CHAPTER 3

METHODOLOGY

3.1 INTRODUCTION

Woody and cellulose plants capture solar energy and store it in a form that is readily utilized in gasifier stoves. The crop, if a perennial and diverse plant community, will grow and add organic matter and carbon to the soil in the form of yearly leaf drop and sympathetic life processes. The biomass, when harvested causes some root die-back adding more organic matter to the soil. Other ecological services; such as pollination, niche building, soil friability, fertility, bio-diversity also occur in the diverse crop planting, adding an important economic and ecological contribution to our social condition. Finally, the bio-char by-product of this energy system can be returned to the soil adding still more carbon that acts as an ecological catalyst, contributing significantly to the ecological services of the land. Theoretically, almost all kinds of biomass moisture content of 5-30% can be gasified however, not every biomass fuel can lead to the successful gasification (Foley and Barnard 1983). Most of the development work is carried out with common fuels such as coal, charcoal and wood as shown in Figures 3.1 and 3.2 (Appendix 6) as shown in Table A 6.1. It was recognized that fuel properties such as surface, size, shape as well as moisture content, volatile matter and carbon concentration influence gasification.

Charcoal is a product of wood carbonization (absence of air). By burning around 5 ton of firewood, 1 ton of charcoal is produced. Charcoal
offers twice as much as heat produced by wood. Energy lost during the conversion of wood to charcoal can be compensated by using efficient charcoal oven or cook stove. Unlike firewood, it burns slowly and does not produce any smoke.

Figure 3.1 Feeds used for the gasification

When biomass is burnt, CO₂ is released to the atmosphere. Released CO₂ is absorbed by growing plants during the photosynthesis, keeping CO₂ content in the atmosphere same. Biomass gasification is one of the technologies of energetic use of biomass (Frey et al 2005).

Figure 3.2 Biomass feed used in the work

Wood gasification is the process of heating wood in an oxygen-starved environment until volatile pyrolysis gases (carbon monoxide and hydrogen) are released from the wood. Depending on the final use of the typically low-energy wood (producer) gas (150 Btu/ft³) (5.6 MJ/m³), the gases
can be mixed with air or pure oxygen for complete combustion and the heat produced transferred to a boiler for energy distribution (Graboski and Bain 1979). Otherwise, the gases can be cooled, filtered, and purified to remove tars (a major concern for any wood gasification process) and particulates and used as fuel for internal combustion engines, micro turbines, and gas turbines.

Biomass gasification means incomplete combustion of biomass resulting in production of Combustible gases consisting of Carbon monoxide (CO), Hydrogen (H₂) and traces of Methane (CH₄). This mixture is called producer gas. Producer gas can be used to run internal combustion engines (both compression and spark ignition), can be used as substitute for furnace oil in direct heat applications and can be used to produce, in an economically viable way, methanol an extremely attractive chemical which is useful both as fuel for heat engines as well as chemical feedstock for industries. Since any biomass material can undergo gasification, this process is much more attractive than ethanol production or biogas where only selected biomass materials can produce the fuel. As wood contains high volatile matter, updraft gasifier system produce the gas containing tar, which need to be cleaned before using in engines. Cleaning of gas is difficult and labour Intensive process. Hence, wood is not suitable in updraft gasifier coupled with internal combustion engines.

Besides, there is a problem that solid wastes (available on the farm) are seldom in a form that can be readily utilized economically e.g. wood wastes can be used in hog fuel boiler but the equipment is expensive and energy recovery is low. As a result it is often advantageous to convert this waste into more readily usable fuel from like producer gas. Hence the attractiveness of gasification.
3.2 THEORY OF GASIFICATION

The production of generator gas (producer gas) called gasification, is partial combustion of solid fuel (biomass) and takes place at temperatures of about 600°C. The reactor is called a gasifier. The combustion products from complete combustion of biomass generally contain nitrogen, water vapor, carbon dioxide and surplus of oxygen. However in gasification where there is a surplus of solid fuel (incomplete combustion) the products of combustion are combustible gases like Carbon monoxide (CO), Hydrogen (H₂) and traces of Methane and non useful products like tar and dust as shown in Figure 3.3 and also reported in Tables A 7.1 and A 7.2 (Simons 2001). The production of these gases is by reaction of water vapor and carbon dioxide through a glowing layer of charcoal (Perry and Chilton 1973). Thus the key to gasifier design is to create conditions such that

i) Biomass is reduced to charcoal

ii) Charcoal is converted at suitable temperature to produce CO and H₂

![Figure 3.3 Product of gasification](image)
Since there is an interaction of air or oxygen and biomass in the gasifier, they are classified according to the way air or oxygen is introduced. There are three types of gasifiers Downdraft, Updraft and Cross draft (Kohan 1981). As the classification implies updraft gasifier has air passing through the biomass from bottom and the combustible gases come out from the top of the gasifier. Similarly in the downdraft gasifier the air is passed from the tuyers in the downdraft direction. With slight variation almost all the gasifiers fall in the above categories.

