APPENDICES

Appendix A

Proximate and Ultimate Analysis of Corn Cob

Appendix A

Proximate and Ultimate Analysis of Corn Cob

Table 7 Compositions of Corn Cob from Proximate and Ultimate Analysis. Tested and reported by the Department of Science Service, Bangkok on 23 June 2004.

Proximate Analysis		Ultimate Analysis	
Description	Weight %	Description	Weight %
Moisture	12.1	Carbon	41.4
Volatile Matter	68.2	Hydrogen	6.4
Fixed Carbon	17.8	Oxygen	44.6
Ash	2.2	Nitrogen	0.29
Calorific Value, kcal/kg	3605	Sulphur	0.08
		Ash	1.9

Appendix B

Equilibrium Model in the Reactor

Appendix B

Equilibrium Model in the Reactor

To understand the parameters affecting the performance of the system is important for the design and operation of a gasifier set. An equilibrium model is used in this case as all the reactions are in thermodynamic equilibrium. The pyrolysis production burns and achieves equilibrium in the reduction zone before leaving the reactor the reactions are as follows:

$C + CO_2 = 2CO$ (1)

$C + H_2O = CO + H_2$ (2)

$C + 2H_2 = CH_4$ (3)

$CO + H_2O = CO_2 + H_2$ [shift reaction from (1) and (2)] (4)

The model comprises sets of linear and non-linear equations of chemical species conservation. According to designed analysis, corn cob consists of Carbon (C), Hydrogen (H), Nitrogen (N), Oxygen (O), Sulphur (S) and ash. However, nitrogen and sulphur proportion is corn cob is considerably low, less than 1%. Therefore, C-H-O basis is usually given. In this research, the compositions of corn cob for C,H,N,O,S, ash are 41.4%, 6.4%, 0.29%, 49.9%, 0.08% and 1.9% respectively. Thus an empirical formula of corn cob can be written from this consideration.

One kg of corn cob contains:

Carbon	= (414/12.0107)	= 34.47 Mole
Hydrogen	= (64/1.00794)	= 63.50 Mole
Oxygen	= (446/15.9994)	= 27.88 Mole
Nitrogen	= (29/14.0067)	= 2.07 Mole
Sulphur	= (0.08/32.064)	= 0.0025 Mole

C: (34.47/34.47) = 1

H: (63.50/34.47) = 1.84

O: (27.88/34.47) = 0.81

N: (2.07/34.47) = 0.0601

S: (0.0025/34.47) = 0.000073

Therefore, an empirical formula of corn cob based on a single atom of carbon should be $CH_{1.84}O_{0.81}N_{0.0601}S_{0.000073}$. As can be seen that N and S are not significant so an empirical formula can be $CH_{1.84}O_{0.81}$. The global gasification reaction can be written as follows:

$$CH_{1.84}O_{0.81}+wH_2O+mO_2+3.76mN_2 = x_1H_2+x_2CO+x_3CO_2+x_4H_2O+x_5CH_4+3.76N_2 \qquad (5)$$

Where w is the amount of water per kmol of corn cob, m is the amount of oxygen needed per kmol of corn cob, x_1, x_2, x_3, x_4 and x_5 represent the coefficients of constituents of the products. For the known moisture content (MC, %), w can be calculate from the following equation:

$$w = (24.47)MC / [18(1-MC)] \qquad (6)$$

From equation (5), there are six unknowns, hence the equations of carbon balance, hydrogen balance, oxygen balance, equilibrium constant from methane formation, equilibrium constant from shift reaction and heat balance equation should be untilized to solve the unknowns.

