Chapter 3
Theoritical Considerations

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Theoretical Considerations

3.1 Conceptual Design of Drying System

From the review of literature it was found that a solar and biomass fired integrated drying system demands separate understanding and design for solar collector and biomass fired section. Accordingly, design works were carried out. The schematic of the conceptual design of solar-biomass integrated drying system is given in Fig.3.1 and Fig.3.2. The components of the drying system are solar collector; solar tracking facility, combustion chamber; hot air generation chamber; husk feeding assembly; flue gas chimney; drying chamber; drying trays; insulated body, loading-unloading facility, wind turbine, flow control valves and measuring ports. The details of the design, specification and use of each component are explained in the following sections.

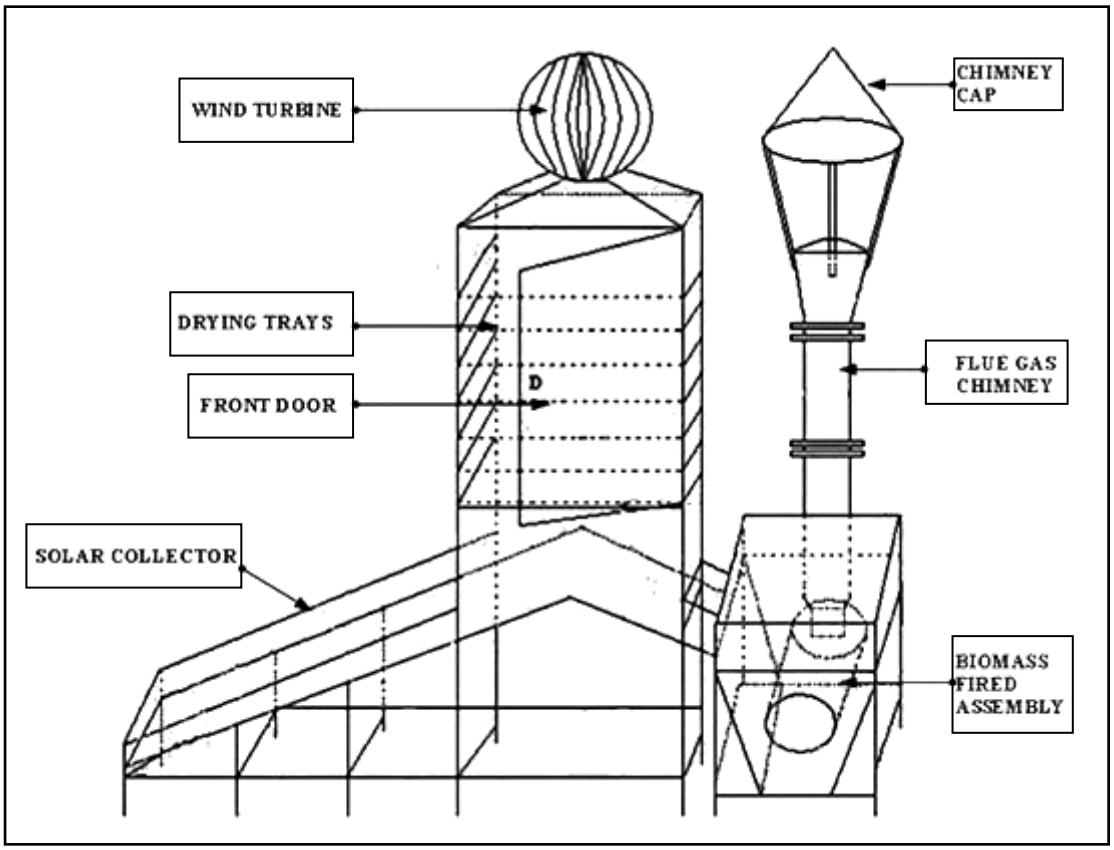


Fig. 3.1 Schematic of integrated drying system

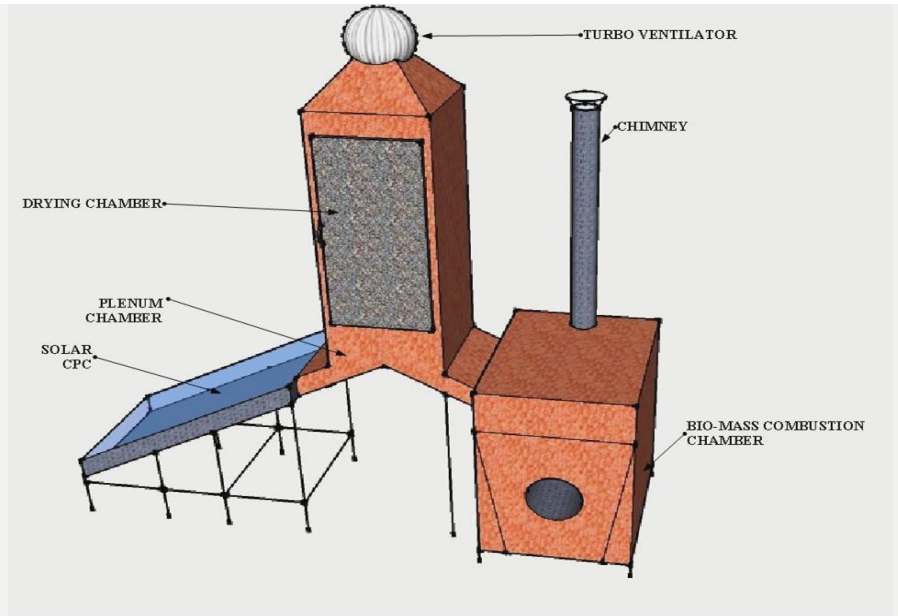


Fig. 3.2 Schematic representation of solar-biomass integrated drying system

3.1.1 Solar flat plate collector

