Hydrothermal Pre-treatment and Gasification of Solid Wastes to Produce Electrical Power and Hydrogen

Kunio YOSHIKAWA
Department of Environmental Science and Technology, Tokyo Institute of Technology
4259 Nagatsuta, Midori-ku, Yokohama 226-8502, Japan
Tel: +81-45-924-5507, Fax: +81-45-924-5518, E-mail: yoshika@depe.titech.ac.jp

1. Introduction

Up to now, the only commercialized ways of waste treatment are mass land-filling and mass burning. In Japan, most of burnable wastes are incinerated, but not in other countries, and still land-filling is the most popular way of waste treatment all over the world. But the world recent trend is to prohibit or limit land-filling of wastes while citizens do not want to increase waste incineration in developed countries as well as developing countries. On the other hand, segregation of wastes is becoming popular in the developed countries and we have limited solutions on the usage of segregated wastes. Thus we have to find out the utilization ways alternative to incineration for each segregated waste.

Based on this background, we are focusing on development and commercialization of new technologies for the utilization of segregated wastes as well as mixed wastes as new energy resources. In general, the economical feasibility of new energy resources are not so good, but in the case of wastes, we can get revenue first by treating wastes and second by selling the product (electricity, steam, hot water, fuels, etc.). The submitted technologies cover total technologies ranging from pre-treatment to final energy production.

2. Overview of the total technologies

Figure 1 shows the overview of the total technologies for Waste-to-Energy presented here.

