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Modification of the Condensation Heat Transfer Model of the MELCOR code under the Thermal-Hydraulic Conditions of a PWR Containment

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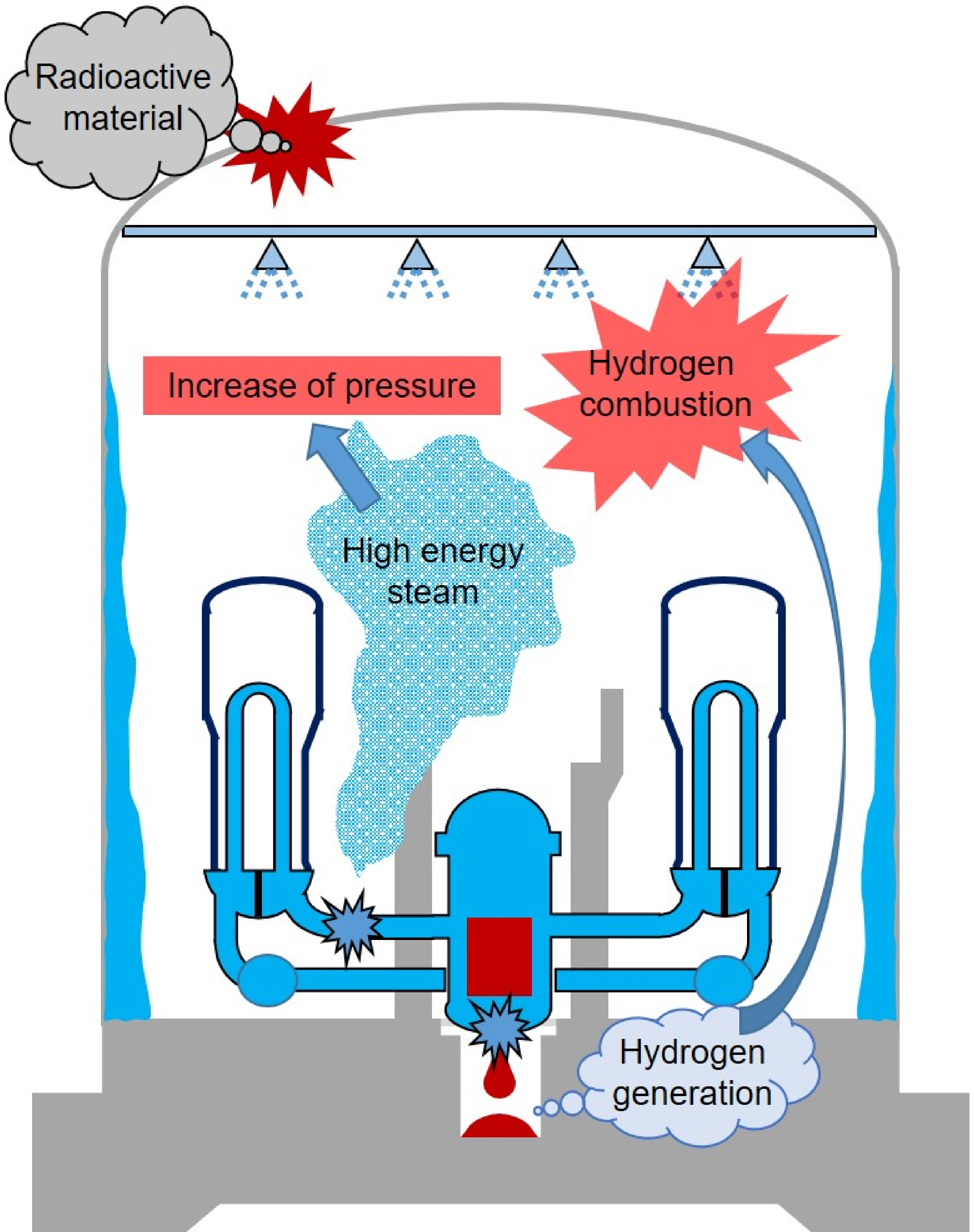
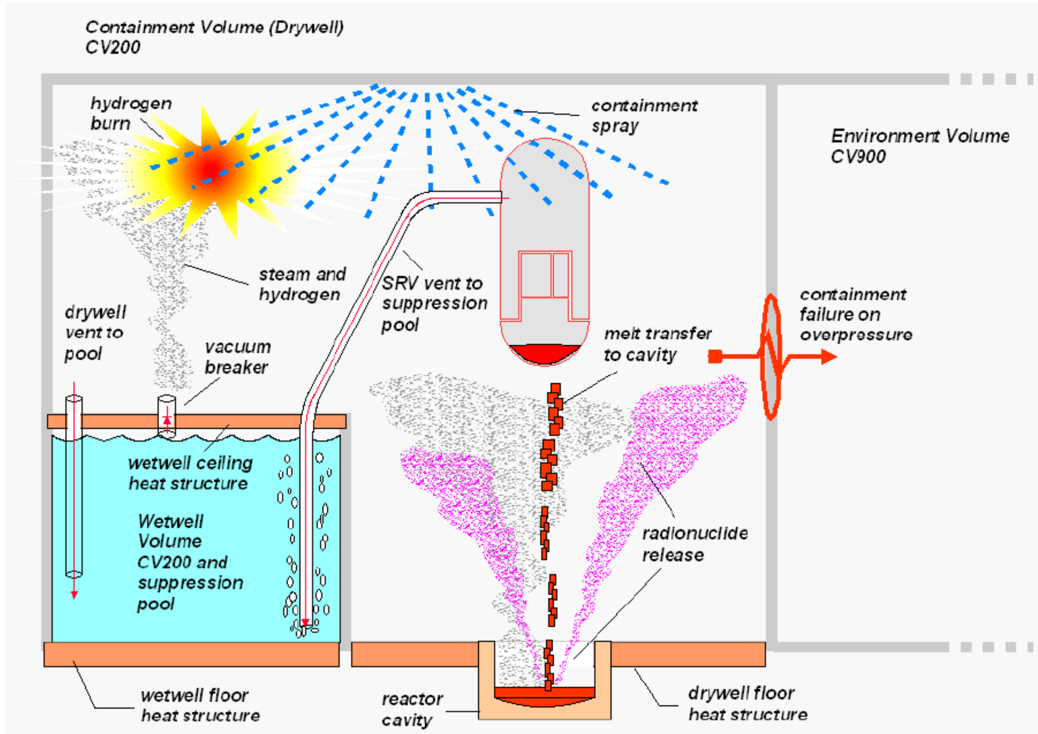


