MEBS6008

Environmental Services II

Heat Rejection
And
Sea Water Cooling

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Reviews on Evaporators and Condensers

With the usual notations in the lecture notes :-

Describe the terms of the following formulas :

(a) $N_u = 0.0264\, R_e^{\,0.8}\, P_r^{\,0.3}$

(b) $$h_i = 0.0264 \frac{K}{d}\left(\frac{pvd}{\mu}\right)^{0.8}\left(\frac{C_p \mu}{K}\right)^{0.3}$$

(c) $$h_b = 6.5\left(\frac{Q_{ev}}{A_o}\right)^{0.7}$$

(d) $$Q = \frac{(T_a - T_b)\ell}{\frac{1}{2\pi r_1 h_1} + \frac{1}{2\pi r_1}\cdot R_f + \frac{1}{2\pi k_m}\ell n\frac{r_2}{r_1} + \frac{1}{2\pi k_i}\ell n\frac{r_3}{r_2} + \frac{1}{2\pi r_3 h_0}}$$

(e) $$U_o = \frac{1}{\frac{1}{h_b} + \frac{A_o R_f}{A_i} + \frac{X_m A_o}{K_m A_m} + \frac{A_o}{h_i A_i}}$$

where X_m = thickness of the metal pipe = r_2-r_1
k_m = thermal conductivity of the metal pipe
r_2 = outer radius of metal pipe
k_i = thermal conductivity of the insulation
r_3 = the radius of the outer surface of the insulation

(f) $$\frac{1}{U} = \frac{1}{h_i} + \frac{1}{h_o}$$

(g) $$\Delta T_m = \frac{\Delta T_{in} - \Delta T_{ex}}{\ell n \frac{\Delta T_{in}}{\Delta T_{ex}}}$$

(h) $Q = F U_o A_o \Delta T_m$

$N_u = 0.0263\, R_e^{\,0.8}\, P_r^{\,0.4}$

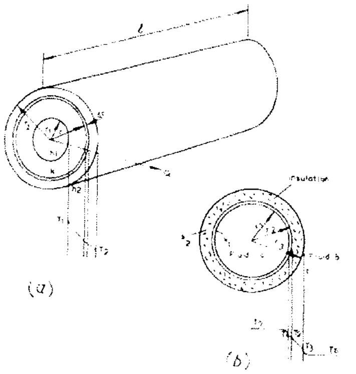

Figure : Radial heat flow through a tube

(i) $$\ell n(1+x) = x - \frac{1}{2}x^2 + \frac{1}{3}x^3 - \frac{x^4}{4} + \ldots \qquad \text{for } -1 < x \le 1$$

Cooling Tower

INTRODUCTION

Following is a list of normal specifications which should be considered for designing a cooling tower:-

1. Service
2. Heat load (Btu/hr)
3. Flow to be cooled (gpm)
4. Hot water temperature (°F)
5. Cold water temperature (°F)
6. Ambient wet-bulb temperature (°F)
7. Pumping heat (ft)
8. Prevailing wind direction and average velocity
9. Type of tower
10. Winter operation provisions
11. Plot plan
12. Water analysis
13. Sound intensity
14. Design wind and earthquake loads
15. Materials of construction (structure, casing, fill)
16. Wood treatment
17. Basin type and capacity
18. Piping and valves
19. Fan type and materials
20. Drive shaft reducing gear
21. Stack height
22. Motor characteristics (single speed or two speed)
23. Mechanical associated equipment
24. Safety provisions
25. Amortization period
26. Evaluation costs
27. Performance test
28. Work and facilities supplied by purchaser
29. Installation date
30. Terms and conditions of sale
31. Any other applicable documents (shipping, tagging, and so on)

HEAT AND MASS TRANSFER

Consider a cooling tower having a volume of fill V, and an extended water surface of area aV m^2, where a is the surface area of the fill per unit volume. Let $\dot{m}_w$ and $\dot{m}_a$ be the mass flow rate of water and air respectively.

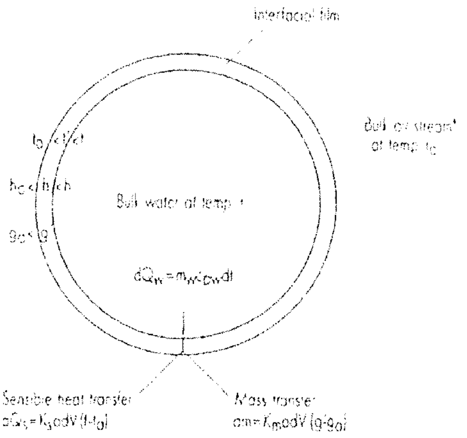

Fig. A Heat and mass transfer between water, interfacial film and air

Fig. A shows the evaporating water droplet with interfacial film. Water drops at a temperature t and is surrounded by an interfacial film of saturated air at an intermediate temperature t', enthalpy h' and moisture content g'. Outside the interfacial film is the bulk of the air stream at a temperature t_a, enthalpy h_a and a moisture content g_a. The sensible heat transfer from the interfacial film to the bulk air stream is given by :

$$dQ_s = K_s\, adV\, (t' - t_a)\ \mathrm{W}$$

where K_s = sensible heat transfer coefficient between the interfacial film and the air stream, W/m^2.K

