Joint ICTP-IAEA Course on Science and Technology of Supercritical Water Cooled Reactors

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HEAT TRANSFER TO SUPERCRITICAL FLUIDS

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Heat Transfer to Supercritical fluids

Joint ICTP-IAEA Course on Science and Technology of SCWRs, Trieste, Italy, 27 June - 1 July 2011

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Objectives

• Outline differences in heat transfer under supercritical conditions
• Identify best methods to estimate heat transfer in supercritical fluids
• Understand the mechanisms for Heat transfer improvement/deterioration
• Understand the differences between tubes, bundles and other orientation heat transfer correlations
• Learn where to find Data/Resources for further investigation of SCWR heat transfer
Basic review of heat transfer

• Introduction to heat transfer for supercritical fluids
  – How does this differ from low pressure water with respect to heat transfer. One major area is CHF- (at pressures above the critical pressure we do not have to worry about boiling phase heat transfer)

At pressures below the critical point normal heat transfer phenomena occurs until a certain critical heat flux is achieved. Above this point rapid boiling occurs and you can get dry-out (CHF).
Introduction to heat transfer (Review)

- Review of heat transfer for “normal fluids”
- Heat transfer is the exchange of thermal energy from one thermodynamic system to another
  
  e.g., Nuclear systems – typically concerned with transferring heat from fuel pins to water

- Types of heat transfer:
  - Conduction, convection and thermal radiation

  \[ q_x'' = -k \frac{dT}{dx} \quad q_x'' = h(T_s - T_\infty) \quad q_x'' = \epsilon \sigma (T_s^4 - T_\infty^4) \]
  \[ \sigma = 5.67 \times 10^{-8} \text{[W/m}^2\text{K}^4] \]

- In order to calculate the fuel pin temperature and the amount of energy we will get from a SCWR need to evaluate the heat transfer.
  - Conduction is straightforward
  - Unless at very high temperatures radiation is component is small
  - Convection coefficient \((h)\) is most important.
Estimation of Convection

• Convection is comprised of two mechanisms
  – Random molecular motion (diffusion)
  – Bulk or macroscopic motion of the fluid

Convection between fluid motion and bounding surface when the two are at different temperatures.

Recall fluid motion over a heated surface: (both hydrodynamic and thermal boundary layers will develop) we need to understand what is happening in the boundary layer.

Random molecular motion dominates at y close to zero. Bulk motion is governed by the boundary layer that develops in the x-direction. The heat conducted into this layer is swept downstream and eventually transferred to the bulk.
Laminar –vs- Turbulent

- The range of heat transfer is dependent on the flow regime and the size/frequency of the turbulent eddies.
- Laminar flow typically occurs during development or with low fluid velocities and has heat transfer coefficients around 10-1000 [W/m²K].
- Turbulent flows are associated with high velocity and fully developed conditions and can have heat transfer coefficients in the 20-20000 [W/m²K].

The Reynolds number (ratio of inertial forces to viscous forces) can be used to characterize laminar or turbulent flow:

\[ Re = \frac{\rho V D}{\mu} \]
Laminar convection coefficients

• For constant surface heat flux it is possible to develop an approximate analytical solution for the heat transfer coefficient if we assume constant properties:

\[
u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial r} = \frac{\alpha}{r} \frac{\partial}{\partial r} \left( r \frac{\partial T}{\partial r} \right)
\]

Energy

Boundary layer approximations

\[v = 0, \ (\frac{\partial u}{\partial x}) = 0, \ \text{and} \ \frac{\partial^2 T}{\partial x^2} = 0\]

Results in

\[h = \frac{48}{11} \left( \frac{k}{D} \right)\]

or

\[N u_D = \frac{h D}{k} = 4.36\]
Turbulent convection coefficients

- Under most reactor conditions the Reynolds number is sufficiently high such that turbulent flow occurs ($Re \gg 5000$)
- It is difficult to develop analytical theory for turbulent flows – therefore we require either CFD solutions to the governing equations or can get the general trends by semi-empirical formulations which include the relevant non-dimensional parameters
- A fuel pin bundle flow channel to a first approximation can be considered internal flow.
- Under these conditions the Dittus Boelter “type equations” are widely used for engineering approximations and are in the form:

$$Nu_D = CR e_D^x Pr^y$$
$$Nu = \frac{hD}{k}$$

$$C = 0.023, x = \frac{4}{5}, y = 0.4$$
$$0.7 \leq Pr \leq 160$$
$$Re_D \geq 8,000$$
$$\frac{L}{D} \geq 10$$

