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Introduction to Thermal- Hydraulics

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Introduction to Thermal-Hydraulics

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Objectives

Objectives of this presentation are to:

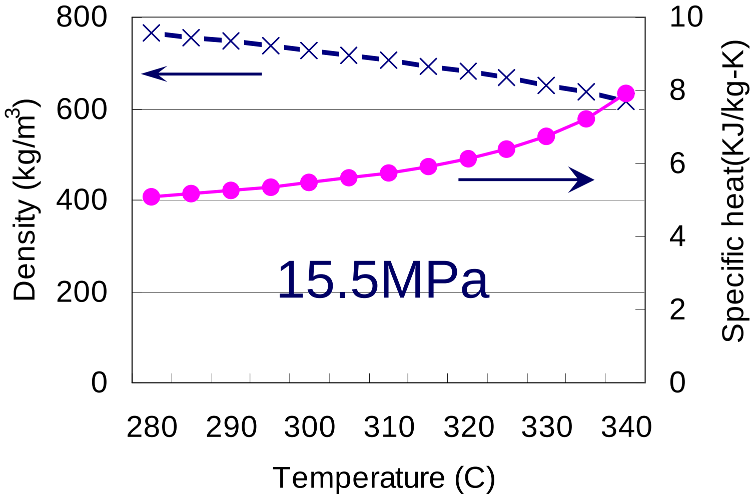
- Compare with existing LWR
- TH challenges deriving from SCWR
- Code development (Sub channel, system)

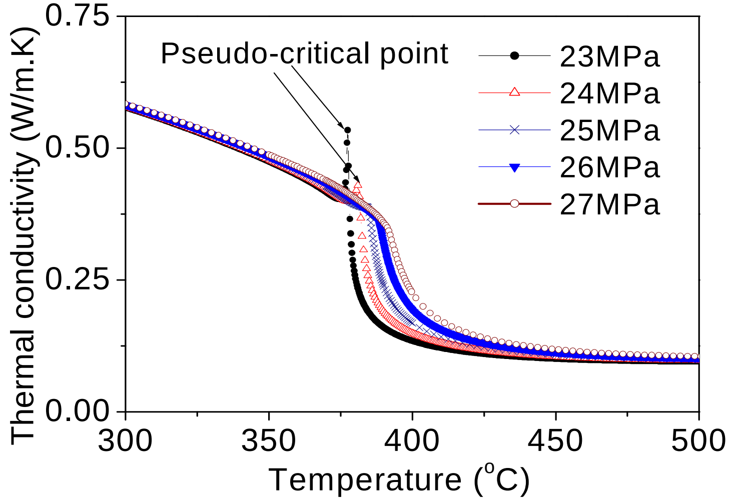
Compare with existing LWR

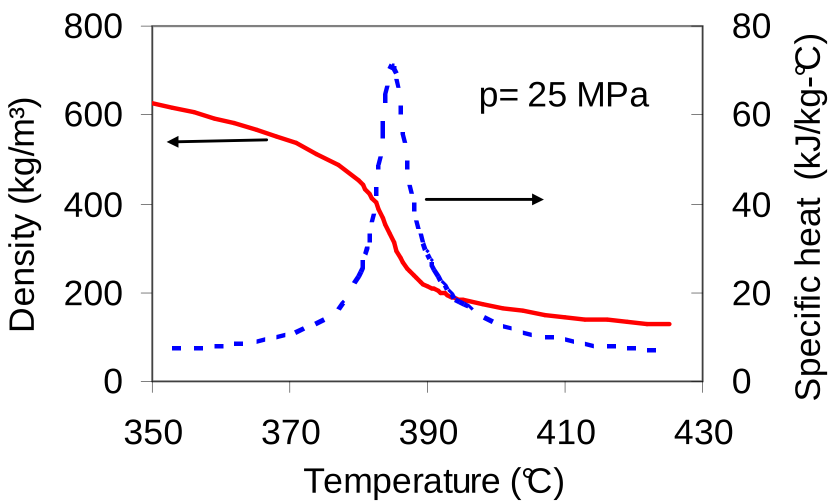
Type / Parameter	Current LWR	SCWR
Pressure (MPa)	7.5/15.5	25.0
Outlet temperature (C)	290/330	>500
Enthalpy increase (KJ/kg)	270/200	>1300
Mass flux (kg/m^2-s)	1648/3200	<1000
Density variation(kg/m^3)	750—>200/720—>650	770—>80
Fuel arrangement	square	square/triangular
Pitch/diameter (-)	>1.3	<1.2
Fuel assembly design	Open/closed	Closed
Two phase flow	occur	not occur
CHF phenomenon	occur	not occur
Downward flow	not occur	occur
Counter-current flow	not occur	occur

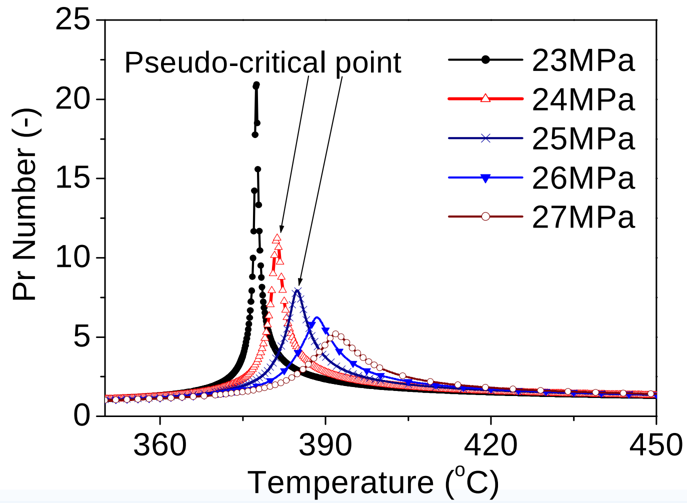
Challenges deriving from the TH properties

Strange properties

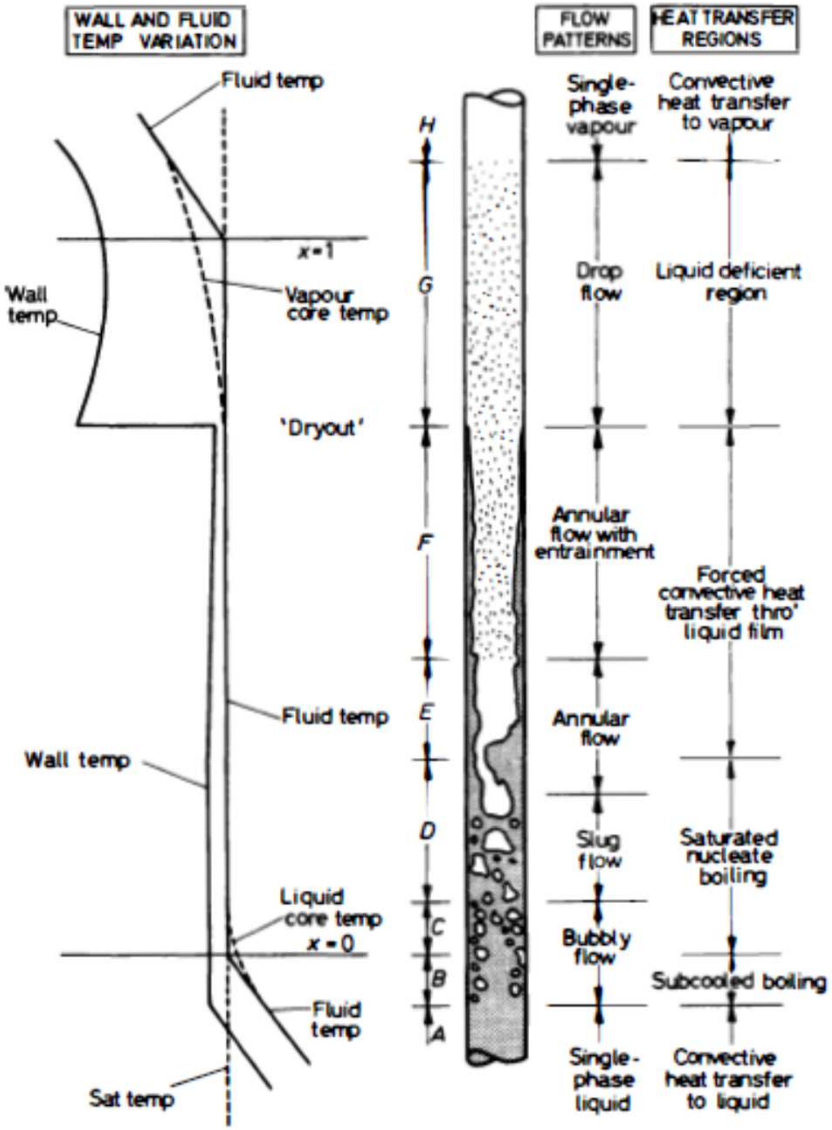


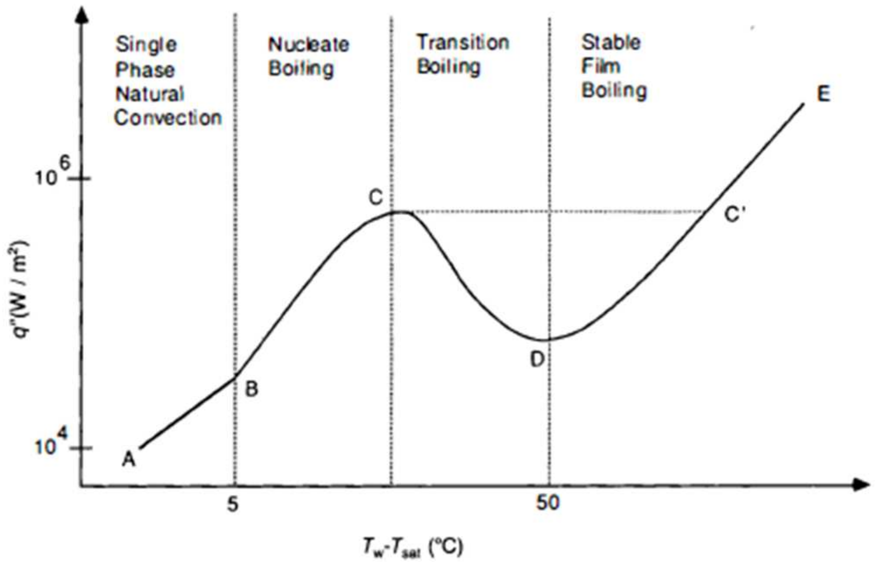






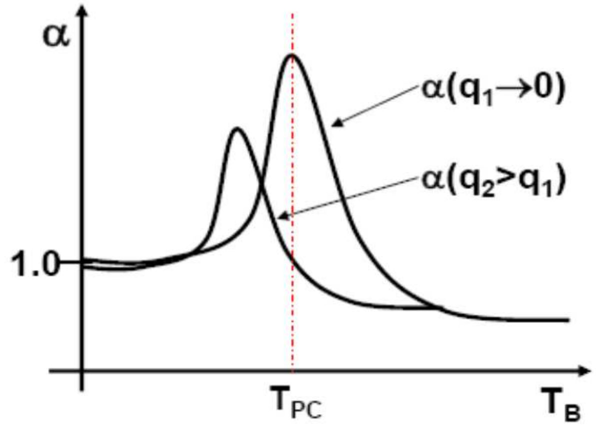
Heat transfer of current LWR





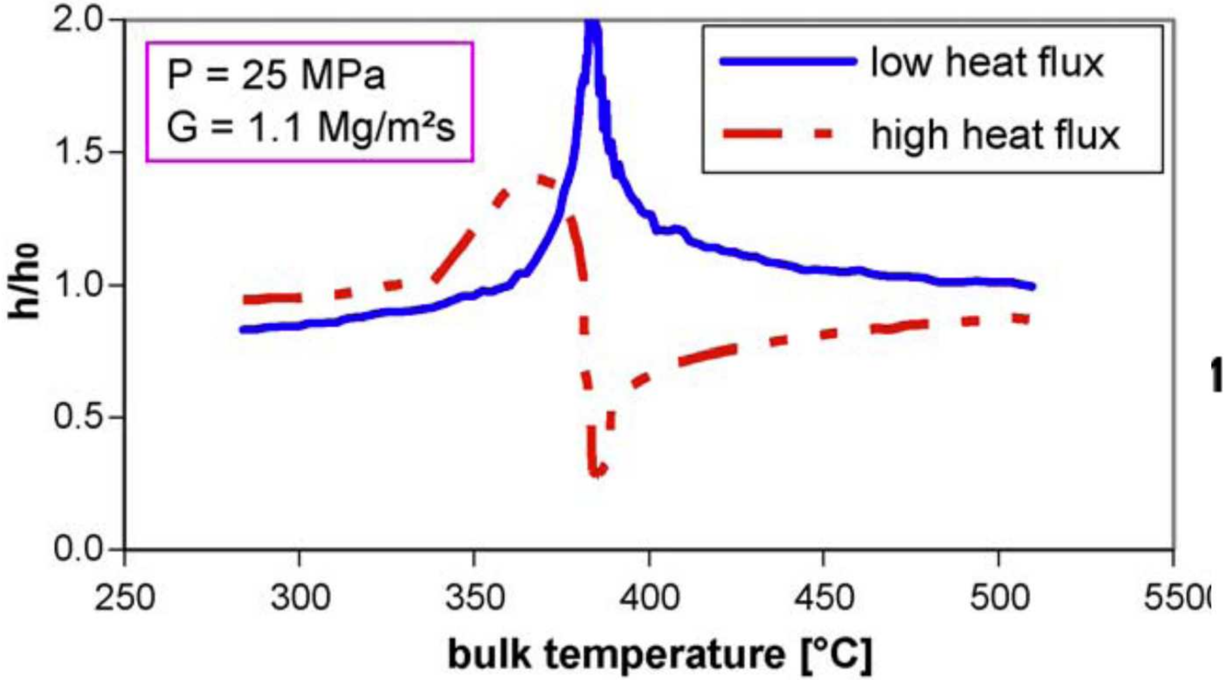
- ✓ **simple correlation for normal HT**
- ✓ **lower value of T_w-T_{sat}**
- ✓ **weak dependence with heat flux**
- ✓ **sharp temperature increase at CHF**

