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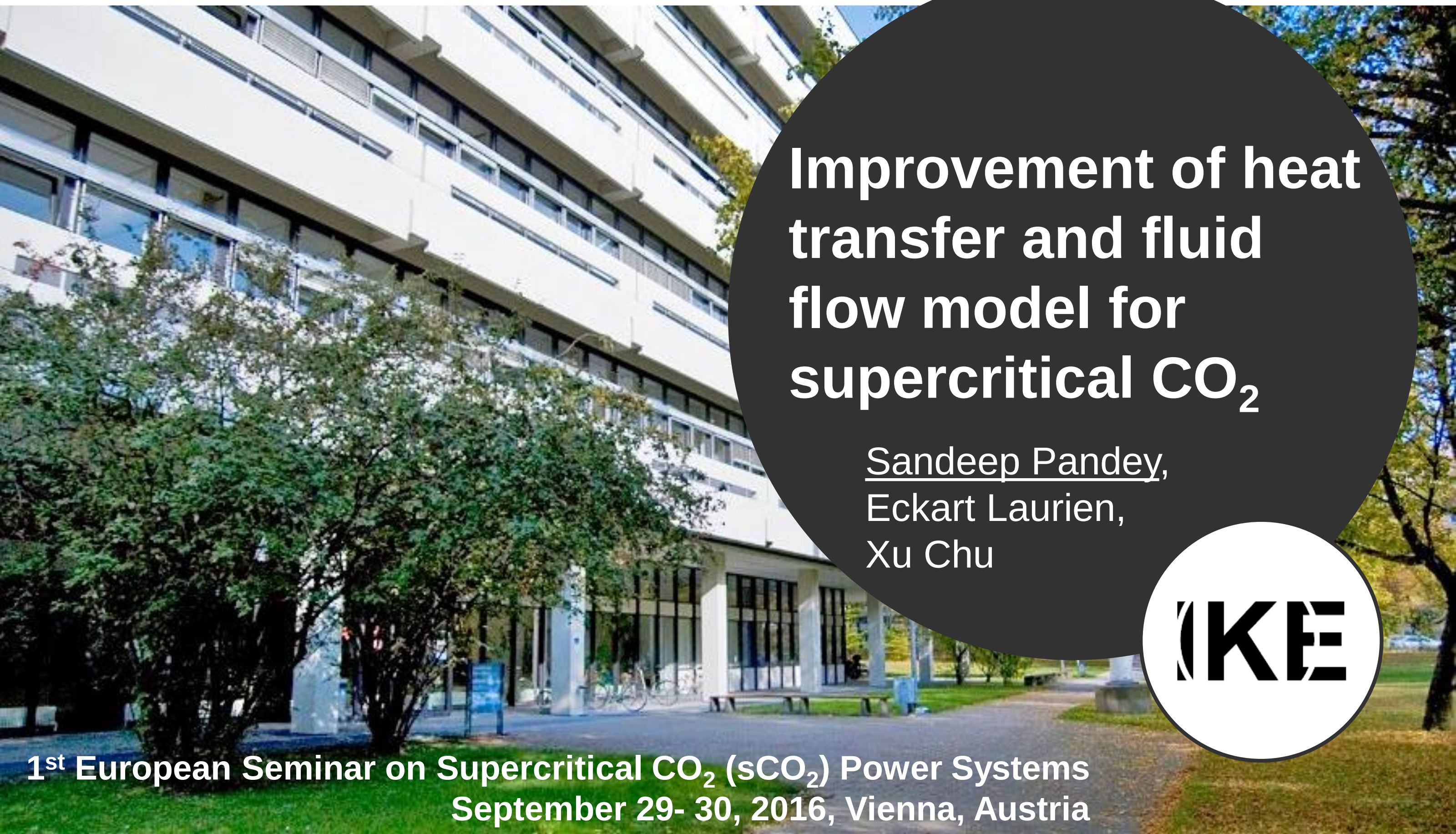

Improvement of heat transfer and fluid flow model for supercritical CO_2

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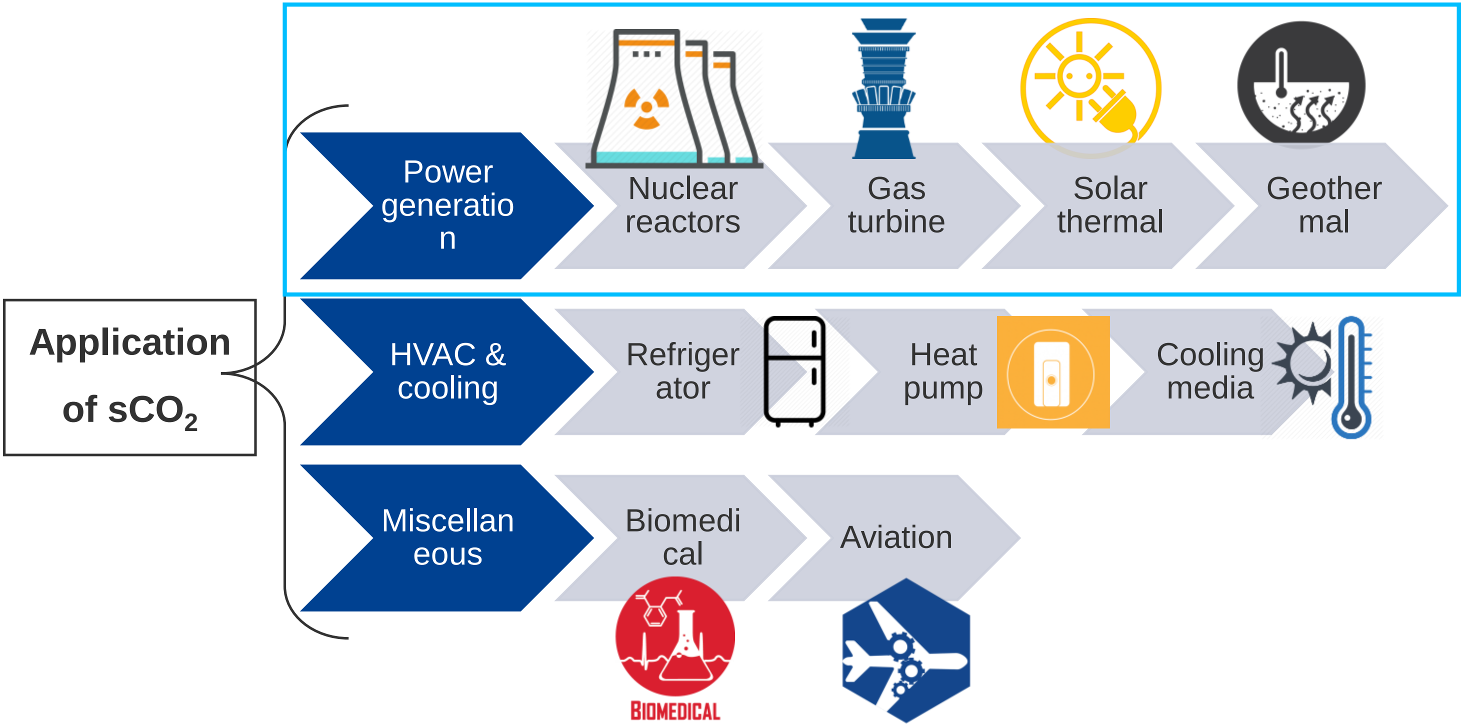
Eckart Laurien,
Xu Chu

1st European Seminar on Supercritical CO_2 (sCO_2) Power Systems
September 29- 30, 2016, Vienna, Austria

Content

- Introduction
- Theory and methodology
  - DNS and its utilization in analytical model development
  - Inclusion of buoyancy and acceleration into two layer model
- Results and discussion
- Summary and future work

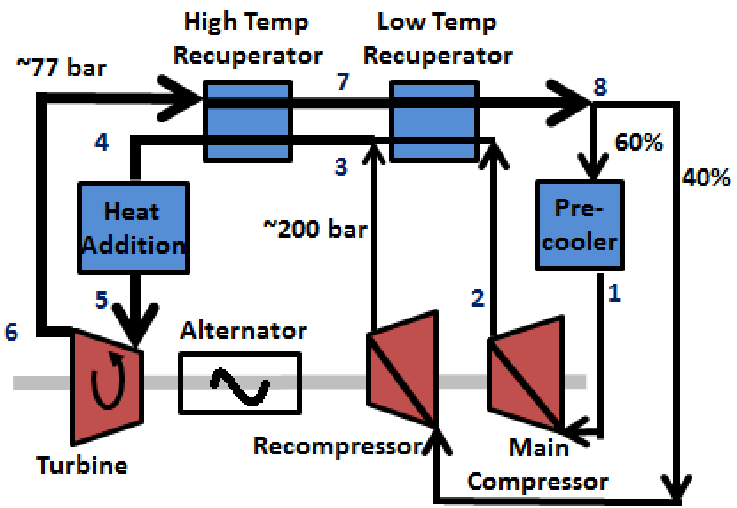
Motivation

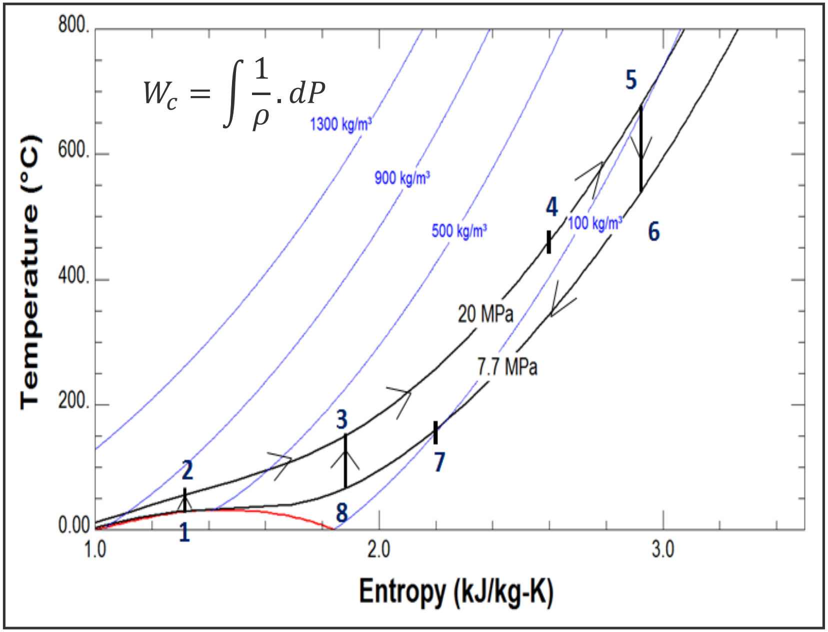


Application of sCO_2
Power generatio n
Nuclear reactors
Gas turbine
Solar thermal
Geother mal
HVAC & cooling
Refriger ator
Heat pump
Cooling media
Miscellan eous
Biomedi cal
BIOMEDICAL
Aviation

