Chapter 2

LITERATURE REVIEW

In the present work, the focus is on characterization of MSW/RDF and its utilization in conventional downdraft gasifiers for energy recovery and on its environmental impact. Thus, the literature presented falls under three broad categories. For the first one, the general literature on MSW/RDF/biomass characterization, state-of-arts and laboratory-scale experimental study using MSW/RDF/biomass gasification is discussed. In the second category, literature on modeling of downdraft gasifier (thermodynamic and CFD model) is reviwed. Lastly, the literature on modeling landfill emissions with focus on methane and carbon dioxide has been reviwed.

Apart from being review of existing literature this chapter also reviews the current technology WTE is used across the world while taking into account the underline fundamentals

2.1 Characterization and utilization of MSW/RDF

2.1.1 Characterization of MSW/RDF

The physical and chemical characterization of the MSW stream is one of the highest priorities in the waste management regulatory regime (EPA US 1996). The composition of MSW as received at the landfill site varies considerably with seasonal changes and the location of landfill. For evaluating the thermal performance and environmental impact due to power production using MSW, the characterization of MSW and biomass for physical, thermal and chemical properties is essential.

Numerous studies are reported on characteristics of local MSW and its by-products i.e., synthesized fuel and energy (Chang et al. 2007; Frey et al. 2003). Tchobanoglous et al. (2002) and Gawaikar (2006) highlighted the importance of source specific quantification and thermochemical characterization of MSW for design and operation of appropriate solid waste management systems for environmentally safe disposal of MSW. Chang and Eric (2008) and Alamgir et al. (2007) investigated the physical and chemical characteristics of MSW to illuminate the role of management policies with greater regional relevancy. Alamgir et al. (2007) characterize MSW from six major cities in Bangladesh. Mor et al. (2006) studied various physico-chemical properties of the MSW to characterize the waste from Gazipur landfill site, Delhi (India). The environmental impact assessment (EIA) for human health and the environment from the potential hazards of waste reuse, recycling, recovery, treatment, and disposal needs the support of a waste characterization database (Forteza et al. 2004).

NEERI characterized the waste from Delhi in 1996. However, this study could not provide complete classification/categorization of waste components. In Delhi, the earliest landfill was started in 1975 and two other landfills were started at Timarpur and Kailash Nagar in 1978. Seventeen landfill sites have been exhausted and closed till date (Mor et al. 2006; City Development Plan Delhi 2006).

2.1.2 Utilization of MSW/RDF

(a) Gasification Systems

The gasification process takes place in gasifiers. It is a partial combustion process where the lignocellulosic feedstock is subjected to drying, pyrolysis, oxidation and reduction in a controlled supply of oxygen. Gasification process yields combustible gas known as producer gas/syngas with carbon-monoxide and hydrogen as prime combustible constituents.

Under high temperature conditions, the solid feedstock loses its moisture and is then subjected to pyrolysis resulting in its decomposition into char and volatiles. The volatile products are a mixture of a large number of short chain hydrocarbons which may crack further to yield compounds like, carbon monoxide, hydrogen, carbon dioxide, water vapour and tar. These pyrolytic yields react with oxygen in high temperature combustion zone where oxidation and reduction reactions yield producer gas. The principal chemical reactions taking place in the oxidation and reduction reaction zones of the reactor are given as (Pinto et al. 2001).

(i) $C + O_2 = CO_2$

(ii) $C + CO_2 = 2CO$

(iii) $C + H_2O \rightarrow CO + H_2$

(iv) $C + 2H_2O \rightarrow CO_2 + 2H_2$

(v) $CO + H_2O \rightarrow CO_2 + H_2$

(vi) $C + 2H_2 \rightarrow CH_4$

The reaction (ii) is called Boudouard reaction and reactions (iii) and (iv) are known as primary and secondary water gas reactions, respectively. The forward reactions in the above are endothermic in nature and takes place at temperature of about 900°C. The excess moisture content in feedstock is unfavourable since it causes the secondary water gas reaction (iv) and water gas shift reaction (v) to proceed in the forward direction and thus reduces the calorific value of the gas. Most of the hydrogen produced in the reduction zone remains free. Only some of it combines with carbon to form methane. However, beyond the temperature of 1000°C, methane does not exit. The reactions (ii), (iii) and (vi) take place in reduction zone to convert char into gaseous products. These are highly endothermic and reversible reactions and high temperature favours the forward reactions

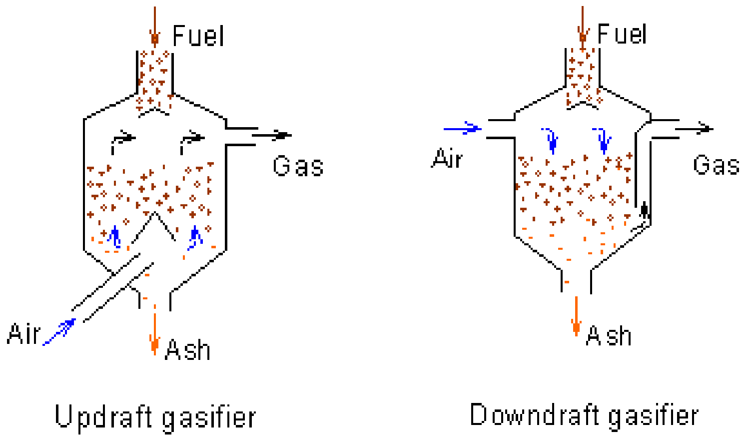
Fixed bed gasifiers typically have a grate to support the feed and maintain a stationary reaction zone, while fluidized bed gasifier keeps bed moving. Bridgewater (1995) provides a neat classification of the various gasifiers. A brief description of a few technologies is presented here.

Updraft gasifier

The simplest gasifier is updraft or counter-current type, in which air enters at the bottom and the gas is drawn at the top. Fuel is fed in at the top and moves downward as shown in Fig. 2.1(a). This design has small pressure drop, good thermal efficiency and high calorific value of the gas. These design exhibits high tendency of slag formation and higher tar in final gas in addition to long starting time. Their role is limited for thermal applications.

Downdraft gasifier

Here solid fuel is fed in at the top and flow of air and gas is in downward direction. Hence flow of air and fuel is in same direction (Fig 2.1b). The drying zone is at the top followed by the pyrolysis zone, combustion zone and reduction zone. The gasifier is designed so that tar is given off in the pyrolysis zone where a high amount will be cracked and reduced to non-condensable gaseous products before leaving the gasifier. In most of the gasifiers, the internal diameter is reduced in the combustion zone to have a throat. Air inlet nozzles are commonly set radially round the throat to distribute air uniformly. Relatively tar-free gas can be obtained, but gas contains significant quantities of ash particle and soot. Also higher exit gas temperature is a problem in these gasifiers that affect, the conversion efficiency. Usually downdraft reactors are preferred for engine applications due to the cleaner nature of gas.



