

HEAT BALANCE

(1) Crusher

The normal power required to crush sugar cane is given by

$$P_N = 0.15 \times F \times n \times D \text{ -----(1)}$$

Where P_N – normal power (h.p)

F – load of crusher (tons)

n – economical rotational speed (rpm)

D – mean diameter of the rollers (m)

Here we will take 2 – roller crusher. Many types of crushers have been designed and tried but only two have achieved general importance. These were

(a) The Krajewski and

(b) The Fulton

The Fulton type is named after the Firm which has predominantly contributed to its design and wide use. It is the only type used at the present day.

For this type usual roller dimensions are 660×1220 mm

Here $D = 660$ mm and $L = 1220$ mm

Load of crusher = $F = 250$ tons

To calculate speed:

The peripheral speed generally adopted for the crusher is 30 – 40% greater than that of the mills.

The economic peripheral speed of mill is given by

$$V_E = (30 \times D) \div (D + 0.73) \text{ m/min}$$

D is calculated in milling tandem calculation = 1016 mm

$$\begin{aligned} \text{Therefore } V_E &= (30 \times 1.016) \div (1.016 + 0.73) \\ &= 17.46 \text{ m/min} \end{aligned}$$

Hence peripheral speed for crusher is given by

$$\begin{aligned} V_{E \text{ crusher}} &= 1.35 \times V_{E \text{ mill}} \\ &= 1.35 \times 17.46 \\ &= 23.57 \text{ m/min} \end{aligned}$$

Now the relation between peripheral speed and rotational speed is given by

$$\begin{aligned} n_E &= V_E \div (\pi \times D) \\ &= 23.57 \div (\pi \times 0.66) \\ &= 11.37 \text{ rpm} \end{aligned}$$

Therefore from equation (1)

$$P_N = 0.15 \times 250 \times 11.37 \times 0.66 = 281.31 \text{ h.p}$$

(2) Milling tandem

Assume 5 mill tandems and each mill consists of three rollers.

Hence number of rollers = $N = 15$

To find L (length) and D (diameter) of rollers:

The capacity of a train mills is the quantity of cane, which that train, is capable of treating in unit time. It is generally expressed in tons of cane per hour and it is given by

$$A = [0.9 \times C \times n \times (1 - 0.06nD) \times L \times D^2 \times \sqrt{N}] \div f \text{ -----(1)}$$

Where A = capacity of tandem = 250 tons/hr

f = fiber content per unit of cane = 0.13

n = speed of rotation of rollers in rpm

Generally used speed is 6 rpm. Hence n = 6 rpm

N = number of rollers in tandem = 15

C = coefficient of preparatory plant

For 2 knife sets of wide pitch, C = 1.15

Thus above equation (1) becomes

$$250 = [0.9 \times 1.15 \times 6 \times (1 - 0.06 \times 6 \times D) \times L \times D^2 \times \sqrt{15}] \div 0.13$$

$$(1 - 0.36 \times D) \times L \times D^2 = 1.3513 \text{ -----(2)}$$

Standard combinations of L and D as given by Hugot are taken as follows:

D × L (mm × mm)	LHS of equation (2)
813 × 1675	0.7831
920 × 2000	1.1321
970 × 2100	1.2859
1016 × 2134	1.3971
970 × 2134	1.3067

Thus choose dimensions as

D × L = 1016 × 2134 (mm × mm)

Power requirements of mills:

The determination of the power consumed by a mill is rather complex because a number of factors enter into it.

To begin with this, the power may be split into 3 different principle terms.

(a) Power absorbed by compression of bagasse

$$P_1 = [0.4 \times (6 \times r - 5) \times F \times n \times D \times \sqrt{\epsilon_A}] \div [\sqrt{r} \times \{1 + \sqrt{(r - 1)}\}]$$

Where $\epsilon_A = 0.0164$

For r = 1.2, $(6 \times r - 5) \div [\sqrt{r} \times \{1 + \sqrt{(r - 1)}\}] = 1.388$

F = 250 tons/hr

n = 6 rpm and D = 1.016 m

$$\text{Therefore } P_1 = 0.4 \times 1.388 \times 250 \times 6 \times 1.016 \times \sqrt{0.0164}$$

$$= 108.36 \text{ h.p}$$

(b) Power absorbed by friction

$$P_2 = (0.075 \times F \times n \times D) + (2 \times L \times n \times D)$$

$$= (0.075 \times 250 \times 6 \times 1.016) + (2 \times 2.134 \times 6 \times 1.016)$$

$$= 140.32 \text{ h.p}$$

(c) Power absorbed for intermediate carrier drive

$$P_3 = 2 \times L \times n \times D$$

$$= 2 \times 2.134 \times 6 \times 1.016$$

$$= 26.02 \text{ h.p}$$

Thus total power consumed by mill is given by

$$P = P_1 + P_2 + P_3$$

$$= 108.36 + 140.32 + 26.02$$

$$= 274.70 \text{ h.p}$$

But usually the efficiency of mill is 80%.