![Figure 3.4 Types of gasifiers](image)

### 3.3 TYPES OF GASIFIER

Fixed-bed gasifiers can be classified primarily as updraft and downdraft as shown in Figure 3.4. Updraft gasifiers represent the oldest and simplest gasifiers.
In the downdraft gasifiers there are two types:

a) Single throat

b) Double throat

Single throat gasifiers are mainly used for stationary applications whereas double throat are for varying loads as well as automotive purposes.

3.3.1 Downdraft Gasifier

In the updraft gasifier, gas leaves the gasifier with high tar vapor which may seriously interfere the operation of internal combustion engine. This problem is minimized in downdraft gasifier. In this type, air is introduced into downward flowing packed bed or solid fuels and gas is drawn off at the bottom as shown in Figure 3.5. A lower overall efficiency and difficulties in handling higher moisture and ash content are common problems in small downdraft gas producers (Mukunda et al 1994). The time (20-30 minutes) needed to ignite and bring plant to working temperature with good gas quality is shorter than updraft gas producer. This gasifier is preferred to updraft gasifier for internal combustion engine.

![Figure 3.5 Downdraft gasifier](image)

Removal of moisture
Crushing
CO\(_2=\) C+O\(_2\) Exothermic
CO\(_2\rightarrow\) CO Endothermic

Figure 3.5 Downdraft gasifier
The maximum dilution of gas takes place because of presence of nitrogen. Almost 50-60% of gas is composed of noncombustible nitrogen. Thus it may be beneficial to use oxygen instead of air for gasification. However the cost and availability of oxygen may be a limiting factor in this regard.

Advantage of this technology is decentralized energy conversion system, which operates economically even for small scale (Ravindran et al., 1995). A gasifier is a simple device consisting of usually cylindrical container with space for fuel, air inlet, gas exit and grate. It can be made of fire bricks, steel or concrete and oil barrels. The design of gasifier depends upon type of fuel used and whether gasifier is portable or stationary. Gasifier alone itself is of little use. The complete gasification system consists of gasification unit (gasifier), purification unit (scrubbers) and energy converter (burners or internal combustion engine).

3.4  GASIFICATION TECHNOLOGY

Gasification is quite complex thermo chemical process. Splitting of the gasifier into strictly separate zones is not realistic, but nevertheless conceptually essential. Gasification stages occur at the same time in different parts of gasifier. The various stages of gasification with the temperatures ranges are given in the Figure 3.6. (Higman and van der Burgt, 2003). The output from producer gas consists of CO, CO₂, H₂ and CH₄, the remaining are ash and some char (unburned carbon). The water is used for cooling and scrubbing of the gas coming from the gasifier. Almost all the impurities present in the gases are carried away by water. This causes the production of the waste water.
Figure 3.6 Representing the stages of gasification

Wastewater from gasification includes liquid discharges from gas cleaning and cooling, blow down and other boiler wastewater purification unit (scrubbers) and energy converter (burners or internal combustion engine) (Jared et al 2002).

3.4.1 The Gasification Process

Four distinct processes take place in a gasifier as the fuel makes its way to gasification. They are

a) Drying of fuel
b) Pyrolysis – a process in which tar and other volatiles are driven off
c) Combustion
d) Reduction
The following major reactions take place in combustion and reduction zone.