Supercritical CO_2-Loop for Energy Conversion

Recompression- Brayton cycle



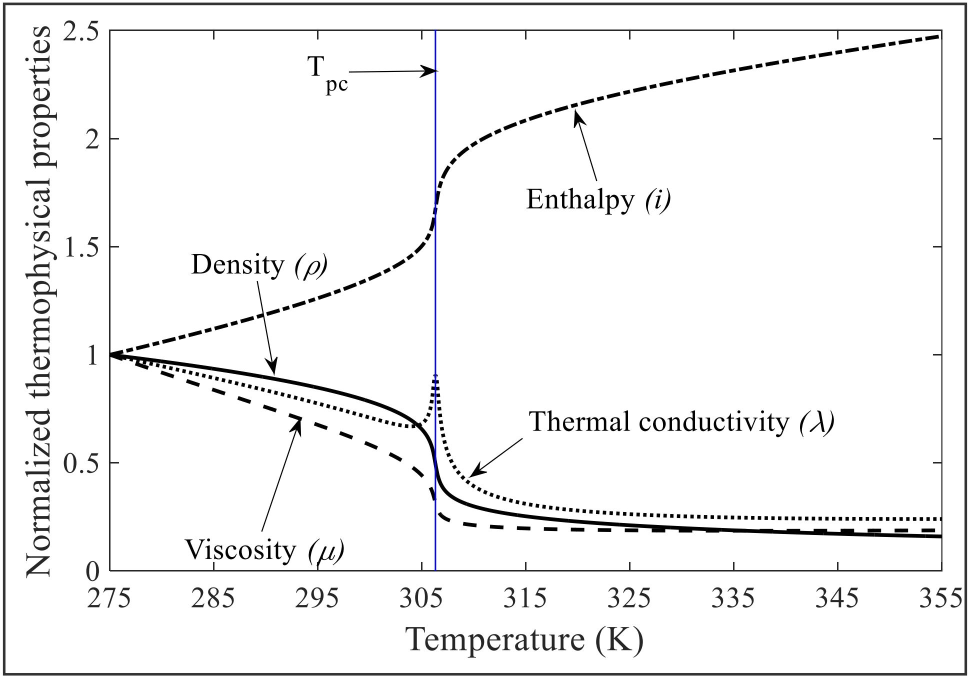


V. Dostal, M.J. Driscoll and P. Hejzlar, A Supercritical Carbon Dioxide Cycle for Next Generation Nuclear Reactors , MIT-ANP-TR-100 (2004)

Thermophysical properties variations for sCO_2

- Rearrangement of Dittus-Boelter equation gives:

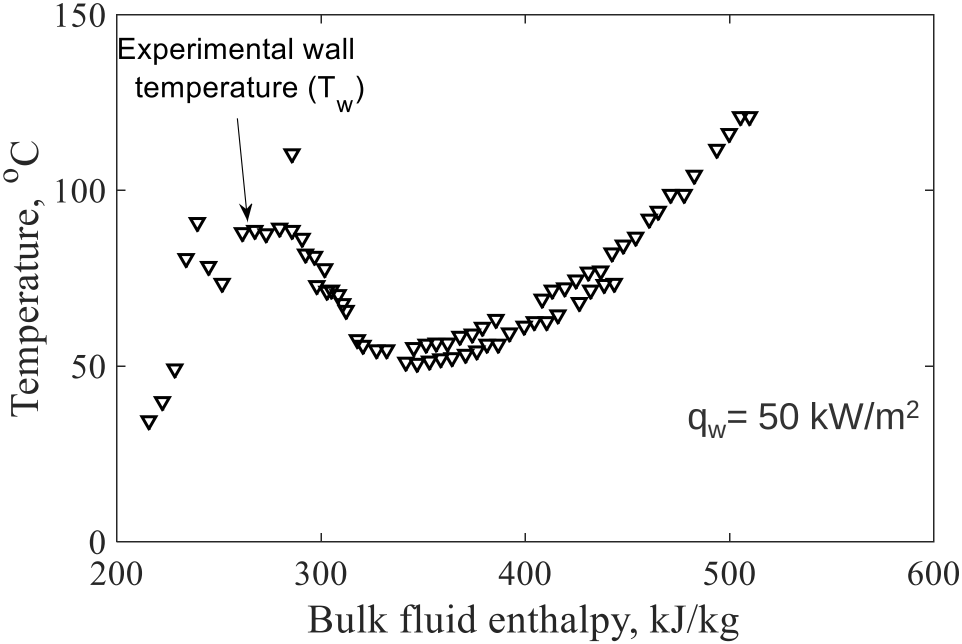
$$\alpha \sim \frac{C_p^{0.4} \quad \lambda^{0.6}}{\mu^{0.4}}$$



Heated pipe flow of sCO_2

- 3 commonly used methods to predict heat transfer to sCO_2

  i) Experiments and correlations derived from them



Parameter	Value
Inner diameter	4.1 mm
Heated length	2.1 m
Mass flux	400 kg/m^2s
Heat flux	10~50 kW/m^2
Pressure	7.75 MPa

Kim H, Bae Y, Kim H, Soong J and Cho B "Experimental Investigation on the Heat transfer characteristics on a vertical upward flow of supercritical CO2", In Proc. ICAPP, Reno, NV., June, 2006.

Heated pipe flow of sCO_2

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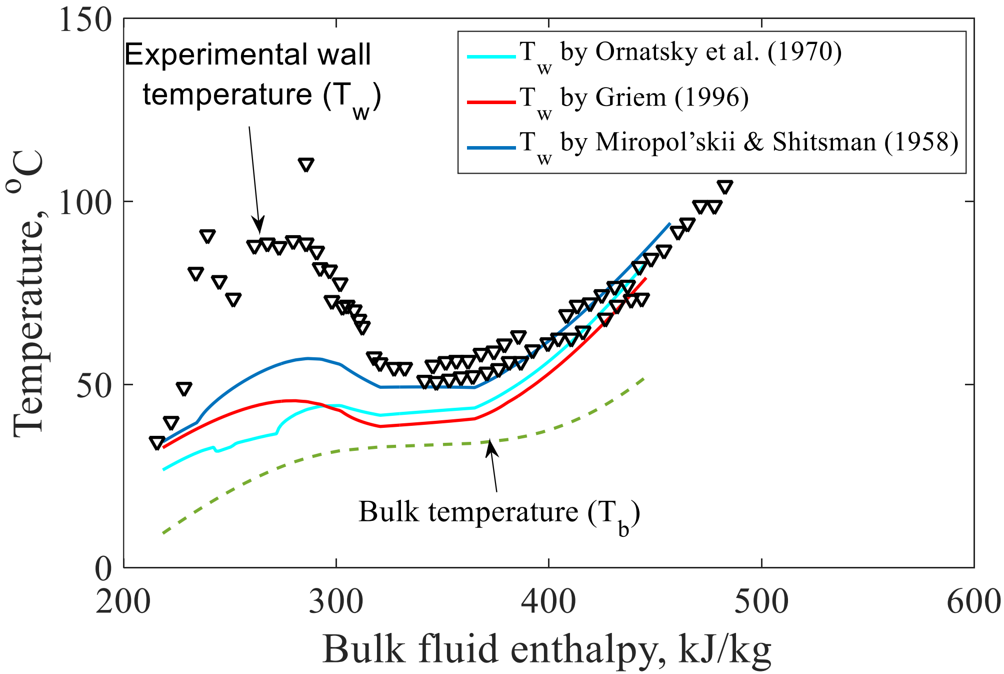


Kim H, Bae Y, Kim H, Soong J and Cho B "Experimental Investigation on the Heat transfer characteristics on a vertical upward flow of supercritical CO2", In Proc. ICAPP, Reno, NV., June, 2006.

