Experimental Investigation of Condensation with Bundle Geometry for the Passive Containment Cooling System

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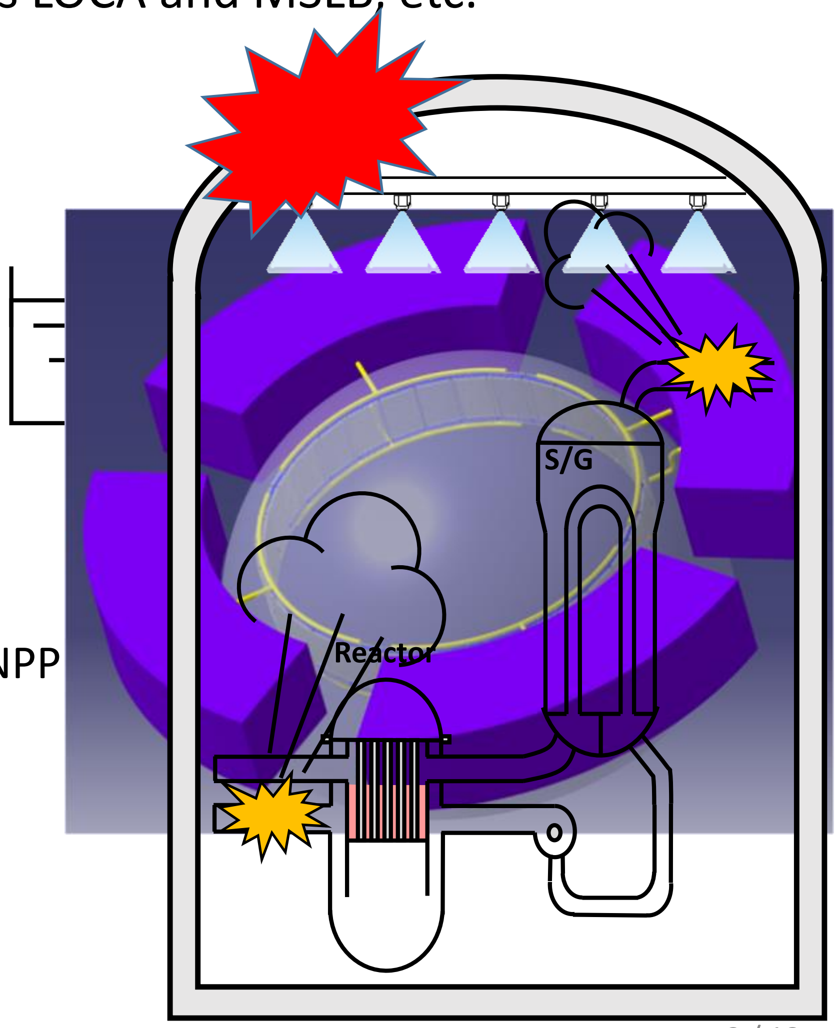
Contents

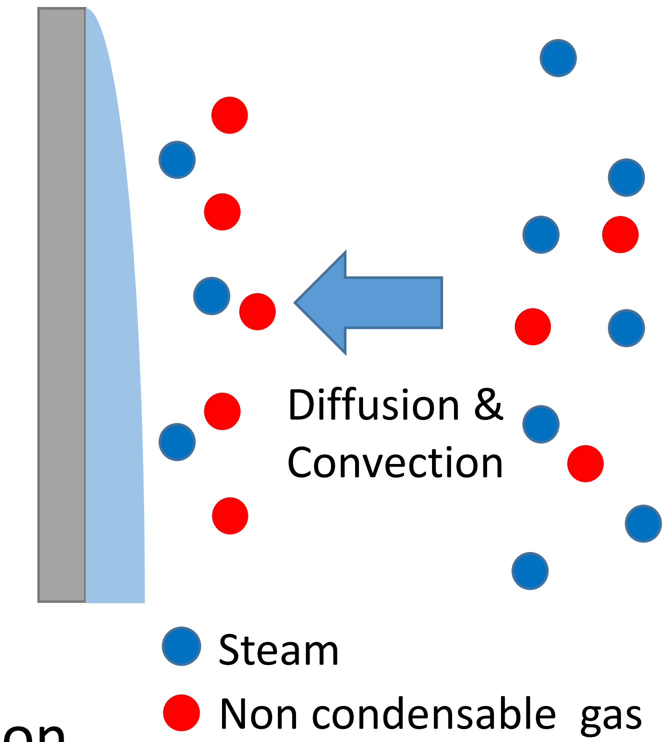
Introduction (1)

- Background
  - In case of postulated accidents such as LOCA and MSLB, etc.
    - High pressure and high energy steam releases to containment building.
    - Containment is threatened by released steam.
  - Passive containment cooling system
    - Replacement of active containment spray system
    - Bundle type condensation heat exchanger
    - Considered in the Korean advanced NPP such as APR+ and IPOWER.
  - Previous investigations
    - Condensation experiments for plate and single tube



Introduction (2)

- Objects of Experiments
  - Condensation phenomena of bundle
  - Effect of parameters
    - Suction of steam
    - Screening of steam by adjacent tubes
    - Geometric effects
      - Inclination
      - Pitch to diameter (p/d)