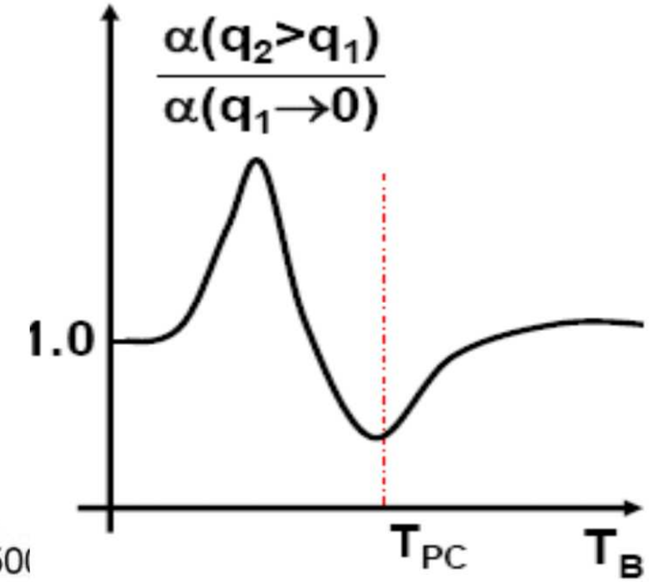
Heat transfer of SCWR



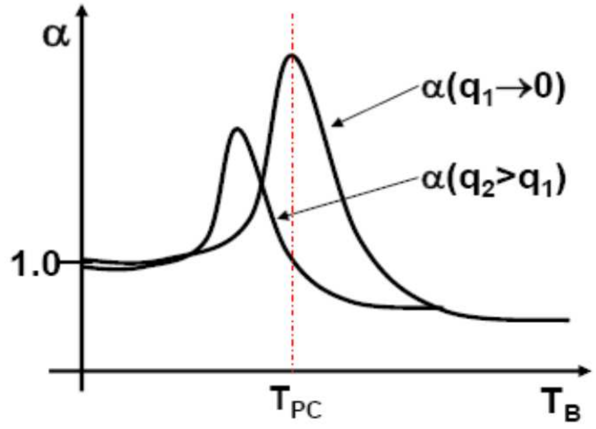
Special feature

- ✓ **Strong dependence on heat flux**
- ✓ **HTD possible**
- ✓ **More complicated in rod bundles**





Heat transfer of SCWR

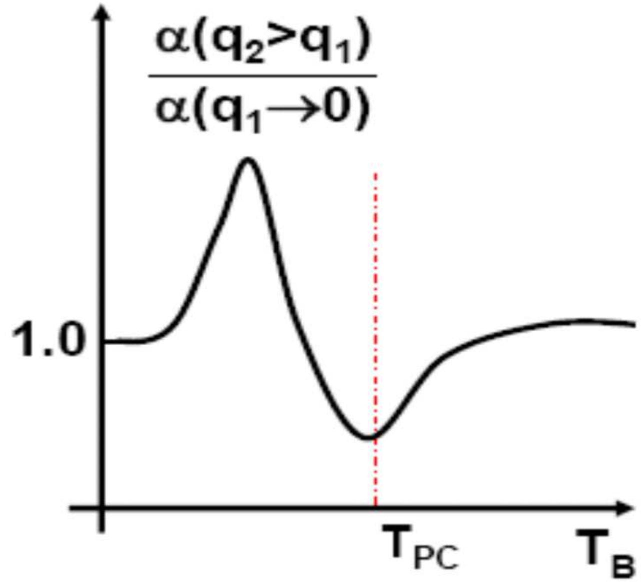


Special feature

- ✓ **Strong dependence on heat flux**
- ✓ **HTD possible**
- ✓ **More complicated in rod bundles**

State-of-the-art

- ✓ **No reliable prediction, even for simple tubes**
- ✓ **Limited test data for SCWR parameters**
- ✓ **Very limited test data in rod bundles**
- ✓ **Main efforts in CFD**
- ✓ **Very limited efforts in experiments**



Existing heat transfer correlation

- **large number of studies since 50's**
- **Mainly empirical correlations**

$$Nu_B = C \cdot \mathrm{Re}_B^n \cdot \mathrm{Pr}_B^m \cdot F$$

$$F = f\left(\frac{P}{P_C}, \frac{T_B}{T_{PC}}, \frac{\rho_W}{\rho_B}, \frac{C_{P,A}}{C_{P,B}}, \frac{\mu_W}{\mu_B}, \frac{\lambda_W}{\lambda_B}, Gr_B, \mathrm{Re}_B, \mathrm{Pr}_B, \frac{q \cdot \beta_B}{G \cdot C_{PB}}, \frac{q \cdot \beta_B D}{\lambda_B}, \frac{q}{G \cdot h_B}, \ldots\right)$$

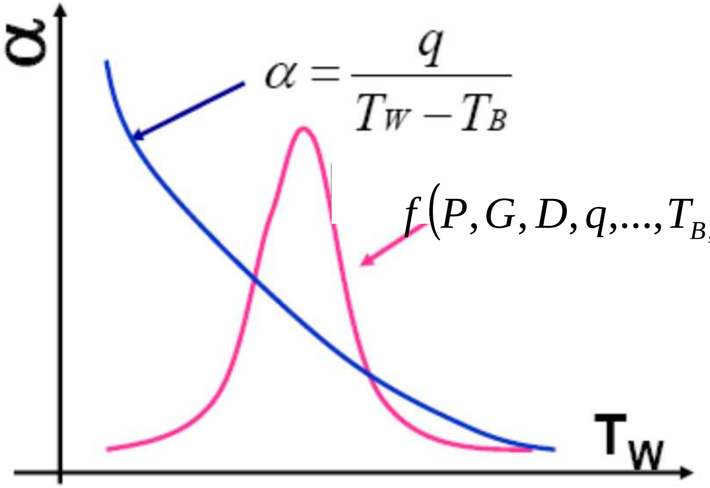
➡ **Up to 12 numbers are used in one correlation!**

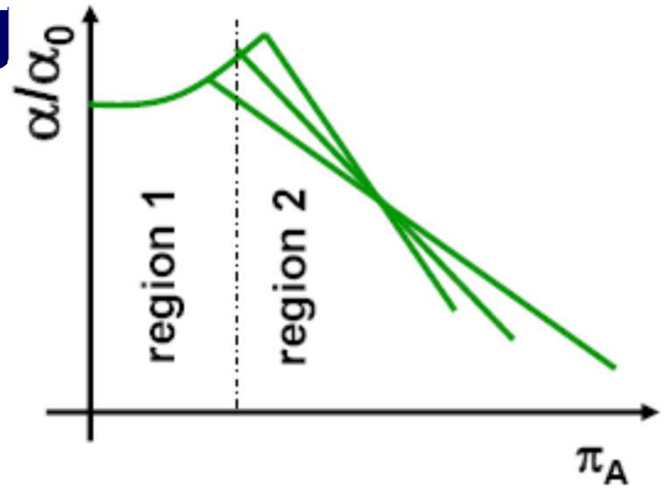
- **Future needs**

  - more test data, incl. micro-scale test data
  - simple & mechanistic models

New correlation at SJ

$$\frac{q}{T_W - T_B} = f\left(P, G, D, q, ..., T_{B,} T_W\right)$$





$$F = \frac{Nu}{0.023 \, \mathrm{Re}^{0.8} \, \mathrm{Pr}^{0.33}} = f\left(\pi_A\right)$$

$$F = \min\left(F_1, F_2\right)$$

$$F_1 = 0.85 + 0.776\left(\pi_A\right)^{2.4}$$

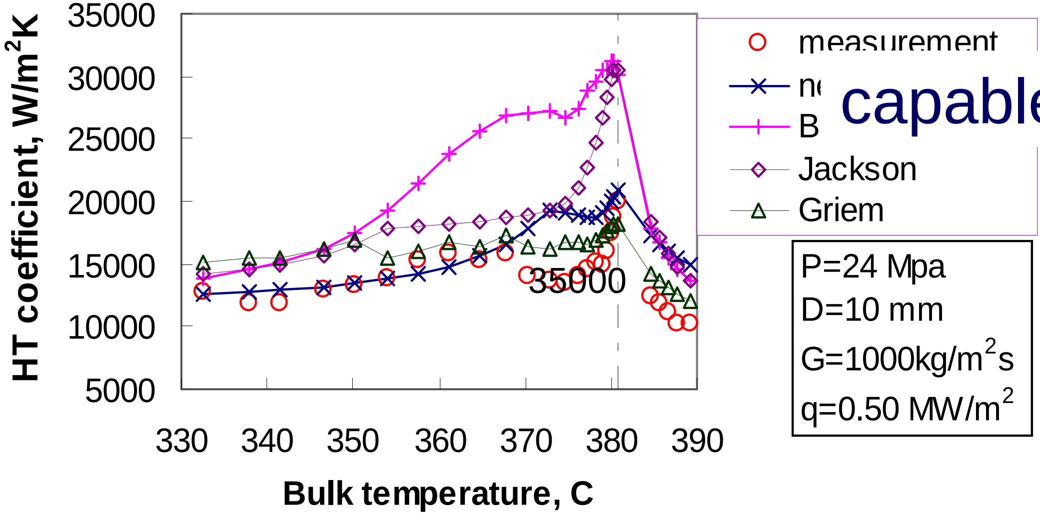
$$F_2 = \frac{0.48}{\pi_{A,PC}^{1.55}} + 1.21 \cdot \left(1 - \frac{\pi_A}{\pi_{A,PC}}\right)$$

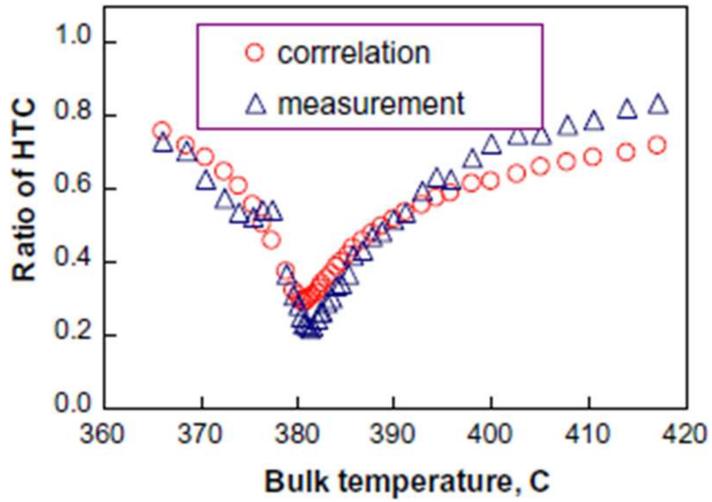
$$\pi_A = \frac{\beta}{C_P} \frac{q}{G}$$

New equation

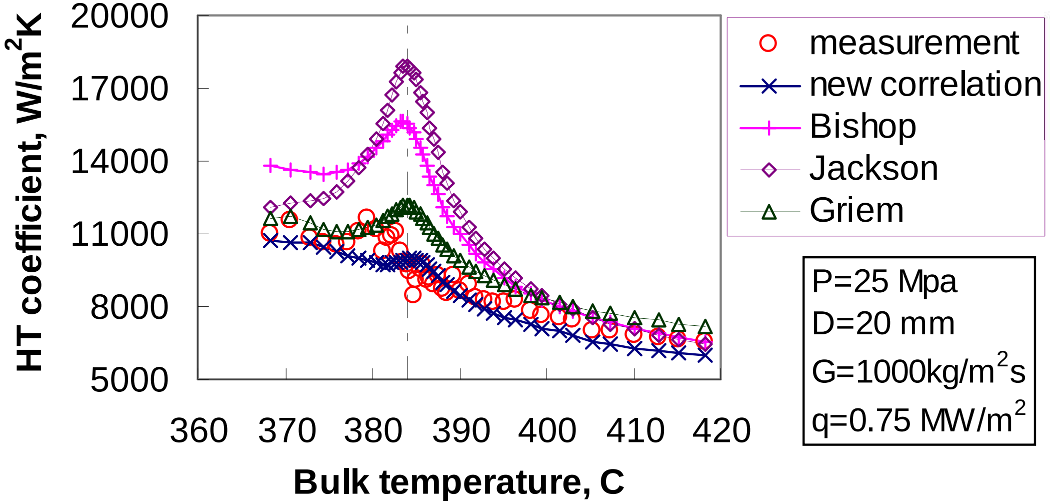
- Simplicity of the correlation structure
- Explicit connection with the physical phenomena
- Excludes the direct dependence of HTC on the Tw

capable of predicting HTD behavior

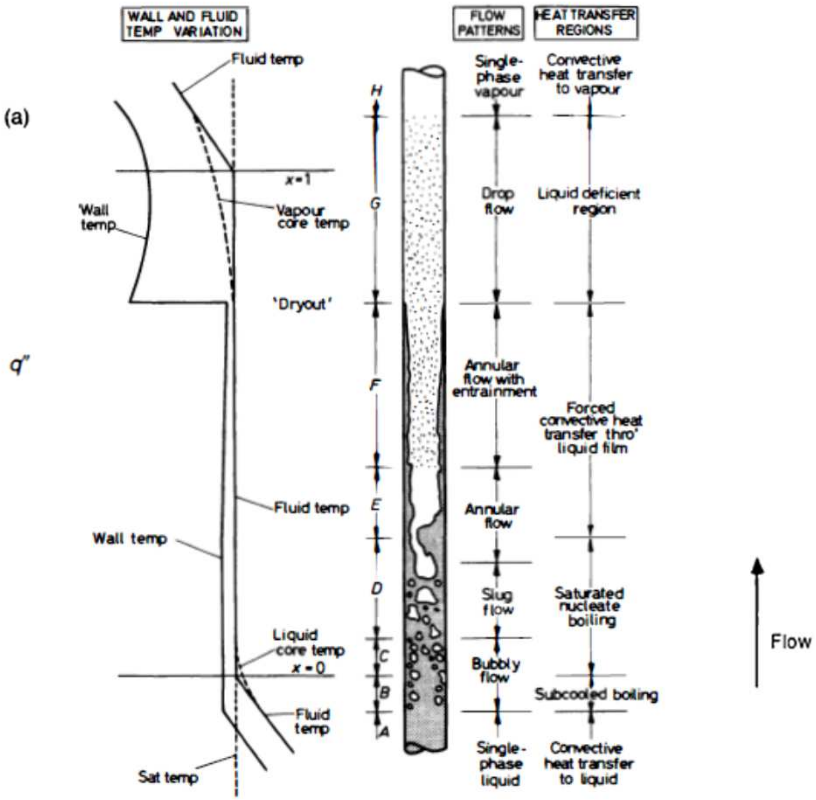


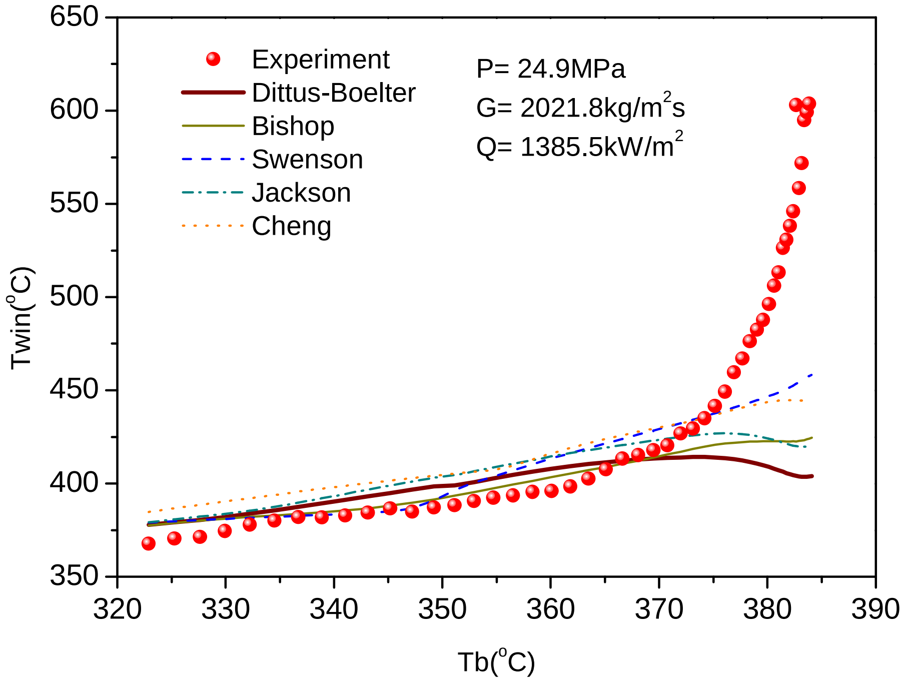


Measured and calculated heat transfer ratio (a/a0) at conditions: D = 20 mm, P = 24.0 MPa, G = 1000 kg/m2 s and q = 800 kW/m2.