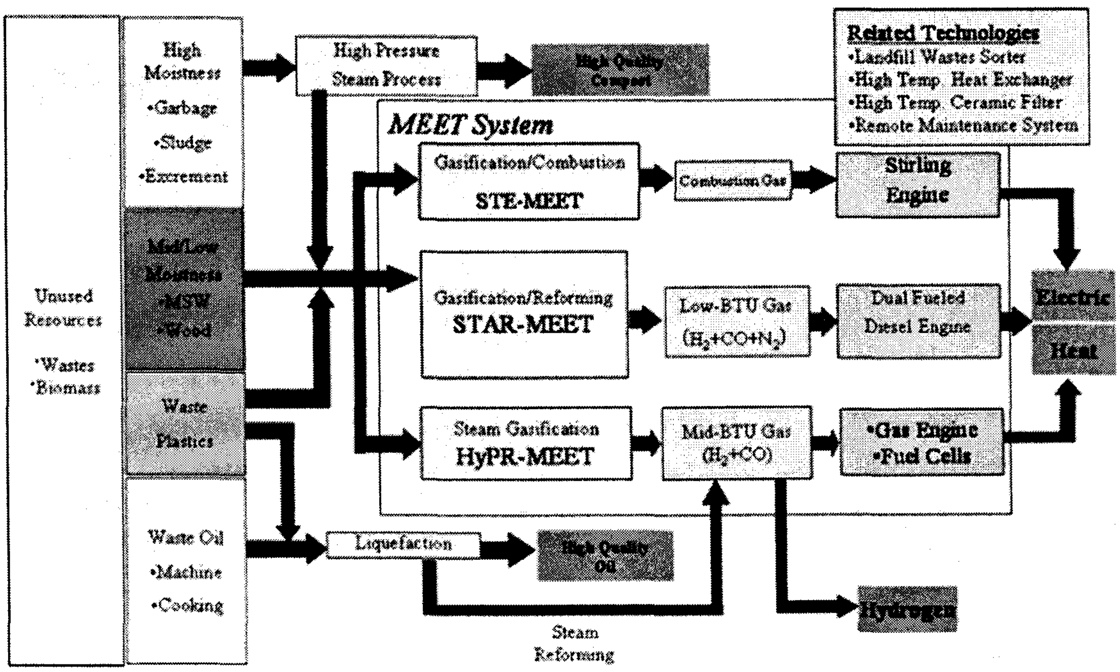


Fig.1 Total technologies for Waste-to-Energy

Unused resources can be classified into high moisture content material (garbage, sludge, excrement, etc.), mid/low moisture content material (wood, paper, etc.), waste plastics and waste oils (machine oils and cooking oils). The high moisture content material will be treated by hyigh pressure steam process to convert into powder-like dry solid fuels. If the raw material is pure biomass (sewage sludge, excrement, food residue, etc.), high quality organic solid and liquid fertilizers can be produced. Then these solid fuels as well as mid/low moisture content material can be converted into gaseous fuels (low-BTU and medium-BTU gases) through gasification processes to generate electric power as well as thermal energy (hot water, steam) by use of dual-fueled diesel engines or Stirling engines. The medium-BTU gas can be utilized as a fuel for burning alternative to natural gas and for extracting hydrogen. Finally, waste plastics and waste oils can be converted into high quality liquid fuels alternative to gasoline, kerosene and diesel oil through the liquefaction process based on the pyrolysis and catalytic reforming processes.

3. Pre-treatment technology

Pre-treatment of wastes requires crushing, drying and deodorizing, which are normally different processes. But we have devised innovative pre-treatment system named as the MMCS (Multi-purpose Material Conversion System) which can perform these three pre-treatment functions in one process utilizing high pressure steam. This technology is characterized by low energy consumption for drying. Figure 2 shows the operating principle of the MMCS and Fig.3 shows a photograph of its commercial plant. Figures 4 and 5 show the photographs of raw material and products.

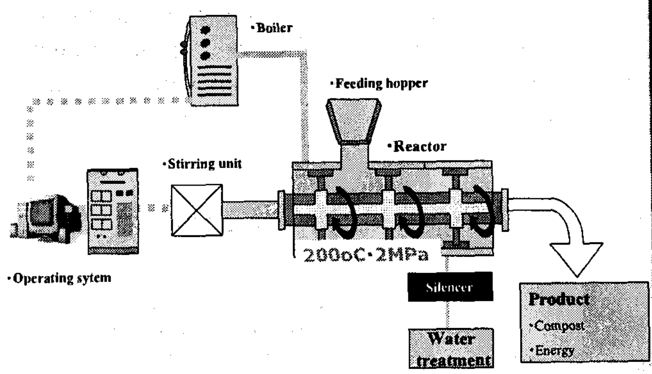


Fig.2 Operating principle of the MMCS

Fig.3 Photograph of the MMCS commercial plant

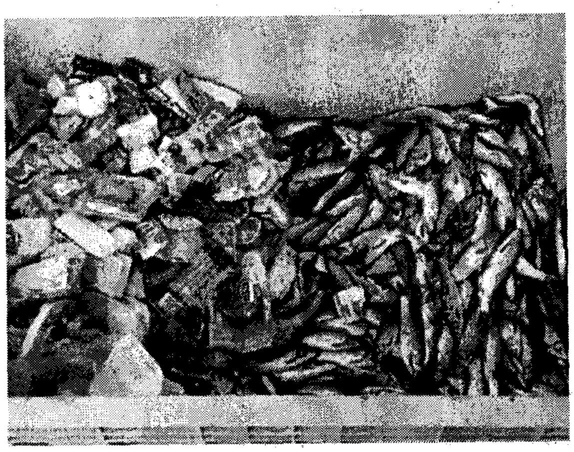


Fig.4 Before treatment by the MMCS

Fig.5 After treatment by the MMCS

Solid wastes are fed into the reactor, and then, 200C, 2MPa saturated steam is supplied into the reactor for about 30 minutes and the blades installed inside the reactor rotates to mix the wastes for about 10 minutes. Then the product is discharged after extracting steam. The product is powder-like substance and the moisture content is almost the same as the raw material, but easily to be dried by natural drying. This means that this MMCS process itself is not a drying process, and drying can be done using natural energy which results in low energy consumption for drying. There is almost no bad smell in the solid products, and the products can be used as liquid and solid organic fertilizers (in the case of biomass such as sewage sludge, food residue and excrement) or solid fuels (in the case of mixed wastes containing plastics) which can be easily mixed with coal for power generation. The commercial plant built by private companies in Japan (shown in Fig.3) accommodates two 5 m^3 reactors whose treatment capacity is about 50tons/day. In this plant, sewage sludge is treated to produce liquid and solid organic fertilizers.

