Dairy Process Engineering

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Module 1. Evaporation

Lesson-4

Calculation of Heat Transfer Area and Water Requirement of Condensers

4.1. INTRODUCTION

In the evaporation system, steam is used as a heating medium as well as vapour produced from the previous effect is used as a heating medium in next effect. While the vapour from the final effect enters in the vapour condenser where cooling water is circulated to condense the vapour and thereby maintains the vacuum. The proper calculation of heat transfer area and the water requirement will decide the energy requirement and the capacity of each system components.

4.2. HEAT TRANSFER IN BOILING LIQUIDS

Heat transfer in boiling liquids and condensing vapour is accompanied by a change in the phase of liquid or vapour, the saturation temperature of the forming vapour (t_s) is determined by the ambient pressure P. This temperature t_s remains constant through out the process of boiling of any liquid at constant pressure. Experience however shows that the boiling liquid is usually overheated. (feed temperature, t_f is greater than t_s).

Experience shows that a sharp increase in the temperature is observed only in a layer 2-5mm thick over the heated surface. Hence the temperature of the liquid on the heating surface is higher than the saturation temperature by $\Delta t = t_w - t_s$. The value of Δt rises with an increase in the rate of heat transfer q ($W/m^2 . K.$). The temperature profile of liquid near heating surface is shown in following curve.
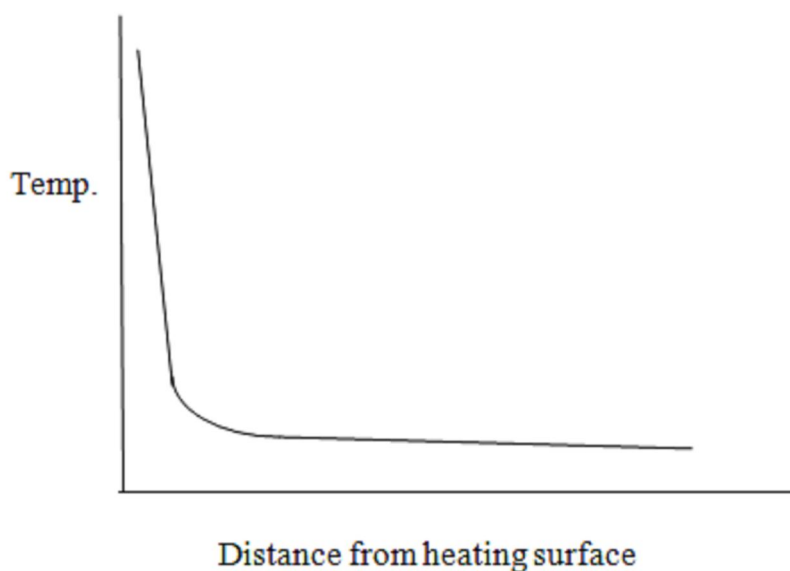
Fig-4.1:Temperature profile in heating tube

It has been established by visual observation that vapour bubbles form only on the heated surface, where liquid superheat is maximum, and only at individual points of that surface called starting boiling. The surface where the effect of adhesion is minimum may become evaporation starting points. Adhesion is defined as the effort required detaching the liquid from unit area of the hard surface.

Further, experience shows that the number of starting points of bubble (Z) depends on the degree of superheat at the heating surface, i.e. on the temperature difference, $\Delta t = t_w - t_s$. A rise in Δt entails an increase in Z and boiling intensifies. Essentially, this dependence is traced to the phenomenon of surface tension appearing at the liquid vapour interface.

Surface tension is defined as the stress causing the free surface of the fluid to contact; this stress is tangential to the surface. The pressure inside a bubble p_1 is greater than the surrounding liquid pressure p owing to surface tension. According to the Laplace equation, for a bubble in equilibrium the difference between the two pressures is determined by the equation $\Delta p = p_1 - p = 2s/r$, Where s = surface tension kg/m, r = curvature radius of bubble, m.

