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Process Intensification of Waste to Energy Power Plants

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Abstract— Increasing interest is focusing on plasma-assisted gasification applied to the treatment of municipal solid waste (MSW), especially as it may be a new way to increase Waste-to-Energy (WTE) worldwide. The aim of this paper is to redesign a process intensified MSW waste to energy plant and find out the efficiency, level of external syngas degraded and their technical and economic viability. As a means of process intensification, plasma torch is used which is a way to generate heat, via the passage of an electric current through a gas flow. Plasma technology has been used for a long time for surface coating and for destruction of hazardous wastes but its application to MSW has not been explored fully..

Keywords: Plasma technology, Municipal Solid Waste, Conventional Waste to Energy plants, Syngas, Process Intensification

1 Introduction

Waste management has become an issue of growing global concern, according to United Nations Environment Programme in 2013, as urban populations continue to increase and consumption patterns change [2]. The disposal of municipal solid waste is a public service that has important impacts on resident health and the appearance of towns and cities. However many government municipalities seem to be losing the battle of coping with the ever-increasing quantities of waste. The problem increases as the diversity of materials in the solid waste, is no longer mainly food waste and ash, but includes more and more plastic packaging, paper and discarded electronic equipment. We have chosen Canada, which was ranked as the last place out of 17 countries internationally and it has attained a "D" grade on the municipal waste generation ranking; as shown in Figure 1. Statistics from [6] states that nearly 13 million tonnes of municipal solid waste was generated by Canadian households in 2008 and the waste generation has been rising spontaneoussly since 1990 as shown in Figure 2 compared to another developed and economically sound countries.

Canada in 2008, disposed nearly 8.5 million tonnes of solid waste in landfills or other methods whereas the remaining 4.4 million tonnes went to recycling, reuse, or composting [5]. Therefore, particularly in countries such as Canada, new methods of waste destruction techniques are a topic of ongoing research. The demand for efficient methods must be introduced for eliminating municipal solid waste.

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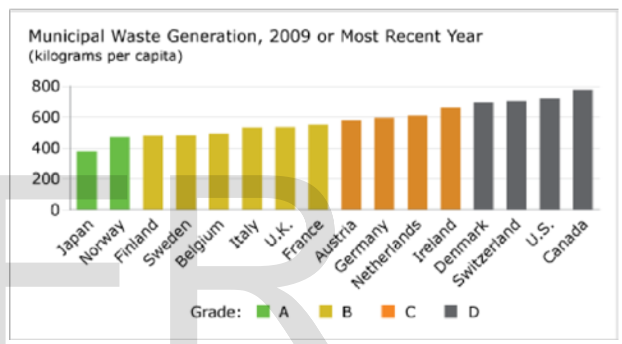

Fig. 1. Shows the list of countries in the survey of MSW generation and Canada ranked last [5]

1.1 Background

Traditionally since the earliest of times, landfills had been the most feasible methods of garbage disposal. In a study, it was proven that landfills still occupy globally, accounting for ap proximately 60% of all existing methods today of waste disposal, by the U.S. Environmental Protection Agency (EPA) [7]. A picture of a typical Municipal landfill is shown in figure 4.

Thus, governments in many countries are looking for better alternatives to dispose their MSW. Many countries have set a goal, as shown as in figure 4, to reduce the use of landfills as their option for waste destruction

1.2 Problem Statement

Data from the International Energy Agency represents an increase of 10% in the average energy use per person whilst world population increased 27% from 1990 to 2008 [11]. Energy consumption, amongst the Great 20 countries, increased by more than 5% in 2010 [9]. This pressing needs for new energy production substitutes as stocks of energy fuels are reaching extinction.

The rapid increase of population and intensified economic growth has led to an increase in global consumption and waste generation. The world is facing a waste disposal method as lesser lands for traditional landfilling methods are decreasing.