(a) **(b)**

Fig. 2.1 Fixed bed gasifier configurations (a) Updraft (b) Downdraft

Fluidized bed gasifier

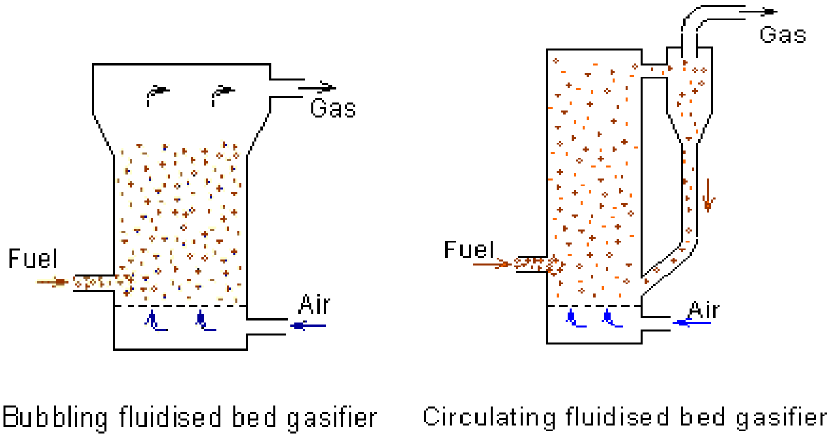
Fluidized beds offer the best vessel design for the gasification of MSW. In this gasifier, air is blown upwards through an alumina sand bed at sufficient velocity to keep it in a state of suspension, and thus behaving like a fluid. Initially the bed is heated by an external fuel source; as it reaches at sufficiently high temperature, the waste in the form of small particles is introduced on the top through a feed chute or into the bed through an auger. The fluidized-bed gasifier is most suited for low-density materials. Fluidized bed technology is more suitable for generators with capacities greater than 10 MW because it can be used with different fuels, requires relatively compact combustion chambers and allows for good operational control (Morris 1998). Better control over temperature, multi-fuel capability and no slag/clinker formation are the main advantages of this system. Poor load-following characteristics, high tar, ash and unburned carbon particle content in the gas are the disadvantages associated with this design. Klein and Themelis (2003) provide an overview of fluidized bed gasifiers used for power generation applications.

Bubbling Fluidized Bed

In this design, the gas velocity must be high enough so that the solid particles, comprising the bed material, are lifted, thus expanding the bed and causing it to bubble like a liquid as shown in Fig. 2.2(a). A bubbling fluidized bed reactor typically has a cylindrical or rectangular chamber designed so that contact between the gas and solids facilitates drying and size reduction (attrition). The large mass of sand (thermal inertia) in comparison with the gas stabilizes the bed temperature. The bed temperature is controlled to attain complete combustion while maintaining temperatures below the fusion temperature of the ash produced by combustion. As waste is introduced into the bed, most of the organics vaporize pyrolytically and are partially combusted in the bed. The exothermic combustion provides the heat to maintain the bed at temperature and to volatilize additional waste. The bed can be designed and operated by setting the feed rate high relative to the air supply. Under these conditions, the product gas and solids leave the bed containing unreacted fuel. Typical desired operating temperatures range from 900°C to 1000°C. Bubbling fluidized-bed boilers are normally designed for complete ash carryover, necessitating the use of cyclones and electrostatic precipitators or baghouses for particulate control.

Circulating Fluidized Bed

As the gas velocity increases in a turbulent fluidized chamber, the bed of solids continues to expand, and an increasing fraction of the particles is blown out of the bed. A low efficiency particle collector can be used to capture the larger particles that are then returned to the bed. This suspended-combustion concept is a called a circulating fluid bed (Fig. 2.2b). A circulating fluid bed is differentiated from a bubbling fluid bed in that there is no distinct separation between the dense solids zone and the dilute solids zone. Circulating fluid bed densities are on the order of 560 kg/m, as compared to the bubbling bed density of about 720 kg/m (Babcock and Wilcox 1992). To achieve the lower bed density, air rates are increased from 1.5-3.7 m/s of bubbling beds to about 9.1 m/s (30 ft/s) (Hollenbacher 1992). The particle size distribution, attrition rate of the solids and the gas velocity determine the optimal residence time of the solids in a circulating fluid bed. A major advantage of circulating fluid bed boilers is their capacity to process different feedstocks with varying compositions and moisture contents. As with bubbling-bed boilers, bed agglomeration is a concern. High alkaline content fuels cause particles in the bed to agglomerate, eventually defluidizing the system. In general, gasification technology is selected on the basis of available fuel quality, capacity range, and gas quality conditions.



(a) **(b)**

Fig. 2.2 Fluidized bed gasifiers (a) Bubbling fluidized bed (b) Circulating fluidized bed

Table 2.1 shows the thermal capacity range of the main gasifier designs. Larger capacity gasifiers are preferable for treatment of MSW as they allow variable fuel feed, uniform process temperatures due to highly turbulent flow through the bed, good interaction between gas and solid phase, and due to high carbon conversion.

Table 2.1 Thermal Capacity range of Different Gasifier Designs (Klein and Themelis 2003)

Gasifier Design	Fuel Capacity
Downdraft	1KW – 1MW
Updraft	1-12MW
Bubbling fluidized bed	1-50MW
Circulating fluidized bed	10-200MW

The costing of power generation from solid fuels coal, biomass and solid waste including woody biomass, agricultural wastes, municipal solid waste, refuse-derived fuel, scrap tires and tire-derived fuel) was studied by Niessen et al. (1996). The power technologies include pulverized coal and natural gas/combined cycle power plants, co-firing with coal, coal-fired utility boilers, direct combustion in dedicated mass burn, stoker and fluidized bed boilers, and wood gasification/combined cycle power plants.

Larsona et al. (1996) studied the production of clean transportation fuels (methanol or hydrogen) from MSW. Dong et al. (2008) analysed the energy potential of the RDF obtained from combustible solid waste was evaluated for Korea; they reported that utilization of 50% or 100% of the RDF as fuel, the industrial city can save disposal costs approximately 17.6% or 35.2%.

Yoshikawa (2004) developed a small-scale gasification and power generation systems for solid wastes (a 20 tons/day scale slagging MSW gasifier combined with 900 kW dual-fuelled diesel engines). The combustion of RDF in the cement industry was analysed by Gronli (1996) in a study on a Norcem plant in Norway. The study showed that the use of poor quality fuels such as RDF resulted in lower production levels, emissions problems and worsening chlorine salt build-up cycles due to high chlorine content of the fuel. They concluded that the upper limit for fuel substitution with RDF is 30% and that there is no economical advantage in burning RDF in cement manufacture without subsidy due to the initial cost of investment in equipment and operation costs.

Zubtsov et al. (2005) studied the aspects of using the advanced, high-temperature air/steam-blown gasification and pyrolysis technologies for converting solid fuels into syngas. He summarizes the present R&D status of Multi-staged Enthalpy Extraction Technology (MEET), which employs high-temperature air and steam as oxidizer agents for converting the solid fuels into syngas and has many features that are advantageous for power generation. The low-cost gasifier/pyrolyzer is extremely compact and flexible, capable of operating efficiently on a wide range of low-caloric-value fuels. Choy et al**.** (2004) assessed the feasibility of installing a small-scale MSW gasifier on a university campus.

(b) Gasification and WTE Process

Thermal treatment of biomass and waste with energy recovery is a one of the choice for its safe disposal. Research activities are going on in many countries including India to workout efficient, cost effective and reliable gasification systems for biomass and wastes.

Gang et al. (2008) studied five kinds of organic components (i.e. wood, paper, kitchen garbage, plastic and textile) and simulated three types of MSW in a fluidized-bed gasifier. Li (2002) developed a model to compare the life-cycle inventory (LCI) of gasification and WTE facility utilizing MSW for energy production.

Calaminus (1998) reported the Thermoselect High Temperature Recycling (HTR) process for waste treatment by eliminating the major problems of traditional techniques like landfills or ashes, filter dust and emission producing processes. The heat of reaction leading to temperatures up to about 2000°C in the core of the lower HTR section acts to also smelt the metal and mineral components of the waste. Chlorinated hydrocarbons such as dioxins and furans are reliably destroyed along with other organic compounds in the gaseous and the liquid phase. The synthesis gas is purified before use as combustible or primary material.

Lee (2006) determined the gasification characteristics of combustible wastes in a 5 ton/day fixed bed gasifier. Kikuchi et al. (2005) performed a semi-pilot scale test for production of hydrogen-rich fuel gas from different wastes by means of a gasification and smelting process with oxygen multi-blowing. Bain (2008) experimentally updates the technical & economic performance of an integrated hydrogen production process based on biomass steam gasification. He et al. (2009) investigated the catalytic steam gasification of MSW to produce hydrogen-rich gas or syngas with calcined dolomite as a catalyst in a bench-scale downstream fixed bed reactor. Gang et al. (2007) carried out experiments to recover energy and materials from waste tire efficiently from a low-temperature gasification in a lab-scale fluidized bed. Thamavithya et al. (2008)

present the experimental results of MSW gasification in a spout-fluid bed reactor. Three scenarios (primary air, secondary air and effect of the recirculation) were investigated in this study.

