CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

An extensive literature survey was done on fixed bed biomass gasification and its application to engine operation by referring to books, journals, and internet. The collected literatures may be broadly classified into those on:

a) modelling of gasification in fixed bed gasifiers,

b) changes in biomass properties during gasification,

c) gasification of wood pieces,

d) gasification of bioresidues,

e) producer gas (PG) cleaning prior to supply to engine, and

f) dual fuel (PG + diesel) operation of engine.

Even though under each category hundreds of research papers have been published, only certain salient works are highlighted here.

2.2 MODELLING OF GASIFICATION IN FIXED BED GASIFIERS

Many papers deal with equilibrium modelling and kinetic modelling of gas-char reactions in the reduction zone of downdraft biomass
gasifier. Few papers report overall modelling of biomass gasification processes involving drying, pyrolysis, oxidation, and reduction.

Many reactions that occur in coal gasification also occur in biomass gasification. Due to certain commonalities between them, some literatures on coal gasification are also useful in modelling biomass gasification. The various reactions involving coal, char, and other solid fossil fuels have been dealt in a classic book written by Smoot and Smith (1985). Some important chemical mechanisms for H\textsubscript{2}-O\textsubscript{2} system, carbon monoxide oxidation, oxidation of higher paraffins, and methane combustion are available in the book authored by Turns (2000).

By steady state modelling of gas-char reactions, Giltrap et al., (2003) predicted the PG with a composition similar to that found experimentally. The accuracy of the model was limited by the availability of data corresponding to initial condition at the top of reduction zone. They suggested that the model could be improved by a) applying more data at the top of reduction region, b) relating the amount of pyrolysis products produced with temperature, and c) taking into account the variation of char reactivity along the height of gasifier bed.

The model used by Jayah et al., (2003) consisted of two sub-models, namely Milligan’s (1994) flaming pyrolysis zone model and Chen’s (1987) gasification zone model. The flaming pyrolysis zone sub-model was used to determine the maximum temperature and the product concentration of gas leaving that zone. The gasification zone sub-model assumed that a single char particle moved vertically downwards the gasifier.

Sharma (2008) reported that CO and H\textsubscript{2} components of PG and the calorific value are sensitive to reaction temperature. By kinetic modelling, it was found that complete char conversion takes place at a critical reaction
temperature of 950 K and critical char bed length of 25 cm. The results obtained by modelling were influenced by the composition of reactants entering the reduction zone and the initial temperature.

Tinaut et al., (2008) developed a one dimensional stationary model of biomass gasification. The temperature profiles were compared with the experimental results obtained during the operation of a small-scale inverted moving bed downdraft gasifier having air entry at the bottom. The propagation velocity of the reaction through biomass bed was estimated from the experimental results.

2.3 CHANGES IN BIOMASS PROPERTIES DURING GASIFICATION

Raveendran (1995) studied the effect of biomass composition on pyrolysis products and concluded that silica has no detectable influence on pyrolysis product distribution. But, potassium and zinc were found to have pronounced effect on biomass pyrolysis.

According to Di Blasi (1997), the physico-chemical properties of biomass depend on the type of biomass feedstock. For instance, density might vary from 70 kg/m$^3$ to 1200 kg/m$^3$. It was reported that permeability to gas flow and thermal conductivity of the bed not only vary with woody and fibrous biomass, but also with biomass of similar species. In gasifiers and pyrolysers, temperatures high enough for reaction to start were found to be reached within a short time.

Peters et al., (2002) measured the heat-up and the drying of a packed bed consisting of large wood particles and compared the predictions of a particle resolved approach to measurements.
Biagini et al., (2002) stressed that proper gasification equipment design requires the knowledge of reaction mechanisms, devolatilization rate, reaction kinetics, etc. during gasification. Biomass was found to have very high devolatilization rate when compared to coal.

Bellais et al., (2003) determined that the longitudinal shrinkage of char increases with temperature and approaches approximately 22 % whereas the radial and tangential shrinkages are up to 40 % depending on temperature and heating rate.

