GEN IV International Forum

Expertise | Collaboration | Excellence

Thermal Hydraulics of Supercritical Water Reactor (SCWR)

Prof. Xiaojing Liu

30 July 2025

cea | INL Idaho National Laboratory | PAUL SCHERRER INSTITUT PSI | KAERI | Pacific Northwest NATIONAL LABORATORY | U.S. DEPARTMENT of ENERGY Office of Nuclear Energy | 上海交通大學 SHANGHAI JIAO TONG UNIVERSITY

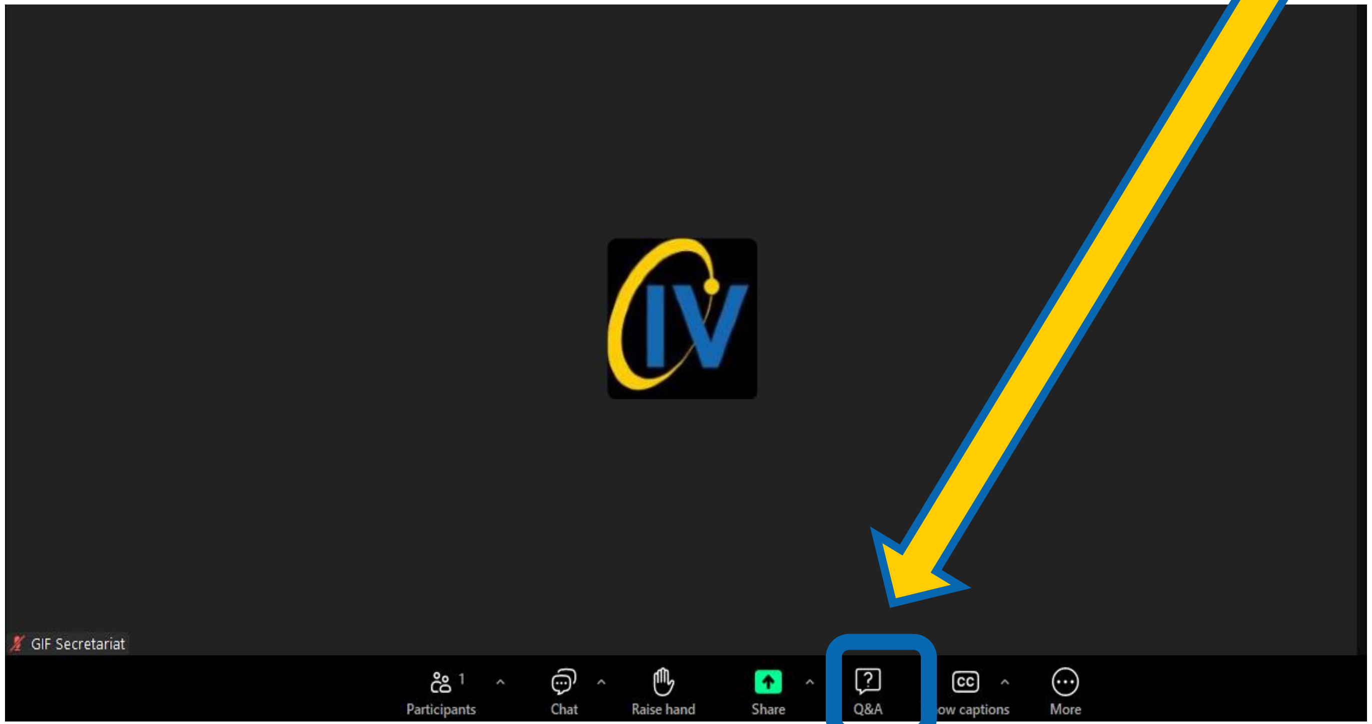
Some Housekeeping Items

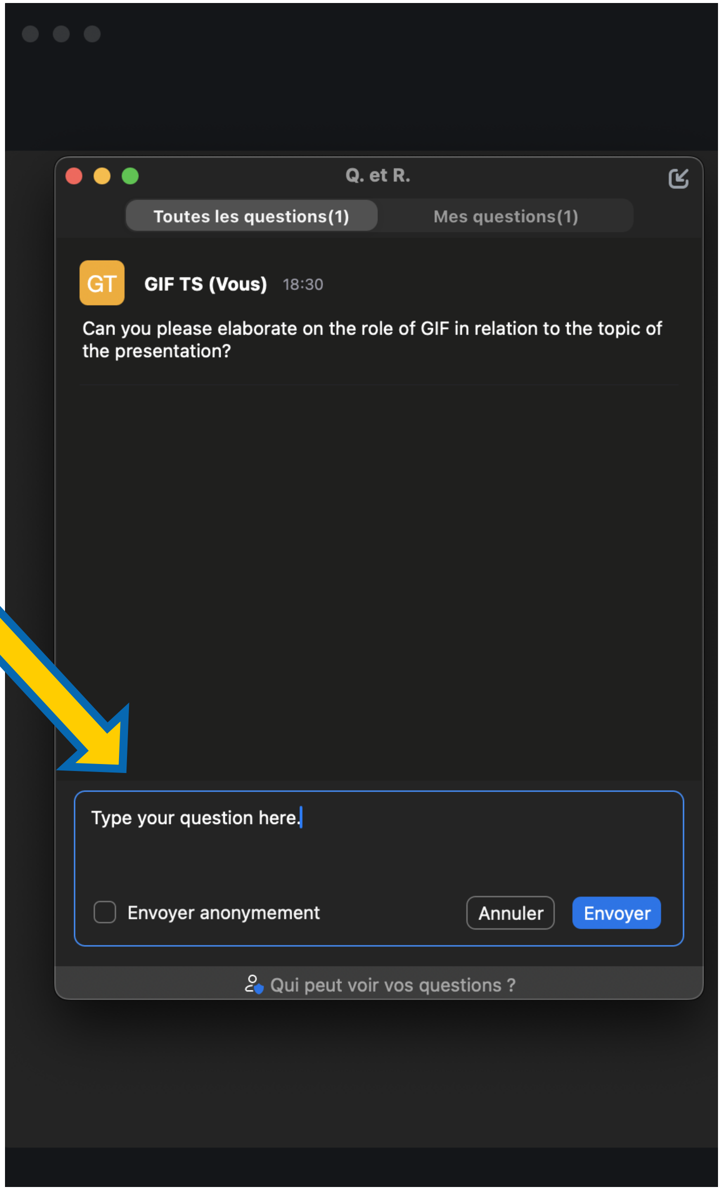
Listen through your computer	Please select the "use computer audio" option and check that your speakers/headphones are not muted.
Technical Difficulties	Search the Zoom Webinars Support https://support.zoom.com/hc/en/article?id=zm_kb&sysparm_article=KB0064143
To ask a question	Select the "Q&A" pane on your screen and type in your question
Share with others or watch it again	A video/audio recording of the webinar and the slide deck will be made available at www.gen-4.org
Please take the survey	A brief online survey will follow the webinar.

To Ask a Question – Use the Q&A function

Click the Q&A buton in the zoom menu.

You will then see a window that will allow you to type your question.





Thermal Hydraulics of
Supercritical Water Reactor (SCWR)

Prof. Xiaojing Liu

30 July 2025

Meet the Presenter

Professor **Xiaojing Liu** from Shanghai Jiao Tong University in China obtained his Ph.D. degree from SJTU in 2010. He was a postdoctoral fellow at the Karlsruhe Institute of Technology (KIT) in Germany from 2012 to 2013.

He is currently the director of the Shanghai integrating innovation center for digital reactors, leader of the Innovative Nuclear System Laboratory (INSL) in SJTU and has long been engaged in research on advanced and digital nuclear energy systems. He has published over 200 papers in renowned journals such as Applied Energy, Energy Conversion and Management, and Annals of Nuclear Energy.

He serves as a board member of the Nuclear Reactor Thermal-Hydraulics Division of the Chinese Nuclear Society, Associate editor of ASME Journal of Nuclear Engineering and Radiation Science (JNERS), Editorial Advisory Board member of Nuclear Engineering and Design, Youth editorial board member of Nuclear Science and Techniques and Frontiers in Energy.

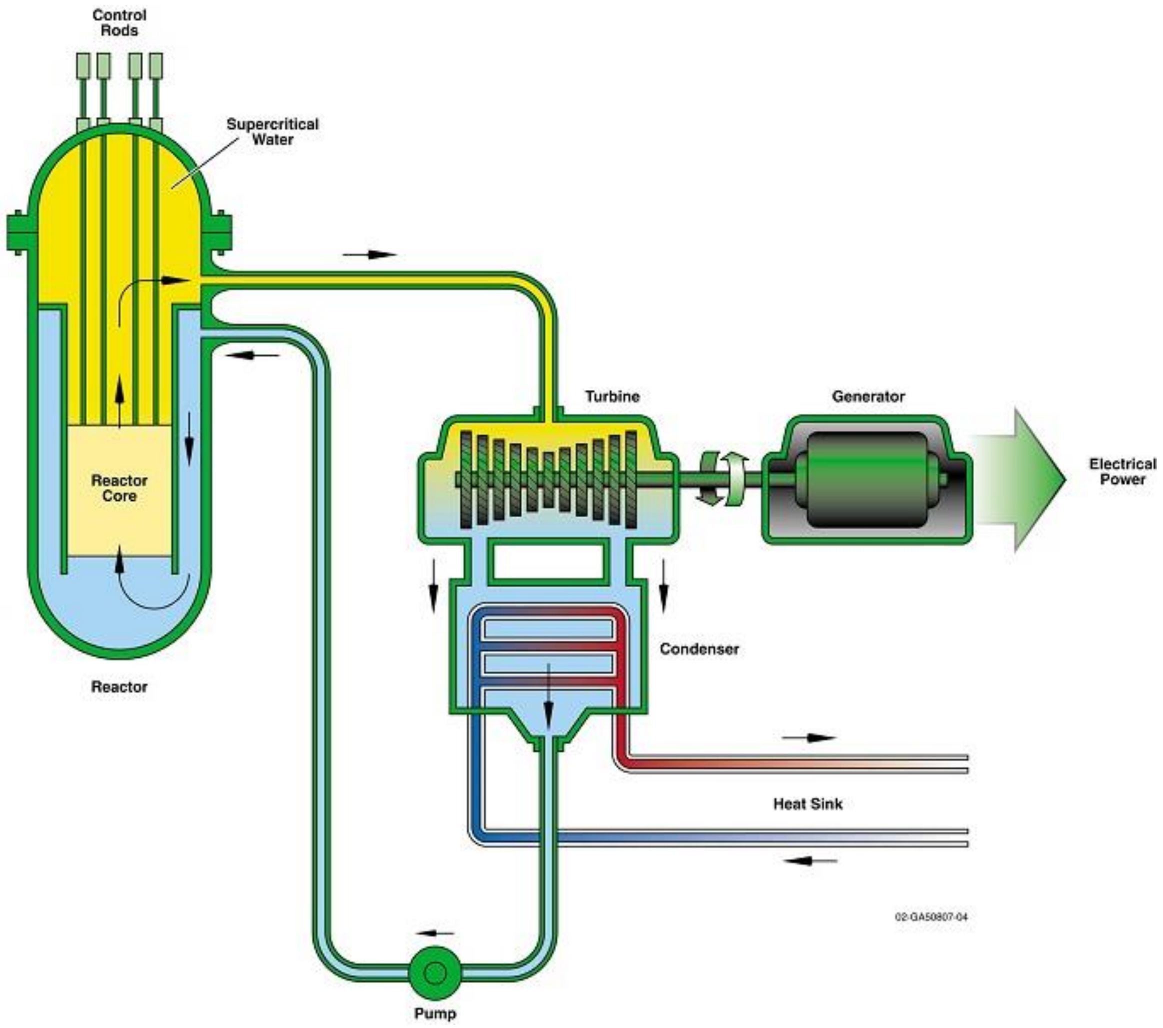
Email: xiaojingliu@sjtu.edu.cn

Introduction

Supercritical Water Cooled Reactor (SCWR)

P: 25MPa

T: 500℃



Introduction

✓Simple & compact plant systems

✓No water/steam separation

✓Low flow rate(1/8-1/5), high enthalpy coolant

✓High temperature & thermal efficiency (510 C, ~44%)

✓Flexibility of the neutron spectrum, increase the utilization of the fuel

✓Utilizations of current LWR and Supercritical FPP technologies

✓Major components are used within the temperature range of past experiences

Introduction

Features	PWR	BWR	SCWR
System structure	Two loop	one loop	One loop
Flow path in core	Once through	Recirculation	Multi paths
Flow direction	Vertical upward	Vertical upward	Up- & downward
TH parameter	Sub-critical; sub-cooled	Sub-critical, high void fraction	Supercritical
Pressure	15-16 MPa	7 MPa	25 MPa
Temperature	290°C – 330°C	215°C – 285°C	280°C – 500°C
Mass flux	High	Medium	low
Geometry	Large FA	Small FA	both
Lattice	Square, wide		Semi-tight
Spacers	Grid	Grid	Grid & wire wrap
Moderator channel	No	yes	Co- & count current flow
Design criteria	Fuel temperature & CHF		Temperature