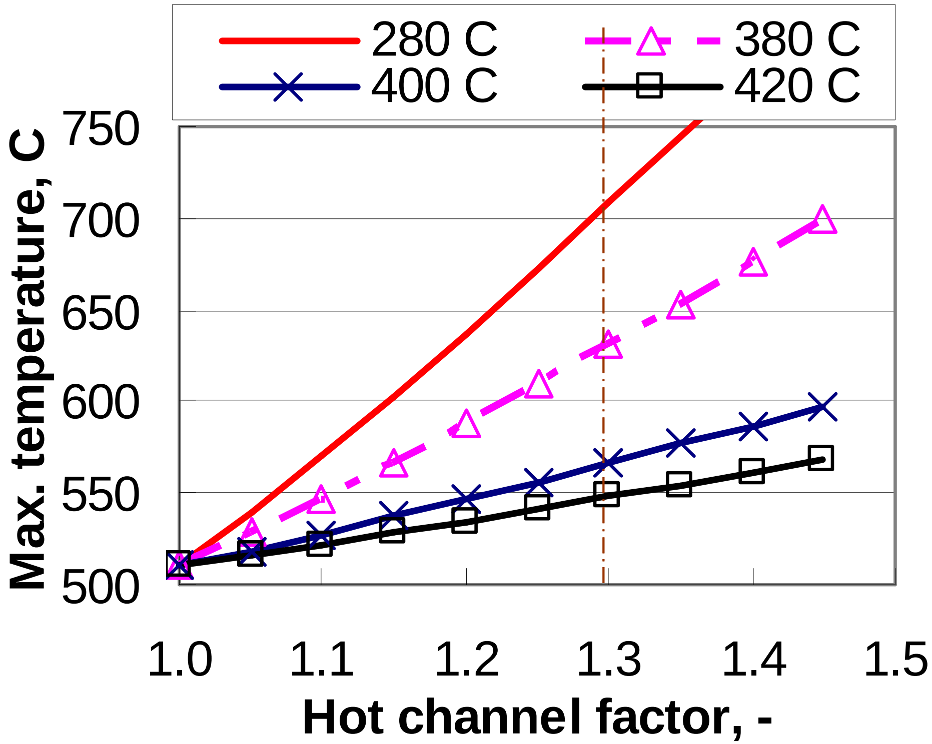
Heat transfer deterioration

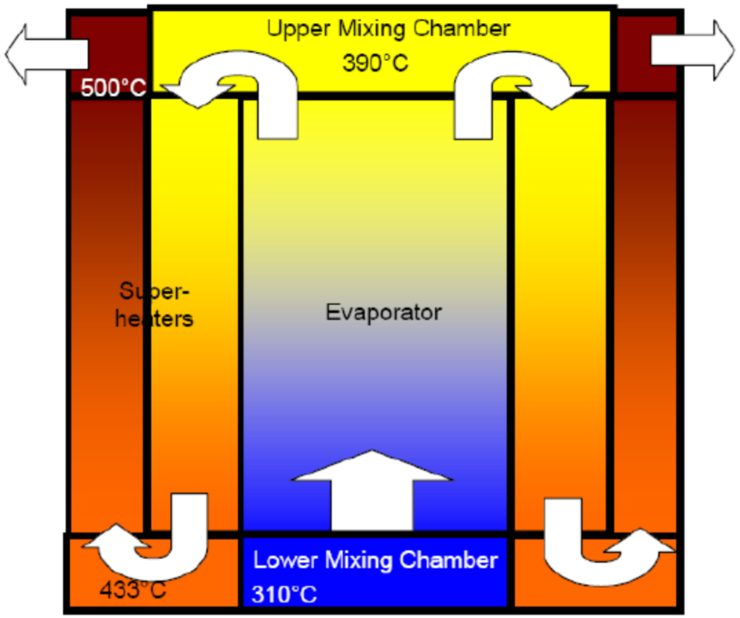




the reduction in the heat transfer coefficient, or the increase in the wall temperature behaves rather smoothly

Problem arise from large enthalpy rise





✓high coolant outlet temperature
✓multi-path design
✓increasing the inlet temperature

CHF Scaling for LWR

- to simplify CHF testing facilities
- the system pressure can be reduced by a factor of 6, heating power can be reduced by a factor of 10
- AHMAD derive 4 modeling criteria based on 13 dimensionless group
- some parameters can not be applied to SC condition

$$\left(\frac{L}{D}\right)_M = \left(\frac{L}{D}\right)_P \qquad \left(\frac{\Delta h_{in}}{h_{fg}}\right)_M = \left(\frac{\Delta h_{in}}{h_{fg}}\right)_P$$

$$\left(\frac{\rho_l}{\rho_v}\right)_M = \left(\frac{\rho_l}{\rho_v}\right)_P \qquad \left(\frac{\Phi_{CHF}}{Gh_{fg}}\right)_M = \left(\frac{\Phi_{CHF}}{Gh_{fg}}\right)_P$$

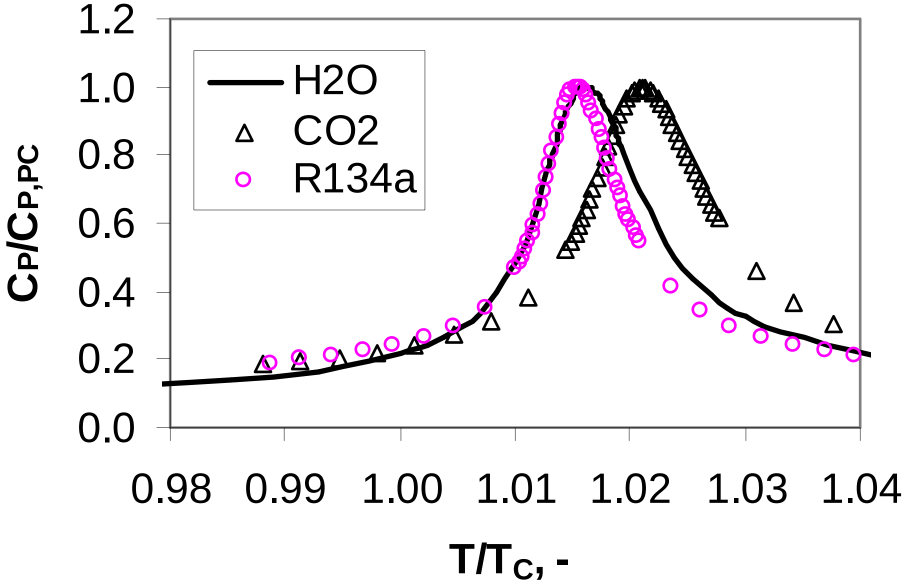
$$\psi_{CHF} = \left(\frac{GD}{\mu_l}\right)\left(\frac{\mu_l}{\sqrt{\sigma D \rho_l}}\right)^{2/3}\left(\frac{\mu_l}{\mu_v}\right)^{1/5}$$

Scaling of heat transfer

Why fluid-to-fluid scaling law?

- **HT relies on experimental work & empirical correlations**
- **Large expenditure using SC water**
- **Model fluid technique desirable, well applied in nuclear engineering**
- **Simple scaling law**

$$\left(\frac{p}{p_{cr}}\right)_{CO_2} = \left(\frac{p}{p_{cr}}\right)_{Water}$$



Scaling of heat transfer

What is scaling law?

- **Object considered**

  circular tubes, vertical oriented

  uniformly heated
- **Parameter to be separately controlled are:**

  tube diameter

  heated length *(neglected for developed flow)*

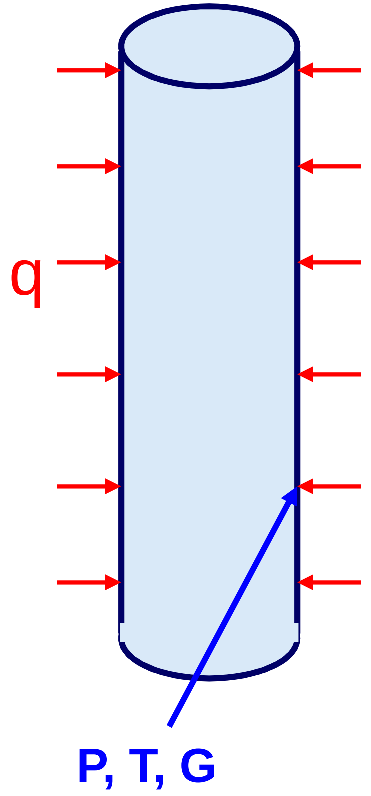
  pressure

  fluid temperature

  mass flux

  heat flux
- **Parameter to be studied**

  heat transfer coefficient, or wall temperature



Scaling of heat transfer

How to derive scaling factors?

- ✓ **Dimension analysis (Buckingham theory)**
- ✓ **Non-dimension of conservation equations & boundary conditions**
- ✓ **Empirical**
- ✓ **...**

Challenges

- ✓ **Not sufficient number of parameters to be tuned**
- ✓ **Identification and selection of mot important parameters**
- ✓ **Combination of parameters (distortion approach)**

Scaling of heat transfer

What is scaling law?

Required parameters in prototypical fluid (water):

D_P, p_P, T_P, G_P, q_P

→

$$f_D = \frac{D_M}{D_P}$$

$$f_P = \frac{P_M}{P_P}$$

$$f_T = \frac{T_{B,M}}{T_{B,P}}$$

$$f_G = \frac{G_M}{G_P}$$

$$f_q = \frac{q_M}{q_P}$$

→

Experimental parameters in model fluid, e.g. CO_2:

D_M, p_M, T_M, G_M, q_M

↓

Experimental results in model fluid:

α_M

←

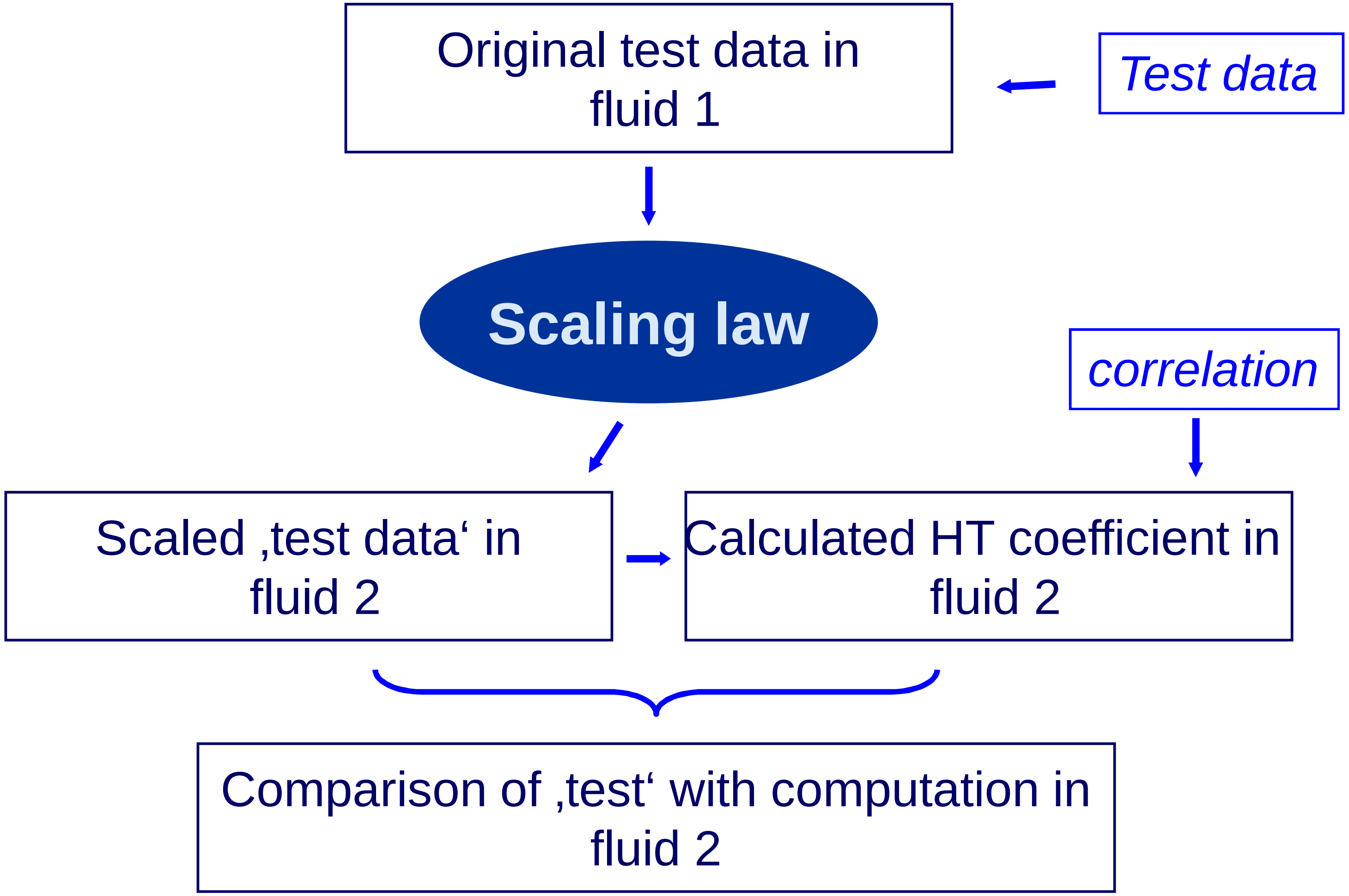
$$f_\alpha = \frac{\alpha_M}{\alpha_P}$$