Bryden and Hagge (2003) interpreted that the pyrolysis process could be separated into three separate regimes based on particle thickness and moisture content as a) thermally thin, b) thermally thick, and c) thermal wave regimes. In thermally thin regime, temperature was nearly constant across the particle. In thermally thick regime, there were significant temperature gradients, but reaction rate was slow relative to heat transfer rate and the reaction region extended throughout the particle. In thermal wave regime, wet unreacted wood, pyrolysis zone, and char existed simultaneously. The drying and pyrolysis regions travelled through the particle like a wave.

Gupta et al., (2003) found the specific heat of softwood (spruce wood) as 1172 J/kg·K at 313 K. When temperature was increased, the specific heat also got increased. The particle thermal conductivity for softwood was 0.0986 – 0.1114 W/m·K at 310 – 341 K. When temperature was increased, the particle thermal conductivity also got increased.

In the case of oxygen gasification of combustible wastes, with an increase of bed height, the concentrations of H\textsubscript{2}, CO, and CH\textsubscript{4} were found to be increasing by Na et al., (2003). However, beyond a certain value of bed height, the gasification became difficult due to excessive pressure drop of oxygen.
Rath et al., (2003) probed the pyrolysis process and concluded that it is a two stage reaction with heat of pyrolysis being positive in the first stage and becomes negative later.

The decomposition during thermal treatment of selected biomass species was found by Strezov et al., (2004) to commence at around 150°C with a small endothermic reaction followed by primarily exothermic decomposition starting at 250°C. But, they reported the specific heats of biomass species to be approximately 2 - 2.5 kJ/kg·K.

Hanaoka et al., (2005) experimentally analysed the gasification of biomass components like cellulose, xylan, and lignin individually in a ceramic tubular downdraft gasifier using air and steam as gasifying agents. They suggested that the fundamental information which was obtained in the gasification of each component could possibly be used to predict the composition of PG generated in air-steam gasification of woody biomass.

The hydrogen production by steam gasification of woody biomass using CaO as CO₂ sorbent was probed by Hanaoka et al., (2005). They reported that maximum yield of hydrogen from wood is obtained at a pressure of 0.6 MPa which is lesser when compared to that of coal and heavy oil by steam gasification using a CO₂ sorbent.

Fujimoto et al., (2007) examined the product distribution at different reaction temperatures ranging from 473 to 923 K to obtain fundamental information on the biomass degradation during gasification. The kinetic constants of primary and secondary degradations were calculated from the product distribution.

Sreekanth et al., (2008) found that thermal diffusivity has noticeable influence on devolatilization time of wood particles. They
determined the devolatilization time and char yield of cylindrical wood particles in a bubbling fluidized bed combustor. The particle shrinkage showed significant influence on the char yield.

### 2.4 GASIFICATION OF WOOD PIECES

The gasification of wood pieces vis-a-vis bioresidues in fixed bed and fluidized bed gasifiers was compared by Warnecke (2000). He identified the main advantages of fixed bed gasifiers as a) high carbon conversion efficiency, b) acceptability of wide range of ash content in the feedstock, and c) possibility to melt the ash. He also confirmed that co-current fixed bed gasifiers could produce a clean gas with very low tar content. But for large capacity plants, the limited scale-up feature of fixed beds involves higher investment costs if a cascade of single fixed bed gasifiers is to be established.

Cummer and Brown (2002) reviewed the various methods for drying, sizing, and feeding of wood pieces into gasifier. They concluded that even though downstream equipments for particulate, tar and contaminant removal have been researched well, some of the equipments are yet to reach technical maturity.

Dasappa et al., (2003) described the use of open-top downdraft reburn reactors lined inside with ceramic material for low temperature and high temperature heating applications in industries. In each case, a suction blower drew air through the top of gasifier and also through the air tuyeres provided circumferentially. Even though it was meant for direct burning, the gasifier along with cleaning and cooling system generated PG which was so clean as to run an internal combustion engine.

Abdul Salam and Bhattacharya (2006) conducted experiments on charcoal gasification in spouted bed by supplying air through two types of
distributors namely central jet distributor and circular slit distributor. At higher spouting velocities, they showed that the latter gives a slightly more gasification efficiency than the former.

Sheth and Babu (2009) investigated the gasification of wood wastes resulting from furniture production. For their research work, an Imbert downdraft gasifier provided with two air entry ports directly at oxidation zone was used. Each experimental run was carried out for a period of 25 minutes only.