Carbon balance:

$$1 - x_2 - x_3 - x_5 = 0 \qquad (7)$$

Hydrogen balance:

$$2w + 1.8 - 2x_1 - 2x_4 - 4x_5 = 0 \qquad (8)$$

Oxygen balance:

$$w + 0.81 + 2m - x_2 - 2x_3 - x_4 = 0 \qquad (9)$$

Equilibrium constant from methane formation:

$$K_1 = \frac{P_{CH_4}}{(P_{H_2})^2} \tag{10}$$

$$K_1(x_1)^2 - x_5 = 0 \tag{11}$$

Equilibrium constant from shift reaction:

$$K_2 = \frac{P_{CO_2}P_{H_2}}{P_{CO}P_{H_2O}} \tag{12}$$

$$K_2(x_2x_4) - x_1x_3 = 0 \tag{13}$$

The process is assumed to be adiabatic, the heat balance equation for the gasification process is :

$$\begin{aligned} H^0_{f,corncob} + w(H^0_{f,H_2O(l)} + H_{fg}) + mH^o_{f,o_2} + 3.76mH^0_{f,N_2} &= x_1H^0_{f,H_2} + x_2H^0_{f,CO} \\ &+ x_3H^0_{f,CO_2} + x_4H^0_{f,H_2O(g)} + x_5H^0_{f,CH_4} + (T_2 - T_1)(x_1C_{p,H_2} + x_2C_{p,CO} \\ &+ x_3C_{p,CO_2} + x_4C_{p,H_2O} + x_5C_{p,CH_4} + 3.76mC_{p,N_2}) \end{aligned} \tag{14}$$

Whereas T_1 is the ambient temperature and T_2 is the gasification temperature in the reduction zone. Cp is the specific heat of substances. The formation of $CH_{1.84}O_{0.81}$ is given as the following:

$C + O_2 \text{ --> } CO_2$ $\Delta H_C = -393509$ (15)

$0.92H_2 + 0.46O_2 \text{ --> } 0.92\ H_2O$ $\Delta H_C = (0.92)(-241818)$ (16)

$CO_2 + 0.92H_2O \text{ --> } CH_{1.84}\ O_{0.81} + 1.055\ O_2$ $\Delta H_C = 501787$ (17)

$C(S) + 0.92H_{2(g)} + 0.405O_{2(g)} \text{ --> } CH_{1.84}O_{0.81}$ $\Delta H_f = -115345$ (18)

The heat formation of corn cob is -115345 kJ/kmol. Thus the heat formation for any biomass material can be determined if the ultimate analysis and the heating value of the material are known. The heating formation of any biomass material can be calculated with good accuracy from the following:

ΔH_c = HHV (kJ/kmol) = 0.3491C + 1.1783H + 0.1005S - 0.10340O
- 0.0151N - 0.00211A (19)

Where C, H, S, O, N and A are the percentage of carbon, hydrogen, Sulphur, oxygen, nitrogen and ash contents in biomass.

The specific heat is depend on the temperature of substances. It can be calculated from the following equation.

$$C_p = R\,[A + BT_{ave} + \frac{C}{3}(4T_{avg}^2 - T_1T_2) + \frac{D}{T_1T_2}] \qquad (20)$$

Where R is the universal gas constant, 8.341 kJ/kmol.K , $T_{avg}=(T_1+T_2)/2$ and A,B,C and D are the constants for the properties of the gases concerned which expressed in the following table.

Table 8 Heat Capacities (constants A, B, C and D).

Formula	A	10^3B	10^6C	10^{-5}D
CH4	1.702	9.081	-2.164	0
H2	3.249	0.422	0	0.083
CO	3.376	0.557	0	-0.031
CO2	5.457	1.047	0	-1.157
N2	3.280	0.593	0	0.040
H2O	3.470	1.450	0	0.121
C	1.771	0.771	0	-1.867

The general equation for $\ln(K_1)$ is given by

$$\ln(K_1) = \left[\frac{7082.848}{T} - 6.567\ln T + \frac{7.466}{2000}T - \frac{2.164}{6(10^6)}T^2 + \frac{0.701}{2(10^5)T^2} + 32.541\right] \quad (21)$$

$$\ln(K_2) = \left[\frac{5870.53}{T} + 1.86\ln T - 2.7(10^4)T - \frac{58200}{T^2} - 18.007\right] \quad (22)$$

The set of equations can be solved using the following algorithm:

1. Specified T_2 and MC, calculate w
2. Calculate K_1 and K_2 and HHV
3. Assume x_1, using equation (7)-(14) which were combined to be function of x_1. Solving by Newton-Ralphson method.
4. Repeat the above steps until successive value of all x becomes constant.

