# CHAPTER 3

# METHODOLOGY

The 400 kW electrical two-stage gasification system used for producing electricity at a pilot plant of this study consists of a feeding device, bubbling fluidized bed pyrolysis, downdraft gasifier, heat exchanger, cyclone, wet scrubber device and fabric filter device. For the 400 kW electrical two-stage gasification process, rice husks are fed into the bubbling fluidized bed pyrolysis unit by a screw conveyer. In the pyrolysis unit, the primary air is introduced and the volatiles escape from the rice husks at temperatures between 500-600°C. The char and the volatiles from pyrolysis unit fall through the high temperature (800-1100°C) partial oxidation zone directly into the fixed bed gasification chamber. Adding secondary air in a turbulent swirl causes the partial oxidation of the volatiles. In gas reduction, char is gasified in the downdraft gasifier into combustible gases that produced gas escapes at approximately 700-800°C. Ash falls at the bottom of char gasifier that has water to protect outside air. Since there is suction at the end of process, pressure in the reactor is lower than atmosphere. After the coarse particle removal in a cyclone, the produced gas is cooled in a heat exchanger. Then the remaining particles are removed in a wet scrubber and fabric filter respectively.

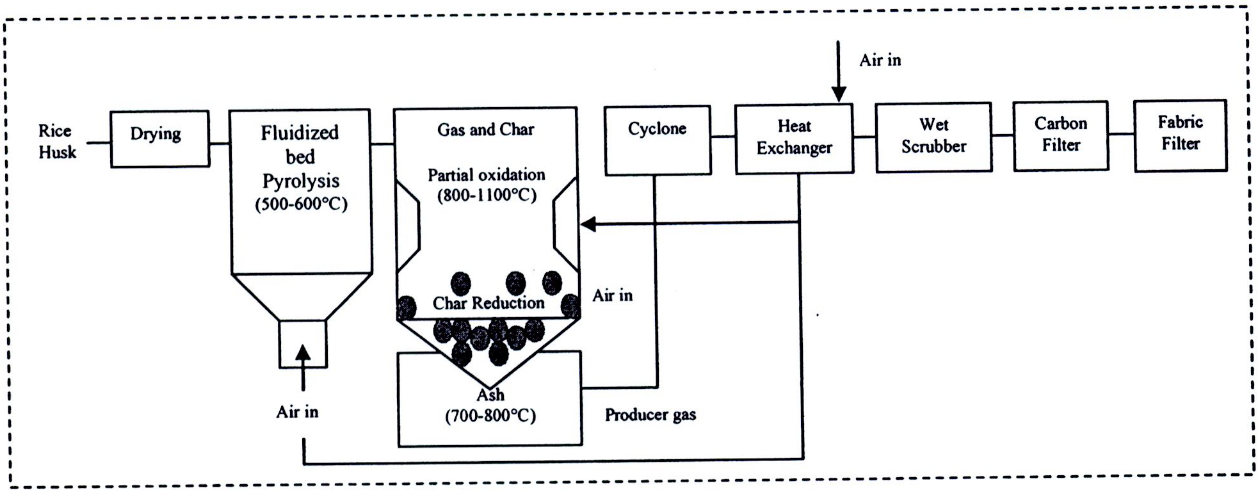


Figure 3.1 Schemetic layout of a 400 kW electrical two-stage gasification system.

The results of operations of the pilot plant could not easily cope with load changes as operating parameters have not been studied and tested in a lab-scale before. To support future development of this technology, this study will study design criteria of a lab-scale two-stage gasification system which is modified from the pilot plant to prepare a detail design of a small scale prototype for construction. A designed two-stage gasification system can cope with load changes and vary the parameters such as ER ratio and superficial velocity to achieve the optimum gas condition at different thermal outputs.

The designed 50 kW thermal two-stage gasification system consists of a feeding device, bubbling fluidized bed pyrolysis, downdraft gasifier, gas cooling and cleaning devices. According to a lab-scale, a wet scrubber was not designed in this study.