Introduction

- Extreme operating conditions

- high pressure
- high temperature
- high heat flux
- neutron irradiation

- Challenges in core/fuel assembly design

- large property variation
- non-uniformity of moderation
- sensitive to hot channel factor
- non-uniformity of local heat transfer
- Blockage of the bundle
- upper limit of cladding temperature

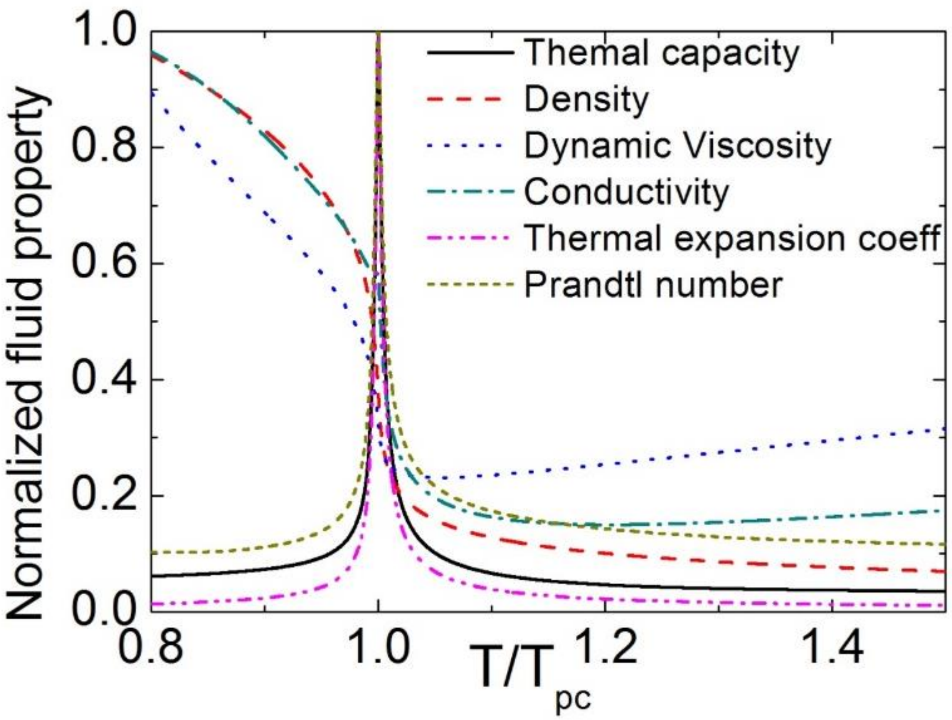
Large number of FA and Core designs

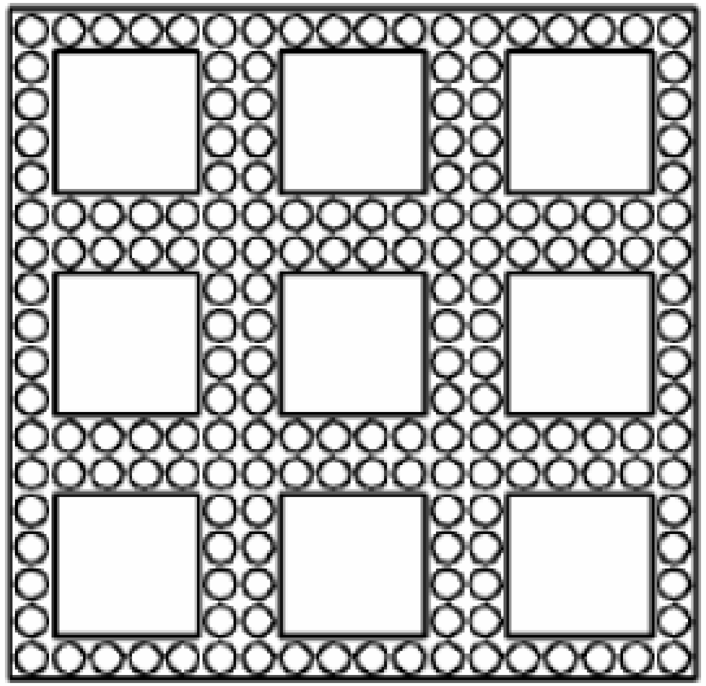
Introduction

Supercritical Water Cooled Reactor (SCWR)

P: 25MPa

T: 500℃

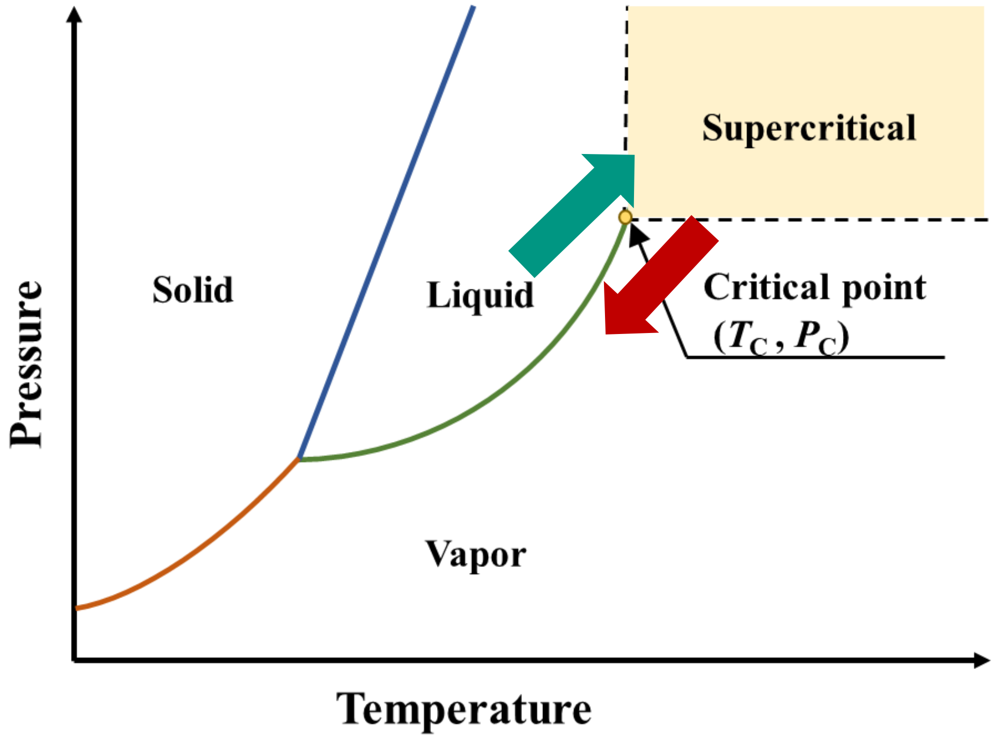




Introduction

Supercritical Water Cooled Reactor (SCWR)

- **Supercritical condition**
  - Single-phase
  - No Boiling crisis
- **Trans-critical transient**
  - Start-up
  - Shut-down
  - Accident



Contents

Supercritical condition

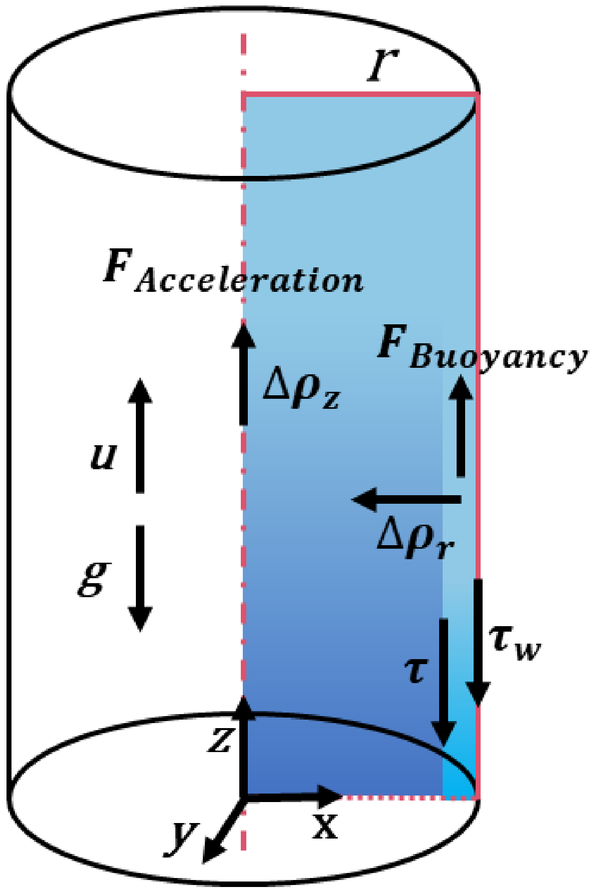
- **Heat transfer databank at supercritical condition**

  - **More than 90 000 data points**
    - **Supercritical H_2O : 31 516 data points**
    - **Supercritical R134a : 47 075 data points**
    - **Supercritical CO_2: 21 113 data points**

Pressure (MPa)	Mass flux (kg/m^2s)	Heat flux (MW/m^2)	Tube diameter (mm)
22.3 - 41.0	100 - 3600	0.1 - 9.4	1.3 - 46.0

Supercritical H_2O databank

Supercritical condition



- **Acceleration effect: Main flow direction**

$$\pi_A \propto \frac{\partial \rho}{\partial z} \propto \frac{\beta q}{c_p G}$$

- **Buoyancy effect: Radial direction**

$$\pi_B \propto \frac{\partial \rho}{\partial y} \propto \frac{\beta D q}{\lambda} \propto \pi_A \cdot Re \cdot Pr$$

Supercritical condition

$$h = 0.023 \cdot Re^{0.8} \cdot Pr^{\frac{1}{3}} \cdot \frac{\lambda}{D} \cdot \mathrm{F_1} \cdot \mathrm{F_2}$$

$$\mathrm{F_1} = \begin{cases} 0.98 & \pi_\mathrm{A} < 1.75 \cdot 10^{-4} \\ 0.85 + 0.056 \cdot (10^4 \cdot \pi_\mathrm{A})^{1.5}, & 1.75 \cdot 10^{-4} < \pi_\mathrm{A} < 3.75 \cdot 10^{-4} \\ \dfrac{13.2}{4.5 + (10^4 \cdot \pi_\mathrm{A})^{1.35}} & \pi_\mathrm{A} > 3.75 \cdot 10^{-4} \end{cases}$$

$$\mathrm{F_2} = \begin{cases} 0.96 \cdot \left(\dfrac{\mathrm{Pr}}{2.5}\right)^{0.265}, & \mathrm{Pr} < 2.5 \\ 1.66 \cdot \left(\dfrac{\mathrm{Pr}}{2.5}\right)^{-0.333}, & \mathrm{Pr} > 2.5 \end{cases}$$

Supercritical condition

➢ Model validation

	Supercritical H_2O (N=23547)		Supercritical R134a (N=47075)		Supercritical CO_2 (N= 21113)	
	μ	σ	μ	σ	μ	σ
Present Model	**-0.008**	**0.163**	**0.035**	**0.163**	**0.135**	**0.247**
Cheng correlation	-0.037	0.171	0.112	0.120	0.038	0.208
Bishop correlation	-0.082	0.103	-0.063	0.076	-0.058	0.132
Jackson correlation	-0.101	0.143	-0.005	0.096	-0.076	0.136

Scaling analysis

- **Object considered**

  circular tubes, vertical oriented

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

  tube diameter

  heated length *(neglected for developed flow)*

  pressure

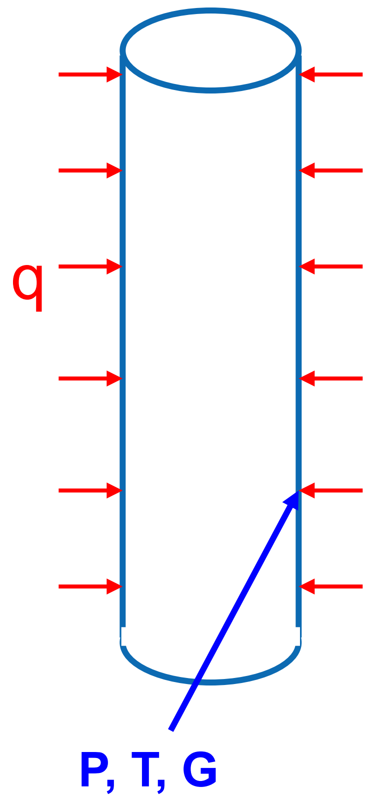
  fluid temperature

  mass flux

  heat flux
- **Parameter to be studied**

  heat transfer coefficient, or

  wall temperature



Scaling analysis

Required parameters in prototypical fluid, water:

D_P, p_P, T_P, G_P, q_P

$$f_D = \frac{D_M}{D_P} = 1.0$$

$$f_P = \frac{P_M}{P_P} = \frac{P_{C,M}}{P_{C,P}}$$

$$f_\theta = \frac{\theta_{B,M}}{\theta_{B,P}} = 1.0$$

$$f_G = \frac{G_M}{G_P} = \frac{\Pr_{B,P}^{5/12}}{\Pr_{B,M}^{5/12}} \cdot \frac{\mu_{B,M}}{\mu_{B,P}}$$

$$f_q = \frac{q_M}{q_P} = \frac{\lambda_{B,M}\left(T_{PC} - T_C\right)_M}{\lambda_{B,P}\left(T_{PC} - T_C\right)_P}$$

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

D_M, p_M, T_M, G_M, q_M

Experimental results in model fluid:

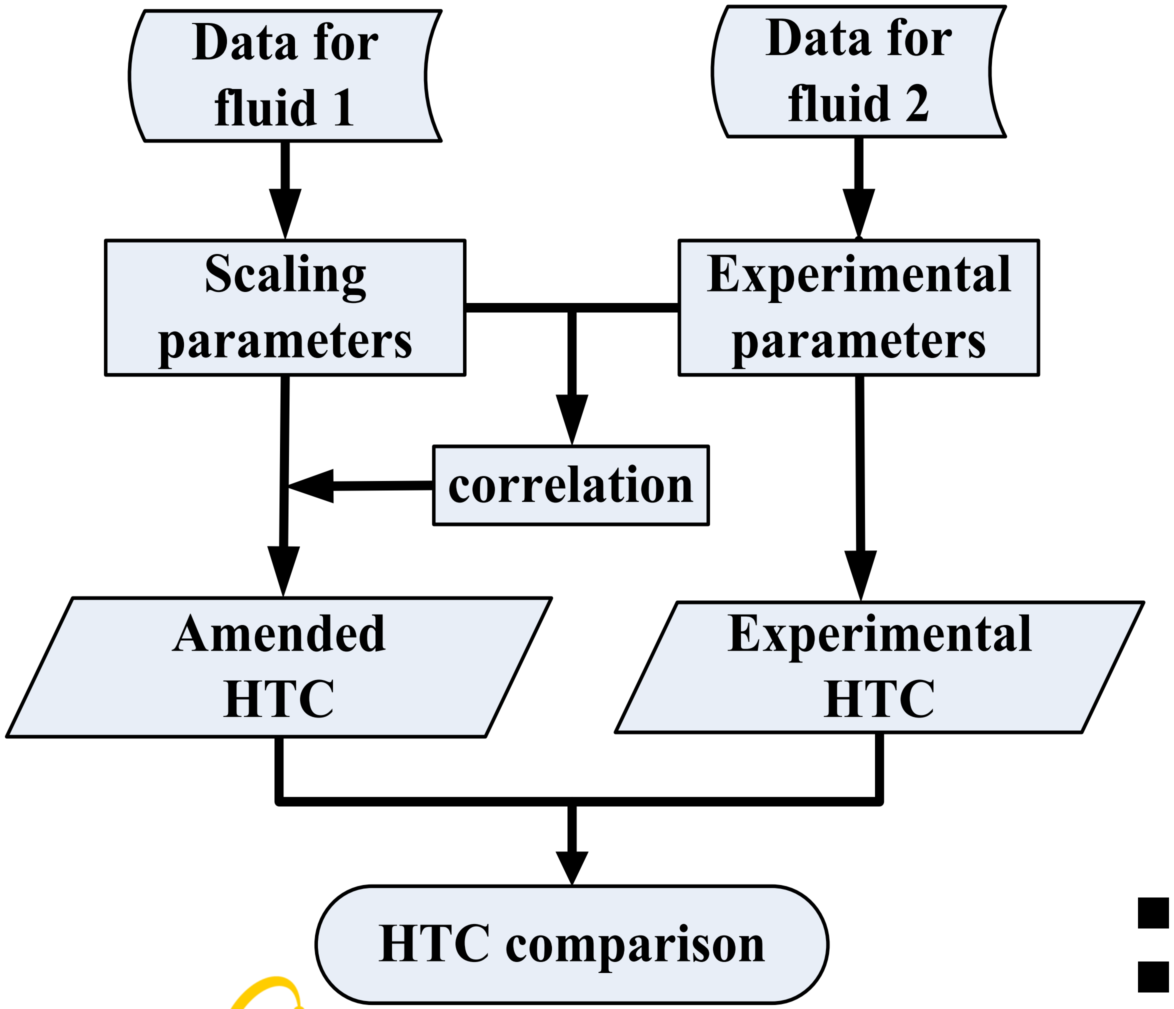
α_M

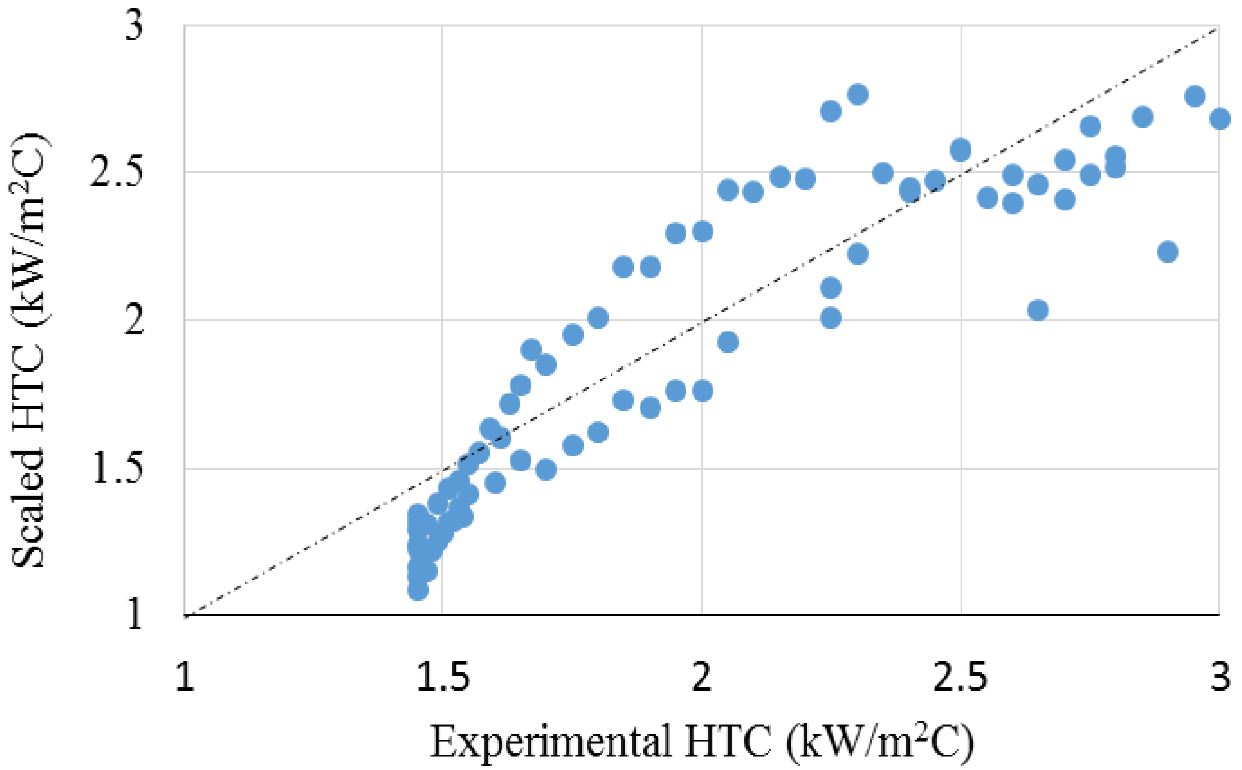
$$f_\alpha = \frac{\alpha_M}{\alpha_P} = \frac{\lambda_{B,M}}{\lambda_{B,P}}$$

Experimental results in model fluid:

α_P

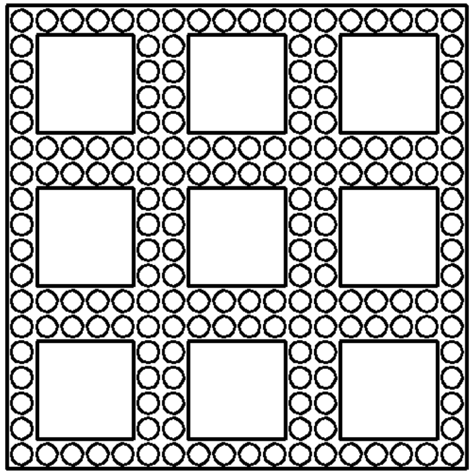
Scaling method validation

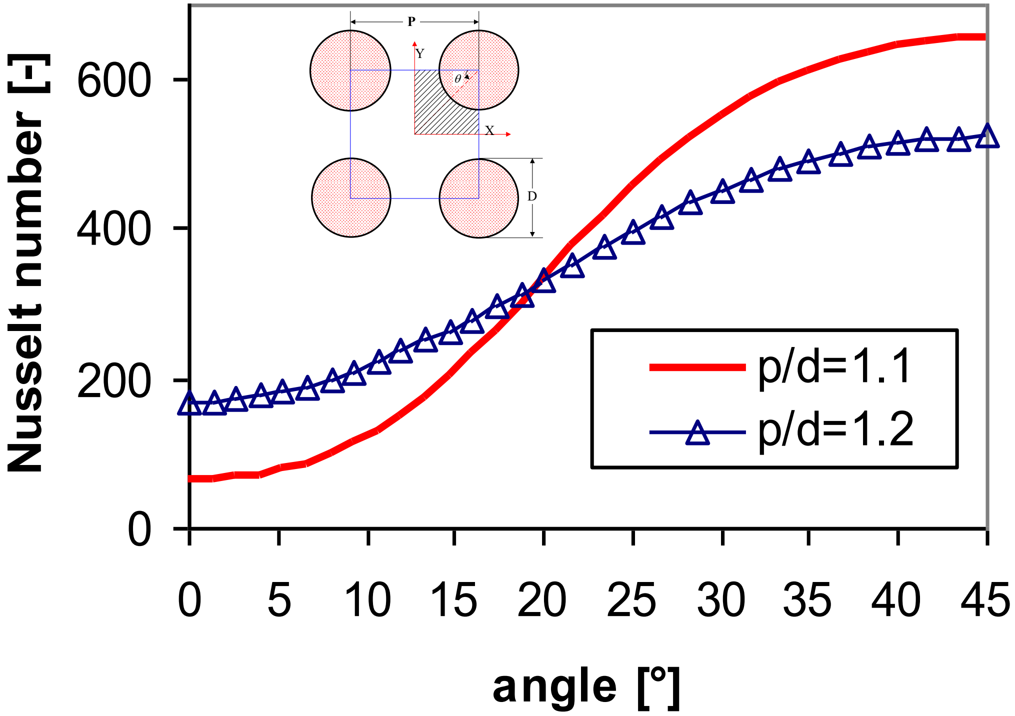


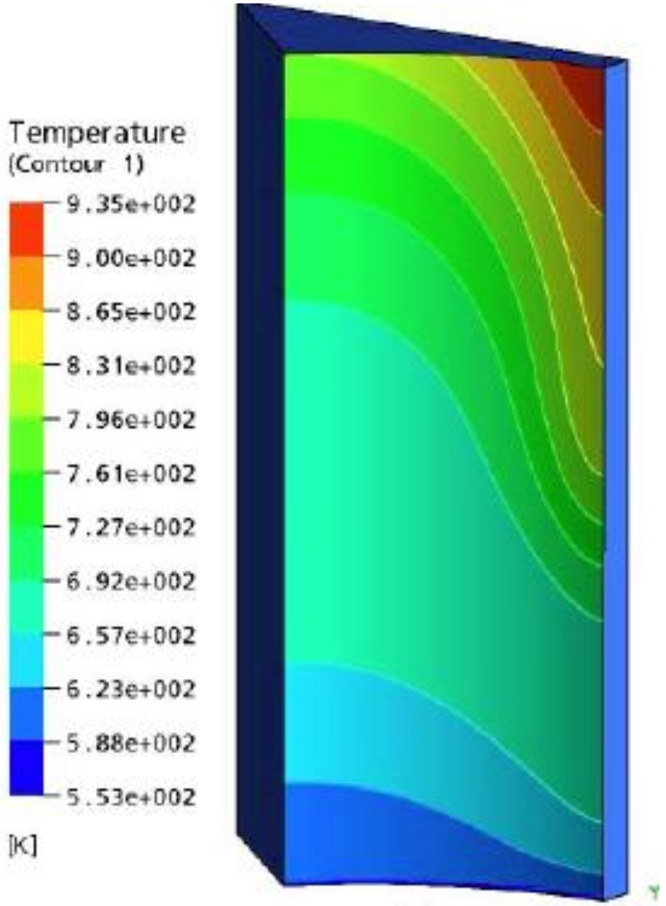


- 76 heat transfer point for R134a,
- Average deviation between the scaled heat transfer coefficient and experimental data is 11%