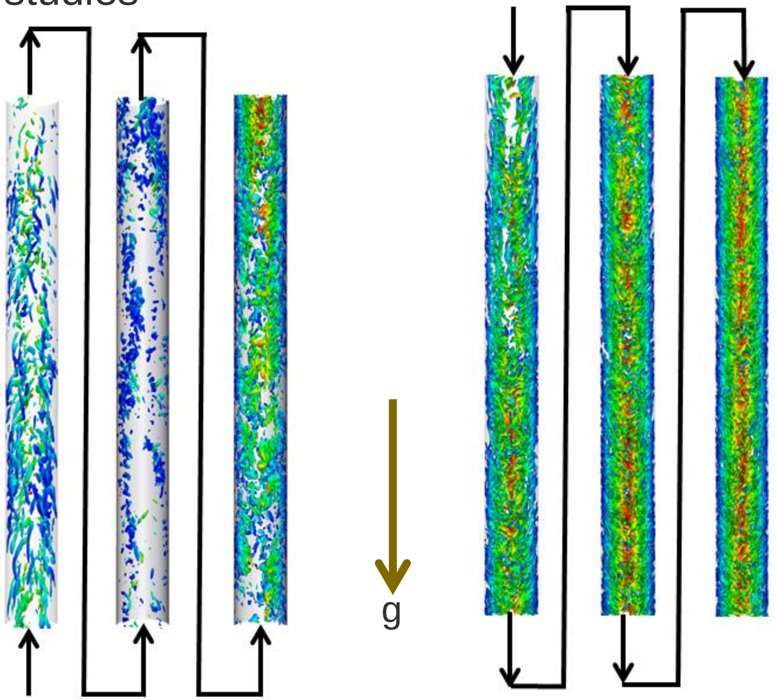
Heated pipe flow of sCO_2 and use of CFD

- 3 commonly used methods to predict heat transfer to sCO_2

  ii) CFD and DNS studies

Upward

buoyancy damps turbulence



Downward

buoyancy induces turbulence

Visualization of turbulence structures using the λ_2 criterion

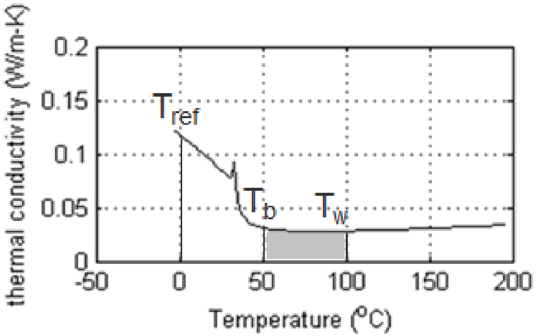
Heated pipe flow of sCO_2 and two layer model

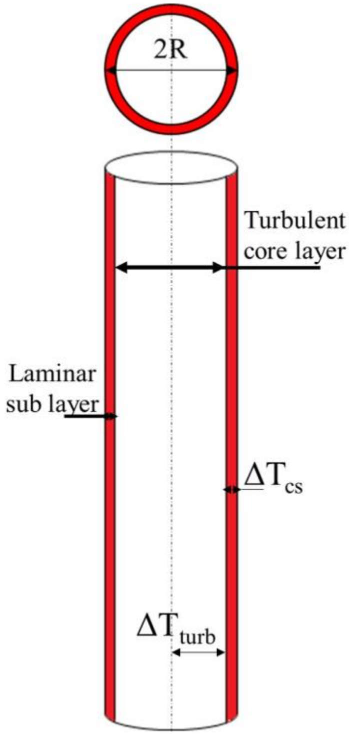
- 3 commonly used methods to predict heat transfer to sCO_2

  iii) Model based upon heat transfer and fluid dynamics theories

$$\Delta T_{turb} = \frac{Pr_T}{\kappa}\left(lnR^{+b} - lny_{cs}^{+b}\right) \times \frac{q_w}{\rho_b c_{pb} u_{\tau b}}$$

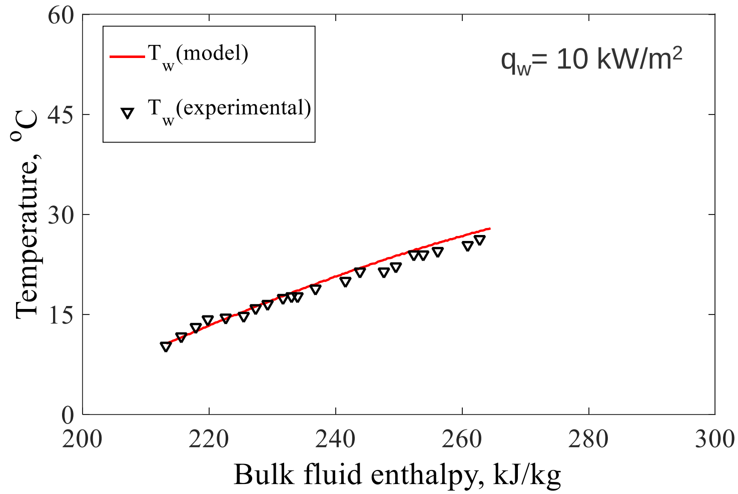
$$\Delta T_{cs} = \frac{q_w}{\left(\frac{1}{y_{cs}}\right)\frac{\int_{T_{ref}}^{T_w} \lambda(T).dT - \int_{T_{ref}}^{T_{cs}} \lambda(T).dT}{(T_w - T_{cs})}}$$

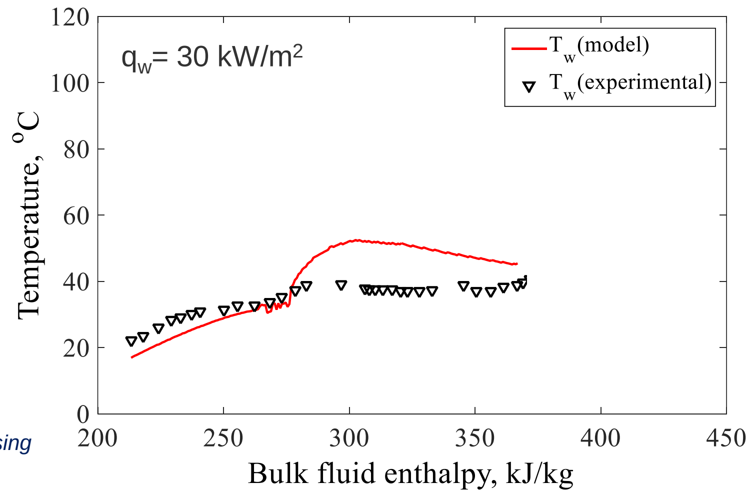




Two layer model

- Computer modelling was done in MATLAB corresponding to Kim et al. experiments
- Good agreement at smaller heat flux
- Heat transfer enhancing effects at mid heat flux

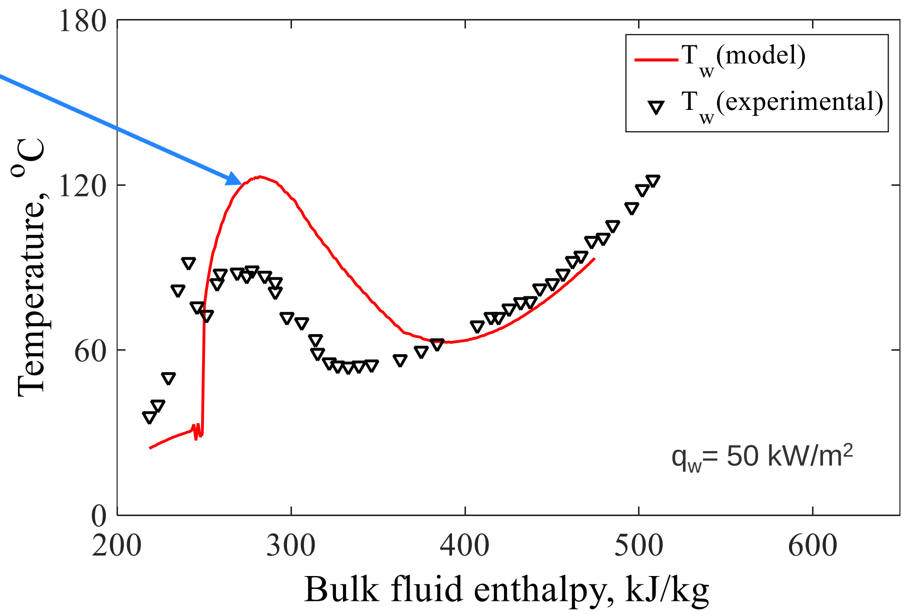




S. Pandey and E. Laurien, Heat transfer analysis at supercritical pressure using two layer theory, Journal of Supercritical Fluids 109 (2016)

Two layer model

Positive outcome-
without any supplementary correction factor!

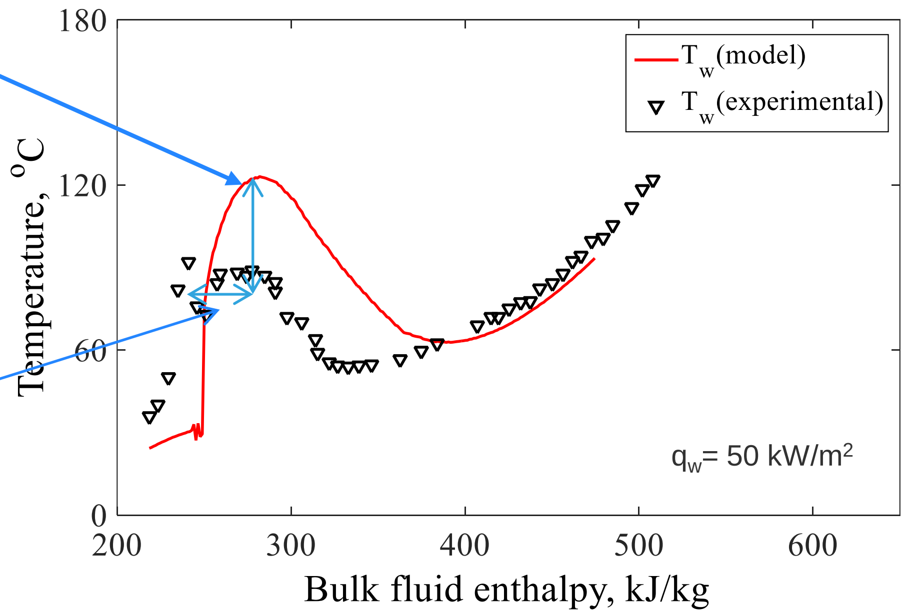


S. Pandey and E. Laurien, Heat transfer analysis at supercritical pressure using two layer theory, Journal of Supercritical Fluids 109 (2016)

Two layer model

Positive outcome- without any supplementary correction factor!