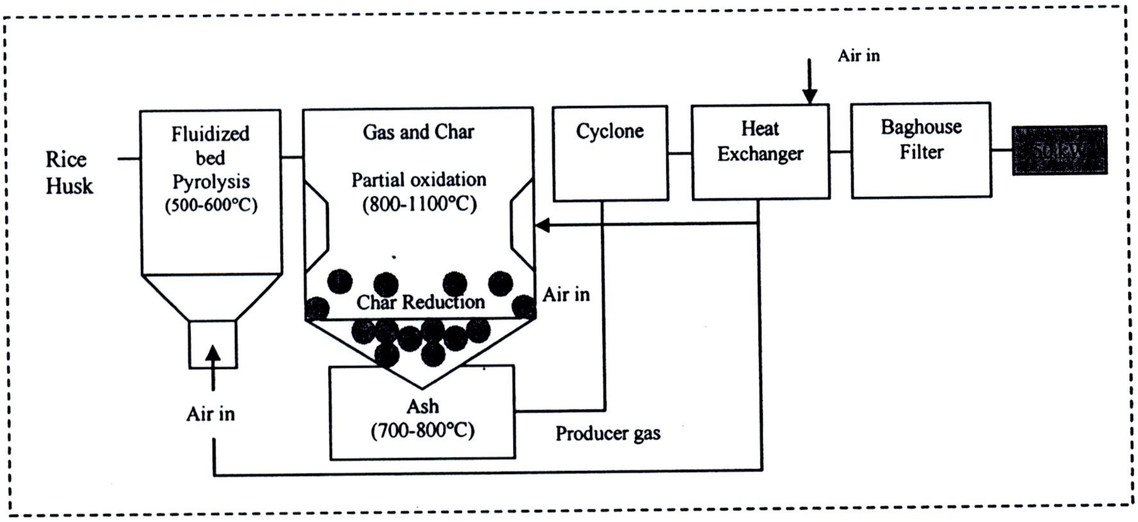


**Figure 3.2** Schemetic layout of a 50 kW thermal two-stage gasification system.

## 3.1 Raw Rice Husks Analysis

### 3.1.1 Biomass preparation

The type of biomass is used in this study is rice husks. The raw rice husks are milled into the particle size less than 75 μm for the experiments for the physical and chemical compositions analysis. The selected rice husks are dried in vacuum oven at 70°C for 24 hours before the experiments. The prepared rice husks are shown in Figure 3.3.

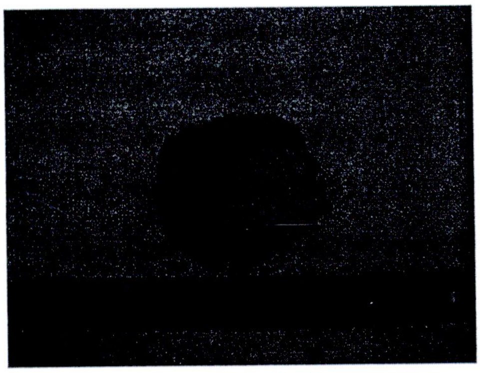


**Figure 3.3** Rice husk

### 3.1.2 Ultimate Analysis

The ultimate analysis gives the composition of rice husks in percent by weight (wt%) of carbon (C), hydrogen (H), oxygen (O), sulfur (S), and nitrogen (N). Dried ground rice husks were analyzed in the Organic Elemental Analysis (Thermo Finnigan Flash 1112 series) as shown in Figure 3.4. In this technique, a sample is burned in an excess of oxygen, and various traps collect the combustion products.

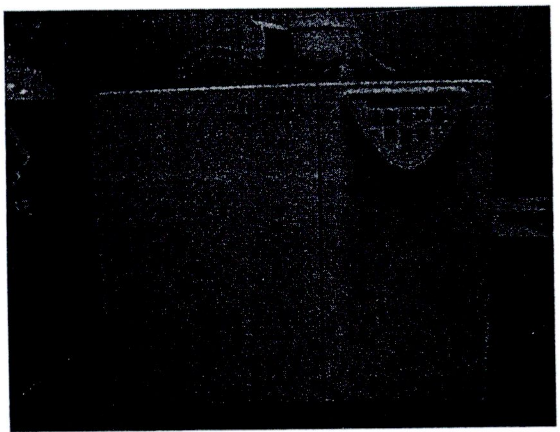


**Figure 3.4** Organic Elemental Analysis (Thermo Finnigan Flash 1112 series)

The percentages of C, H, N, S and O are important for determining the theoretical air requires for completing combustion and the amount of air required for gasification. They were also used for determining the higher heating value of the biomass.