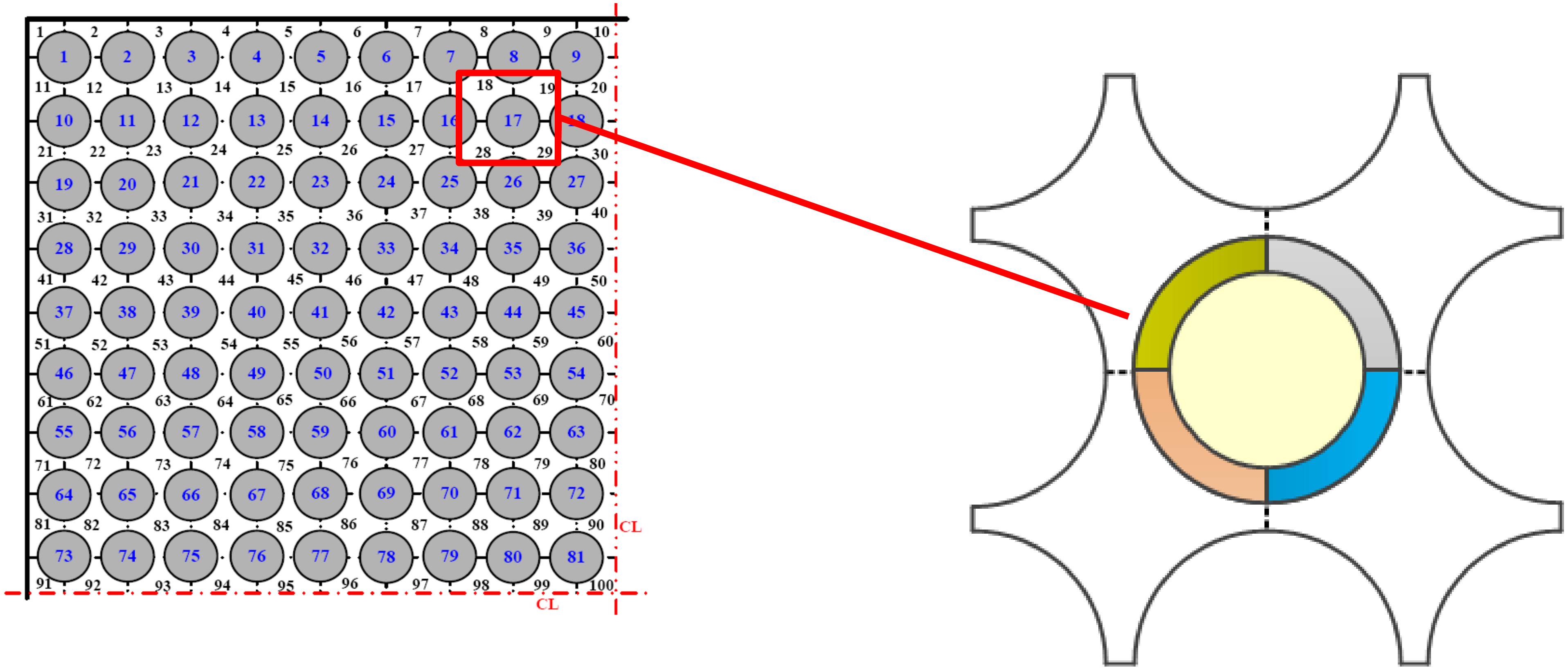
Supercritical condition: non-uniformity







Supercritical condition: non-uniformity

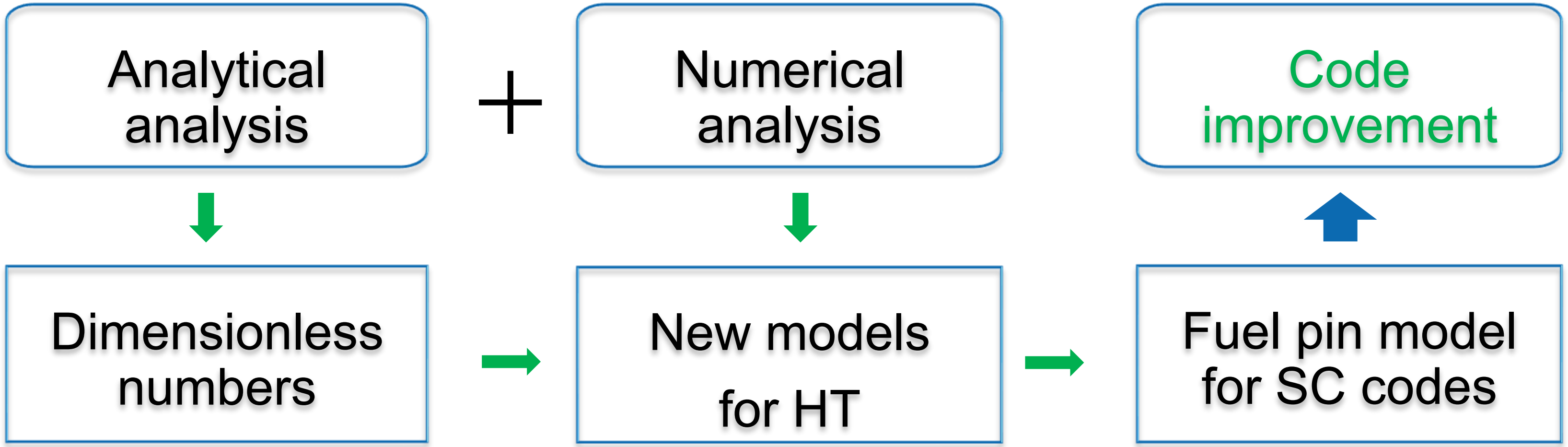


$$T = T\left(z, r, \varphi\right)$$

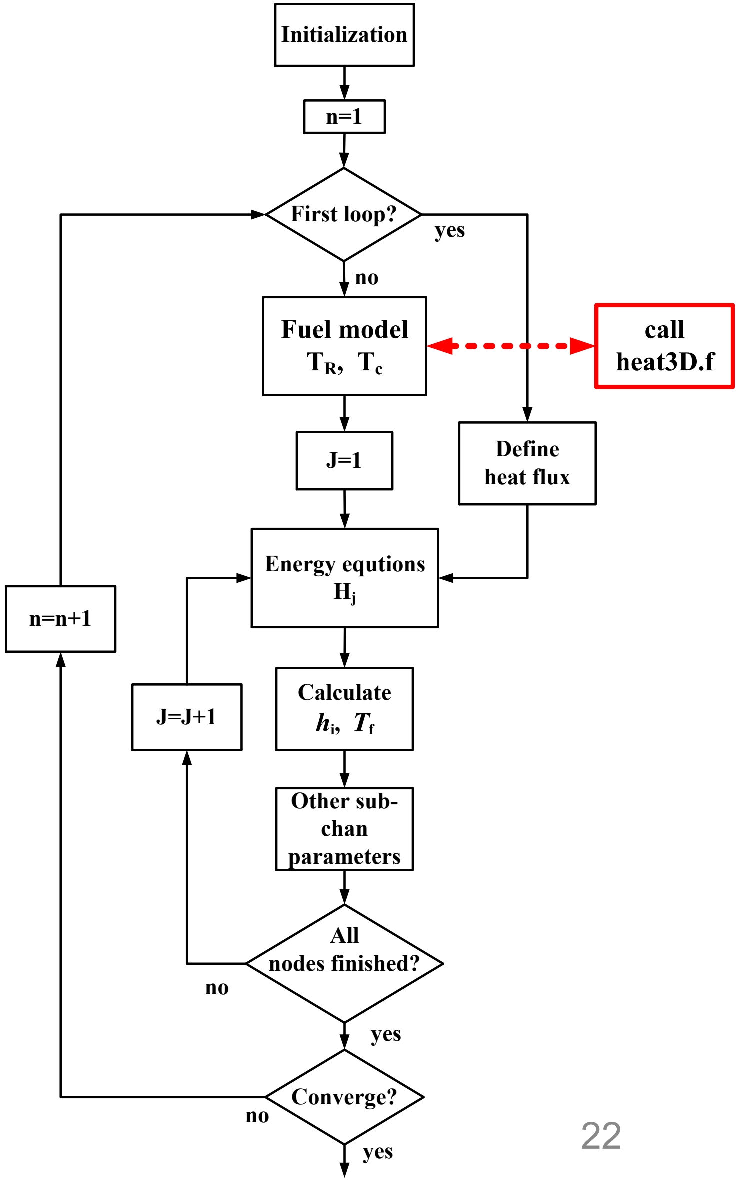
$$\frac{htc_{local}}{\overline{htc}} = f\left(\varphi, Re, Pr, \frac{p}{d}, \frac{R_{fuel}}{R_{clad}}, \frac{\lambda_{fuel}}{\lambda_{clad}}, \frac{\lambda_{clad}}{\lambda}\right)$$

Supercritical condition: non-uniformity

- Important for tight lattices &blockage
- Limited investigations & no reliable models
- not considered in sub-channel analysis



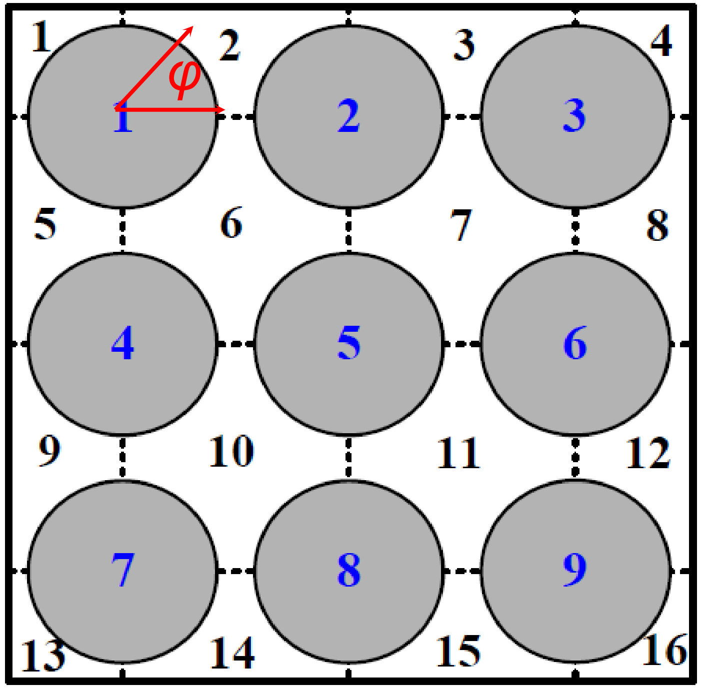
$$htc_N = 1 - \frac{\cos(4\varphi)}{1 + 46.8\left(\frac{p}{d} - 1\right)^{1.873} Pr^{0.244} \left(\frac{\lambda_{clad}}{\lambda_{coolant}}\right)^{0.229}}$$

