Neutronics Exercises

5. LWR Plants

5.1 *Pressurizer in PWR*

Exercise description:

Using the definition of isobaric thermal expansion and isothermal compressibility, explain why in a system completely filled with an incompressible fluid (e.g. water) subject to temperature variation there is a need for a pressurizer? Please use https://link.springer.com/chapter/10.1007/978-3-662-53219-5_5 for the numerical data.

(a) A vessel having a cross-section A is filled with water at T_0=323K. The vessel is open. By means of a heater, the water temperature is increased by 5K. Estimate the variation of the water level in the vessel.

(b) A closed vessel is filled with water at an initial pressure of p_0=1bar and an initial temperature T_0=323K. By means of a heater, the water temperature is increased by 5K. Estimate the variation of pressure in the vessel.

(c) A closed vessel is filled with a mixture of steam and water at an initial pressure of p_0=1bar and an initial temperature T_0=423K. By means of a heater, the water temperature is increased by 5K. Estimate the variation of the pressure in the vessel.

Expected results: (a)0.00229 (b) $\Delta P = 52 bars$ (c) $\Delta P = 0.012 bars$

Exercise solution:

Derivative properties: their value depends on the derivative of the properties characterizing the state of a fluid

$$\beta = \frac{1}{v}\frac{\partial v}{\partial T}\Big|_p = -\frac{1}{\rho}\frac{\partial \rho}{\partial T}\Big|_p$$

Isobaric thermal expansion

v = specific volume = $\frac{V}{M} = \frac{1}{\rho}$ $[m^3/kg]$

$$K = -\frac{1}{v}\frac{\partial v}{\partial p}\Big|_T = \frac{1}{\rho}\frac{\partial \rho}{\partial p}\Big|_T$$

Isothermal compressibility

Isobaric thermal expansion: measure of volume change with temperature at constant pressure. Unit of $[K^{-1}]$

Isobaric compressibility: measure of density change with pressure at constant temperature. Unit of $[Pa^{-1}]$

(a) $\beta = 4.57e-4\ K^{-1}$ at 1bar and 50C for water

See p 284 of https://link.springer.com/chapter/10.1007/978-3-662-53219-5_5

Then $\Delta V = V_0 \beta \Delta T$ and $\Delta h = \frac{\Delta V}{A} \beta \Delta T$ and finally $\Delta h = \frac{\Delta h}{h_0} = \beta \Delta T = 0.00285$

(b) $\kappa = 0.44e - 6\ Pa^{-1}$ at 1bar and 50C for water

$$dv = \left.\frac{\partial v}{\partial T}\right|_P dT + \left.\frac{\partial v}{\partial p}\right|_T dp = v\beta \Delta T - v\kappa \Delta p$$

V is constant so $\Delta v = V_0(\beta \Delta T - \kappa \Delta p) = 0$

$$\Delta p = \beta \frac{\Delta T}{\kappa} = 52 bars!$$

(c) for steam at 150 C, $\beta = 2452.4e - 6\ K^{-1}$ and $\kappa = 10086e - 6\ Pa^{-1}$

$$\Delta p = \beta \frac{\Delta T}{\kappa} = 0.012 bars$$

To avoid large pressure changes in the system, a pressurizer, e.g. a closed volume connected to the primary coolant look, is needed.

5.2 *Power of a PWR main circulation pump*

Exercise description:

Consider a typical 1300 MWe PWR at 155 bar, with thermal power of 3817 MWth, with temperature in cold leg and hot leg of TCL = 290 C and THL = 320 C respectively. Knowing that there are 4 main loops and therefore 4 main circulation pumps and considering that the pressure drop across a loop is of 8 bar, compute the power needed to operate one main circulation pump. Assume a pump efficiency of 80%.

Exercise solution:

Q: how to calculate the power we need to operate the main circulation pumps?

$P_{th} = 3817$ MW $\quad T_{inl} = 290\,°C$ cold leg

$P_{el} = 1300$ MW $\quad T_{out} = 320\,°C$ hot leg

$N_c = 4$ loops $\quad p = 155$ bar

$\Delta p \simeq 8$ bar friction losses along primary circuit

$$\dot{m}_{core} = \frac{P_{th}}{c_p \Delta T} = 31000 \text{ kg/s}$$

$$\eta P_p = \frac{\dot{m}}{\rho}\left[\rho g \Delta H + \Delta p_{fr}\right]$$ (closed loop: $\rho g \Delta H = 0$)

$$\dot{m}_{loop} = \frac{\dot{m}_{core}}{N_c} = 7758 \text{ kg/s}$$

$$P_{pump} = \frac{\dot{m}_{loop} \times \Delta p_{losses}}{\eta \cdot \rho} = \frac{7758 \times 8 \times 10^5}{0.8 \times 1000} = 7.76 \text{ MW}$$

4 loops $\Rightarrow 4 \times 7.76 = 31$ MW $\Rightarrow$ In a PWR about 2% of the electric power is needed for the main circulation pumps

5.3 Energy balance on condenser

Exercise description:

Consider a 900 MWe reactor with a Rankine cycle efficiency of about 30%. Knowing that, for environmental reasons, the temperature increase on the secondary side of the condenser cannot exceed 10 K, compute the mass flow-rate needed for the secondary side of the condenser.

Exercise solution:

The outlet water temperature in a condenser $T_{c,out}$ is limited by environmental regulations. Generally

$$(T_{c,out} - T_{c,inl}) \approx 10\ K$$

Because $\eta \approx 30\%$ ⇒ 70% of the thermal power produced by the reactor is released to the condenser coolant (river, sea)

$70\%\ P_{th} \approx 2100\ MW = P_c$

Energy balance on condenser

$$\dot{m}_c (h_{c,out} - h_{c,inl}) = P_c$$

$$\Rightarrow \dot{m}_c\, c_p\, \Delta T_c = P_c$$

(c_p = 4180 J/kgK; ΔT_c = 10 °C; P_c = 2100 MW)

$$\Rightarrow \boxed{\dot{m}_c \approx 50'000\ kg/s}$$

(50 m³/s !)