Hence actual power consumed by mill = $274.7 \div 0.8 = 343.37 \text{ h.p}$

Thus power required for a five mill tandem = $5 \times 343.37 = 1716.86 \text{ h.p}$

(3) Heater (clarifier)

Assuming the raw juice from milling tandem is available at 30°C. Before adding lime to juice, the juice has to be heated. Thus the final temperatures to which juices are heated in clarification varies from extremes of 90 to 115°C, although by far the commonest practice is to heat slightly above the boiling point. Superheating was advocated by some in earlier studies, but it is generally believed today that superheating is not advantageous and temperatures just above the boiling point say 103°C are the maximum for good practice.

Assume it is heated to 96°C and steam is available at 1 atm for heating.

Latent heat of vapourisation at this pressure is $\lambda = 2256.9 \text{ kJ/kg}$

Heat required to raise the temperature of raw juice from 30 to 96°C is given by

$$Q = m \times C_p \times \Delta T = m_s \times \lambda \text{ -----(1)}$$

$C_p = \text{heat capacity of raw juice} = 4.19 - 2.35 \times X \text{ kJ/kg}^\circ\text{K}$

Where X is fraction of dissolved solids.

Feed to the clarifier is 244 tons/hr and % of solids content is 16.70 (from material balance).

Therefore $C_p = 4.19 - 2.35 \times 0.167 = 3.7976 \text{ kJ/kg}^\circ\text{K}$

And $m = (244 \times 1000)/3600 = 67.78 \text{ kg/s}$

$\Delta T = 96 - 30 = 66^\circ\text{C}$

Thus from equation (1),

$Q = 67.78 \times 3.7976 \times 66 = 16988 \text{ kW}$

Steam requirement is $m_s = Q/\lambda = 16988/2256.9 = 7.53 \text{ kg/s}$

(4) Evaporator

Saturated steam required, which is calculated in process design part is

$$S = 12.3625 \text{ kg/s}$$

Saturation temperature of steam = 113.89°C at which $\lambda = 2218.2 \text{ kJ/kg}$

Therefore heat supplied by this steam = $S \times \lambda$

$$= 12.3625 \times 2218.2$$

$$= 27422.5 \text{ kW}$$

Steam economy = amount of water evaporated (i.e. evaporator load)/steam used

$$= 50.245/12.3625$$

$$= 4.064$$

(5) Crystallizer 1

As we known from material balance calculation, crystallizer operates at 580 mmHg vacuum.

At this pressure, boiling point of water is 61.42°C.

But boiling point rise (BPR) is 4°C.

Temperature in crystallizer = 65.42°C

Heat balance in crystallizer can be written as

$$Fh_F + m_s \lambda_s = Lh_L + V H \text{ -----(1)}$$

F = feed rate to crystallizer

$$= (22.37 + 33.25 + 1.25 + 0.25) \times (1000 \div 3600)$$

$$= 15.87 \text{ kg/s}$$

$$C_{pf} = 4.19 - 2.35 \times X$$

Here X = 0.6084

Therefore $C_{pf} = 2.7603 \text{ kJ/kg}^\circ\text{K}$

Feed temperature = $T_f = 55.45^\circ\text{C}$

Taking base temperature as 0°C.

But $h_F = C_{pf} \times (T_f - 0) = 2.7603 \times 55.45 = 153.06 \text{ kJ/kg}$

m_s = steam rate required in kg/s

Assume steam is available at same pressure as that of clarifier.