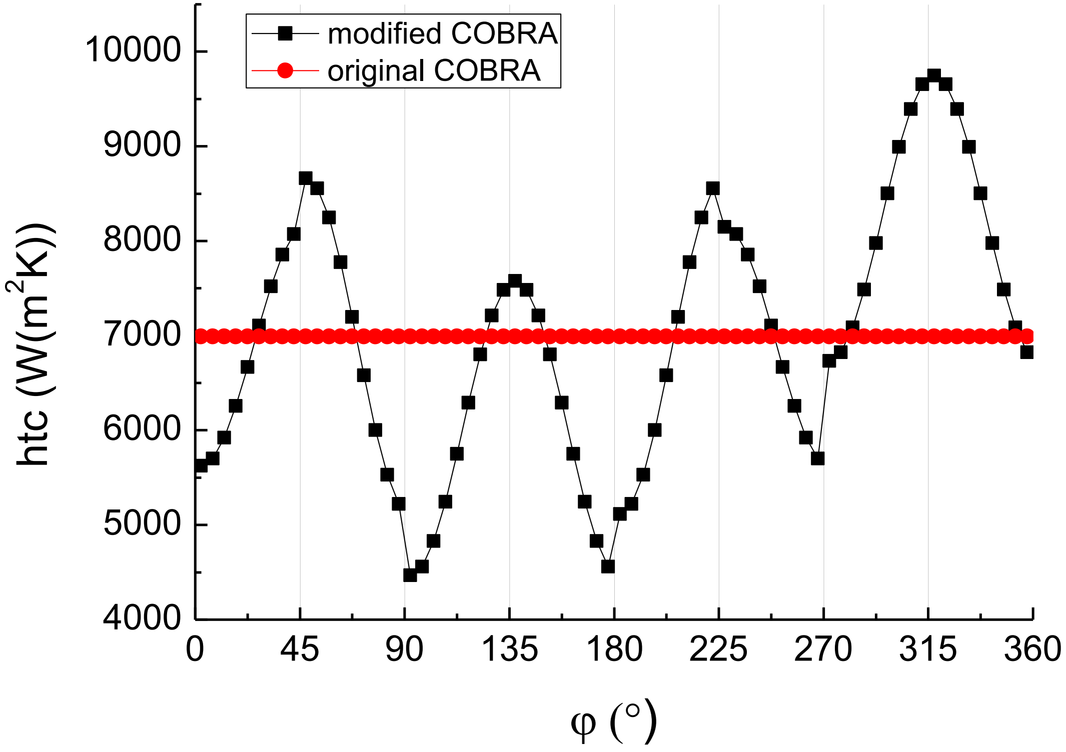


GEN IV International Forum
Expertise | Collaboration | Excellence

Supercritical condition: non-uniformity

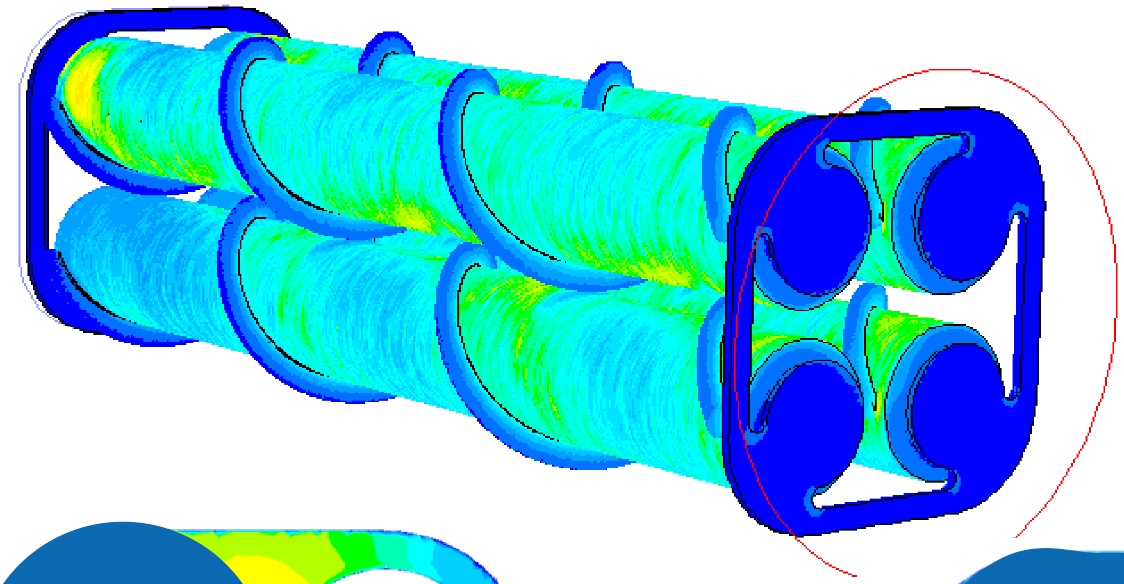
p/d -	elevation m	T_{inlet} ℃	p MPa	q” kW/m^2	G $kg/(m^2s)$
1.15	1.94	395.0	25.0	454.5	1000

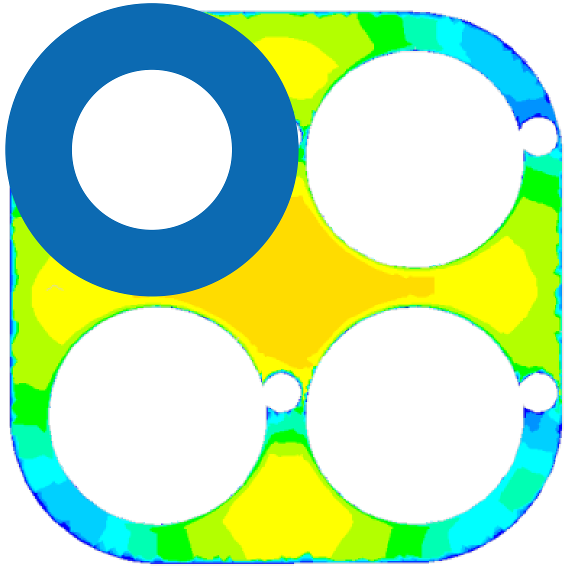




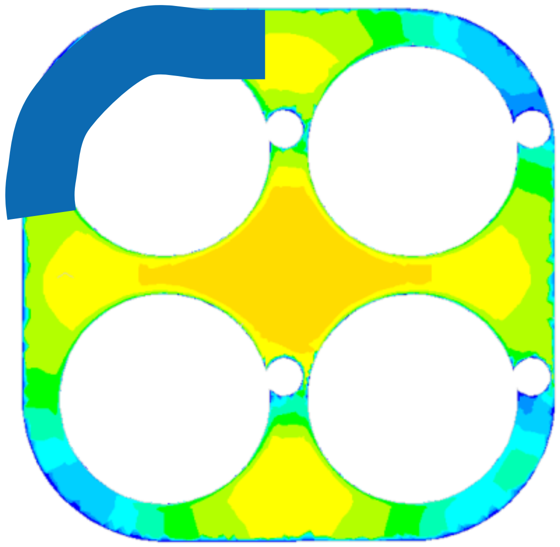
Local htc distribution around Rod 1

Supercritical condition: blockage



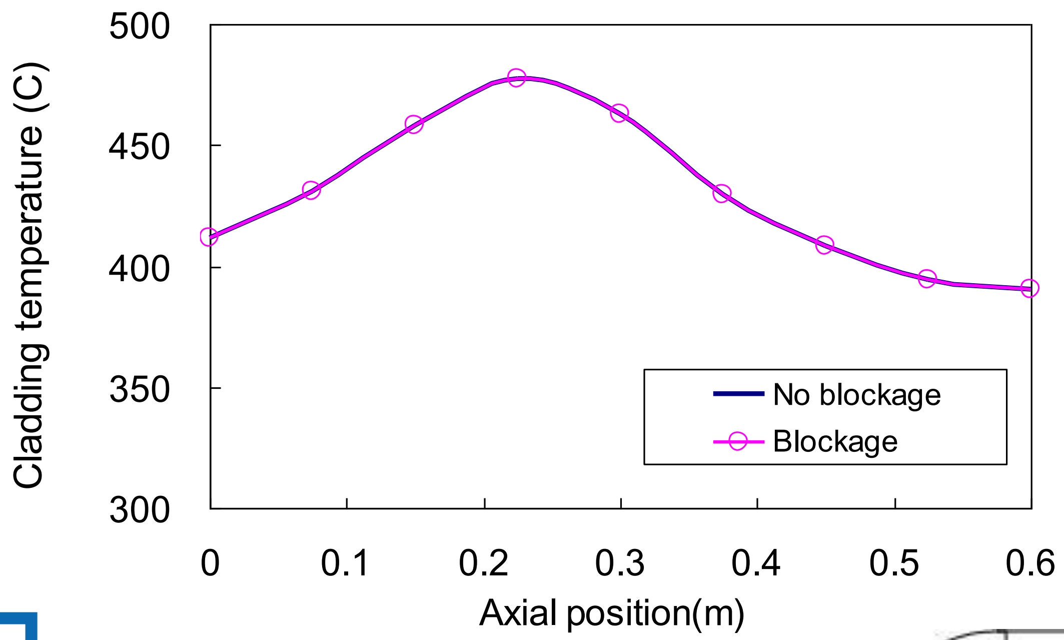


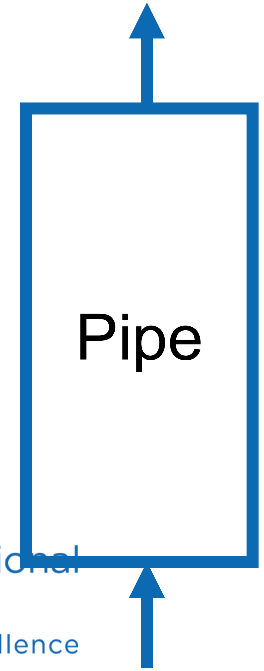
(a) 360 degree blockage of the subchannel around a rod