These equations were developed from air water data at room temperature but are typically extended outside this range by using different $C, x, y$ values adding some corrections for property variations. Most reactor systems have specific correlations for their geometries typically of this form.
Forced -vs- Free convection

- Forced convection – caused by external means (e.g., pump, fan)
- Free (natural) convection- flow is induced by buoyancy forces which arise from density differences caused by temperature variations

We can have:

Pure forced convection
- Gases – $h=25-250$ W/m²K
- Liquids – $h= 50- 20,000$ W/m²K

Pure Free convection
- Gases – $h = 2-25$ W/m²K
- Liquids – $h = 50- 1000$ W/m²K

Mixed convection
- Typically between forced and free

Boiling/condensation
- $h = 2500- 100,000$ W/m²K

Supercritical fluids forced convection
- $h= 1000-50000$ W/m²K

$$Gr = \frac{g\beta(T_w - T_b)D^3}{\nu^2}$$

$$\beta = -\frac{1}{\rho} \left( \frac{\partial \rho}{\partial T} \right)_p$$

Ratio of Buoyancy to viscous forces

$$Nu = C \left( Gr^a Pr^b \right)$$
What are the issues with SCF’s

Property variations!

- Specific heat is theoretically infinite at the critical point and the location of the peak defines the pseudo critical point.
- Density changes by a factor of 10x
- Thermal conductivity changes by a factor of 6x
- Viscosity changes by a factor of 4x
- The fact that the properties change so drastically over a small temperature causes unique phenomena in the flow and in correlating heat transfer data.
- Requires modifications to the existing correlations

Thermophysical property variation of water as a function of temperature at 25 Mpa calculated with Steam_IAPWS formulae (Kestin et al., 1984, Saul et al., 1987)
NIST REFPROP - program
EES (Engineering Equation solver) – This is convenient since it also allows you to solve non-linear sets of equations
A look at what happens going through the critical point \( P=220.6 \text{ Bar} \)

Heating up through critical point  
\( T_C = 373.9 \text{C} \)

Cooling down from above critical point  
\( T_C = 373.9 \text{C} \)

http://www.science.uva.nl/research/mgrd/video-cp.htm  
(Universiteit van Amsterdam)
Properties of water as a function of pressure
Quick way to calculate properties

"Calculation of properties using EES code"

\[ P = 35 \]
\[ P_C = P_{\text{crit}}(\text{Steam IAPWS}) \]
\[ T_C = T_{\text{crit}}(\text{Steam IAPWS}) \]
\[ c_p = c_p(\text{Steam IAPWS}, T = T, P = P) \]
\[ \rho = \text{Density}(\text{Steam IAPWS}, T = T, P = P) \]
\[ h = \text{Enthalpy}(\text{Steam IAPWS}, T = T, P = P) \]
\[ \mu = \text{Viscosity}(\text{Steam IAPWS}, T = T, P = P) \]
\[ k = \text{Conductivity}(\text{Steam IAPWS}, T = T, P = P) \]

\[ c_p_J = \text{convert}(\text{kJ, j}) \times c_p \]
\[ \text{Prandlt} = c_p_J \times \mu / k \]

We can get the properties of any fluid in this manner and could compare the changes in properties of water with surrogate fluids CO2, helium, air, Refrigerants, etc.

We will focus on water for this lecture but data from other fluids with similar fluid property variations are relevant.
What does the data tell us

- Pioro and Duffy, *Heat transfer and Hydraulic Resistance*, 2007 has an excellent summary of data for a wide range of Supercritical conditions.
- There have been 100’s of experiments measuring heat transfer with water and other fluids above the critical pressure.
- Most of the data have been in circular tubes, with a limited set in annuli and even fewer in bundle geometries.
- In general what was found is that the variation in properties affect the convection heat transfer - three different modes of heat transfer were observed
  - normal heat transfer – occurs at high mass flux low heat flux
  - Improvement in the HTC near the pseudo critical point.
  - Deteriorated heat transfer with low mass flux and high heat flux under some orientations
- The following tables have the conditions of several of the tests that have been conducted in the past – we will focus on a few for discussion purposes.
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Edited from Pioro and Duffy 2007

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International Atomic Energy Agency
Normal and improved heat transfer - Yamagata data

- Note drastic improvement in HTC near the critical point
  - magnitude of peak increases with lower heat flux
  - magnitude of peak decrease with increased pressure
Observation of deterioration

