Experimental investigation of effect of buoyancy on supercritical carbon dioxide heat transfer in round tubes

Sandeep Pidaparti, Mark Mikhaeil, Jacob McFarland, Devesh Ranjan, Mark Anderson

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Motivation for the study

- Heat exchangers in the cycle
  - High temperature recuperator (HTR)
  - Low temperature recuperator (LTR)
  - Cooler

- Expected operating conditions
  - 7.6 – 20 MPa
  - 20 – 50 KW/m²
  - 200 – 300 Kg/m²s

- For these conditions, there is a need for fundamental understanding of effects of buoyancy on heat transfer
  - Various channel sizes

From ANL Plant Dynamics Code [Moisseytsev et al]
Experimental facility

- Heat transfer deterioration due to buoyancy effects and flow acceleration
- Key components of the test facility – A high pressure CO\textsubscript{2} supply pump, circulation pump, flow meter, precooler, preheater, and DC power supply
- Test section orientation can be changed with minor tubing modifications

<table>
<thead>
<tr>
<th>Component</th>
<th>Capabilities</th>
</tr>
</thead>
<tbody>
<tr>
<td>HPLC pump</td>
<td>Up to ~ 10,000 psi</td>
</tr>
<tr>
<td>Circulation pump</td>
<td>0.6 – 7.0 GPM</td>
</tr>
<tr>
<td>Coriolis flow meter</td>
<td>0 – 0.27 Kg/sec</td>
</tr>
<tr>
<td>Pre-heater</td>
<td>Maximum 5.5 KW</td>
</tr>
<tr>
<td>Water chiller</td>
<td>Maximum 5.28 KW</td>
</tr>
<tr>
<td>Pre-cooler</td>
<td>Double tube HEX</td>
</tr>
<tr>
<td>DC power supply</td>
<td>0 – 5 KW</td>
</tr>
<tr>
<td>Buffer Tank</td>
<td>~ 0.5 m\textsuperscript{3}</td>
</tr>
</tbody>
</table>
Test section

- Direct current volumetric heating
  - 10 V, 500 A power supply

- \( L = 1m, D_{\text{in}} \sim 10.9 mm, D_{\text{out}} \sim 12.7 mm \)

- RTD probes are calibrated against boiling water and ice bath

- Wall temperatures are measured using 20 E type thermocouples
  - Calibrated against RTDs under no heat flux conditions
Data analysis procedure

- Data recorded for 500 s @ 1Hz

\[ Q''_{PS} = \frac{V_{PSI PS}}{\pi D_i L} \] [PS – power supply]

\[ T_{wi} = T_{wo} + \frac{\dot{q}}{4k_{ss}} \left[ \left( \frac{D_{out}}{2} \right)^2 - \left( \frac{D_{in}}{2} \right)^2 \right] - \frac{\dot{q}}{2k_{ss}} \left( \frac{D_{out}}{2} \right)^2 \ln \left( \frac{D_{out}}{D_{in}} \right) \]

\[ \dot{q} = \frac{V_{PSI PS}}{\pi (D_{out}^2 - D_{in}^2)L} \]

Where, \( k_{ss} \) is the thermal conductivity of stainless steel 316

\[ T_{b+1} = T_b + \frac{Q''_{PS}}{m C_p} \pi D x \]

- Local heat transfer coefficients and Nusselt numbers are calculated as,

\[ h = \frac{Q''_{PS}}{A(T_{wi} - T_b)} \]

\[ Nu_b = \frac{hD}{k_b} \]
# Results

- Effect of
  - Operating pressure
  - Flow direction
  - Inlet temperature
  - Heat flux

<table>
<thead>
<tr>
<th>Control Parameters</th>
<th>Range of Study</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inlet Temperature</td>
<td>20 – 55°C</td>
</tr>
<tr>
<td>Operating pressure</td>
<td>7.5, 8.1, and 10.2 MPa</td>
</tr>
<tr>
<td>Mass flux</td>
<td>195, 320 Kg/m²·sec</td>
</tr>
<tr>
<td>Heat flux</td>
<td>0 - 65 KW/m²</td>
</tr>
<tr>
<td>Flow direction</td>
<td>Horizontal, Upward, and Downward</td>
</tr>
</tbody>
</table>

- Buoyancy factor calculations
Effect of operating pressure

- Test conditions
  - Mass flux, 195 Kg/m²sec
  - Heat flux, 13.5 KW/m²
  - Downward flow

- Heat transfer enhancement close to the pseudo-critical point

- $T_b < T_{pc}$, lower operating pressure results in higher HTC’s

- $T_b > T_{pc}$, higher operating pressure results in higher HTC’s

- Attributed to variation of isobaric Prandtl number
Effect of flow direction

- Test conditions
  - Mass flux, 195 Kg/m$^2$sec
  - Heat flux, 24 KW/m$^2$
  - Operating pressure, 10.2 MPa
  - Bulk inlet temperature, 46$^0$ C