Functional design of a solar flat plate collector was carried out to harness maximum solar intensity. The absorber plate consisted of black painted aluminum sheet with ply board insulation at the bottom and the two sides. For trapping solar radiation, 8 mm thick transparent glass Pyrex was selected for use over the collector surface area. The collector dimension of 2220 mm x 1230 mm was finalized with an inclination of 15^0 facing south (26.75^0N and 94.22^0E) for maximum exposure to insolation (Jamil and Tiwari, 2009). To increase the air velocity the neck of collector was designed tapered towards outlet.

3.1.2 Compound Parabolic Collector (CPC)

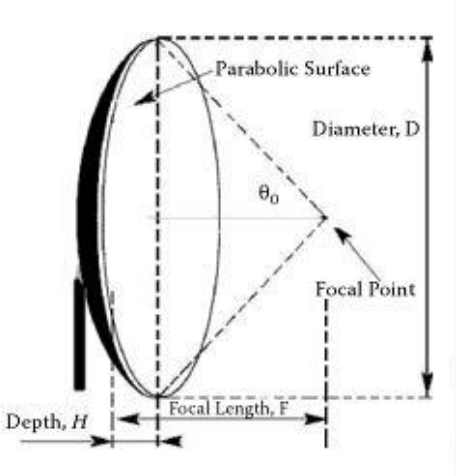
To increase the intensity of solar radiation thereby to increase the temperature, a double parabolic concentrator was selected for the design.

The equation for the parabola in cylindrical coordinates is:

$$Z = \frac{r^2}{4f} \qquad \text{---------- (3.1)}$$

Where, ‘r’ is radius and ‘f’ is focus.

The focal distance is given by the expression,



$$f = \frac{d^2}{16h} \quad \text{---------- (3.2)}$$

where, 'h' is the depth of the dish.

From this geometrical representation of double parabola the total area covered and total arc length of the design was calculated (Ringeisen, 2011).

Fig. 3.3 Graphical representation of CPC

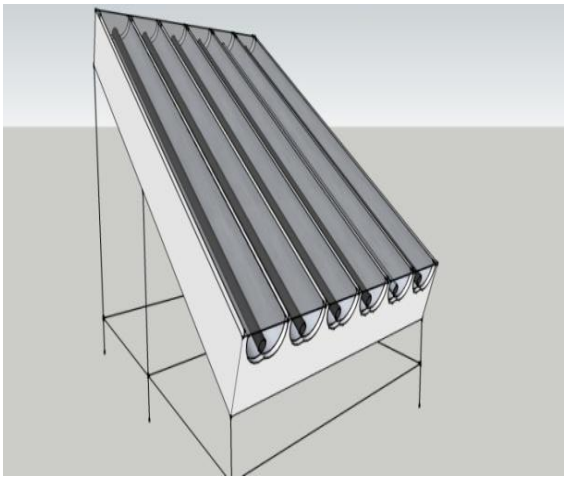


Fig. 3.4 Schematic of modified CPC

Area of each parabola:

$$S = \frac{2}{3} \times a \times b \quad \text{---------- (3.3)}$$

Where, a = vertical height and b = diameter of parabola

And arc length of the parabola is given by,

$$L = \frac{1}{2}\sqrt{b^2 + 16a^2} + \frac{b^2}{8a} ln\left(\frac{4a+\sqrt{b^2+16a^2}}{b}\right) \quad \text{---------- (3.4)}$$

For a= 8 cm and b = 12cm (from Fig.3.2)

$$L_1 = \frac{1}{2}\sqrt{12^2 + 16 \times 8^2} + \frac{12^2}{8\times8} ln\left(\frac{4\times8+\sqrt{12^2+16\times8^2}}{12}\right) = 20.9 \text{ mm} = 209 \text{ mm}$$

Similarly, L_2 = 209 mm and the total arc length covered by both parabola

$= L_1 + L_2 = 2L = 2 \times 209 = 418$ mm

Therefore, half of each parabola = 104.5 mm.

The intersection of two parabolas cuts at a point which was at a distance of 70 mm from diameter of the parabola. Similarly from (Fig. 3.3) the arc length of parabola at the intersection where, 'a' and 'b' were 10 mm and 60 mm were 64.16 mm.

So, the arc length of the parabola from the intersection to the diameter which needed to be subtracted in the design: = 104.5 - (64.16/2) = 2.42 mm.

Therefore, arc length required for the design

$$= 418 - (72.42\ x\ 2) = 273.16 \text{ mm}$$

Using Fig. 3.2, the following calculations were done:

a) For d = 120 mm and h = 80 mm, (Eq. 3.2) the focus '*f*' of each parabola was calculated to be 11.25 mm.

b) Diameter of the compound parabolic concentrator = 180 mm

The overall dimension of solar receiver was designed as 1860 mm in length and 1220 mm in breadth. A total of six parabolic concentrators were to be accommodated with equal spacing of 15 mm (Fig. 3.4) over previously fabricated flat plate collector. The parabolic reflectors made up of glazed aluminum sheets expected to reflect the solar rays on the face of a receiver placed at the focal position of the concentrator. Metallic tubes of outer diameter 32 mm, thickness 15 mm and length of 1860 mm would act as receivers along the focus of each CPC. To ensure a nominal tracking of the sun to reduce the shadow effect of adjoining CPC's thereby further increase the effective drying time, the collector was decided to be placed on a directional support according to the two axes. For the same reason, a space of 40 mm each was to be left open in the two sides of the collector area.

3.1.3 Limited Sun tracking provision

To increase the effective drying time, a manual tracking facility was designed along the two axes. Horizontal and vertical tracking incorporated on receiver were designed to provide tracking by $11.54^0$and 4.68^0, respectively (Fig.3.5).

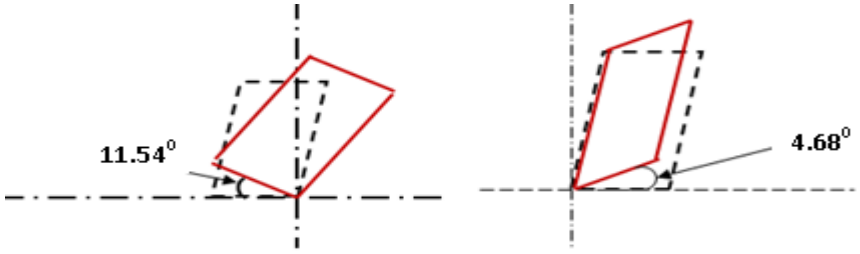


Fig. 3.5 Horizontal and vertical tracking

3.1.4 Design of bio-waste fired assembly

The unit was conceived to be operated by paddy husk and also other solid biomass viz. wood, stem etc. A detachable grate type husk feeding system was designed. A single lever slot movement mechanism was designed to control the inclinations of the grates for facilitating air flow during burning. A hopper with agitating drive mechanism for husk feeding was designed as an attachment for feeding of husk.