Styrikovich et al 1965

- Note as the heat flux is increased we start to see deterioration in the HTC
  - Deterioration starts to occur when wall temperature increases above pseudo critical temperature
  - It was observed as an increase in wall temperature along the tube
  - Mainly seen to occur in upward vertical flow and to a much lower extent in horizontal

Shitsman et al. 1968
Effect of orientation

The effect of orientation is seen in this data. Low mass flux and increasing heat flux in vertical up flow and vertical down flow

- Note the increase in the wall temperature in upward flow
- Also note the somewhat periodic change in wall temperature as you move along the tube
- The increase in wall temperature is not observed in downward flow

These modes of heat transfer have been seen actually been seen in many fluids where the properties change continuously but drastically. The larger the change the larger the effect

Pis’mennyy et al. 2005
P=23.5MPa, G=248 kg/m²s
To correlate the data we have to categorize it based on the flow conditions (forced, mixed convection – i.e. buoyancy induced, acceleration affected)

As noted several studies showed that the deterioration typically occurs when the mass flux is low and the heat flux is high $q^+ / G > 0.4$

This effect was attributed to a change in the turbulent shear stress due to the influence of buoyancy forces

$$\frac{Gr_b}{Re_b^{2.7}} < 10^{-5}$$

$$\frac{Nu_b}{Nu_{bo}} = \left[ 1 \pm C_B Bo_b^* \left( \frac{Nu_b}{Nu_{bo}} \right)^{-0.46} \right]$$

$$Bo_b^* = Gr_b^*/(Re_b^m Pr^n)$$

$C_b \sim 10^5$
Forced convection

Under forced convection conditions we have normal heat transfer with some improvement due to enhanced properties

\[ Nt_D = CRe_D^x Pr^y \]

\[ C = 0.023, \ x = \frac{4}{5}, \ y = 0.4 \]

\[ 0.7 \leq Pr \leq 160 \]

\[ Re_D \geq 8,000 \]

\[ \frac{V}{D} \geq 10 \]

\[ Nu = \frac{hD}{k} \]

\[ Pr = \frac{c_p\mu}{k} \]

\[ Re = \frac{\rho V D}{\mu} \]

\[ h \propto (\rho v)^{0.8} D^{-0.2} \mu^{-0.4} c_p^{0.4} k^{0.6} \]

This means that we can correlate the data similar to what we did for normal fluids if we include factors that account for the property changes

\[ \left( \frac{\rho_a}{\rho_b} \right)^c \]

\[ \left( \frac{c_{p,a}}{c_{p,b}} \right)^d \]

\[ \left( \frac{k_a}{k_b} \right)^e \]

\[ \left( \frac{\mu_a}{\mu_b} \right)^f \]
Improvement under force convection, why does it decrease with increasing heat flux

\[ h = \frac{q''}{(T_w - T_b)} \]

High mass flux low heat flux independent of orientation

Improvement

High mass flux low heat flux independent of orientation

Wall

Bulk

Flow

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Several different investigators used this procedure and developed correlations of the form below: Where \(a,b\) could be the properties evaluated at the wall, bulk or pseudo critical point.

\[
\text{N}_{t,x} = C_1 \text{Re}_{t,x}^{m_1} \text{Pr}_{t,x}^{m_2} \left( \frac{\rho_t}{\rho_t} \right)_x^{m_3} \left( \frac{\mu_t}{\mu_t} \right)_x^{m_4} \left( \frac{k_t}{k_t} \right)_x^{m_5} \left( \frac{c_p}{c_{p,t}} \right)_x^{m_6} \left( 1 + C_2 \frac{D_{hy}}{L_h} \right)^{m_7}
\]

Last term accounts for entrance effects.
Pioro and Duffy (2007) summarized several of the major correlations for forced convection as follows:

<table>
<thead>
<tr>
<th>Reference</th>
<th>Flow geometry</th>
<th>Characteristic parameters in Nu, Re and Pr</th>
<th>( m_1 )</th>
<th>( m_2 )</th>
<th>( m_3 )</th>
<th>( m_4 )</th>
<th>( m_5 )</th>
<th>( m_6 )</th>
<th>( m_7 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>McAdams et al. 1950</td>
<td>Annulus</td>
<td>( D_{by} ), ( t_w ) or ( t_{pc} )</td>
<td>0.8</td>
<td>0.33</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Bringer, Smith 1957</td>
<td>Tube</td>
<td>( t_w ), ( t_{pc} ) or ( t_u )</td>
<td>0.77</td>
<td>0.55</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Shitsman 1959, 1974</td>
<td>Tube</td>
<td>( t_b ), ( t_w ) or ( t_u )</td>
<td>0.8</td>
<td>0.8</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Krasnoshchekov, Protopopov 1959</td>
<td>Tube</td>
<td>( t_b ), ( D )</td>
<td>~0.8</td>
<td>~0.33</td>
<td>0</td>
<td>0.11</td>
<td>~0.33</td>
<td>0.35</td>
<td>0</td>
</tr>
<tr>
<td>Swenson et al. 1965</td>
<td>Tube</td>
<td>( t_w ), ( D )</td>
<td>0.923</td>
<td>0.613</td>
<td>~0.231</td>
<td>0.231</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Kondrat’ev 1969</td>
<td>Tube, annulus</td>
<td>( t_b ), ( D_{by} )</td>
<td>0.8</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Ornatsky et al. 1970</td>
<td>Tube</td>
<td>( t_b ), ( D )</td>
<td>0.8</td>
<td>0.8</td>
<td>~0.3</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Yamagata et al. 1972</td>
<td>Tube</td>
<td>( t_b ), ( D_{by} )</td>
<td>0.8</td>
<td>0.4</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Dyadyakin, Popov 1977</td>
<td>Bundle</td>
<td>( t_b ), ( D_{by} )</td>
<td>0.8</td>
<td>0.7</td>
<td>~0.45</td>
<td>0.2</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Kirillov et al. 1990</td>
<td>Tube</td>
<td>( t_b ), ( D )</td>
<td>~0.8</td>
<td>~0.33 or</td>
<td>~0.1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Gorban’ et al. 1990</td>
<td>Tube</td>
<td>( t_b ), ( D )</td>
<td>0.9</td>
<td>~0.12</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

\[
\text{Nu}_{t,x} = C_1 \text{Re}_{t,x}^{m_1} \text{Pr}_{t,x}^{m_2} \left( \frac{\rho_t}{\rho_i} \right)^{m_3} \left( \frac{\mu_i}{\mu_r} \right)^{m_4} \left( \frac{k_i}{k_r} \right)^{m_5} \left( \frac{\overline{c}_p}{c_{p,r}} \right)^{m_6} \left( 1 + C_2 \frac{D_{by}}{L_h} \right)^{m_7}
\]
Recommended correlations

A modified Kranoshechekov et al. correlation proposed by Derek Jackson seems to correlate to the broadest existing data sets the best for single tube and annulus.

\[ Nu_b = 0.0183 \cdot Re_b^{0.82} \cdot Pr_b^{0.5} \left( \frac{\rho_w}{\rho_b} \right)^{0.3} \left( \frac{C_p}{C_{p,b}} \right)^{n} \]

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

for \( T_b < T_w < T_{pc} \) and for \( 1.2T_{pc} < T_b < T_w \)

for \( T_b < T_w < T_{pc} \)

for \( T_{pc} < T_b < 1.2T_{pc} \)
Comparison of forced convection correlation with data

\[ \text{Nu}_{DB, f} = 0.023 \text{Re}_{f}^{0.8} \text{Pr}_{f}^{0.4} \]

\[ \text{Nu}_{JA, b} = 0.0183 \text{Re}_{b}^{0.82} \text{Pr}_{b}^{0.5} \left( \frac{\rho_{w}}{\rho_{b}} \right)^{0.3} \left( \frac{c_{p}}{c_{pb}} \right)^{n} \]

\[ n = f\left(T_{b}, T_{w}, T_{pc}\right) \]

Data from Licht et.al 2008
Mixed convection – effect of buoyancy

\[ \frac{Gr_b}{Re_b^{2.7}} < 10^{-5} \]

\[ \frac{Nu_b}{Nu_{bo}} = \left[ 1 \pm C_b Bo_b^* \left( \frac{Nu_b}{Nu_{bo}} \right)^{-2.46} \right] \]

\[ Bo_b^* = \frac{Gr_b^*}{(Re_b^m Pr^n)} \]

\[ C_b \sim 10^5 \]
Deterioration occurs under mixed convection

Upward flow low mass flux high heat flux, effect increases with increase heat flux or decrease in mass flux

The increase in the buoyancy force in upward flow causes changes in the turbulent boundary layer causing a reduction in the turbulent shear stress (laminar like boundary layer)
**Requirements:**
- High P → 25 MPa
- High T → 600 °C
- Wide G → 2000 kg/m²s
- High Q” → 1.5 MW/m²
- Prototypic Geometry
- Optical Access

Look at a specific experiment to understand the phenomena.