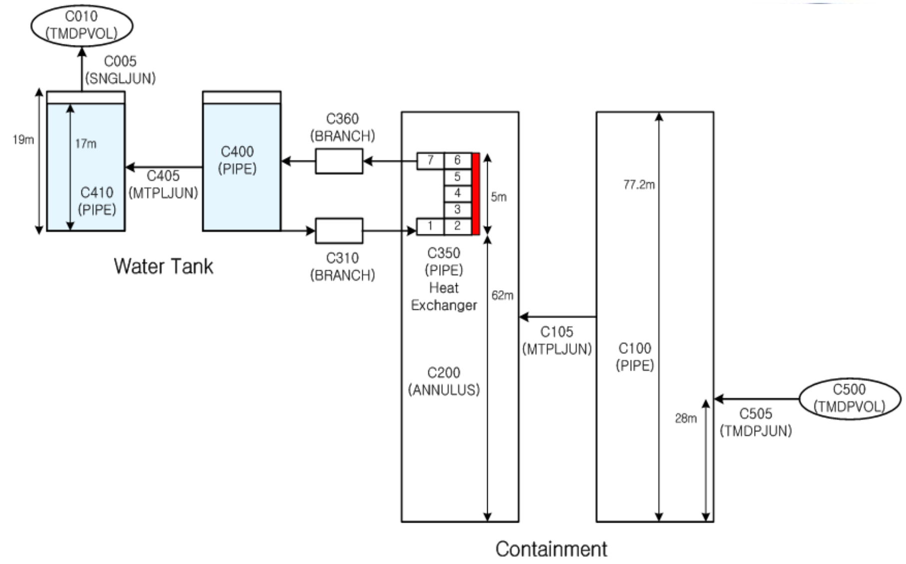


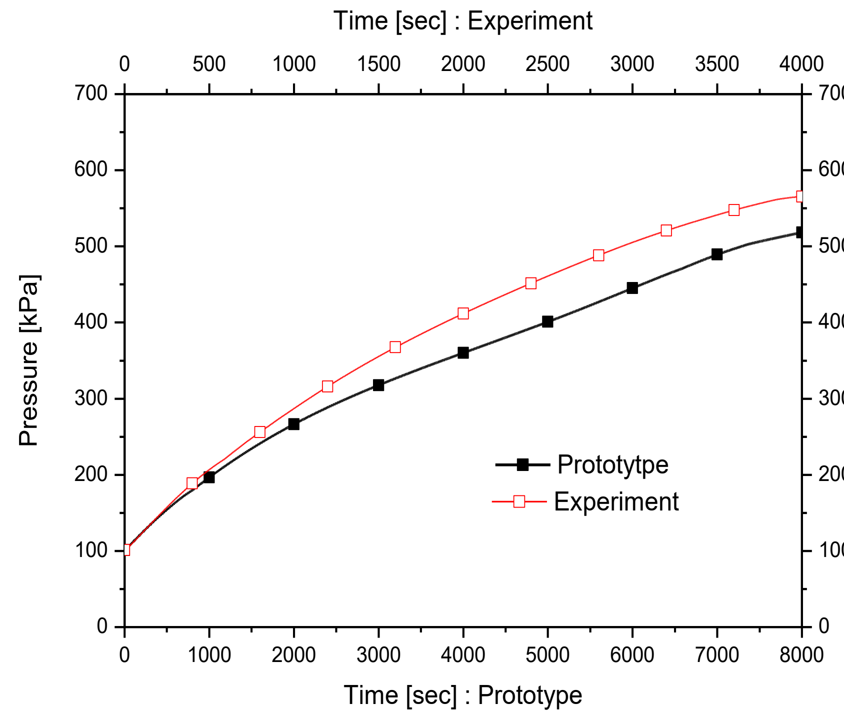
- Development of condensation correlation
  - Correction of deviation between experimental data for bundle and existing correlation for single tube

Experimental Facility (1)

- Scaling analysis

Parameter	Scaling Law	Scaling ratio	Value (Proto/Test)
Tube Diameter(OD/ID)	$l_{oR}^{1/2}$	1/2	(40/34) / (21.5/15.5)
Heat Flux Ratio	1/1	1/1	24.35kw/m^2
Height Ratio	l_{oR}	1/4	5/1.25m
Tube Number Ratio	$a_{oR}l_{oR}^{-1}$	1/8032	3ea
Containment Volume Ratio	$a_{oR}l_{oR}$	1/42837	2.18m^3
Total Heat Removal Ratio	$a_{oR}l_{oR}^{1/2}$	1/21418	122885kW/ 5.737kW





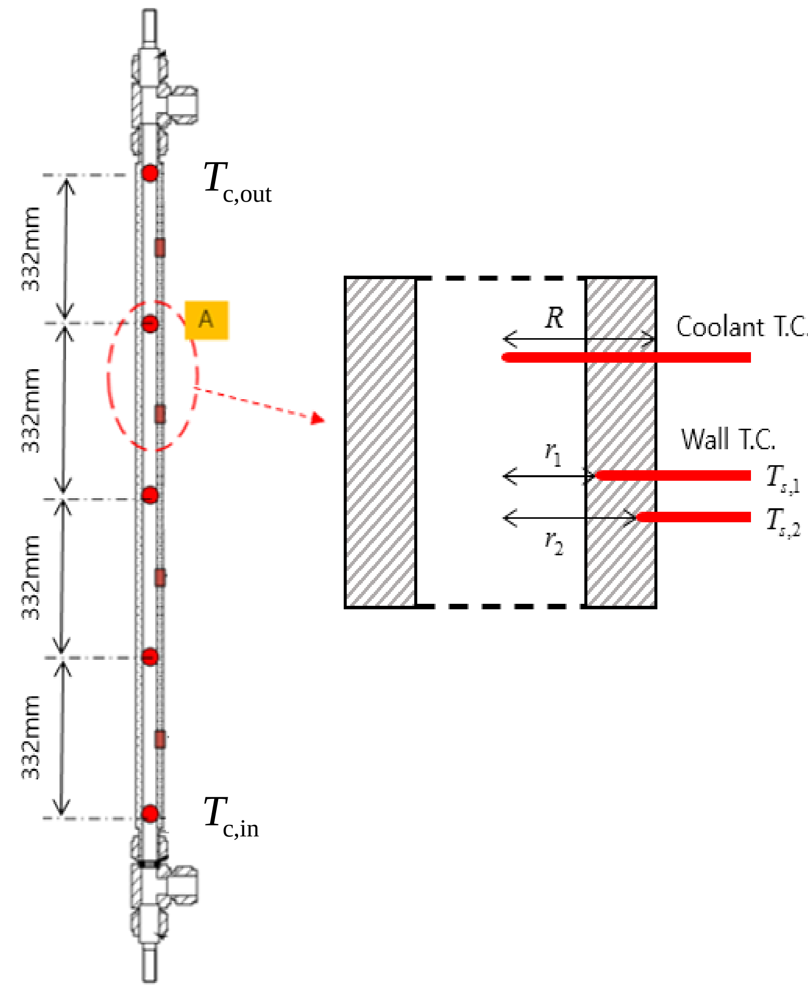
< Analysis results of containment >
pressure with ideal scaling