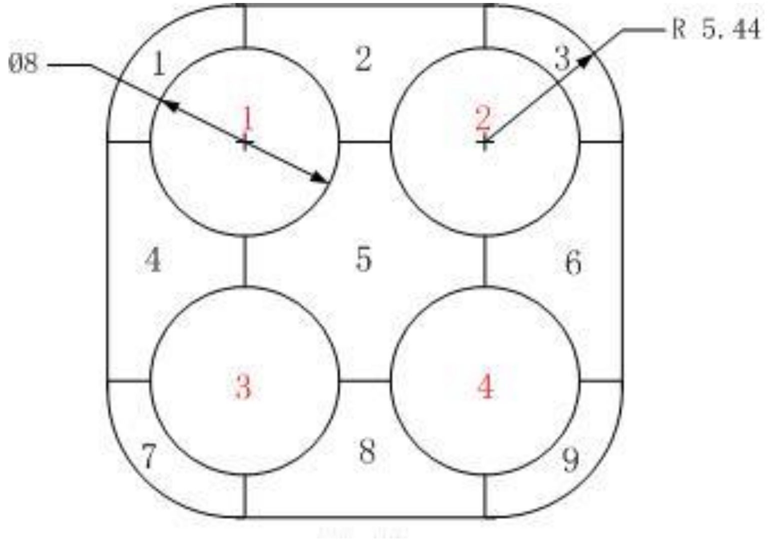


(b) 90 degree blockage of the subchannel around a rod

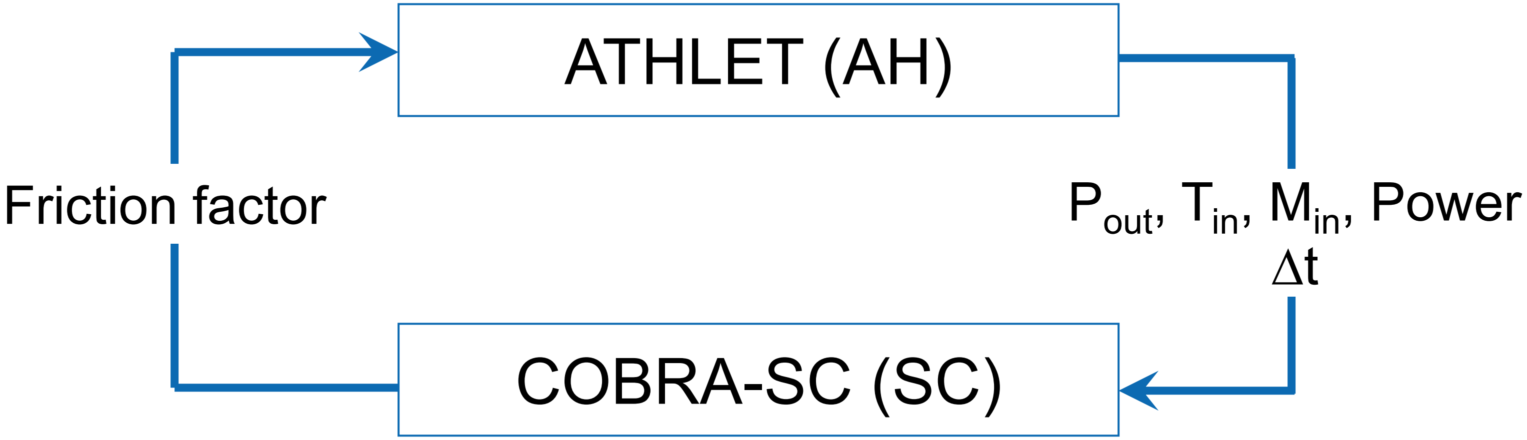
Supercritical condition: blockage







Supercritical condition: blockage

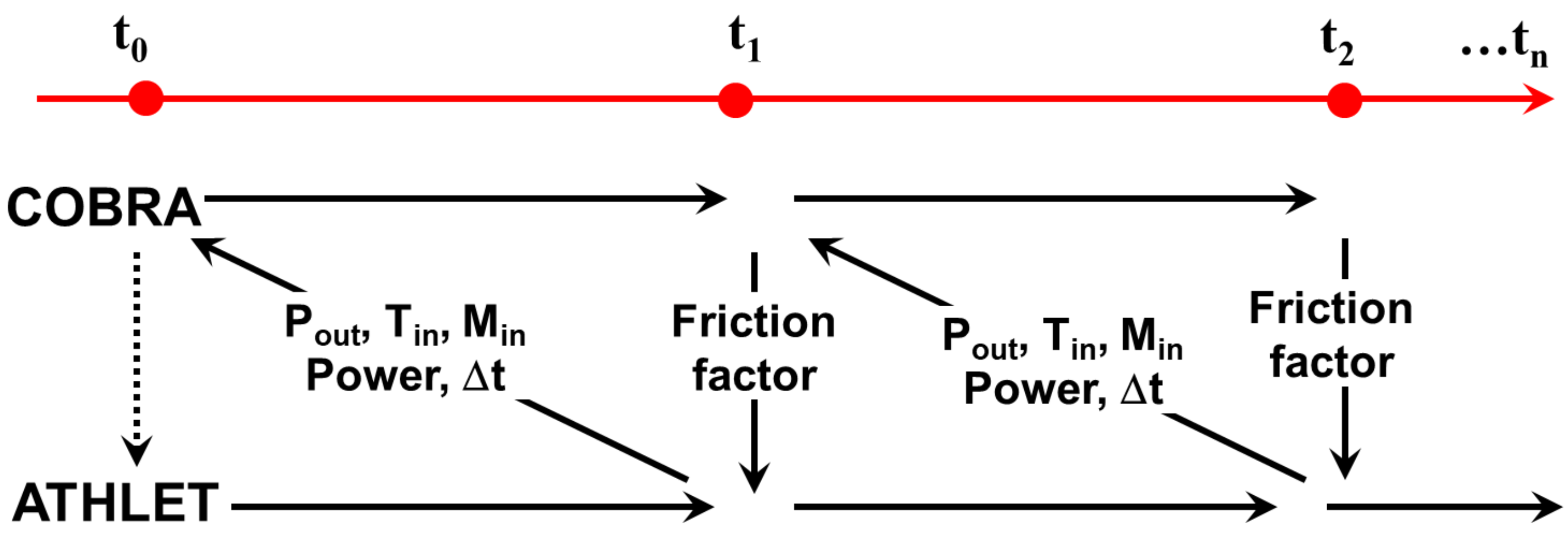


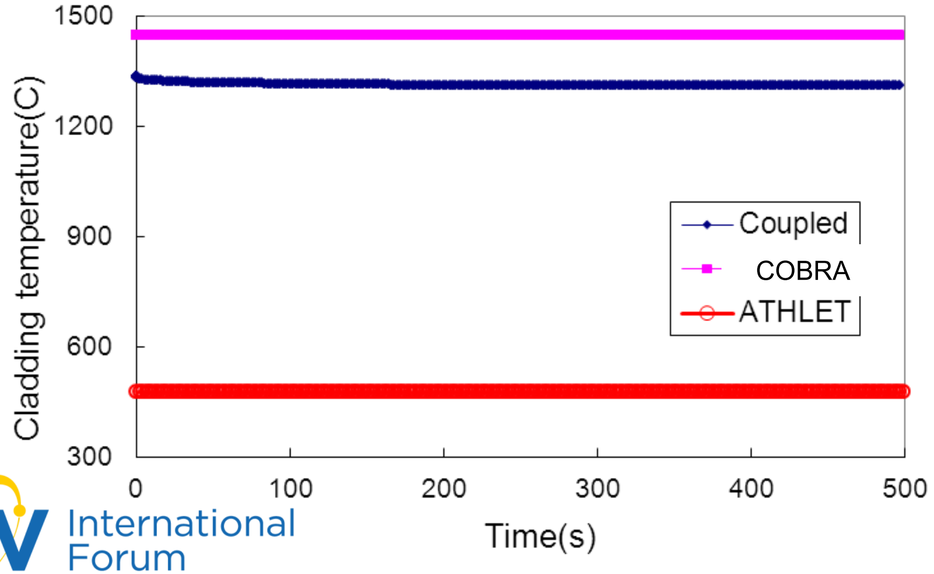
Common variables

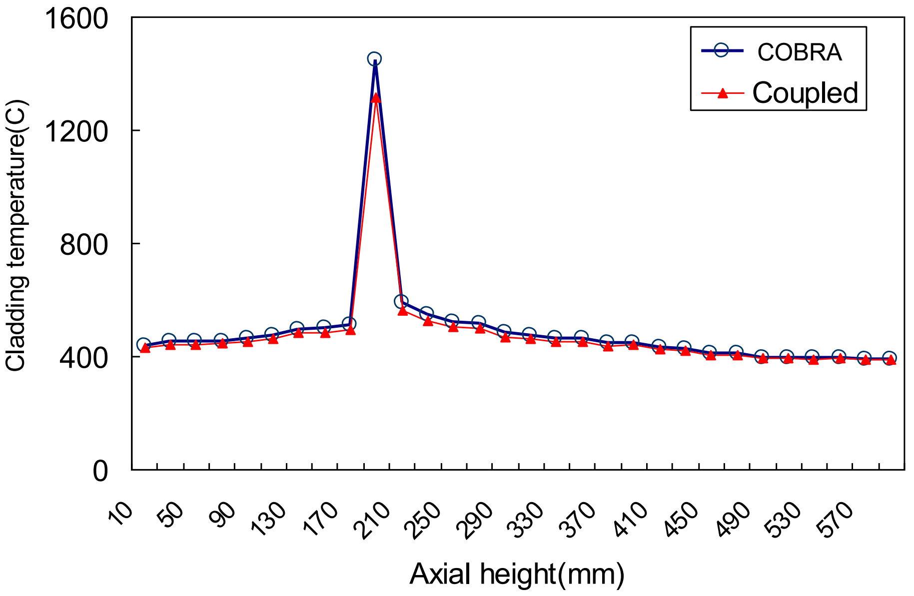
P_{out}= PRESS (outlet-CV)
T_{in} = TDOM (inlet-CV)
M_{in}= GJ (inlet-junction)
Power= rod power- heat loss from active channel to other channel
Δt = DT

Frication factor: $ALAMO_{(New)} = \Delta P_f(SC) / \Delta P_f(AH) \times ALAMO_{(old)}$

Supercritical condition: blockage



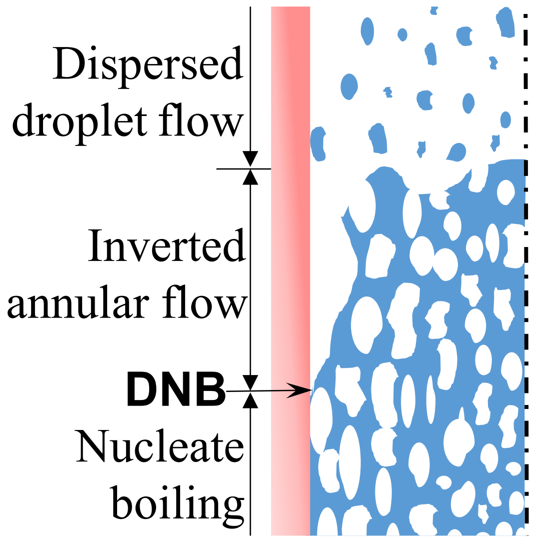




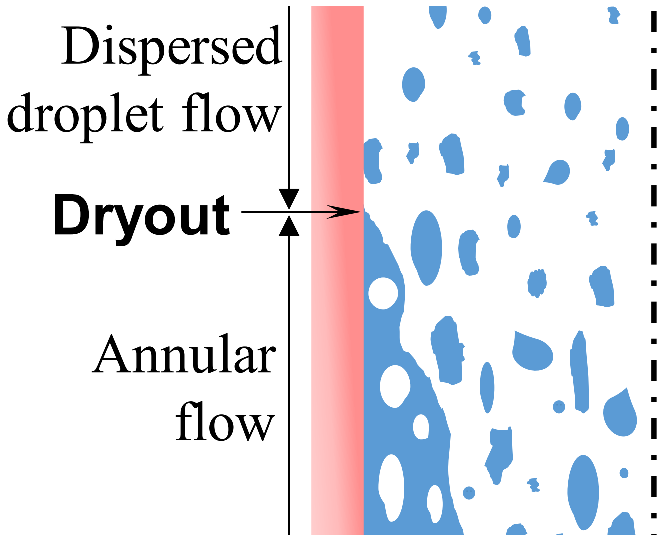
Contents

Subcritical condition

■ Boiling crisis in subcritical condition



Departure from nucleate boiling (DNB): Low quality



Dryout: High quality

Lose continuous liquid contact → **Drastic temperature rise** → **Challenge safety**

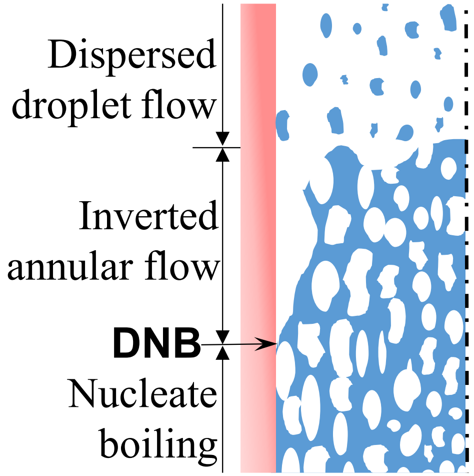
Subcritical condition- CHF

- **High-pressure CHF experimental databank**
  - **Water, R12, CO_2**
  - **Reduced pressure: P/P_C>0.7,**
  - **2652 data points, reliable checked**

	H_2O	R12	CO_2
P, MPa	15.5 - 21.5	2.9 - 3.5	6.2 - 7.1
G, kg/(m²·s)	156 - 6907	121 - 10440	494 - 2041
D_h, mm	1.9 - 24.7	3.0 - 15.8	8.0
x_C, -	-1.768 - 0.955	-0.745 - 0.902	-0.771 - 0.294
q_C, kW/m²	135.0 - 7770.0	18.0 - 991.0	53.6 - 225.2
No., -	1484	1140	28

Subcritical condition- CHF

DNB: Low quality



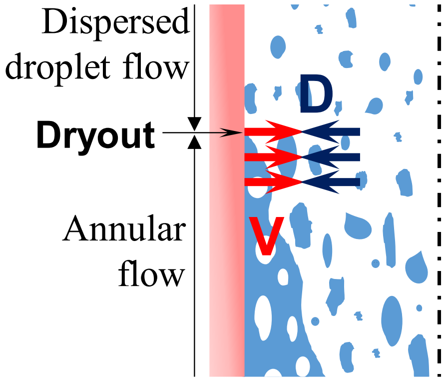
- Sublayer dryout

$$q_C = \frac{\rho_L H_{VL} \delta}{L_B / U_B}$$

- Helmholtz instability
- Drag force = Buoyancy force

$$\frac{q_C}{G H_{LV}} = f(We_V, Re_L, Pr_L, \pi_D, \pi_\rho, x_c)$$

Dryout: High quality



- Film dryout
- Evaporation rate =Deposition rate
- Work of evaporation force

= Turbulent kinetic energy of droplet

$$\frac{q_C}{G H_{LV}} = f(Re_V, We_V, \pi_\mu, \pi_\rho, x_c)$$

Subcritical condition- CHF

$$\frac{q_c}{GH_{LV}} = f(We_V) \cdot f(x_c)$$

$$f(We_V) = \max(A_1, A_2)$$

$$f(x_c) = (B_1 + B_2 + B_3) - \max(B_1, B_2, B_3) - \min(B_1, B_2, B_3)$$

$$A_1 = 7.796 \times 10^{-2} \cdot We_V^{-0.439}$$
$$A_2 = 1.530 \times 10^{-3} \cdot We_V^{-0.0803}$$
$$B_1 = 2.156 \cdot (1 - x_c)^{0.688}$$
$$B_2 = 1.841 \cdot (1 - x_c)^{2.137}$$
$$B_3 = 0.672 \cdot (1 - x_c)^{0.219}$$

- **Assessment of new CHF correlation with water experiments**

Models	ME	RMS	N
Present	**0.02**	**0.374**	**1484**
Miropol'skii	-0.233	0.510	1484
Levitan	0.548	3.223	1484
Chernobai	0.958	2.069	1484
Chen	-0.380	0.706	1254
Becker	-0.952	0.953	1188
Hall	0.133	0.424	414
Lombardi	-0.125	0.881	1188
2006 CHF LUT	0.116	0.537	1387
Katto	0.225	0.891	414
Kariya	0.148	0.960	1484
Vijayarangan	-0.593	0.793	1316
Shah	1.181	2.020	1316

Subcritical condition- CHF

- Validation of the new CHF correlation with R12 and CO_2

	R12			CO_2		
Models	ME	RMS	N	ME	RMS	N
Present	**-0.020**	**0.333**	**1140**	**0.068**	**0.304**	**28**
Miropol'skii	-0.807	0.809	1140	-0.805	0.812	28
Hall	-0.162	0.236	356	0.785	0.886	9
Lombardi	-0.349	0.487	1140	-0.607	0.620	28
Katto	0.113	0.319	356	0.002	0.376	9
Kariya	0.434	0.879	1140	0.093	0.304	28
Shah	0.368	1.169	1140	1.277	1.526	28

Subcritical condition- Post-CHF

Post-CHF experimental databank

- Water, R134a, CO_2
- More than 32 000 data points

	H_2O	CO_2	R134a	H_2O (non-uniform)
P, MPa	2.98 - 21.51	6.49 - 7.01	1.10 - 2.82	0.99 - 16.03
G, kg/(m²·s)	499.68 - 3500	497 - 1991	294.6 - 1517.4	496.6 - 3117.9
D_h, mm	2.5 - 24.7	8.0	10.0	15.0
q, kW/m²	147 - 1923	59.8 - 225.2	24.8 - 139.8	70.0 - 1587.0
x_e, -	0.001 - 0.999	0.003 - 0.965	0.263 - 0.999	0.129 - 0.999
$T_w - T_s$, ℃	8.66 – 499.68	24.56 - 213.12	30.81 - 190.81	3.74 - 540.82
No., -	9902	497	2806	18895