- **Combustion zone**

  The combustible substance of a solid fuel is usually composed of elements carbon, hydrogen and oxygen. In complete combustion carbon dioxide is obtained from carbon in fuel and water is obtained from the hydrogen, usually as steam. The combustion reaction is exothermic and yields a theoretical oxidation temperature of $1450^\circ$C. The main reactions are represented in equation 3.1 and 3.2 (Sanjay Gupta 2006).

  \[
  C + O_2 = CO_2 + 393 \text{ MJ/kg mole} \quad (3.1)
  \]

  \[
  2H_2 + O_2 = 2H_2 O - 242 \text{ MJ/kg mole} \quad (3.2)
  \]

- **Reduction zone**

  The products of partial combustion (water, carbon dioxide and uncompensated partially cracked pyrolysis products) now pass through a red-hot charcoal bed where the reduction reactions represented in equations 3.3-3.7 take place (Mon and Amundson 1978).

  \[
  C + CO_2 = 2CO - 164.9 \text{ MJ/kg mole} \quad (3.3)
  \]

  \[
  C + H_2O = CO + H_2 - 122.6 \text{ MJ/kg mole} \quad (3.4)
  \]

  \[
  CO + H_2O = CO + H_2 + 42 \text{ MJ/kg mole} \quad (3.5)
  \]

  \[
  C + 2H_2 = CH_4 + 75 \text{ MJ/kg mole} \quad (3.6)
  \]

  \[
  CO_2 + H_2 = CO + H_2O - 42.3 \text{ MJ/kg mole} \quad (3.7)
  \]

  Equations (3.3) and (3.4) are main reduction reactions and being endothermic have the capability of reducing gas temperature. Consequently
the temperatures in the reduction zone are normally 800-1000°C. Lower the reduction zone temperature (~ 700-800°C) lower is the calorific value of gas.

- **Pyrolysis zone**

  Wood pyrolysis is an intricate process that is still not completely understood. The products depend upon temperature, pressure, residence time and heat losses. However the following conclusion can be drawn up to the temperature of 200°C only water is driven off. Between 200 to 280°C carbon dioxide, acetic acid and water are given off (Ravindran et al 1996). The real pyrolysis, which takes place between 280 to 500°C, produces large quantities of tar and gases containing carbon dioxide. Besides light tars, some methyl alcohol is also formed. Between 500 to 700°C the gas production is small and contains hydrogen (Higman and van der Burgt 2003).

### 3.4.1.1 Air gasification

Gasification takes place usually at 700-1000 °C. Fredriksson and Kjellstrom (1996) experimented in their cyclone gasifier with the gasification temperature and found that a minimum temperature of 800 °C was required for stable gasification (wall temperature above 600°C). The yield of products and operating temperature depends on the amount of oxidant added to the system. Values of the air excess ratio for gasification are usually between 0,2 and 0,4, being the optimum value about 0,25. If the air excess ratio is lower, the char will not be gasified and some energy will be retain in the wood as charcoal; if the air excess ratio is higher, then some of the gas will be burned and temperature will rise rapidly. Reed and Das (1988) and other investigators have observed that in a fixed bed, the equivalence ratio is self-controlled by having a constant bed height. This phenomenon has been experienced in this investigation. The ratio CO/CO₂ (or H₂/H₂O) is a measure of the producer gas quality. About the 30% of the biomass is burned to
provide energy for gasification of the rest. The amount of excess oxygen depends on the efficiency of the process that can be improved by insulation, drying of the biomass or air preheating (Reed and Das 1988). Wang and Kinoshita (1992) performed parametric tests for atmospheric nitrogen/oxygen gasification. They examined the effect of residence time, equivalence ratio, gasification temperature and steam injection on the gas yield, composition and heating value. Among their conclusions it is interesting to point that the concentrations of CO and H₂ were found smaller than theoretically predicted and still CO₂ and CH₄ yields were higher than predicted (Johnson 1973).

3.4.1.2 Steam gasification

The gasification process referred as “steam gasification” can use as a gasifying agent either only steam, a mixture air/steam, a mixture oxygen/steam, or others. A higher steam content of the gasifying agent results in an enhanced H₂ content of the product gas (Larson and Williams 1990). Pure steam gasification produces synthesis gas (syngas), that mainly contains hydrogen and carbon monoxide and that can be used for methanol production among other applications. However, the raw syngas also contains unwanted components like methane and tar that have to be removed in a conditioning process. For methanol production as well as for some fuel cell applications, the H₂/CO has to be adjusted to a certain value. These processes do always involve catalytic reactions and are slightly out of the scope of this work. The steam atmosphere enhances the reforming reactions and the char gasification reactions producing then lighter gases such as H₂, CO and CO₂ (Rapagnà and Foscolo 1996; Rapagnà and Latif 1997). On the other hand, since the steam gasification reactions are very endothermic, the heating rate diminishes and consequently, the formation of methane also decreases (Fredriksson and Kjellstrom 1996).
3.4.1.3 Oxygen gasification