Experimental Facility (2)

- Experimental Apparatus
  - Components
    - Bundle : 12 tubes
    - Pressurized vessel
    - Coolant supply line
      - Preheater and pump, etc
    - Immersion heater
  - Measurements
    - Coolant flow
      - Coriolis, Magnetic
    - Temperature
      - K-type thermocouple
    - Pressure
      - Transmitter

Experimental Facility (3)

- Measurement methods
  - Wall temperature
    - $T_w = T_{s,2} + \dfrac{\ln(R/r_2)}{\ln(r_2/r_1)}(T_{s,2} - T_{s,1})$
  - Heat transfer coefficient of a tube
    - $h_{tube} = \dfrac{\dot{m} c_p (T_{c,out} - T_{c,\mathrm{in}})}{\pi \,\mathrm{dL} (T_\infty - T_w)}$
  - Average heat transfer coefficient of a bundle
    - $h_{bundle} = \dfrac{h_1 + h_2 + h_3 + \cdots + h_{12}}{12}$
  - Air mass fraction
    - $W = \dfrac{\rho_{air}(P_{air}, T_\infty)}{\rho_{air}(P_{air}, T_\infty) + \rho_{steam}(T_{\infty,sat})}$



Experimental Facility (4)

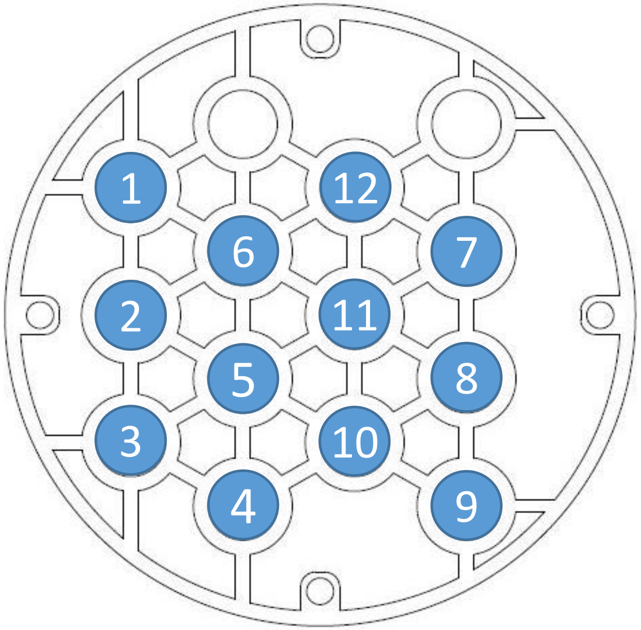
- Uncertainty of measurement system
  - Temperature sensor (TC)
    - Calibrated with 0.5°C uncertainty
    - Signal line from TC to DAS was checked with FLUKE 754 calibrator.
  - Flow meter, pressure measurement system
    - Calibration sheets were provided from manufacturer

Parameter	Thermocouple (K type)	Coriolis flow meter	Magnetic flow meter	Pressure transmitter	Differential pressure transmitter
Range	-200°C ~ 1000°C	2~226.8 kg/min	0~2m^3/h	0~1000kPa	0~60kPa
Error	±0.5°C	0.05%(Reading)	0.50%(Reading)	0.08%(FS)	0.40%(FS)

Experiments and Results (1) : Test Matrix and Conditions

- Test matrix
  - Single tube experiments
  - Tube Bundle experiments
    - 12 tubes condensation tests
  - Obstacle experiments
    - Each single tube condensation test with 11 dummy tubes

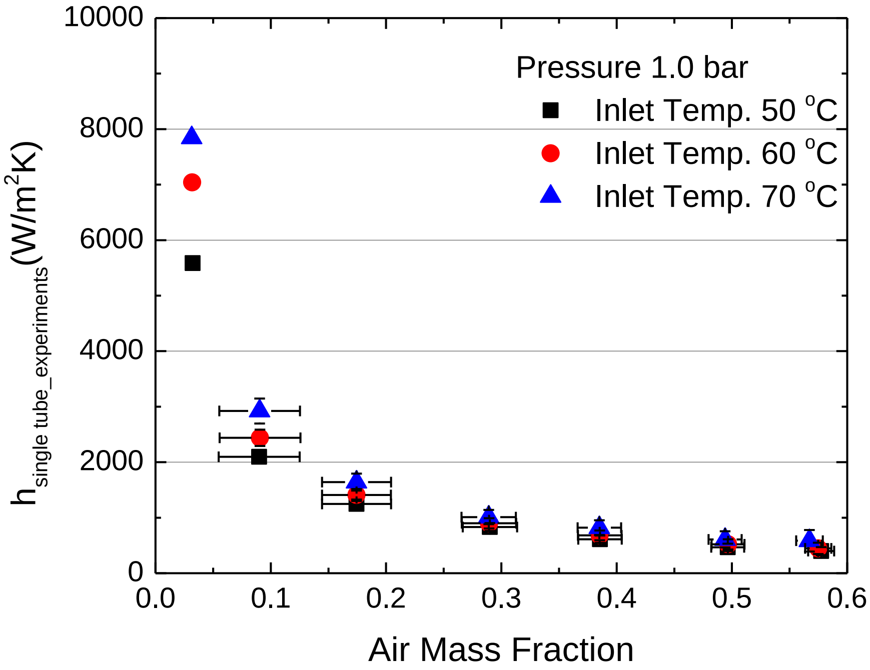
- Bundle Experimental conditions
  - Pitch to diameter of bundle : 2.0, 2.5
  - Vessel pressure
    - 1.5, 2.0, 3.0 and 4.0 bar
  - Inlet temperature of coolant: 70^{o}C
  - Air mass fraction
    - 0.3 ~ 0.8
  - Inclination : Vertical, 14.5^{o}