Milne and Evans (1998) reviewed the formation of Tar in gasifier its nature and Conversion. “Tar” is the most cumbersome and problematic parameter in any gasification commercialization effort.

Yassina et al. (2008) studied the techno-economic performance of energy-from-waste fluidized bed combustion and gasification processes in the UK context. Mass and energy balances of the processes were performed and the cost effectiveness of the different waste treatment options, for the generation of electric power, was assessed using a discounted cash flow analysis.

Yang et al. (2007) attempted to convert moving-grate incineration from combustion to gasification. In this study, burning characteristics, including burning rate, gas composition, temperature and burning efficiency as a function of operating parameters are investigated using advanced, mathematical models. Detailed comparisons between the combustion mode and gasification mode are made.

Hamel (2005) demonstrated that in order to increase the efficiency of waste utilization in thermal conversion processes, pre-treatment is advantageous. The dried and homogenized waste-derived Stabilats fuel has a relatively high calorific value and contains high volatile matter which makes it suitable for gasification. As a result of extensive mechanical treatment, the Stabilats produced is of a fluffy appearance with a low density.

Arena (2011) proposes a critical assessment of MSW gasification. The analysis indicates that gasification is a technically viable option for the solid waste conversion, including residual waste from separate collection of MSW. It is able to meet existing emission norms and can remarkably reduce the landfill option.

Niessen et al. (1996) summarize the state of the art for seven technologies involving gasification and other innovative thermal processing technologies for MSW. Although, the technologies are at the level of "incipient commercial availability", they have passed through the "idea" stage. A company “Advanced Energy Strategies” (2004) studied three technologies namely pyrolysis, conventional gasification, and plasma gasification for thermal processing of MSW, while Murphy (2004) has comparatively analysed incineration, gasification, generation and utilisation of biogas in a combined heat and power (CHP) plant.

The researchers (Malkow 2004; Collin 2004) also studied the existing WTE technologies for thermal treatment of MSW. A brief review is given below

Sofresid/Caliqua process (ANDCO-TORRAX)

The air gasification is carried out in a fixed bed updraft reactor. MSW can be handled without separation for even hazardous hospital wastes. By preheating the air to some 1000°C, the gasification temperature can be maintained well above 1200°C in the bottom of the shaft and the countercurrent gas can leave the reactor at high temperature. Combustion air is added before the combustion unit and the flue gases will have immediate temperature of order of more than 1200°C. Steam is produced in a conventional boiler and after an electrostatic precipitator the flue gases are discharged to the atmosphere. The slag from the gasifier as well as from the combustor is quenched by circulating water and collected as granules. Output of this process is only power and steam (hot water) for district heating.

Motala Pyrogas, Sweden

Motala Pyrogas was an atmospheric air-blown updraft fixed bed gasifier coupled to a boiler in a rubber and tyre manufacturing plant. The fuel was waste rubber, MSW (without any pre-treatment) and coal. The co-gasification with coal was used to stabilize the lower char layer in the bed. To be able to feed the MSW stream, a new robust lock hopper cell with 1 m^3 volume was designed and installed. The lower part of the reactor was cooled, and produced steam to moderate the ash temperature, thus limiting clinkering formation. A two-stage design was used to control the tar condensation in the gas pipeline of the boiler. A lower hot gas exit has been mixed with the cool top gas which forced to pass through an electrostatic filter. The recovered tar was fired in a separate burner in the boiler.

Purox process

The Purox process is a high temperature oxygen gasification process. The MSW is stored and shredded before feeding through the top of the high temperature updraft shaft furnace operated on oxygen. Molten slag is quenched with water and constitutes a material that can easily be deposited. The raw product gas is cleaned by conventional techniques, for instance, in the chemical industry. A small part of the product gas is fed to the reactor to ensure high reaction temperature and the rest is a “clean fuel”. The thermal efficiency has been reported to be more than 60%.

Landgard process (Monsanto)

MSW is shredded and fed to a rotary kiln where it meets hot gases from an oil burner. At a maximum temperature of 1000°C, a solid residue is collected in the lower part of the kiln while pyrolysis gases exit at the upper end (feed inlet of MSW). The gases are directly burned with steam production and the flue gases are scrubbed before exhausting in the atmosphere.

Destrugas process

In a downdraft (concurrent) with indirect heating (retort) reactor shredded MSW is fed at the top. The shredded MSW flows downwards in the shaft while it is indirectly heated to about 1000°C. The energy required to obtain 900-1050°C in the shaft is supplied indirectly through the walls and is originally formed by combustion of some of the gas. The gas is further cleansed in a scrubber where the water (at that time) was considered no more polluted that it could be sent to the communal sewage treatment. About 50 % of the energy in the MSW is obtained as gas.

Omnifuel process (Eco-fuel, University of Sherbrooke)

The raw material can be fed either from the middle or at the lower half of the reactor. Fluidized bed consists of inert material. Gas and solids leave the reactor top where a cyclone separates the solids to be recycled to the reactor. The gas is further cleaned in another cyclone. The thermal efficiency achieved, based on cold and hot conditions has been nearly 75 % and 90%, respectively.

Ebara process

It utilizes the concept of two fluidized sand beds, one for combustion and one for steam gasification, with circulating sand as the heat carrier between the two beds. The energy supply is carried out in the combustion reactor where residual char is burnt. The heat is transferred to the pyrolysis reactor by means of the fluidized bed material (sand), which flows between the reactors. The energy balance requires some extra fuel to match deficiencies. In the pyrolysis reactor RDF is pyrolysed by means of the hot bed material in the temperature range of 650-750°C. In all fluidized systems certain homogeneity of the feed is vital. The outgoing raw gas from the pyrolysis unit contains tar and char and has to be cleaned before exhaust. The resulting gas has a high heating value and the overall thermal efficiency is reported in the range of 50 - 60 %.

Flash Pyrolysis process (Garrett - Occidental)

The flash pyrolysis process was developed for coal, and also as part of a more general separation system for MSW. RDF is fed to a reactor. At a temperature range of 450-500°C and a short residence time (few seconds) and a slight over-pressure, nearly 40 % of pyrolytic oil or tar is formed. This tar is in the vapour phase and the gases are separated from the char in a cyclone. Upon cooling tar condensates and it is separated from the lighter gases. The lighter gas is used as fuel together with the solid char to provide the necessary heating for the process.

Erco/Power recovery system process

This process is a complete process from MSW to power generation. The MSW is upgraded into RDF and fed to the fluidized bed where it is primarily gasified by air at temperatures of 760-820°C. In waste gasifications a "reactive" bed material is used instead of sand. The "reactive" material is claimed to include an adsorbent for SO_2. The solids are separated from the gas in one or two cyclones. The gas is further cleaned in a multistage system including scrubbing and mist elimination. Solid – tars are returned to the gasification and the rest is treated in the water. When the gas is to be used in an engine for power production a fabric filter is also used in the gas cleaning. The thermal efficiency is reported up to 75%.

Elajo/Tornegaard/Komako, Sweden

The Elajo gasifier is a downdraft bed gasifier operated on air as oxidant. The intention was to combust the gas and then applying wet/dry flue gas cleaning with a fabric filter. The raw material was initially RDF Fluff, and after testing only RDF pellets a small scale modular unit was planned as standard. In the presented design, a rotating movable grate should allow control of pressure drop and ash discharge. Gas cooling/heat exchanger decreases the temperature up to 500°C. The gasifier was directly coupled to a boiler. A bottom ash that could be partly treated and recycled was anticipated, heavy metals retained in the ash, and dioxin formation should be low.