After their formation, the bubble grows rapidly and detach from the surface on attaining a certain size. The size of bubble at the moment of its separation from the surface is determined mainly by the interaction of the weight of gravity and surface tension. Besides, the generation of bubbles and their separation from the surface depend to a great measure on whether or not the liquid wets the surface.

The wetting capacity of a liquid is characterized by the contact angle q, formed between the wall and the free surface of the liquids, the larger the angle q, the poorer the wetting capacity of the liquid. Following figures illustrate the same.
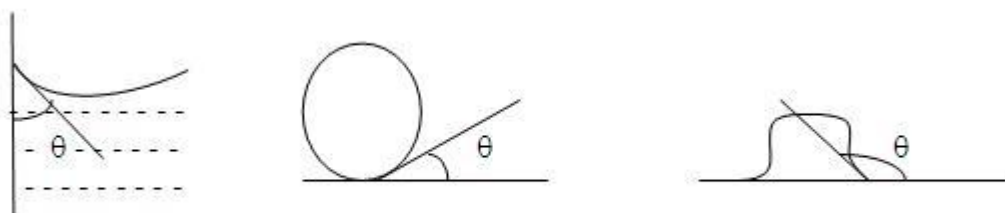

Fig-4.2: waiting capacity of the liquid based on angle θ

Since the temperature of the boiling liquid t_f, is higher than the saturation temperature t_s, intensive heat transfer between the liquid and bubble takes place, and that causes the bubble to continue to grow after its separation from the surface. The bubble increases in volume dozens of times, this depending on the rise time and degree of liquid superheat.

The multiple increase in the volume of separated bubbles evidences that from the heating surface that is transferred mainly to the liquid; it is then transported into the volume by convection and is further utilized to evaporate the liquid into bubbles. Direct transfer of heat from the heating surface to the vapour is possible only during the growth of bubbles prior to their detachment from the surface. But,

owing to the small bubble-to-surface contact area and the low thermal conductivity of vapour, only a relatively small amount of heat can be transferred to the bubbles in that period.

Boiling is classified in three types:

1) Interface evaporation

2) Nucleate boiling

3) Film boiling.

In interface evaporation, regime first, liquid contacts heated surface to produce vapour which rises due to convection forming convection currents to circulate the liquid, the phenomenon is free or natural convection. With further rise in temp, $\Delta t = (t_w - t_s)$ bubbles are formed adjacent at the surface due to high energy in liquid particles; they rise above the water surface but condense before reaching liquid surface.

The phenomenon, nucleate boiling commences in the next regime in figure. With further rise in temperature, Δt, liquid gets heated up, bubbles do not condense, they help evaporation, and this phase is known as nucleate boiling as shown in the next regin in the diagram. There is limit to this phenomenon as shown by crest of the curve in the figure. The peaking point is a critical point and heat flux at this critical state is called critical heat flux.

Beyond the crest of the curve, bubbles cover metal surface providing an insulating effect, thereby decreasing heat flux. The film of bubble is unstable during the next regime, it reforms and collapses. On further increase of Δt the stable film forms and the heat flow is low. Any further increase of Δt involves heat transfer by radiation also.

Fig-4.3: Boiling Phenomenon

4.3. HEAT TRANSFER DURING CONDENSATION

The condensation phenomenon is very important in the evaporators for efficient heat transfer. The condensation of steam in the calandria is of two types i.e. (i) Film condensation (ii) Drop wise condensation. Film condensation gives steam side film co-efficient in the range of 10,000 to 12,000 W/m^2K, where as drop wise condensation gives steam side film co-efficient in the range of 25,000 to 30,000 W/m^2K.

a) Factors affecting the boiling point:

(1) The pressure or vacuum respectively in the evaporating space.
Vapour and liquid are in equilibrium with each other and their temperature at any time is a function of the saturated vapour pressure. A lowering of the pressure lowers the boiling point.

(2) The concentration of the solution (as osmotic pressure)
Boiling point is influenced by the amount of dissolved matter. Dissolved substances exert osmotic forces which lower the vapour pressure of a solution at constant temperature or raise the boiling point

if the pressure is constant.

(3) The hydrostatic pressure of a column of liquid.