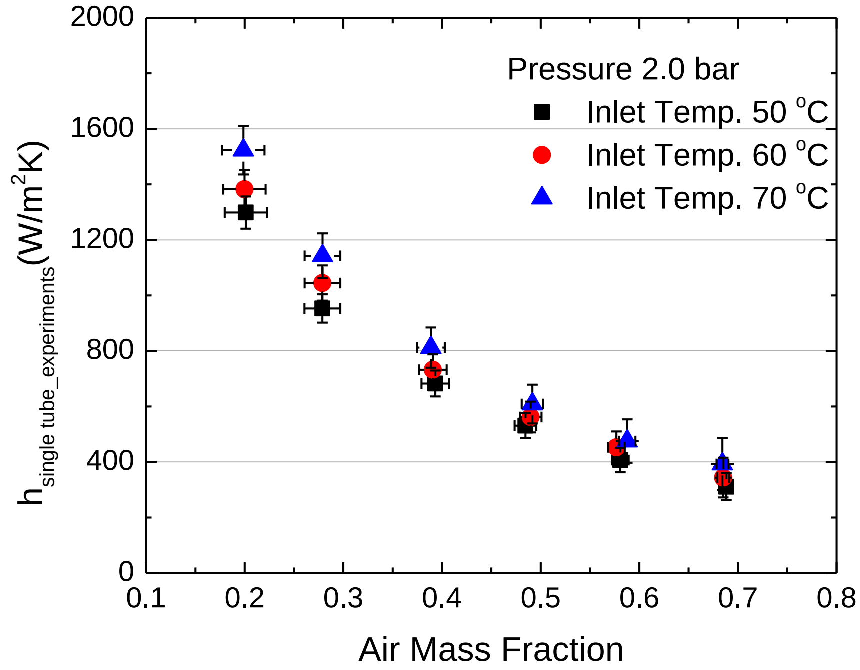


<Single experiments> <Bundle experiments> <Obstacle experiments>

Experiments and Results (2) : Single Tube Experiments

- Heat transfer coefficient according to air mass fraction and inlet temperature
  - Increase of the heat transfer coefficient with decrease in air mass fraction and a increase in inlet temperature.
  - Drastic increase of heat transfer coefficient under air mass fraction 0.1



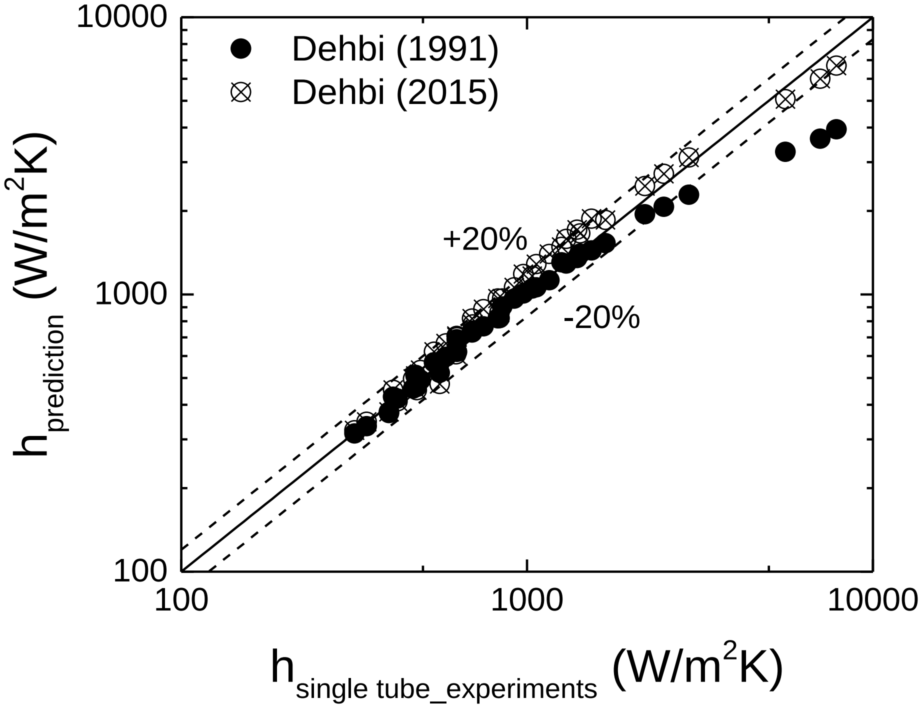


Experiments and Results (3) : Single Tube Experiments

- Single tube experiments
  - Evaluation of Dehbi correlations(1991, 2015) against single tube data

- $h_{Dehbi,1991} = 1.25 \dfrac{L^{0.05}\left[(3.7+28.7P)-(2438+458.3P)\log W_\infty\right]}{(T_\infty - T_w)^{0.25}}$ [1]