3.1.4.1 Combustion chamber design

A combustion chamber was conceived to have a horizontal grate for proper burning of solid fuel. A chimney on the exhaust side would create necessary draught for complete combustion and escape of flue gas.

Paddy husk was considered as fuel to generate required heat as a normal situation. The following assumptions were taken for functional design calculations:

Length of combustion chamber	=	1620 mm
Diameter of combustion chamber	=	450 mm
Material of fabrication	=	Mild steel
Husk feed rate	=	1.8 kg / h
Diameter of chimney	=	200 mm

For complete combustion of husk per unit time, creation of sufficient natural draught was critical. Design calculations were carried out for determination of height of the chimney to create necessary draught.

3.1.4.1.1 Design calculations

From ultimate analysis, composition of rice husk:

$$\left.\begin{array}{l} \mathrm{C} = 36.4\% \\ \mathrm{H} = 4.84\% \\ \mathrm{O} = 25.115 \\ \mathrm{S} = 0.17\% \\ \mathrm{N} = 0.44\% \end{array}\right\} \text{(Srinath and Reddy, 2011)}$$

Calculation of minimum oxygen required for burning 1 kg. of rice husk

1) $C + O_2 = CO_2$
$12 + 2 \times 16 = 44$ [∴ molecular weight of carbon = 12]
$=> 1 + 8/3 = 11/3$

2) $2H_2 + O_2 = 2H_2O$
$2 \times 1 \times 2 + 2 \times 16 = 36$ [∴ molecular weight of hydrogen = 2]
$1 + 8 = 9$

3) $S + O_2 = SO_2$
$32 + 2 \times 16 = 64$ [∴ molecular weight of sulfur = 32]
$1 + 1 = 2$

'N' was not considered owing to very high combustion temperature.

Therefore total amount of oxygen required for that particular composition of rice husk

$$= \frac{8}{3} \times 0.364 + 8 \times 0.0484 + 0.0017 \times 1 - 0.25$$

$$= 1.109567 \text{ kg}$$

As air contains 23% oxygen by weight, 1 kg of O_2 contained in $= \frac{100}{23} = 4.35$ kg of air.

Therefore minimum quantity of air required for complete combustion of 1 kg rice husk:

$$= 4.35 \times 1.109567 = 4.82 \text{ kg.}$$

Considering 50% excess air to compensate the non-participating portion of air in burning, then actual air required per kg of fuel

$$= 1.5 \times 4.82 = 7.23 \text{ kg.}$$

For husk feed rate of 1.8 kg/hr, total air required per hour

$$= 7.23 \times 1.8 = 13.014 \text{ kg/h}$$

We know, $Q = \rho A V_{air}$ ---------- (3.5)

where, Q= air flow rate to the combustion chamber = 13.014 kg/h

ρ = density of air at room temperature = 1.2 kg/m^3

A = cross-sectional area of combustion chamber = $\pi/4 \times D^2_c = \pi/4 \times 0.45^2$

V_{air}= velocity of air through the chamber

Therefore, $V_{air} = \frac{Q}{\rho A} =$ 0.02 m/s

For, p_a = atmospheric pressure =1.01325 bar = 101.325 N/m^2

p_g = pressure of flue gas at temperature $T_1 = 400 + 273 = 673^0$ K

h = draught measured in water column, mm

R = gas constant = 287 J kg^{-1} K^{-1}

ρ_a = mass density of air = 1.20 kg/m^3
(at std. atm. pressure & temperature)

ρ_g = average mass density of flue gas = 0.59703 kg/m^3
(Experimentally obtained at 400^0 C)

ρ_0 = density of flue gas at 273^0 K = 1.471kg/m^3Std. Value

H = chimney height, m

T_1 = absolute ambient temperature = $30+273 = 303^0$ K

T = flue gas absolute temperature = $400+273 = 673^0$ K

w = weight of the air required to burn the fuel = 7.23 kg

$$p_a = \rho_a R T_1 = 1.01325 \times 10^5 \text{ N/m}^2$$

Static draught is given by, $\Delta p = p_g - p_a$

$$\Delta p = 101325 - 101306.76$$

$$\Delta p = 18.24 \text{ N/m}^2 \quad \text{[Since 1 N/m}^2 \text{ = 0.1 mm of } H_2O\text{]}$$