The convective mass transfer of water vapour from the saturated air film to the air stream may be expressed as:

$$d\dot{m} = K_m adV(g' - g_a)\ \mathrm{kg/s}$$

where K_m = convective mass transfer coefficient between the interfacial film and the air stream, kg/s.m^2

Assuming that the latent heat of vaporization h_{fg} is a constant during this heat and mass transfer process, then the latent heat transfer from the vaporization of water at the interface is :

$$dQ_e = h_{fg}\, d\dot{m} = h_{fg}k_m adV(g' - g_a) \quad W$$

$$\because dQ_w = dQ_s + dQ_e$$
$$= \dot{m}_w c_{pw} dt$$
$$= [K_s(t' - t_a) + h_{fg}K_m (g' - g_a)]adV \quad kW \; \ldots\ldots\ldots\ldots \; [4]$$

where c_{pw} = specific heat of water and may be taken as a constant with a value of 4.19 kJ/kg.K

In the above equation [4], convective mass transfer coefficient K_m is approximately equal to the sensible heat transfer coefficient K_s divided by specific heat of air c_{pa}, that is, $K_m = K_s/c_{pa}$.

So, by substitution, we have

$$\dot{m}_w c_{pw} dt = [c_{pa}(t' - t_a) + h_{fg}(g' - g_a)]K_m adV$$
$$= [(c_{pa}t' + h_{fg}g') - (c_{pa}t_a + h_{fg}g_a)]K_m adV \; \ldots\ldots\ldots\ldots [5]$$

But, $c_{pa} = c_{pd} + g.c_{ps}$

Where c_{pd}, c_{ps} = specific heat of dry air and water vapour, kJ/kg
g = moisture content, kg/kg

Then the enthalpy of the saturated air film h' can be treated as:

$$h' = c_{pa}t' + h_{fg}g'$$

and the enthalpy of the air stream h_a is :

$$h_a' = c_{pa}t_a + h_{fg}g_a$$

Thus Eq. [5] can be rewritten as :

$$\dot{m}_w c_{pw} dt = (h' - h_a)K_m adV$$

Integrating from water leaving temperature t_{w1} to water entering temperature t_{w2} gives :

$$\int_{t_{w1}}^{t_{w2}} \frac{dt}{h'-h_a} = \int_o^v \frac{k_m a dV}{\dot{m}_w c_{pw}}$$

Let the overall heat transfer coefficient $K = K_m/c_{pw}$.
Then,

$$\int_{t_{w1}}^{t_{w2}} \frac{dt}{h'-h_a} = \frac{kaV}{\dot{m}_w}$$

By using the numerical integration method, the tower coefficient is :

$$\frac{KaV}{\dot{m}_w} = \frac{(t_{w2} - t_{w1})}{(h'-h_a)}$$

$KaV/\dot{m}_w$ is generally known as the number of transfer units NTU of a cooling tower or tower coefficient.

Question 1

A counter flow induced draft cooling tower is installed to cool down the condenser water from 37°C to 32°C. The wet-bulb temperature of the entering air is 28°C. The water flow rate is 64 kg/s and the water-air ratio $\dot{m}_w/\dot{m}_a$ is 1.25. The following table shows the enthalpies of the saturated air film at various water temperatures.

Water temperature t_w°C	32	33	34	35	36	37
Enthalpy of saturated film h' kJ/kg	111.0	116.8	123.0	129.4	136.2	143.2

At a wet-bulb temperature of 28°C, the enthalpy of saturated air is 89.98 kJ/kg. The relationship between the enthalpies of air and water is given by :

$$dh_a = 1.25 \times 4.18\, dt_w = 5.23\, dt_w$$

(i) By using the numerical integration method, determine the tower coefficient from the following formula :

$$\frac{KaV}{\dot{m}_w} = \int_{tw1}^{t_{w2}} \frac{dt_w}{h^1 - h_a}$$

(ii) Determine the number of decks N and the height of the fill H of the tower by using the following emperical formula :

$$\frac{KaV}{\dot{m}_w} = 0.0167 + 0.033N\left(\frac{\dot{m}_w}{\dot{m}_a}\right)^{-0.6}$$

Given that the height of each deck is 0.6m.

(iii) If the flow rate of water through the cooling tower is 2.75 kg/s.m^2, calculate the cross-sectional area of the fill A and also the mass flow rate of air m_a.

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Question 2

A small-size cooling tower is designed to cool 5.5 litres of water per second, the inlet temperature of which is 44°C. The motor-driven fan induces 9 m^3/S of air through the tower and the power absorbed is 4.75 kW. The air entering the tower is at 18°C, and has a relative humidity of 60%. The air leaving the tower can be assumed to be saturated and its temperature is 26°C. Assuming that the pressure throughout the tower is constant at 1.013 bar, and make-up water is added outside the tower, calculate :

(i) the mass flow rate of make-up water required;
(ii) the final temperature of the water leaving the tower.

