

### Problem Set 5

## Single-phase Coolant Flow and Heat Transfer

### 1) Hydraulic Analysis of the Emergency Core Spray System in a BWR

The emergency spray system of a BWR delivers cold water to the core after a large-break loss of coolant accident has emptied the reactor vessel. The system comprises a large water pool, a pump, a spray nozzle and connecting pipes (Figure 1). All pipes are smooth round tubes made of stainless steel with 10 cm internal diameter. The pipe lengths are shown in Figure 1. Two sharp  $90^\circ$  elbows connect the vertical pipe to the horizontal pipe and the horizontal pipe to the spray nozzle. Each elbow has a form loss coefficient of 0.9. The spray nozzle has a total flow area of  $26 \text{ cm}^2$  and a form loss coefficient of 15. The suction pipe in the pool has a sharp edged entrance with a form loss coefficient of 0.5.

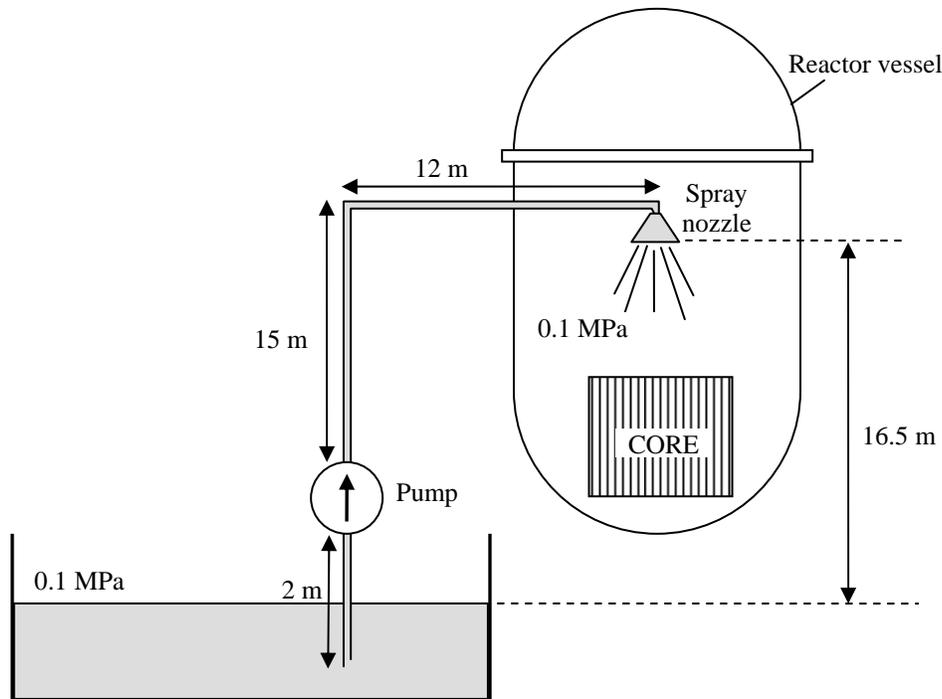


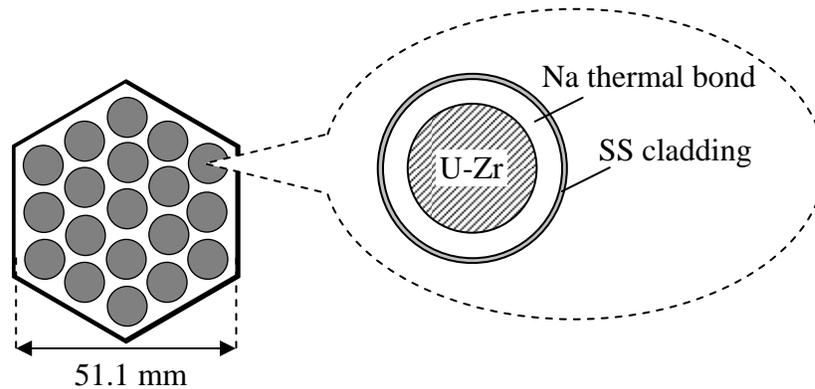
Figure 1. The emergency spray system.