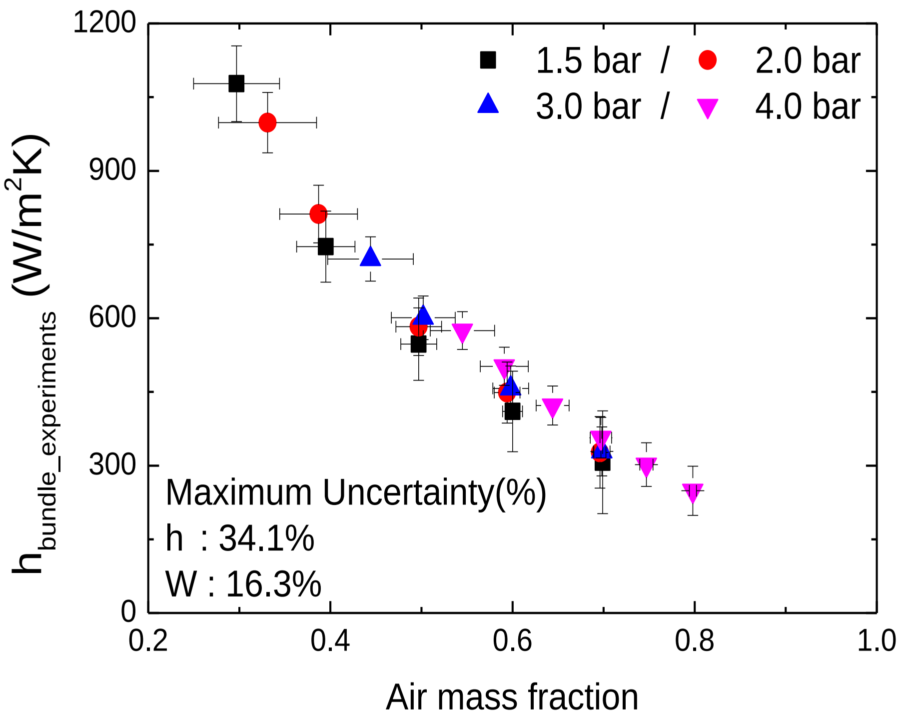
- $h_{Dehbi,2015} = 0.185 D^{2/3}(\rho_w + \rho_\infty)\left(\dfrac{\rho_w - \rho_\infty}{\mu}\right)^{1/3} \dfrac{h_{fg}}{T_\infty - T_w} \ln\left(\dfrac{W_w}{W_\infty}\right)\left(1 + 0.3\left(\sqrt{32}Gr^{-1/4}\dfrac{L}{d}\right)^{0.909}\right)$ [2]



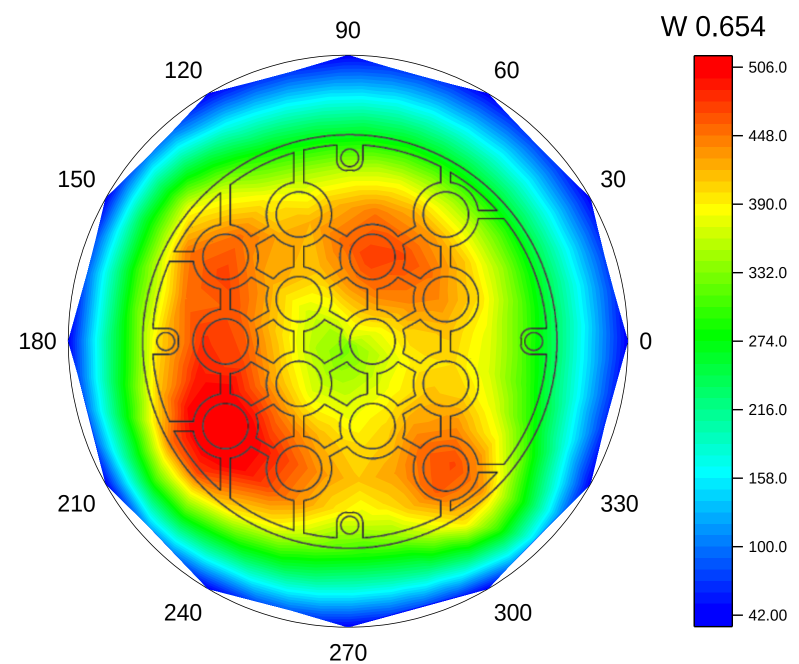
[1] Dehbi, A. "The effect of noncondensable gases on steam condensation under turbulent natural convection conditions," Diss. Massachusetts Institute of Technology, (1991).
[2] Dehbi, A. "A generalized correlation for steam condensation rates in the presence of air under turbulent free convection," International Journal of Heat and Mass Transfer 86, pp. 1-15 (2015).

Experiments and Results (4) : Bundle Experiments

- Bundle experiments
  - Degradation of heat transfer coefficient by screen effect of air mass fraction
  - Enhancement of heat transfer coefficient by
    - Suction effect of steam
    - Containment pressure



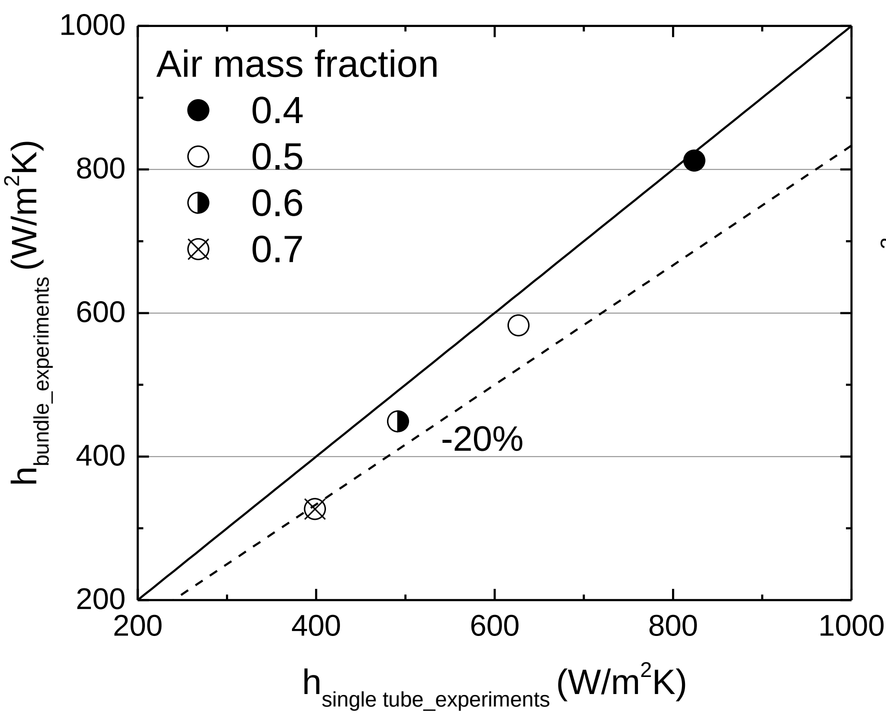
<Variation of condensation heat transfer>
coefficient with air mass fraction



