sin\theta\left[C_8\sqrt{\frac{\rho_l}{\rho_v}} - C_9\frac{\rho_l}{\rho_v}\left(\frac{c_{pl}\Delta T_{sub}}{h_{fg}}\right)\right] = \boxed{f(\theta,\Delta T_{sub})}$$



**Increase subcooling** $\Delta T_{sub}\uparrow$

↓

**TP boundary layer motion decreases** $Fr_*,\ u_v\downarrow$

↓

**Decreased CHF** $CHF\downarrow$

# Summary & Future work

- ***Most of existing CHF models applicable to downward facing heating surface is for***
  - ✓ *IVR-ERVC condition (curved heater surface)*
  - ✓ *Small heater (two phase boundary layer could not be developed)*
  - ✓ *Low thermal inertia of heater*

  → Lack of CHF model for ex-vessel core catcher application (NC and flat surface)

- ***Most of CHF models predict higher CHF value compared to experimental data (present study), probably due to one of following:***
  - ✓ Difference in flow pattern/bubble behavior between the model and observation
  - ✓ Large size difference in heater dimension: formation of two phase boundary layer
  - ✓ Heater shape: Flat or Curved (RPV) → difference in vapor velocity
  - ✓ Surface condition: Clean (present) VS. Fully aged

- ***Significant discrepancy in subcooling effect on the CHF***
  - ✓ Only consideration of Jacob No. : Clear linearity between CHF and subcooling
  - ✓ Additional consideration of interrelation between bubble motion and subcooling : Weak and negative effect of subcooling on CHF
  - ✓ CHF data of own show weak or adverse effects in subcooling ranging 5~15K

1. **Subcooling effect on CHF seems to be nonlinear and complex under certain condition (e.g. ex-vessel core catcher)**
2. **For improvement, interrelationship between subcooling and buoyancy induced flow motion should be modeled**

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# Question & Answer