Or

$$h = 1.86 \text{ mm of water}$$

Now chimney height from the equation, (Pandha and Shah, 1967)

$$h = 353H\left[\frac{1}{T_1} - \frac{w+1}{w} \times \frac{1}{T}\right] \qquad \text{---------- (3.6)}$$

$$h = 353 \times H\left[\frac{1}{303} - \frac{8.23}{7.23} \times \frac{1}{673}\right]$$

$$H = 3.29\text{m} \quad = 3290 \text{ mm}$$

Again,

$$H' = \text{height of column of hot gas in meter}$$

$$= H \times \left(\frac{w}{w+1} \times \frac{T}{T_1} - 1\right) \quad \text{---------- (3.7)}$$

$$= 3.12\text{m}$$

$H'_a = \text{actual draught (80\% of theoretical draught)}$

$= 0.8 \times 3.12$

$= 2.496\text{m of hot gas column}$

Theoretical velocity of the gas flow,

$$V = \sqrt{2gH'_a} \quad \text{---------- (3.8)}$$

$$= \sqrt{2 \times 9.81 \times 2.496}$$

$= \frac{6.997\text{m}}{\text{s}} \approx 7\ \text{m/s}$ (Resemble to I S value for natural draught)

$$V_{actual} = 30\%\sim50\%\ \text{of V}$$

$= 0.5 \times 7 = 3.5\ \text{m/s}$

So, $Q = \text{volume of flue gas handeled in } \frac{m^3}{s} \text{ by the chimney}$

$$= kAV$$

where, k = velocity co-efficient = 0.3 to 0.5

and A = cross sectional area of the chimney

$= 0.5 \times \frac{\pi}{4} \times D^2 \times 3.5$ (D = diameter of the chimney)

$= 0.055\ m^3/s$

3.1.4.1.2 Analysis of flue gas

From the composition of the particular rice husk, we can determine the weight of flue gas produced per kg of fuel.

1kg carbon needs 2.66 kg of oxygen and produce 11/3 kg of carbon dioxide.

Therefore, 0.364 kg of carbon would require,

$0.364 \times 2.66 = 0.968$ kg of oxygen and

$0.364 \times 3.66 = 1.334$ kg of CO_2 would be produced.

Similarly, 0.4356 kg of water vapour and 0.0034 kg of SO_2 would be produced after combustion of 1kg of rice husk.

O_2 in excess air $= 0.23 \times 0.5 \times 4.82 = 0.55$ kg

N_2 in air $= 0.77 \times 1.5 \times 4.82 + 0.0044 \times 1 = 5.5715$ kg

Therefore total weight of flue gas produced by burning 1kg rice husk would be

$= 1.334 + 0.4356 + 0.0034 + 0.55 + 5.5715$

$= 7.8945$kg

Since fuel combustion rate = 1.8 kg/hr = 0.00052 kg/s

Therefore flue gas production rate $= 0.00052 \times 7.8945 \approx 0.004$ kg/s

Density of flue gas for that composition of rice husk = 0.5907 kg/m^3 (Calculated)

Volume flow rate of flue gas $= \frac{0.004}{0.5907} = 0.006$ m^3/s

3.1.4.2 Design of chimney

The draught available in the chimney should take care of all the draught losses. The height and diameter of the chimney should be so chosen as to obtain the necessary draught and the necessary exit velocity (IS chimney design).

a) Draught losses through the chimney d_e in mm of water column may be calculated as:

$$d_e = \frac{4fHV^2}{2gD} \times \rho_g \quad \text{---------- (3.9)}$$

b) Draught losses through the ducts d_d in mm of water column may be calculated as:

$$d_d = \frac{4flV_1^2}{2gD_1} \times \rho_g \quad \text{---------- (3.10)}$$

c) Draught losses in bends d_b in mm of water column may be calculated as:

$$d_b = \frac{K_1 V^2}{2g} \times \rho_g \qquad \text{---------- (3.11)}$$

d) Draught losses due to sudden change of sections d_s in mm of water will depend upon the degree of sharpness, form of section and the ratio of area of the section after and before the change.