←

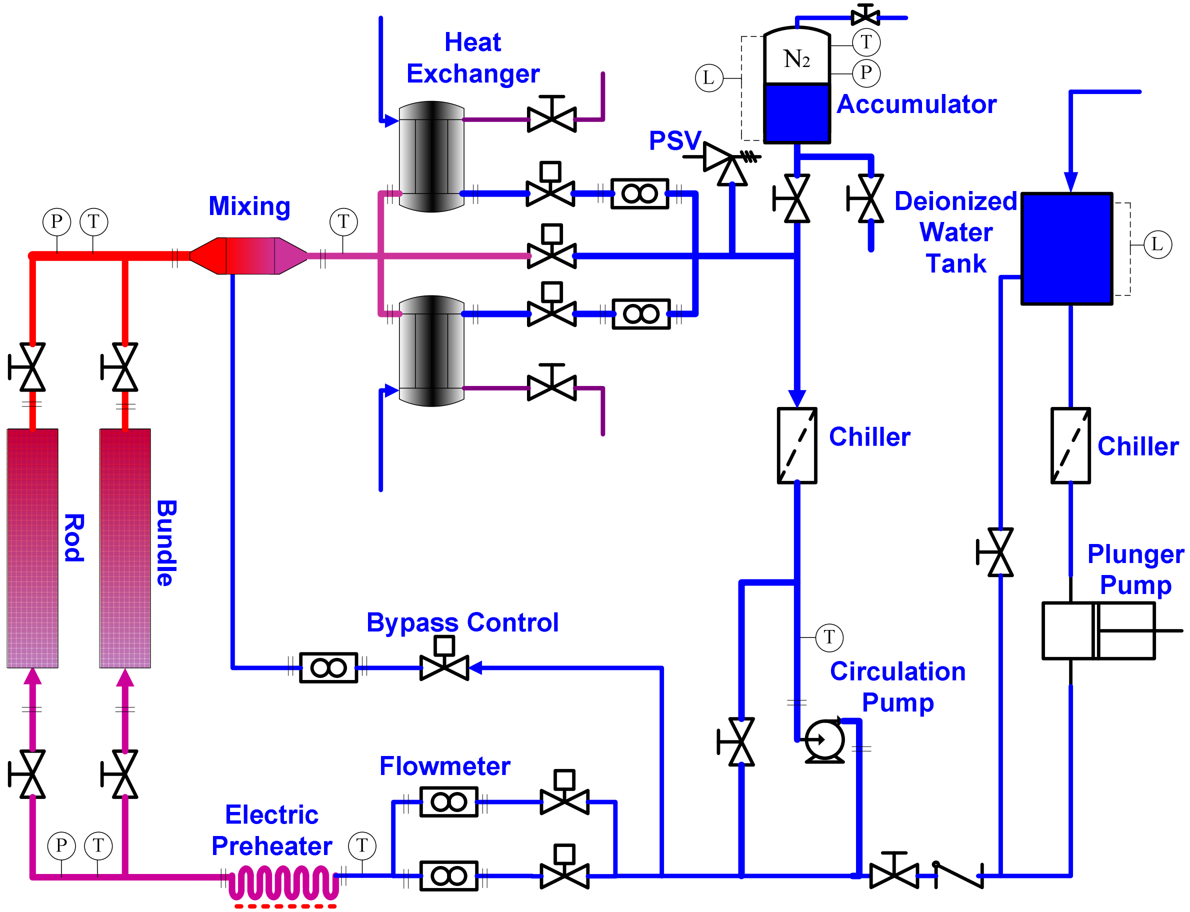
Results in prototypical fluid (water):

α_P

Validation


Original test data in fluid 1
Test data
Scaling law
correlation
Scaled ‚test data' in fluid 2
Calculated HT coefficient in fluid 2
Comparison of ‚test' with computation in fluid 2

Introduction to SWAMUP at SJTU

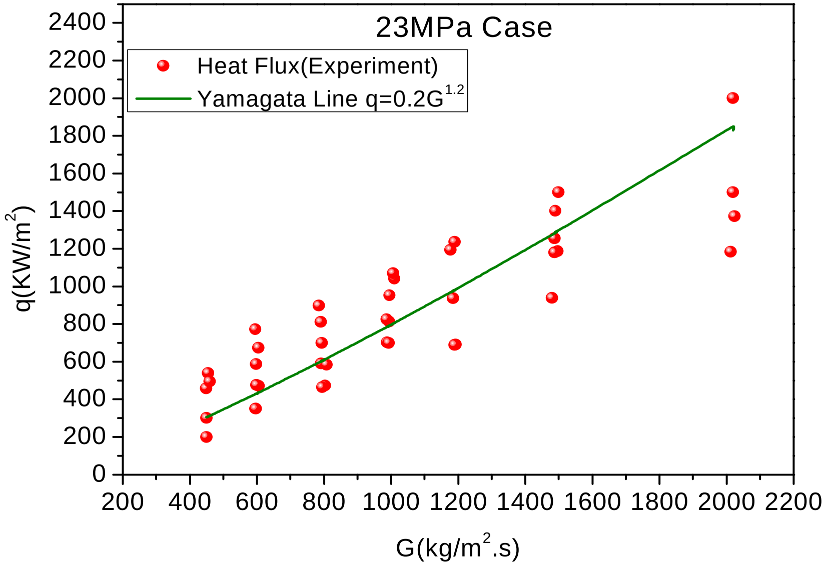


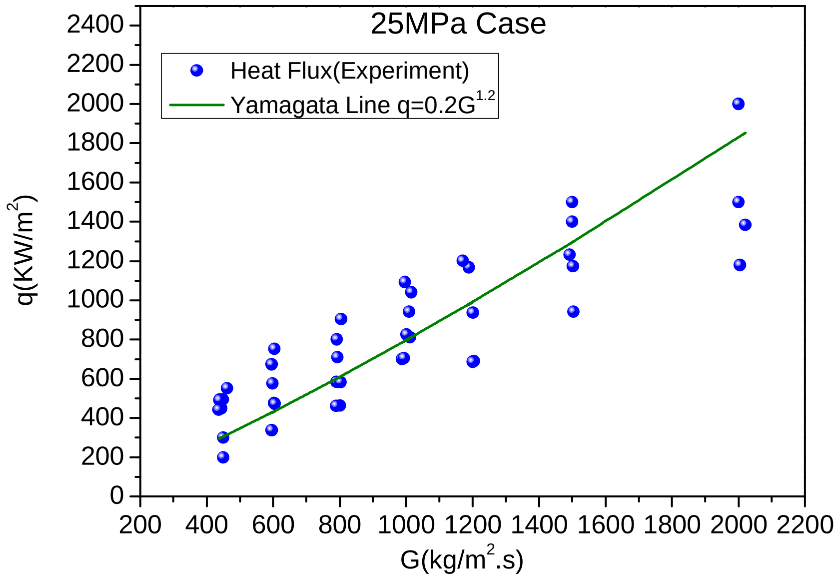
Main loop of SWAMUP

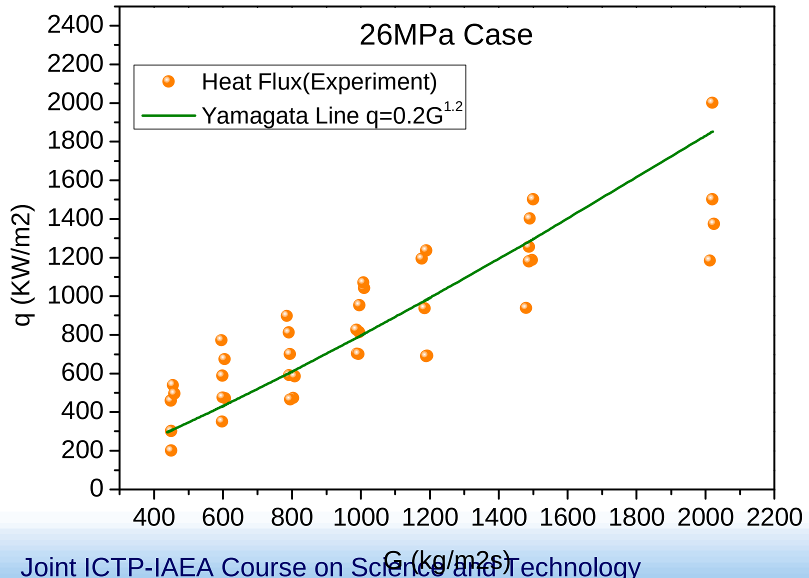
Main parameters:

- **Pressure** 30MPa
- **Temperature** 550ºC
- **Flow rate** 5.0 t/h
- **Pump head** 0.8 MPa
- **Total power** 1.2 MW DC

Results of SWAMUP at SJTU

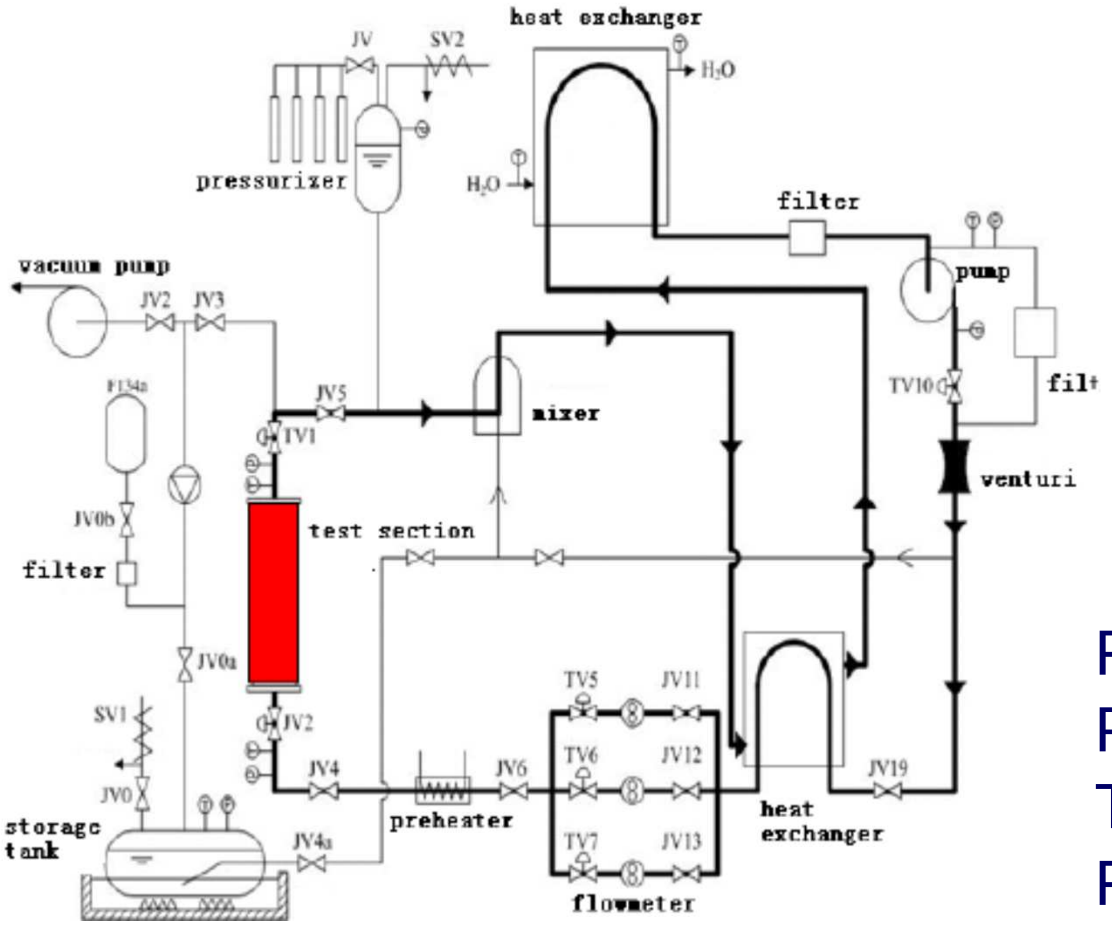






DN7.6mm、DN10mm

Introduction to SMOTH at SJTU



Main loop of SMOTH

Fluid: Freon 134a
Pressure: 6.0 MPa
Temperature: 200°C
Flow rate: 10 t/h
Heat power: 300 kW

Flow instability

- loop oscillations during natural circulation
- static instability
- density wave oscillations
- Flow regime transition oscillations
- multi-channel instability
- neutronic/thermal-hydraulic instability

* LaSalle 2 on March 9, 1988-power oscillation of 25-60 percent
* WPPS WNP 2 on August 15, 1992-power oscillation of 23-43 percent

Analysis method

Linear stability analysis in the **frequency domain**

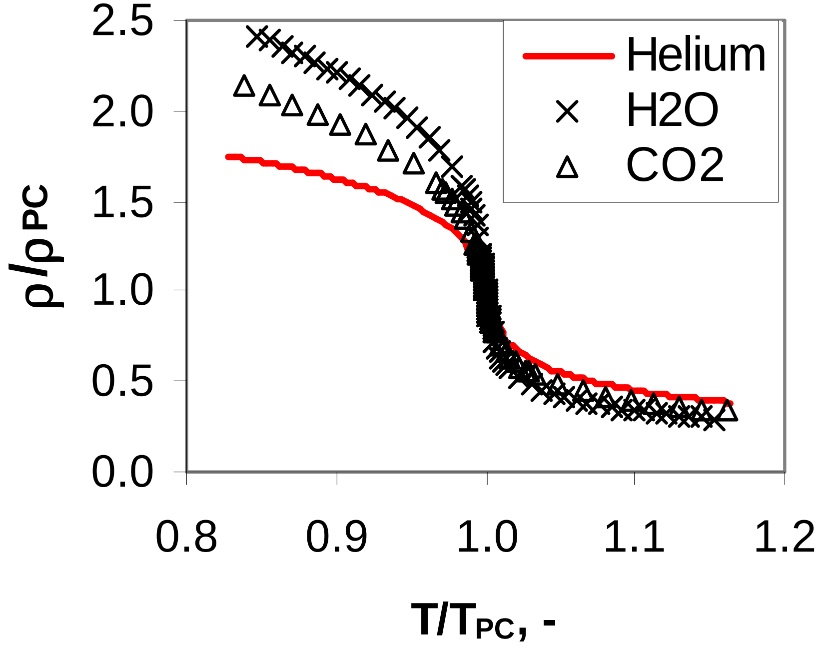
- single-channel TH models coupled with point-kinetics models
- using the decay ratio (searching the dominant root of the system characteristic equation directly in the complex plane)

Time **domain analysis**

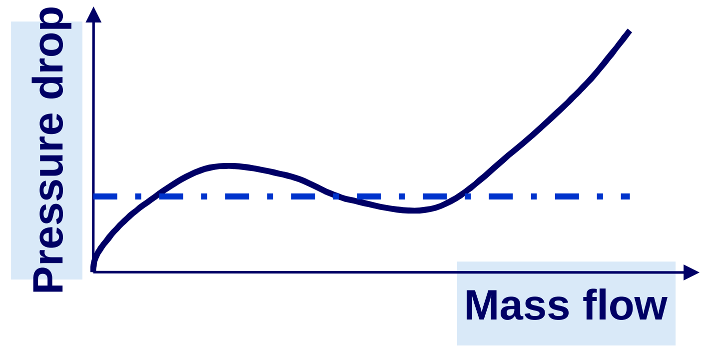
directly calculates the time domain response to a flow perturbation and the decay ratio is calculated based on the transient behavior predicted