Due to hydrostatic pressure boiling point increases. A column of liquid of height H produces an increase in pressure of $P = H.\rho.g$

b) Factors affecting the size of heating surface:

It depends upon the amount of heat to be exchanged.

If milk enters at boiling point: Then $m_w.L = A.U(t_H - t_B)$, t_B=Boiling point, t_H=Temp. of steam

If cold milk enters: $m_w L + m_M C_M (t_B - t_o)$, t_o=Initial temp., t_B milk at boiling point.

For superheated milk: $m_w.L - m_M C_M (t_V - t_B)$, t_V=High temp. than boiling point.

Surface area is also dependent on the over all heat transfer coefficient and the temperature difference.

In practice, following table gives the normal range of values of overall heat transfer coefficients (U):

Table-4.1: Normal range of values of overall heat transfer coefficients

Number of Effect	Skim milk (W/m^{2}K)	Whole milk (W/m^{2}K)
1st effect	2300-2600	2000-2200
2nd effect	1900-2200	1700-1900
3rd effect	1000-1200	900-1100

Note: 1 Watt=0.86 kcal/h, 1kcal/h =1.163 Watt

During continuous operation 'U' drops as deposition of precipitated protein or calcium phosphate on the calendria tubes. Deposits may also form on steam side if complete separation of product from vapour is not carried out in vapour separator and this vapour taken in steam chest of the next effect. So plant must be cleaned at regular interval with sequence of water-caustic soda solution-water-nitric acid-water.

c) Factors affecting the heat transfer coefficients:

    (i) Steam side film coefficient:

        (a) It depends on the temperature drop.

        (b) Condensing temperature of steam. (a) and (b) are fixed by condition of operation.

        (c) Amount of non condensable gas present. It depends on evaporator construction.

    (ii) Boiling liquid side surface coefficient:

        (a)Velocity of flow of milk

        (b) Viscosity of fluid

(c) Cleanness of the heating surface.

4.4. HEAT AND MATERIAL BALANCE OF SINGLE EFFECT EVAPORATOR:

Fig- 4.4: **Heat Balance in single effect evaporator**

Heat Balance

$F.h_f + S.H_s = L.h_L + V.H + Sh_c$ (neglecting heat losses)

Therefore , $F.h_F + S(H_s-H_c) = Lh_L + VH$ ……………………(1)

Where, F= Feed rate, kg/h

$\qquad$ h_f= heat content of feed, kJ/kg

$\qquad$ S=steam supply rate, kg/h

$\qquad$ H_s= Enthalpy of steam, kJ/kg

$\qquad$ L= output rate of concentrate, kg/h

$\qquad$ h_L= heat content of concentrate, kJ/kg

$\qquad$ V= rate of vapour production, kg/h

$\qquad$ H= Heat content of vapour, kJ/kg

$\qquad$ h_c=heat content of condensate, kJ/kg

Material Balance:

$F= L+V$…………(2)

Based on the total solid, we have

$Fx_F = Lx_L + Vy$ ……………(3)

Where, x_F = Feed concentration, % TS

$\qquad$ x_L= Concentration of condensed milk, % TS

$\qquad$ y= solids in vapour (taken as zero)

Capacity:

From equation (3)

$Fx_F = Lx_L$ as Vy=0

Therefore , $F= L.(x_L / x_f)$ and $L= F.(x_f/ x_L)$

Therefore , $(F-V) = F. (x_f/ x_L)$, (as L= F-V)

Therefore , $V = F[1- (x_f/ x_L)]$ …………………………..(4)

4.5. MATERIAL AND HEAT BALANCE OF DOUBLE EFFECT EVAPORATOR

Fig. 4.5: **Heat Balance in double effect evaporator**

Material Balance:

1st effect, $F = L_1 + V_1$ …………………………..(1)

2nd effect, $L_1 = L_2 + V_2$…………………………(2)

Substituting for L_1 in equation (1) from equation (2)

$F = L_2+ V_2+V_1$

Therefore , $F = L_2+ E$ …………………………..(3) where, $V_1 + V_2 = E$

Based on solid,

1st effect, $F.x_F = L_1 x_{L1}$ …………………………(4)