It may be calculated as:

$$d_s = \frac{K_2 V_2^2}{2g} \times \rho_g, \qquad \text{---------- (3.12)}$$

(when the change in section is abrupt)

e) Draught loss due to kinetic energy at the exit:

$$d_k = \frac{V^2}{2g} \times \rho_g \qquad \text{---------- (3.13)}$$

Where,

f = fanning friction factor

H = height of the chimney, m

l = Length of the duct, m;

D = diameter of the chimney, m

D_1 = diameter of the duct, m

V = velocity of gas, m/sec

V_1 = velocity of gas in the flue duct, m/sec

V_2 = velocity of gas after the change in section, m/sec

K_1 = coefficient of friction

K_2 = coefficient of friction due to sudden change in section

g = acceleration due to gravity, m/s^2

ρ_g = average density of fuel gas within the chimney, in ducts, in bends or at the exit; as appropriate, kg/m^3

The draught induced by the chimney, d_a in mm of water column is:

$$d_a = H(\rho_a - \rho_g) \quad \text{---------- (3.14)}$$

Where, ρ_a = density of air at ambient temperature and pressure in kg/m^3,and

ρ_g = density of gas at average temperature and pressure within chimney in kg/m^3

Therefore, $d_a \geq$ total draught loss $\geq d_e + d_d + d_d + d_s + d_k \geq d_t$

Recommended minimum efflux velocities from air pollution point of view for natural draught system is equal to 6 m/s (Fig.3.6) IS Code of practice for chimney design).

Therefore, we can consider $V = V_2 = 6\, m/s$

Whereas, $V_1 = 1.18 \frac{m}{s}$ (from continuity equation)

$$\left.\begin{array}{r} \rho_g = 0.525\ \frac{kg}{m^3} \\ \mu = 31.7 \times 10^{-6} Pa.s \end{array}\right\} \text{at 400°C for that particular flue gas composition}$$

(http://www.pipeflowcalculations.com)

From the above value we can calculate Reynolds's No. of the flue gas, which is given as:

$$R_{eD} = \frac{\rho_g V D}{\mu} \quad \text{---------- (3.15)}$$

$$= 1.9 \times 10^4 \text{ (Transient condition)}$$

Now fanning friction factor f for this Reynolds's No. is (Lienhard and Lienhard, 2006)

$$f = \frac{64}{R_{eD}} = 0.0033 \quad \text{---------- (3.16)}$$

K_1 = coefficient of friction = 0.75

K_2 = coefficient of friction due to sudden change in section = 0.4

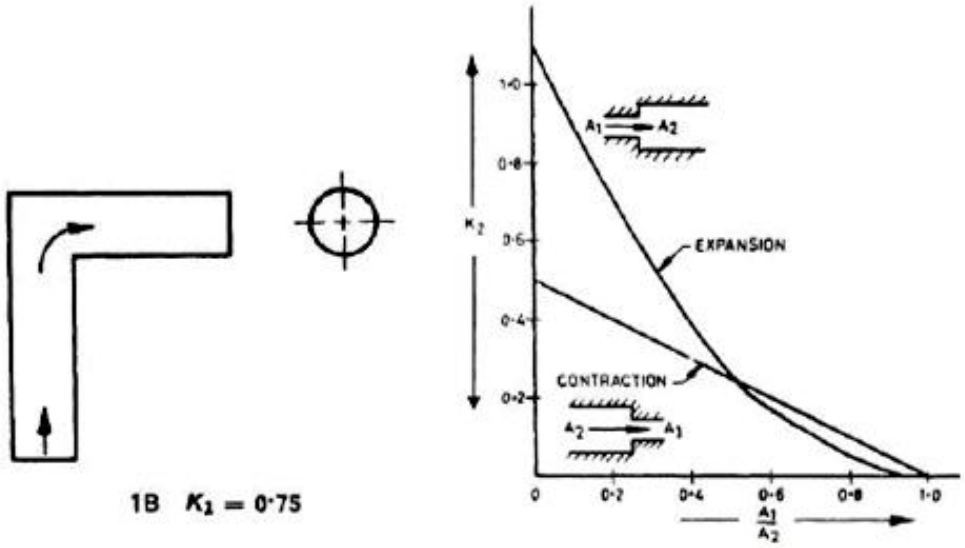


Fig. 3.6 K_1 and K_2 (Standards, 2001)