Voest Alpine process

The Voest Alpine process involves a fixed bed, updraft reactor where the gasification is carried out at high temperature (more than 1500°C). This high temperature is obtained with air as gasification medium by means of a fuel mixture to some extent including materials with high heat contents. With the high temperature a molten slag is quenched and collected in the bottom of the reactor. The specific feature giving Voest Alpine a special character is a coke bed through which the gas is cleaned from certain components. This coke bed is built into the gasification reactor.

In the pilot plant reactor a mixture of about a third of waste oil (including a part of fuel oil), a little more than half of RDF and some ten percent of coke is used as fuel. These different parts are introduced at various positions: the oils at the bottom of the shaft, the RDF in the middle and the coke at the top in a special shaft through which the top gas passes. The hot coke bed acts as a catalytic bed where tar and other tar components are broken down. After combustion they are less than 1 mg/m^3 flue gas;

for Cd, Hg, Ti, As, Co, Ni and Se less than 0.01 mg /m3. Although, the gas was cleaned for use in IC engine, yet further gas cleaning is still suggested. For the molten slag, approximately 1 m^3 of water for quenching per ton of fuel is used. The energy efficiency of the process is reported 83 % and RDF as well as shredded car waste has been used.

Scanarc (Plasma) process

To produce reducing gas for iron manufacture, plasma was introduced in the bottom of the shaft producing H_2 and CO from air and coal. Two of these processes were installed full-scale: the PlasmaZinc and the PlasmaChrome for handling Zinc dust and Chrome materials. The Scanarc (former "SKF Plasma") process is a fixed bed, high temperature process with a molten slag in similarity to the Andco-Torrax and Voest Alpine processes. In line, the gasification is also carried out in an updraft shaft. In the ScanArc process the gas cleaning is obtained in plasma, where the gas is heated to very high temperatures causing a decomposition of tar, chlorinated hydrocarbons and ammonia. The ScanArc process uses a shaft reactor outlined as simple as possible and fed with a mixture of air and oxygen in the bottom, or in the middle. Oxygen is needed when the effective heat content of the wastes is too low to result in a temperature of 1200°C or more. The raw gas is fed to a second reactor which in fact is more or less an empty shaft with a plasma generator on top. The electric plasma generates a theoretical temperature of more than 1500°C through which the gas is passed (lowering the temperature) into the shaft. The fuel to the plasma is composed of power and air for combustion (oxidation). After the second reactor, chlorine is present as Cl_2 or HCl, nitrogen as N_2, all organic compounds and several others are decomposed. The gas after the plasma reactor is cooled and washed. The molten slag is tapped from the bottom of the first reactor. The power consumption for the plasma is reported 200-400 kWh/ton of feed - depending on heat value of the feed.

Thermoselect process

In the Thermoselect process MSW is gasified and melted in two steps: first one is indirect drying/pyrolysis and second step belongs to high temperature oxygen-gasification. High temperature treatment effects molten slag and enables the process to handle a large range of solid wastes. The high temperature gasification is achieved by oxygen and support fuel taken from the product gas but also - to some extent - by the preceding drying and pyrolysis of the wastes. This reaction is carried out in a compressing and feeding system attached directly to the high temperature gasifier. MSW are mechanically compressed and transported through a "tube" by a piston. In the indirectly heated tube reactor, the temperature is gradually raised to about 600°C facilitating the drying of the material and subsequently the pyrolysis. The pyrolysis solid residues are intermittently pushed into the gasifications shaft where the temperature is raised to 1200-2000°C by means of oxygen and extra fuel provided from the product gas. The gases and volatiles including tars are concurrently fed into the shaft together with the solids. Metals, minerals and other types of inorganic material in the wastes are melted in the gasifier and withdrawn as a liquid at temperature of 1800°C from the bottom. After cooling, a harmless solid residue is claimed which might even be used as a raw material source for certain metals but which is basically deposited. The exiting raw product gas consists to a large extent of carbon monoxide and hydrogen giving a fuel gas of medium heating value or what might be called a synthesis gas (Sumio et al. 2004).

Lurgi CFB processes (Oko-gas, Wikonex)

These processes are applications of the Lurgi CFB gasification operating at atmospheric pressure. The feed is biomass, RDF or similar raw materials and fluidized by oxygen enriched air. The fluidized bed reactor requires a certain homogenity in the feed material. Thus, the municipal waste has to be sorted, milled and sometimes dried into a RDF before entering the CFB gasifier. In the fast fluidization shaft the material is gasified with air and oxygen in an inert bed. The temperature is about 900°C and the reaction time is few seconds. At the top unreacted material and other solids are separated in a cyclone and recycled to the fluidization shaft. From the bottom of the reactor ash is taken out, cooled and separated from metals. From the cyclone the raw product gas is fed to a “gas cracker" which operates at some 1400°C. The temperature is raised by oxygen in the raw (fuel) gas. At these elevated temperatures a cracking or rupture of dioxin like components is ensured. The gas is cooled in a waste heat boiler and further quenched by water. After a subsequent scrubber where ammonia, metals, etc are removed, specific cleaning of sulphur and mercury are applied. A considerable amount of waste water has to be treated with precipitations and neutralizations. With the extensive gas treatment, a pure fuel gas with medium heat value may be distributed.

Kiener-Siemens process

Unsorted wastes of different types such as MSW, industrial waste and sludge are mixed homogeneously and then treated in a rotating pyrolysis drum with flue gases near 450°C temperatures. In the drum a drying and pyrolysis occur, producing gases (including tar) and solids. In the end of the drum the gases are fed directly to the air blown combustion unit running at high temperature; some 1300°C. The flue gases from the combustion are subjected to conventional flue gas cleaning.

DANECO

A 10 MW air-blown updraft gasifier is fed with RDF pellets from the top. Air is inducted through a rotation bottom grate. The raw gas is fed to a fixed bed cracker with recycled ashes and fuel gas cleaning residues (lime). The cracking temperature is around 800°C and soot is recycled to the gasifier. After gas cooling through air and steam heat exchangers to 600°C, the gas enters a recovery boiler. A wet dry lime system operating at approximately 250°C precedes a bag-house filter. After scrubbing/cooling the gas is sent to a dual fuel engine.

Energy Products of Idaho (EPI)

The EPI incineration system uses a bubbling-type fluid bed concept that accepts a prepared 10 cm top size RDF. Within the bed, RDF particles are exposed to a vigorously turbulent hot environment that promotes rapid drying, gasification, and char burnout. In the bed, EPI's proprietary design features provide continuous removal of oversized noncombustible materials. The hot gases from the bed are passed through a boiler to generate the high-pressure, superheated steam that is used either to produce electricity or for process applications.

Pedco Incorporated

The Pedco Rotary Cascading Bed Combustor (RCBC) is a robust solid-fuel burner and heat-recovery system (it is not a gasifier). The RCBC burner comprises a rotating, horizontal, cylindrical combustion chamber. A bundle of boiler tubes projects into one end of the chamber. The rotational speed of the chamber is high enough to keep a substantial fraction of the bed material continually airborne. This activity produces an environment similar to that of a fluid bed but, in this case, a mechanically fluidized bed. The hot falling solids cascade across the whole diameter so that the boiler tubes are submerged in hot fuel and bed material. The hot solids recycle preheats the combustion air, drying and igniting the incoming fuel. The RCBC burner could discharge into a boiler making superheated steam for electrical generation. As a fuel flexible burner, the RCBC system is intended to burn coals, coal waste, wood, chipped tires, RDF, and a variety of other fuels having the common denominator of low cost.

PROLER International Corporation

The PROLER SynGas Process is a patented technology that reforms hydrocarbon-containing wastes into a reactor gas. The process accepts preshredded material and produces a fuel gas suitable for power generation. The residue is discharged in the form of commercially useful vitrified by-products as well as wastes acceptable for landfills. The system, referred to as the Proler SynGas Process, is designed to produce recyclable solid by-products together with a clean fuel gas from ASR and other wastes, including MSW. The demonstration unit has a capacity of 1.9-Mg/h shredded MSW, equivalent to 2.6-Mg/h raw MSW. The unit includes a feeding system; a horizontal, rotary re-actor; a gas-cleaning train; and a compressor that supplies cleaned fuel gas to a dual-fuel-fired engine/ generator.