Hence $\lambda_s = 2256.9 \text{ kJ/kg}$

L = output of crystallizer

$$= (31.4375 + 4.9535) \times (1000 \div 3600)$$

$$= (36.391 \times 1000) \div 3600$$

$$= 10.11 \text{ kg/s}$$

$$C_{pl} = 4.19 - 2.35 \times X$$

Where X = fraction of solids in crystallizer output

$$= 31.4375/36.391$$

$$= 0.955$$

Thus $C_{pl} = 4.19 - 2.35 \times 0.955 = 1.95 \text{ kJ/kg}^\circ\text{K}$

Temperature of output of crystallizer = $T_1 = 65.42^\circ\text{C}$

But $h_L = C_{pl} \times (T_1 - 0) = 1.95 \times 65.42 = 127.31 \text{ kJ/kg}$

V = amount of water evaporated in the crystallizer

$$= (20.729 \times 1000) \div 3600$$

$$= 5.76 \text{ kg/s}$$

$$H = \lambda \text{ at } 65.42^\circ\text{C} + (\text{BPR} \times C_{p\text{steam}})$$

$$\lambda \text{ at } 65.42^\circ\text{C} = 2618 - 275.8 = 2342.2 \text{ kJ/kg}$$

$$C_p \text{ steam at } 65.42^\circ\text{C} = 1.928 \text{ kJ/kg}^\circ\text{K}$$

$$\text{Therefore } H = 2342.2 + (4 \times 1.928) = 2349.91 \text{ kJ/kg}^\circ\text{K}$$

Now equation (1) becomes,

$$(15.87 \times 153.06) + (m_s \times 2256.9) = (10.11 \times 127.31) + (5.76 \times 2349.91)$$

$$\text{Hence } m_s = 12394/2256.9 = 5.49 \text{ kg/s}$$

Steam to be supplied to the crystallizer is $m_s = 5.49 \text{ kg/s}$

(6) Centrifugal separator

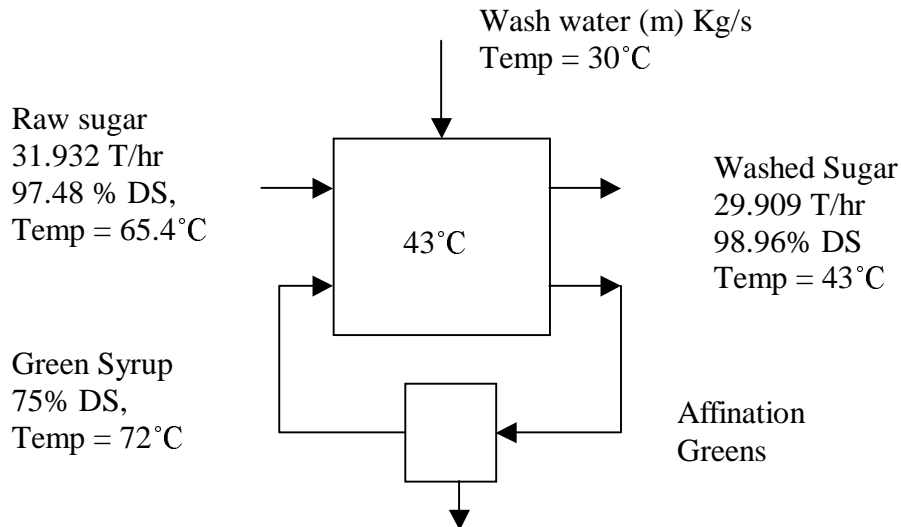
$$\text{Feed to the separator} = 31.4375 + 4.9535$$

$$= 36.391 \text{ tons/hr}$$

For this capacity and for speed of 1500 rpm, the power required for an operation as suggested by Hugot = 45 kW

(7) Affination

For every 45 kg of raw sugar, 9 to 13 kg of green syrup is required. Green syrup is a low – purity sugar solution has an affinity for sugar and impurities and can dissolve and retain more sugar & impurities in solution than a pure sugar solution, it will also dissolve non-sugars more readily, and when recirculated through the affination station will gradually decreases in purity.



$$\text{Therefore for } 31.932 \text{ tons/hr, green syrup has to be added} = (10 \times 31.932) \div 45$$

$$= 7.096 \text{ tons/hr}$$

C_p of water at $30^\circ\text{C} = 4.184 \text{ kJ/kg}^\circ\text{K}$

C_p for raw sugar $= 4.19 - 2.35 \times 0.9748 = 1.9105 \text{ kJ/kg}^\circ\text{K}$

C_p for green syrup $= 4.19 - 2.35 \times 0.75 = 2.4275 \text{ kJ/kg}^\circ\text{K}$

Assume base temperature 43°C .