Therefore,

$d_e = 0.0642H$

$d_d = 3.24 \times 10^{-4}$mm of water

$d_b = 0.716$ mm of water

$d_s = 0.381$ mm of water

$d_k = 0.954$ mm of water

Total draught loss

$d_t = 0.0642\text{H} + 3.24 \times 10^{-4} + 0.716 + 0.381 + 0.954$

$= 0.0642\text{H} + 2.051$ mm of water

Now,

$d_a = \text{H}(\rho_a - \rho_g) \geq \text{d}_t$ ---------- (3.17)

(http://www.pipeflowcalculations.com)

$\text{H}(1.2 - 0.525) \geq 0.0642\text{H} + 2.051$mm of water

$0.675\text{H} \geq 0.0642\text{H} + 2.051$

$\text{H} \geq 3.35$ m

Therefore, from friction loss point, the height of the chimney for sufficient draught creation: = 3350 mm.

A difference of 60 mm was found from flue gas composition analysis, which was satisfactory. Thus, the final calculated design values considered were:

a) Maximum calculated draught can be obtained at a chimney height, H = 3350 mm.
b) Flue gas handled by the chimney for the given dimension = 0.055 m^3/s
c) Flue gas production for given fuel combustion rate = 0.006 m^3/s
d) Minimum air required for 1 kg rice husk for complete combustion = 7.23 kg
e) Required air velocity in the combustion chamber = 0.02 m/s.

3.1.5 Drying chamber design

The capacity of the dryer was planned to accommodate 100 kg of raw sliced ginger or turmeric per batch in perforated trays. It consisted of plenum chamber; trays; free board; air inlet and exit port; measuring ports, provision for loading and unloading; insulation and rain protection.

3.1.5.1 Drying trays

Considering sliced raw ginger of 2-3 mm thick in thin layers of ≤ 50 mm thickness, it was found that a total of six numbers of perforated trays were required of dimension 950 mm x 950 mm x 150 mm. The side enclosures of the trays (150 mm) were required to protect from spilling over of products during loading, unloading and sequencing.

3.1.5.2 Plenum chamber

The plenum chamber bottom design was inclined upwards towards the centre from both the ends. The hot air from both solar collector and bio-waste fired assembly was expected to enter the plenum chamber at an angle. The angle between the slopes of the air inlet plates was calculated to be 127^0. The height of the chamber from the sides was designed to be 410 mm so as to make the above angle by the bottom plates while meeting the centre of the chamber. The width and breadth of the chamber were computed to be 1000 mm x 1000 mm in order to accommodate the drying trays.

3.1.5.3 Air flow mechanism

To ensure smooth flow of hot air through the drying trays the concept of a wind turbine ventilator was envisaged to be placed over the free board. The collar of the turbine ventilator was chosen to be 380 mm in diameter. Two half turn butterfly dampers for air flow regulation were to be incorporated on the necks of solar and bio-waste fired assembly. With minimum ambient air flow, the wind turbine was expected to induce a draft within the chamber creating air flow current. A cycle of air current thus expected to start, where ambient air after getting heated in solar collector as well as in bio-waste fired unit would pass through the trays, get loaded with moisture before being sucked out to atmosphere by the wind turbine at the top.

3.1.5.4 Loading and unloading

The dryer was designed for 100 kg of raw sliced ginger or turmeric to be accommodated in 6 wire mesh bottom trays of 4 mm square perforations. The trays were to slide into the drying chamber after loading on channels without much effort. However they were to fit snugly to force the drying air only through the products and not through the sides (Imre, 1995).

A multi slot concentric pipe and T-frame assembly was designed to provide support to the trays during unloading of products and sequencing of tray positions.

3.1.6 Safety precautions

A barricaded platform at elevation matching the base of the plenum chamber was designed to provide the necessary safety and ease of operation. An angle iron ladder was designed at 45^0 angle with base equipped with hand railings of MS pipe. A scooper was designed to scoop out the burnt ashes from the combustion chamber with sufficiently long handle to avoid burn hazard to the operator.