4I10 CRIB 2016-2017

1

(a) AGRs use once-through steam generators with superheat. The superheated steam has temperatures above 500 °C, which is substantially higher than in LWRs, which use saturated steam at about 300 °C. Therefore, AGRs have much higher thermal efficiency – on the order of 42%, comparable to fossil fuel fired stations and higher than 33% typical of LWRs.

[20%]

(b)

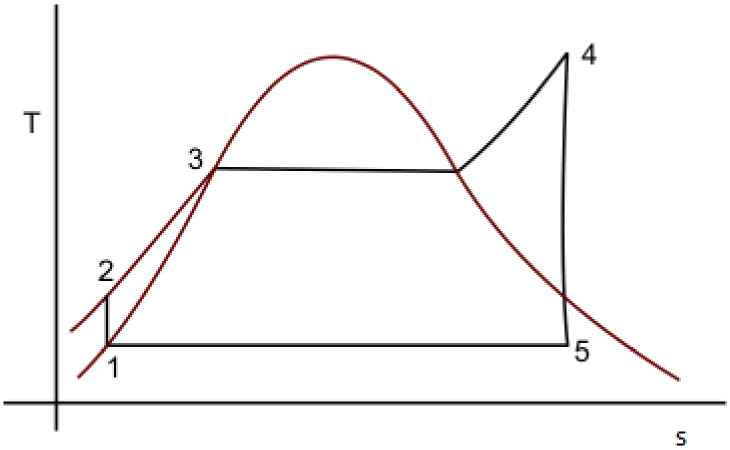
1-2 Pumping condensed water to boiler pressure

2-3 Heat addition in economiser

3-4 Heat addition in evaporator and super-heater

4-5 Expansion in turbine

5-1 Condensation



[5%]

(c)

$$\eta = \frac{Net\ Work}{Heat\ added} = \frac{(h_4 - h_5) - (h_2 - h_1)}{(h_4 - h_2)}$$

From steam tables: $h_4 = 3310.8\ kJ/kg$, $s_4 = 6.348\ \frac{kJ}{kg\ K}$

$h_{f5} = h_1 = 191.8\ kJ/kg$, $s_{f5} = 0.649\ \frac{kJ}{kg\ K}$

$h_{g5} = 2583.9\ kJ/kg$, $s_{g5} = 8.149\ \frac{kJ}{kg\ K}$

$$x = \frac{(s_5 - s_{f5})}{(s_{g5} - s_{f5})} = \frac{(s_4 - s_{f5})}{(s_{g5} - s_{f5})} = \frac{(6.348 - 0.649)}{(8.149 - 0.649)} = 0.76$$

$$h_5 = h_{f5} + xh_{fg5} = 191.8 + 0.76 \times (2583.9 - 191.8) = 2009.8\ kJ/kg$$

$$W_t = (h_4 - h_5) = 3310.8 - 2009.8 = 1301\ kJ/kg$$

$$h_2 \approx h_1 + v_{f1}(p_2 - p_1) = 191.8 + 0.00101 \times (15 - 0.1) \times 10^6 = 191.8 + 15.05 = 206.8\ kJ/kg$$

$\eta = \frac{1310.8 - 15.05}{3310.8 - 206.8} = 41.7\%$ [25%]

(d) Molten salts are high density fluids. Therefore, they are easier to pump (less pumping power). They also have larger heat capacity. Therefore, the volume of coolant in the core can be reduced, reducing the core size and increasing the core power density. Or, alternatively, for a given core size, the volume of fuel can be increased, allowing production of more power from a given core volume. [20%]

(e) Assuming that the heat exchange area, heat transfer coefficient and power transferred across the steam generator stay the same. The mean temperature difference across the steam generator would also have to stay the same if all the mentioned parameters are fixed. Therefore, to compensate for larger temperature difference at the water entry into the steam generator, the steam outlet temperature will have to be higher.

The MTD can be approximated as: $MTD \approx \overline{T_{coolant}} - \overline{T_{SG}} \approx \frac{T_{out} + T_{in}}{2} - \frac{T_{FW} + T_{Steam}}{2}$ (more accurately, this would need to be Logarithmic MTD)

For AGR with CO_2 coolant: $MTD \approx \frac{650 + 350}{2} - \frac{46 + 500}{2} = 227\ °C$

With molten salt coolant, to maintain the same MTD, the steam temperature needs to increase:

$$T_{Steam} = (T_{out} + T_{in}) - 2MTD - T_{FW} = 650 + 450 - 2 \times 227 - 46 = 600°C$$

At 600 °C, from steam tables: $s_4 = 6.68\ \frac{kJ}{kg\ K}$; $x = \frac{(6.68 - 0.65)}{(8.15 - 0.65)} = 0.804$; $h_4 = 3583.3\ kJ/kg$

$h_5 = 191.8 + 0.804 \times (2583.9 - 191.8) = 2115\ kJ/kg$

Specific enthalpy gain by the feed water is higher, thus smaller steam flow rate would be required to maintain the heat balance.