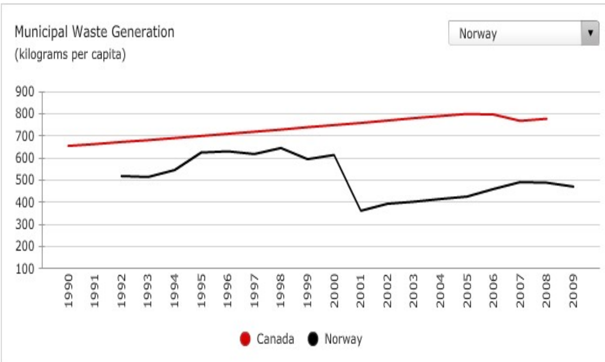

Fig. 2. The increasing trend of Canadian MSW disposal while Norway managed to reduce its per capita volumes of disposable solid waste [5].

MSW according to [10] consists of:

- Biodegradable waste from homes include food and kitchen waste, green waste, paper. Recycling waste from homes or offices include papers, metals, plastics, clothes, bottles, etc.
- Inert waste from industries and construction sites including demolition waste, dirt, rocks, debris.
- Electrical and electronic waste (WEEE) - electrical appliances, TVs, computers, screens, etc.
- Composite wastes: waste clothing, Tetra Packs, waste plastics such as toys.
- Hazardous waste including most paints, chemicals, light bulbs, fluorescent tubes, spray cans, fertilizer and containers.
- Toxic waste including pesticide, herbicides, fungicides.
- Medical waste from hospitals.

All the materials above have a high value of biomass. Thus making use of the energy content available in these above "wastes" would be an alternative idea for solving the scarce energy demand problem. The last materials on the list are hazardous and cannot be landfilled directly. Therefore substitutes to purifying them, then decompose them should be brought forward.

Combing the problem of disposal municipal solid waste (MSW) and the demanding need for development of alternative energy can be joined hand in hand, to develop new ideas complementing one another [12]. Waste-to-energy (WTE) plants, coverts discarded MSW to energy, heating up steam turbines to produce electricity or the steam is used for heating a city [12]. Waste to Energy plants are recognized as a renewable source of energy supply and are playing an increasingly important role in MSW management globally [12].

The greatest concerns for MSW Waste to Energy plants is that the highly toxic fly ash must be safely disposed of and that involves additional waste treatment processes and the need for specialist toxic waste landfill elsewhere[13]. This may cause concerns for local residents [14, 15].

Fig. 3. A large landfill at United States [7]

In 2008 Eunomia, report found that under some circumstances and assumptions, Waste to Energy plants using blast furnace may cause less CO_2 reduction than other emerging Energy from Waste and combined heat and power (CHP) technology combinations for treating residual mixed waste [16]. The authors found that CHP WtE technology was ranked 19 out of 24 combinations (where all alternatives to incineration were combined with advanced waste recycling plants); being 228% less efficient than the ranked 1 Advanced MBT maturation technology; or 21. 1% less efficient than plasma gasification/autoclaving combination ranked 2.This is one of the major reasons for reduction in growth of WtE plants globally [13]. Thus the need to increase the waste to energy efficiency by using new approaches should be developed.

1.3 Plant Model Considerations

In order to set the goals of our project it is necessary to understand the definition of Process Intensification by Stankiewicz and Moulijn (2000) which is :

"Any chemical engineering development that leads to a substantially smaller, cleaner, safer and more energy efficient technology is process intensification"

So the model considerations was to redesign the MSW waste to energy plant overcoming all the problems in section 1.2 using PI techniques from [17] as follows :

- Energy use reduction by reducing start-up and shut-down times that causes energy losses or by heat integration.
- Cost reduction by new developed equipment by reducing the use of fuels for combustion.
- Increased process flexibility by using more integrated reactors.
- Inventory reduction by decreasing the size of the flu gas treatment unit.
- Greater attention to quality and increase waste to energy conversion efficiency.
- Better environmental performance by eliminating many off gas volumes and components.

