**22.312** **ENGINEERING OF NUCLEAR REACTORS**

Tuesday, December 19th, 2006, 9:00am-12:00 pm

OPEN BOOK FINAL EXAM 3 HOURS

**Problem 1 (35%) – Analysis of a Liquid-Metal Reactor Vessel**

Fast reactors have attracted renewed attention within the nuclear community because of their ability to consume the actinides from the LWR spent fuel. Consider the vessel of a liquid-lead-cooled fast reactor, which is made of stainless steel with the dimensions shown in Figure 1. The top of the vessel is filled with a cover gas (nitrogen) whose operating temperature and pressure are 400°C and 0.5 MPa, respectively. The pressure outside the vessel is 0.1 MPa.

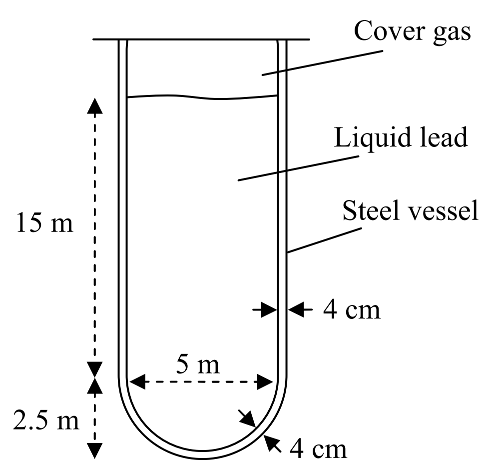


**Figure 1. Schematic and dimensions of the vessel.**

i) Assuming that the stresses can be calculated using the local value of the pressure, identify the location of maximum primary general membrane stress intensity in the vessel and calculate the margin to the ASME limit ($S_m$) at that location. Use the thin shell approximation and consider the effect of gravity on pressure within the liquid lead. (10%)

ii) A violent earthquake causes a 10 $cm^2$ crack in the vessel. Calculate the mass flow rate through the crack, immediately after the earthquake, for the following two cases:

- The crack occurs at the very bottom of the vessel (10%)
- The crack occurs at the top of the vessel, i.e., in the cover gas region (10%)

(The flow through the crack can be treated as steady-state, adiabatic and inviscid in both cases. The pressure outside the vessel can be assumed constant at 0.1 MPa. Liquid lead can be treated as an incompressible liquid and nitrogen as a perfect gas.)

J. Buongiorno, 2006

Cite as: Jacopo Buongiorno, course materials for 22.312 Engineering of Nuclear Reactors, Fall 2007. MIT OpenCourseWare (http://ocw.mit.edu/), Massachusetts Institute of Technology. Downloaded on [DD Month YYYY].

iii) Which of the two cases considered in Part 'ii' would you judge more dangerous from a safety viewpoint? (5%)

*Properties*

| | |
|---|---|
| Stainless steel | $S_m$=138 MPa at 400°C, Density 7500 kg/m$^3$, Young's modulus 170 GPa |
| Lead | Density 10500 kg/m$^3$, Viscosity $1.6\times10^{-3}$ Pa·s, Boiling point 1750°C |
| Nitrogen | $c_p$=1039 J/kg·K, $R^*$=297 J/kg·K, $\gamma$=1.4 |

J. Buongiorno, 2006

Cite as: Jacopo Buongiorno, course materials for 22.312 Engineering of Nuclear Reactors, Fall 2007.
MIT OpenCourseWare (http://ocw.mit.edu/), Massachusetts Institute of Technology. Downloaded on [DD Month YYYY].

**Problem 2 (30%) – Boiling Crisis in the Plasma Divertor of a Fusion Reactor**

To remove the heat from the plasma divertor of a fusion reactor, water at 1.5 MPa is pumped through a tube of 8 mm inner diameter and 200 mm length. Because only one side of the tube faces the plasma, the wall heat flux has the semi-circular *azimuthal* distribution shown in Figure 2. However, the *axial* distribution of the heat flux can be considered uniform. When the reactor operates at 100% power, the values of the heat flux and mass flux are 18 MW/m$^2$ and 8000 kg/m$^2$s, respectively.