BUT, shifted and exaggerated peak in T_w



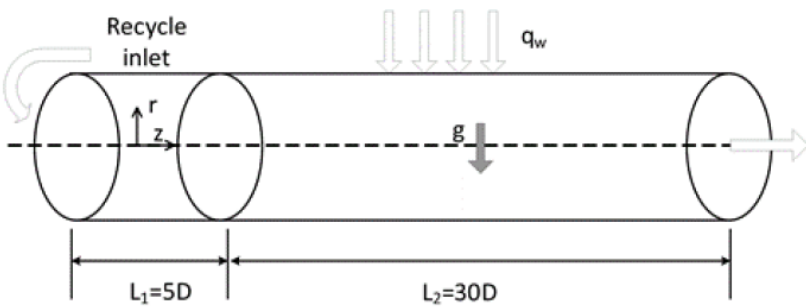
S. Pandey and E. Laurien, Heat transfer analysis at supercritical pressure using two layer theory, Journal of Supercritical Fluids 109 (2016)

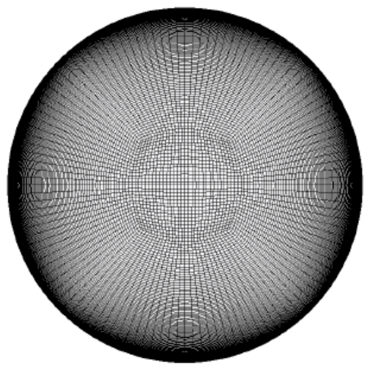
Aim of study

- Development of an approach to use DNS data in analytical modelling
- Improve fluid flow and heat transfer (heating and cooling) model based upon two layer model for sCO_2
- Validate proposed model with the available experiments

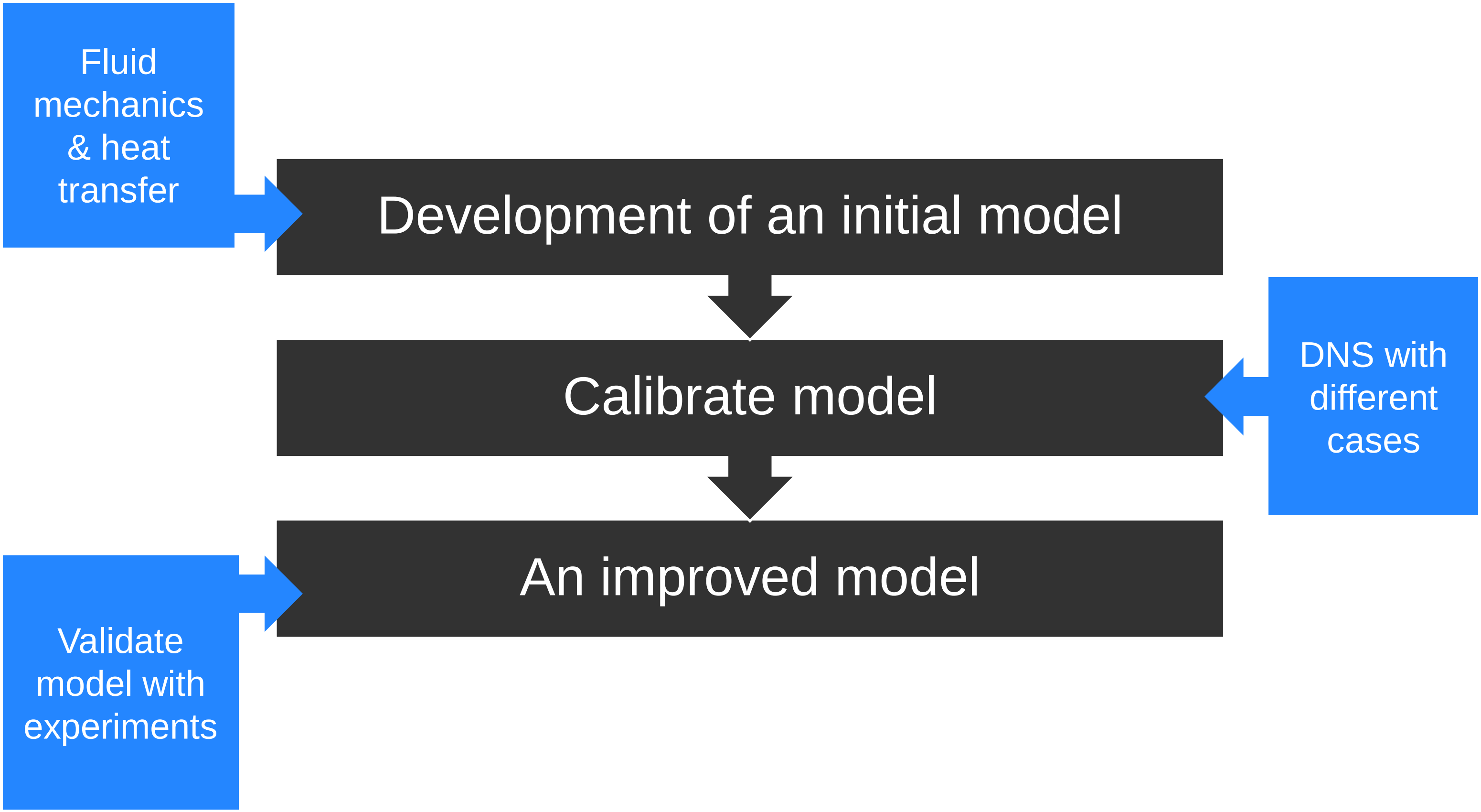
DNS and its utilization in analytical model development

- Low-Mach incompressible N-S equations in Cartesian Coordinates
- OpenFOAM V2.4 as solver, FVM
- Semi-implicit P-U coupling, 2-Order Spatial/ temporal
- Tabulated properties library: from NIST
- Parallel computation on HLRS, Stuttgart



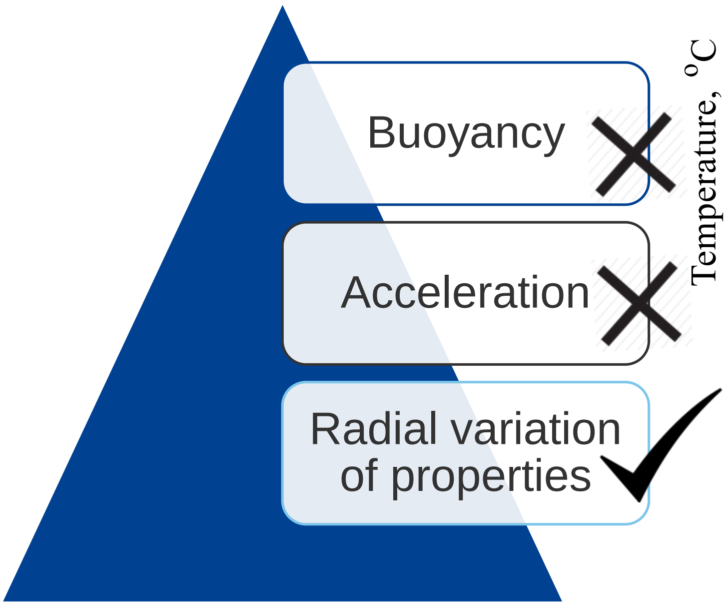


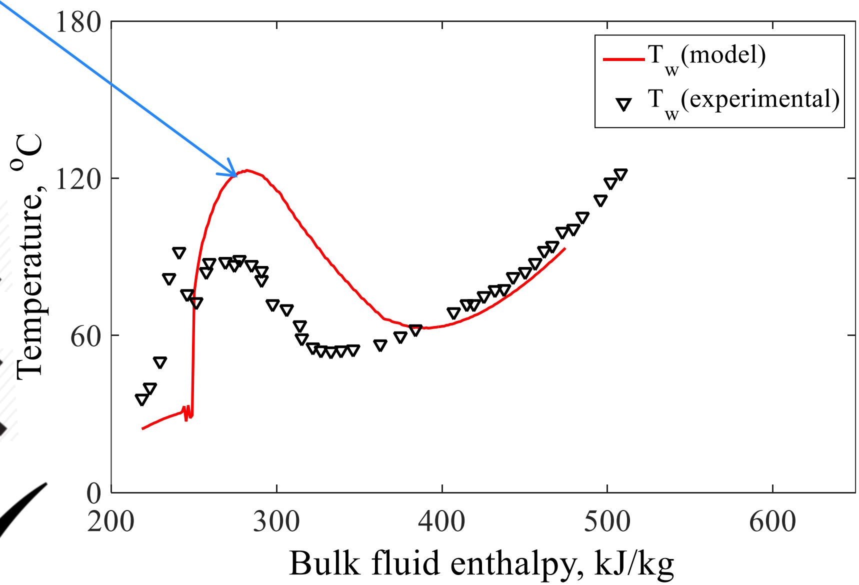
DNS and its utilization in analytical model development