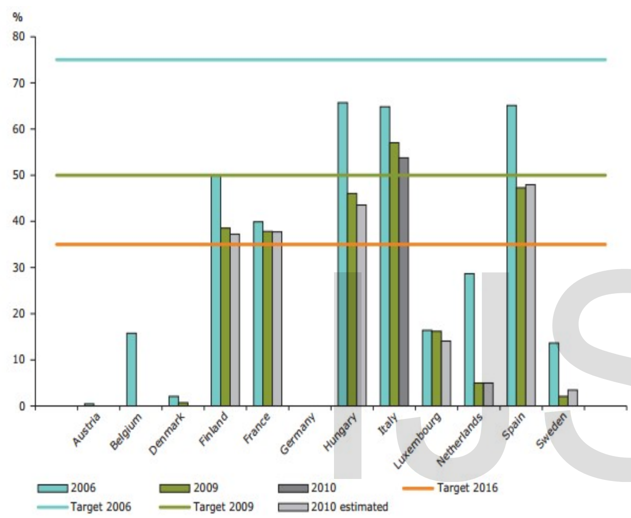

Fig. 4. Percentage of reduction of municipal waste land filled in 2006, 2009 and 2010 in certain EU countries and their set target of percentage reduction in 2016. [8] [5].

2 Traditional Process Description

Globally approximately 130 million tonnes of MSW is converted to produce electricity and steam for district heating while recovering metals for recycling, annually in over 600 WTE plants [12]. Japan is the largest producer of energy from waste having 40 million [18] tones output. China uses the fluidized bed combustion or direct smelting of solid waste, owning 50 WtE plants locally [18].

The process in figure 6 is a design of a typical MSW Waste to Energy plant treating MSW with calorific values of greater than 3300 kJ/kg and moisture contents of less than 55% producing approximately 200 kWh electricity [12]. This plant reduces waste up to 90% in volume.

The plant consists of four major processes:

- Waste pit and Feeding unit
- Furnace
- Heaters
- Flue gas removal

2.1 Feed Input

Waste is brought into the MSW plant by governmental municipalities. They are weighted in the bunker and stored. There are visual incompatible material detectors and metal detectors in the bunker for removal. The control room serves for operation of mixing and arranging the waste for the entry into the plant. The operator here controls feed input to the plant and for this particular plant, it operates at 100–500 t/d.

The Feed hoper is located between the pit and the furnace and has high mechanical and thermal stress bearing capacities. After the feed has been added to the furnace, the hopper valves are closed in order to restrict backfiring of the heat from the furnace destroying the feed in the bunker as shown in Figure 4. Hydraulic cylinders are used, to keep the waste into the plant, by using the rams which constantly moving back and forth [19].

2.2 Combustion Chamber

The feed enters the combustion chamber and is introduced to different temperatures at a certain cycle. The waste is dried by radiation or convection [19] at the beginning of the furnace and this is the lowest temperature of 100 °C. At the next point, the temperature rises to 250 °C and the pressure reduces, the heat in the furnace increases causing pyrolysis to take place, burning volatile components [20]. The final section of the grate is where the complete burn out of the feed takes place with temperatures between 600°C and 1300°C. At this part of the grate the heat content requirement for the MSW is greater than 6000– 6500 kJ/kg, so a supplementary fuel is necessary with an an air/fuel ratio (λ) value between 1.5 and 2.0 [19, 12]. The main products of this combustion are heat, carbon dioxide, water and ashes – infact the last part of the chamber is where afterburning occurs, in order to convert any unreacted carbon monoxide to carbon dioxide [19]. The residence time for the afterburning of the flu gas is 2 seconds and the temperature is 850°C according to European Union Standards, 2008. The fuel triangle in Figure 5 shows the graphical interpretation of the relationship between the mean value of compost of waste and the use of fuel during combustion. The heat value and the waste compost determines the speed of transition amongst the phases below. European waste is reported to have a mean composition of 35 percent combustibles, 30 percent ashes and 35 percent water, resulting this in a heating value of approximately 6.0 MJ/kg [20]. For Chinese waste, moisture content is 50%, the rest same as European, the heating value is 6000– 6500 kJ/kg [12]. Waste with low heating value ranging below 10 MJ/kg, are used to run an combined cycle gas turbine (IGCC) or to run a boiler in steam engines[29]. Wastes of Medium-heating value ranging from 10 to 20 MJ/kg are used to generate gas turbines in IGCC system or ugraded to natural gas. Canadian waste has medium heat-

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ing values as shown in Table 1 compared to other nations [30] but higher than many Europen countries, which states that it can be upgraded to syngas easily.