Sharma (2010) determined the overall pressure drop across the open-top, twin air entry type gasifier. It was developed by IISc., Bangalore and was operated by inducing air partly through the open-top of gasifier and partly through circumferential air tuyeres. The overall pressure drop across the gasification system and the pumping power to cause desired gas flow rate through the system were closely related to the volumetric efficiency and the net power output of the internal combustion engine.

2.5 GASIFICATION OF BIORESIDUES

Because of different physical forms of bioresidues, complexities are involved in their gasification. Few researchers homogenized the bioresidues by means of charification and then the resulting char was gasified. Similar to charcoal gasification, corn cobs were first partially pyrolysed in a pyrolyser to reduce the volatile matter content and then the resulting char was gasified in a co-current flow gasifier by Gaur (1989). The initial volatile matter content of corn cobs was 80 % and by partial pyrolysis it was brought down to 38 %. By using char as gasifier feedstock, the tar content in PG was reduced.
The chemical elemental characteristics of 280 samples of biomass fuels were compiled by Nordin (1994). He classified the biomass fuels on the basis of elements responsible for ash and deposit formation.

In an overview of combustion and gasification of rice husk in fluidized bed reactors, Natarajan et al., (1998) reported that fluidized bed reactors are suitable for rice husk combustion and gasification especially in large scale commercial implementations. The technical feasibility and the economic and environmental performance of atmospheric circulating fluidized bed gasification of biomass wastes and residues integrated with a combined cycle for electricity production were investigated for Dutch conditions by Faaij et al., (1997). From these two papers, it appears that fluidized bed technology can be applied for bioresidues in large scale plants.

Jain and Goss (2000) studied the reactor scaling factors for throatless rice husk gasifiers by conducting experiments with four gasifiers having different diameters. The specific gasification rate of rice husk was found to be 192 kg/h·m$^2$ corresponding to maximum gasification efficiency of 62%.

Hazelnut shells were gasified in a downdraft gasifier and temperature profile along the gasifier was obtained by Dogru et al., (2002). He reported that the significant properties of shells which influence the gasification process are moisture content, size and shape, absolute and bulk densities, chemical composition (i.e., proximate and ultimate analyses), and higher heating value.

The Cuban bagasse was gasified in a two stage bench scale reactor by De Filippis et al., (2004). Oxygen and steam were used as gasifying agents with Nickel catalyst supported on Al$_2$O$_3$ inside the reactor and the composition of outgoing syn gas was reported to be close to that predicted at the equilibrium conditions.
Bhoi et al., (2006) reported large variations in bed temperatures above the grate and pressure drop across the gasifier for GNS, resulting in very poor quality of PG. Poking/ramming at regular intervals of time was required to maintain uniform fuel flow which got hindered due to its low bulk density.

The gasification of cashew nut shell char in a downdraft gasifier was probed by Venkata Ramanan (2008). He found that gasification of cashew nut shell char generates PG with lesser CO$_2$ content. Pressure drop and throat temperature were higher and more clinker was formed during cashew nut shell char gasification when compared to wood gasification.

Pyrolysis of wheat straw and subsequent low temperature reforming of pyrolysis gas using a nickel based commercial catalyst were investigated by Hornung et al., (2009) experimentally. They showed that volumetric flow rate of pyrolysis gas could be increased to about 58% by low temperature reforming.

Recently, Subramanian et al., (2011) reported about the gasification of coir pith, rice husk, and saw dust in a fluidized bed gasifier and they have determined CO content to be 8 - 19 % and CO$_2$ content to be 10 - 17 %.

Owing to its high inherent oil content, cashew nut shells are considered unfit for gasification (Sethumadhavan and Renganarayanan 2006). But, bio-oils can be produced by pyrolysis from the oil rich cashew nut shells. Patel et al., (2011) studied the effects of extraction parameters such as pressure and temperature on super critical fluid extraction of bio-oils from cashew nut shells.
2.6 PRODUCER GAS CLEANING PRIOR TO SUPPLY TO ENGINE

Hasler and Nussbaumer (1999) determined the tar and particle collection efficiencies of various gas cleaning devices which were supplied with PG generated by fixed bed gasifiers. They concluded that 90% particle removal is easier to achieve than 90% tar removal. Catalytic tar cracking alone can meet a tar reduction exceeding 90%.