**Static Seal**
- Internal Heater
- Heated Section

**Dynamic Seal**
- Optical Access
Mean and Turbulent Velocity Measurements

Laser Doppler Velocimetry (LDV)  Fluid velocity from light scattered off seeded particles

~1μm

33μm

200μm
High Mass Velocity: Experimental Conditions

\[ G = 1000 \, \text{kg/m}^2\text{s} \]

Square geometry heat transfer data

- **Bulk Temperature (°C)**
  - 273.8
  - 330.6
  - 370.9
  - 384.2
  - 390.2
  - 411.4

- **Nu (Jackson)**
- **\( Q'' = 440 \, \text{kW/m}^2 \)**
- **\( Q'' = 220 \, \text{kW/m}^2 \)**

- \( G = 1000 \, \text{kg/m}^2\text{s} \)
- \( P = 250 \, \text{Bar} \)

- **Wall Temperature (°C)**
  - 273.8
  - 330.6
  - 370.9
  - 384.2
  - 390.2
  - 411.4

- **Bulk Enthalpy (kJ/kg)**
  - 1200
  - 1500
  - 1800
  - 2100
  - 2400
  - 2700

- **\( H \) (kJ/m²K)**
  - 5
  - 10
  - 15
  - 20
  - 25
  - 30
  - 35
  - 40

- \( T_{pc} \)
- \( 393 \)
- \( 386 \)
- \( 393 \)
- \( 1967 \)
- \( 1978 \)

International Atomic Energy Agency
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Normalized Velocity/Turbulence

Normalized Properties

Heat Transfer Coef.

Wall Heat Transfer Coef. (W/m²K x 10⁻³)

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Low Mass Velocity: Experimental Conditions

Square geometry heat transfer data

$G = 300 \text{ kg/m}^2\text{s}$

$Q'' = 440\text{ kW/m}^2$

$Q'' = 220\text{ kW/m}^2$

$G = 315 \text{ kg/m}^2\text{s}$

$P = 250\text{ Bar}$
Low Mass Velocity

Velocity

Normalized Properties

Axial $T_w$

R-R$_i$ (mm)  

R-R$_o$ (mm)  

~log scale

L (m)

250°C

175°C

Inner wall

Outer wall

Isothermal

$\rho$

$C_p$

$T_b$ ($^\circ$C)

440 kW/m$^2$

220 kW/m$^2$
Low Mass Velocity

- Velocity/T_w suggest similar effects sub/supercritical

![Graphs showing velocity, normalized properties, and axial T_w.](image)

- ~Isothermal
- ~log scale

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Turbulence measurements in SCF

LDV Measurements

\[ G = 300 \text{ kg/m}^2\text{s} \]
\[ T_b = 175 \, ^\circ\text{C} \]
\[ Q'' = 220 \text{ kW/m}^2 \]
\[ P = 250 \text{ Bar} \]
Experimental Turbulence measurements

Axial Velocity

Isothermal

Turbulent Shear Stress

Radial Turbulence

Diffusivity of Momentum

Turbulent Production

\( q'' = 0 \)

Joint ICTP-IAEA Course on Science and Technology of SCWRs, Trieste, Italy, 27 June - 1 July 2011 (SC11) Heat transfer to Supercritical Fluids
Effect of increased heat flux

Axial Velocity

Axial Turbulence

Turbulent Production

Turbulent Shear Stress

Radial Turbulence

Diffusivity of Momentum

Isothermal
Experimental Turbulence measurements

- Increase in very near wall turbulence
- Decrease in turbulence further from wall

Pr_T = \frac{\varepsilon_m}{\varepsilon_H} \approx 1
\varepsilon_m = u'v' \sqrt{\frac{\partial U}{\partial r}}
\varepsilon_H = v' t' \sqrt{\frac{\partial T}{\partial r}}
Mechanism of heat Transfer Deterioration

Use CFD to help understand the mechanisms seen in experiments

Reynolds Stress Model, Standard Wall Function
Mechanism of heat transfer deterioration