- Containment
  - The last barrier of defense-in-depth
    - Maintenance of the integrity of the containment
  - Threats to the containment
    - Increase of pressure
    - Hydrogen combustion

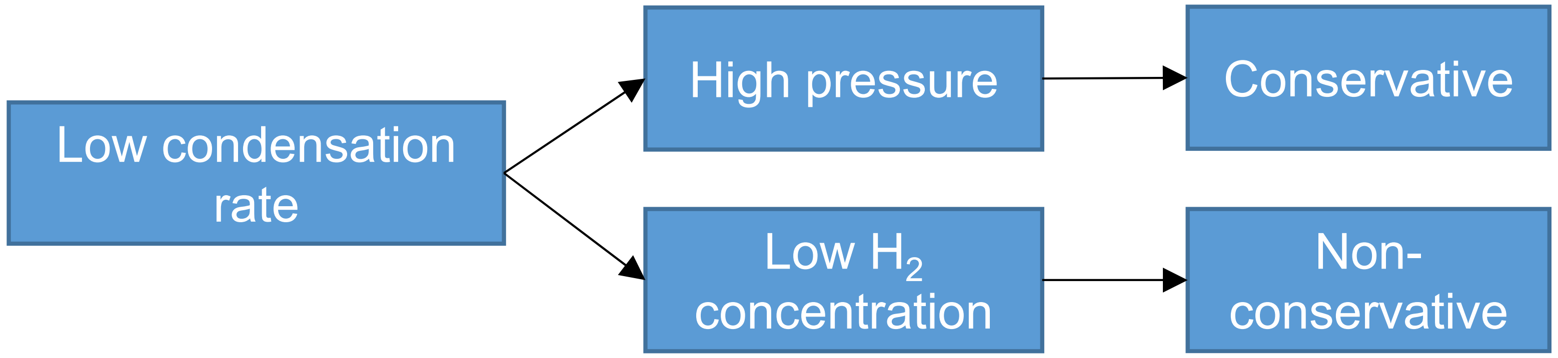
- Importance of the condensation
  - Condensation heat transfer on the containment wall and PCCS
    - Contribution to decompression of containment
  - Relationship between condensation rate and hydrogen concentration
    - Condensation rate ↑, hydrogen ratio ↑
    - Condensation rate ↓, hydrogen ratio ↓

Introduction (2)

- **MELCOR code**
  - Fully integrated, engineering-level computer code.
  - Primary purpose: severe accident analysis of a LWR.
  - Analysis of the whole process of the accident:
    - Thermal-hydraulic behavior, core damage process, behavior of a fission product, hydrogen generation, combustion…
  - Conservative condensation model for pressure (= under-prediction of the condensation rate)

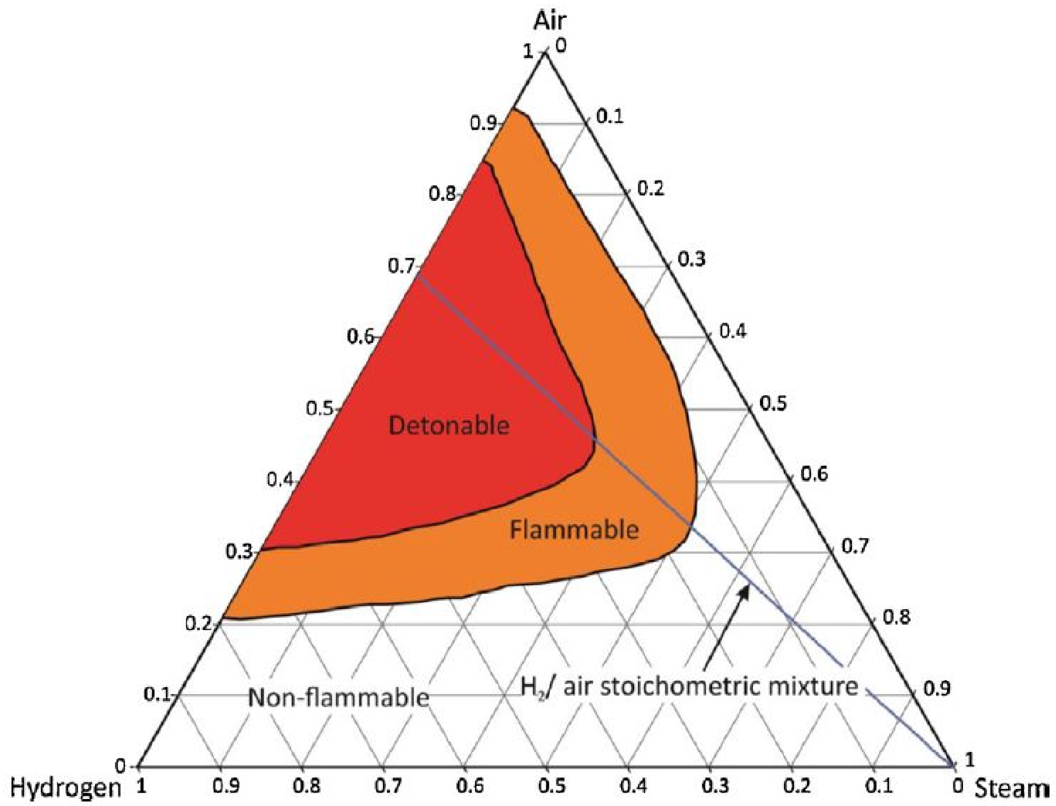


- **Problem of the conservative model**



→ Conflict between pressure calculation and hydrogen distribution calculation.

→ So, the accurate condensation model is required.



M.K. Yadav et al. (2016)

I. Introduction

II. Description of the models and experiments

- Condensation models
- Selected experiments for model assessment

III. Assessment and improvement

- Assessment results
- Improvements of the MELCOR model
- Validation of the improved model

IV. Summary & conclusion

Condensation models

Model	Types	Correlation	Features
MELCOR	Theoretical	$h_f(T_i - T_w) = h_{fg} h_m \rho_v \ln\left(\frac{P_t - P_{s,i}}{P_t - P_{s,b}}\right) + h_{conv}(T_b - T_i)$ $h_m = Sh\frac{D}{L_c},\quad Sh = NuSc^{0.33}Pr^{-0.33}$	- Stagnant film, diffusion only - Molar based Fick's law & HMTA* - h_f: film tracking model - Wide application range**
Liao (2007)	Theoretical	$h_f(T_i - T_w) = h_{cond}(T_b^{sat} - T_i) + h_{conv}(T_b - T_i)$ $h_{cond} = Sh\frac{k_c}{L_c},\quad k_c$=condensation thermal conductivity	- Mass based Fick's law & HMTA - h_f: Nusselt film theory - Suction and fog formation effect - Wide application range
Dehbi (2015)	Semi-theoretical	$q" = h(T_b - T_w)$ $h = 0.185D^{2/3}(\rho_w + \rho_b)\left(\frac{\rho_w - \rho_b}{\mu}\right)^{1/3}\frac{h_{fg}}{(T_b - T_w)}\ln\left(\frac{1 - W_{s,w}}{1 - W_{s,b}}\right)$	- Neglect of the convection and film - Mass based Fick's law & HMTA - Data fitting (six experiments) - Natural convection only - No local parameter
Uchida (1965)	Empirical	$q" = h(T_b - T_w)$ $h = 380\left(\frac{W_s}{1 - W_s}\right)^{0.7}$	- Simple form - Partial pressure of NC gas: 1atm - Natural convection only - Conservative result for pressure - No local parameter

*HMTA: Heat and Mass Transfer Analogy.