4. Fuel oil production from waste plastics and oils

By use of the pyrolysis and catalytic reforming processes, waste plastics and oils (mechanical and cooking) can be converted into fuel oil. Figure 6 shows its operating principle. Waste plastics or oils are pyrolyzed in an externally heated reactor and are vaporized. By cooling, this vapor condenses and becomes oil, but this oil is mixture of light oils and heavy oils, and the quality as a fuel is not so good. But as shown in Fig.7, by passing this vapor through a reforming catalyst, its molecule is cut, and good quality lighter oils can be produced. These fuel oils can be utilized alternative to gasoline, kerosene and diesel oils. A world largest capacity commercial plant (3tons/hour) is now under construction in Japan, and will be operational at the beginning of 2007.

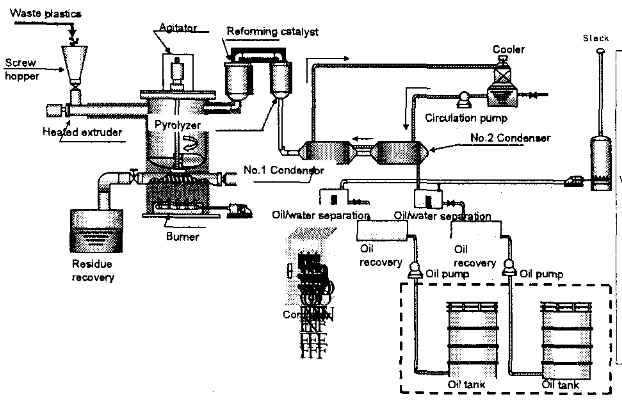


Fig.6 Fuel oil production from waste plastics and oils

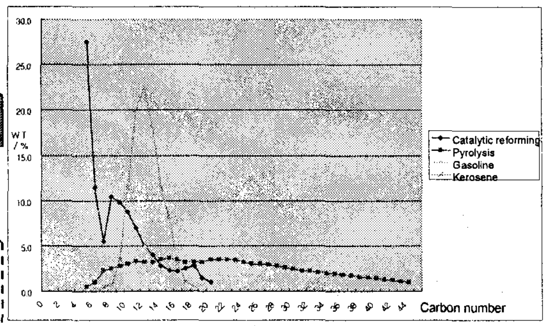


Fig.7 Carbon number distribution

5. Gasification and power generation

5.1 Low-BTU gas production (STAR-MEET)

Figure 8 shows a typical system flow of the STAR-MEET system. Solid fuels are fed into a fixed-bed pyrolyzer using a continuous feed device. Thermal energy for pyrolysis of the solid fuels is supplied from the partial combustion of char at the bottom of the pyrolyzer or melting furnace. Residual ashes are extracted from the bottom of the pyrolyzer in the form of calcinated ashes or from the melting furnace in the form of molten slag. Pyrolysis gas contains H_2, CO, CH_4, N_2, CO_2, O_2, light hydrocarbon and tar. In the reformer, tar and soot components are reformed with high temperature steam in the following endothermic reactions;

$$C_nH_m + nH_2O \rightarrow nCO + (n+m/2)H_2 \quad (1)$$

$$C + H_2O \rightarrow H_2 + CO \quad (2)$$

These reactions are activated under the condition of high temperature over 800C. To sustain this temperature, high temperature steam is employed as well as using high temperature air for partial combustion of the pyrolysis gas. Main components of the reformed gas are H_2, CO, CO_2, N_2, CH_4 and gaseous hydrocarbons such as C_2H_2.