Subcritical condition- Post-CHF

$$Nu = F \cdot 0.023 Re_{TP}^{0.8} Pr_{W}^{0.4}$$

Non-equilibrium | Wall superheat | Two-phase property

$$F = F_1 \cdot F_2 \cdot F_3$$

$$F_1 = 8.345824 \times 10^{-3} \cdot Re_{TP}^{0.3186}$$

$$F_2 = \max(0.795 Pr_{W}^{-1.752}, 0.809 Pr_{W}^{1.287})$$

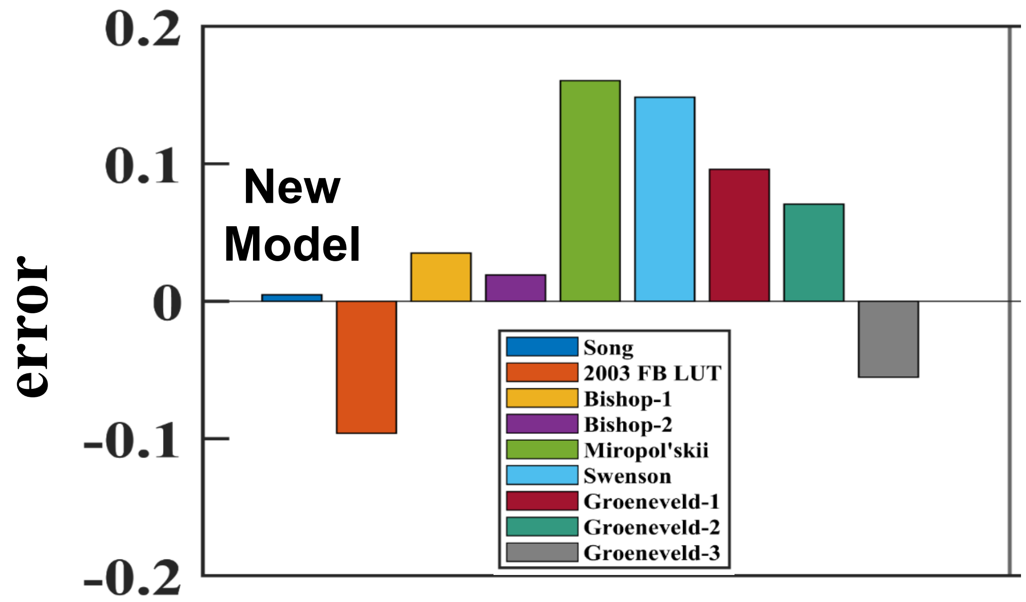
$$F_3 = \min[0.715(1 - x_e)^{-0.678}, 1.0]$$

■ Model prediction error

H_2O, -1.5%

CO_2, -7.9%

R134a, 2.7%



GEN IV International Forum
Expertise | Collaboration | Excellence

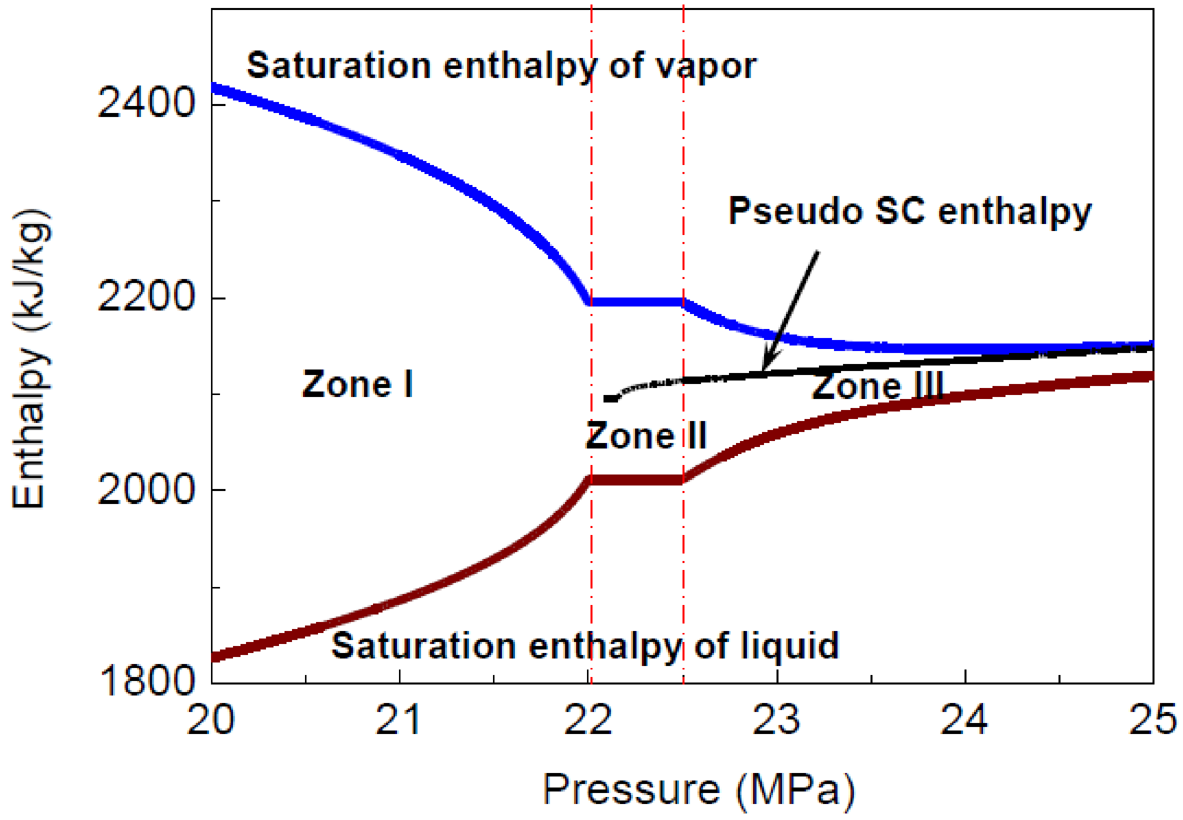
Contents

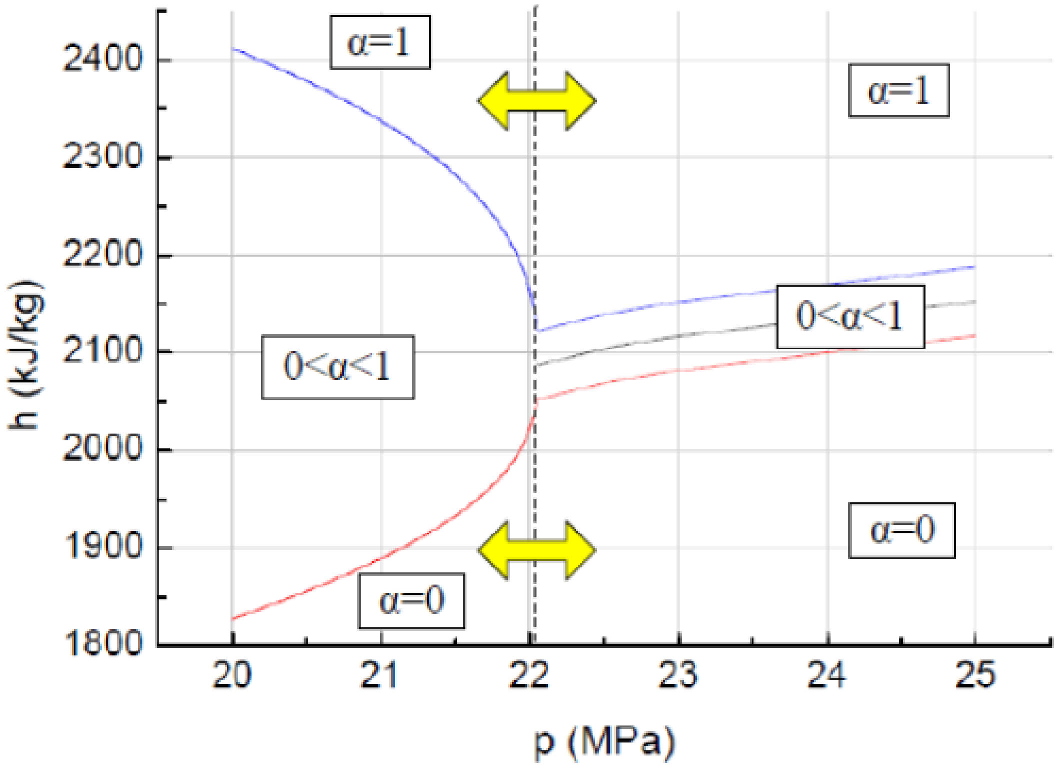
Trans-critical transient

- **ATHLET-SC**
  - System thermal-hydraulic (STH) code
  - From Gesellschaft für Anlagen- und Reaktorsicherheit (GRS)
  - Unreliable prediction for trans-critical transient
- **Modification of ATHLET-SC**
  - ✓ Supercritical heat transfer correlation
  - ✓ High-pressure post-CHF heat transfer correlation
  - ✓ High-pressure CHF model
  - ✓ Minimum film boiling temperature

Trans-critical transient

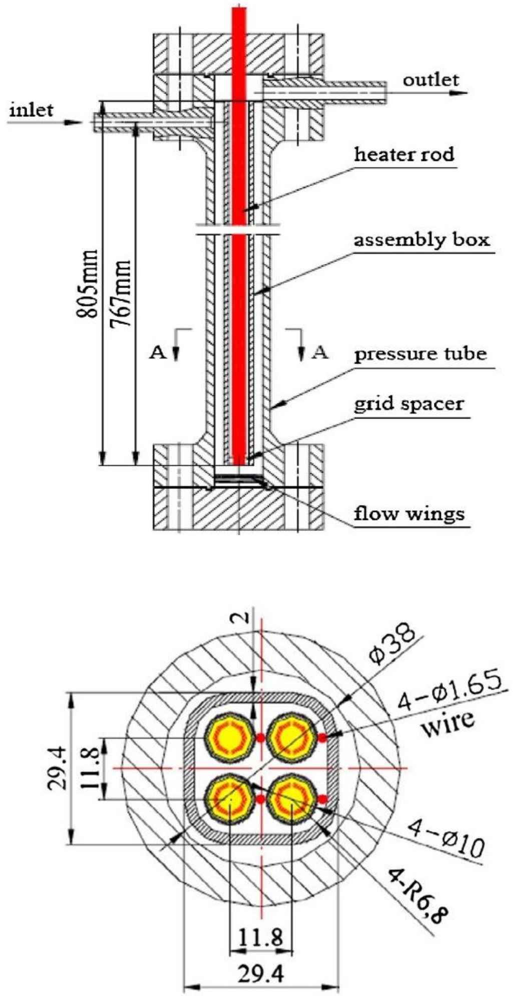
■ Simulation with modified ATHLET-SC





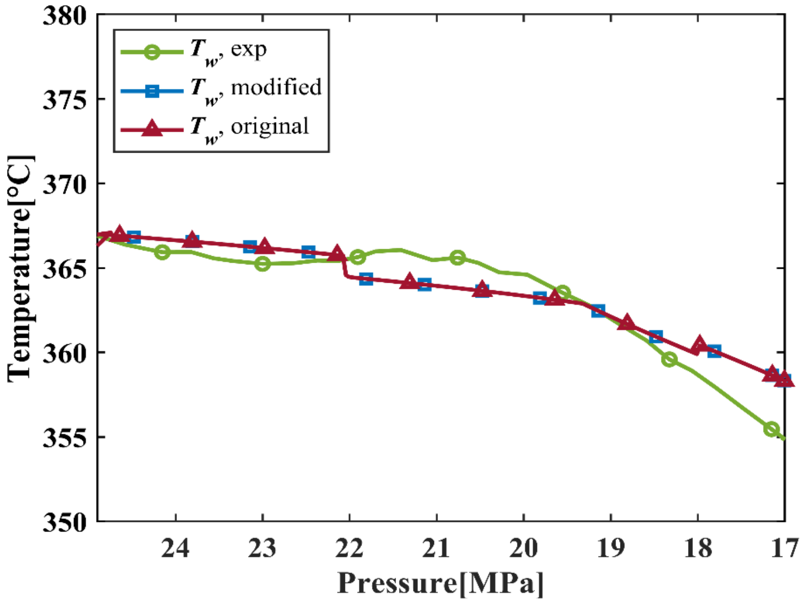
Trans-critical transient

■ Simulation with modified ATHLET-SC



■ Pressure drops from supercritical to subcritical

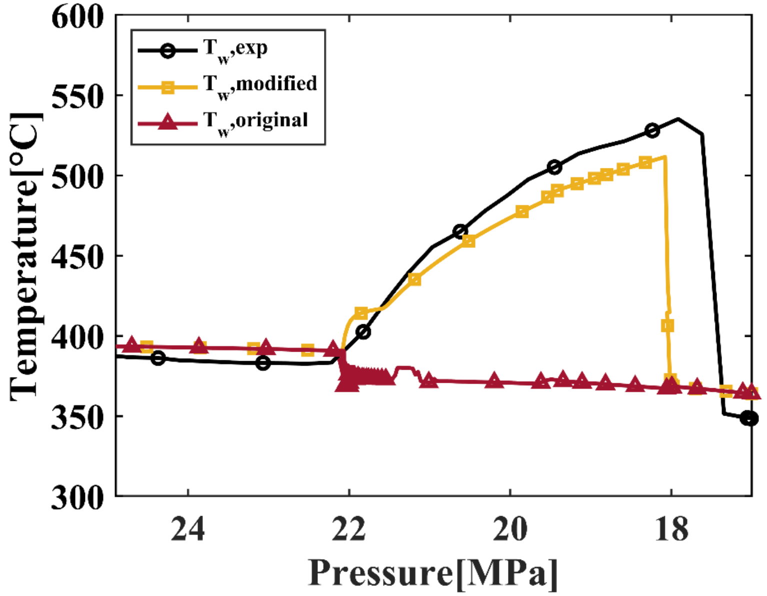
■ Without wall heat up



G = 1415 kg/(m²·s)