### 3.1.3 Proximate Analysis

Proximate analysis gives moisture, volatile matter, fixed carbon and the ash content of the rice husks. The apparatus used in proximate analysis is a Thermal Gravimetric Analyzer (TGA). The test method, in which the mass of substance is heated at a controlled rate in an appropriate environment, is recorded as a function of time or temperature. The loss of mass over specific temperature range and in a specific atmosphere provided a compositional analysis of that substance.

The oven dried rice husks with particle sizes less than 75 µm about 5 mg is heated in a nitrogen stream from room temperature to 900°C in order to quantify moisture and volatile matter. At 900°C, the condition will be changed into an oxygen or air atmosphere in order to quantify fixed carbon from loss weight in oxygen atmosphere and ash from remaining solid. Figure 3.5 shows a schematic representation of TGA apparatus.

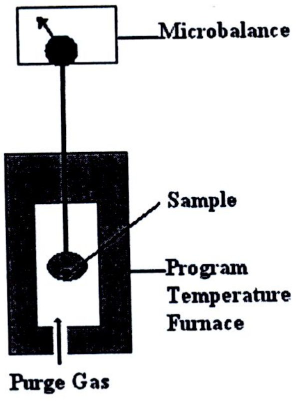


**Figure 3.5** A schematic representation of TGA system

### 3.1.4 Calorific Value Analysis

The calorific value of a sample is determined by burning the sample in a controlled environment. The heat released by combustion is proportional to the calorific value of the substance. The apparatus used in calorific value analysis is bomb calorimeter (LECO AC-350) as shown in Figure 3.6. In the bomb calorimeter, the sample being analysed is placed in a high pressure oxygen environment called a bomb. The bomb is surrounded by water and the sample is ignited. Then the temperature of the water is measured by an electronic thermometer. During analysis, the stirrer is rotated to control the uniform temperature.

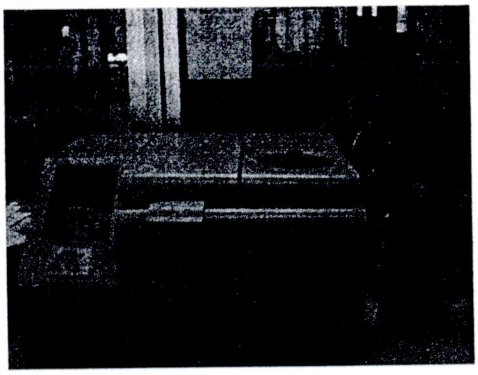


**Figure 3.6** Bomb calorimeter (LECO AC-350)

### 3.1.5 Ash Analysis

The ash content is a measure of the amount of minerals present within ash. For sample preparation, rice husks were combusted from room temperature to 575°C at the rate of 10°C/min for 8 hours. This rice husk ash was analyzed by wavelength dispersive x-ray fluorescence spectrometry method by Scientific and Technological Research Equipment Centre.

## 3.2 Minimum Fluidization Velocity Test

Minimum fluidization velocity, $U_{mf}$, is an essential factor for a bubbling fluidized bed reactor operation. If a superficial velocity in the reactor is set lower than the minimum fluidization velocity, the phenomenon is shown as a fixed bed reactor. For a bubbling fluidized bed operation, the superficial velocity must be set higher than the minimum fluidization velocity.

Superficial velocity, $U_s$, is defined as the volume flow of gas divided by the cross-sectional area of the reactor I. The minimum fluidization velocity test, ambient air was applied to the reactor under the distributor plate to investigate the relation between the pressure drop across the bed, ΔP, and the superficial velocity. The pressure drop in the bed was measured as the air's linear velocity increased progressively. The pressure drop increased with linear velocity going through a maximum. Thereafter, the pressure drop reached a more stable value. The minimum fluidization velocity was the velocity at which the pressure drop across the bed is constant.

The apparatus used to test the minimum fluidization velocity is shown in Figure 3.7. In the experiments, ambient air was fed by pump and the velocity was varied by a regulator valve, while the air velocity was measured by air flow – TA3 meter.

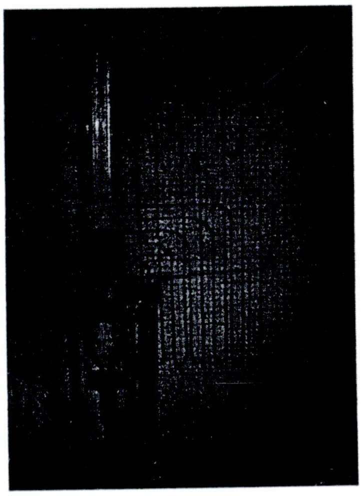


**Figure 3.7** minimum fluidization velocity test apparatus

### 3.3 Two-Stage Gasification System Equipment

The system consists of a feeding device, bubbling fluidized bed pyrolysis, downdraft gasifier, ash removal device, air supplied system, and gas cooling and cleaning devices.