**Sherwood number correlation is decided by the flow regime.

Selected experiments for model assessment

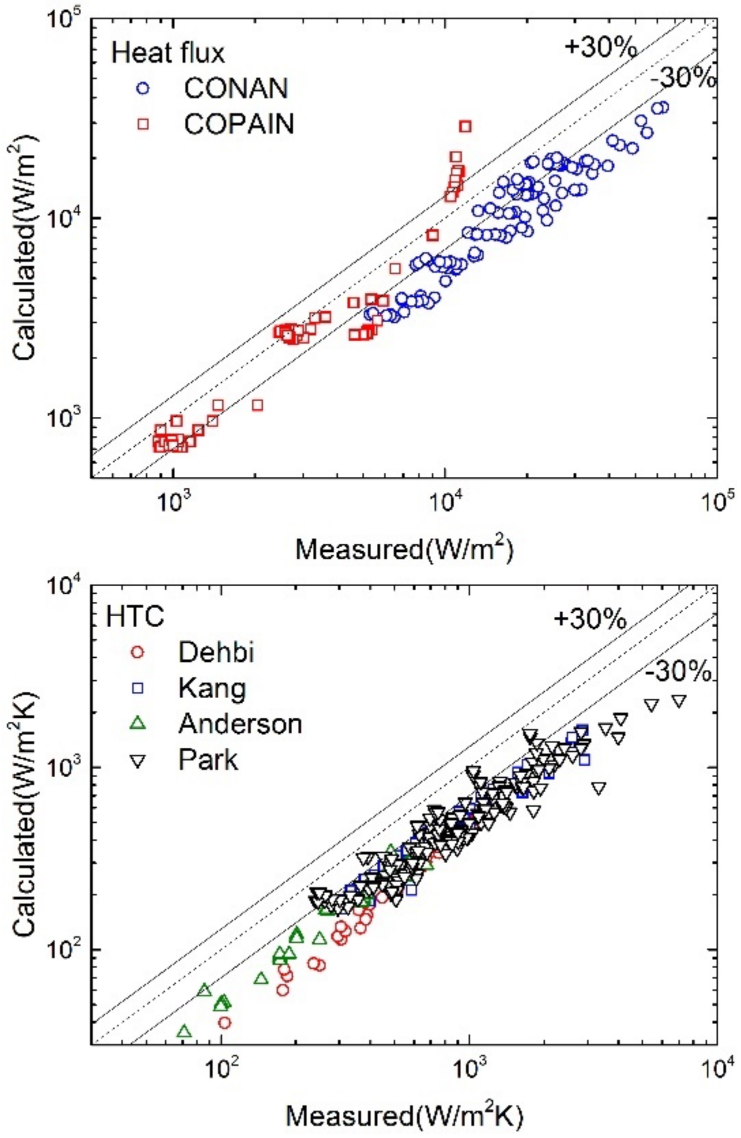
- Selection criteria
  - Thermal-hydraulic conditions similar to those inside the containment during accidents
    - Pressure: 1.0-5.0 bar, air mass fraction: 0.1-0.9, superheated-saturated steam, natural-forced convection
  - External surface condensation on a containment wall and PCCS
    - Vertical plate: COPAIN, CONAN, Park, Anderson
    - Vertical pipe: Dehbi, Kang

Experiment (geometry)	Air mass fraction	Pressure [bar]	Steam condition [K]	Wall subcooling [K]	Flow condition	Number of data sets (points)
COPAIN (plate)	0.49-0.87	1.0-4.0	7-10	14-45	Natural-Forced	6 (68)
CONAN (plate)	0.13-0.72	1.0		40-45	Mixed	10 (80)
Park (plate)	0.20-0.70	1.0		20-50	Natural-Forced	16 (160)
Anderson (plate)	0.40-0.86	1.0-3.0	Saturated steam	10-60	Natural	32 (32)
Dehbi (pipe)	0.25-0.89	1.5-4.5		10-50	Natural	42 (42)
Kang (pipe)	0.1-0.7	1.0-4.0		10-50	Natural	52 (52)

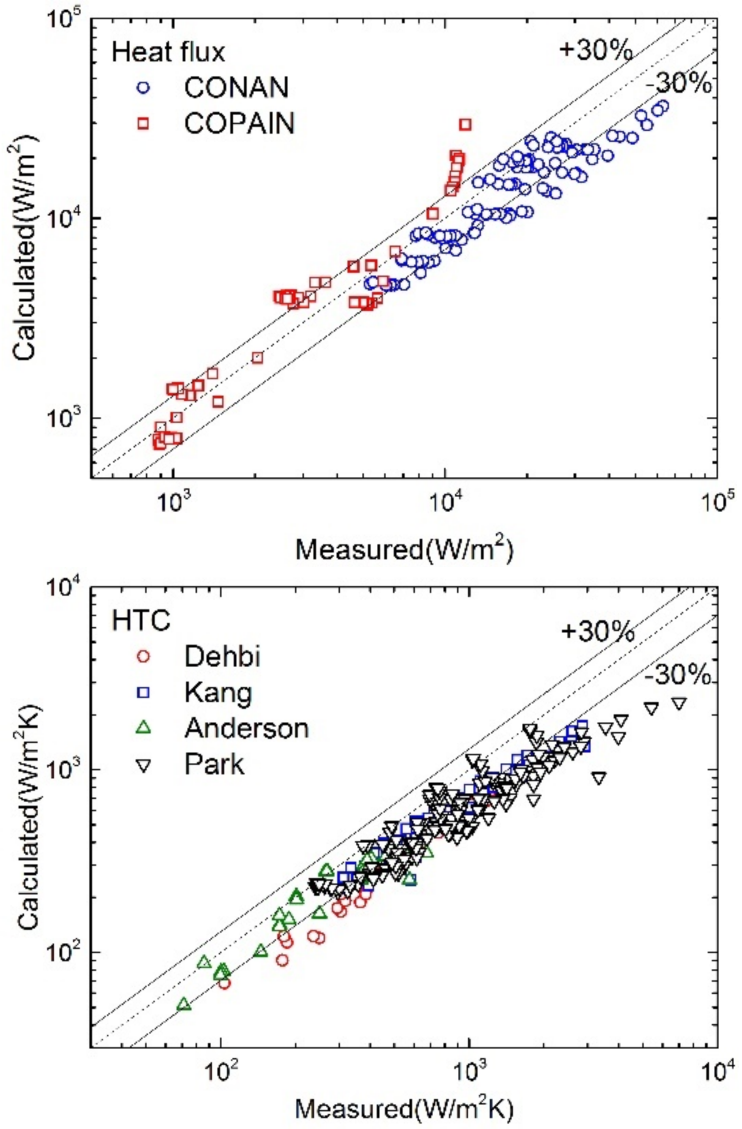
Assessment results (1)