This is used in the process in figure 4. The waste has to be processed so that non-combustable items are eliminated. Then it is burnt in heated inert material such as sand but coal is used in the above process. They can operate in only excess of 30 - 40% excess air and in low temperatures – thus they are more energy saving [19]. In paper [23] the primary airflow rate was 42,500 Nm^3 / h at 20 and the secondary airflow rate is $9450Nm^3h$. In this plant as shown in figure 11, primary air enters the combustion chamber from five air hoppers underneath the grate, each interval of 16, 32, 26, 18, and 8% of the total primary air, respectively [23].

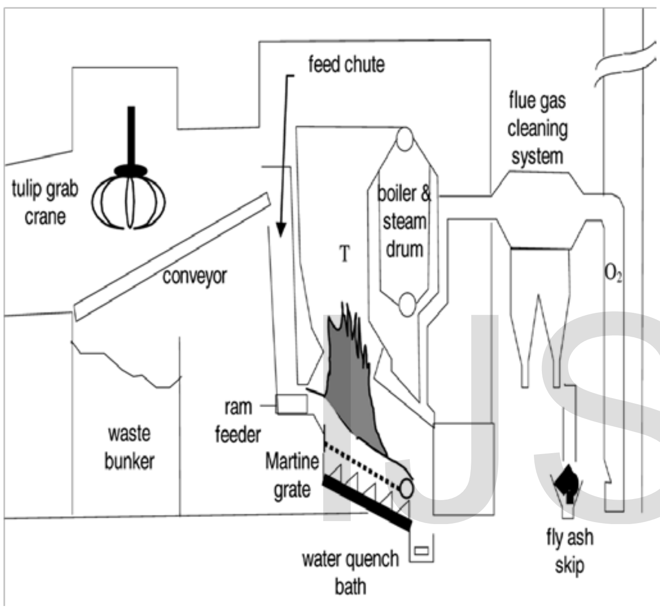

Fig. 4. The Schematic diagram of the conventional MSW incinerator in Sheffield [23]

After combustion of the waste, the slag and metals are collected and separted at the bottom discharger. The ashes are prevented from reaching a melting point of 950 and 1000°C by water-cooling and take the form of paste like structure. Sometimes the water is may be recirculated and the ash is used for road constructions [19].

The heat released from the combustion is used in the super heaters to heat the water pipes into steam. The heated steam is then utilized to run turbines to generate electricity. After passing through the turbines, the steam passed through the steam drum and is cooled down, condensing to a liquid form to recirculate around the process again [19]. " To reduce the acid gas corrosion attack the boilers are typically operate at rather low steam conditions resulting in relatively low overall thermal cycle efficiencies 20%." [12]

2.3 Flu Gas removal

The flu gas goes from the reheater to the cyclone (2) where "

TABLE 1
HEATING VALUES OF WASTE IN DIFFERENT COUNTRIES

County	***Waste Heating Value (HHV)(J/kg)***
China	6000 – 6500 KJ/ kg
European Countries	6.0 MJ/kg
Canada	14.3 MJ/kg

the gas swirls around an immersed tube and the particulates are carried by inertia to the cylinder wall, from where they exit through the conical section on the bottom while the clean gas exits through the top" [20]. Spray electrostatic precipitators (23) use high voltage to electrically charge the particles contained in the flue gas by making contact with ions and electrons, attracting the charged particles toward the precipitation electrode [19]. When the process has ended the, power supply is ceased and the precipitator drops the dust down [19]. Fabric filters passes the raw gas through a filter, which allows airflow out, but traps particle material. The trapped residue remains in the filter and is removed by air is blown in the opposite direction, cleaning the filter [19].