### 3.3.1 Biomass Feeding System

The feed rate of biomass into the gasifier is controlled by the biomass feed system. The design of biomass feeding system involves type of feeder, average size of fuel particle, bulk density of fuel. The characteristic of rice husk is a bulk solid. A screw conveyor is suitable for rice husk feeding because screw is a bulk material handling device capable of handling a great variety of materials that have good flow abillity.

Screw conveyors are volumetric conveying devices. With each revolution of the screw, a fixed volume of material is discharged. The purpose of a screw conveyor is to transfer products from one point to the next. Screw conveyors are always control-fed at the inlet by another conveyor or metering device. Rotary valves, screw feeders, belt conveyors, grinders, or even other screw conveyors typically are connected to the inlet of a screw conveyor. Screw feeders are designed to volumetrically meter material from a hopper, bin or silo at a controlled rate. Many screw feeders utilize adjustable speed drives to allow for varying the material flowrate. There are certain parameters for sizing a screw feeder. The capacity calculation takes into account the outside diameter of the screw, the outside diameter of the pipe, the pitch of the screw and the trough loading. A cross-section of the screw conveyor is shown in Figure 3.8.

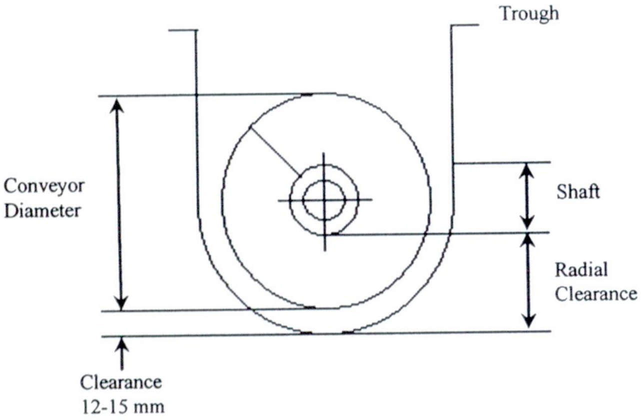


**Figure 3.8** A cross-section of screw conveyor

The design process of the screw is as follows:

1. Study the characteristics of rice husks, which are the bulk materials
2. Determine a cross-sectional loading area and the mass flow rate of the rice husks
3. Define the shaft diameter, speed of screw and pitch
4. Calculate the diameter of screw from Equation 3.1 as follows:

$$m_s = \frac{\rho\pi(D^2 - d^2)kpN}{4} \tag{3.1}$$

Where $m_s$= mass flow rate of material (kg/min)

ρ = density of material (kg/m$^3$)

D = diameter of screw (m)

d = diameter of shaft (m)

k = factor of trough loading

p = pitch of screw (m)

N = speed of the screw (rpm)

Factor of trough loading is based on the material being conveyed as follows:

- **Type 1:** light, free flowing and mildly abrasive materials such as wheat grain, rice, corn, graphite, wheat flour and others. Factor of trough loading is 0.45.
- **Type 2:** mildly abrasive materials, free flowing less than type 1 such as crushed corn and crushed coal. Factor of trough loading is 0.30.
- **Type 3:** flowing property is similar to type 2 such as dry ash, cement, salt, charcoal and others but moderately abrasive which needs low speed of the screw. Factor of trough loading is 0.30.
- **Type 4:** extremely abrasive and sluggish flow materials, such as coal ash, alumina, crushed bauxite, dry sand and others. Factor of trough loading is 0.15.

These factors of trough loading used for materials are for handling with screw conveyor along the level only.

### 3.3.2 Air Supplied System

There are two parts of air used for a two-stage gasification system. The primary air is supplied for bubbling fluidized bed at the pyrolysis stage. The secondary air is supplied from the air tuyers placed radially around the circumference of the partial oxidation region. Therefore the related parameters are the airflow of each part, the diameter and the amount of air tuyers. Size of diameter depends on air volumetric flow rate.