Appendix C

Calculation of Air Flow Rate into a Reactor

Appendix C

Calculation of Air Flow Rate into a Reactor

The diameter of pipe is 1.5 inches (0.0381 m). Thus the cross sectional area is

$$A = \frac{22}{7} x (0.0381/2)^2$$

$$A = 1.14 x 10^{-3} \quad m^3$$

Air flow rate $\dot{m} = \rho V A$ (1)

At 310 K, $\rho = 1.19468 \quad kg/m^3$

Air velocity is 4 m/s. Substitute value to (1). Thus the mass flow rate of air should be

$$\dot{m} = 5.44 x 10^{-3} \quad kg/s$$

Appendix D

Solving for Gas Heating Value

Appendix D

Solving for Gas Heating Value

HHV of 25°C, 1 atm.

$$CO = 11.77 \quad MJ/m^3$$
$$H_2 = 11.80 \quad MJ/m^3$$

Therefore,

Heating value of procedure gas

$$= \%CO\,(11.77) + \%H_2\,(11.80)$$
$$= 0.193\,(11.77) + 0.074\,(11.80)$$
$$= 2.271614 + 0.8732$$
$$\text{HHV} = 3.14 \quad MJ/m^3$$

LHV of 25OC, 1 atm

$$CO = 11.77 \quad MJ/m^3$$
$$H_2 = 11.06 \quad MJ/m^3$$

Thus

$$\text{LHV} = \%CO\,(11.77) + \%H_2\,(11.06)$$
$$= 0.193\,(11.77) + 0.074\,(11.06)$$
$$= 2.27161 + 0.81844$$
$$\text{LHV} = 3.09 \quad MJ/m^3$$

Available heat from gas

The heat made available from the gas per unit height of carbon gasified can be calculated as follows:

Available heat from gas = heating value x gas yield

$$= 3.14 \;\frac{MJ}{m^3}\; x\; 1.8 \;\frac{m^3}{kg\ C}$$

= 5.652 MJ / kg C

It can be written as 314 MJ from 60 kg of corn cob or 39.25 MJ/hr.

Gas yield per unit weight of carbon gasified

The producer gas flow rate was 12.5 m^3/h and the working time of the gasification process was 8 hours, hence the producer gas, which was generated from 60 kg of corn cob was 100 m^3.

Therefore,

$$\text{Gas yield} = \frac{100 \times 100}{12\,(\%CO + \%CO_2 + \%H_2}$$

$$= \frac{100 \times 100}{12\,(19.3 + 18.5 + 7.4)}$$

$$= \frac{1000}{542.4}$$

$$= 1.8 \quad m^3 / \text{kg C}$$

Calculation of the air-fuel ratio

At air flow rate of 5.44 x 10^{-3} kg/s, the gas composition by average are CO=19.3%, CO_2=18.5%, H_2 = 7.4%, O_2 = 1.52%, N_2 = 82.9%

Combustion Equation

$$CO + 0.5\,O_2 \longrightarrow CO_2$$

$$CH_4 + 2\,O_2 \longrightarrow CO_2 + 2\,H_2O$$

$$H_2 + 0.5\,O_2 \longrightarrow H_2O$$

Air by theory for 1 mole to burn 1 mole of producer gas can be calculated from Table 9.

Table 9 The Calculation for Air to Burn Producer Gas.

Producer Gas	mole	O_2, mole	Flu Gas mole		
			CO_2	H_2O	N_2
CO	0.193	0.193 x 0.5	0.193x1	-	0.193x1.88
H_2	0.0074	0.0074x0.5	-	0.0074x1	0.0004x1.88
O_2	0.0152	-0.0152	-	-	0.078x3.76
N2	0.72	-	-	-	0.72
Total	1	0.085	0.193	0.0074	1.376

Producer gas 1 mole needs 0.085 mole of oxygen. Air 1 mole comprises O_2= 0.21 mole.

