PROBLEM 1.86 (c)

KNOWN: Water storage tank initial temperature, water initial pressure and temperature, storage tank configuration.

FIND: Identify heat transfer processes that will promote freezing of water. Determine effect of insulation thickness. Determine effect of wall thickness and tank material. Determine effect of transfer tubing material. Discuss optimal tank shape, and effect of applying thin aluminum foil to the outside of the tank.

SCHEMATIC:

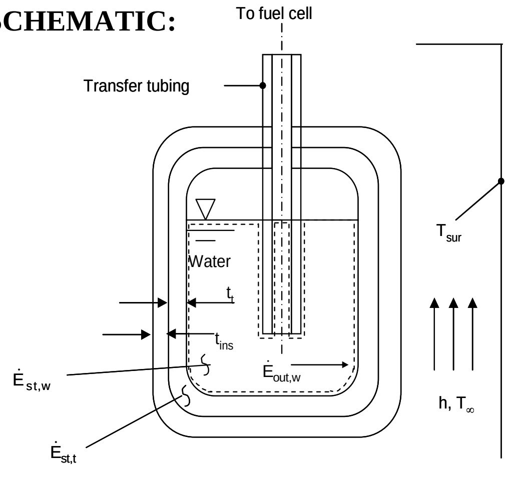

Figure 1 Rapid Response.

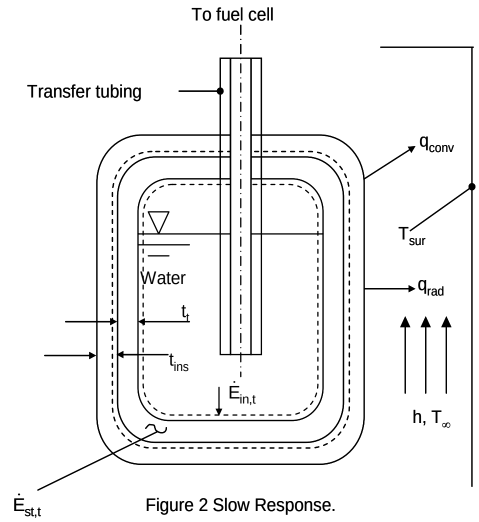

Figure 2 Slow Response.

ANALYSIS: The thermal response of the water may be analyzed by dividing the cooling process into two parts.

Part One. Water and Tank Rapid Response.

We expect the mass of water to be greater than the mass of the tank. From experience, we would not expect the water to completely freeze immediately after filling the tank. Assuming negligible heat transfer through the insulation or transfer tubing during this initial rapid water cooling period, no heat transfer to the air above the water, and assuming isothermal water and tank behavior at any instant in time, an energy balance on a control volume surrounding the water would yield

$$\dot{E}_{st,w} = -\dot{E}_{out,w} \tag{1}$$

An energy balance on a control volume surrounding the tank would yield

$$\dot{E}_{in,t} = \dot{E}_{st,t} \tag{2}$$

where $\dot{E}_{out,w} = \dot{E}_{in,t}$ (3)

Combining Eqs. (1) – (3) yields

Continued…

$$\dot{E}_{st,w} = -\dot{E}_{st,t} = M_w c_{p,w} \cdot (\overline{T} - T_{i,w}) = M_t c_{p,t} \cdot (T_{i,t} - \overline{T}) \qquad (4)$$

where $\overline{T}$ is the average temperature of the water and tank after the initial filling process. For $M_w c_{p,w} >> M_t c_{p,t}$, $\overline{T} \approx T_{i,w}$, thus confirming our expectation.

<u>Part Two. Slow Water Cooling.</u>

The heat transfer processes that would promote water freezing include:

- heat transfer through the insulation to the cold air
- heat loss by conduction upward through the wall of the transfer tubing <

As the insulation thickness, t_{ins}, is increased, Fourier's law indicates that heat losses from the water are decreased, slowing the rate at which the water cools. <

As the tank wall thickness, t_t, is increased, the tank wall mass increases. This, along with increasing the tank wall specific heat, will serve to reduce the average temperature, $\overline{T}$, to a lower value, as evident by inspecting Eq. (4). This effect, based on the first law of thermodynamics, would decrease the time needed to cool the water to the freezing temperature. As the tank wall thickness is increased, however, heat losses by conduction through the tank wall would decrease as seen by inspection of Fourier's law, slowing the cooling process. As the tank wall thermal conductivity is reduced, this will also decrease the cooling rate of the water. Therefore, the effect of the tank wall thickness could increase *or* decrease the water cooling rate. As the thermal conductivity of the transfer tubing is increased, heat losses from the water upward through the tube wall will increase. This suggests that use of plastic for the transfer tubing would slow the cooling of the water. <

To slow the cooling process, a large water mass to surface area is desired. The mass is proportional to the volume of water in the tank, while the heat loss from the tank by convection to the cold air and radiation to the surroundings is proportional to the surface area of the tank. A spherical tank maximizes the volume-to-area ratio, reducing the rate at which the water temperature drops, and would help prevent freezing. <

Heat losses will occur by convection and radiation at the exposed tank area. The radiation loss, according to Eq. 1.7, is proportional to the emissivity of the surface. Aluminum foil is a low emissivity material, and therefore a wrap of foil would slow the water cooling process. The aluminum foil is very thin and has a high thermal conductivity, therefore by Fourier's law, there would be a very small temperature drop across the thickness of the foil and would not impact the cooling rate. <