2nd effect, $L_1x_{L1} = L_2x_{L2}$ ………………………...(5)

Therefore, $F.x_f = L_2 x_{L2}$ ………………..……...(6)

Therefore, $L_2 = F (x_F / x_{L2})$

Substituting the value of L_2 into equation (3) we get,

$F = (Fx_F / x_{L2}) + E$ or $F = (Fx_F / x_{L2}) + V_1 + V_2$ ………………..(7)

In terms of total evaporation, E kg/h

$E = F - (Fx_F / x_{L2})$

Therefore , $E = F [1- (x_F / x_{L2})]$ ………………..(8)

Heat balance:

$F.h_F + SH_s = L_1 h_{L1} + V_1 H_1 + Sh_{c1}$

Therefore, $Fh_F + S(H_s - h_{c1}) = L_1 H_{L1} + V_1 H_1$ ……………………..…..…(i)

Therefore, $Fh_F + S(H_s - h_{c1}) = (F - V_1) h_{L1} + V_1 H_1$ (as $L_1 = F - V_1$)

Therefore, $Fh_F + S(H_s - h_{c1}) = F h_{L1} - V_1 h_{L1} + V_1 H_1$

Therefore, $F (h_F - h_{L1}) + S (H_s - h_{c1}) = V_1 (H_1 - h_{L1})$ ………………......(ii)

Similarly taking heat balance on 2nd effect,

$L_1 h_{L1} + V_1 H_1 = L_2 h_{L2} + V_2 H_2 + V_1 h_{c2}$

Therefore , $L_1 h_{L1} + V_1 (H_1 - h_{c2}) = L_2 h_{L2} + V_2 H_2$ ……………………………(iii)

Therefore , $L_1 h_{L1} + V_1 (H_1 - h_{c2}) = (L_1 - V_2) h_{L2} + V_2 H_2$ (as $L_2 = L_1 - V_2$)

Therefore , $L_1 h_{L1} + V_1 (H_1 - h_{c2}) = L_1 h_{L2} - V_2 h_{L2} + V_2 H_2$

Therefore , $L_1 (h_{L1} - h_{L2}) + V_1 (H_1 - h_{c2}) = V_2 (H_2 - h_{L2})$ ……………………(iv)

4.6. HEAT AND MATERIAL BALANCE OF TRIPLE EFFECT EVAPORATOR

Fig-4.6: **Heat Balance in triple effect evaporator** Heat balance

1st effect:

$Fh_F + SH_s = V_1 H_1 + S h_{c1} + L_1 h_1$

Therefore , $Fh_F + S(H_s - h_{c1}) = V_1 H_1 + L_1 h_1$

Therefore , $Fh_F + S(H_s - h_{c1}) = V_1 H_1 + (F - V_1) h_1$

Therefore , $F(h_F - h_1) + S(H_s - h_{c1}) = V_1 (H_1 - h_1)$ ……………………..(i)

2nd effect:

$L_1 h_1 + V_1 (H_1 - h_{c2}) = V_2 H_2 + L_2 h_2$

$= V_2 H_2 + (F - V_1 - V_2) h2$

$= V_2 H_2 + (L_1 - V_2) h_2$

$= V_2 H_2 + L_1 h_2 - V_2 h_2$

Therefore , $L_1 (h_1 - h_2) + V_1 (H_1 - h_{c1}) = V_2 H_2 - V_2 h_2$

$= V_2 (H_2 - h_2)$ ………………..(ii)

3rd effect :

$V_2 H_2 + L_2 h_2 = V_3 H_3 + V_2 h_{c2} + L_3 h_3$

Therefore , $V_2 (H_2 - h_{c2}) + L_2 h_2 = V_3 H_3 + (F - V_1 - V_2 - V_3) h_3$

$= V_3 H_3 + (L_2 - V_3) h_3$

$V_2 (H_2 - h_{c2}) + L_2 (h_2 - h_3) = V_3 (H_3 - h_3)$ ……………………..…………(iii)