### 3.3.3 Gasifier

A two-stage gasifier consists of two parts. The first part is pyrolysis which is designed as a bubbling fluidized bed. The second part is partial oxidation of gas products from pyrolysis and char in the top and gas reduction in the bottom which is designed as downdraft gasifier. When rice husk is fed into the reactor, rice husk is overflown at the top of reactor after occurred reaction. Because density of rice husks is less than silica sand after occurred reaction.

#### 1) Pyrolysis Stage

The determining size of a fluidized bed reactor is a tentative method based on available information. This stage was mainly designed from the feed rate of rice husks. This stage was designed as a bubbling fluidized bed, the involved parameters needed to be considered were minimum fluidization and terminal settling velocity of bed particles, internal diameter and height of reaction chamber.

### Fluidization Velocity

The range of fluidizing velocity depends on the mean particle size of the bed particles. In the case of bubbling fluidized bed, fluidizing velocity should reside within the minimum fluidization from experimented previous and terminal settling velocities from calculations.

### The internal diameter

The internal diameter of the reactor column is divided into two parts; the lower and the upper part to cope with the varying of the superficial velocity. The calculation of the internal diameter is shown in the following steps:

1. Calculate $O_2$ required for rice husks
2. Calculate stoichiometric air required for gasification
3. Calculate air volume flow rate, covering ER ratio from 0.16 to 0.26
4. Separate air volume flow rate for the pyrolysis step
5. Fix the velocity range for bubbling fluidization
6. Calculate cross-sectional area (A):

$$A = \frac{V}{v}$$

Where
$V$ = air volume flow rate ($m^3/s$)
$v$ = air velocity (m/s)

7. Calculate the radius of reactor (r):

$$r = \sqrt{\frac{A}{\pi}}$$

8. Calculate the internal diameter (D):

$$D = 2 \times r$$

### Reactor Height

The height of the reactor is determined by the residence time for releasing the volatiles from the solid char which is considered from the review of the study of effect of pyrolysis reaction time on pyrolysis weight loss and then calculates the height of the reaction chamber from the volume of silica sand and rice husk in a control volume.

### 2) Char Gasifier Stage

In a downdraft gasifier with a throat, the gas is forced to pass through a constriction or a narrow part called throat of the gasifier. Due to the reduction in the area, the gas velocity increases and a temperature rises and become uniform in this zone where the oxidation zone is formed at the throat. The high and uniform temperatures help with better quality of producer gases from the gasifier in terms of higher CO and $H_2$ and also helps in thermal cracking and combustion of tar and the resultant gas has low tar and high calorific value. The related parameters are the internal diameter and the height of each part.

**The Internal Diameter**

There are two diameters: throat and reactor. The diameter of the throat refers to the volume of the produced gas. Diameter of reactor refers to the size of the reactor in terms of the diameter of the cross-section of the cylinder where char is being gasified. This is a function of the fuel mass flow rate ($m_s$) to the specific gasification rate (SGR) of rice husks. As shown below, the reactor diameter, which is in term of cross-sectional area, can be computed using the formula:

$$A = \frac{m_s}{SGR}$$

**Reactor Height**

The height of the char gasifier stage consists of two parts: above and beneath the throat. The important parameters to design the height of the char gasifier are the char bed height and the height between beneath the throat and char bed for reducing the temperature from approximately 1000 - 1100°C to less than 800°C to prevent ash melting. Determination of the char bed height was studied from the review of the influence of the char bed height of biomass on molar percentage of gaseous products, the calorific value of produced gas. Determination of the height between the beneath throat and grate was studied from the review of the relation of temperature and distance from.

### 3.3.4 Ash removal device

Rice husks contain a high percentage of ash when compared with other type of biomass and the ash produced in a gasifier also contains incompletely burned fuel in the form of char. Therefore the ash removal device must remove the char in any form. The ash filter grate is placed at the bottom of char gasifier that has water to protect outside air. A screw conveyor is selected for this part with the same reason of biomass feeding system and its ease for usability. The design process is similar to the design of screw conveyor for biomass feeding system but the round per minute of the screw is different.

### 3.3.5 Gas Cooling Device

A gas cooling device or a heat exchanger is a device that is used for transfer of thermal energy (enthalpy) between two or more fluids, between a solid surface and a fluid, or between solid particulates and a fluid, at differing temperatures and in thermal contact. A suitable type of gas cooling device for a small scale is firstly determined and the size that provides enough space for a produced gas is determined. Shell and tube heat exchanger is used in this system because of the numerous advantages. The advantages of shell and tube heat exchangers are:

- Fluids can be accommodated in either the tubes or the shell, and the orientation can be horizontal or vertical.
- The pressures and pressure drops can be varied over a wide range.
- There is substantial flexibility regarding materials of construction to accommodate corrosion and other concerns. The shell and the tubes can be made of different materials.
- Extended heat transfer surfaces (fins) can be used to enhance heat transfer.
- Cleaning and repair are relatively straightforward, because the equipment can be dismantled for this purpose.