Fluid Temperature

Mean Velocity

Axial Wall Temperature

Diffusivity of Momentum

Turbulent Shear Stress
Mechanisms of heat transfer deterioration

Fluid Temperature

Mean Velocity

Axial Wall Temperature

Diffusivity of Momentum

Turbulent Shear Stress

\[ E_m \]
Heat Transfer Recovery

Axial Wall Temperature

Fluid Temperature

Mean Velocity

Diffusivity of Momentum

Turbulent Shear Stress
Mixed convection

- It is difficult to develop a correlation that can include buoyancy and acceleration effects
- Work is on going in this area

Jackson has recently proposed the following correlation

\[
\frac{\text{Nu}_b}{\text{Nu}_{b_o}} = \left[ 1 + \frac{C_B}{F_{TD}} \frac{\text{Gr}^*_b}{\text{Re}_b^{3.425} \text{Pr}_b^{2n}} \left( \frac{\overline{\mu}}{\rho_b} \right)^{1/2} \left( \frac{\rho_w}{\rho_b} \right)^{-0.3} \left( \frac{c_p}{c_p} \right)^{-0.4} \left( \frac{\text{Pr}}{\text{Pr}_b} \right)^{-0.4} \frac{\bar{\rho} \beta}{\rho_b \beta_b} \left( \frac{\text{Nu}_b}{\text{Nu}_{b_o}} \right)^{-2.1} \right]^{0.46}
\]

\[
\text{Nu}_{b_o} = K F_{TD}^{0.8} \text{Re}_b^{0.4} \text{Pr}_b^{0.4} F_{VP_2} \quad \text{This is the Nu for forced convection}
\]

\[
F_{TD} = 1 + 2.35 \text{Re}_b^{-0.35} \text{Pr}_b^{-0.4} (x/d)^{-0.6} \exp(-0.39 \text{Re}_b^{-0.1} (x/d)) \quad \text{Entrance effect}
\]

\[
\text{Gr}_b^* (= g \beta_b q_w d^4 / k_b \nu_b^2) \quad \text{Gr based on applied heat flux}
\]
A word on CFD

- There are several groups working on CFD applications (SC17)
- The thermal boundary layer for SCF’s is typically very thin and it is necessary to resolve very close to the wall $y^+ < 1$
- It is also important to use real thermo-physical properties for the fluid (i.e. call RefProp to get actual properties) This is time consuming – It may be possible to use look-up tables but you need to ensure correct properties.
- $k-\omega$ models have been found to give the best result but these were still developed with the assumption of constant properties.
- In general CFD is capable to accurately predict forced flow (improvement) it is more difficult to get deterioration since the properties influence the turbulent boundary layer significantly and most methods RANS rely on constant property equations.

\[
\begin{align*}
\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_j} (\rho u_j) &= 0 \\
\frac{\partial}{\partial t} (\rho u_i) + \frac{\partial}{\partial x_j} (\rho u_j u_i) &= \frac{\partial}{\partial x_j} (\sigma_{ij}) + X_i \\
\frac{\partial}{\partial t} \left[ \rho \left( i + \frac{1}{2} u_i u_i \right) \right] + \frac{\partial}{\partial x_j} (\rho i u_j) &= \frac{\partial}{\partial x_j} \left( k \frac{\partial T}{\partial x_j} \right) + \frac{\partial}{\partial x_j} \left( u_i \sigma_{ij} \right) + u_i X_i + S
\end{align*}
\]

Governing equations for turbulent boundary layer

RANS
\[
\overline{F} = \overline{F} + \overline{F}'
\]

Favre Averaging
\[
\overline{f} = \frac{\partial \overline{f}}{\partial \overline{p}} = \overline{f} + \frac{\partial \overline{f}'}{\partial \overline{p}}
\]

\[
\overline{F} = \frac{1}{\Delta t} \int_{t_0}^{t_0 + \Delta t} \overline{F}'\, dt
\]

\[
\overline{F''} = \overline{F} - \frac{\partial \overline{F}}{\partial \overline{p}} = \overline{F'} - \frac{\partial \overline{F}'}{\partial \overline{p}}
\]
Comparison of CFD simulations

High mass flux

- Yamagata Data
- Jackson correlation
- Fluent (CFD)

Q'\'' = 933 kW/m\(^2\)
Q'\'' = 698 kW/m\(^2\)
Q'\'' = 465 kW/m\(^2\)
Q'\'' = 233 kW/m\(^2\)

Mass Velocity = 1260 kg/m\(^2\)s

Low mass flux

- Shitsman Data
- Jackson Corr.
- Fluent (CFD)

Q'\'' = 386 kW/m\(^2\)
Q'\'' = 210 kW/m\(^2\)

Mass Velocity = 430 kg/m\(^2\)s

CFD has trouble with deterioration
There are a lot of “tricks” to improve this but there are issues due how the properties effect the turbulence
Heat transfer enhancement

For more complicated geometry we need CFD or a correlation for the desired geometry

As with normal fluids it is possible to enhance heat transfer in SCF’s either for internal tube flow or external flow; this can be done with ribs, wire wraps, fins, pins or various other structures.