In dry absorption processes no aqueous solution is used as in the wet scrubbers. Instead the flue gas passes through absorption agents calcium hydroxide or lime ($Ca(OH)_2$), and sodium bicarbonate. The solid reaction products are removed from the gas by filtering as shown in Figure 13 [19]. "The ratio used with lime is typically two or three times the stoichiometric amount of the substance to be deposited with sodium bicarbonate the ratio is lower"[19]. Below are the reactions that occur in the scrubber:

Reducing sulphides:
$Ca(OH)_2 + SO_2 \rightarrow aSO_3 + H_2O$ [19]
Or, $Ca(OH)_2 + SO_2\ ½O_2 \rightarrow aSO_4 + H_2O$ [19]

Reducing Acids:
$Ca(OH)_2 + 2H\ l \rightarrow a\ l_2 + 2H_2$ [19]
Or, $Ca(OH)_2 + 2HF \rightarrow aF_2 + 2H_2O$ [19]

2.4 Stack

The clean gas is tested for the level of air contaminant regulations met, and then exited to the atmosphere via the stack. The stack is build up high in order to disperse the exhaust gases over a greater height and reduce the concentration of the remaining pollutants to the levels required by the government [19].

3 Limitations to the Conventional Process

3.1 Heater Efficiency

The WtE plant in the City of Sheffield is a two stream 10 tonnes/hour plant fitted with steam raising boilers of conventional water tube design [23]. Electrostatic precipitators are used for flu treatment. "The maximum evaporation rate of each boiler is 31.8 tonnes of steam/hr with an estimated boiler efficiency of 57.8% [2]." When burning refuse with a high calorific value of 11,000 kJ/kg, each furnace will produce 24.4 MW or 57 × 106 kJ/hr of continuous maximum output of useful heat for export, but the caloric value of many developing countries are not high so their energy production will be much lesser. The efficiency of the boiler must be increased to get better energy to electricity conversions. Other forms of heat recovery from various parts of the process can be added in the later design.

3.2 Waste Elimination and Greener technology

The weight reduction of the plant was destruction of the waste only less than 75% but the volume up to 90% [12]. Technology with higher efficiency can be used. Incineration is used increasingly but high off-gas flow rates and the treatment of these gases is expensive, as well, the side production of slags containing toxic materials, showing that incineration is not a complete destruction to the waste problem. Wastes in many different counties have a low caloric value, and their combustion requires additional sources of fuel. This wastes the resources like coal and fuel which already extinct in nature.

3.3 Cost Reduction

The reduction of costs due to no longer usage of extra fuels and the start up and shut down of the plant causes a wastage of electricity and increases costs. Technology of instant start up and shut down costs must be used.

4 Process Intesification of WtE

4.1 Plasma Torch

MSW can be processed using high-energy plasma torches. The paper in [24] describes many successful experiments involving vitrification of simulated MSW (municipal solid waste), in a plasma reactor. The plasma torches operates at temperatures between 5,000 C and 100,000 C converting waste into syngas with caloric value [24]. It is also proved in [24] that flu gases are much reduced whereas the dioxins emissions were 100 times lower than from an incineration plant (e.g., < 0.01 ng/nm3 measured in stack gas. The thermal efficiency of plasma is 90%.

The energy generated from in an ideal conditions for plasma is given in [33] as below :

$C_6H_{10}O_4 + 3O_2 = 3CO + 3CO_2 + 4H_2 + H2O + 1300$ kWh per ton of MSW.

Gas turbine combustion (assuming no turbine heat loss):

$3CO + 4H_2 + 3.5O_2 = 3CO_2 + 4H_2O + 1500$ kWh per ton of MSW.

Typically, from what can observe in the processes using plasma, the syngas produced has about 30% of the heating value of natural gas. When using in a gas engine or turbine, natural gas has to be added to the syngas to raise the calorific value so that it can be processed by the gas turbine.

This option is not the best one because it will increase the operational costs with the purchase of natural gas.