A sampling method to determine tar and particulates and which allowed for long duration sampling was developed and tested by Hasler and Nussbaumer (2000). It was reported that the method had been used at eight different gasifier installations and seven gas cleaning systems within Europe.

A draft protocol for the development of a method to sample and analyse tar and particulates was reported by Abatzoglou et al., (2000). The system was proposed to consist of an iso-kinetic probe for sample extraction, a heated filter for particulate collection, a water condenser and a series of impingers containing cooled solvent to collect the organic contaminants.

A two stage gasifier featuring separate pyrolysis and gasification was used by Hindsgaul et al., (2000) to study the characteristics of particulates present in producer gas. They found that 77% of the particulates to be basically carbon structures. But the engine wear was found to be caused by ash particles which must be removed by better gas cleaning methods.

Knight (2000) reported about a method which was employed for raw gas analysis at a test facility for pressurized gasification of biomass. The sample was withdrawn iso-kinetically at process conditions; sequentially removing particulates in a hot filter and cooling the gas stream to condense unreacted steam and oils, which were then collected in a series of cold traps at
system pressure. The vessels of sampling system were later rinsed with dichloromethane to obtain quantitative oil samples.

For tar removal, although secondary methods are proven to be effective, treatments inside the gasifier i.e., primary methods are gaining much attention as these may eliminate the need for downstream cleanup. Devi et al., (2003) reviewed the various primary measures for tar elimination in biomass gasification.

2.7 DUAL FUEL (PG + DIESEL) OPERATION OF ENGINE

Coovattanachai (1989) measured quantities like electrical output, wood consumption rate, PG flow rate, PG heating value, PG composition, etc. and from them derived certain quantities like specific fuel consumption, gas-to-air ratio, energy inflow into gasifier, energy input to engine, gasifier efficiency, overall electrical conversion efficiency of a gasification-engine-generator system. He found that the performance of engine is sensitive to the variation in gas quality which could even cause stalling of the engine in worst condition. Direct injection engines were found to be more suitable than swirl chamber and high speed pre-combustion chamber diesel engines.

Ramachandra (1993) tested a 3.75 kW engine by operating it using diesel, (diesel + PG) and PG alone. The PG was generated from a wood gasifier. For PG alone operation, the same diesel engine was retrofitted to run as a SI engine. He reported that the engine power got de-rated by 20 % in PG alone operation.

In hybrid biomass-charcoal gasification, when air was supplied at three levels along the gasifier height and at one point for charcoal combustion, Bhattacharya et al., (2001) obtained a very low tar content of 28
mg/Nm$^3$. In dual fuel operation of the engine, a maximum of 81% of the total energy input to the engine was estimated to be available from PG combustion.

Sridhar et al., (2001) used PG generated from an open-top, downdraft and twin air entry type of gasifier in a spark ignition engine at a compression ratio of 17:1 without any tendency of auto-ignition. As a result of PG usage at a higher compression ratio of the engine, they obtained an overall electrical conversion efficiency of 21%.

A number of research papers reported about the use of bio-based liquid fuels in conjunction with diesel in internal combustion engines with the objective of reducing diesel consumption. Arulmozhiselvan et al., (2009) investigated the combustion characteristics of diesel-biodiesel-ethanol blends in a variable compression ratio engine. They found that the total fuel consumption for blends is higher than that for neat diesel.

2.8 CONCLUDING REMARKS OF LITERATURE REVIEW

Literatures relating to various aspects of fixed bed biomass gasification were reviewed to arrive at the scope for present research. The following conclusions were drawn on the basis of the review:

- It was found that the characteristics of biomass beds formed by loose bioresidues have not been probed in terms of pressure distribution, bed permeability, bed voidage, etc. Only one paper reported about loose GNS gasification in fixed bed gasifier. But, it was an open core gasifier operated in suction mode without PG scrubbing.

- Almost in all the gasification systems reviewed in the literature, PG was cleaned by wet scrubbing method. But for small scale gasifiers, supply of fresh water and disposal of
contaminated water would cause additional maintenance problems.

- The information pertaining to propagation of oxidation zone in the fixed bed gasifier, changes in properties of bed particles, effect of bed height on gasifier performance were rare.

- In the case of dual fuel operation of diesel engine, a comprehensive research including an analysis of diesel injection pump parameters was not found.

These conclusions helped to formulate the objectives of the present research.