- Horizontal flow – Circumferential variation in wall temperature

- Upward flow – Localized spikes in wall temperature

- Downward flow – Wall temperatures are significantly lower than upward flow
Effect of flow direction

- **Upward flow** – Turbulent shear stress is reduced by buoyancy force
- **Downward flow** – Turbulent shear stress is enhanced by buoyancy force
Effect of inlet temperature

- Test conditions
  - Mass flux, 320 Kg/m$^2$/sec
  - Heat flux, 24 KW/m$^2$
  - Operating pressure, 7.5 MPa
  - Horizontal, upward and downward flow

- Horizontal flow – Severe discontinuity in the wall temperature as the inlet temperature is changed

- Thermal entrance length effects

- Temperature differences between top and bottom sides reduce for $T_b > T_{pc}$
Effect of inlet temperature

- Upward flow – Location of spikes can be readily be changed by changing the inlet temperature
- Downward flow – Sharp increase in wall temperature for $T_{in} \sim T_{pc}$
- Pseudo-film boiling phenomenon similar to film boiling at subcritical pressures
- For $T_{b} > T_{pc}$, wall temperatures similar for both upward and downward flows
Effect of heat flux

- Test conditions
  - Mass flux, 195 Kg/m²sec
  - Operating pressure, 7.5 MPa
  - Downward flow

- Heat transfer enhancement reduces with heat flux

- Area integrated values of $C_p$ reduces

- Pseudo-film boiling phenomenon is evident for all heat fluxes
Buoyancy criteria – Vertical flows

- Experimental Nusselt numbers normalized with Jackson correlation (developed for forced convection)

\[ Nu_{Jackson} = 0.0183Re_b^{0.82}Pr_b^{0.5} \left( \frac{\rho_w}{\rho_b} \right)^{0.3} \left( \frac{C_{av}}{C_{pb}} \right)^n \]

Where, \( n \) is defined as

\[ n = 0.4 \text{ for } T_b < T_w < T_{pc} \text{ and } 1.2T_{pc} < T_b < T_w \]

\[ n = 0.4 + 0.2 \left( \frac{T_w}{T_{pc}} - 1 \right) \text{ for } T_b < T_w < T_{pc} \]

\[ n = 0.4 + 0.2 \left( \frac{T_w}{T_{pc}} - 1 \right) \left( 1 - 5 \left( \frac{T_b}{T_{pc}} - 1 \right) \right) \text{ for } T_{pc} < T_b < 1.2T_{pc} \]

- Jackson, 2013 buoyancy criteria

\[ Bu = C_B Bo_b F_{VP1} F_{VP3} F_{VP4} < 0.04 \]

\[ C_B = 4600, \quad Bo_b = \frac{Gr_b}{Re_b^{2.625}Pr_b^{0.4}}, \quad F_{VP1} = \left( \frac{\mu_{av}}{\mu_b} \right) \left( \frac{\rho_{av}}{\rho_b} \right)^{-0.5} \]

\[ F_{VP3} = \left( \frac{Pr_{av}}{Pr_b} \right)^{-0.4}, \quad F_{VP4} = \frac{\rho_b - \rho_{av}}{\rho_b - \rho_w} \]
Buoyancy criteria – Upward flow

Recovery from Laminarization

Normal heat transfer regime

Principle of Natural convection

\[ \text{Bu}, C_B F_{VP1} F_{VP3} F_{VP4} B_{Ob} \]
Buoyancy criteria – Downward flow

\[ \text{Pseudo-film boiling phenomenon near pseudo-critical region} \]

\[ \text{Bu, } C_B F_{VP1} F_{VP3} F_{VP4} Bo_b \]
Jackson, 1976 suggested a criteria to neglect buoyancy effects for horizontal flows

\[ Buoyancy \text{ criteria} \rightarrow \text{Horizontal flow} \]

- Flow dominated by natural convection
  \[ Bo_j < 10 \]

- For forced convection regime
  \[ Bo_j = \frac{Gr_b}{Re_b^2} \left( \frac{\rho_b}{\rho_w} \right) \left( \frac{x}{D} \right)^2 < 10 \]
Buoyancy criteria – Horizontal flow

Horizontal Flow - Bottom side

Approaching forced convection regime

Pseudo-film boiling phenomenon near pseudo-critical region

$B_{oj} < 10$

$\frac{\text{Nu}_{\text{exp}}}{\text{Nu}_{\text{Jackson}}}$ vs $B_{oj}$
Summary

- Effect of buoyancy on heat transfer was investigated

- For $T_b < T_{pc}$, effect of buoyancy was significant resulting in
  - Circumferential variation of wall temperature for horizontal flow
  - Localized peaks in wall temperature for upward flow
  - Enhancement in heat transfer for downward flow

- For $T_b > T_{pc}$, effect of buoyancy was minimum leading to similar wall temperature profiles for all the flow orientations

- Buoyancy criteria suggested by Jackson can be used to predict the effect of buoyancy for both horizontal and vertical flows
Thank you for your time!

Questions?