Calculate the pump “head” (i.e. the pressure rise created by the pump) required to deliver 50 kg/s of cold water to the core. (Assume steady-state and constant water properties. Do not neglect the acceleration terms in the momentum equation. Neglect entry region effects in calculating the friction factor. To calculate the irreversible term of the spray nozzle form loss, use the value of the mass flux in the pipe. Neglect the vertical dimension of the pump.)

**Properties of water at room temperature (25 °C)**

Property	Value
Density	997 kg/m <sup>3</sup>
Viscosity	9×10 <sup>-4</sup> Pa·s
Thermal conductivity	0.61 W/m·K
Specific heat	4.2 kJ/kg·K

- 2) An innovative fast reactor concept uses molten lead as the coolant with the small hexagonal fuel-assembly design shown in Figure 1. The geometry and operating conditions of the fuel assembly are described in Table 1. Each fuel pin consists of a cylindrical slug made of U-Zr with a stainless steel cladding. Since U-Zr swells significantly under irradiation, a relatively large gap must be provided for between the fuel slug and the cladding (Figure 1). The gap is filled with a “thermal bond” to prevent excessive temperatures in the fuel, when the reactor is at power. The thermal bond material is molten sodium. Useful properties for all materials in the fuel assembly are reported in Table 2 at the end of the problem statement.



**Figure 1. Cross sectional view of the fuel assembly.**

**Table 1. Operating conditions and geometry of the fuel assembly.**

Parameter	Value
Fuel assembly power (thermal)	456 Kw
Inlet / outlet temperature	400°C / 550°C
Local / axial peaking factor	1.0 / 1.0
Fuel assembly inner width	51.1 mm (see Figure 1)
Number of fuel pins	19
Fuel pin pitch	11.0 mm
Fuel pin outer diameter	9.0 mm
Cladding thickness	0.6 mm
Fuel slug diameter	6.8 mm
Active fuel length	1.2 m

- i) Calculate the coolant mass flow rate in the fuel assembly.
- ii) Select a suitable heat transfer correlation from the Todreas&Kazimi handout. (Assume fully-developed velocity and temperature profiles)

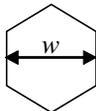
- iii) Evaluate the length of the entry region for the fuel assembly, and comment on the accuracy of the fully-developed velocity and temperature profiles assumption used in answering the previous question. Will the actual heat transfer coefficient be over- or under-estimated if a correlation for fully-developed flow is used? Explain.
- iv) Assuming a uniform axial power profile, sketch the coolant bulk temperature and the cladding outer temperature as a function of the axial coordinate. (Assume constant coolant properties)
- v) Calculate the peak outer cladding temperature and the fuel centerline temperature. (In calculating the temperature drop across the gap, consider only heat conduction).
- vi) Suppose the plant operator increases the reactor power by 10% without changing the coolant mass flow rate and the inlet temperature. How do the peak cladding temperature and fuel centerline temperature change at these new operating conditions?
- vii) Wire wrapping is often used for fuel pin spacing in liquid-metal-cooled fast reactors. If this approach were used for the fuel assembly in Figure 1, would the coolant velocity, bulk temperature, heat transfer coefficient and pressure drop increase, decrease or remain the same? Why? (Assume that power, mass flow rate, inlet temperature and fuel pin geometry remain the same)

**Table 2. Properties** (all properties independent of temperature)

Material	$\rho$ (kg/m <sup>3</sup> )	$k$ (W/m·K)	$\mu$ (Pa·s)	$c_p$ (J/kg·K)
Molten Pb	10,400	16	$1.9 \times 10^{-3}$	155
Stainless steel	8,000	14	/	470
Molten Na	780	60	$1.7 \times 10^{-4}$	1,300
U-Zr	16,000	20	/	120