The main consequence of having a nitrogen free gasification agent, and consequently also a nitrogen free product gas, is the considerable increase in the heating value (11.5 MJ/Nm$^3$) (Reed et al 1982). However, oxygen gasification is economically unattractive in the opinion of many. A possible alternative could be to use oxygen-enriched air, what could be less expensive and improve considerably the syngas quality. In some cases, oxygen is added in the steam gasification process to provide some energy for the endothermic reactions so the process is auto-thermal. However, in the opinion of Aznar et al (1993), this procedure is not recommended because the heating value of the product gas will diminish with oxygen addition.

3.5 CHARCOAL MANAGEMENT

After the gasification of the biomass in the reactor, approximately 8-10% of the charged material is collected in wet condition as residues in the form of unreacted charcoal and ash, out of which approximately 80% will be charcoal and 20% will be ash (Mahishi et al 2005). Normally this residue is collected in mixed slurry form. The ash will be in the form of slurry and charcoal in floating lightweight material. This charcoal should be separated from the ash by washing in the water. The cleaned charcoal to be dried in the sun and kept in gunny bags which can be used for the following

(a) For the primary charging fuel for firing of gasifier after shutdown/start up

(b) Activated carbon for purification of the raw water as a deodorant agent.

(c) Can be sold in the market for commercial use.
3.6 ASH HANDLING

During the operation of the gasifier, about 2 to 3% of the charged materials are collected as ash along with the charcoal. When segregating the charcoal, the ash dissolves in water and forms slurry. The slurry containing the ash can be filtered and kept for drying in the ash pit that can be provided near the charcoal dump. Since the ash is generated from the biomass, it can be used for organic forming. The same slurry can be utilized for in-house farming of energy plantation or gardening. The slurry form of the ash can be used as pest control device in and around the plant area.

Proper care should be taken while handling the ash. The ash pit should be kept closed and dry all the times. All safety appliances provided to be used at the time of handling the slurry. The few of other waste management in biomass gasification were given in Appendix 10.

3.7 COMPARISON OF GASIFIERS

The choice of the type of gasifier over others is dictated by the feed, its final available form, its size, moisture content and ash content. Table 3.1 lists the advantages and disadvantages of the various classes of gasifiers.

The producer gas is affected by various processes as outlined above hence one can expect variations in the gas produced from various biomass sources (Jenkins 1980). Table 3.2 lists the composition of gas produced from various sources. The gas composition is also a function of gasifier design and thus, the same fuel may give different calorific value as when used in two different gasifiers. Table 3.2 therefore show approximate values of gas from different fuels.
### Table 3.1 Advantages and disadvantages of various gasifiers

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Gasifier Type</th>
<th>Advantage</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Updraft</td>
<td>Small pressure drop - good thermal efficiency- low tendency towards slag formation</td>
<td>- sensitivity to tar and moisture content of fuel- relatively long time required for start up of IC engine- poor reaction capability with heavy gas loads</td>
</tr>
<tr>
<td>2</td>
<td>Downdraft</td>
<td>- Flexible adaptation of gas production to load- low sensitivity to charcoal dust and tar content of fuel</td>
<td>- Design tends to be tall- not feasible for very small particle size of fuel</td>
</tr>
<tr>
<td>3</td>
<td>Cross draft</td>
<td>- Short design height- very fast response time load- flexible gas load- flexible gas production</td>
<td>- Very high sensitivity to slag formation - high pressure drop</td>
</tr>
</tbody>
</table>

### Table 3.2 Composition of producer gas from various feed stocks

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Gasification method</th>
<th>Volume percentage</th>
<th>Calorific value MJ/m³</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>CO</td>
<td>H₂</td>
</tr>
<tr>
<td>Charcoal</td>
<td>Downdraft</td>
<td>28-31</td>
<td>5-10</td>
</tr>
<tr>
<td>Wood with 12-20% Moisture content</td>
<td>Downdraft</td>
<td>17-22</td>
<td>16-20</td>
</tr>
<tr>
<td>Coconut shells</td>
<td>Downdraft</td>
<td>19-24</td>
<td>10-15</td>
</tr>
<tr>
<td>Peat</td>
<td>Downdraft</td>
<td>30</td>
<td>19.7</td>
</tr>
<tr>
<td>Rice husks</td>
<td>Downdraft</td>
<td>15-21</td>
<td>5-6</td>
</tr>
</tbody>
</table>
The maximum dilution of gas takes place because of presence of nitrogen. Almost 50-60% of gas is composed of noncombustible nitrogen. Thus it may be beneficial to use oxygen instead of air for gasification. On an average 1 kg of biomass produces about 2.5 m$^3$ of producer gas at S.T.P. In this process it consumes about 1.5 m$^3$ of air for combustion. For complete combustion of wood about 4.5 m$^3$ of air is required. Thus biomass gasification consumes about 33% of theoretical Stoichiometric ratio for wood burning (Goss 1983).

