Flow stratification of supercritical $\text{CO}_2$
in a heated pipe

Xu Chu and Eckart Laurien
Institute of Nuclear Technology and Energy Systems (IKE)
University of Stuttgart
xu.chu@ike.uni-stuttgart.de
Agenda

- Introduction
  - Motivation
  - Previous work
  - Aim of study
- Numerical method
  - Governing equations
  - Simulation conditions
- Results and discussion
  - Bulk properties
  - Flow stratification
  - Secondary flow
  - Turbulence statistics
- Conclusions
Motivation

Supercritical water reactor (SCWR, HPLWR):

- High efficiency
- Compact and simpler system design
- Water is cheap, non-toxic and transparent
- Gen IV reactor concept

sCO₂ facility (SCARLETT) at IKE, University of Stuttgart

- Max. mass flux \( \dot{m} = 0.1 \) (Kg/s), \( P_{max} = 120 \) bar
- Followed by development of PCHE (sCO₂-HeRo Project in EU)
Motivation

CFD of heat transfer with supercritical fluid

- **RANS-Application oriented**
  - Various attempt with different models and solvers
  - modelling (classical/advanced) proved to be **unreliable**
  - DNS is needed for further understanding and model improvement

- **DNS-A powerful tool for turbulence research**
  - Details resolved without turbulence modeling
  - Limited to simple geometry
  - Very rare, extremely high computational cost
  - Bae *et al.*, 2005, Nemati/Pecnik, 2015: vertical pipe, CO₂, Re₀=5400, P₀=8 MPa, house code
Previous work
DNS of vertical pipe

DNS vs. DNS (Bae et al., 2005, Nemati/Pecnik, 2015)

- $Re_0=5400$, $P_0=8$ MPa/8.8 MPa, $D=1$ mm/2 mm, variable $q_w$, $T_0$
- Up to 80 Mio. cells
- DNS data base (10 cases) with average field, turbulence field, budget, spectrum

DNS vs. Experiments
- Experiments from Jiang et al. (U Tsinghua, China), $Re_0=9000$, $P_0=8.8$ MPa, $D=2$ mm
- Well resolved DNS with 150 Mio. cells
Aim of Study

- Using DNS to investigate heat transfer of sCO$_2$ under different conditions including vertical/horizontal pipe, complex geometry and conditions in the future

- Data serves for model improvement/development (see companion paper by Laurien, Pandey and McEligot)
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- Conclusions and future work
Variation of thermo-physical properties:

Low-Mach N-S equations based on Cartesian Coordinates

\[
\frac{\partial (\rho)}{\partial t} + \frac{\partial (\rho U_j)}{\partial x_j} = 0
\]

\[
\frac{\partial (\rho U_i)}{\partial t} + \frac{\partial (\rho U_i U_j)}{\partial x_j} = -\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\mu\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right)\right) \pm \rho g \delta_{i1}
\]

\[
\frac{\partial (\rho h)}{\partial t} + \frac{\partial (\rho U_j h)}{\partial x_j} = \frac{\partial}{\partial x_j}\left(k \frac{\partial T}{\partial x_j}\right)
\]

\[h = h(P_0, T), T = T(P_0, h), \rho = \rho(P_0, h), \mu = \mu(P_0, h), k = k(P_0, h), C_p = C_p(P_0, h)\]

- OpenFOAM V2.4 as solver, FVM
- PISO as the algorithm for P-U coupling, 2-Order spatial/temporal
- Implementation of properties library: NIST
Numerical method
Computational details

- Structured Mesh based on Cartesian Coordinate, 80 Mio. cells
- Fully developed turbulent flow at inlet (Recycle/Rescale BC)
- Used and validated on experiments with heated air (Shehata and McEligot, 1998)

### Resolution

<table>
<thead>
<tr>
<th>Resolution</th>
<th>$r$</th>
<th>$\theta$</th>
<th>$z$</th>
<th>$\Delta r_1^+$</th>
<th>$(R \Delta \theta)^+ \text{(wall)}$</th>
<th>$\Delta z^+$</th>
<th>$\Delta t^+$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>168</td>
<td>172</td>
<td>2800</td>
<td>0.11</td>
<td>6.5</td>
<td>4.6</td>
<td>1.1x10^{-4}</td>
</tr>
</tbody>
</table>
Numerical method
Computational details

- Parallel computation on 1400 CPU cores, 4 days for 10 FTT
- $C_f$ at inlet 0.15% difference as Blasius estimation → numerical quality
- Inflow turbulence quality, validated with Wu and Moin, 2008

### Simulation conditions, $P_0 = 8$ MPa

<table>
<thead>
<tr>
<th>Case</th>
<th>Type</th>
<th>$D$ (mm)</th>
<th>$q_w$ (kW/m²)</th>
<th>$T_0$ (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SC160</td>
<td>Mixed</td>
<td>1</td>
<td>61.74</td>
<td>301.15</td>
</tr>
<tr>
<td>SC230F</td>
<td>Forced (g=0)</td>
<td>2</td>
<td>30.87</td>
<td>301.15</td>
</tr>
<tr>
<td>SC230</td>
<td>Mixed</td>
<td>2</td>
<td>30.87</td>
<td>301.15</td>
</tr>
<tr>
<td>SC260</td>
<td>Mixed</td>
<td>2</td>
<td>61.74</td>
<td>301.15</td>
</tr>
</tbody>
</table>

$T_{pc} = 307.8$ K
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Results and discussion

Bulk properties

Mean wall temperature $T_w$

- $q_w \approx 60$ kW/m$^2$
- $q_w \approx 30$ kW/m$^2$

Nusselt number $Nu$

- $q_w \approx 30$ kW/m$^2$
- $q_w \approx 60$ kW/m$^2$
Results and discussion

Bulk properties

- $C_f$ strongly inhomogenous
- Non-monotonical tendency
Results and discussion
Flow stratification, SC230, $q_w \approx 30$ kW/m$^2$

Average flow field, SC230

$\theta = 0^\circ$
$\theta = 45^\circ$
$\theta = 90^\circ$
$\theta = 180^\circ$
Results and discussion

Flow stratification, SC260, $q_w \approx 60$ kW/m$^2$
Results and discussion

Secondary flow

Vector plot of $\vec{U}_r$ and $\vec{U}_\theta$

SC230

Z=10D
Z=15D
Z=20D
Z=25D

SC260

Z=10D
Z=15D
Z=20D
Z=25D

$\bar{\rho}/\rho_0$
Results and discussion

Turbulence statistics

\[ TKE = \frac{1}{2} \rho U_i U_i'' \]

- \( D = 1 \text{mm}, \quad q_w \approx 30 \) for SC160
- \( D = 2 \text{mm}, \quad q_w \approx 60 \) for SC230 and SC260

Graphs showing the TKE profiles for different locations and orientations:
- SC230 at \( z = 0D \)
- SC260 at \( \theta = 0^\circ \)
Results and discussion

Turbulence statistics

(a) SC230

(b) SC260

\[ P_k \]

\[ r/R \]
Conclusions

- Effect of buoyancy to the heat transfer of sCO2 in a horizontal pipe using DNS
- Wall temperature $T_w$ and skin friction coefficient strongly inhomogeneous in the circumferential direction
- Secondary flow is built up due to density difference and it transports the heated fluid to the top surface
- Modified mean velocity field and turbulence field
Thank you for your attention.