Battelle

The Battelle High Throughput Gasification System (BHTGS) is an indirectly heated, two-stage process that uses CFB reactors. In a high-throughput gasifier, RDF or other biomass feedstocks is gasified (using steam without oxygen as the fluidizing medium) into a medium-heating-value gas (18.6 to 22.4 Nm^3). Residual char is consumed in an associated CFB combustor. A circulating-sand phase is the method for heat transfer between the separate reactors.

The Battelle biomass gasification process produces a medium-Btu product gas without the need for an oxygen plant. The process consists of two reactors and their integration into the overall gasification process. This process uses two physically separate reactors:

- A gasification reactor in which the biomass is converted into a medium-heating-level gas and residual char
- A combustion reactor that burns the residual char to provide heat for gasification.

Heat transfer between the reactors is accomplished by circulating sand between the gasifier and the combustor. The Battelle process provides a cooled, clean, 18.6- to 22.4 MJ/Nm^3 product gas. Waste heat in the flue gas from the combustor can be used to preheat incoming air and then to dry the incoming feedstock. The condensed, organic phase scrubbed from the product gas is separated from the water and injected into the combustor.

Thermo Chem

The Manufacturing and Technology Conversion International, Inc. (MTCI) Steam Reforming Process is an indirectly heated fluidized bed reactor using steam as the fluidizing medium. Pulse Enhanced™ indirect heating combined with a fluid bed and steam reforming provides a process for converting organics to fuel gas while separating the inorganics without oxidation or melting. The heart of the process is the Pulsed Enhanced™ heater, which is immersed in the fluidized bed. This pulsed heater, with unique aerovalves, generates an oscillating flow in a bundle of heat-transfer tubes that pass through the fluidized bed gasifier. The pulsed combustion phenomenon results in turbulent mixing and significantly enhanced heat transfer between the gases in the tube and the RDF. Part of the product gas is used in the pulsed heater as the energy source. The exhaust from the heater never enters the fluid-bed steam reformer and does not dilute the product gas. The organic waste fed to the fluid-bed steam reformer reacts solely with the steam in a reducing atmosphere, producing the fuel gas.

TPS Termiska Processer-AB

The TPS technology uses a starved-air gasification process in a combined bubbling and circulating fluidized bed reactor operated at 850°C and near atmospheric pressure. RDF is fed to the fluidized bed. Air is used as the gasification/fluidizing agent. Part of the air is injected into the gasifier vessel through the bottom section and the remaining higher up in the vessel. This pattern of air distribution causes a density gradient in the vessel. The lower part maintains bubbling fluidization that allows coarse fuel particles adequate residence time for good gasification reactions. The remaining air introduced higher up in the vessel increases the superficial velocity of air through the reactor so that smaller, lighter particles are carried away in the gas flow. The process gas from each gasifier passes through two stages of solids separation before being fed to a furnace/boiler. The flue gas exiting the boiler is then cleaned in a three-stage dry scrubber before being exhausted through the stack. Alternatively, some of the raw gas stream can be sent to a nearby cement factory, without cleaning, to be used as fuel in the cement kilns. Immediately downstream of the gasification vessel, a dolomite (mixed magnesium-calcium carbonate) containing vessel catalyzes most of the tars formed in the gasification process and breaks them down into simpler compounds of lower molecular weights and melting points. The dolomite also will absorb acids in the flue gas, including HCl and sulphur oxides. The product gas can then be cooled and passed through conventional scrubbing systems without operational problems. After cooling, the syngas can be compressed and cleaned up to acceptable limits for a combined cycle turbine.

Essex County

The Essex County Mass Burn WTE facility is New Jersey's largest resource recovery facility and is owned and operated by American Ref-Fuel. The Essex facility combusts about 2800 tons of MSW per day and generates approximately 65 MW of electricity. The facility does not shred or processes MSW, so the sizes of the items deposited to the combustion chamber can be large and the rates of mass transfer and oxidation are relatively slow. As a result a very large combustion chamber and grate are required and the intensity of combustion is correspondingly low. Energy is generated via steam production from waterwall tubes and a superheater. Flue gas is cleaned with three DBA electrostatic precipitators and dry scrubbing systems. The stack height is nearly 300 feet.

SEMASS RDF Combustion

In this process waste brought to the plant is loaded onto conveyors, shredded and exposed to overhead magnets that recover ferrous metals from the waste. The RDF is then sent into the combustion chambers through inclined chutes. A portion of the feed is burned in suspension, while the remainder falls onto a horizontal moving grate. The grate moves slowly and it takes materials approximately one hour to move from the front to the rear of the boiler. The feed rate can be adjusted automatically by installed temperature controls to provide maximum efficiency. Underfire and overfire air are introduced to enhance combustion. Waterwall tubes, a superheater and an economizer are used to recover heat for production of steam. Detailed operating data show that 650 kWh of electricity are generated per ton of MSW combusted. Of this, 100kWh are used in the plant operation.

Integrated Gasification Combined Cycle (IGCC)

IGCC concept is based on the combination of a gasification system with a gas turbine and a steam cycle and has the potential to provide thermal energy to power conversion efficiencies exceeding 40 %. Critical for the success of the IGCC is the maintenance of the gas turbine. The IGCC turbine’s lifetime can be limited due to erosion and high temperature corrosion caused by impaction of particles and deposition of impurities such as alkali metals in the product gas.

Corrosion of the turbine blades is accelerated by formation of low melting eutectic salt mixtures, of which alkali sulfates are believed to be important constituents. Turbine manufactures have set specifications for the maximum tolerable alkali metal concentration of the fuel gas to be less than 0.1 ppm of the fuel by weight. These specifications are often based on operating experience with fossil fuels.

(c) WTE Technologies

Combustion, gasification and pyrolysis belong to thermal conversion processes which can be used for thermal treatment of solid wastes. Different products are gained from the application of these processes and different energy and matter recovery systems can be used to treat these. The thermal treatment with heat recovery "WTE technologies" is prefered due to environmental consequences, energy generation and recycling of material. Several studies with achievements have been summarized as below,

Granatstein (2003) performed a case study on a waste-fuelled gasification project at Greve (Italy) using wide range of feedstocks. He observed poor gas quality, heavily contaminated with tar. Consonni and Federico (2012) investigated two gasification technologies with conventional WTE plants and found their energy performances are very similar to those of conventional plants. The potential benefits that may justify their adoption relate to material recovery and operation/emission control: recovery of metals in non-oxidized form; collection of ashes in inert, vitrified form; combustion control; lower generation of some pollutants.

Pyrolysis

Complex polymeric substances like MSW, coal, wood or biomass, plastic, black liquor, and distillery effluent decompose or depolymerize when heated at high temperature and release pyrolysis products largely in the form of gases.Danheux et al. (1997) compared the incineration with thermolysis.

Sanchez(2007) studied the energetic valorisation of the products. Owing to the specific characteristics of the plant, two products were obtained from the process: gas and carbonized solid. No liquid fraction was obtained, so the gas fraction is a greater percentage made up from both condensable and non-condensable compounds, while at the laboratory scale were obtained separately.

Liu (2009) studied the characteristics of oxygen-enriched air combustion of raw MSW by thermo gravimetric analysis. Experiments on oxidative pyrolysis of MSW were carried out under different atmospheres.

Yang et al. (2006) mathematically modeled the slow pyrolysis of segregated solid wastes in a packed-bed pyrolyser. It was found that packed-bed pyrolysis produces 30–100% more char compared to standard TGA tests and the local heating rate across the packed-bed reactor differs remarkably from the programmed wall-heating rate and varies greatly in both time and space.