Air = 0.085/0.21 = 0.405 mole

Producer gas 1 mole needs air to combust = 0.405 mole

= 0.405 mole air / mole fuel

= 0.405 m^3 air/m^3 fuel

1 mole of producer gas generates 1.576 mole of flue gas.

The flue gas composition should be:

$\%CO_2$ = 0.193/1.576 = 12.25 %

$\%H_2O$ = 0.0074/1.576 = 0.47 %

$\%N_2$ = 1.376/1.576 = 87.30 %

Appendix E

Gasifier Efficiency

Appendix E

Gasifier Efficiency

An important factor determining the actual technical operation as well as the economic feasibility of using a gasifier system is the gasification efficiency. A use ful definition of the gasification efficiency is

$$\eta_G = \frac{H_g x Q_g}{H_f x M_f} x100(\%)$$

In which

η_G = gasification efficiency, (%)

H_g = heating value of the gas, (MJ/m^3)

Q_g = Volume flow of gas, (m3/h)

H_f = lower heating value of gasifier fuel, (MJ/kg)

M_f = gasifier solid fuel consumption, (kg/h)

Heating value of corn cob is 3605 kcal/kg = 15.1 MJ/kg

Thus $$\eta_G = \frac{3.14\, x\, 12.5}{15.1\, x\, 7.5} = \frac{39.25}{113.25} = 0.3466$$

$$\eta_G = 34.7 \quad \%$$

Appendix F

Necessary Parameters for Solar Dryer Design

Appendix F

Necessary Parameters for Solar Dryer Design

1. Air flow rate

To reduce the moisture content of 20 kg chillies from 370%db to be 7%db at 35^{o}C of ambient temperature with 52.5% of relative humidity and 2.4 MJ/kg of latent heat. From the following equation, day matter or chillies can be calculated:

$$M_d = \frac{w-d}{d}$$

M_d= 3.7, w = 20, Thus d = 20/(3.7+1) = 4.25 kg then dried chillies should be 4.25 kg. The moisture content of 7% db is needed hence the final weight of chillies should be as follows:

$$w = (M_d + 1)d$$

M_d = 0.07 and d = 4.25 kg then

$$w = (0.07+1)\ 4.25 = 4.5475 \quad \text{kg}$$

The water should be evaporated for 20 – 4.55 = 15.45 kg. Assume that the temperature in the drying chamber is 70^{o}C and the outlet temperature is 45^{o}C.

From $$m_a = \frac{m_w h_{fg}}{C_P(T_{in} - T_{out})}$$

Where m_a = mass of air, kg

T_{in} = inlet temperature of air, ^{o}C

T_{out} = outlet temperature of air, ^{o}C

m_w = water evaporated, kg

h_{fg} = latent heat, kJ/kg (2400 kJ/kg)

Then $m_a = (15.45\ x\ 2400) / [1\ x\ (70 - 45)]$

$m_a = 1483.2$ kg

If 20 hours of the drying time is needed, the air flow rate will be

$$\dot{m} = \frac{1483.2}{(3600\ x\ 20)}$$

$$\dot{m} = 0.0206 \quad kg/s$$

2. Solar collector area

Assumption:

- Air mass flow is 0.0206 kg/s
- Temperature difference of air between inlet and outlet of a solar collector is 30^oC.
- The solar collector efficiency is 60%.
- Total solar radiation is 725 W/m^2

From $$m_a C_p (T_O - T_i) = \eta A_C G_T$$

Hence $$A_C = \frac{(0.0206\, kg/s \quad x\, 1000\, kJ^OC\, x\, 40^OC)}{(0.60\, x\, 725)}$$

$$A_C = 1.89 \approx 1.9\, m^2$$

Appendix G

Chemical Properties of Dried Chilli

Appendix G

Chemical Properties of Dried Chilli

The dried chillies from biomass/solar dryer were investigated for chemical properties by the laboratory of Department of Science Service, Ministry of Science and Technology. The results were shown in the following table.