Question 3

Air enters a natural draught cooling tower at 1.1013 bar and 13°C and relative humidity 50%. Water at 60°C from turbine condensers is sprayed into the tower at the rate of 22.5 kg/s and leaves at 27°C. The air leaves the tower at 38°C, 1.013 bar and is saturated.

Calculate:-

(i) the airflow required in cubic meters per second;
(ii) the make-up water required in kilograms per second.

Cooling Tower

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Then, the enthalpy of the saturated air film h' can be calculated as

$$h' = c_{pa} t' + h_{fg} g', \text{ and}$$

the enthalpy of air stream, h_a

$$h_a = c_{pa} t_a + h_{fg} g_a$$

$$\therefore \quad dQ_w = (h' - h_a) K_m a\, dV$$

But $\quad dQ_w = \dot{m}_w c_{pw} dt$.

<u>i.e.</u> $\quad \dot{m}_w c_{pw} dt = (h' - h_a) K_m a\, dV$

<u>Integrating</u>, $\quad \displaystyle\int_{t_{w_1}}^{t_{w_2}} \frac{dt}{h' - h_a} = \int_0^V \frac{K_m a\, dV}{\dot{m} c_{pw}}$

$$= \frac{K_m a V}{\dot{m} c_{pw}}$$

Let $K = \dfrac{K_m}{c_{pm}}$, overall heat transfer coefficient

$$\left. \int_{t_{w_1}}^{t_{w_2}} \frac{dt}{h' - h_a} = \frac{KaV}{\dot{m}_w} = NTU \right]$$

N.B. K_s := Sensible heat transfer coefficient between the interfacial film and air-stream, W/m²K

K_m := Convective mass transfer coefficient between the interfacial film and air stream kg/s.m²

h_{fg} = Latent heat of vaporization

1. A 2200 kW single-stage centrifugal chiller, with R-11 as the refrigerant, employs a two-pass shell-and-tube water cooled condenser with 550 copper tubes. This centrifugal chiller is operated under the following conditions :

Evaporating temperature t_{ev}	2°C
Outer surface area of the copper tubes for condensation	290 m^2
Ratio of outside to inside surface area A_o/A_i	3.2
Water side heat transfer coefficient h_i	12500 $W/m^2 \cdot K$
Condensing coefficient h_{con}	5000 $W/m^2 \cdot K$
Temperature of water entering the condenser	32°C
Temperature of water leaving the condenser	37°C
THR at the condenser	2800 kW

Assume no subcooling

(a) Calculate the power input to the centrifugal compressor if the mean value of the fouling factor for the condenser tubes is 0.00020 $m^2 \cdot K/W$, the compression efficiency is 0.85 and the mechanical efficiency is 0.9.

$$\text{Take } h_l = 221.2 + [(t_{ev} + 273) - 270] \times 0.517$$

$$h_3 = h_4 = 56.06 + 0.908\,[t_{con} - 27]$$

$$w_{in} = 0.55\,(t_{con} - t_{ev})$$

(b) Recommend the means to reduce the condensing temperature.

Question 2

A three-pass shell and tube liquid cooler with flooded refrigerant feed is designed as follows :

Refrigerant :	R-11
Number of copper tubes :	510
Inside diameter of copper tube :	15mm
Ratio of outside to inside surface area due to external fins :	3.8
Leaving chilled water temperature :	7·5°C
Entering chilled water temperature :	12.5°C
Mass flowrate of chilled water :	102 kg/s
Evaporating temperature :	5°C
Fouling factor	4.4 x 10^{-5}m^{2}K/W

Assuming that thermal resistance of copper tubes is negligible, estimate the length of the copper tubes.

Note :

1. Properties of chilled water at 10°C are as follows :

   Specific heat capacity = 4.2 kJ/kg K
   Density = 998.7 kg/m^3
   Dynamic viscosity = 1.39 x 10^{-3}Ns/m^2
   Thermal conductivity = 0.578 W/mK
   Prandtle number = 10.4

Question 3

A 1000kW shell-and-tube liquid cooler with flooder refrigerant feed uses R-134a as refrigerant. In this evaporator, there are 400 copper tubes. The internal diameter of the tube is 12mm and the ratio of the outside to inside surface area due to the external fins is 3. Chilled water enters and leaves the evaporator at 12°C and 8°C respectively whilst liquid refrigerant evaporates at a temperature of 5°C in the evaporator.

Take, $Q_{evp} = A_oU_o\Delta T_m$

Where Q_{evp} = cooling capacity of the liquid cooler
C_{pw} = specific heat of the chilled water = 4.2 kJ/kgK
U_o = the overall heat transfer coefficient over the outer surface of the liquid cooler tube wall = 1.6kW/m^{2}K

Calculate :-

i. The mass flow rate of the chilled water, m_w;
ii. The log mean temperature difference between the chilled water and the refrigerant, ΔT_m;
iii. The total outer surface area required for the liquid cooler, A_o;
iv. The length of the copper tubes of the liquid cooler;
v. Estimate the corresponding evaporating temperature, if the chilled water temperature entering the evaporator is now at 10.5°C instead of 12°C.

Ignore the differences in properties of the chilled water due to the change of the temperature of chilled water for the estimation.