Phan (2007) investigated the role of pyrolysis and found its importance in the thermal processing of municipal solid wastes, since it decomposes wastes into three types of intermediate products to be collected as fuel feedstock or to be gasified. In this study, the main products from slow pyrolysis of key segregated waste materials were characterised for mass yield, energy content, elemental composition and chemical compounds.

Baggio et al. (2008) studied the energy and the environmental impact analysis of an innovative system based on the pyrolysis of MSW which produces solid (char), liquid (tar) and gas (syngas) fuels used in a combined cycle for electric power generation.

Wang et al. (2005) experimentally studied the low-temperature pyrolysis of the mixture of nine typical components from municipal household garbage, in an externally heated fixed-bed pyrolyser, at temperatures ranging from 300°C to 700°C. The solid product yield decreases with the increase of temperature in the test temperature range, and reduces quickly at 300–550°C but very slowly at 550–700°c.

Incineration

The new generation of incineration plants are being designed and developed to meet strict emission limits. Comparing emission limits valid for waste incinerators and other large combustion plants it can be stated that new WTE systems are among the cleanest and most reliable sources of energy in the form of heat as well as electrical power.

Otoma (1997) demonstrated that using the heat from waste incineration to generate electricity requires the addition of generating equipment, while the manufacture, construction, and operation of this equipment also use energy. It was found these are effective methods for energy recovery, and that the gas turbines combined with waste incinerators for repowering have an optimum size that will improve overall efficiency. Murphy (2004) found that the major current technology is based on direct combustion of wastes in a moving-grate furnace. However, general public opinion prefers non-direct burning technologies. Waste gasification is one of those nearest technologies available. Detailed comparisons between the combustion mode and gasification mode are made.

Magrinho (2008) analysed the recycling of packaging wastes and found that it may be compatible with incineration within integrated waste management systems. To study this, a mathematical model was used to calculate the fraction composition of residual MSW only as a function of the MSW fraction composition at source and recycling fractions of the different waste materials.

Shen et al. (2005) studied the influences of different catalysts on the ignition and combustion of MSW using thermo gravimetric (TG) analysis.

Plasma gasification

Plasma technology for waste treatment is now a viable alternative to other potential treatment/disposal options. Thermal plasma technology is expected to become commercially viable in the future.

Gomez et al. (2008) and Lemmens (2006) analysed the available scientific and technical literature on waste plasma treatment of a variety of hazardous wastes such as residues from municipal solid waste incineration, slag and dust from steel production, asbestos-containing wastes, health care wastes and organic liquid wastes. The principles of thermal plasma generation and the technologies available were outlined, together with potential applications for plasma vitrified products. Lemmens developed a test facility to evaluate the feasibility of plasma gasification and the impact of this process on the environment with aim: (1) to evaluate the technical feasibility of making a stable synthesis gas; (2) to characterize the composition of this synthesis gas; (3) to define a suitable after-treatment configuration for purification of the syngas and (4) to characterize the stability of the slag, i.e., its resistance to leaching for use as a secondary building material. The tests illustrate that plasma gasification can result in a suitable syngas quality and slag with acceptable leachability.

Gasification of RDF pellets

Incineration has many drawbacks including producing hazardous emissions and harmful residues. To enhance the resource recovery from MSW, the RDF is considered as a better solution in industrialized countries. RDF obtained is a value added material with a higher calorific value, low moisture and a homogeneous particle size. The few relevant studies reported in past are quoted in this section.

Cristo (1999) researched the gasification of RDF pellets in different countries and analysed the performance of gasification of RDF pellets. Ravelli et al., (2008) carried out steam gasification of two different RDFs, differing slightly in composition as well as thermal stability, in a fixed-bed reactor at atmospheric pressure. The proximate and ultimate analyses reveal that the major components in RDFs are carbon and hydrogen. Rao et al. (2004) conducted air-blown gasification studies on a counter current fixed-bed gasifier for municipal residue-based RDF pellets and compared these with the mass and energy performance features of a gasifier with other biomass and residual fuels. The mass conversion efficiency and cold gas efficiency (CGE) of the gasifier were observed to be 83% and 73%, respectively for RDF pellets. The higher heating value and global energy content of the producer gas generated from gasification of RDF pellets was observed to be 5.58 MJ/Nm^3 and 12.2 MJ/kg, respectively. They reported that the tar content of gas from RDF pellets was dramatically less than (up to 45% less) that of wood chips. Dalai et al. (2008) studied steam gasification of RDF in a fixed bed reactor. They studied the steam gasification (fixed-bed reactor at atmospheric pressure) of two different RDFs and thermal stability. The proximate and ultimate analysis revealed that carbon and hydrogen are the major components in RDFs, while thermal analysis indicates the presence of cellulose and plastic based materials in RDFs. They reported that H_2 and CO are two major combustible products from gasification of RDFs.

Cleaning of Syngas and pollution

The emissions, dioxin and furan, are primary catalyst for political and environmental opposition to the WTE industry. Over the past decade, progress has been made in reducing dioxin/furan release from U.S. WTE plants lowering them from 4000 g/year in 1990 to 400 g/year in 1999. Klein (2002) states that "The most effective capturing techniques have been adsorption on activated carbon and the use of baghouse filters instead of electrostatic precipitators. Cunliffe et al. (2007) investigated the influence of temperature on the levels of pcdd and pcdf remaining in, and desorbed from, a municipal solid waste incinerator fly ash. Considerable desorption of pcdd/pcdf from the fly ash was seen at 275 ^{o}C and above. The results indicate that formation of pcdd /pcdf on fly ash deposits in the post-combustion plant of incinerators can result in the release of significant pcdd /pcdf.

Lasagni et al. (2008) performed a simultaneous study of the native carbon oxidation and formation of pcdd /f. The experimental study was carried out to gain information on the role of fly ash deposits in cold zones of municipal solid waste incinerators in pcdd /f formation reaction. Yokohama et al., (2007) investigated the gasification behaviour of pcdd and pcdf in fly ash by thermal treatment to estimate gas-particle partition in flue gas. For all samples, pcdd /f started to gasify at 350°C treatments, whereas 53-98% of pcdd /f homologs gasified at 400°C treatment, implying that gaseous pcdd /f are dominant in flue gas at temperatures in the range 350-400°C regardless of particle concentration.

Santisirisomboon et al. (2003) tested calcined limestone and calcined dolomite at bench scale to study their usefulness in cleaning hot raw gas from a fluidized bed gasifier of a synthetic or simulated RDF with a high (3 wt%) content in chlorine. Kusar et al. (2003) studied catalytic combustion for gas turbine application using a low heating-value gas derived from gasified waste. A selective catalytic oxidation for decreasing the NO_X formation from fuel-bound nitrogen was examined using two different approaches: fuel-lean and fuel-rich conditions.

Stehlik (2009) studied a number of recent advances in technologies and improvements in units for the thermal processing of MSW and various other types of waste. This study revealed achievements include low-NOx burners, improved efficiency, heat exchangers, waste heat recovery systems, newly developed equipment for wet scrubbing, dioxin filters and systems for the treatment of sewage sludge.

Lee et al. (2006) studied the environmental aspects of gasification of Korean municipal solid waste in a pilot plant. Municipal solid waste was gasified via thermoselect process in a 3 ton/day capacity pilot plant with oxygen at a temperature of nearly 1200°C. A vitrified slag of dark brown colour with glassy shining and non-hazardous in nature was found, which can be used as natural raw material in cement and construction industry. Sangtongam et al. (2007) studied parameters influencing clean syngas production from biomass, solid waste, and coal during steam gasification.