Material balance:

$F = L_1 + V_1$, $L_1 = L_2 + V_2$, $L_2 = L_3 + V_3$

Therefore , $L_1 = L_3 + V_3 + V_2$

Therefore , $F = L_3 + V_1 + V_2 + V_3$ ……………………………………………(i)

Based on solids,

$Fx_f = L_1x_1$, $L_1x_1 = L_2x_2$, $L_2x_2 = L_3x_3$

Therefore , $Fx_f = L_3x_3$, Therefore , $F = L_3 (x_3/x_f)$

Therefore , $F = (F - V_1 - V_2 - V_3) (x_3/x_f)$

Therefore , $E = F - F(x_f/x_3) = F [1 - (x_f/x_3)]$

Combined:

$Fh_F + SH_s = S h_{c1} + V_1h_{c2} + V_2h_{c3} + V_3 H_3 + L_3 h_3$

Different Vacuum producing devices:

Production and maintenance of vacuum in the evaporator is very important for the smooth and efficient evaporation operation. The various vacuum producing devices used in dairy industry are as follows

1) Indirect (Shell and Tube) type condenser

2) Direct type condenser

1) Indirect type:

The surface condenser is an indirect type heat exchanger in which cold water on one side causes vapour coming from the product to condense on the other side. A common indirect heat exchanger used as a surface condenser is the tubular unit.

Fig. 4.7 Indirect type condenser

2) Direct type:

A jet condenser is a heat exchanger in which cooling water is sprayed into the unit where vapour is to be condensed. Jet type condenser can be further classified as parallel flow or counter flow type. The parallel flow condenser is normally operated as a wet condenser and the counter current flow condenser as a dry condenser. In parallel flow condenser, air and water are removed at the same temperature whereas in counter current condenser, the non-condensable are removed at the temperature of incoming water.

Fig. 4.8 Direct type condenser

In case of dry condenser, the cooling water is removed by one pump and the non-condensable including the air removed by another pump. In a wet condenser, condensed vapour and non condensable are all removed together.

A jet condenser will use cooling water amounting 20 to 50 times the weight of vapour. Thus, the vapour being removed from the product and the cooling water is mixed. A jet condenser is normally used in milk evaporating operation in preference to a surface condenser, the surface condenser being more expensive

The quantity of water required is less for a counter flow type of condenser. Another advantage is that the air and vapour need not enter at the top of the unit as is done with parallel flow. The quantity of air

removed from the evaporator system is about 15-25% of the volume of cooling water. Leaks in the system can cause the quantity of air to be considerably higher and result in expensive operation.

Boiling Point $^\circ$C	mm of Hg absolute pressure	Specific Volume of Vapour (m^3/kg)
75	434	2.8
70	233	4.8
60	149	7.7
50	92	12.0
40	55	19.6

Table 4.1 Pressure, volume and boiling point relationship

Barometric Leg Condenser:

It is placed high enough so that water and condensate from the condenser escapes from it by a **barometric leg.** In order to remove water and condensate from the plant without losing vacuum it is necessary that a leg of liquid be maintained with a hydrostatic head Hρ, equal to the difference between vacuum and atmospheric pressure; where H is the height and ρ is the density. In this manner the upper surface of the liquid in the tail pipe is at a pressure corresponding to the vacuum and the liquid at the bottom of the tail pipe is at atmospheric pressure due to the weight of the hydrostatic head. Thus liquid under vacuum continuously enters the tail pipe and liquid at atmospheric pressure continuously leaves from the bottom of the tail pipe by way of the hot well at the bottom. Atmospheric pressure corresponds to a hydrostatic head of 10.35 meters of water and complete vacuum corresponds to zero hydrostatic head. To maintain a process at substantially complete vacuum requires a leg of 10.35 meter of water be maintained between the barometric condenser and the hot well.

Fig. 4.9 Barometric Leg Condenser

If a pump is used to remove the tail pipe liquid instead of a total barometric height, whatever head is supplied by the pump can be deducted from the total barometric height and the assembly is known as a low-level condenser.