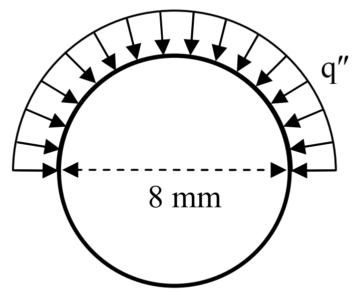


**Figure 2. Cross-section of the divertor tube.**

i) Consider the power range 20-100%. In this power range the mass flux is varied proportionally to power, while the inlet temperature is held constant at 50°C ($h_{in}$=210 kJ/kg). At what power level within this range does the Minimum Departure from Nucleate Boiling Ratio (MDNBR) in the tube have its minimum value? What is the minimum value of the MDNBR? (Assume that the heat flux scales linearly with power. To calculate the DNB heat flux, use the Tong-68 correlation) (25%)

ii) Is it accurate to assume $x_e$=x at the tube outlet at 20% power? (5%)

*Tong -68 correlation*

$$q''_{DNB} = K_{Tong}\frac{G^{0.4}\mu_f^{0.6}h_{fg}}{D_e^{0.6}} \text{ with } K_{Tong} = [1.76 - 7.433x_e + 12.222x_e^2]\cdot\left[1 - \frac{52.3 + 80x_e - 50x_e^2}{60.5 + (10P)^{1.4}}\right]$$

P in MPa

*Properties of water at 1.5 MPa*

| **Parameter** | **Value** |
|---|---|
| $T_{sat}$ | 198°C |
| $h_f$ | 844 kJ/kg |
| $h_g$ | 2791 kJ/kg |
| $\mu_f$ | $1.3\times10^{-4}$ Pa·s |
| $\mu_g$ | $1.5\times10^{-5}$ Pa·s |

J. Buongiorno, 2006

Cite as: Jacopo Buongiorno, course materials for 22.312 Engineering of Nuclear Reactors, Fall 2007.
MIT OpenCourseWare (http://ocw.mit.edu/), Massachusetts Institute of Technology. Downloaded on [DD Month YYYY].

**Problem 3 (35%) – Flow Dynamics of Nanofluids**

Nanofluids are suspensions of solid nanoparticles in a base fluid (e.g., water), and are being investigated at MIT for their potential as coolants in nuclear systems. The flow behavior of nanofluids can be analyzed as a two-phase liquid/solid mixture. Since the particles are so small, they can be assumed to move homogeneously with the base fluid, i.e., the slip ratio is equal to one.

Consider a water-based nanofluid with alumina nanoparticles. It flows at steady state through a tube of 2.5 cm diameter. The nanofluid volumetric flow rate is 400 $cm^3/s$ and the nanoparticle volumetric fraction is 0.05.

i) Find the mass flow rate of the nanoparticles and the total mass flow rate of the nanofluid. (10%)

ii) Find the pressure gradient within the tube if the flow direction is vertically downward. To calculate the friction pressure gradient, assume fully developed flow, zero surface roughness and $f_{TP}=f_{\ell o}$. (15%)

iii) If the nanoparticles were made of a material denser than alumina, how would the components of the pressure gradient (friction, gravity, etc.) change? Assume that the nanofluid volumetric flow rate and the nanoparticle volumetric fraction are held at 400 $cm^3/s$ and 0.05, respectively. The slip ratio is still equal to one. Provide a qualitative answer. (10%)

*Properties*

| | |
|---|---|
| Water | Density 1 $g/cm^3$, Viscosity $10^{-3}$ Pa·s |
| Alumina | Density 4 $g/cm^3$, Specific heat 780 J/kg·K |

J. Buongiorno, 2006

Cite as: Jacopo Buongiorno, course materials for 22.312 Engineering of Nuclear Reactors, Fall 2007. MIT OpenCourseWare (http://ocw.mit.edu/), Massachusetts Institute of Technology. Downloaded on [DD Month YYYY].