Shell and tube heat exchanger consists of a series of tubes. One fluid flows inside the tubes, while the other fluid flows inside the shell. The major components of this heat exchanger, as shown in Figure 3.9, are tubes (tube bundle), shell, front-end head, rear-end head, baffles, and tube sheet.

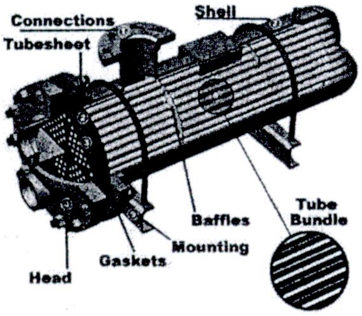


**Figure 3.9** The major components of shell and tube heat exchanger

In this study, there are 2 shell and tube heat exchangers. The first one is used for reducing temperatures from 600°C to around 250°C. And another one is used for reducing temperatures from 250°C to around 60°C to get rid of tar in the liquid phase that tar is condensed from vapor to liquid phase and flow out below through a small tube. Then cold cleaned gas is heated up from hot producer gas to vaporize some of the liquid prevents the fouling in the pipeline through a bigger tube. There are 2 parts: the upper and the lower part. The upper part is heat transfer of hot producer gas and cold producer gas. The lower part is heat transfer of air/water and hot producer gas. The components of the condensed tar heat exchanger is shown in Figure 3.10

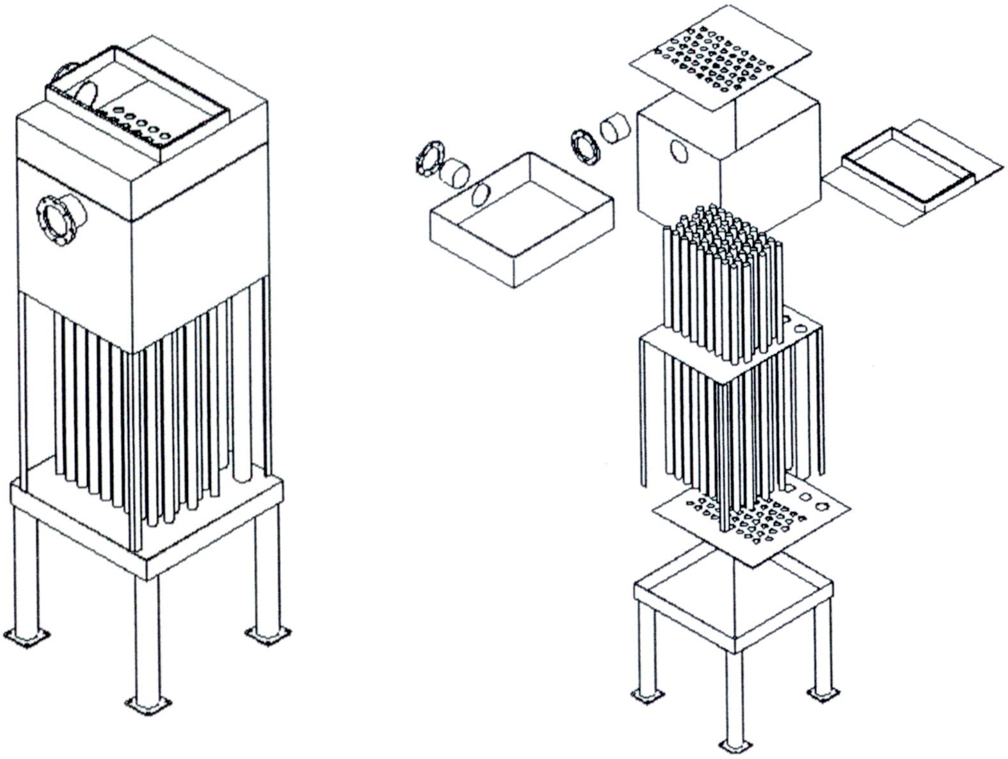


**Figure 3.10** The components of condensed tar heat exchanger

The design process is shown in the following steps:

- Consider outlet temperature of produce gas and air
- Calculate mass flow rate of air
- Estimate size
- Rating of shell and tube heat exchangers

### 3.3.6 Gas Cleaning Device

There are two gas cleaning devices: cyclone and baghouse filter. A cyclone is a simple device providing a high degree of separation for initial gas treatment using centrifugal force after gas cooling device. Baghouse filter is commonly used for particulate emission control, so it is placed in the last section.