The new thermal efficiency is then:

$$\eta = \frac{(h_4 - h_5) - (h_2 - h_1)}{(h_4 - h_2)} = \frac{3583.3 - 2115 - 15.05}{3583.3 - 206.8} = 43\%$$

[30%]

Q1 Advanced Gas-cooled Reactors and power conversion cycles

10 attempts, Average mark 13.2/20, Maximum 17, Minimum 5.

The most popular question attempted by all candidates. The question assessed understanding of basic principles of steam power cycles in nuclear reactors. It also included elements on understanding the importance of properties of heat transfer fluids and loss of efficiency through heat exchange. Most candidates managed the steam cycle thermodynamics part well. It is the latter part that proved more difficult and resulted in wider range of scores.

2

(a) - Containment spray, condenses the steam and reduces pressure.

- Controlled depressurisation through IRWST and steam condensation in the tank.
- Controlled venting to atmosphere through filters and tall chimney.
- Dedicated heat exchange loop removing the energy from containment to a heat sink. For example, collecting water from containment sump, pumping it through an external heat exchanger and reintroducing it into the containment through sprays. In case of AP1000, containment wall serves as a heat exchange surface cooled on the outside by air or water from a large storage tank on the containment roof.

[20%]

(b) Containment pressure has two components – air and steam.

Assume air is an ideal gas, thus $\frac{pV}{T} = const;$

Partial air pressure $\frac{10^5}{273+25} = \frac{p_{air}}{273+150};$ $p_{air} = 1.42\ bar$

Saturated steam pressure at 150 C: $p_{steam} = 4.76\ bar$

Containment pressure = $p_{air} + p_{steam} = 6.18\ bar$ [25%]

(c) Steam density at 4 bar = 2.163 kg/m^3

Containment volume = 500,000/2.163 = 231,196 m^3 [20%]

(d) Containment wall temperature would be the highest at the inner surface. The heat will then have to be conducted through the wall and removed by convection of air. The two thermal resistances associated with the two processes are:

$Q = Ah(T_{wo} - T_{air})$ convection by air

$Q = A\frac{k}{t}(T_{wi} - T_{wo})$ conduction through wall

Here, we assume that the inner and outer surface areas are roughly the same (i.e. t << R).

Eliminating T_{wo} and noting that thermal conductivity of carbon steel (form databook) is 48 W/m/K

$$Q = \frac{(T_{wi} - T_{air})}{\frac{1}{Ah} + \frac{t}{Ak}} = \frac{(150 - 30)}{\frac{1}{20{,}000\times 5} + \frac{0.025}{20{,}000\times 48}} = 11.97\ MW$$ [35%]

Q2 Reactor safety: integrity of containment

9 attempts, Average mark 10.4/20, Maximum 16, Minimum 6.

The question aimed at testing the basic knowledge and engineering principles of nuclear reactor containment design. It required application First Law, ideal gas equations as well as conductive and convective heat transfer. Surprisingly, many candidates have missed that pressure of a mixture of gases is a sum of partial pressure of the components. Describing features of systems designed to keep the containment pressure within safety limits was another differentiating factor among the candidates.

3

(a)

Heat conduction in the fuel: $\frac{d}{dx}k_f\frac{dT}{dx}+q''' = 0$

Integrating once: $k_f\frac{dT}{dx}+q'''\,x = C_1$

In the centre of the plate, heat flux should be zero (no temperature gradient)

$k_f\frac{dT}{dx}\Big|_{x=0} = 0$ thus, $C_1 = 0$ and

$k_f\frac{dT}{dx}+q'''\,x = 0$

Second integration between T(x) and the surface temperature T_{fo}, assuming $k_f \neq f(T) = const$

$$T(x) = T_{fo} + q'''\frac{x^2}{2k_f}$$

In the, cladding: $\frac{d}{dx}k_c\frac{dT}{dx} = 0$

Integrating once: $k_c\frac{dT}{dx} = C_2$ i.e. the heat flux is the same at any location x

BC: heat flux from the fuel $q'' = -k_c\frac{dT}{dx}$ or $q'' = q'''a = -k_c\frac{dT}{dx}$

Integrating twice: $T(x) = T_{fo} - \frac{q''}{k_c}(x-a) = T_{co} + \frac{q'''a}{k_c}(x-a)$

At outer surface x = (a + t): $T_{co} = T_{fo} - \frac{q''}{k_c}(a+t-a) = T_{fo} - \frac{a\,t\,q'''}{k_c}$

Finally, outer cladding surface temperature: $T_{co} = T_f + \frac{q''}{h} = T_f + \frac{q'''a}{h}$