**Hexagon area:**  $A = \frac{\sqrt{3}}{2} w^2$

**Hexagon perimeter:**  $p = 2\sqrt{3}w$



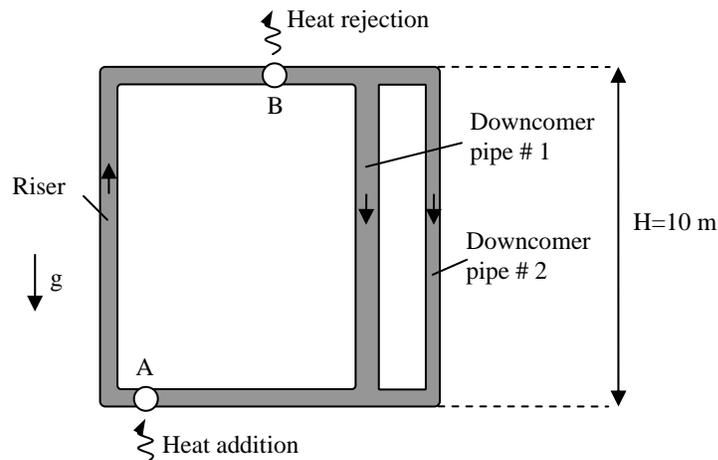
### 3) Natural circulation flow

Water is flowing in a loop with a single riser pipe and two downcomer pipes (see Figure 2). Heat is added at point A and rejected at point B, so that the temperature difference between the riser and downcomer sections is 30°C. The diameter of the two downcomer pipes is  $D_1=10$  cm and  $D_2=5$  cm, respectively.

Calculate the mass flow rate in the loop.

*Assumptions:*

- Neglect all acceleration, friction and form pressure changes in the loop, except for the friction pressure changes in the downcomer pipes.
- To calculate the friction factor in the pipes, ignore entrance effects, assume the flow is turbulent and use the McAdams correlation.
- Assume water density is a linear function of temperature:  $\rho(T) = \rho_c - \rho_c (T - T_c)$  (this is the so-called Boussinesq's approximation). ( $\beta = 3 \times 10^{-4} \text{ K}^{-1}$ ,  $\rho_c = 1000 \text{ kg/m}^3$ )
- Other properties of water at the conditions of interest:  $\mu = 8 \times 10^{-4} \text{ Pa}\cdot\text{s}$ ,  $k = 0.61 \text{ W/m}\cdot\text{K}$ ,  $c_p = 4.18 \text{ kJ/kg}\cdot\text{K}$