Inclusion of Buoyancy and Acceleration

shifted and exaggerated peak in T_w

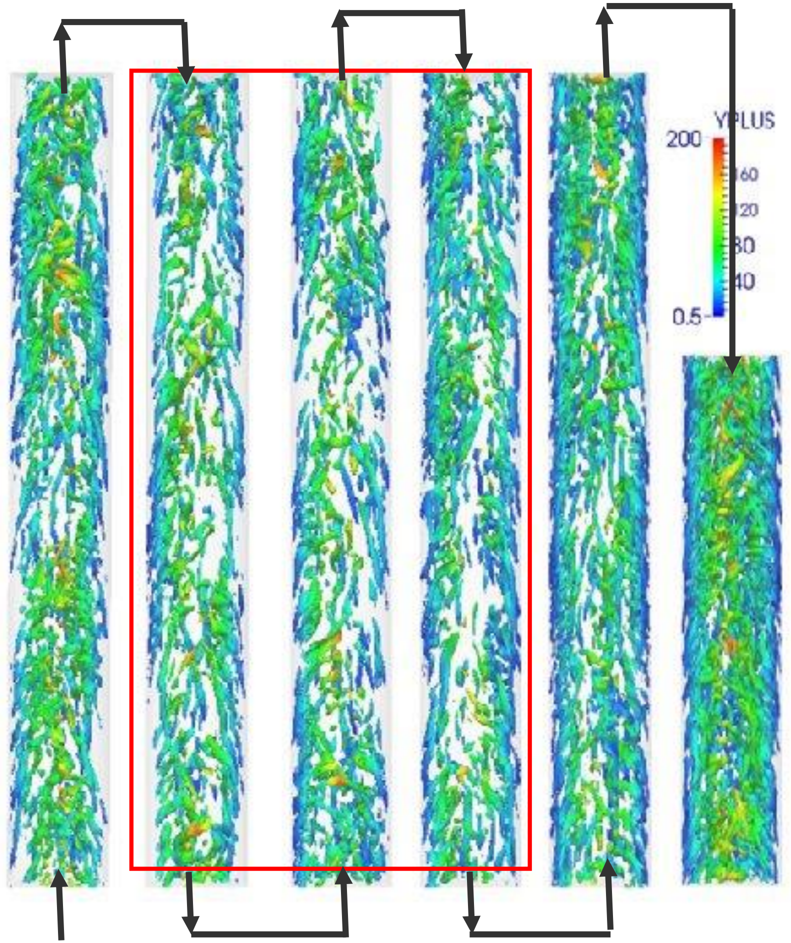




Relaminarization brought by flow acceleration

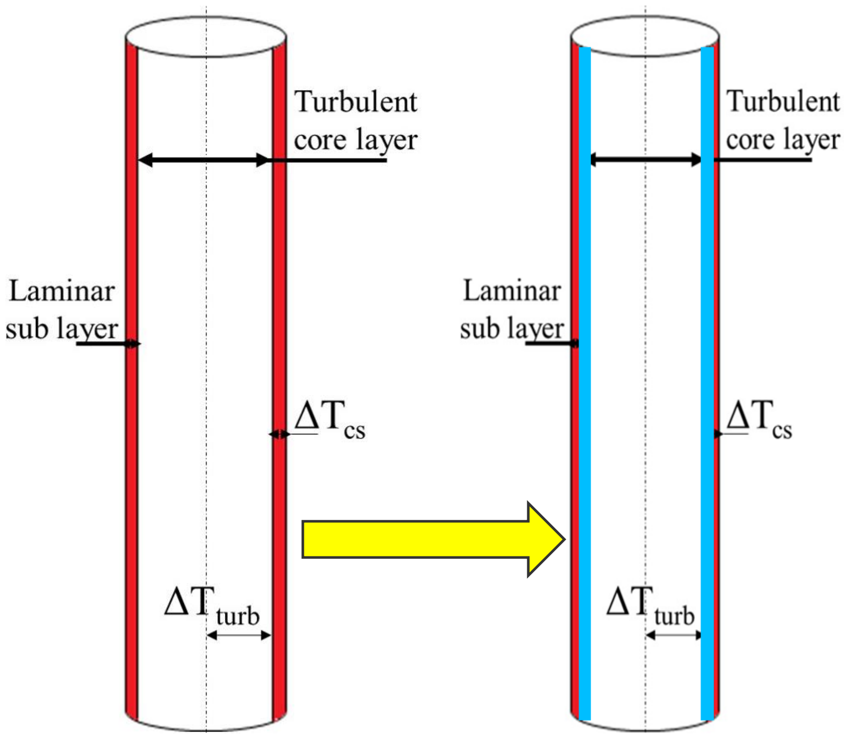
Forced convection (vertical orientation) : No buoyancy

- Heating will decrease density
- ↓
- Increase in velocity
- ↓
- Stream wise acceleration
- ↓
- Favorable pressure gradient
- ↓
- Stabilize the laminar sub layer
- ↓
- Reduce the turbulent transport



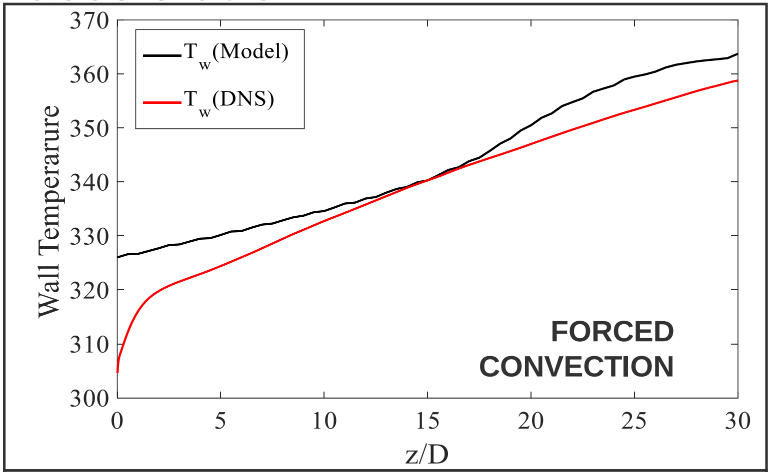
Relaminarization brought by flow acceleration

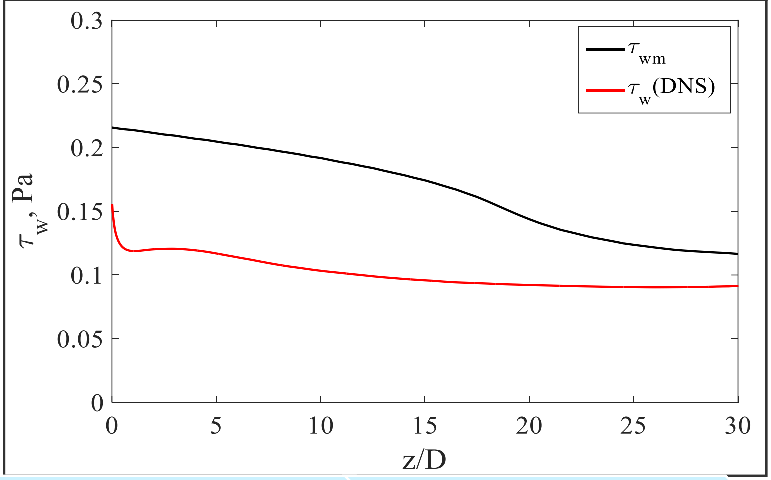
- **Relaminarization brought by flow acceleration**
  - $y_{vs}^{+} = 11.8 + c_v K_v$
  - $K_v = \frac{4q^+}{Re_{Dh}}$
  - $q^+ = \frac{\beta q_w}{G c_p}$
  - Empirical fitting with DNS data



Relaminarization brought by flow acceleration

- **Relaminarization brought by flow acceleration**
  - $y_{vs}^{+} = 11.8 + c_v K_v$
  - $K_v = \frac{4q^+}{Re_{Dh}}$
  - $q^+ = \frac{\beta q_w}{G c_p}$
  - Empirical fitting with DNS data
  - $c_v = 10^7$



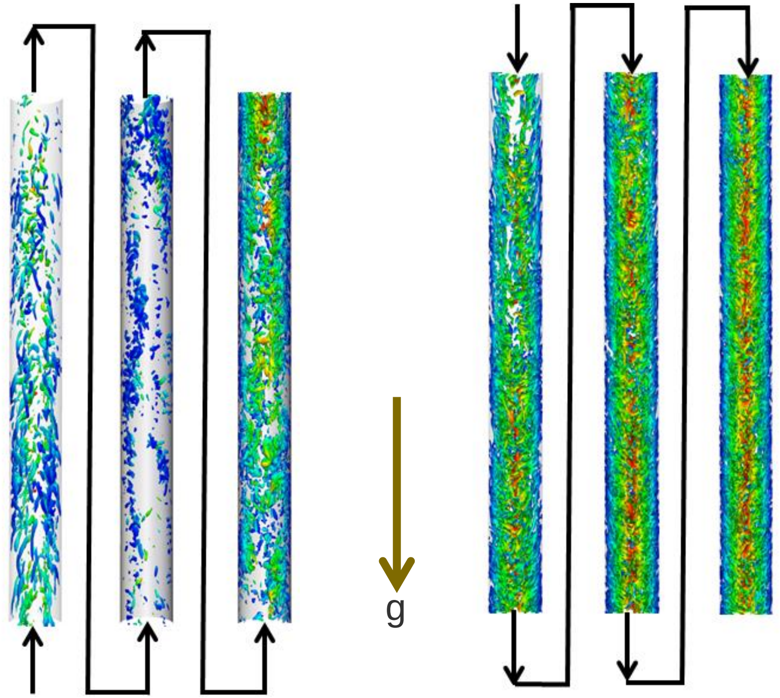


Effects of buoyancy

- **Effects of buoyancy (for heating)**

Upward: thermally stable

buoyancy damps turbulence



Downward: thermally unstable

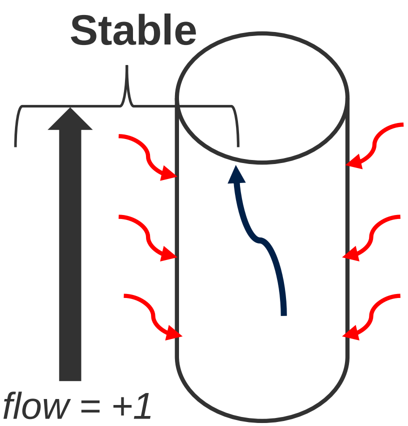
buoyancy induces turbulence

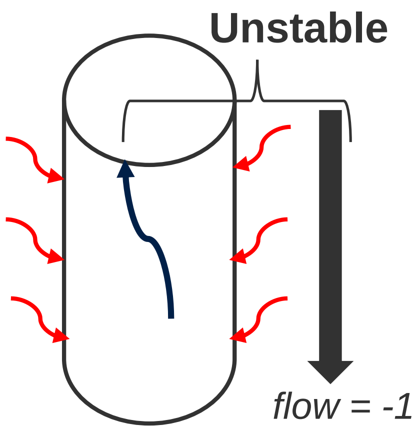
Visualization of turbulence structures using the λ_2 criterion