In summary: in cladding $T(x) = T_f + \frac{q'''a}{h} + \frac{q'''a}{k_c}(x-a)$

in fuel $T(x) = T_f + \frac{q'''a}{h} + \frac{q'''a\,t}{k_c} + q'''\frac{x^2}{2k_f}$ [30%]

(b)

Heat transfer coefficient: Nu = hD/k = 0.023 $Re^{0.8}$ $Pr^{0.4}$

Assume the channel geometry, and coolant properties (Pr) are not affected by blockage. The only difference is in $= f(\dot{m}) = Const \times \dot{m}$, thus heat transfer coefficient:

$$h(\dot{m}) = Const \times \dot{m}^{0.8}$$

$\frac{h_{original}}{h_{blocked}} = \frac{\dot{m}^{0.8}_{original}}{\dot{m}^{0.8}_{blocked}} = 2;$ $\frac{\dot{m}_{original}}{\dot{m}_{blocked}} = 2^{\frac{1}{0.8}} = 2.38$ [30%]

(c)

Integrating twice the heat conduction equation in the fuel:

$$T(x) = -\,q''' \frac{x^2}{2k_f} + C_1 x + C_2$$

Substituting BC at each surface to find C_1 and C_2:

$$T(a) = T_{foR} = -\,q''' \frac{a^2}{2k_f} + C_1 a + C_2 \qquad T(-a) = T_{foL} = -\,q''' \frac{a^2}{2k_f} - C_1 a + C_2$$

Adding and subtracting the two equations:

$$C_1 = \frac{T_{foR} - T_{foL}}{2a}$$

$$C_2 = \frac{T_{foR} + T_{foL}}{2} + q''' \frac{a^2}{2k_f}$$

$$T(x) = q''' \frac{(a^2 - x^2)}{2k_f} + \left(\frac{T_{foR} - T_{foL}}{2a}\right) x + \frac{T_{foR} + T_{foL}}{2}$$

$$\left.\frac{dT}{dx}\right|_{x_{max}} = 0 = -\,q''' \frac{x_{max}}{k_f} + \left(\frac{T_{foR} - T_{foL}}{2a}\right)$$

$$x_{max} = \frac{k_f}{q'''} \left(\frac{T_{foR} - T_{foL}}{2a}\right)$$

$$T_{max} = T(x_{max}) = -\,q''' \frac{(a^2 - {x_{max}}^2)}{2k_f} + \left(\frac{T_{foR} - T_{foL}}{2a}\right) x_{max} + \frac{T_{foR} + T_{foL}}{2}$$

[40%]

Q3 Heat transfer in fuel elements

3 attempts, Average mark 14.3/20, Maximum 19, Minimum 9.

This question required working out a solution of heat conduction equation in 1D Cartesian coordinates with a range of boundary conditions. It was conceptually simple but required relatively long derivations. This is perhaps the reason why this question was the least popular. Nevertheless, one of the candidates who has attempted the question managed to complete it nearly flawlessly.

(a) - Compressed gas is used in water accumulators for reactor vessel refill following LOCA.
- Passive autocatalytic hydrogen re-combiners.
- Gravity driven flow from IRWST into the core as passive low pressure water injection.
- Natural circulation of coolant through steam generators in case of loss of power to primary pumps.
- Containment outside surface cooling by water from a storage tank at the top of the containment and natural circulation of air later on (AP-1000). [25%]

(b) - Make up water in case of LOCA.
- Heat sink for steam condensation during depressurization.
- Source of water for containment atmosphere cooling and pressure control.
- Scrubbing of fission products from condensing steam during depressurisation, in case the fuel has already been partially damaged. [25%]

(c) Decay heat three hours after shutdown and following infinite operation:

$$Q = Q_0\, 0.066\, t^{-0.2} = 3000 \times 10^6 \times 0.066 \times (3600 \times 3)^{-0.2} = 30.9 \times 10^6\ W$$

Assume: heat removed by the IC heat exchanger is equal to instantaneous decay heat:

$$Q = A\, h\, (T_{steam} - T_{pool}); \qquad T_{steam} = T_{pool} + \frac{Q}{Ah} = 100 + \frac{30.9\times10^6}{8100\times20} \approx 290°\text{C}$$

Neglecting pressure losses along the IC pipes and heat exchanger, from steam tables at saturation:

$$p_{steam} = 74.418\ bar$$

[30%]

(d) $Q = \dot{m}\, h_{fg}(@290°\text{C});$ $\dot{m} = \frac{Q}{h_{fg}} = \frac{30.9\times10^6}{1476.7\times10^3} = 20.93\ kg$ [20%]

Q4 LWR safety systems design

8 attempts, Average mark 10.9/20, Maximum 14, Minimum 5.

This question tested the knowledge of engineering principles in the design of LWR safety systems. The main differentiators were parts requiring to explain principles of passive safety systems operation and the functions of In-containment Refuelling Water Storage Tank. The computational part on emergency heat removal system performance was relatively straight forward and has been worked out successfully by most candidates.