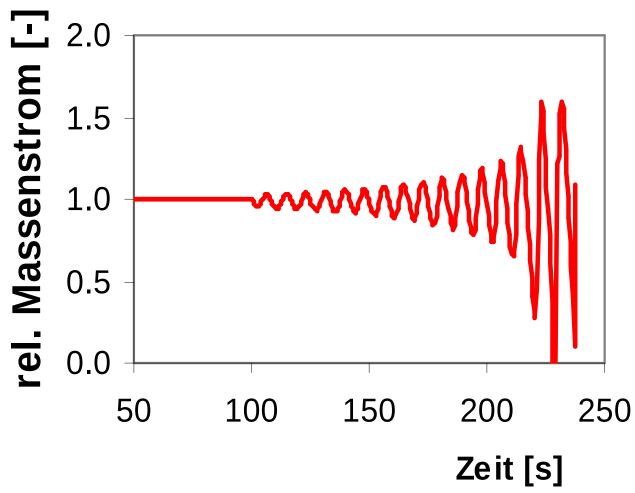
Flow instability

Strong density change

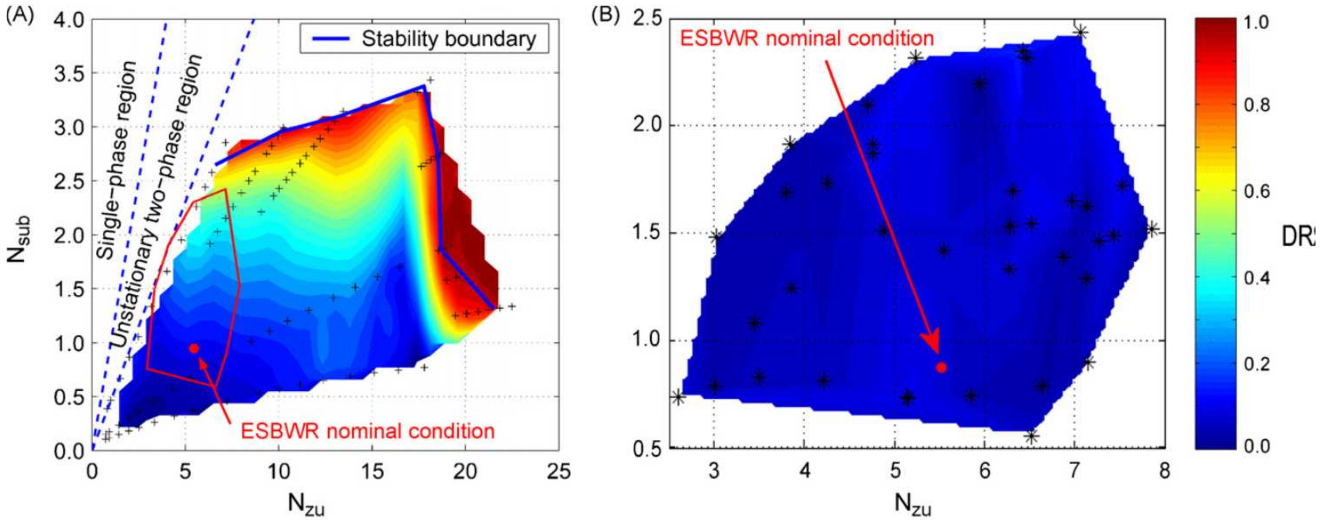


Flow instability



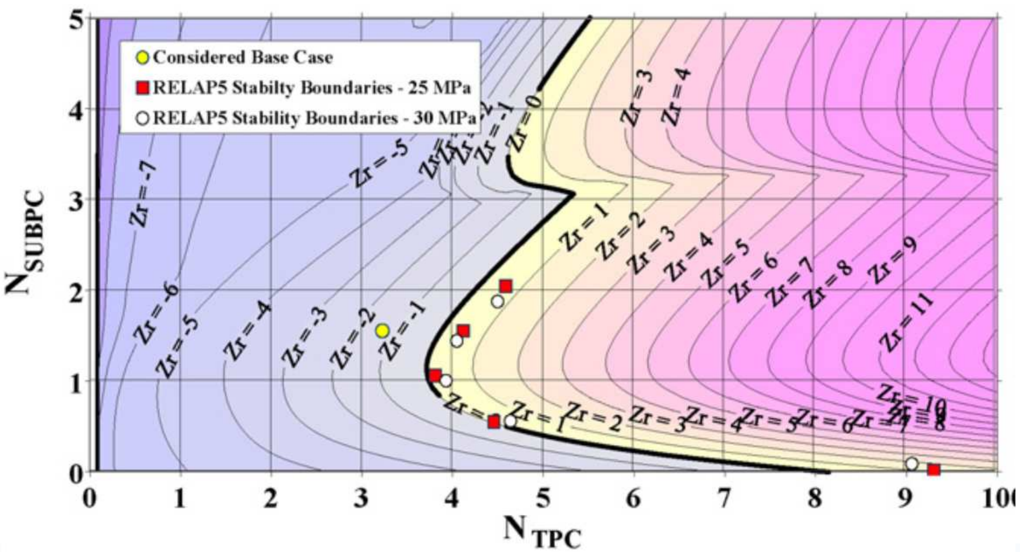


Results



$$N_{sub} = \frac{h_{in} - h_{sat}}{h_{fg}} \frac{\rho_l - \rho_v}{\rho_v}$$

$$N_{Zu} = \frac{q}{G_{m,0} A_{core} h_{fg}} \frac{\rho_l - \rho_v}{\rho_v}$$



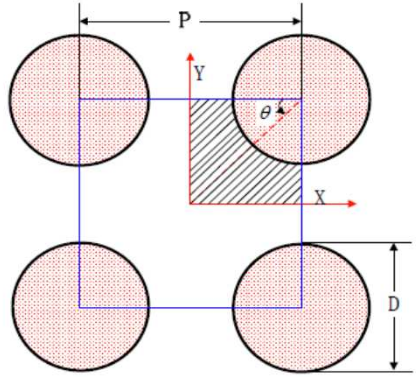
$$N'_{TPC} = \frac{q''_0 \Pi_h L}{\rho_{pc} w_0 A} \frac{\beta_{pc}}{C_{p,pc}}$$

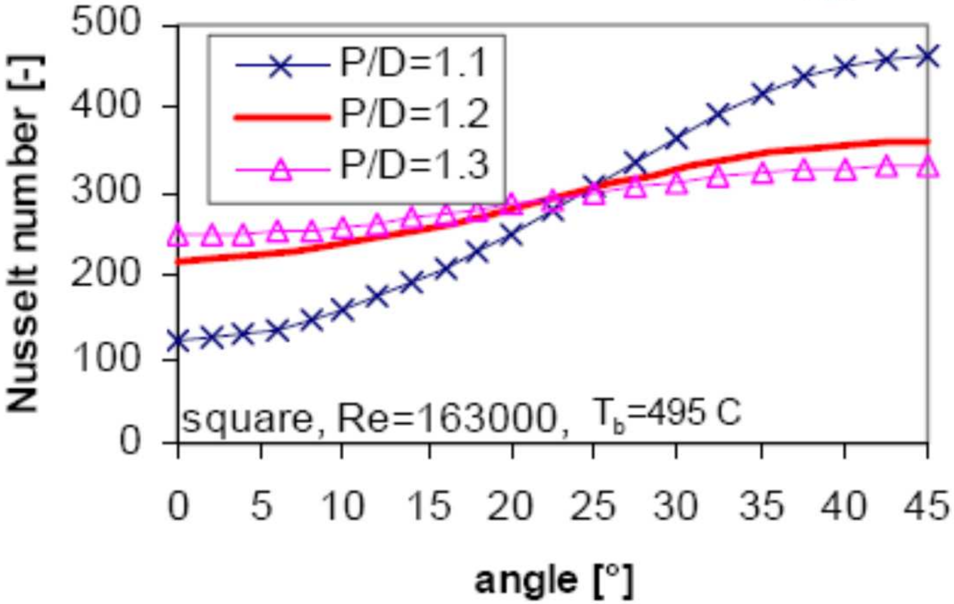
$$N_{SUBPC} = \frac{\rho_{pc}}{C_{p,pc}} (h_{pc} - h_{in})$$

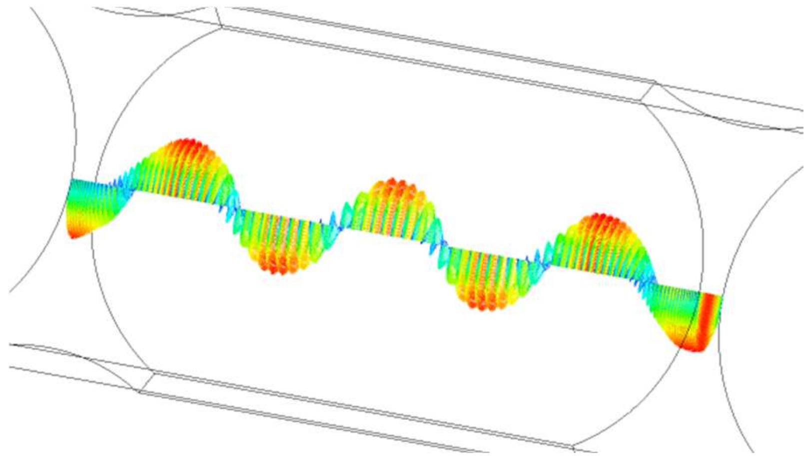
Challenges deriving from the geometry

Challenge derive from tight lattice

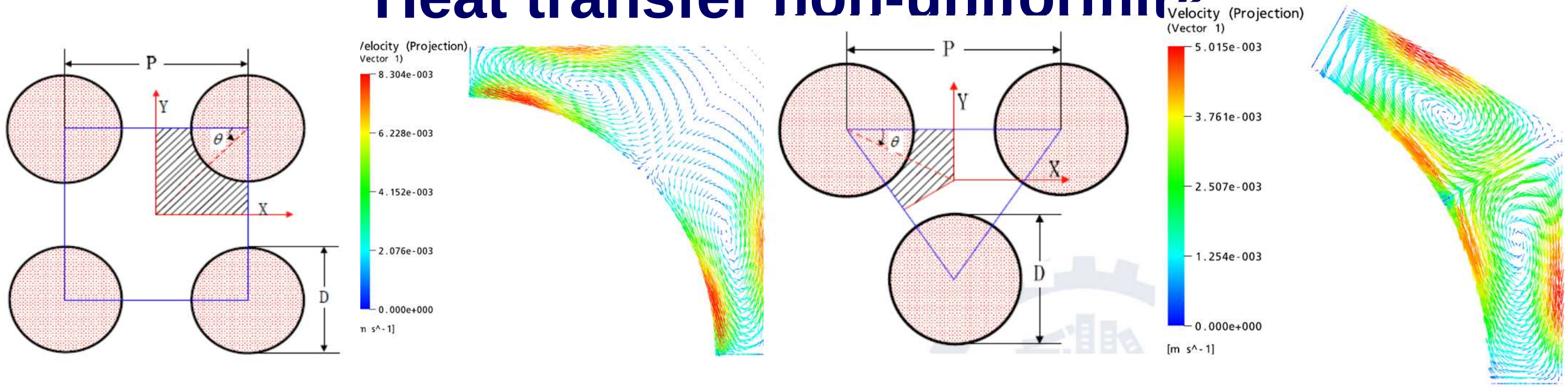
- Non-uniformity of circumferential heat transfer coefficient
- Transversal velocity through the gap of tight lattice

