Reactor Engineering (Fission)

Fall 2011

1. **(15 minutes)** In a 1D pipe of constant cross section, the following governing equations are written to describe the flow of fluid:

\[
\begin{align*}
\frac{\partial \rho}{\partial t} & = -\frac{\partial \rho u}{\partial z}, \\
\frac{\partial \rho u}{\partial t} & = -\frac{\partial \rho u^2}{\partial z} - \rho g - \tau_w P_{\text{wet}} - \frac{\partial P}{\partial z}, \\
\frac{\partial \rho e}{\partial t} & = -\frac{\partial (\rho u e + uP)}{\partial z} + q'' P_{\text{wet}} + u \tau_w P_{\text{wet}} + \frac{\partial}{\partial z} \left( k \frac{\partial T}{\partial z} \right),
\end{align*}
\]

where \( \rho, \ u, \ e, \ P, \ T, \ \tau_w, \ k \) represent the fluid density, velocity, total energy (\( e = i + 0.5u^2 + gz \), where \( i \) is the internal energy), pressure, temperature, stress tensor, and conductivity. \( P_{\text{wet}} \) is the wetted perimeter. \( q'' \) is the heat flux.

Answer the following questions:

a. **(3 minutes)** What physical principle is described by each of these equations?

b. **(12 minutes)** Explain each term in these equations (there are 12 terms; discuss the physical meaning of each).

2. **(10 minutes)** A 1 m thick containment wall with thermal conductivity of 1.2 W/(m·°C) is maintained at 30°C at one face and 230°C at the other face. Determine the heat transfer rate across the 1,000 m² surface area of the wall. If you are making simplifying assumptions, make sure they are stated explicitly in your solution.

3. **(15 minutes)** Fuel design parameters and economics determine the optimum amount of energy extracted from a fuel element. List at least five major factors to be considered. To get credit, you must justify your selections.
4. **(15 minutes)** During the April 1986 accident in the 1000-MW(e) RMBK Chernobyl reactor, the water in the cooling tubes of the graphite-moderated reactor was allowed, through operator error, to boil into steam and cause a supercritical, run-away chain reaction. The resulting energy excursion resulted in the destruction of the reactor. List design features of the reactor that facilitated the accident and explain why the boiling in the cooling tubes led to supercriticality.

5. **(25 minutes)** Answer the following questions:
   
   a. **(5 minutes)** Sketch the boiling curve.
   
   b. **(5 minutes)** Assume the shape of the curve for a PWR nuclear fuel rod at reactor operating conditions is similar to the curve shape in part a. Describe the approach to CHF on a fuel rod surface and the undesirable phenomena which would occur if the CHF point is exceeded.
   
   c. **(5 minutes)** Sketch the following as a function of elevation in a hot channel from coolant inlet to coolant outlet:
      
      1) Hot channel heat flux,
      2) DNB heat flux,
      3) DNB ratio.
   
   d. **(5 minutes)** An important point is that the minimum DNBR does not occur at the maximum heat flux. Why not?
   
   e. **(5 minutes)** Experiments with uranium dioxide have shown that melting does not occur until the linear heat rate in the fuel exceeds about 70 kW/m. Comment on the average linear heat rate from the clad surface for a PWR given the following specifications:
      
      \[ a = \text{radius of fuel pellet} = 0.00405 \text{ m}, \]
      \[ b = \text{outer radius of fuel clad} = 0.00475 \text{ m}, \]
      \[ Q = \text{maximum heat generation rate in the PWR} = 8.7 \times 10^8 \text{ W/m}^3, \]
      \[ h = \text{heat flux hot channel factor} = 2.5. \]

6. **(10 minutes)** Explain differences in the shape and locations of movable control elements for PWRs and BWRs. Would control elements of the same shape be adequate for all LWRs?
7. **(10 minutes)** The ECCS system in a typical PWR utilizes a high head safety injection (HHSI) pump and a low head safety injection (LHSI) pump. In the event of a drop of reactor coolant system (RCS) pressure due to LOCA, the pumps will start and draw water from the refueling water storage tank and inject into the RCS.

   a. **(5 minutes)** Sketch the volumetric flow rate versus discharge head for the HHSI pump and LHSI pump operating in parallel. Repeat for pumps operating in series. See table below.

   b. **(5 minutes)** Discuss the differences between sketches for pumps operating in parallel and in series and why one arrangement is preferred.

   Given:

<table>
<thead>
<tr>
<th></th>
<th>Shutoff Head psid</th>
<th>Runout Head psid</th>
<th>Max Flow Rate gpm</th>
</tr>
</thead>
<tbody>
<tr>
<td>HHSI Pump</td>
<td>1600</td>
<td>500</td>
<td>800</td>
</tr>
<tr>
<td>LHSI Pump</td>
<td>800</td>
<td>200</td>
<td>1600</td>
</tr>
</tbody>
</table>

   Shutoff Head - the maximum head produced by a centrifugal pump at a set operating speed

   Runout Head - the head associated with the maximum volumetric flow condition produced by a centrifugal pump without damaging the pump

8. **(20 minutes)** A high-pressure turbine stage uses saturated steam at 500°F and exhausts to a moisture separator at 50 psia with a moisture content of 10%. The separator is an isobaric process with a wet steam at 98% quality at the outlet. The process fluid is directed to a reheater producing a process stream with 40°F of superheat. The steam then expands through a low-pressure turbine stage to a moisture content of 10% at 1.5 inHg.

   a. **(5 minutes)** Draw the associated processes on the provided enthalpy-entropy diagram,

   b. **(15 minutes)** Calculate the efficiency for the low-pressure turbine stage.
The values shown on the chart are in accordance with the tolerance established by the Third International Steam Tables Conference and are derived from the properties of the perfect vapor as described in "Thermodynamic Properties of Vapors" by Dr. E. F. Leib and Combustion Engineering Company, Inc., at the Spring Meeting of the American Society of Mechanical Engineers, May 3-5, 1940, and subsequently published in the "Transactions of the A.S.M.E.," Feb. 1941.

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