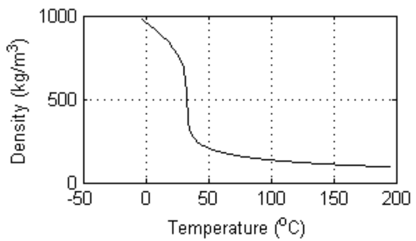
Effects of buoyancy

- **Effects of buoyancy (for heating)**

Effect	Direction of buoyancy	Flow direction	Effect on HT	Additional wall shear stress	Type of HT
Stable	Upward (+)	Upward (+)	reduce	positive	Heating
Unstable	Upward (+)	Downward (-)	intensify	negative	







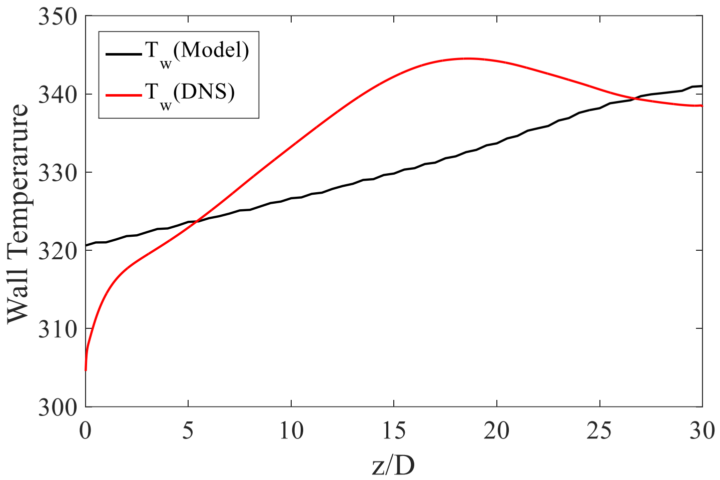
Density will decrease with increase in temperature

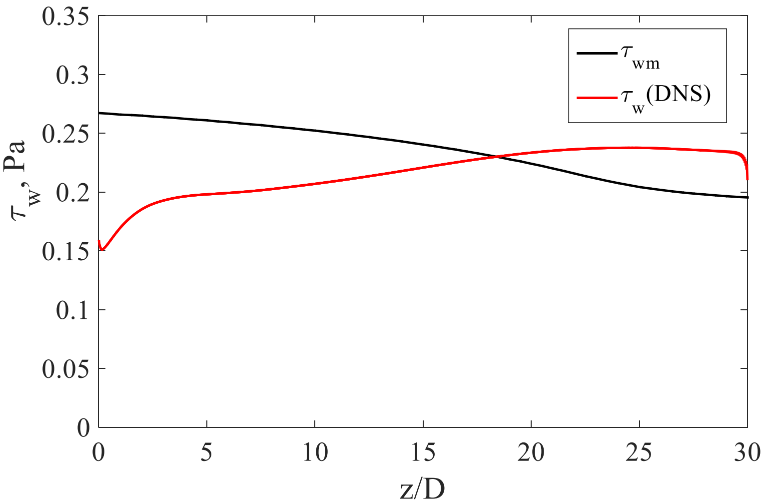
Effects of buoyancy

- Effects of natural convection cannot be ignored.
- Buoyant shear stress was introduced in the wall shear stress as:
- $\tau_{w,m} = \tau_w + (flow \times \tau_b);\qquad \tau_b = y_b g(\rho_b - \bar{\rho})$
- $flow = \begin{cases} -1, & Downward\ \ (unstable) \\ 0, & Forced\ (no\ buoyancy) \\ 1, & Upward\ (stable) \end{cases}$ Vice versa for cooling
- $\bar{\rho} = \frac{1}{(T_w - T_b)} \int_{T_b}^{T_w} \rho . dT \quad ; \qquad y_b = \frac{y_{vs}}{Pr_{cs}^{\frac{1}{3}}}$

Effects of buoyancy

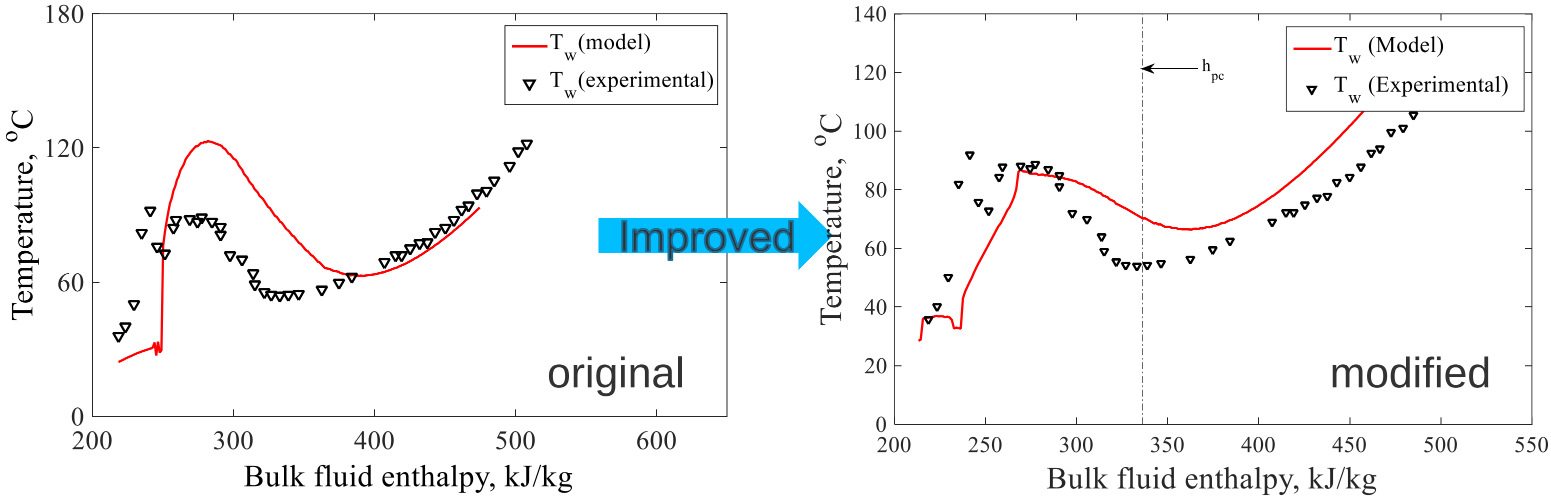
- Upward flow only





Upward flow

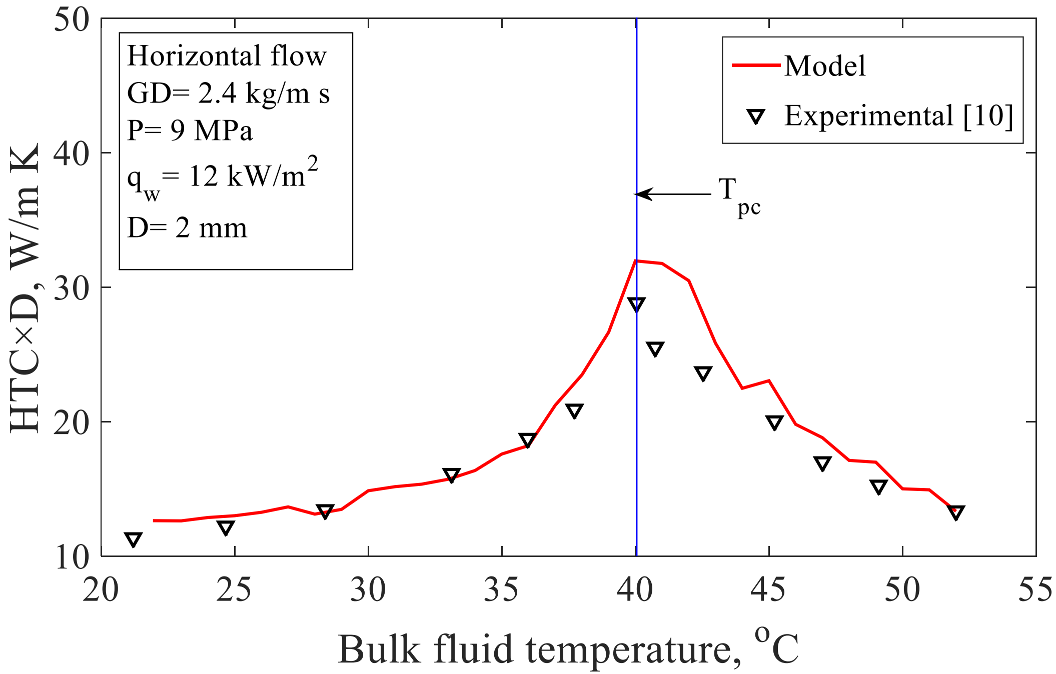
Results and discussion



- Mean relative error for heat transfer coefficient was improved from 18.34% to 10.65%