Table 10 Chemical properties of dried chilli from the experiment
Tested and reported by the Department of Science Service, Bangkok on 23 June 2006.

Properties	Fixture of standard
1. Moisture content (percentage) not to exceed	7.96
2. All ashes (on dry basis), percent by weight not to exceed	5.18
3. Acid-insoluble ashes (on dry basis), percent by weight not to exceed	0.02
4. Non-volatile ether extract (on dry basis),percent by weight not to exceed	12.9
5. Crude fiber (on dry basis), percent not to exceed	39.1
6. Aflatoxins, µg/kg of samples not to exceed	Absent
7. Added Color	Absent, Paprika oleoresin (red chilli color) found

Appendix H

The Design of Biomass Gasifier

Appendix H

The Design of Biomass Gasifier

In order for high capacity utilization of corn cob biomass gasifier, assume that total energy required from the reactor is 600 MJ in 10 hours. The reactor can be designed by various parameters as follows:

<u>Volume of reactor</u>

Working hour of the reactor is 10 hours with total energy required from the reactor was 600 MJ. Thus heat rate could be 60 MJ/Nm^3.

Assume that heating value of producer gas from corn cob is 4.0 MJ/Nm^3

Flow rate of producer gas	=	60/4
	=	15.0 Nm^3/h
	=	0.0043 Nm^3/s
1 kg of corn cob can produce producer gas	=	2.2 Nm^3
Hence, corn cob feed rate	=	15.0/2.2
	=	6.82 kg/h
Total corn cob consumption	=	6.82 x 10
	=	68 kg
Bulk density of corn cob	=	170 kg/m^3
Volume for total corn cob	=	68/170
	=	0.4 m^3
The diameter of hopper, d	=	$\{0.42 \times 2/(22/7)\}^{1/3}$
	=	0.63 m
Height of Hopper, h	=	1.26 m

<u>Size of Throat</u>

Producer gas flow rate	=	15.00 Nm^3/h
This reactor will be design to for Double Throat.		
Hearth load for down draft reactor	=	0.3 - 0.9 $Nm^3/h\text{-}cm^2$
Hearth Load	=	0.5 $Nm^3/h\text{-}cm^2$
Cross sectional area of Throat	=	15.00/0.5
	=	30 cm^2
Diameter of Throat	=	6.18 cm
Allow to be 20% for over design estimation	=	7.42 cm

<u>Nozzle Size</u>

Total corn cob consumption	=	68 kg
Corn cob 1 g needs 1.6 g of air (Equivalent Ratio = 0.255 approximate value of wood)		
	=	1.49 g Air/g corn cob
Total air required in combustion	=	68x1.49
	=	101.32 kg
Air flow rate	=	10.13 kg/h
Mass flow rate of air	=	0.0028 kg/s
The density of Air 30 ^{o}C, 1 atm	=	1.16 kg/m^3
Volumetric flow rate	=	0.0028/1.16
	=	0.0024 m^3/s
Air velocity to the combustion Zone	=	15-30 m/s
Set the air velocity to be	=	20 m/s
Area of air channel	=	0.0024/(1.16x20)
	=	1.03×10^{-4} m^2
Nozzles suppose to be 6	=	2.67×10^{-5}
Diameter of each Nozzle	=	2.34 mm
Allow to be 10% for over design estimation	=	2.57 mm

The distance between Nozzle and Throat

From the Design guideline of Imbert Gasifier

The distance between Nozzle – Throat = 0.5-1.4 Throat diameter

For small Gasifier (<50 kW)

The distance between Nozzle-Throat ≅ 1.2 Throat diameter

Thus, the distance between Nozzle-Throat = 7.42 cm

Reduction Zone Length

For small Gasifier (<50 kW)

Length of Reduction Zone ≅ 3x Throat diameter

Hence, Reduction Zone length = 22.26 cm

Size of Combustion Zone

The size of the combustion zone can effect to the temperature and quality of producer gas

The combustion zone size ≅ 2-4 x Throat diameter

Combustion Zone = 3 x Throat diameter

Hence, combustion zone size = 22.26 cm

Cyclone

The following data is needed for cyclone design.

