Water flows through the horizontal tube. In order to compute the tube-side film heat transfer coefficient, \( h_{\text{tube}} \), we must guess the tube-side outlet temperature, \( T_{\text{tube,out}} \), and iterate with respect to \( T_{\text{tube,out}} \). Use an initial guess of \( T_{\text{tube,out}} = 303K \) and perform one iteration up to the point where you have a new guess for \( T_{\text{tube,out}} \). Along the way, show me the numerical values you obtain for (a) \( N_p \), (b) \( N_R \), (c) \( N_{Nu} \), (d) \( h_{\text{tube}} \), (e) the rate of heat transfer THROUGH THE WATER FILM, \( q \), and finally (f) \( T_{\text{tube,out}} \).

Use Table A.2-11 of Geankoplis on page 862 for all physical properties: \( C_p, k, \mu, \rho \).

Steam condenses on the shell-side. The steam is at a pressure, \( P = 892kPa \) and is saturated. Compute the shell side film heat transfer coefficient, \( h_{\text{shell}} \).

Use Table A.2-9 of Geankoplis on page 857-858 for the saturation temperature, \( T_{\text{sat}} \), and latent heat of vaporization. Use Table A.2-11 of Geankoplis on page 862 for all other physical properties.

In addition to (a) \( h_{\text{shell}} \), report the value of (b) \( N_{Nu} \), (c) write the equation used to calculate the Nusselt number, and (d) the rate of heat transfer THROUGH THE STEAM FILM, \( q \).

**Solution:**

From the steam tables

\[
T_{\text{shell}} = T_{\text{sat}} = 175C = 448.15K
\]

\[
\Delta H_{\text{vap}}(T_{\text{shell}}) = (2773.6 - 741.17) \times 1000.0 = 2.032 \times 10^6 \frac{J}{kg}
\]

1. calculate average tube-side bulk temperature \( T_{\text{tube}} = \frac{1}{2}(T_{\text{tube,out}} + T_{\text{tube,in}}) \)
2. obtain saturation temperature \( T_{\text{sat}} \), and equate \( T_{\text{shell}} = T_{\text{sat}} \)
3. calculate wall temperature \( T_w = 0.5(T_{\text{shell}} + T_{\text{tube}}) \)
4. calculate tube-side film temperature \( T_{\text{tube,f}} = 0.5(T_w + T_{\text{tube}}) \)
5. calculate shell-side film temperature \( T_{\text{shell,f}} = 0.5(T_w + T_{\text{shell}}) \)
6. obtain tube-side fluid properties at tube-side film temperature \( C_p, k, \mu \) at \( T_{\text{tube,f}} \)
7. obtain shell-side fluid properties at shell-side film temperature \( C_p, k, \mu \) at \( T_{\text{shell,f}} \)
8. obtain tube-side fluid properties at tube-side average temperature \( C_p, \mu, \rho \) at \( T_{\text{tube}} \)
9. obtain shell-side fluid properties at shell-side average temperature $C_p, \mu, \rho$ at $T_{shell}$

10. obtain fluid viscosity at tube-side wall temperature, $\mu$ at $T_{w,tube}$

11. Calculate tube-side Prandtl Number

$N_{Pr,tube} = \left( \frac{\mu C_p}{k} \right)_{tube,f}$

12. Obtain tube-side velocity $\bar{V}_{tube} = \frac{\dot{m}_{tube}}{\rho(\bar{T}_{tube}) \cdot A_{tube,cross}}$

13. Calculate tube-side Reynolds Number

$N_{Re,tube} = \frac{D_{tube} \bar{V}_{tube} \rho(\bar{T}_{tube})}{\mu(\bar{T}_{tube})}$

14. Calculate tube-side Nusselt Number, $N_{Nu,tube} = 0.027 N_{Re}^{0.8} N_{Pr}^{1/3} \left( \frac{\mu_b}{\mu_w} \right)^{0.14}$

15. Calculate shell-side Nusselt Number, $N_{Nu,shell}$

$N_{Nu} = 0.72 \left[ \frac{\rho_{liq} (\rho_{liq} - \rho_{vap}) g \Delta H_{vap} D_{pipe, outside}}{N_{tube, \mu} (T_{shell,f}) k(T_{shell,f}) (T_{shell} - T_w)} \right]^{0.25} \left( \frac{3}{N_{Nu,tube}} \right)^{0.25}$

16. Calculate tube-side heat transfer coefficient $h_{tube} = \frac{k(T_{tube,f}) N_{Nu,tube}}{D_{tube}}$

17. Calculate shell-side heat transfer coefficient $h_{shell} = \frac{k(T_{shell,f}) N_{Nu,shell}}{D_{eff}}$

18. Calculate the outside area, inside area, and log mean area

19. Calculate the overall heat transfer coefficient based on the outside area

$U_o = \frac{1}{A_{outside} h_{tube} + A_{outside} \Delta r_{pipe} k_{pipe} + A_{inside} h_{shell}}$

20. Calculate the log mean temperature, which since the shell temperature is constant, is just the arithmetic mean $\Delta T = (T_{shell} - T_{tube})$

21. Calculate the heat transfer rate $q = U_o A_{outside} (T_{shell} - T_{tube})$

22. Compute new temperature at surface of wall on tube-side, from

$q = h_{tube} A_{inside} (T_{w,tube} - T_{tube})$

23. Compute new temperature at surface of wall on tube-side, from

$q = h_{shell} A_{outside} (T_{shell} - T_{w,shell})$
24. Compute tube-side energy balance on fluid to check initial guess of tube-side temperature
\[ q = \dot{m}_{\text{tube}} \cdot C_p \left( T_{\text{tube}} \right) \left( T_{\text{tube, out}} - T_{\text{tube, in}} \right), \]
Rearrange to solve for
\[ T_{\text{tube, out}} = T_{\text{tube, in}} + \frac{q}{\dot{m}_{\text{tube}} \cdot C_p \left( T_{\text{tube}} \right)} \]

25. Iterate until \( T_{\text{tube, out}} \) is converged

The program output yielded in five iterations:

**Shell-side contains the hot fluid & tube-side the cold.**
initial guess: \( T_{\text{tube, out}} = 303.000000 \) \( T_{\text{shell, out}} = 448.150000 \)
at \( j = 1, i = 22 \): \( T_{\text{tube, out}} = 371.516009 \) \( T_{\text{shell, out}} = 448.150000 \)
Tube-side Temp (K) inlet: 273.000000, outlet 371.516009, avg 322.257970
Shell-side Temp (K) inlet: 448.150000, outlet 448.150000, avg 448.150000
Wall Temp (K): Tube-side = 425.686510, Shell-side = 441.083099, avg = 433.384805
Heat Transfer coefficients shell film, heat film, overall (W/m^2/K):
\( h_{\text{shell}} = 2436.852719 \) \( h_{\text{tube}} = 227.372873 \) \( U_o = 144.493316 \)
\( U_i = 197.318829 \)
Heat Transferred (W): \( q = -4122.523275 \) \( q_{\text{tube}} = 4122.522545 \) \( q_{\text{shell}} = 4122.521240 \)
Enthalpy Changes (W): \( \Delta h_{\text{tube}} = 4122.517560 \) \( \Delta h_{\text{shell}} = 4122.522343 \)

Dimensionless numbers from the last iteration:
\( N_{\text{p RT tube}} = 1.7363 \)
\( N_{\text{RT tube}} = 863.1380 \)
\( N_{\text{Nu shell}} = 449.1382 \)
\( N_{\text{Nu tube}} = 8.4733 \)