- Calculation vs experiment

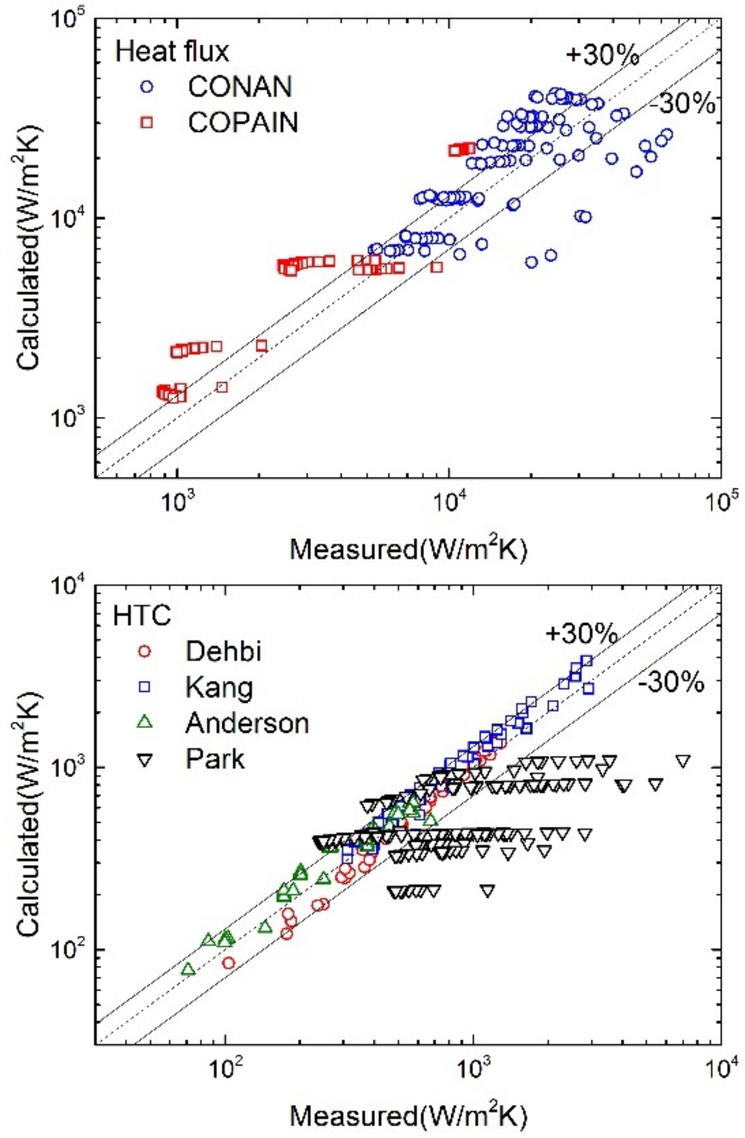
MELCOR model



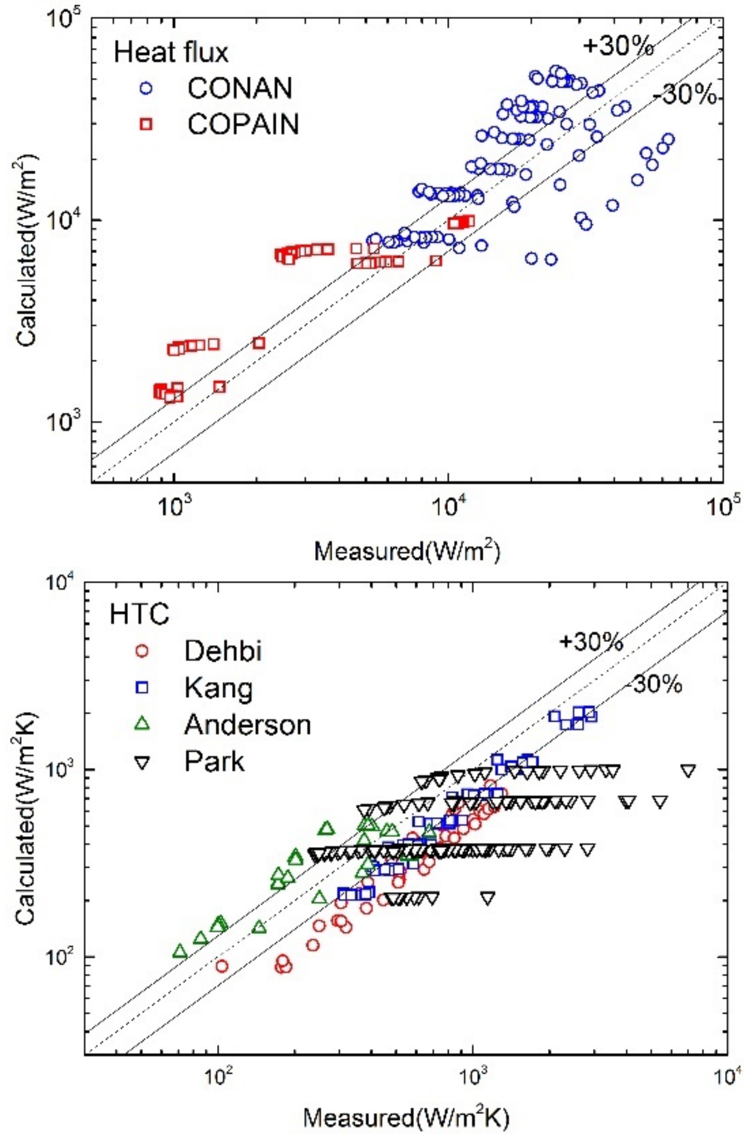
Liao model



Dehbi model



Uchida model



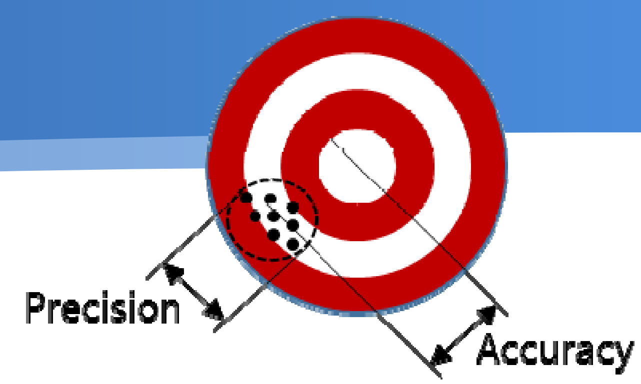
Assessment results (2)

- Quantitative analysis
  - Accuracy
    - Mean relative error (MRE)

$$MRE = \frac{\sum_{i}^{n} \left| \frac{C_i - M_i}{M_i} \right|}{n}$$

    - Standard deviation (SD)

$$SD = \sqrt{\frac{\sum_{i}^{n} \left(\frac{C_i - M_i}{M_i} \right)^2}{n-1}}$$



  - Precision
    - To find a linear fitting line, $C_i = aM_i + b$ using a least-square approach

$$f(a, b) = \sum (aM_i + b - C_i)^2$$

    - Deviation from the fitted line (DFL)

$$DFL = \frac{1}{n} \sqrt{\sum_{i}^{n} (aM_i + b - C_i)^2}$$

Selected!