**Cyclone**

When the stream of hot gas leaves the gasifier, it carries dust particles of ashes. The dust collection device used in this study is a cyclone. A cyclone has no moving parts in which the velocity of an inlet gas stream is transformed into a confined vortex. The gas is supplied tangentially in the cylindrical upper part of the cleaner. In the center of the cleaner is a driving pipe, the gas is first forced down into the cleaner, then sucked upward by this pipe. The dust separation from the gas stream takes place through centrifugal forces. The suspended particles tend to be driven to the wall of the cyclone and are collected in the ash bin at the bottom. The efficiency of a cyclone is highly dependent on the intake gas velocity. The principle of the cyclone is shown in Figure 3.11.

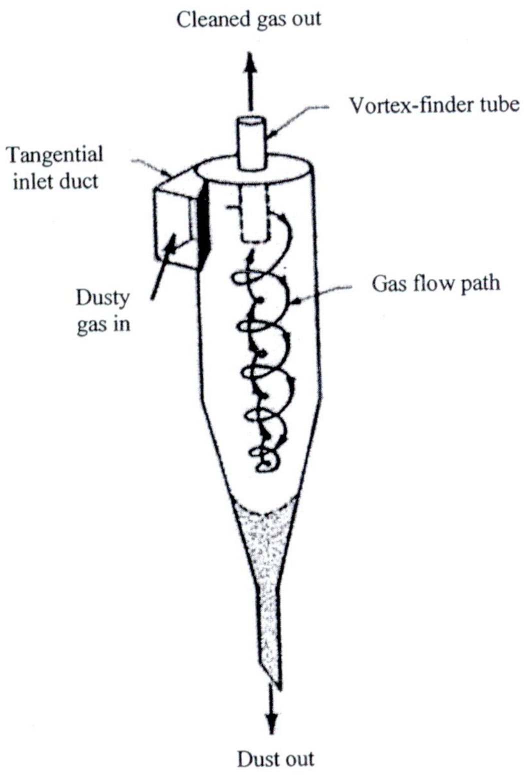


**Figure 3.11** Principle of the cyclone

Cyclones are usually designed with geometric similarity such that the ratios of the dimensions remain constant at different diameters, and these dimensions can be expressed in terms of the body diameter, $D_c$ as shown in Figure 3.12. The considered parameters are as follows:

**The Number of Effective Turns ($N_e$)**

The number of effective turns in a cyclone is the number of revolutions the gas spins while passing through the cyclone outer vortex. A higher number of turns of the air stream result in a higher collection efficiency. The Lapple model for $N_e$ calculation is as follows (Wang, 2004):