- Producer gas inlet temperature to cyclone
- Producer gas flow rate to cyclone
- Producer gas velocity to cyclone

Producer gas flow rate = 15.00 Nm^3/hr

= 0.0043 Nm^3/s

Producer gas inlet temperature to cyclone = 200 ^oC (473 K)

From Ideal Gas Law

PV/T = Const.

Let P = Const.

Producer gas flow rate to cyclone, Q = 0.0043 x (473/303)

= 0.0027 m^3/s

The velocity of producer gas in cyclone, V = 15 m/s

$Q = VA$

Inlet cross sectional area of cyclone, $A = 0.0027/15$

$= 0.00018\ m^2$

Pipe size at the inlet area = 2x4 cm

Actual velocity of producer gas in the cyclone $= 0.0027/(2\times4\times10^{-4})$

$= 3.38$ m/s

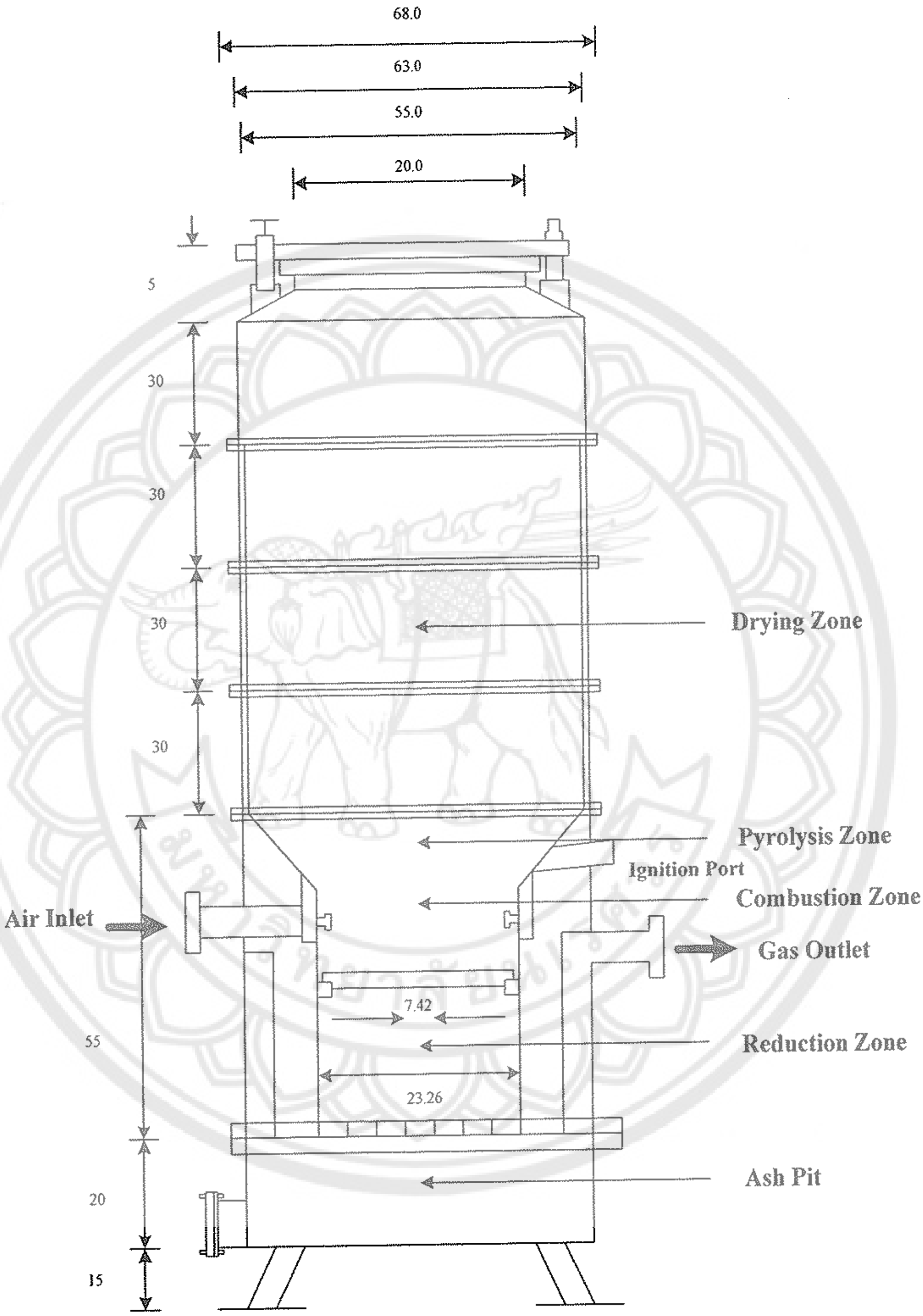

Figure 44 The Design of Corn Cob Down Draft Gasifier

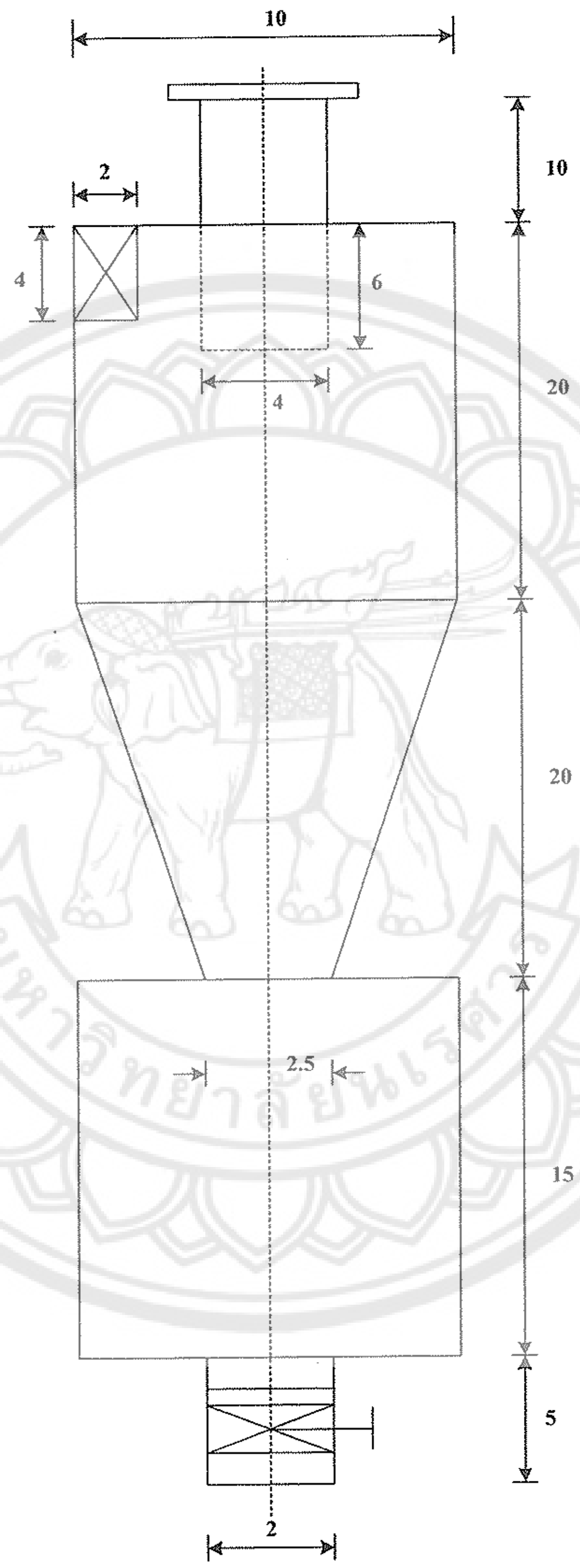

Figure 45 The Front View of a Cyclone (Unit in cm)