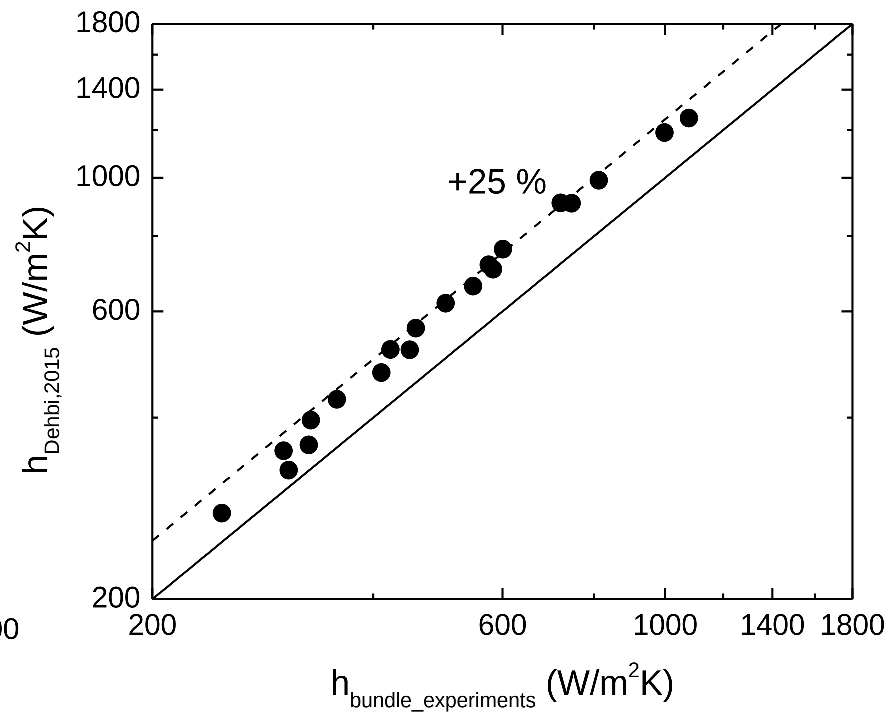
<Distribution of heat transfer coefficient>
on bundle (4 bar, W 0.65)

Experiments and Results (5) : Bundle Experiments

- Bundle experiments
  - Comparison between experiments for single tube and bundle under 2.0 bar
    - The deviation decreases with decrease of air mass fraction
  - Evaluation of the Dehbi (2015) correlation against bundle data



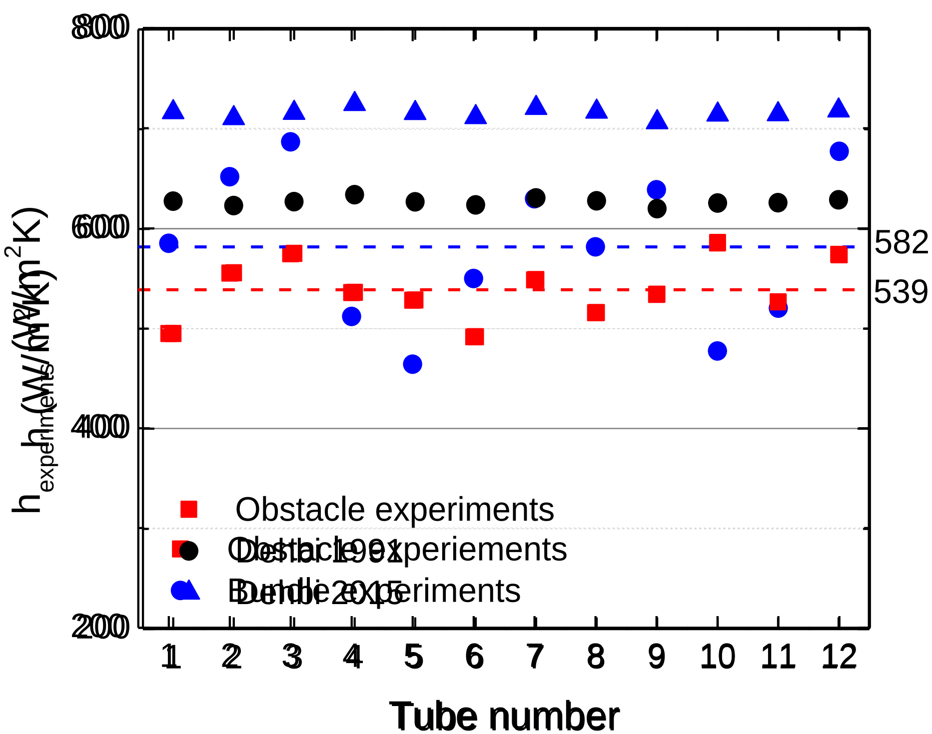
<Comparison between bundle>
and single rod under 2 bar