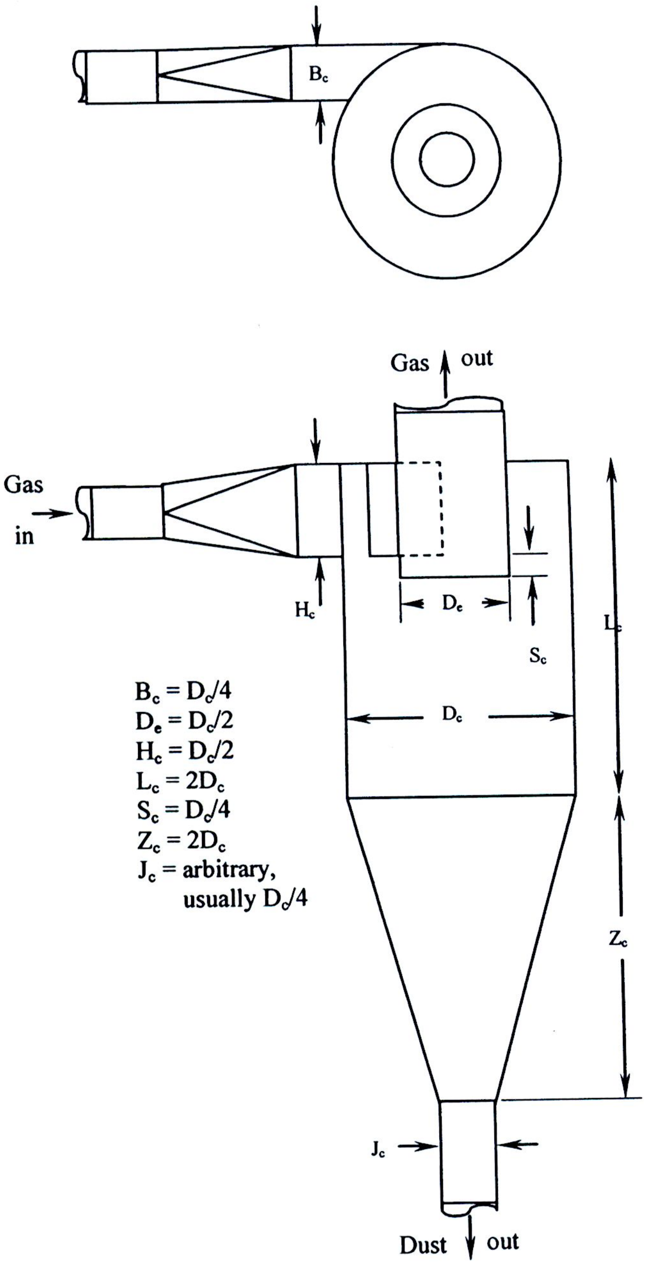
$$N_e = \frac{1}{H_c}\left[L_c + \frac{Z_c}{2}\right]$$

**Particle cut point ($d_{50}$)**

The cut-point of a cyclone is the aerodynamic equivalent diameter (AED) of the particle collected with 50% efficiency. As the cut-point diameter increases, the collection efficiency decreases. The Lapple cut-point model was developed based upon force balance theory. The Lapple model for cut-point ($d_{50}$) is as follows (Wang, 2004):

$$d_{50} = \left[\frac{9\mu B_c}{2\pi N_e V_i(\rho_p - \rho_g)}\right]^{1/2}$$

Where $\mu$ = viscosity of producer gas (kg/m·s)
$N_e$ = the Number of Effective Turns
$V_i$ = cyclone inlet velovity (m/s)
$\rho_p$ = density of solid (kg/m$^3$)
$\rho_g$ = density of producer gas (kg/m$^3$)



$B_c = D_c/4$
$D_e = D_c/2$
$H_c = D_c/2$
$L_c = 2D_c$
$S_c = D_c/4$
$Z_c = 2D_c$
$J_c$ = arbitrary,
usually $D_c/4$

**Figure 3.12** Standard cyclone dimensions (Reed and Das, 1988)

The design process of the cyclone is as follows:

1. calculate the gas flow rate through the cyclone
2. calculate the body diameter, $D_c$
3. calculate the dimension follow the standard cyclone dimensions as Figure 3.12
4. predict the cyclone pressure drop (Buonicore and Davis, 1992)

$$\Delta P = \frac{1}{2}\rho_g V_g^2 H_v$$

Where:
$\Delta P$ = pressure drop, Pa (N/m$^2$)
$\rho_g$ = gas density, kg/m$^3$
$V_g$ = gas velocity, m/s

**Baghouse filter**

Baghouse filter is used to capture fine dust particles and fly ash from combustion gases. A baghouse filter consists of one or more fibrous filter bags supported on metal cages enclosed in a chamber through which the gases must pass. A deposit of the separated particles soon builds up on the bag and establishes a dust cake of appropriate pore size through which additional particles cannot pass. As more dust is accumulated, the pressure drop increases. When the cake is an optimal thickness for removal, the bag is agitated either by gas pressure or by mechanical means, causing the excess cake to drop to the bottom of the housing where it is eventually removed.

The design process of the baghouse filter is as follows:

1. Select the filter material and determine the inlet temperature
2. Calculate the total cloth area ($A_c$)

$$A_c = \frac{Q}{v_f}$$

Where:
Q = volumetric air flow rate (cm$^3$/sec)
$v_f$ = filtration velocity (cm/sec)

3. Determine the amount of fabric required per bag ($A_b$)

$$A_b = \pi dh$$

Where:
d = the fabric bag diameter
h = the fabric bag height

4. Calculate the number of bags required in the baghouse

$$Number\ of\ bags = \frac{A_c}{A_b}$$