Model		Mean relative error (%)	Standard deviation (%)	Linear fitting: Slope, a	Linear fitting: Intercept, b	Deviation from the fitted line
MELCOR	Heat flux	34.7	39.2	0.54	1615.8	265.7
	HTC	46.6	47.9	0.43	80.2	7.61
Liao	Heat flux	28.9	35.3	0.62	2957.8	319.9
	HTC	31.0	33.9	0.47	163.1	10.12
Dehbi	Heat flux	51.4	63.3	0.69	6510.3	681.4
	HTC	32.4	39.6	0.33	350.2	25.46
Uchida	Heat flux	56.2	71.7	0.76	6139.0	877.1
	HTC	43.3	47.2	0.23	285.17	14.40

*C_i : calculated value M_i : measured value

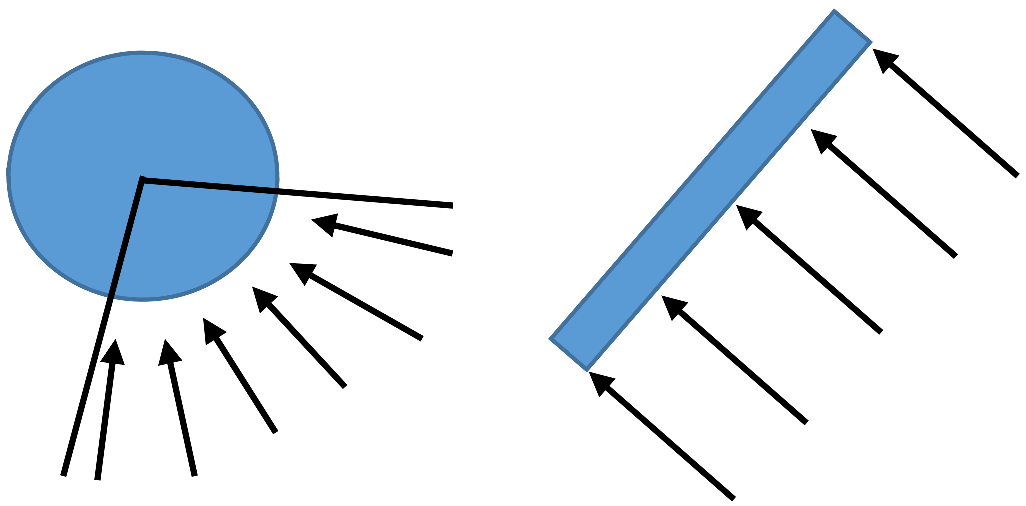
Improvements of the MELCOR model (1)

■ Curvature effect

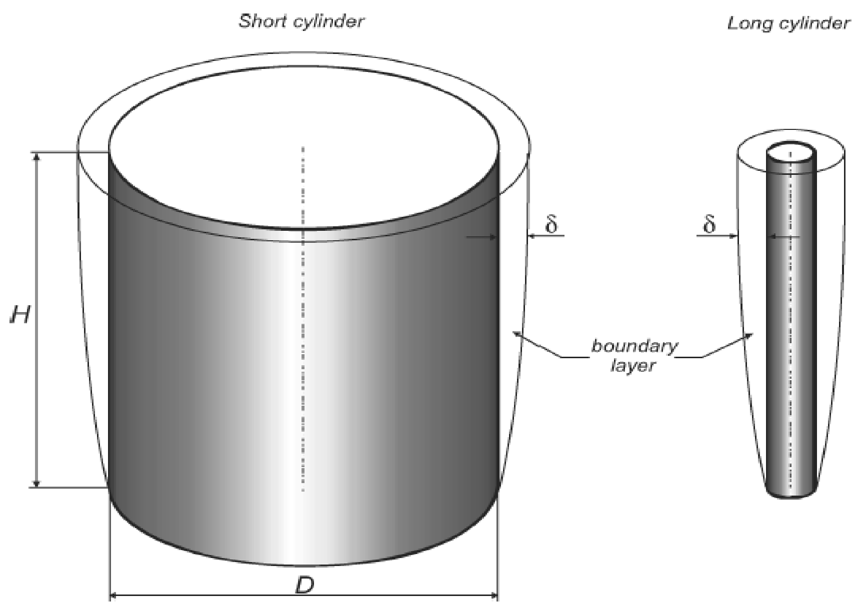
- Comparison of the MRE between vertical pipe and vertical plate.

	Pipe	Plate
MRE	50 %	35 %

➡ The presence of effects depending on the shape.