q = 270 kW/m²

■ With wall heat up

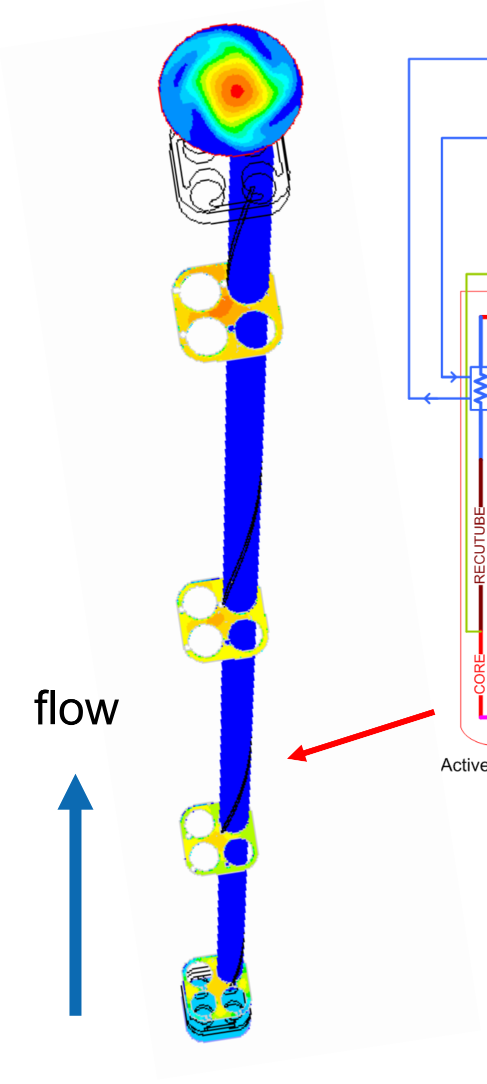


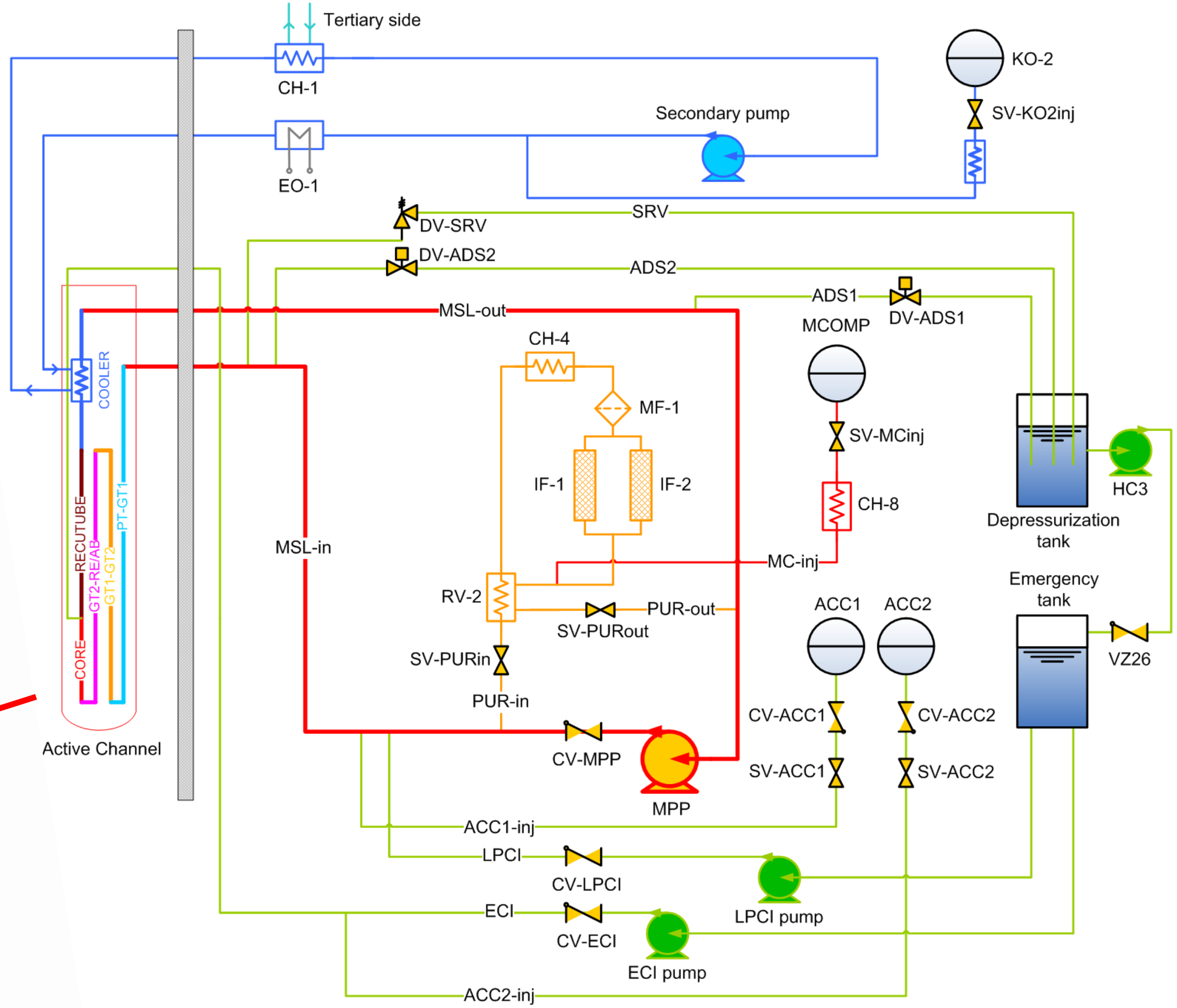
G = 1415 kg/(m²·s)

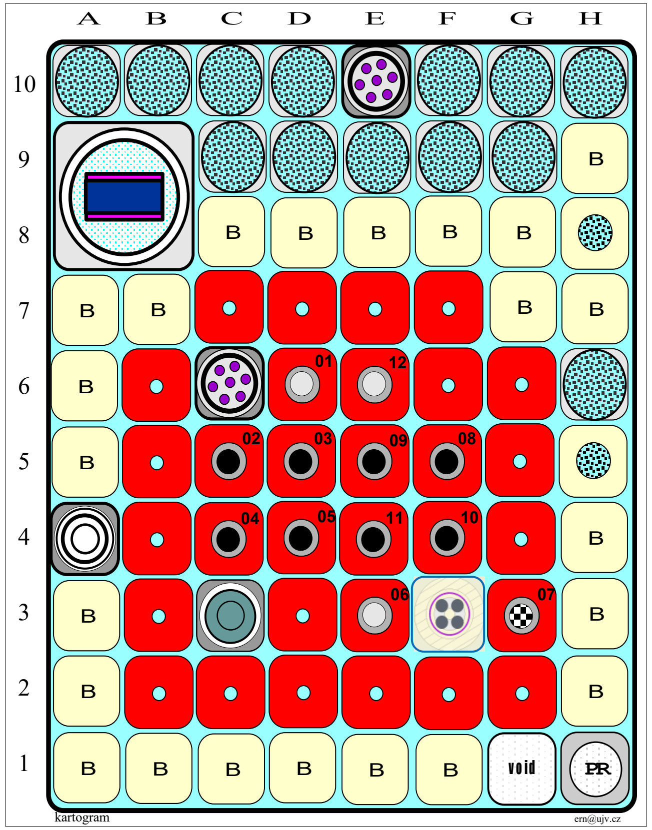
q = 638 kW/m²

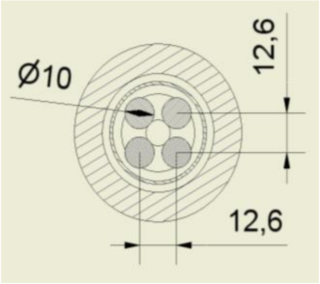
Trans-critical transient

■ Simulation of SCWR-FQT





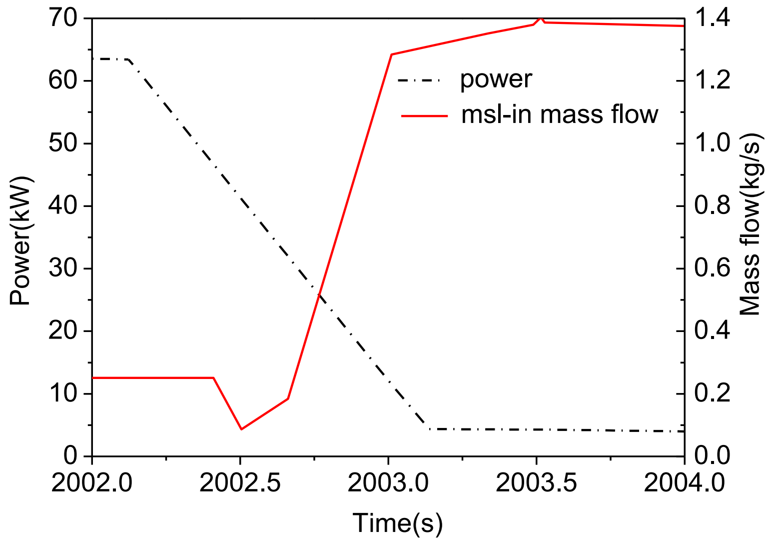


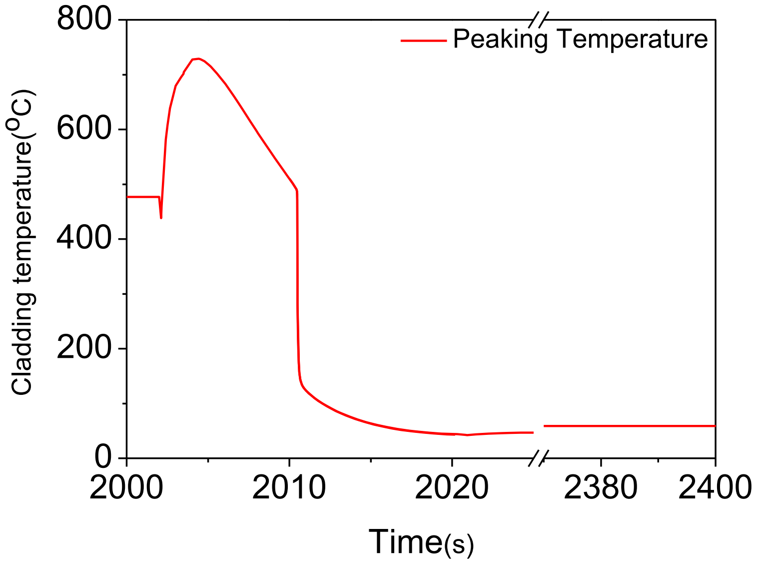


Trans-critical transient

■ Simulation of SCWR-FQT

Accident	Peaking claddi PCT (℃)
LOCA • MSL-out • MSL-in • ECI injection line	 703 714 752
Trip of the primary pump MPP	685
Coolant bypassing the test section • PT-GT1 – COOLER shortcut • COOLER – ECI shortcut	 1000 705
Blockage of the coolant flow path • MSL-out • MSL-in	 750 533





Contents

Conclusions

- **Supercritical heat transfer databank and prediction model**

  More than 90 000 data points

- **Subcritical databank and prediction model**

  CHF: 2652 data points

  Post-CHF: More than 32 000 data points

- **Modification of the STH program ATHLET-SC**

  Validated by trans-critical experiment

  Safety analysis of the SCWR-FQT

上海交通大學

SHANGHAI JIAO TONG UNIVERSITY

谢谢

Thank you!

饮 水 思 源　爱 国 荣 校

Upcoming Webinars

Date	Title	Presenter
24 September 2025	3S interfaces of a pebble-bed small modular advanced reactor	Dr. Bryan van der Ende, Canadian Nuclear Laboratories, Canada
08 October 2025	Science for the safe disposal of nuclear waste – a German perspective	Dr. Francesca Quinto and Dr .Frank Eberling, Karlsruhe Institute of Technology, Germany
05 November 2025	Severe accidents in Sodium Fast Reactors: Safety Study Approach, Prevention and Mitigation by Design	Dr. Frederic Bertrand, Commissariat a l'Energie Atomique et aux Energies Alternatives (CEA), France