With 50% of thermal efficiency from the gas turbine, the electricity generated is:

1500 kWh x 50% = 750 kWh from per ton of MSW.

Furthermore, energy can be recovered from the sensible heat of the syngas as well as from the gas engine or turbine. It can be used to produce steam that can then be used to produce more electricity in a steam turbine or used for district heating.

In the case of the steam turbine generator (with assumed thermal efficiency of 32%) as the steam can be assumed with 10% heat loss in the gasifier plus 10% heat loss in the steam boiler, the additional electricity that can be generated is:

1300 kWh x 80% x 32% = 332 Wh per ton of waste processes.

The other possibility is that the sensible heat of the syngas is lost during quenching of the syngas.

For such a process, both industrial grade oxygen and electricity to power the torches have to be provided. The production of one ton of industrial oxygen (95% O_2) requires about 250 kWh of electricity. The equation of gasification shows that one mole of combustible waste requires 3 moles of oxygen. Based on the respective molecular weights, we find that for 148 kg of $C_6H_{10}O_4$, we need 3 x 32 = 96 kg of oxygen. Moreover, we saw that there is about 60% combustible in the waste stream.

Thus, the amount of oxygen required to gasify one ton of MSW is:

1000 kg x 60% x 96/146 = 304 kg of oxygen.

Therefore, the electricity needed to gasify one ton of MSW is:

304/1000 x 250 kWh = 75 kWh of electricity per ton of MSW which has to be provided by the electricity generated using the syngas.

4.2 Integration Heat Exchange

The automotive thermoelectric generator (ATEG) is a device that converts waste heat of a furnace into electricity [26]. The ATEG composed of four main elements: A hot-side heat exchanger, a cold-side heat exchanger, thermoelectric materials, and a compression assembly system [26].

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ATEGs is a technology to convert waste heat from an engine's coolant or exhaust into electricity [26]. The exhaust temperatures of 700° or more, the temperature difference between exhaust gas on the hot side and coolant of the cold side is capable of generating 500-750 W of electricity [26].

Gas Heat exchangers are also used which is a heat exchanger with the slag pit through a shower of fluid that is compressedwater in Figure 5, and the fluid is then taken to the steam heater. This helps to increase the efficiency of heat needed to be fed for the steam and gas engines. This is commonly used for heating gases.

4.3 Membrane Separation Technology

Membrane system is a new method to separate the syngas from the steam by using the principles of diffusion of water vapour through a non-porous ionic membrane.

The selection membrane polymer, a copolymer of perfluorinated ethylene and perfluorinated vinyl compose containing its acid (sulphonic or carboxylic) or a salt [31]. One widely used membrane is sulphonic acid copolymer Nafion®, a copolymer of tetrafluoroethylene and perfluoro (4-methyl-3,6-dioxa-7-octene-1- sulphonic acid). The basic concept is the membrane should be syngas impermeable, but permeable to vapour which has permeability index three orders greater than the permeability of CO_2 or CO, and some six orders greater than the permeability of oxygen or nitrogen[31]. PVA/silica nanoparticle composite membranes have been used as steam recoverers and could be used also as separators in steam recovery for transporting to the steam engines [32].

TABLE 3: SUMMARY OF PI DESIGN

	Time	Operating Temperature	Volume reduced / recov-	Economical Cost	Emission/ By product	Efficiency
Plasma Technology for waste conversion into syngas and steam						
Integrated Heat Exchanger for heat exchange between syngas and compressed steam						
Membrane Technology to Separate Steam from Syngas						