- Pipe has a large solid angle (=curvature effect)
- Increase of the heat and mass transfer
- The larger L/D, the greater the curvature effect
- Dehbi: L/D = 92, Kang: L/D = 62



→ Application of the factor suggested by Popiel (2008) under natural convection condition

$$Nu_{tube} = Nu_{plate} \times \left(1 + 0.3\left(\sqrt{32}Gr^{-1/4}\frac{L}{D}\right)\right)^{0.909}$$

✓ MRE of the pipe: 50 % → 40 %

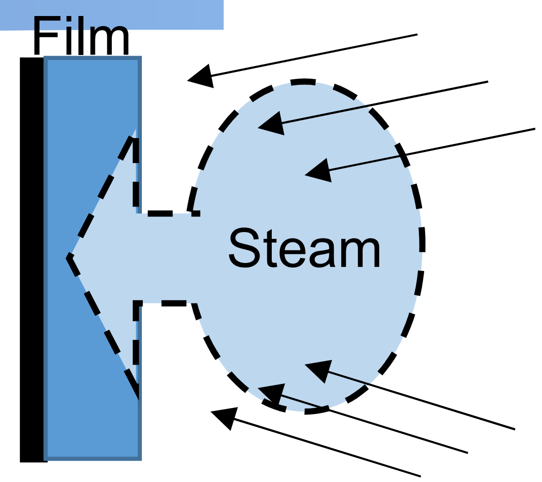
Improvements of the MELCOR model (2)

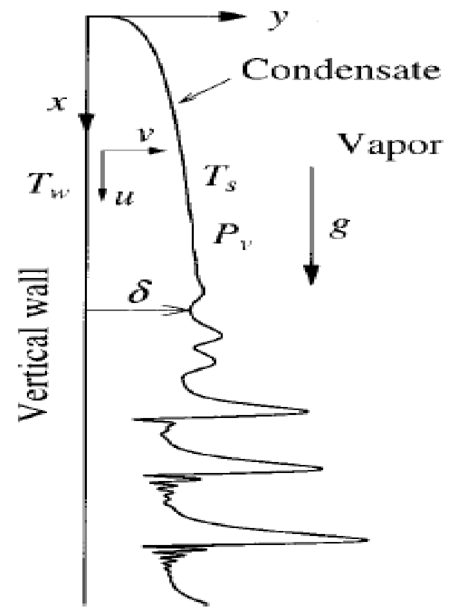
- **Multiplier**
  - Under-prediction of MELCOR model
  - → Adoption of the multiplier obtained through the data fitting

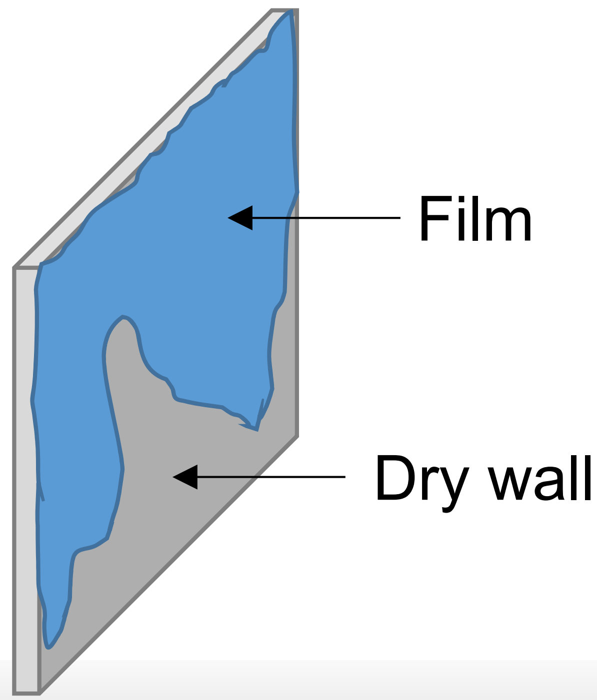
$$Nu_{new} = \boxed{1.71} Nu_{original}$$

Estimated physical meaning of the multiplier

- Suction
  - ✓ Phase change (Steam → Water): large volume change
  - ✓ This leads to the mixture gas being drawn near the film
  - ✓ Enhancement of the heat and mass transfer
- Film waviness
  - ✓ Increase of the interfacial area
  - ✓ Thinning of the film thickness
  - ✓ Enhancement of the heat and mass transfer
- Change of the film coverage rate
  - ✓ Formation of the dry wall due to the interface friction and NCGs
  - ✓ Drop-wise condensation
  - ✓ Increase of condensation rate







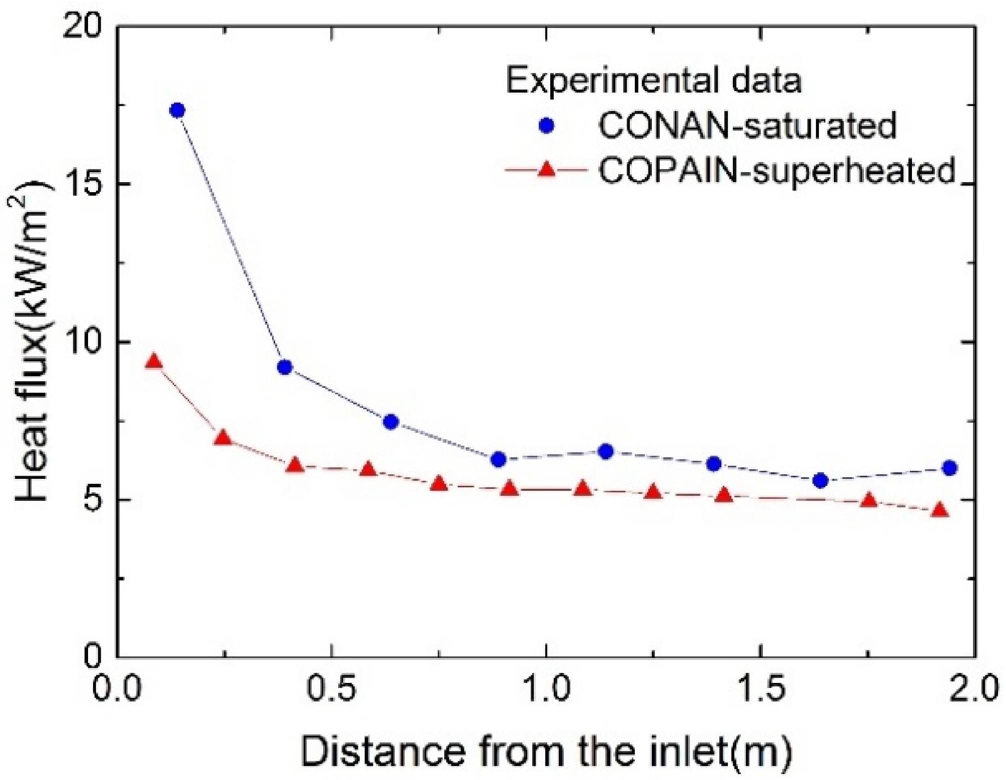
Improvements of the MELCOR model (3)