Bundles and grid-spacers

As we have seen the heat transfer coefficient of SCF’s can vary significantly and is highly dependent on the fluid dynamic conditions (buoyancy, acceleration, up-flow, down-flow, horizontal, mass flux, Temperature, Pressure, etc.)

For forced flow high Reynold number flows our current best method is modified Nu correlations
Example of CFD simulation of complex flow

S-CO2 flow in a small zig-zag channel

Meshing was performed with hexahedral cells aligned with the predominate flow orientation

Mesh was inflated at the boundaries

$y^+$ value around 1.0 for wall adjacent cells (~1 micron in height)

Full-length models typically used 1.0 to 2.5 million cells

Inlet plenum was also modeled to aid in damping oscillations

Helical flow on the outside of the bends

Large wake regions behind every bend
## Bundle data

<table>
<thead>
<tr>
<th>Reference</th>
<th>$p$, MPa</th>
<th>$t$, °C $(H$ in kJ/kg)</th>
<th>$q$, MW/m²</th>
<th>$G$, kg/m²·s</th>
<th>Flow geometry</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dyadyakin and Popov 1977</td>
<td>24.5</td>
<td>$t_b=90–570$; $H_b=400–3400$</td>
<td>&lt;4.7</td>
<td>500–4000</td>
<td>Tight bundle (7 rods (6+1), $D_{rod}=5.2$ mm, $L=0.5$ m), each rod has four helical fins (fin height 0.6 mm, thickness 1 mm, helical pitch 400 mm), pressure tube hexagonal in cross section</td>
</tr>
<tr>
<td>Silin et al. 1993</td>
<td>23.5; 29.4</td>
<td>$H_b=1000–3000$</td>
<td>0.18–4.5</td>
<td>350–5000</td>
<td>Vertical full-scale bundles ($D_{rod}=$4 and 5.6 mm, rod’s pitch 5.2 and 7 mm)</td>
</tr>
</tbody>
</table>

Dyadyakin and Popov 1977 recommend the following correlation for bundles

$$
Nu_x = 0.021 \, Re_x^{0.8} \, Pr_x^{0.7} \left( \frac{\rho_w}{\rho_b} \right)_x^{0.45} \left( \frac{\mu_b}{\mu_{in}} \right)_x^{0.2} \left( \frac{\rho_b}{\rho_{in}} \right)_x^{0.1} \left( 1 + 2.5 \frac{D_{hy}}{x} \right)
$$
Future Bundle data

- There has been significant discussion of several groups getting ready to do heat transfer test and a few claiming to be setting up to conduct bundle test, but to date none is available in the open literature

- Xi’an Jiatong university (XJTU) has plans for a 4-rod bundle
  
  Pressure: 23, 25, 28MPa  
  Mass velocity: 400 - 2000 kg/m²s  
  Heat fluxes: 200 - 1000 kW/m²  
  Inlet fluid temperature: 300 °C  
  Outlet fluid temperature: 600 °C

- AECL and University of Ottawa – Plan to do a three rod bundle with S-CO₂
Where to find Data

The IAEA in cooperation with the OECD/NEA has made a data base of relevant experimental data at the following site; http://www.oecd-nea.org/crp_scwr_ht/ (At this time the data is not open to the public /

AECL
.Supercritical carbon dioxide test in a tube

BARC
Supercritical pressure natural circulation experiments with CO₂

IPPE
Experimental data on heat transfer to carbon dioxide under supercritical pressure

KAERI
E1 : Upward flow in eccentric annular channel
R1 : Upward flow in concentric annular channel
R1D : Downward flow in concentric annular channel
T4 : Upward flow in tube with 4.4 mm inner diameter
T457 : Upward flow in tube with 4.57 mm inner diameter
T457D : Downward flow in tube with 4.57 mm inner diameter
T6 : Upward flow in tube with 6.32 mm inner diameter
T6D : Downward flow in tube with 6.32 mm inner diameter
T6W : Upward flow in tube with 6.32 mm inner diameter (with wire type turbulence generator)
T9 : Upward flow in tube with 9.0 mm inner diameter
T9D : Downward flow in tube with 9.0 mm inner diameter