### 3.8 TEMPERATURE OF THE SYNGAS

The temperature of gas coming out of gasifier is normally is 300-500°C. This gas has to be cooled in order to raise its energy density. Various types of cooling equipment have been used to achieve this end. Most coolers are gas to air heat exchangers where the cooling is done by free convection of air on the outside surface of heat exchanger. Since the gas also contains moisture and tar, some heat exchangers provide partial scrubbing of gas. Thus ideally the gas going to an internal combustion engine should be cooled to nearly ambient temperature (Dutta and Dutt 1981, Johansson 1980).

### 3.9 CLEANING METHODOLOGY

Cleaning of the gas is trickier and is very critical. Normally three types of filters are used in this process. They are classified as dry, moist and wet. In the dry category are cyclone filters. They are designed according to the rate of gas production and its dust content. The cyclone filters are useful for particle size of 5 μm and greater. Since 60-65% of the producer gas contains particles above 60 μm in size the cyclone filter is an excellent cleaning device (Manjunath et al 2004). After passing through cyclone filter the gas still contains fine dust, particles and tar. It is further cleaned by passing through either a wet scrubber or dry cloth filter.
In the wet scrubber the gas is washed by water in countercurrent mode. The scrubber also acts like a cooler, from where the gas goes to cloth or cork filter for final cleaning. Since cloth filter is a fine filter, any condensation of water on it stops the gas flow because of increase in pressure drop across it. Thus in quite a number of gasification systems the hot gases are passed through the cloth filter and then only do they go to the cooler. Since the gases are still above dew point, no condensation takes place in filter.

The mineral content in the fuel that remains in oxidized form after complete combustion is usually called ash. The ash content of a fuel and the ash composition has a major impact on trouble free operation of gasifier. Ash basically interferes with gasification process in two ways:

a) It fuses together to form slag and this clinker stops or inhibits the downward flow of Biomass feed.

b) Even if it does not fuse together it shelters the points in fuel where ignition is initiated and thus lowers the fuel’s reaction response.

Ash and tar removal are the two most important processes in gasification system for its smooth running. Various systems have been devised for ash removal (Ferrero et al 1989). In fact some fuels with high ash content can be easily gasified if elaborate ash removal system is installed in the gasifier. Slagging, however, can be overcome by two types of operation of gasifier

1) Low temperature operation that keeps the temperature well below the flow temperature of the ash.

2) High temperature operation that keeps the temperature above the melting point of ash.
The first method is usually accomplished by steam or water injection while the latter method requires provisions for tapping the molten slag out of the oxidation zone. Each method has its advantages and disadvantages and depends on specific fuel and gasifier design. Keeping in mind the above characteristics of fuel, only two fuels have been thoroughly tested and proven to be reliable. They are charcoal and wood. They were the principal fuels Charcoal, specifically, because of being tar free and having relatively low ash content property. However there is a major disadvantage of charcoal in terms of energy. Charcoal is mostly produced from wood and in conversion of wood to charcoal about 50% of original energy is lost. Besides with the present energy crisis where most countries do not have enough supply of wood it is advantageous and attractive to use agricultural residues. For the agricultural sector this is an extremely attractive alternative. Many agricultural residues and fuels have, therefore, been gasified. However the operating experience is very limited and most of the work has been on laboratory type.

3.10 COMPOSITION OF THE YIELD

To study the concept of the composition of the gas yield Gas chromatograph (GC) is used as shown in Figure A 12.6. Working of Gas chromatography is based on the chromatographic technique that can be used to separate organic compounds that are volatile. A gas chromatograph consists of a flowing mobile phase, an injection port, a separation column containing the stationary phase, a detector, and a data recording system. The organic compounds are separated due to differences in their partitioning behavior between the mobile gas phase and the stationary phase in the column (Appendix 1).