■ Superheated steam effect

- The absence of model for condensation of the superheated steam in MELCOR
  - ➢ Degradation of the condensation rate by superheated steam which needs to energy and time to cool down with saturated steam

<Example of the superheated steam effect>

Test	P [bar]	Air mass fraction	V_{in} [m/s]	T_{in} [°C]	ΔT_{sup}	T_{wall} [K]	Flow regime
COPAIN P0441	1.0	0.77	3.0	80.0	8.4	307.4	Mixed Laminar
CONAN P10-T30-V25	1.0	0.72	2.6	75.6	0.0	309.5	Mixed Laminar



→ Adoption of the degradation factor

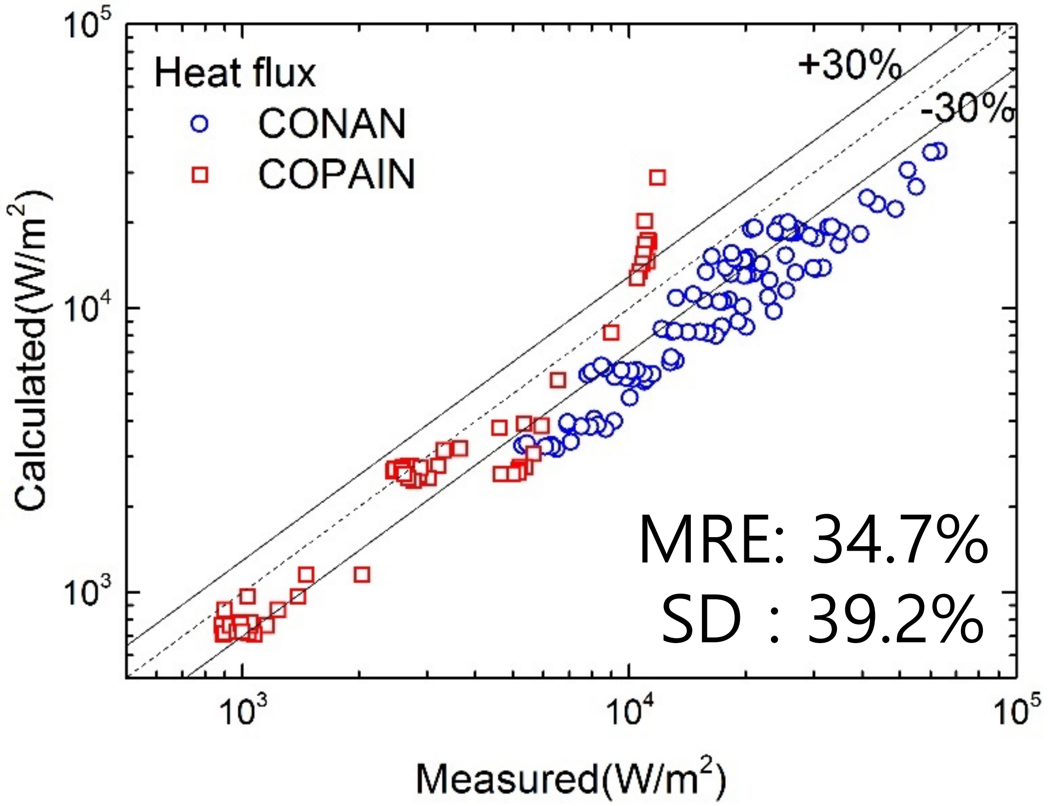
(application range: ΔT_{sup}= ~10K)

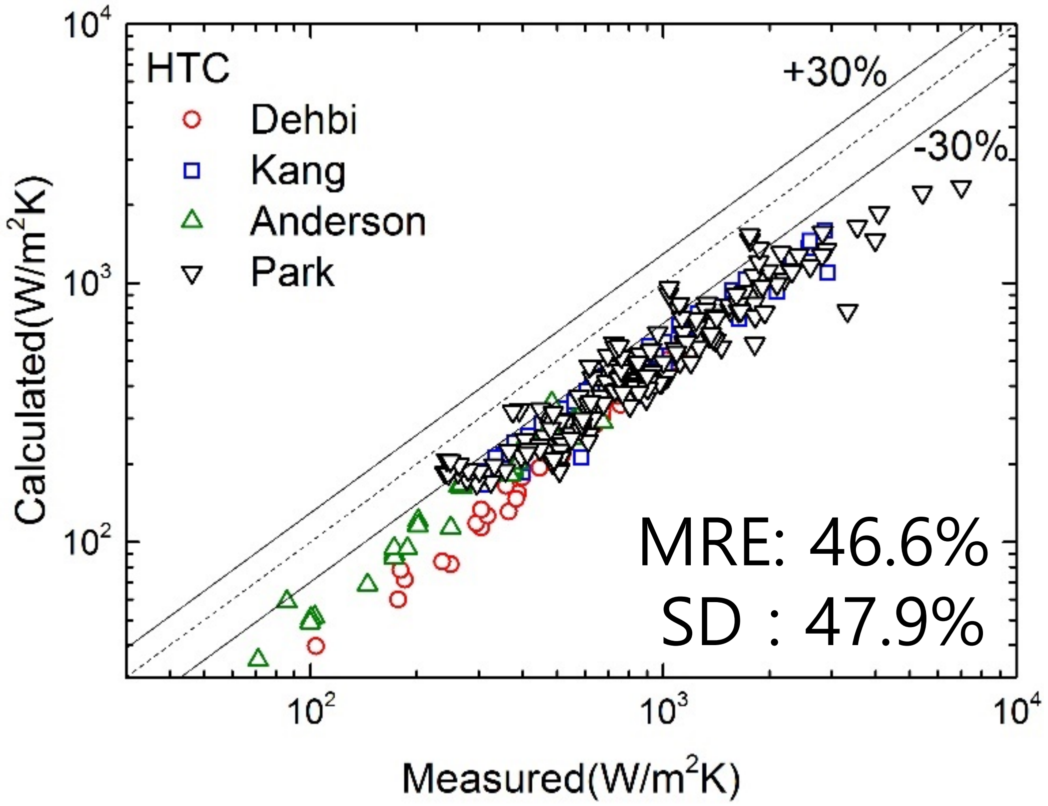
$$h_f(T_i - T_w) = h_{fg} h_m \rho_v \ln\left(\frac{P_t - P_{s,i}}{P_t - P_{s,b}}\right) + h_{conv}(T_b - T_i)$$

$$h_m = Sh\frac{D}{L_c} \longleftarrow Sh_{new} = f(\Delta T_{sup}) Sh_{original}, \quad f(\Delta T_{sup}) = \frac{1}{1 + 0.0032\Delta T_{sup}^{2.4214}}$$