University of Wisconsin - Madison
S-CO₂ depressurization
S-CO₂ mini-channel heat transfer
Annular heat transfer measurements in upflow geometry
Fluid flow measurements in supercritical water in upflow geometry

Shanghai Jiao Tong University
Heat Transfer of Supercritical Water
Where to find data (open literature)

• Major Conferences:
  NURETH – International Topical meeting on Nuclear Reactor thermalhydraulics
  ICAPP – International Congress on Advances in Nuclear Power Plants
 icone – International Conference on Nuclear Engineering
  international symposium on supercritical-water-cooled Reactors
  Supercritical CO2 power cycle symposium
  international conference GLOBAL
  American Nuclear Society (ANL) International meeting

• Books

  Heat transfer and Hydraulic Resistance at Supercritical Pressures in Power Engineering Applications – Pioro and Duffey

  Super light water Reactors and Super fast Reactors – Oka, Koshizuka, Ishiwateri, Yamaji
Summary

• There are hundreds of publications devoted to forced convective heat transfer under SC pressures most in circular tubes.

• Heat transfer in SCF’s are strongly influenced by rapid changes in thermophysical properties.

• Heat transfer data observed three modes of heat transfer (Normal, improved and deteriorated).

• There are several correlations that allow the estimation of the heat transfer coefficient. The currently recommended correlation for forced convection is Jackson’s correlation which is good to within 20% for simple geometries.

\[ \text{Nu}_{JA,b} = 0.0183 \text{Re}^{0.82} \text{Pr}^{0.5} \left( \frac{\rho_w}{\rho_b} \right)^{0.3} \left( \frac{c_p}{c_{pb}} \right)^n \quad n = f(T_b, T_w, T_{pc}) \]

- Heat transfer is enhanced due to increases in the specific heat.
- If better than 20% is needed a specific correlation for a specific conditions is needed.
- If no data exists for similar geometry, CFD analysis may be necessary.
Summary (cont.)

• It is possible to estimate when mixed convection effect are present.

\[
\frac{Gr_p}{Re_b^{2.7}} < 10^{-5}
\]

- Under mixed convection conditions in buoyancy and acceleration effects can result in deterioration of heat transfer.
- This deterioration is difficult to predict (approximate methods for buoyancy and acceleration based on mechanisms have are being developed)

• There are some groups that are also trying to build look-up tables that allow determination of heat transfer coefficients under set geometries.

• There is very little data for bundle geometry, however it is likely that the heat transfer is further improved due to grid structure and there will be little or no deterioration. CFD is necessary for complex geometry

• CFD Techniques are being developed. The k-\omega models seem to work best, however the boundary layer must be resolved to \(y^+<1\) and real fluid properties need to be implemented. Current work on Farve averaging techniques and modification to turbulence models are under way.

• There is currently a lot of work being conducted in this area and are being input into the IAEA data bank. China, Canada, Japan, EU and US are working on facilities to conduct additional heat transfer and bundle tests.
References

1. Pioro and Duffy, Heat transfer and hydraulic Resistance at supercritical pressures in power engineering applications
8. Shitsman, M. E. Impairment of the heat transfer at supercritical pressures. High Temperatures (Teplofzika Vysokikh Temperaure ctp. 267-275) 1, 2, 237–44. (1963)
11. Incoropera and Dewitt, Introduction to heat transfer, John Wiley & Sons, 1990
...Thank you for your attention!

email: manderson@engr.wisc.edu
Turbulence measurements

\[ U^+ = y^+ \]

\[ U^+ = \left( \frac{1}{\kappa} \right) \ln(y^+) + C \]

Viscous sublayer
Buffer layer
Wall region

Scaling variables:

\[ U^+ = \frac{u}{u_r} \]
\[ u_r = \sqrt{\frac{\tau_w}{\rho}} \]
\[ y^+ = y \frac{u_r}{v} \]
\[ \tau_w = \mu \frac{\partial u}{\partial y} \bigg|_{y=0} \]
Previous Work: Shiralkar 1970 – Deterioration Regardless of Orientation

Dia ~ 6.35/3.2mm
300-450 kW/m²
73e3 < Re < 400e3

Heat Transfer behavior was independent of flow orientation.