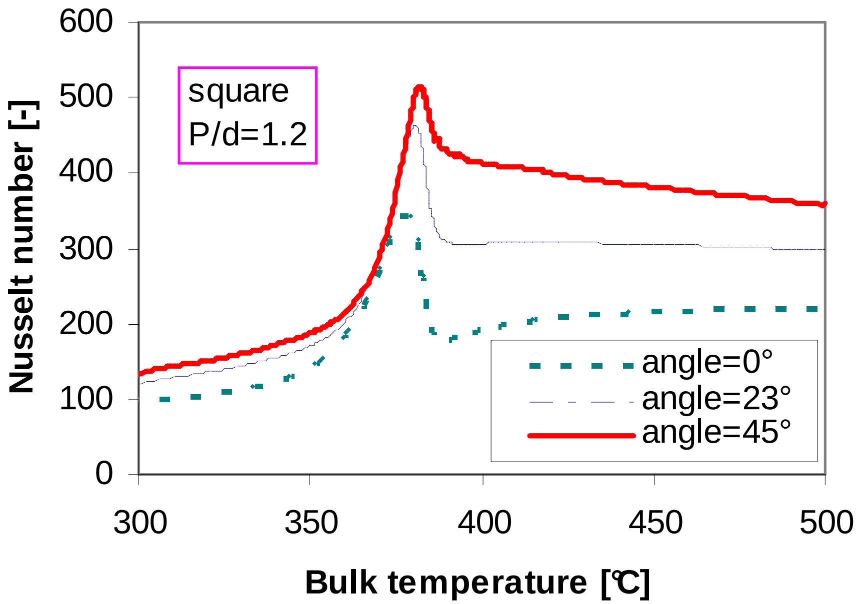


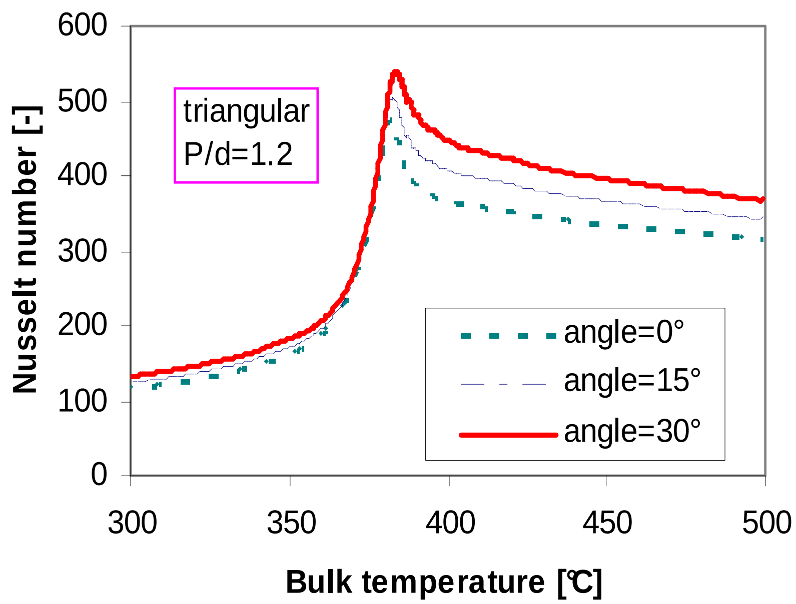




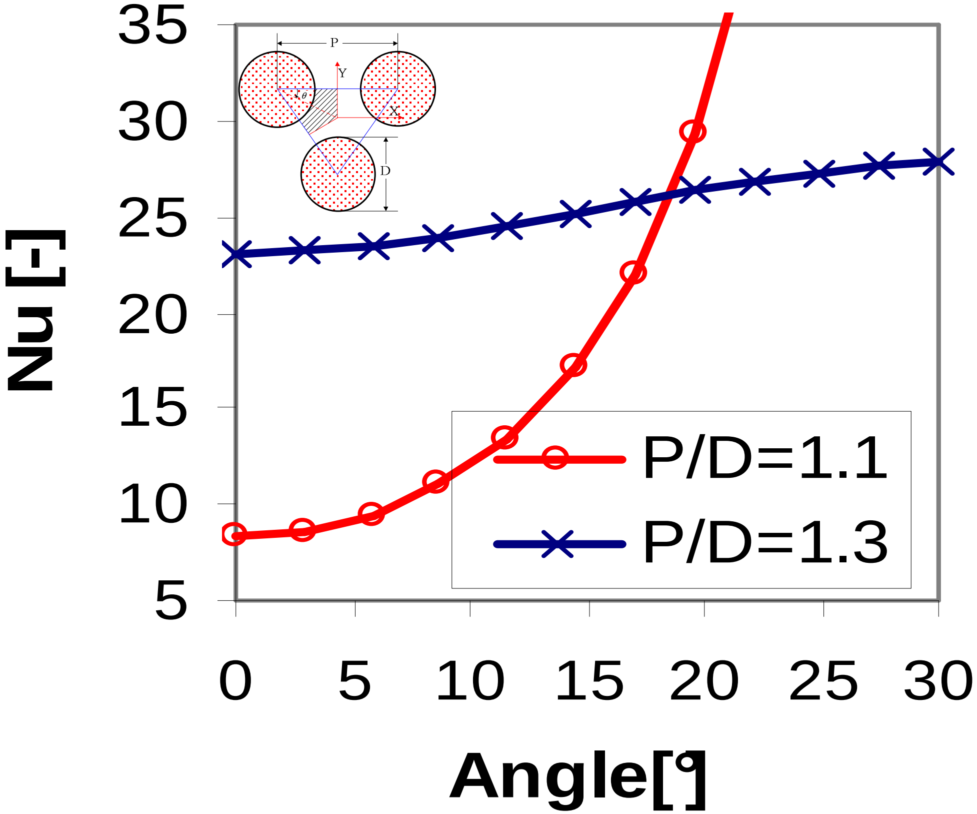
Heat transfer non-uniformity

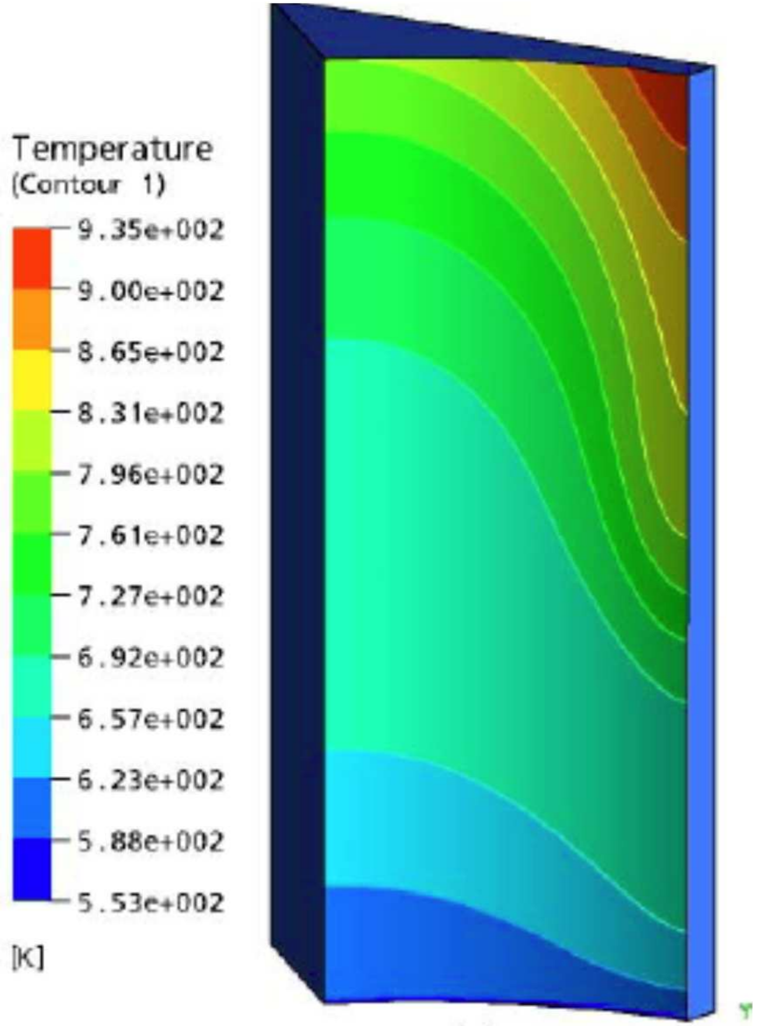






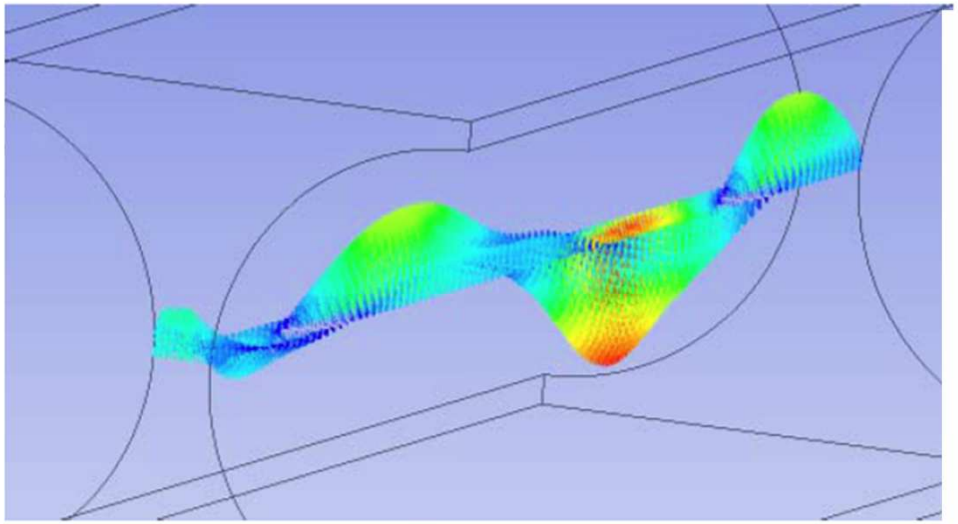
Strong circumferential non-uniformity



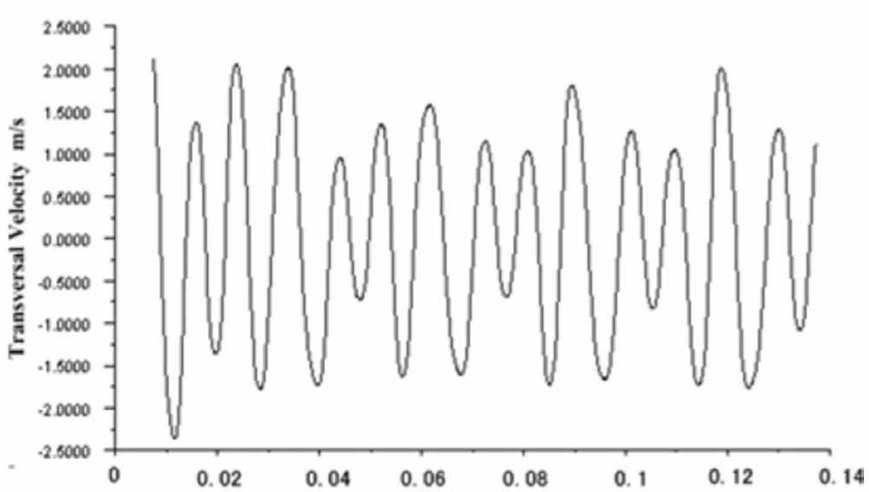


Flow pulsation phenomenon in tight lattice

- turbulent flow in a rod bundle different from that in a pipe.
- high mixing in the gap region was observed
- it was explained by the secondary flow
- flow pulsation phenomenon is responsible for this high mixing
- this effect is very strong in the tight lattice



(b) 4 rod parallel array



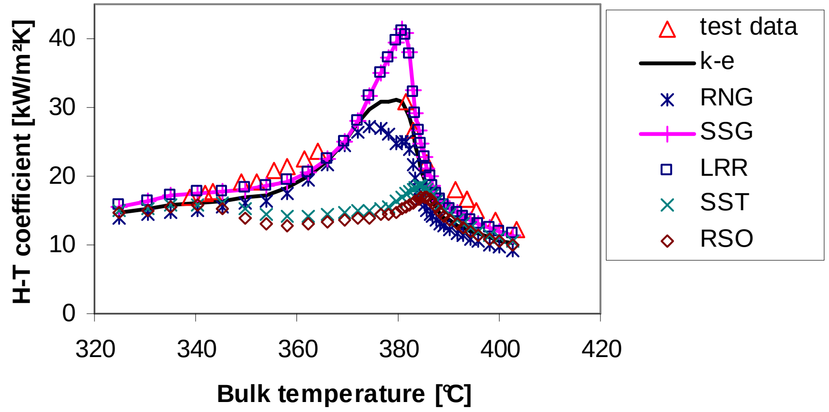
Objectives

Objectives of this presentation are to:

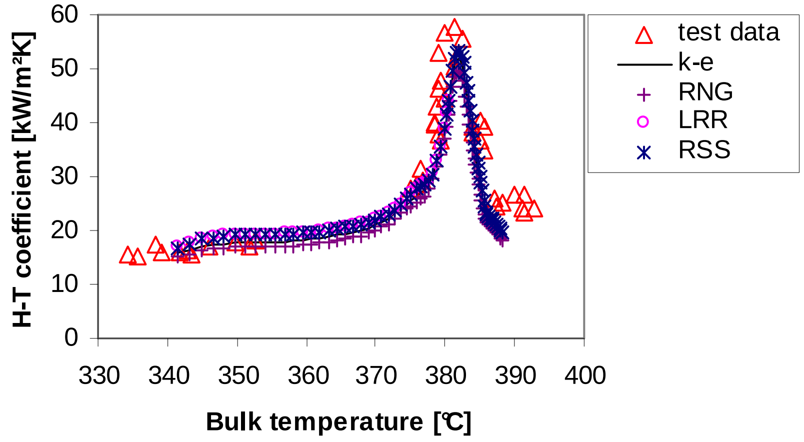
- Compare with existing LWR
- TH challenges deriving from SCWR
- Code development (Sub channel, system)

CFD application-Circular tubes

q = 698 kW/m²

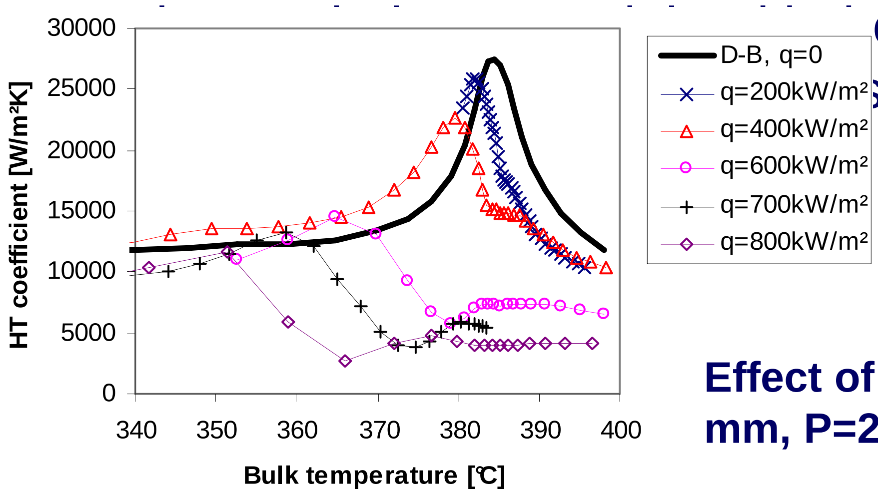


q = 233 kW/m²



e test data of Yamagata: (D=7.5

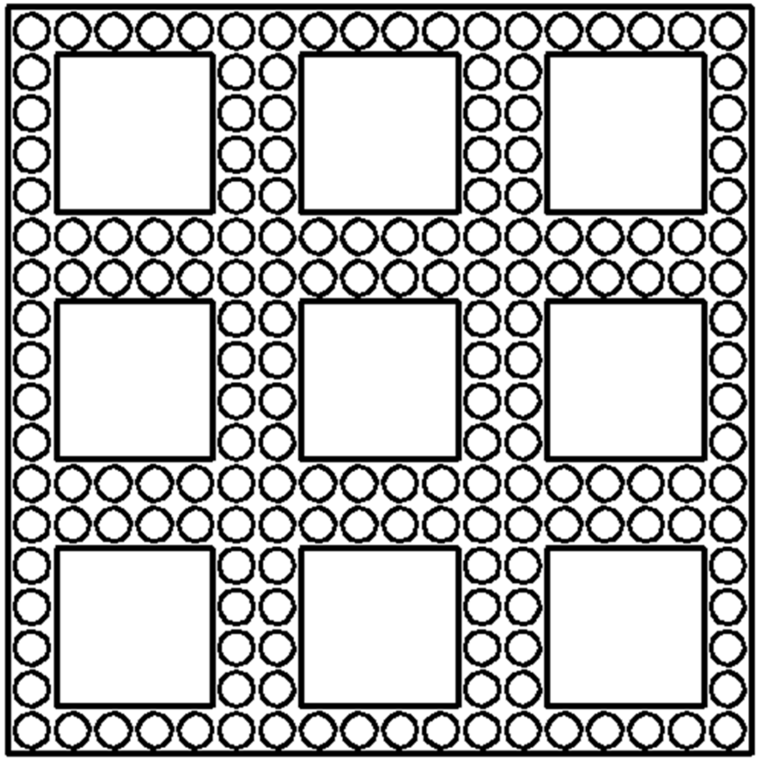
s $y_1^+ \approx 1$



Effect of heat flux on heat transfer coefficient (D=7.5 mm, P=25.0MPa, G=740 kg/m²s, k-ε model, $y_1^+ \approx 1$