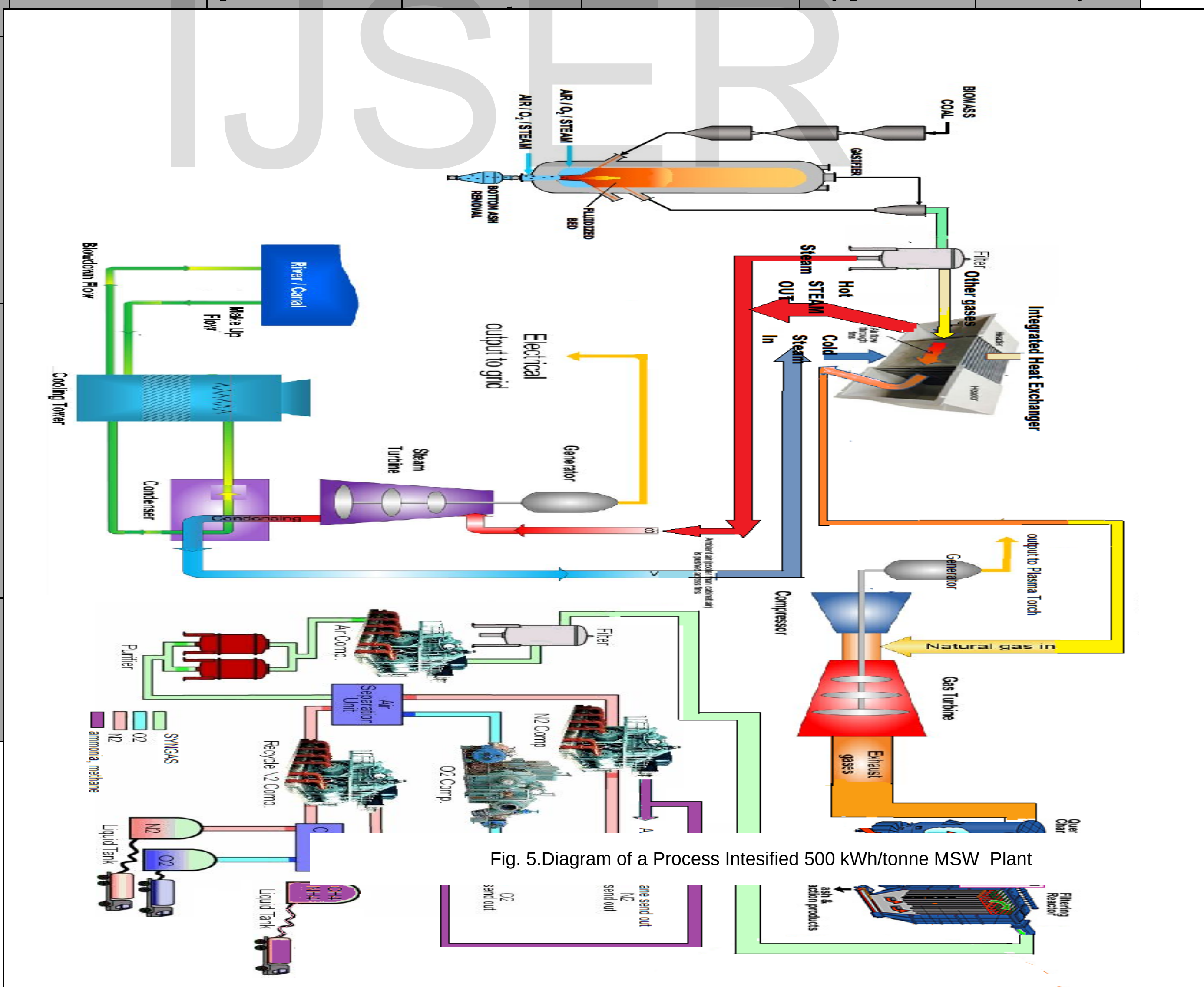

Fig. 5.Diagram of a Process Intesified 500 kWh/tonne MSW Plant

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TABLE 3

ECONOMIES OF SCALE IN A CONVENTIONAL INCINERATOR [1]

Waste (tonne per day)	Heat Input (MWht)	Net Mwe	Overall Efficiency
500	83.3	16.1	19.3

TABLE 4

ECONOMIES OF SCALE IN AN INTESSIFIED WASTE TO ENERGY PLANT

Waste (tonne per day)	Heat Input (MWht)	Net Mwe	Overall Efficiency
500	67.6	25.24	37.3

5 RESULTS AND ANALYSIS

The objectives of the design criteria for the process intesified approach should be advantageous over the traditional approaches.