Gas chromatography (GC) is a method of separation which employs a gas mobile phase and either a solid (GSC) or a liquid (GLC)
adsorbed on a solid as a stationary phase. Gas chromatography is capable of separating very complex mixtures as shown in Figures A 12.7 and A 12.8 and the selectivity can be adjusted to separate almost any given pair of solutes by judicious choice of the stationary phase. The major limitation of gas chromatography is the requirement that the solute have a reasonable vapor pressure at a temperature where it is still stable.

The primary classification of chromatography is based on the physical nature of the mobile phase. The mobile phase can be a gas or a liquid which gives rise to the two basic forms of chromatography, namely, gas chromatography (GC) and liquid chromatography (LC). The stationary phase can also take two forms, solid and liquid, which provides two subgroups of GC and LC, namely; gas solid chromatography (GSC) and gas liquid chromatography (GLC), together with liquid solid chromatography (LSC) and liquid liquid chromatography (LLC). Most thin layer chromatography techniques are considered liquid-solid systems although the solute normally interacts with a liquid-like surface coating on the adsorbent or support or, in some cases an actual liquid coating although the solute normally interacts with a liquid-like surface coating on the adsorbent or support or, in some cases an actual liquid coating.

Mobile phases are generally inert gases such as helium, argon, or nitrogen. The injection port consists of a rubber septum through which a syringe needle is inserted to inject the sample. The injection port is maintained at a higher temperature than the boiling point of the least volatile component in the sample mixture. Since the partitioning behavior is dependant on temperature, the separation column is usually contained in a thermostat-controlled oven. Separating components with a wide range of boiling points is accomplished by starting at a low oven temperature and increasing the temperature over time to elute the high-boiling point
components. Most columns contain a liquid stationary phase on a solid support. Separation of low-molecular weight gases is accomplished with solid adsorbents. Separate documents describe some specific GC Columns and GC Detectors.

3.11 GAS FLOW MEASUREMENT

![Figure 3.7 Venturimeter]

A  – Inlet Section   E – Holes to piezometer chambers
B  – Throat Section  F – Upstream pressure tap
C  - Outlet Section  H – Linear
D, G – Piezometer Chambers  I – Downstream pressure tap

Figure 3.7 Venturimeter

It is desirable to know the materials entering and leaving the process. As the materials are transported in the form of fluids wherever possible, it is important to measure the rate at which a fluid is flowing through a pipe or other channel. Meters involving weighing or volume
measurement are simple. Most widely used instrument for the flow measurement is venturimeter. A venturimeter is shown the Figure 3.7, it is constructed from a flanged inlet section ‘A’, consisting of a short cylindrical portion and a truncated cone; a flanged throat section ‘B’; and flanged outlet section ‘C’, consisting of a long truncated cone. In the upstream section at the junction of the cylindrical and conical portion, an annular chamber ‘D’ is provided, and a number of small holes ‘E’ are drilled from the inside of the tube into the annular chamber. The annular ring and the small holes constitute a piezometer ring, which has the function of averaging the individual pressures transmitted through the several small holes. The average pressure is transmitted through the several small holes. The average pressure is transmitted through the upstream pressure connection ‘F’. A second piezometer ring is formed in the throat section by an integral annular chamber ‘G’ and a linear ‘H’. The linear is accurately bored and finished to a definite diameter, as the accuracy of the meter is reduced if the throat is not carefully machined to close tolerances. The throat pressure is transmitted through the pressure tap ‘I’. A manometer is connected to measure difference in pressure between the taps ‘F’ and ‘I’ (Tanaka 2004).

In the venturimeter, the velocity is increased, and the pressure decreased in the upstream cone. The pressure drop in the upstream cone is utilised to measure the rate of flow through the instrument. The velocity is then decreased, and the original pressure largely recovered in the downstream cone. To make the pressure recovery large, the angle of downstream cone ‘C’ is small, so boundary layer separation is prevented and friction is minimised. Since separation does not occur in a contracting cross section, the upstream cone can be made shorter than the downstream cone with but little friction, and space and material are there by conserved.
The rate of flow from the meter can be measured as (Appendix 2)

$$\Delta p_1 = \text{inference in the gas pressure at the venturimeter opening}$$

$$K = \text{venturimeter constant} = 7$$

Gas flow rate $g/s = k*\sqrt{\Delta p_1}$