Sub-channel code

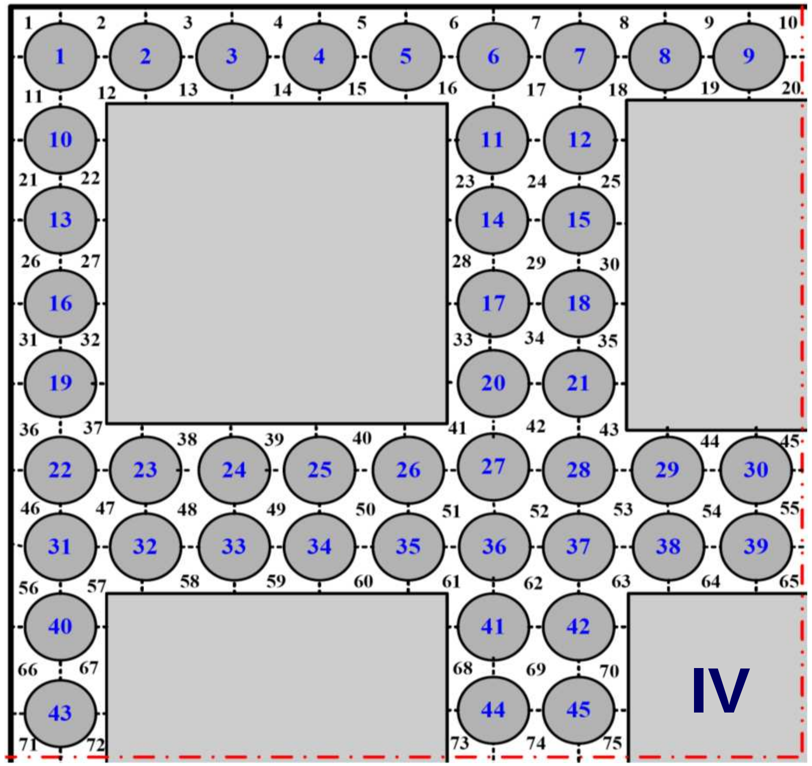
- **Moderator channel model, counter-current flow;**
- **Property of SC fluid;**
- **Special heat transfer and pressure drop model;**

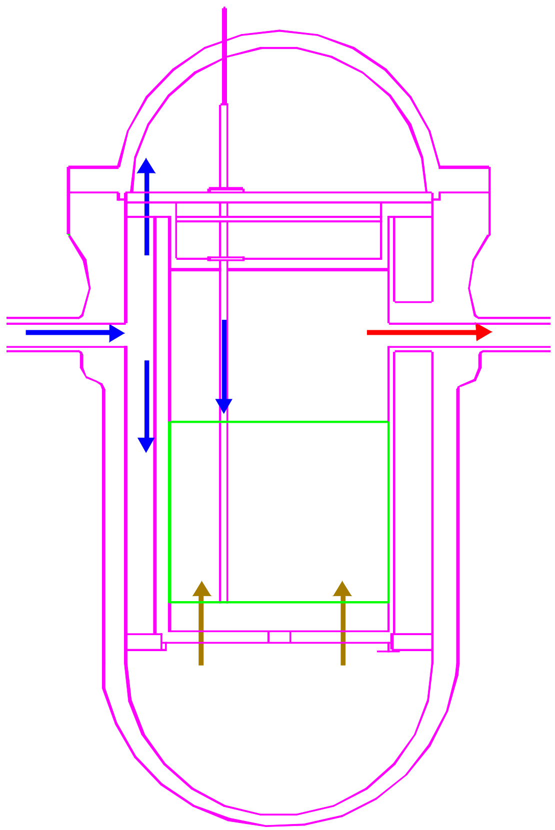


Length, mm	4600
Rod diameter, mm	8.0
P/d, -	1.20
Cladding thickness, mm	0.50
Gas gap, mm	0.05
Moderator box clearance, mm	1.6
Moderator box thickness, mm	2.0
Fuel assembly thickness, mm	2.0
clearance, mm	1.6
Average linear heat, kW/m	16.0
Inlet temperature, °C	280.0
Outlet temperature, °C	510.0
Outlet pressure, MPa	25.0
Moderator fraction , %	50
Material property	_

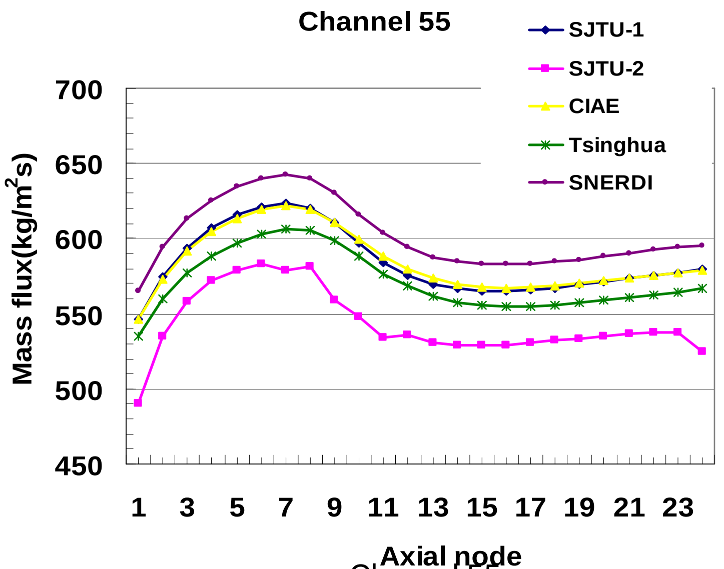
Sub-channel code benchmark(1/2): overview

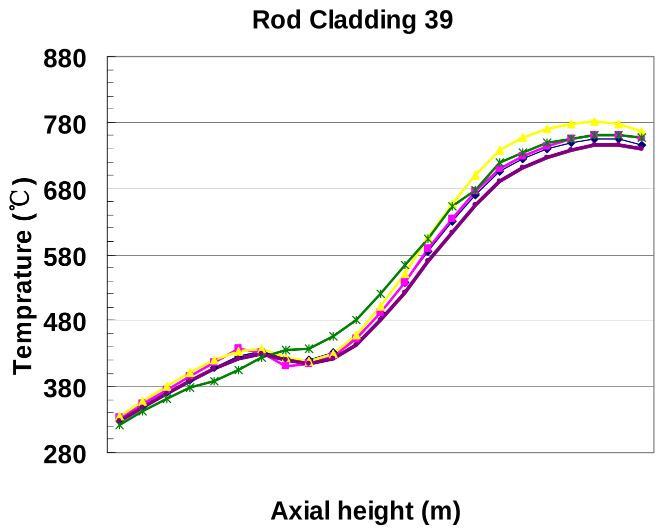
- **Aim: To verify the existing sub-channel codes;**
- **Participant: SJTU, Tsinghua U, CIAE, SNERDI;**
- **Moderator channel mode, inlet flow distribution;**



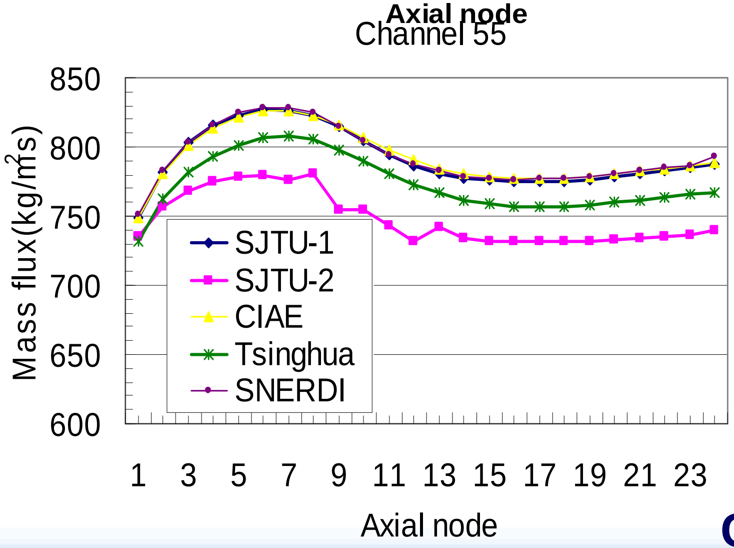


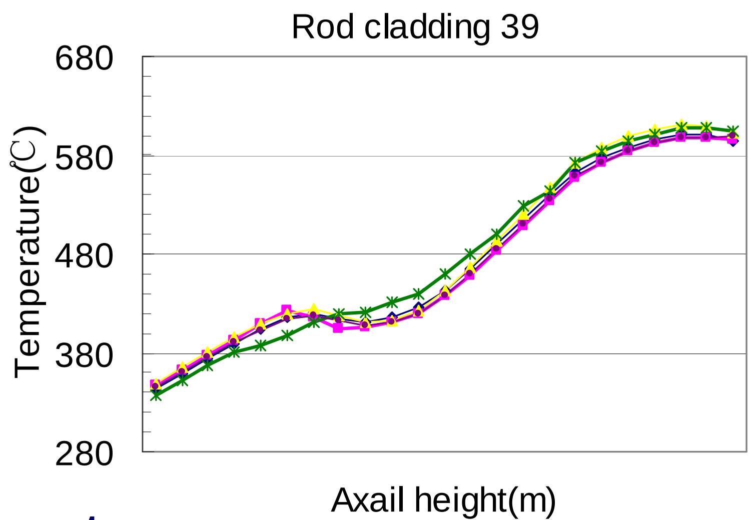
Sub-channel code benchmark(2/2): results





Co-current

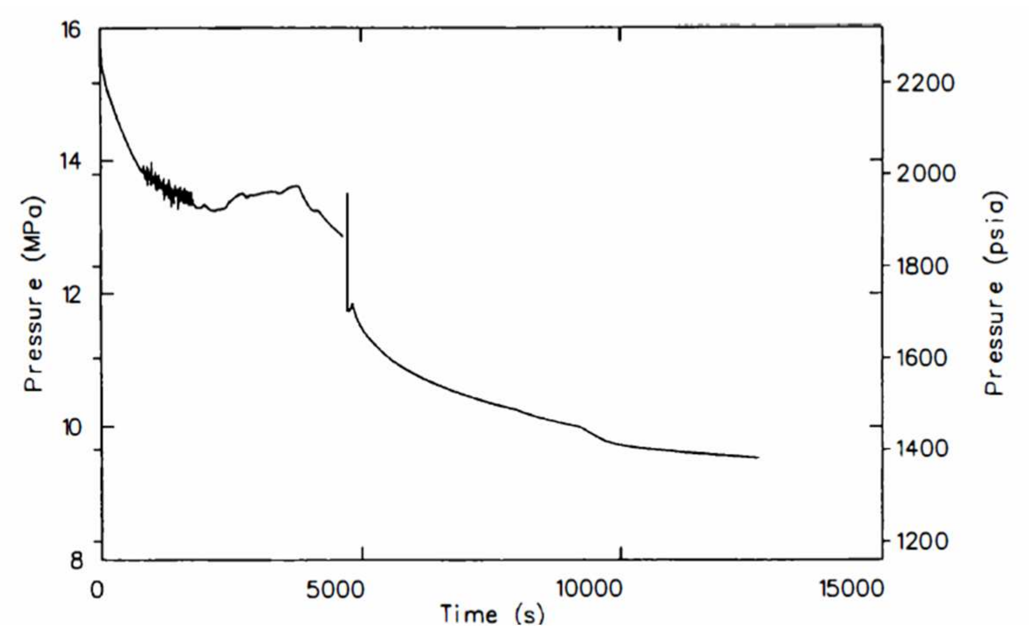


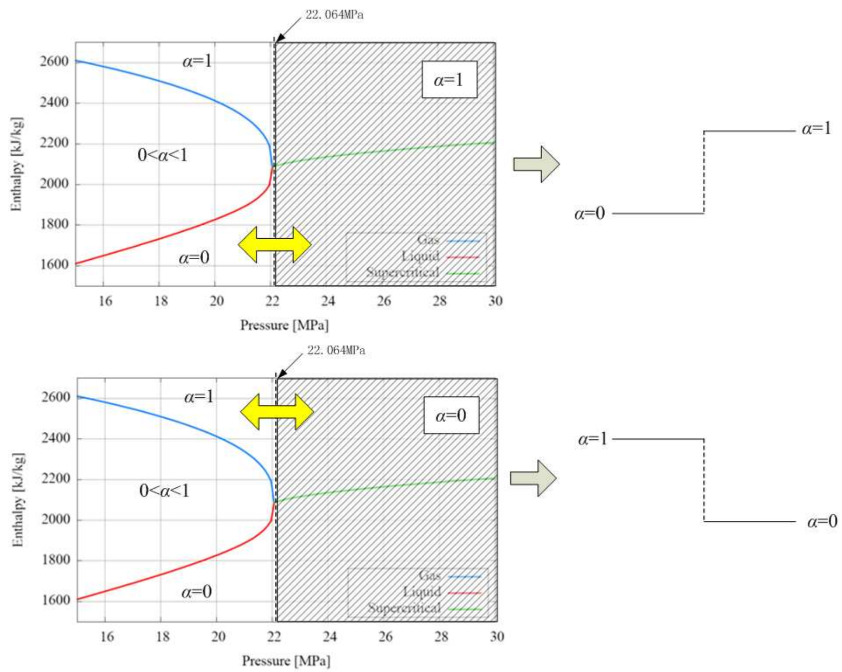


Counter current

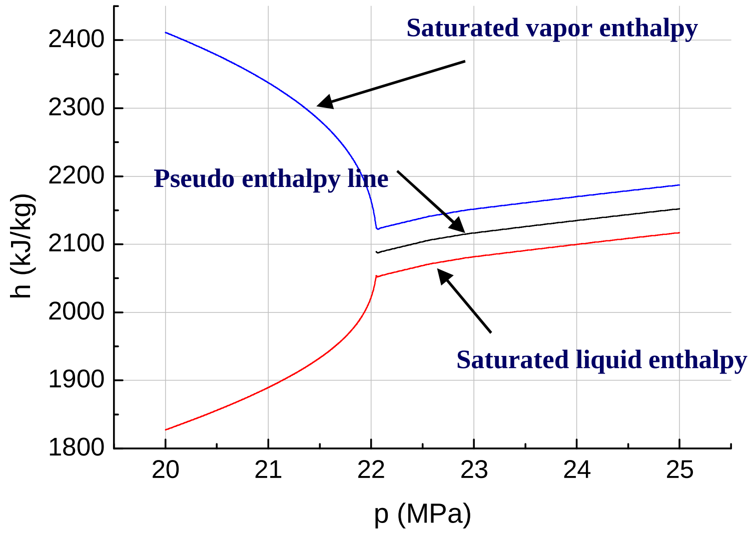
System code application

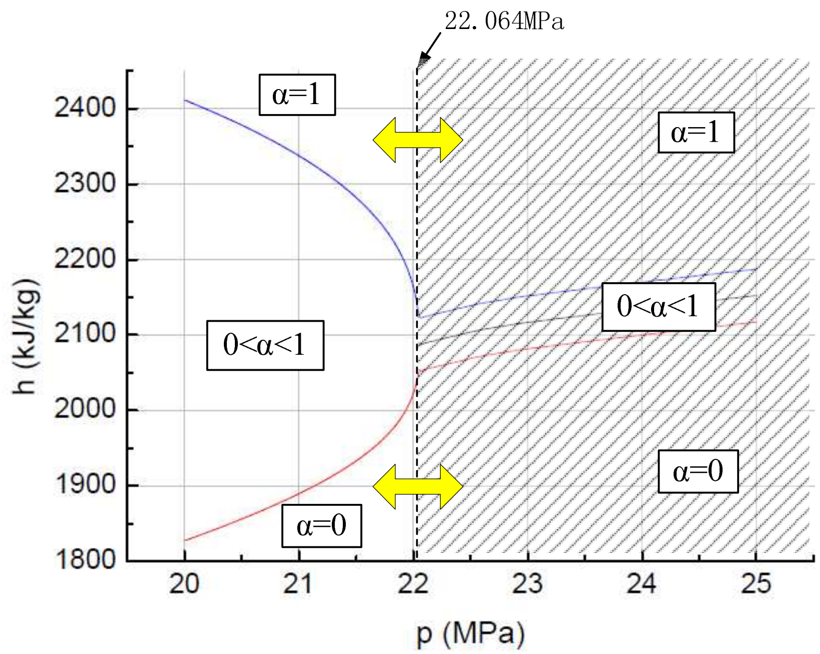
- **Widely used in the current LWR safety analysis: Relap-5;**
- **LOCA analysis by the relap-5 code;**
- **Two-fluid model, void fraction discontinuity at the critical point;**