2.2 Mathematical Modeling

2.2.1 Gasifier Modeling

(a) Thermodynamic modeling

Most gasifier models reported in literature can be classified as equilibrium, kinetic free, kinetic rate and diffusion controlled models. The equilibrium model assumes single control volume to describe the gasifier chemistry. The gasification reactions are assumed to be at thermodynamic equilibrium. However, in the kinetic free models, the reactor is subdivided into two or more separate reaction zones in which distinct processes occur viz., drying, pyrolysis, gasification, combustion. These models assume a fixed reaction temperature, pressure and either heterogeneous or homogeneous chemical equilibrium. Equilibrium and kinetic free models generally use algebraic equations to predict reaction temperatures and exit gas compositions. The equilibrium model has been used by many researchers to analyse the gasification process. These models are based either based on minimizing Gibbs free energy or equilibrium constant.

Equilibrium model has been developed by Zainal et al. (2001) to predict the performance of a downdraft gasifier using different biomass materials. They reported that the calorific value of gas decreases with increase in moisture content in the raw material and gasification temperature in the range of temperatures investigated.

Hau et al (2008) studied thermodynamic model for gasification of solid waste. By solving the equilibrium reaction equations, the model describes pollutants formation and amounts of raw synthesis gas and in the slag. Mountouris et al. (2006) focused on the thermodynamic analysis of plasma gasification technology, which includes prediction of the produced synthesis gas, energy and exergy. Carnevale et al. (2012) analysed two alternative thermo-chemical processes from the thermodynamic point of view for waste treatment namely high temperature gasification and gasification associated to plasma process.

Jarungthammachote and Dutta (2006) investigated thermodynamic model and second law analysis of a downdraft waste gasifier. Buragohain et al. (2011) investigated the gasification of biomass mixtures using thermodynamic equilibrium and semi-equilibrium models. Ntshengedzeni et al. (2010) evaluated the conversion efficiency of the Johansson Biomass Gasifier by using analysis for gas profiles and temperature measurement system. Ratnadhariya and Channiwala (2009) investigated a three zone equilibrium and kinetic free modeling of biomass gasifier. Ratnadhariya and Channiwala (2003) studied parametric sensitivity of downdraft gasifier as predicted by three zone kinetic free (KF) model. Babu and Sheth (2005) reported interesting study on modeling & simulation of biomass gasifier in oxygen rich environment and study the steam-air ratio on gasifier performance.

(b) CFD modeling

CFD numerical models can be used to describe gasification processes because they have become an important analysis and design tool to visualize the flow, concentration and temperature contours. Wang et al. (2009), in their review critically presented and compared CFD modeling applications on biomass thermochemical conversion processes for modeling, design and optimization of thermochemical reactors. Mathematical equations governing the fluid flow, heat and mass transfer and chemical reactions in thermochemical systems are described and sub-models for individual processes are presented.

Giltrap et al. (2003) developed a model for the reduction zone of a downdraft biomass gasifier to predict the composition of producer gas under steady-state operation. Factors affecting the gas composition were the fraction of pyrolyzed gas in the initial gas entering the reduction zone of the biomass gasifier, air-to-fuel ratio, moisture content of biomass, bed temperature, and reactivity of char. Molar balance, energy balance, pressure gradient equation, and Arrhenius type of temperature dependence kinetic equation formed the set of first order differential equations, which were solved by finite difference method. The accuracy of the model was limited by the availability of data on the initial conditions at the top of the reduction zone. Moreover it was assumed that char reactivity factor (CRF), which represented the reactivity of char and the key variable in simulation, was constant throughout the reduction zone. Babu and Sheth (2006) modified Giltrap's model by using variable CRF along the reduction zone. The model was simulated with the finite difference method to predict the temperature and composition profiles in the reduction zone. A finite difference technique was successfully applied to solve such type of partial differential equations in other studies (Babu and Chaurasia 2004; Mathieu et al. 2002). Babu and Sheth (2006) presented the modeling and simulation study on reduction zone to predict the influence of air-fuel ratio. They also studied the effects of pyrolysis fraction on the outlet gas concentration in a downdraft biomass gasifier. Tilmans and Jeanmart (2007) investigated the reactions of pyrolysis gases in the combustion zone of the reactor in a downdraft gasifier. This model includes three average temperatures, which corresponds to solid particles surface, particles interior and the gas phase, respectively. Sivakumar et al. (2008) studied downdraft biomass gasifier with focus on reduction zone using Computational Fluid Dynamics.

Gerun et al. (2008) developed a two dimensional axis symmetric CFD model for oxidation zone in a two-stage downdraft gasifier. The simulations fit satisfactorily to the experimental data for temperature pattern and tar concentration.

Zhou et al. (2007) numerically modelled the combustion of straw in a bench-top stationary fixed bed with focus on NOx formation and reduction. Higman et al. (2003) employed a two-dimensional steady state model for straw combustion in a moving bed, while Kaer (2006) developed a numerical model of a 33 MW straw-fired grate boiler incorporating a stand-alone bed model using commercial CFD code for gas-space computation. He concluded that poor mixing in the furnace is a key issue leading to high emission levels and relatively high amounts of unburnt carbon in the fly ash. The stand-alone bed model is based on a one-dimensional "walking-column" approach and included the energy equations for both the fuel and the gas accounting for heat transfer between the two phases.

Gomez-Barea and Leckner (2010) developed a CFD model for fluidized bed biomass gasifier. Special attention was paid to comprehensive fluidization models, where semi-empirical correlations were used to simplify the fluid-dynamics. For the CFD modelling of combustion processes in industrial-scale reactors the EDC is often used to couple chemical reaction mechanisms to the computed flow field (Rehm et al., 2008). Perkins and Sahajwalla (2007) modelled the heat and mass transport phenomena and chemical reaction in underground coal gasification using two-dimensional axi-symmetric computational fluid dynamic. The model is used to simulate the combined effects of heat and mass transport and chemical reaction during the gasification process. Silaen and Wang (2010) studied the role of turbulence and devolatilization models on simulation of entrained-flow coal gasifier. They employed Eulerian-Lagrangian approach to solve the Navier-Stokes equations and the particle dynamics. Hermansson (2011) performed a CFD modelling of bed shrinkage and channelling in the fixed-bed combustion. In this study, a two-dimensional model of the combustion of fixed fuel beds has been developed for studying the influence of heterogeneous fuel-bed properties on the conversion. Likewise, Porteiro et al. (2009) used CFD modeling on small-scale commercial biomass pellet boiler and reported that CFD computations can be used for design and optimization of biomass combustion systems. Wang and Yan (2008) employed a fluidized bed sewage sludge gasifier for prediction of syngas composition. The CFD code employs standard κ-ε turbulence model for the gas phase in an Eulerian framework, and the discrete phase model for the sludge particles in a Lagrangian framework, coupled with the non-premixed combustion model for chemical reactions. Pablo Cornejo and Oscar Farías (2011) developed a three-dimensional CFD model for describing coal gasification of fluidized-bed reactors. The commercial multi-purpose CFD code FLUENT 6.3 was employed, taking into account drying, volatilization, combustion and gasification processes. Miltner et al. (2007) used CFD-Model for optimisation of an innovative combustion chamber for a solid stem-shaped bio-fuel in the form of compressed biomass bales. Carlsson et al. (2010) studied gas phase reaction schemes for black liquor gasification modeling. Blasi et al. (1999) developed a one-dimensional, unsteady-state model for biomass gasification in a stratified concurrent downdraft reactor. Heat and mass transfer across the bed were coupled with moisture evaporation, biomass pyrolysis, char combustion, and gasification, gas-phase combustion and thermal cracking of tars.

Fletcher et al. (2000) developed a detailed CFD model to simulate the flow and reaction in an entrained-flow biomass gasifier. Biomass particulate is modelled by using Lagrangian approach because it entered the gasifier, released its volatiles and finally underwent gasification. Transport equations were solved for the concentration of CH_4, H_2, CO, CO_2, H_2O and O_2 and heterogeneous reactions between fixed carbon and O_2, CO_2 and H_2O were modelled. The model provided detailed information on the gas composition and temperature at the outlet and allowed different operating scenarios to be examined in an efficient manner.