High temperature steam and air are produced from a high efficiency heat exchanger with hot gas from a furnace burning low-BTU fuel gas. The thermal energy of the reformed gas is used for making saturated steam and hot air for the pyrolysis stage. Impurities such as HCl, H_2S, etc. in the reformed gas is removed in the purifier, which is a scrubber (wet) type and/or a dry type such as a dust filter or an impurity adsorption device. The recovered fly ashes (mainly soot) are supplied into the pyrolyzer again, and the condensed water originated from the moisture in the solid fuels and the steam supplied for reforming is adequately treated and discharged. Finally this purified fuel gas is used as a fuel for an engine with a power generator and for a low-BTU gas burning furnace with a heat exchanger.

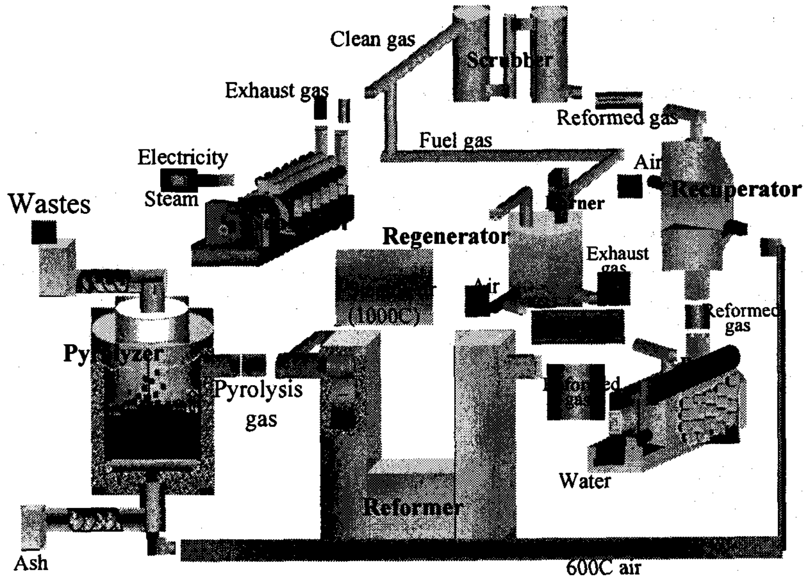


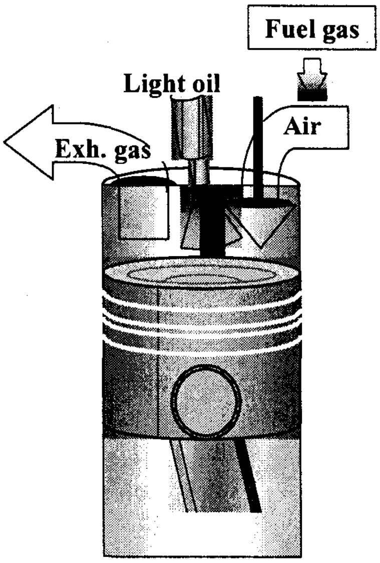
Fig.8 System flow of the STAR-MEET system

5.2 Engines for power generation

5.2.1 Dual fueled diesel engine

Heating value of gaseous fuels produced in STAR-MEET systems are as low as 1/10 of that of natural gas, and there is almost no established energy conversion methods for such low-BTU gases. Therefore, we developed a dual fueled diesel engine for burning low-BTU gases. Figure 9 shows its operating principle. At the start of the plant operation, the engine is fueled by light oil only. Then the produced low-BTU gas is gradually mixed into the combustion air, and in the steady state operation, 20-30% of the total thermal input is supplied by light oil, and 70-80% of the total thermal input is supplied by low-BTU gas. With this method, it is possible to keep the electrical output constant by controlling the amount of light oil supply even if the heating value of the gas fluctuates.

Figure 10 shows the thermal efficiency and NOx emission as a function of the fuel gas rate (thermal input to the engine from fuel gas/total thermal input to the engine) of a duel fueled diesel engine. This figure shows that up to about 80% fuel gas rate can be achievable with almost no substantial drop of the thermal efficiency while significantly suppressing NOx emission. This NOx reduction is due to decrease of oxygen concentration and flame temperature by introducing low-BTU gas into the combustion air.