Pseudo two phase flow method





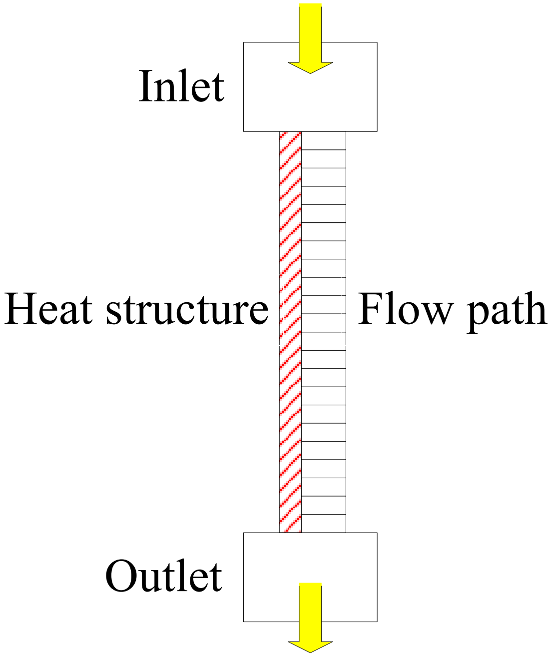
$$h_f^{\sup} = h_{p-critical} - 0.5 h_{fg}^*$$

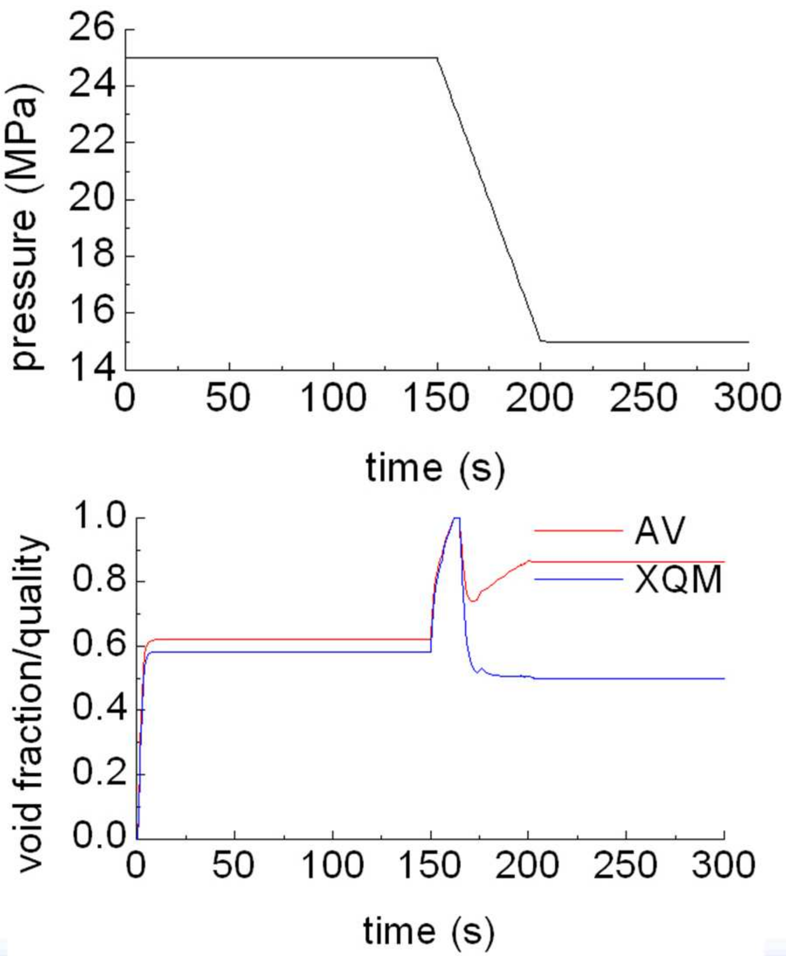
$$h_g^{\sup} = h_{p-critical} + 0.5 h_{fg}^*$$

h_{fg} is a constant defined by the pressure where the pseudo two phase begin to make sure the continuity of the real two phase regime

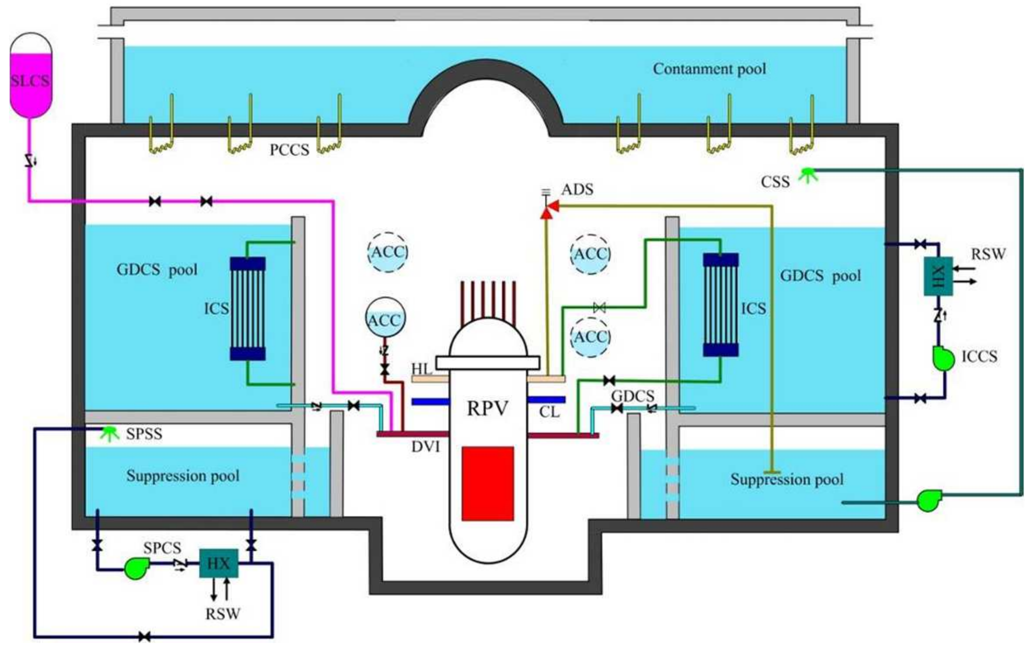
System code development: ATHLET-SC

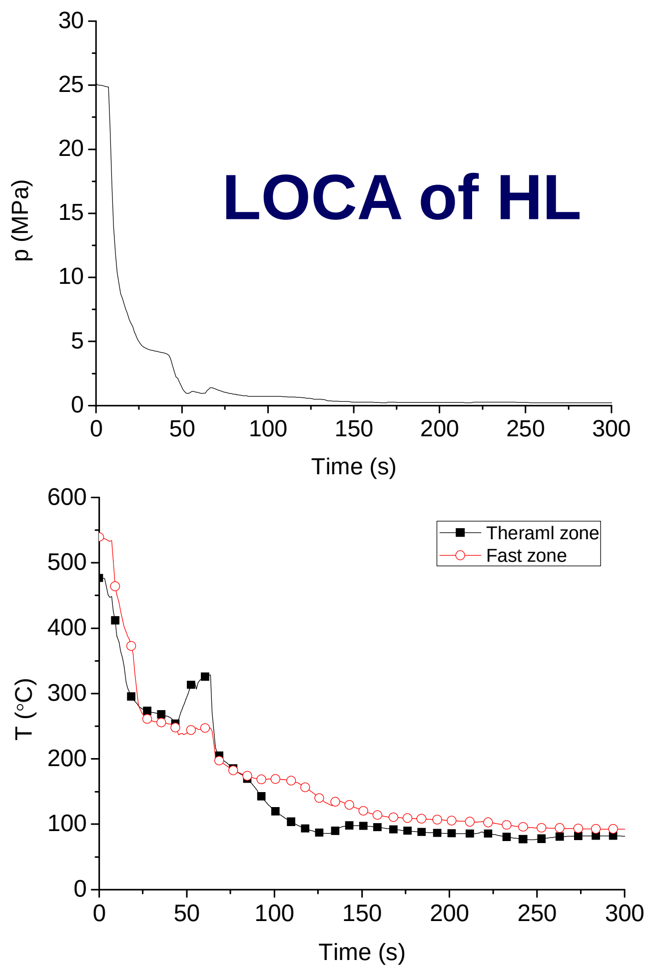
- **Based on the safety code ATHLET;**
- **To calculate the depression transient across the critical point;**





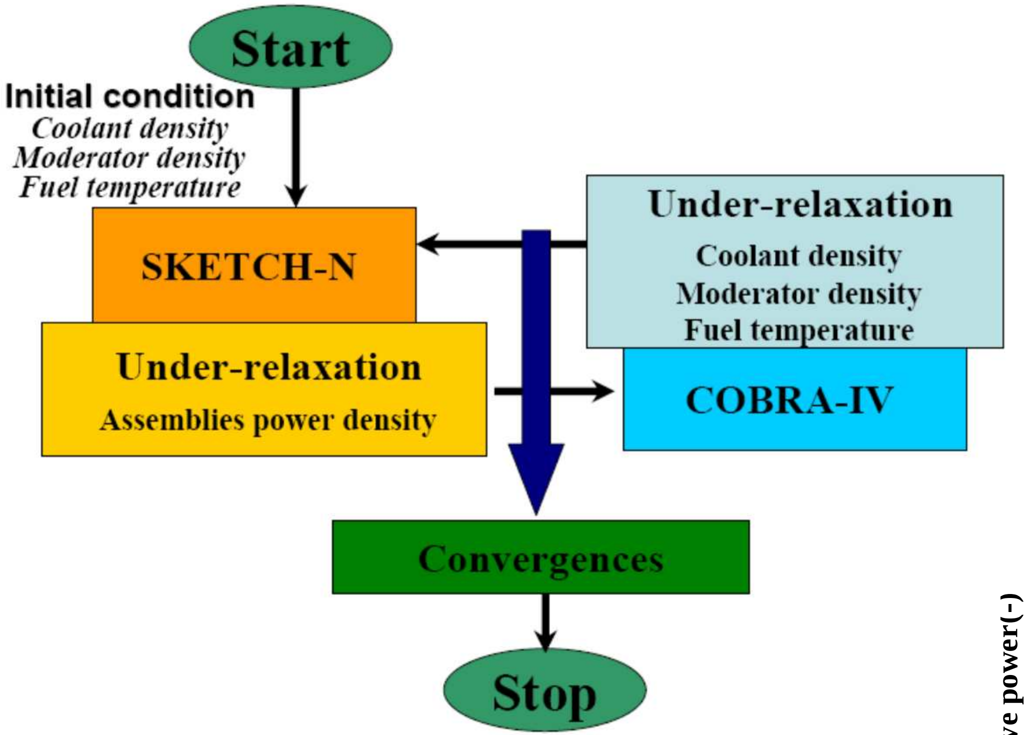
Safety analysis code

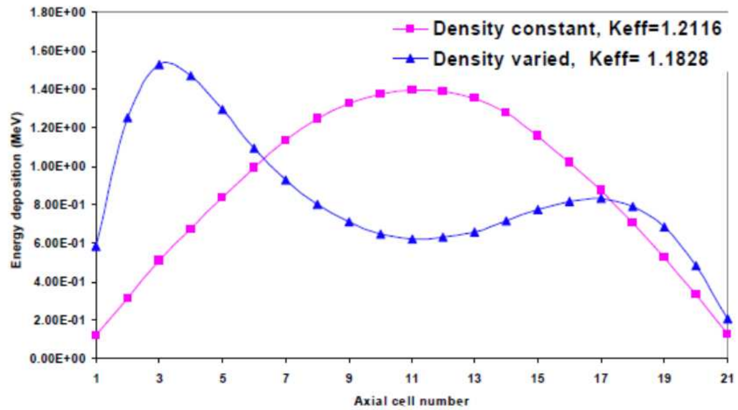


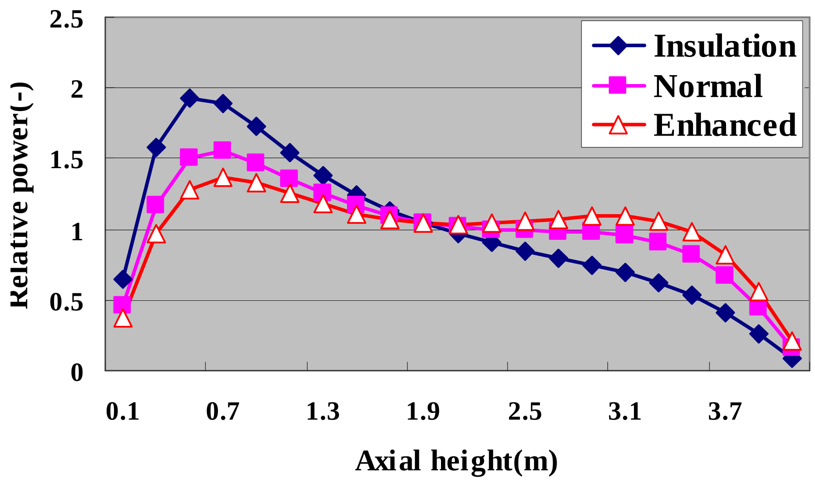


- **Based on the advanced LWR**
- **Passive design**
- **Simply system**

Coupling methods







- **Data transfer scheme**
- **Time step control**
- **Numerical stability**

Conclusion

- heat transfer review
- scaling analysis
- stability analysis
- experimental study
- challenges deriving from the geometry
- code application (CFD, Sub channel, System, Coupling)

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…Thank you for your attention!

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