Table 3 evaluates the traditional WtE incinerators and Table 4 evaluates the process intesified design in Figure 5.

From both of the tables we can presume that the efficiency will be much more increased by the intensification, which is about 2 times of the conventional process.

We also can seen from the table 5, a summary of the extracted syngases energy generation, which can be used in another purposes of industrial uses. This external usage of syngas will obviously put a greater significance to this instensified power plant system.

TABLE 5 ECONOMIES OF SCALE IN SYNGAS PRODUCTION [33]

Amount of oxygen required to gasify 1 ton of MSW Kg	Electricity Needed for oxygen production Kwh	Gross energy of syngas KWh/ton
304	75	808

The process-intensified approach has 27 million tonnes per year of municipal solid waste feed available for the plant in Canada. The cost of generating 25 GWhr per year of electricity for would costs ranging between $0.15 and $0.40 per kWhr [30]. Capital costs of the intesified plant are more than incineration plants, but the intesified plant follows the payback principle as the plant's byproduct can be sold to the market as concrete aggregate whereas its syngas can further be degarded to hydrogen, methane amd oxygen. Our designed plant has an efficiency of nearly 40 % so this reduces the payback period and increase return on investment.

The intensified plasma plant will produce clean syngas convertion with various feed stocks into energy within the standards set by Environment Canada. On the other hand other options of waste conversion such as traditional incineration and landfill are discussed in Table 5. The benefits of a process intensified plant chosen over landfilling is due to saving of land and conversion to energy. Process intensified plant s will be considered as a better option over traditional incinerators due to having non-hazardous by porducts, convertible syngas and higher efficiency of output electricity.

TABLE 6 COMPARING WASTE TO ENERGY TECHNIQUES

Process	Merits	Demerits
Landfilling	Site can be relandscaped once filled. Cheap (in Canada land is available) Convenient and creates nutirents/shelter for wildlife animals	Emissions such as NOx and SOx produce local pollution. Methane is fatal for humans. Land causes harmful leachate of chemicals.
Traditional Incinertors	Combustion results in ash and 30 % of original waste reduction. Energy output is high (70 %) even without oxygen.	Expensive to operate and requires skilled labor. Excess oxygen and coal needed for complete combus-

	All waste conversion is to heat.	tion. Slag is toxic, slag landfilling causes contamination of land. Greater emissions of GHG and other pollutant. Dioxins formed are carcinogenic.
Process Intesified Plant: 1.Plasma Gasifier	Operation without or without oxygen. Weight reduction 60 ~ 80 % and syngas is degraded to steam which is recycled throughout the process. By produced slag is non-harzardous and can reused for making cement or sandblasting. Low levels of emissions as lesser formation of dioxins, furans as complete burnout is assured.	Highest contruction costs close to $ 100 million. Requires electrical energy. Encourages waste production over recycling.
2.Membrane Filters	High Gas permeability and selectivity. Simple flow diagram and no moving operations.	Does not scale up with higher feed inputs. Has operational temperature limits.
3.Heat Exchangers	Heat recovery 4 %. Saves upto 5 % energy losses	Extra investment costs.

6 Conclusion

Municipal Solid Waste to Energy solves disposal of waste and gives out energy and the pollutant emissions with respect to other techniques such as landfilling is reduced. Plasma technology usage is a clean source of energy outputas well heat exchangers cause financial reductions. Plasma-assisted gasification has a potential drive in the growth of WTE industry. First, it is a convenient way to provide thermal energy in a gasification process. Using a reducing atmosphere and producing a relatively smaller amount of process gas facilitates the gas cleaning system. Second, controlling the amount of heat input to the process by means of the plasma torches allows controlling the composition of the syngas. The hydrogen to carbon monoxide ratio can be modified easily, according to the needs of the user. The next decade should research on how inteisifed gasification systems convert MSW to contribute in supplying renewable energy from negative materials. This paper presents an approach to intensify current incineration plants to better designs, which gave better outputs of energy, lower levels of emissions and reusable by products.

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