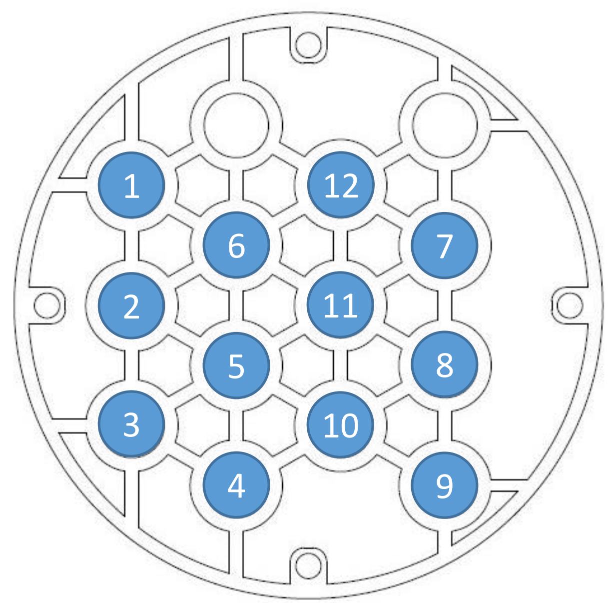
<Comparison between bundle experiments>
and Dehbi correlation

Experiments and Results (6) : Obstacle Experiments

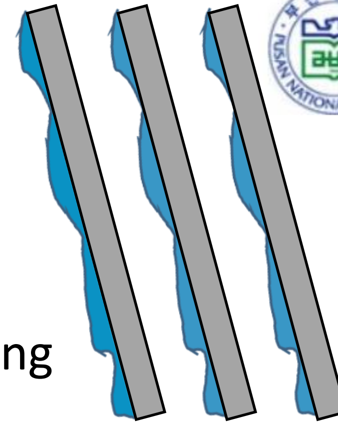
- Comparison data between obstacle tube and bundle
  - Increase of heat transfer of outside tube by suction
  - Decrease of those of inside tube by screening effect
  - Improvement of average heat transfer of a bundle by suction effect of a bundle.



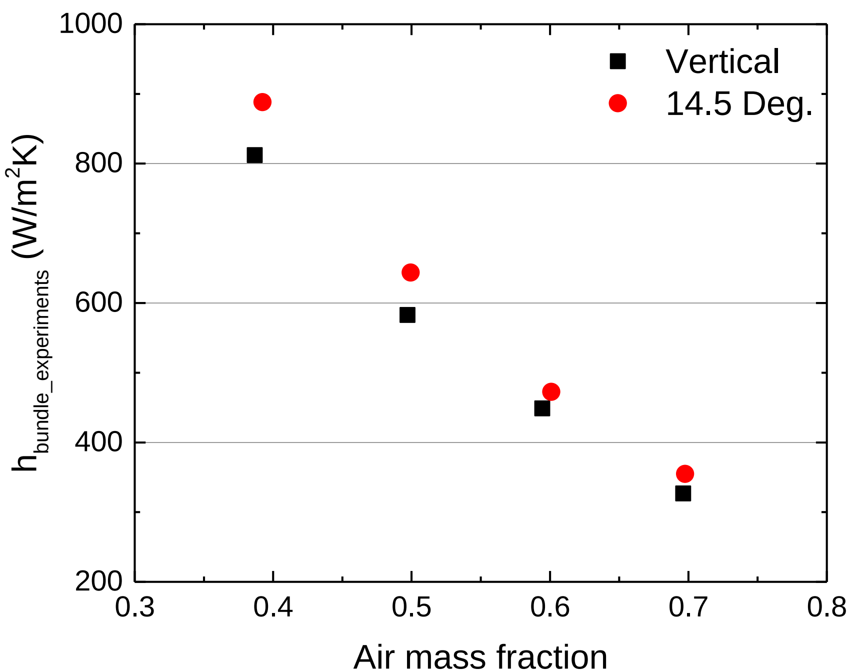
<Pressure 2.5 bar, Air mass fraction 0.52>



Experiments and Results (7) : Bundle Experiments



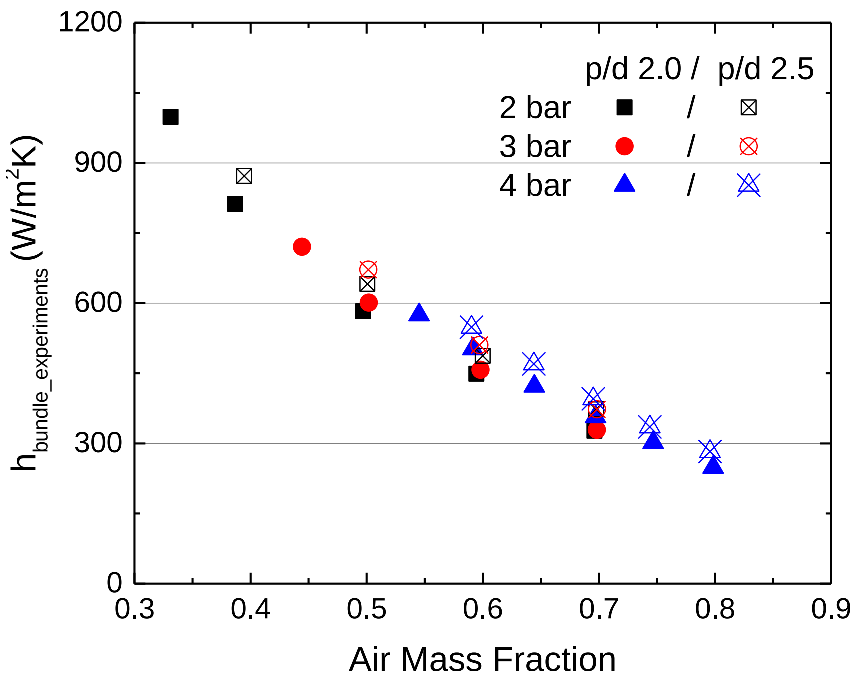
- Inclination effect
  - Inclined bundle 14.5°
  - Increase of heat transfer coefficients owing to water flowing on lower surface of tube