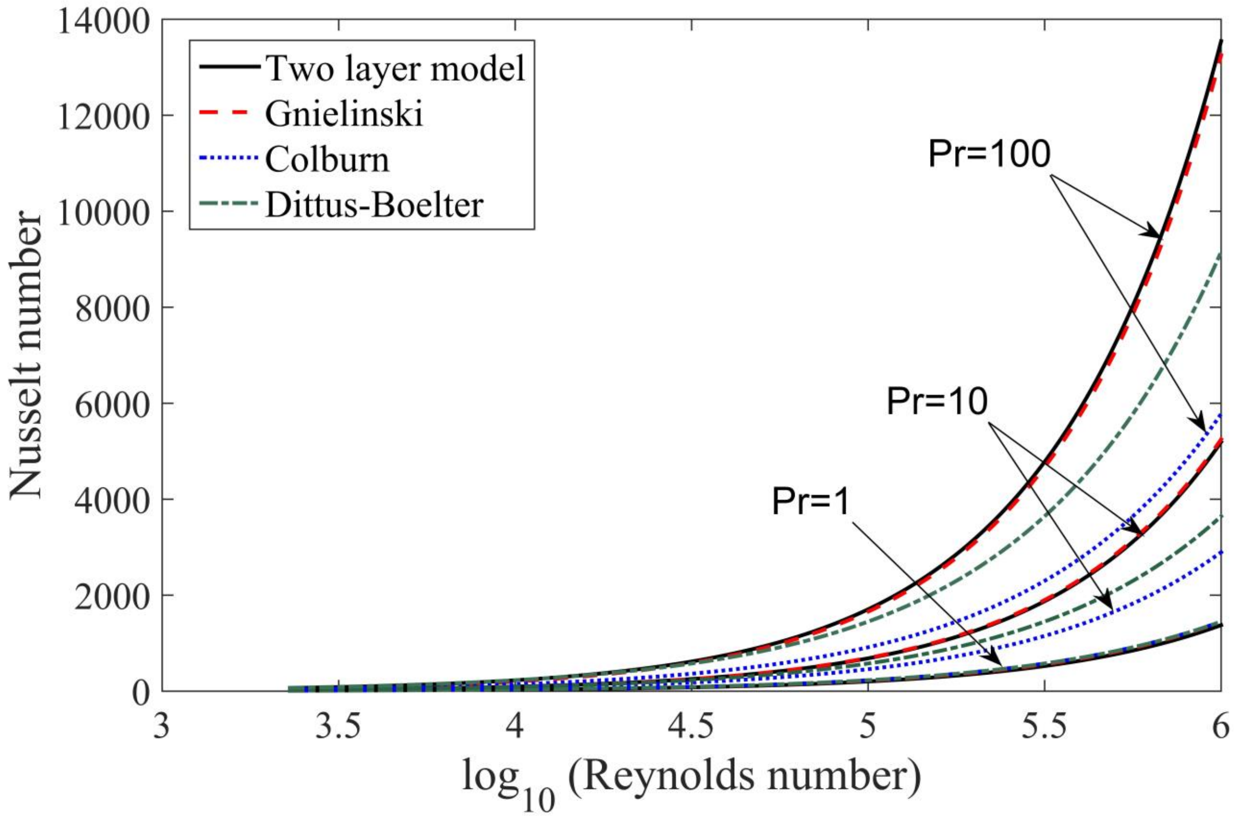
Validation with cooling of sCO_2

- Higher mass flux as compared to heat flux
- Horizontal orientation
- Heat transfer enhancement at pseudocritical temperature



C. Danga, and E. Hihara, In-tube cooling heat transfer of supercritical carbon dioxide. Part 1. Experimental measurement, International Journal of Refrigeration 27, Pages 736–747, 2004.

Comparison with constant property case



Introduction | Theory & methodology | Results & discussion | Summary & Future work

Summary and future work

- An approach to use DNS database for analytical modelling
- An initial model is developed for sCO_2 that predicts both heat transfer and fluid flow
- Fairly well agreement was observed with experiments, **but** more refinement is needed for future application in power cycle
- Perform more DNS to make model generalize and reliable
- Experimental validation with 2 mm diameter is required

Thank you!

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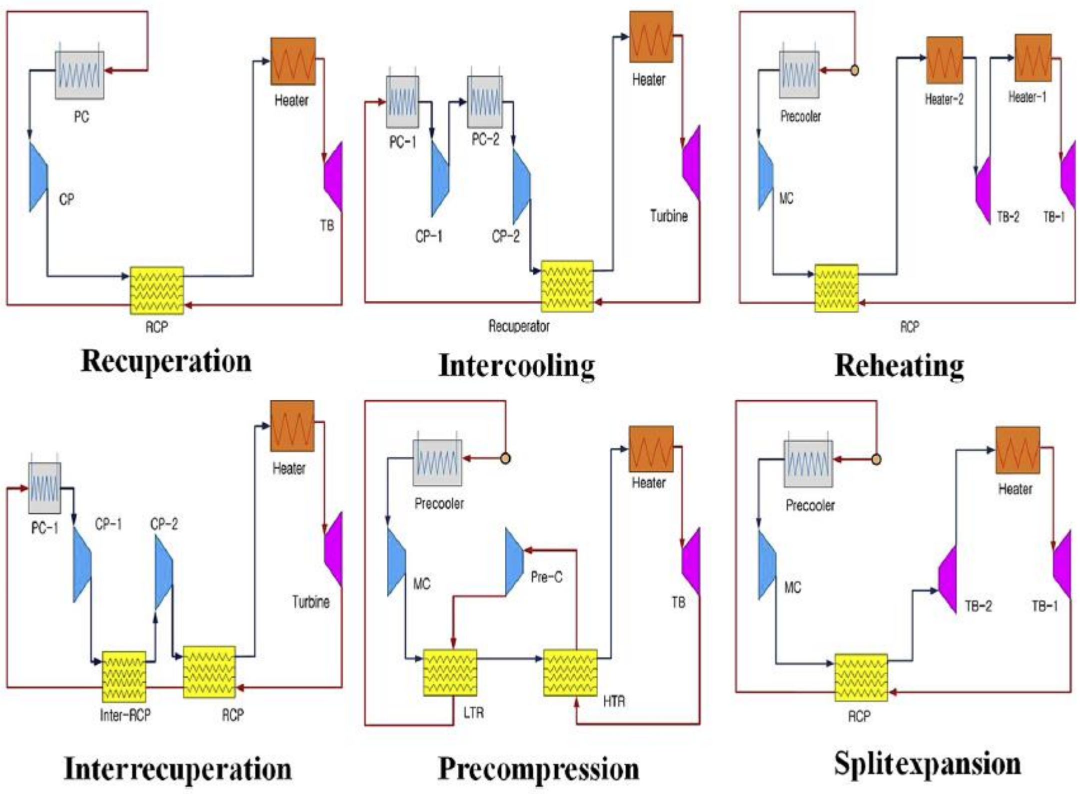
Appendix-A

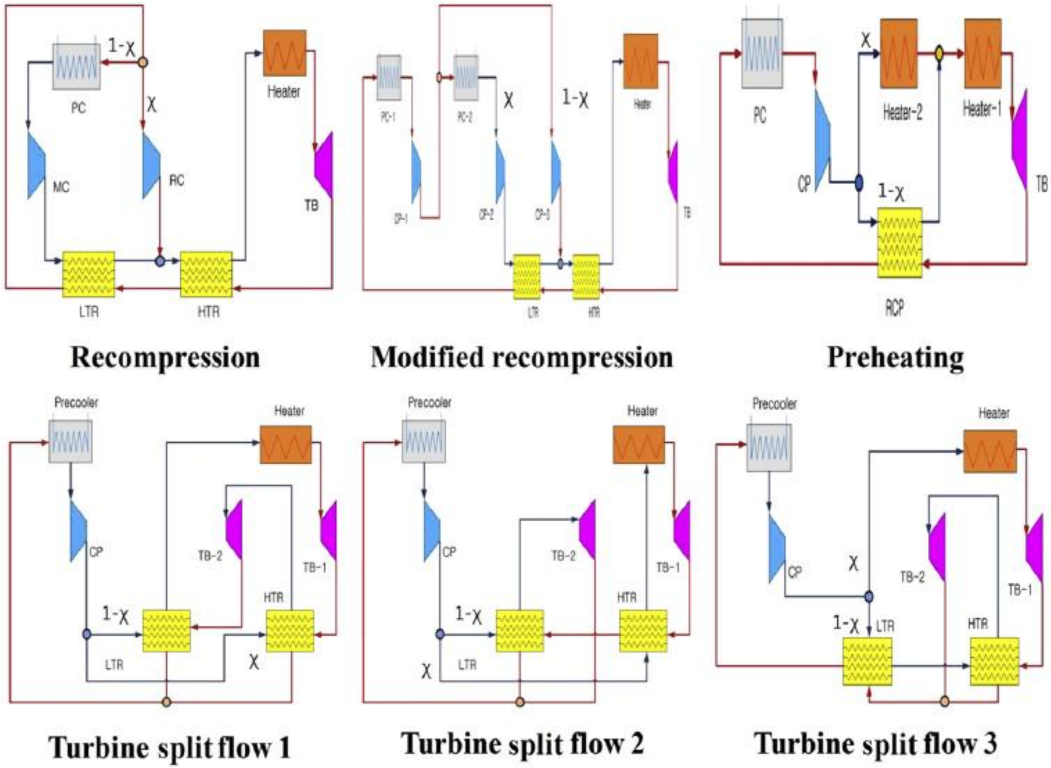
- Cycle layouts



Ahn et al., Review of supercritical CO_2 power cycle technology and current status of research and development, Nuclear Eng. Technol ogy 47 (2015).

Appendix-A

- Cycle layouts



Ahn et al., Review of supercritical CO_2 power cycle technology and current status of research and development, Nuclear Eng. Technol ogy 47 (2015).

Appendix-A

- Condition for figure

Table 2 — S-CO_2 single flow layout design conditions.

Layout	Recuperation	Intercooling	Reheating	Interrecuperation	Precompression	Split-expansion
Turbine inlet temperature (°C)	500					
IHX inlet temperature (°C)	275.9	249.7	334.5	314.6	281.1	270.0
CO_2 mass flow rate (kg/sec)	354.4	315.5	339.0	430.7	363.1	364.2
Compressor inlet temperature (°C)	32					
Compressor inlet & outlet pressure (MPa)	7.5/25				6.16/7.5 7.5/25	7.5/25
Turbine & compressor isentropic efficiency (%)	92/88					
HT/LT recuperator effectiveness (%)	95/95					

HT, high temperature; LT, low temperature; IHX, intermediate heat exchanger; S-CO_2, supercritical CO_2.