P=Hρ, where P=1.013×10^5 Pa =1.013 bar i.e. Atmospheric pressure

Specific steam consumption and water requirement:

The following table gives the idea about steam required to vapourize one kg of water and cooling water requirement.

	Range (steam in kg.)	Average (steam in kg.)	Water required in kg. per kg vapour to condense

Single effect	1.83-1.00	1.17	20.00
Double effect	0.63-0.50	0.57	9.00
Triple effect	0.40-0.34	0.37	6.00
Quadruple effect	0.30-0.26	0.28	5.00
Quintuple effect	0.24-0.22	0.23	4.00

Water requirement in condenser:

In a condenser the circulating water extracts heat from the vapour to be condensed and the temperature of the circulating water is raised. In direct condenser the cooling water and vapour come in direct contact, hence the temperature of condensate is same as that of outlet temperature of circulating water.

Heat received by circulating water from one kg. of vapour = $m \times S \times (t_2 - t_1)$ kJ (i)

Heat given out by one kg. of vapour to circulating water = $H - h_1$ kJ (ii)

From equation (i) and (ii), we get $m \times S \times (t_2 - t_1) = H - h_1$

Therefore $m = (H - h_1) / [S \times (t_2 - t_1)]$ kg.

Where, m = quantity of circulating water required to condense one kg. vapour

S = specific heat of water kJ/kg K

t_1 and t_2 = Inlet and outlet temperature of circulating water

$H = h + x L$ = Heat content of one kg vapour at corresponding vacuum

$h_1 = S \times t_2$ = Heat of one kg condensate of vapour

Example:

Determine the amount of cooling water required in jet condenser to condense one kg vapour, if cooling water inlet and outlet temperature is 20 ^{0}C and 30 ^{0}C respectively. Take heat of vapour (H) as 2556 kJ/kg at 30 ^{0}C and specific heat of cooling water as 4.187 kJ/kg.

Solution:

$m = (2556 - 125.6) / 41.87 = 58$ kg

Working of steam jet ejector:

Positive pump of reciprocating type and steam jet ejectors are commonly used to produce a vacuum. The pump is normally used for producing 24" Hg vacuum or less. The single stage steam jet ejector may be used for 25" Hg vacuum. The two stage steam jet ejector may be used for 28.8" Hg vacuum or three stages to produce 29.8"Hg vacuum using steam at 7.0 bar.

High pressure is admitted to a nozzle A that sends a jet of very high velocity into throat of a venturi.-shaped tube. The non condensable gases to be removed enter through suction chamber as shown in figure. By proper proportioning of a throat of the venturi, volume and velocity of steam used, the steam can be made to entrain (suck) non-condensable gases from the space under vacuum. For a very high vacuum, the steam air mixture from these jets goes to a condenser B, where the water vapour is condensed by a jet of cold water and the residual air passes to a second nozzle c. The discharge from second nozzle can usually be made to reach atmospheric pressure and is discharged at D to the air. Another important advantage of steam jet over reciprocating vacuum pump is that it has no moving parts and repairs are reduced to a minimum.

Fig. 4.10 steam jet ejector

Different type of pumps may be used for evacuation such as mechanically operating pump (ring pump) or steam ejectors which operates on similar principles to steam jet vapour compressors.

Oil lubricated vacuum pumps

The diagram shows a cross-section of a typical rotary vacuum pump. It consists of a horizontal cylindrical casing, with a rotor mounted eccentrically so that it is virtually in contact with the casing at one point of the circumference. The space between the rotor body and the casing is thus crescent shaped, and communicates through the elongated inlet port with the vacuum pipeline, and through the elongated outlet port with the exhaust pipe. The rotor has longitudinal slots, usually four, which house vanes free to slide radially as the rotor turns. The vanes, which are usually made of asbestos fiber composition, are kept in contact with the casing by centrifugal force. In some designs the vanes slide tangentially, the purpose being to reduce frictional losses. As the rotor turns, pockets of air are enclosed between the vanes and transferred from the inlet to the outlet.

Fig. 4.11 vacuum pump

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