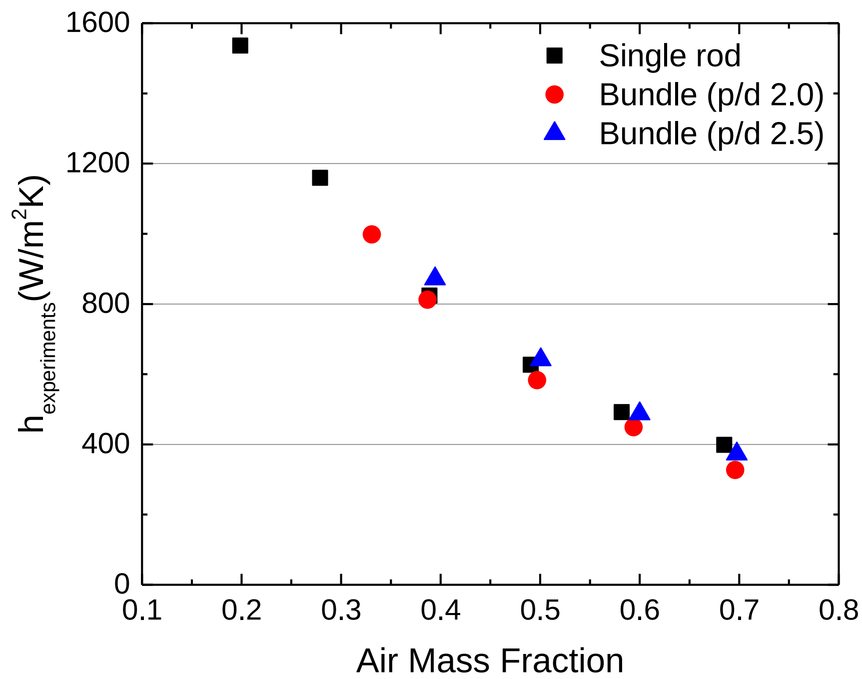
<Variation of condensation heat transfer coefficient >
with air mass fraction and inclination

Experiments and Results (8) : Bundle Experiments

- Pitch to diameter effect
  - Reduction of screening effect on the central region of bundle
  - Increase of heat transfer with increase of pitch to diameter ratio



<Variation of heat transfer coefficient with > air mass fraction and pressure



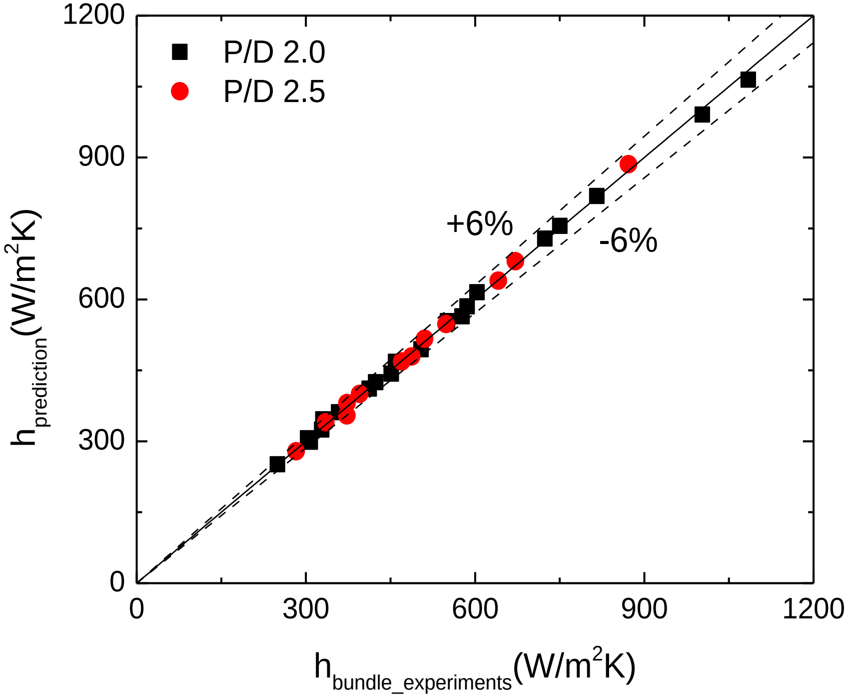
<Variation of heat transfer coefficient with > air mass fraction and heat exchanger type

Development of bundle factor correlation

- Bundle condensation correlation
  - Evaluation of the Dehbi correlation against PNU data

- $f_{bundle} = \dfrac{h_{bundle}}{h_{single-tube}} = \left(1.316\left(\dfrac{P}{P_{cr}}\right)^{0.07}\left(\dfrac{T_{\infty}-T_{w}}{T_{cr}}\right)^{-0.0145} - 11\dfrac{P}{P_{cr}}\right) \times \left(1.08W^{2} - 0.945W + 1.12\right)\left(0.187\dfrac{p}{d} + 0.65\right)$

- $h_{bundle} = h_{Dehbi,2015} \times f_{bundle}$



<Comparison between bundle experiments and >
proposed bundle condensation correlation

Summary & future Plans

- Condensation test with bundle heat exchanger has been performed for the passive containment cooling system (PCCS).
- Major findings from experiments
  - Decrease of heat transfer coefficient is expected because of screening effect of adjacent tubes (structure) in the tube bundle.
  - However, the heat transfer coefficient is not decreased because suction effect compensates screening effect.
  - The heat transfer coefficient increases as inclination and pitch to diameter increase.
- Bundle factor for correction of Dehbi (2015) correlation was proposed.
- Experimental investigation will be continued for the developments of condensation model in the single and tube bundle conditions.

Q & A

Thank you for your attention