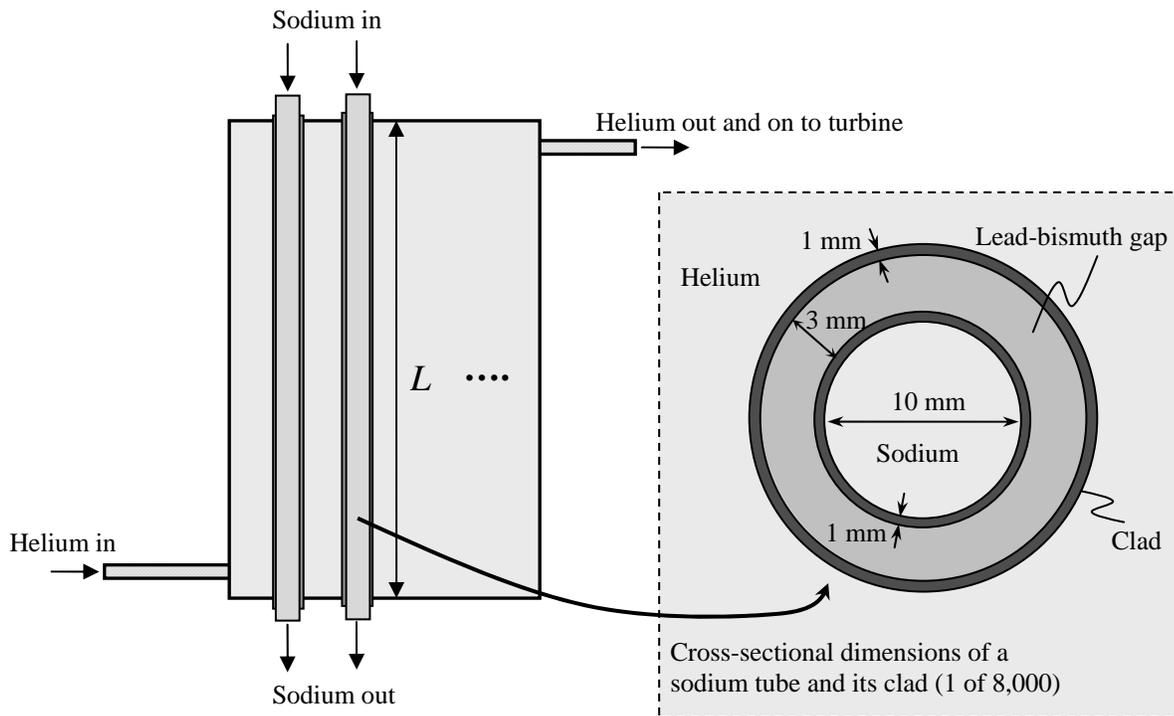


**Figure 2. The natural circulation loop.**

#### 4) Innovative intermediate heat exchanger design for sodium-cooled fast reactors

In an effort to reduce the capital cost of next-generation sodium-cooled fast reactors, some researchers are attempting to simplify the design. This entails a re-design of the intermediate heat exchanger. One approach involves using molten lead-bismuth (a chemically inert liquid metal) in lieu of the secondary sodium and helium (a chemically inert gas) in lieu of steam/water. The design is shown in Figure 3.

This design is a shell-and-tube counterflow heat exchanger. Sodium flows down 8,000 vertical stainless steel tubes. Each sodium tube has a stainless steel clad with stagnant molten lead-bismuth in the gap between the tube and the clad. The dimensions of a sodium tube and its clad are shown in Figure 3. Helium flows upward along the tubes at a pressure of 8 MPa.



**Figure 3. Intermediate heat exchanger design.**

- i) The sodium flow rate, inlet and outlet temperatures are 2000 kg/s, 550°C and 450°C, respectively. The helium inlet and outlet temperatures are 350 and 500°C, respectively. Find the helium mass flow rate and the thermal power exchanged in the heat exchanger.
- ii) Find the length ( $L$ ) of the sodium tubes required for this heat exchanger. Use the following assumptions:
  - Treat helium as an ideal gas ( $R_{\text{He}}=2077 \text{ J/kg-K}$ ) and sodium as an incompressible fluid
  - On the helium side use a heat transfer coefficient of  $1500 \text{ W/m}^2\text{-K}$
  - To calculate the heat transfer coefficient within the sodium tubes, use the following correlation  $Nu=5.0+0.025 \cdot Pe^{0.8}$
  - Heat within the lead-bismuth gap is transferred only by conduction.

iii) Calculate the entropy generation rate ( $\dot{S}_{gen}$ ) in the heat exchanger. (Neglect heat losses to the surroundings. Assume no pressure losses on either the sodium or helium side)

*Properties of materials at the conditions of interest*

<b>Material</b>	<b><math>\rho</math> (kg/m<sup>3</sup>)</b>	<b>k (W/m-K)</b>	<b><math>\mu</math> (Pa·s)</b>	<b><math>c_p</math> (J/kg-K)</b>
<b>Molten sodium</b>	780	60	$1.7 \times 10^{-4}$	1,300
<b>Molten lead-bismuth</b>	10,300	14	$1.6 \times 10^{-3}$	146
<b>Helium</b>	From equation of state	0.278	$3.5 \times 10^{-5}$	5,193
<b>Stainless steel</b>	8,000	14	/	470

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