Table 3 — S-CO_2 split flow layout design conditions.

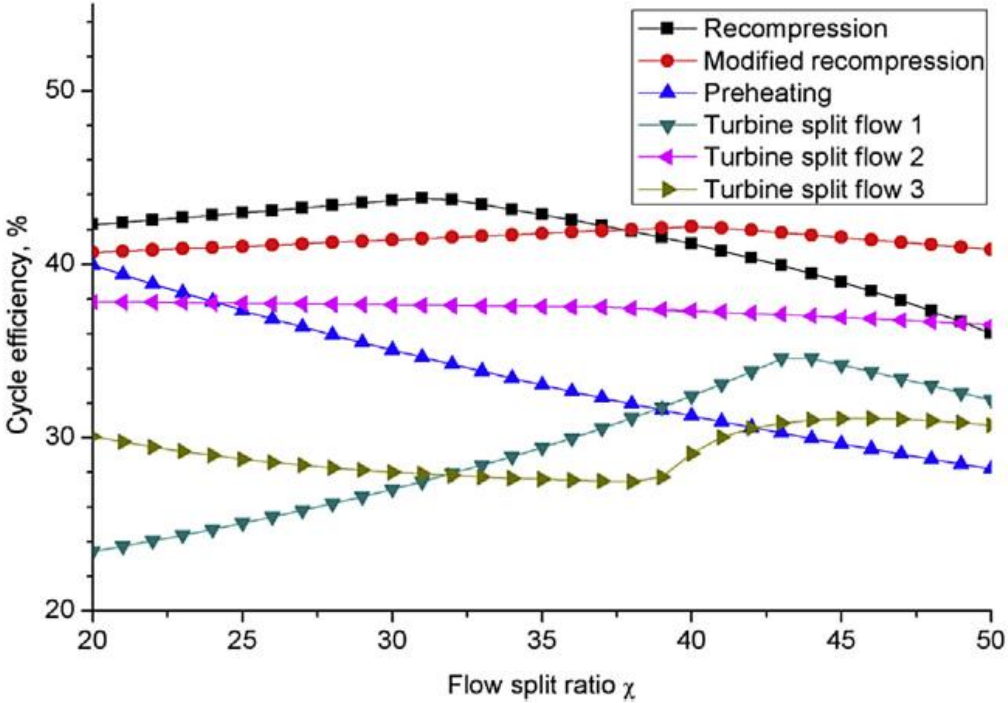
Layout	Recompression	Modified recompression	Preheating	Turbine split flow 1	Turbine split flow 2	Turbine split flow 3
Turbine inlet temperature (°C)		500				
IHX inlet temperature (°C)	335.5	283.3	98.7	150.4	275.9	98.7
CO_2 mass flow rate (kg/sec)	486.1	367.1	262.6	377.1	708.9	383.0
Compressor inlet temperature (°C)	32					
Compressor inlet & outlet pressure (MPa)	7.5/25	5.0/7.5 7.5/25	7.5/25			
Turbine & compressor isentropic efficiency (%)	92/88					
HT/LT recuperator effectiveness (%)	95/95					
Flow split ratio (m_H/m_T)	0.31	0.4	0.5	0.43	0.5	0.46

HT, high temperature; LT, low temperature; IHX, intermediate heat exchanger; S-CO_2, supercritical CO_2.

Ahn et al., Review of supercritical CO_2 power cycle technology and current status of research and development, Nuclear Eng. Technol ogy 47 (2015).

Appendix-A

- Why 60% and 40%



Ahn et al., Review of supercritical CO_2 power cycle technology and current status of research and development, Nuclear Eng. Technol ogy 47 (2015).

Appendix-B

- **The lambda 2 criterion**
  - how turbulent structures can be visualized by proper iso-surfaces of lambda2
  - It identifies vortex cores as pressure minima in a 2-D plane perpendicular to the vortex cores

$$S_{ik}S_{kj} + \Omega_{ik}\Omega_{kj}$$

$$S_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)$$

$$\Omega_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} - \frac{\partial u_j}{\partial x_i}\right)$$

Appendix-C

Review of correlations

- **Shitsman Correlation:** $Nu_b = 0.023 Re_b^{0.8} Pr_{min}^{0.8}$

Ornatsky et al. (1970) correlated experimental data for forced convection inside five parallel tubes at supercritical pressures with the following correlation:

$$Nu_{\mathrm{b}} = 0.023\, Re_{\mathrm{b}}^{0.8} Pr_{\mathrm{min}}^{0.8} \left(\frac{\rho_{\mathrm{w}}}{\rho_{\mathrm{b}}}\right)^{0.3},$$

where Pr_{min} is the minimum value of Pr_{w} or Pr_{b}.

Griem (1996) presented correlation for forced convection heat transfer at critical and supercritical pressures in tubes in the following form:

$$Nu_{\mathrm{b}} = 0.0169\, Re_{\mathrm{b}}^{0.8356} Pr_{\mathrm{b}}^{0.432}.$$

Appendix-D

- **Effects of buoyancy and acceleration**

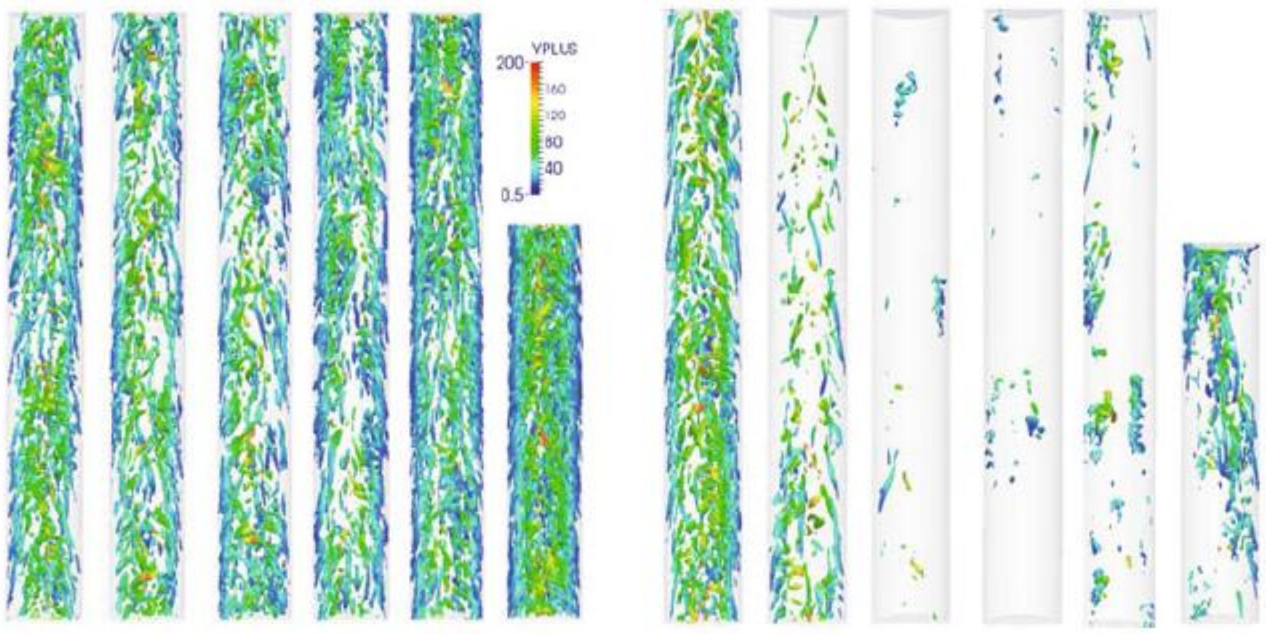


Fig. 12 Vortex structure according to lambda-2 criterium of 2F (*left*) and 2U (*right*)

Appendix-D

Fidelity of DNS

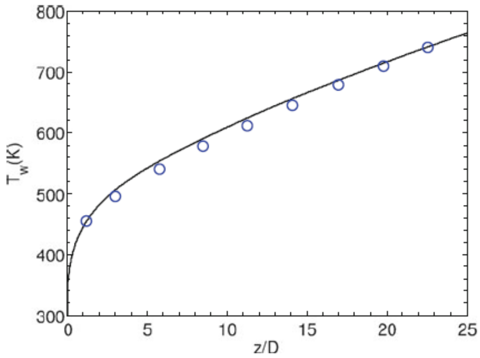


Fig. 4 Average wall temperature T_w of case Run635 from Shehata and McEligot [24] (*symbol*) and the DNS result (*line*)

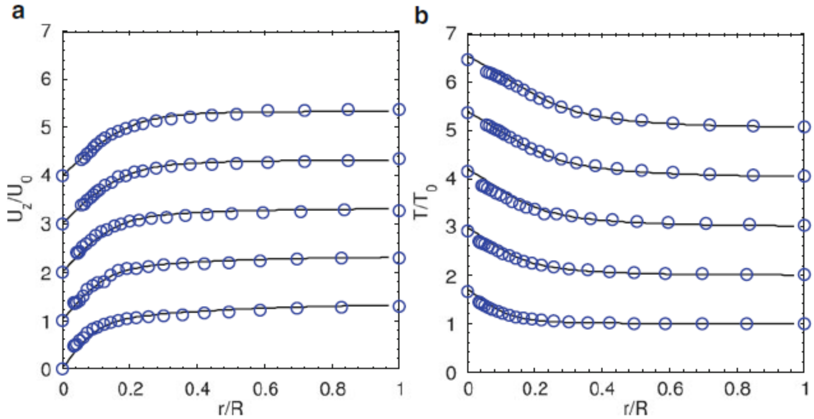


Fig. 5 Average velocity profile U_z/U_0 (*left*) and average flow temperature profile T/T_0 (*right*), DNS results in *line*, experiments in *symbol*, *from bottom to top* are $z = 3.2D$, $z = 8.7D$, $z = 14.2D$, $z = 19.9D$, $z = 24.5D$