Now the heat balance can be written as

$$[31.932 \times (1000 \div 3600) \times 1.9105 \times (65.42 - 43)] + [7.096 \times (1000 \div 3600) \times 2.4275 \times (72 - 43)] = m \times 4.184 \times (43 - 30)$$

$$379.93 + 138.76 = m \times 54.392$$

Hence $m = 9.54 \text{ kg/s}$

Therefore wash water to be added $= m = 9.54 \text{ kg/s} = 34.33 \text{ tons/hr}$

$$\begin{aligned} \text{Amount of affination green} &= (31.932 - 29.909) + 7.096 + 34.33 \\ &= 43.449 \text{ tons/hr} \end{aligned}$$

Analysis of this affination green

Water 38.127

Solids 5.322

$$\% \text{ of dissolved solids} = (5.322 \div 43.449) \times 100 = 12.25$$

$$\begin{aligned} \text{Amount of water to be removed in process to get a recycle of 75\% dissolved solids} \\ &= 43.449 - (5.322 \div 0.75) \\ &= 36.353 \text{ tons/hr} \end{aligned}$$

(8) Melting

Steam coils in the melter regulate the temperature of the melt and maintain it between $82 - 88^\circ\text{C}$. Assuming it as 86°C .

Feed to the melter is 29.909 tons/hr and its temperature is 43°C .

Water entering the melter is 14.5302 tons/hr (as calculated in material balance) and temperature of water is 30°C .

C_p of water at $30^\circ\text{C} = 4.184 \text{ kJ/kg}^\circ\text{K}$

C_p of crystals $= 4.19 - 2.35 \times 0.9896 = 1.8644 \text{ kJ/kg}^\circ\text{K}$

The heat to be supplied to raise the temperature of mixture (melt) to 86°C is given by

$$Q = [29.909 \times (1000/3600) \times 1.8644 \times (86 - 43)] + [14.5302 \times (1000/3600) \times 4.184 \times (86 - 30)]$$

$$\text{Therefore } Q = 666.05 + 945.69 = 1611.74 \text{ kW}$$

Assume steam is available at 1 atm for heating.

Thus $\lambda = 2256.9 \text{ kJ/kg}$

$$\text{Hence flow rate of steam required} = m_s = Q \div \lambda = 1611.74 \div 2256.9 = 0.7141 \text{ kg/s}$$

(9) Crystallizer 2

Assume operation temperature and pressure same as that of crystallizer1.

At this pressure, boiling point of water is 61.42°C .

$$\begin{aligned} \text{Sucrose solution from decolourizer} &= (28.4793 \text{ sucrose} + 14.8403 \text{ water}) \\ &= 43.3196 \text{ tons/hr} \\ &= 12.03 \text{ kg/s} \end{aligned}$$

Weight % of sucrose = $(28.4793 \div 43.3196) \times 100 = 65.74$
 C_p of feed to crystallizer = $C_{pf} = 4.19 - 2.35 \times 0.6574 = 2.65 \text{ kJ/kg}$
 Therefore solids per 100 parts of water = $(65.74 \times 100) \div (100 - 65.74)$
 $= 192$

Thus boiling point rise (BPR) = 4.5°C
 Assume the sucrose solution from decolourizer is at ambient temperature i.e. 30°C .
 Thus $T_f = 30^\circ\text{C}$

Heat balance in crystallizer can be written as
 $Fh_F + m_s\lambda_s = Lh_L + VH$ -----(1)

F = feed rate to crystallizer
 $= 12.03 \text{ kg/s}$
 $C_{pf} = 2.65 \text{ kJ/kg}^\circ\text{K}$

Feed temperature = $T_f = 30^\circ\text{C}$
 Taking base temperature as 0°C .
 But $h_F = C_{pf} \times (T_f - 0) = 2.65 \times 30 = 79.5 \text{ kJ/kg}$
 m_s = steam rate required in kg/s
 Assume steam is available at same pressure as that of clarifier.