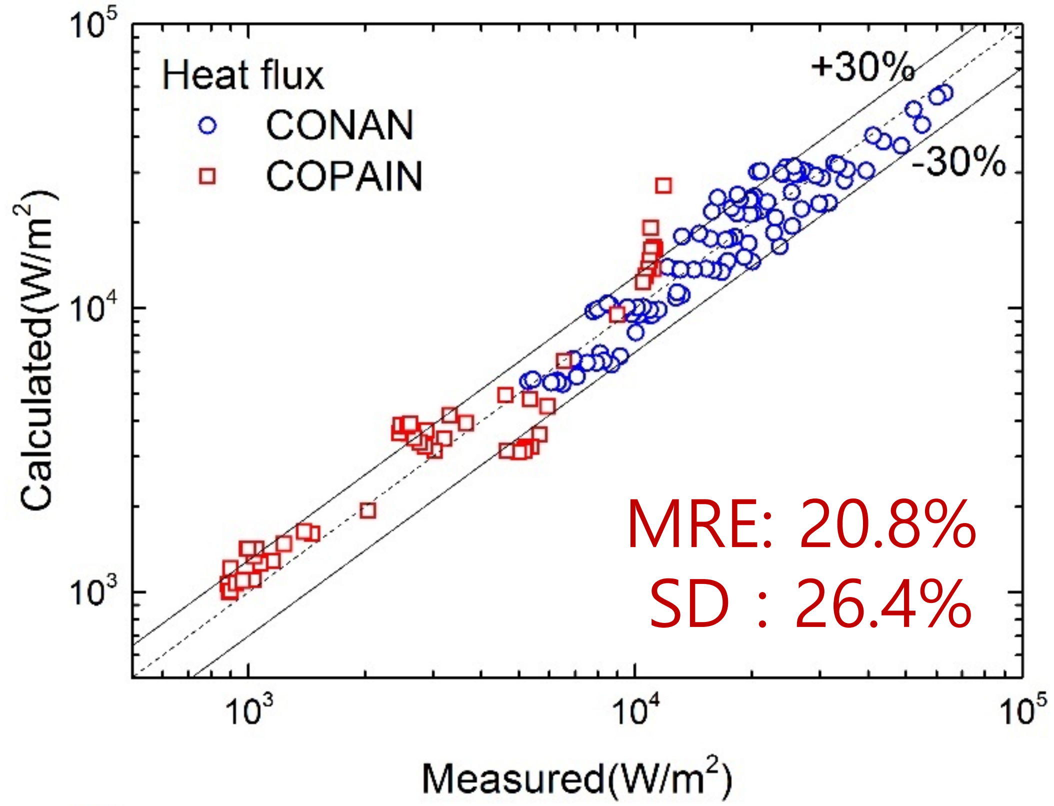
Validation of the improved model

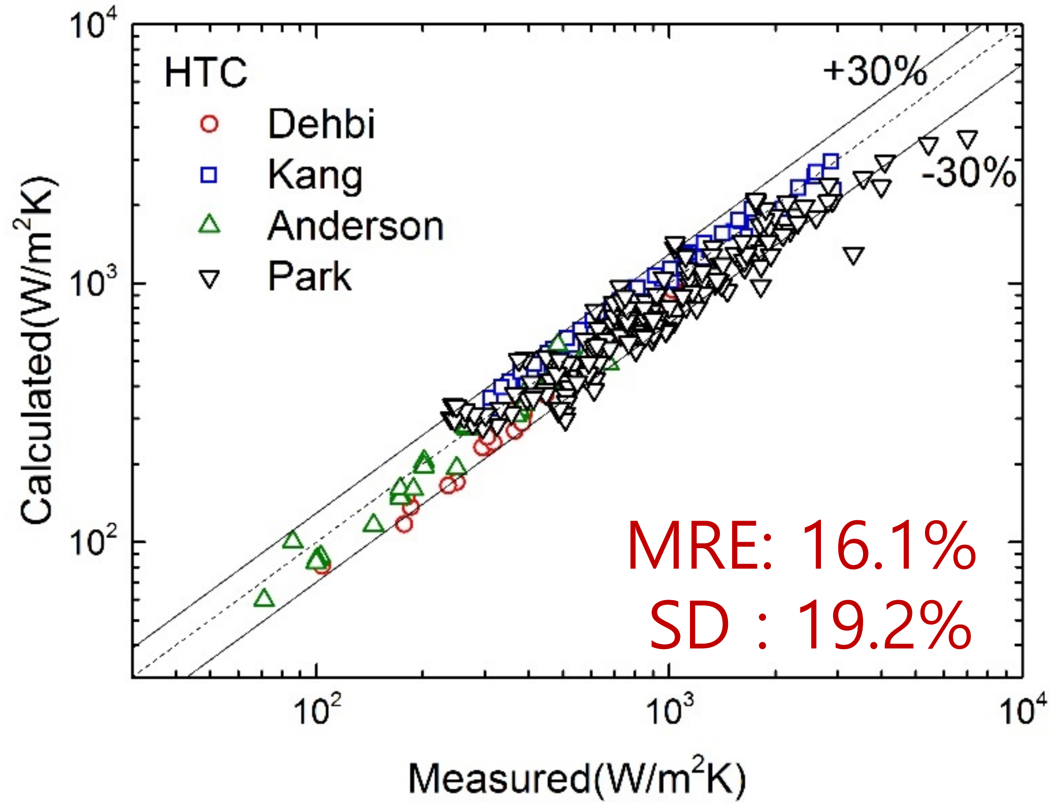
MELCOR model





Improved model





Summary & conclusion

- The assessment of the condensation heat transfer models
  - ➢ Models: MELCOR, Liao, Dehbi and Uchida.
  - ➢ Assessment results
    - ✓ MELCOR model consistently under-predicted most of experimental data about 40%.
    - ✓ The accuracy and precision of the Uchida and Dehbi model were not good.
    - ✓ The accuracy of the Liao model was relatively good, but the precision was worse than the MELCOR model.

  → The MELCOR model was chosen as the base model for improvement.

- Improved MELCOR model shows good agreements with most of experimental data (mean relative error 18 %).
  - ➢ Improvements: curvature effect, multiplier and superheated steam effect

- The improved MELCOR model can be applied to in-containment thermal-hydraulics for safety analysis, PCCS design, and accident management.

Q & A