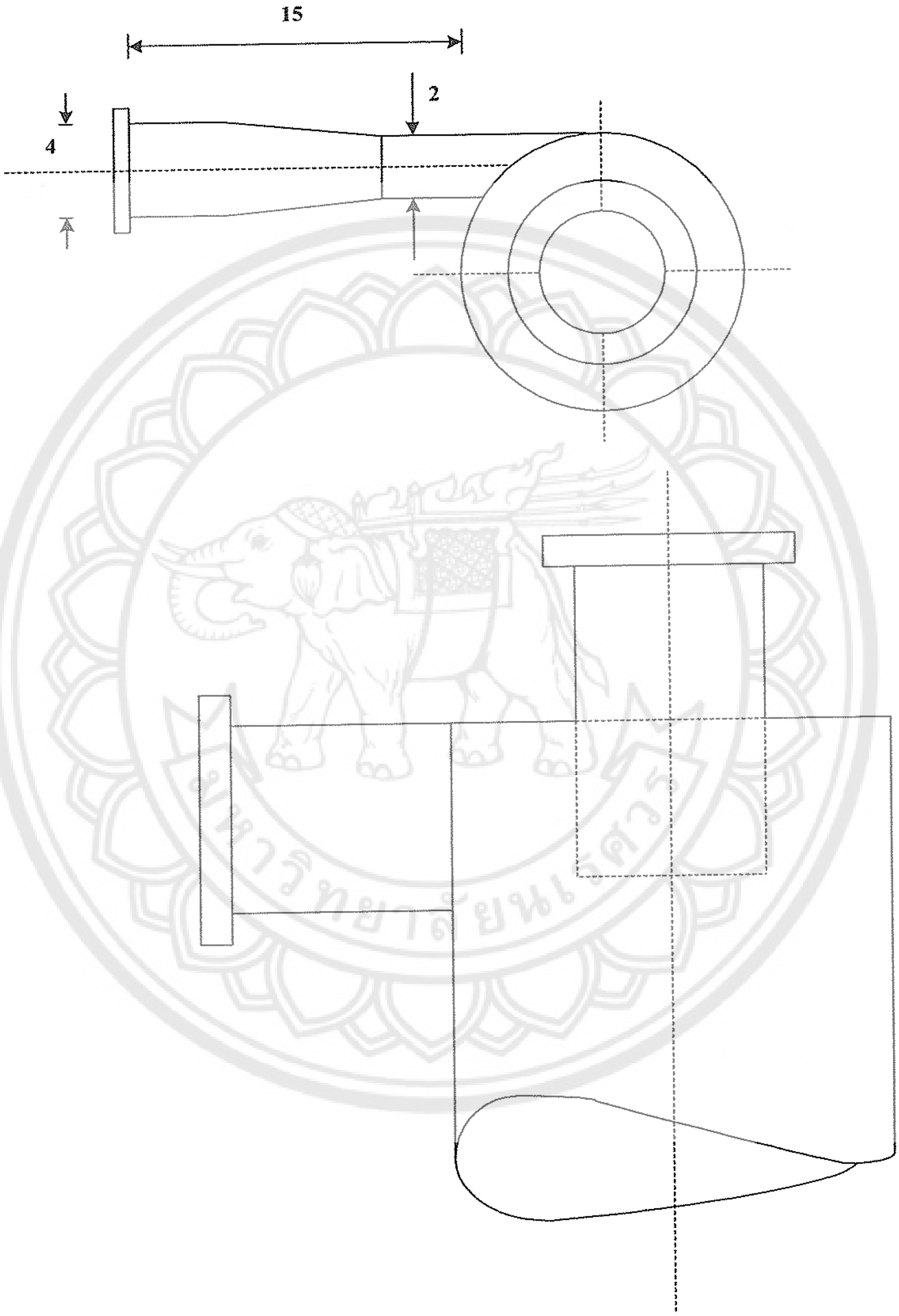

Figure 46 The Dimension of a Cyclone (Unit in cm)