Hence $\lambda_s = 2256.9 \text{ kJ/kg}$
 L = output of crystallizer
 $= (26.4288 + 0.3461) \times (1000 \div 3600)$
 $= (26.7749 \times 1000) \div 3600$
 $= 7.44 \text{ kg/s}$

$C_{pl} = 4.19 - 2.35 \times X$
 Where X = fraction of solids in crystallizer output
 $= 26.4288/26.7749$
 $= 0.9871$

Thus $C_{pl} = 4.19 - 2.35 \times 0.9871 = 1.87 \text{ kJ/kg}^\circ\text{K}$
 Temperature of output of crystallizer = $T_1 = 61.42 + 4.5 = 65.92^\circ\text{C}$
 But $h_L = C_{pl} \times (T_1 - 0) = 1.87 \times 65.92 = 123.27 \text{ kJ/kg}$
 V = amount of water evaporated in the crystallizer
 $= (13.7376 \times 1000) \div 3600$
 $= 3.816 \text{ kg/s}$

$H = \lambda$ at $65.92^\circ\text{C} + (\text{BPR} \times C_{p\text{steam}})$
 λ at $65.92^\circ\text{C} = 2618 - 275.8 = 2342.2 \text{ kJ/kg}$
 C_p steam at $65.92^\circ\text{C} = 1.928 \text{ kJ/kg}^\circ\text{K}$
 Therefore $H = 2342.2 + (4.5 \times 1.928) = 2350.88 \text{ kJ/kg}^\circ\text{K}$

Now equation (1) becomes,
 $(12.03 \times 79.5) + (m_s \times 2256.9) = (7.44 \times 123.27) + (3.816 \times 2350.88)$
 Hence $m_s = 3.958 \text{ kg/s}$
 Steam to be supplied to the crystallizer is $= m_s = 3.958 \text{ kg/s}$

(10) Drying

To calculate the heating surface of air heater:

The air heater generally consists of tubes, which are supplied with steam at about 5 kg/cm². The condensate leaves at bottom.

The heating surface of this small heat exchanger will be given by

$$A = Q \div [U \times \{T - (t_1 + t_0)/2\}]$$

Where A – heating surface of air heater (m²)

Q – quantity of heat to be transmitted in kcal/hr

U – heat transfer coefficient in kcal/(m²hr°C)

T – temperature of saturated steam employed in °C.

t₀ – temperature of cold air entering = 30°C

t₁ – temperature of hot air leaving = 50°C

Assume steam is available at 5 kg/cm² i.e. 490.5 kPa

Therefore T = 152°C (from steam table)

As suggested by Hugot, U = 10 kcal/(m²hr°C)

The quantity of heat Q to be transferred is calculated from the fact that it consists of three principle terms.

(I) The heat necessary to heat the weight of air is given by

$$q_1 = M \times C \times (t_1 - t_0)$$

M = amount of air entering = 7451.69 kg/hr

C = specific heat of air = 0.24 kcal/kg°C

Therefore $q_1 = 7451.69 \times 0.24 \times (50 - 30) = 35768.11$ kcal/hr

(II) The heat necessary to evaporate the water contained in the sugar is given by

$$q_2 = m \times [607 + 0.3 \times t_1 - t_0]$$

m = amount of water evaporated = 293.1 kg/hr

Thus $q_2 = 293.1 \times [607 + 0.3 \times 50 - 30]$

$$= 173515.2 \text{ kcal/hr}$$

The quantity q_2 of heat correspond to that given up by the hot air between T^l reached at the outlet from the air heater and t₁, which has not been included in q_1 .

(III) The heat necessary to heat the vapour contained in the weight M of air, assumed saturated is given by

$$q_3 = M \times H_0 \times C^l \times (t_1 - t_0)$$

C^l = specific heat of vapour = 0.475 kcal/kg°C

H₀ = it is expressed as kg of water per kg of air = 0.026

Therefore $q_3 = 7451.69 \times 0.026 \times 0.475 \times (50 - 30)$

$$= 1840 \text{ kcal/hr}$$

The heat lost to ambient air is taken into account by writing the expression for Q as follows:

$$\begin{aligned} Q &= 1.25 \times (q_1 + q_2 + q_3) \\ &= 1.25 \times (35768.11 + 173515.2 + 1840) \\ &= 263.90 \times 10^3 \text{ kcal/hr} \end{aligned}$$

Therefore heating surface of heat exchanger will be

$$A = 263900 \div [10 \times \{152 - (30 + 50)/2\}]$$
$$= 235.63 \text{ m}^2$$

The steam consumption will be

$$m_s = Q \div \lambda$$

m_s = steam consumption for air heater (kg/hr)

λ = latent heat of steam used = 500 kcal/kg

Therefore $m_s = 263900 \div 500 = 527.8 \text{ kg/hr} = 0.147 \text{ kg/s}$