There are several modeling studies on packed-bed biomass combustion which are given in Table 2.3.

Table 2.3 Summary of CFD modeling attempts

Application	Code Dim	Turb. Model	Extra Model	Exp. validation	Authors
Two-stage downdraft gasifier	Fluen2-D	RNG k-ε	DOM	Satisfactory	Gerun (2008)
Entrained flow gasifier	CFX 2-D	Std k- ε	Langragian,DTRM	N/A	Ma et al. (2007)
Downdraft gasifier	Code 1-D	N/A	Porous	N/A	Sharma (2007)
Horizontal entrained flow	Fluen1-D	N/A	Langragian	Reasonable	Zhou (2006)
Moving packed bed	Fluen2-D	Std k- ε	DOM	N/A	Kaer (2004)
Cone calorimeter reactor	Code 1-D	N/A	Porous	N/A	Giltrap (2003)
Entrained flow	CFX4 2-D	Std k- ε	RSM, Langragian	Acceptable	Feltcher (2000)

2.3 Modeling landfill gas emissions

The decomposition of organic components produces methane, which is a significant contributor to global warming. There are numerous review papers on Landfill gas (LFG) emissions (Abushammala et al 2009; Staniunas and Burinskiene 2011). Abushammala et al. (2009) reported the dependency of LFG production rate on many factors controlling the quality of gas production needs to be accounted for in developing predictable models for LFG emission rates. Staniunas and Burinskiene (2011), on the other hand, studied the assessment of green house gases attributable to waste management sector in urban planning. The result of their study is a carbon dioxide equivalent that refers to waste management sector and possible measures of compensation. They quoted that Lithuania produces 407 kg of MSW per year which is equal to 1.7 tons of CO_2 (equivalent) in 20 years horizon. They recommended that for small cities tree planting is feasible. Roughly 3 trees per person are needed as compensation while for big cities (i.e., districts) they suggested supplementary areas to be identified for tree plantation.

Methane emissions rates from LFG can be obtained through mathematical models, which are generally based on mass balance (Oonk 2010). There are numerous models; most of them are either based on a first-order decay model or a multi-phase model. Mor et al. (2006) have used the first-order decay model for estimating methane generation from Gazipur landfill site. Kumar et al. (2004) estimated CH_4 emissions from MSW landfills using *Default Methodology* and *Triangular model*, while Akolkar et al. (2008) employed *Flux Method* in addition to *Default Method* and *Triangular Method* for monitoring landfill gas emissions. Recently, other ways to deal with oxidation estimates are being developed. Jha et al. (2007) generated greenhouse gas emission inventory from landfills of Chennai by measuring the site specific emission factors in conjunction with relevant activity data as well as using the IPCC methodologies for CH_4 inventory preparation. CH_4 emission estimates were found to be about 0.12 Gg in Chennai from MSW management for the year 2000 which is lower than the value computed using (IPCC 1996). Chakraborty et al. (2011) estimated the methane emissions from municipal waste dumping sites in Delhi, namely three operational landfills Ghazipur, Bhalswa and Okhla. To get true landfills specific methane emissions, well recognized closed Perspex chamber based in-situ method were used and methane concentrations were analyzed by GC-FID. The in-situ methane measurements in Delhi's landfills revealed that the average methane emission flux was 1911±506, 2014±596 and 1041±307 mg/m^2h for Ghazipur, Bhalswa and Okhla landfill sites, respectively. Whereas, average emission factor (EF) for Delhi's landfills was reported to be 6.9±2.4 g/kg. To compare methane emissions developed by in-situ method, other available methods for CH_4 estimation viz. the IPCC (1996) Default Methodology (DM), IPCC First Order Decay (FOD) and Modified Triangular Method (MTM) have also been used.Using in-situ, DM, FOD and MTM methodologies it has been estimated that during 2008-09 periods, the three landfills in Delhi together emit 10 Gg, 46 Gg, 31 Gg, 41 Gg respectively. Chalvatzaki and Lazaridis (2010) compared the LandGEM and IPCC Methodology for prediction of landfill emissions. They concluded that LandGEM modeling is more efficient than IPCC methodology.

Talyan et al. (2006) used system dynamics modeling approach to model methane emission from MSW disposal landfill site in Delhi during period 2005-2025 and proposed a waste management policy for Delhi. According to this waste management policy, the treatment capacity can be enhanced by introducing different available technologies, for instance, biomethanation, composting and refuse derived fuel, replacement of traditional open landfilling by sanitary landfilling having the facility to capture the landfill gas. The implementation of such policy may be expected to reduce the methane emission to the level of 2001 by the year 2025 despite an almost two-fold increase in waste generation.

Petrescu (2011) experimental study revealed the characteristics of gaseous emissions generated by a non-compliant municipal landfill of Radouti (Romania) after its closure. High concentrations of approximately 60% of CH_4 and 39% of CO_2 of the landfill gas captured in two different landfill sites revealed the polluting character of those emissions and also revealed that they directly affect the environment.

Gaur et al. (2010) upgraded LFG to pure methane using the adsorption and absorption processes by removing toxic compounds using granular activated carbon.They also conducted experiments to develop process for removing CO_2 from LFG (Gaur et al. 2011).

2.4 Scope of the present work

Numerous studies have been conducted in the past on biomass gasification with focus on mathematical and experimental modeling, and characterization of woody biomass. The studies on characterization of MSW/RDF, its utilization in conventional gasifier-engine systems for power generation applications and its impact on environment are scant in open literature. In view of above, the present work is focused on development of database, sampling and characterization of processed MSW or RDF (obtained from three landfill sites of Delhi). This work also deals with utilization of RDF in gasifier-engine system for power production, and evaluation of its impact on environment. Since, composition of MSW/RDF vary considerably with seasonal changes and the location of landfill, the tests and measurements have been planed to characterize its properties including calorific value, chemical composition, moisture and ash content etc. Several other characteristics need to be obtained such as ash sintering temperature, char yields, volatile and moisture release rate, moisture content and density of MSW/RDF. The thermograms for TG and DG analysis of RDF sample in reactive (air) environment (as per the conditions prevailed in a gasifier) are expected to be obtained and analyzed. Proximate and ultimate analysis of MSW/RDF, the pH value, potassium and sulphur content is planned and. characterization of residual ash for its composition, EDS analysis, ash deformation and fusion temperature need to be carried out.

For utilization of MSW, it can be upgraded into more energy rich form “RDF”. This RDF can be compressed into briquetes of desired size. A mixture of RDF briquetes and wood chips are prepared in proportion of 1:1 as feedstock for conventional fixed bed downdraft gasifier system. An experimental test rig was developed by coupling the NETPRO downdraft biomass gasifier (capacity 10 kWe) with gas engine of capacity 10 kW convertd to operate with single fuel mode. Experiments were prformed on gasifier-engine system in order to study the syngas composition, exhaust emissions from engine and pollutant concentration in recirculating water used for spray over syngas cooling in order to identify the suitability of RDF in conventional fixed bed gasification systems.

Considerable efforts have been done on understanding the thermochemical conversion processes for efficient and cost effective utilization. A theoretical study was carried out to predict resulting gas composition from conventional downdraft biomass gasifier. A thermodynamic modeling was developed and a commercial CFD software has been adapted to predict the final syngas composition, temperature profile inside the downdraft gasifier operated on mixture of RDF (obtained from major landfill site in Delhi) and wood chips. Predicted syngas composition using equilibrium modeling and CFD software have been compared with experimental data for validation.

Presently, Landfilling practice is very common for MSW disposal. However, it releases volatile organic compounds with leachable toxic heavy metals and greenhouse gases including methane and carbon dioxide. The present work focused on the determination of emissions from the three major landfill site located in Delhi. LandGEM model was employed to compute the landfill gas production. Finally, the potential of energy recovery and greenhouses gases reduction was studied in context of power production through gasifier-engine system utilizing the huge stocks of MSW dumped at various landfill sites.