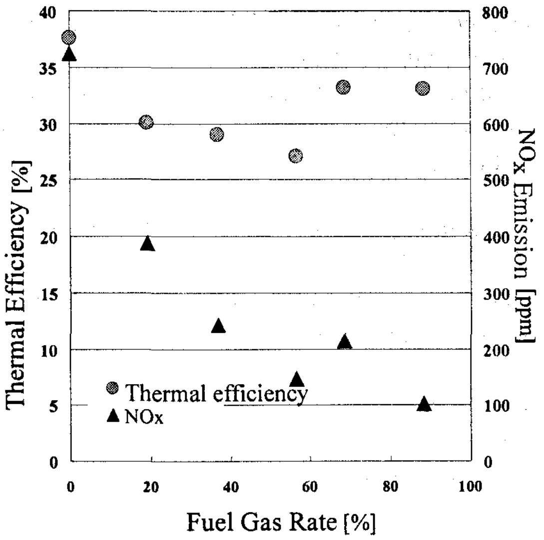


Fig.9 Operating principle of a dual fueled diesel engine

Fig.10 Thermal efficiency and NOx emission of a dual fueled diesel engine

5.2.2 Stirling engine

Internal combustion engines require high level of gas purification to prevent damage to internal engine parts. This gas purification results in high capital and running costs of the plant. In the case of biomass fuels, there are almost no significant pollutants contained, so gas purification can be much simpler if engines are allowed. A US company naming STM Power Co., Ltd. has developed and commercialized a 55kW Stirling engine whose internal structure is shown in Fig.11. It has four cylinders and a swash plate drive which is classified into double acting type Stirling engines. This engine uses hydrogen as a working gas and houses a small hydrogen generator employing water electrolysis. Figure 11 also shows the heat flow in the Stirling engine. The engine has a recuperator to preheat the combustion air up to over 700℃ by getting heat from the hot exhaust gas. Therefore the fuel and high temperature air are supplied into the combustor and are combusted consecutively. Then the combustion gas gives the heat to the hydrogen gas flowing inside of the heater tubes. And then the exhaust gas is cooled to below 300℃ in the recuperator and finally is discharged into the atmospheric air.

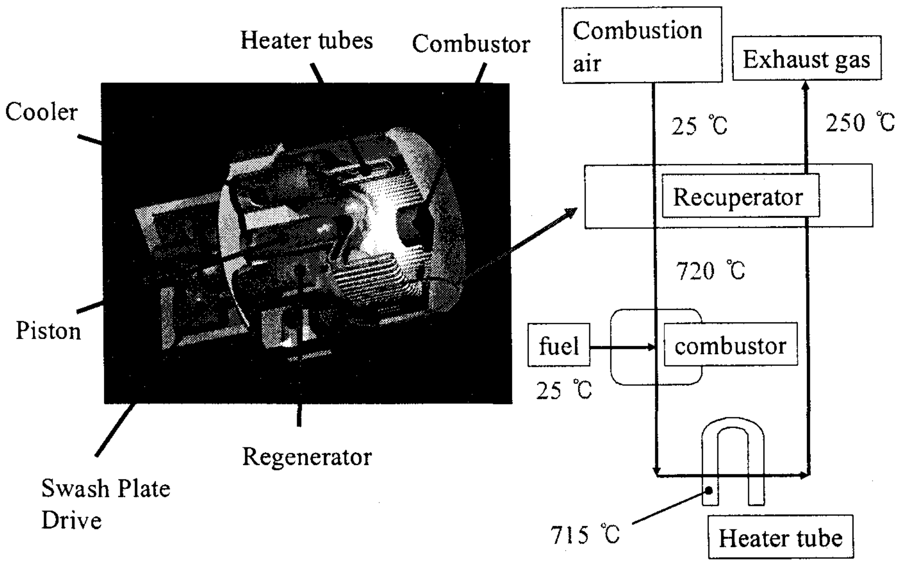


Fig.11 Structure of the Stirling engine of STM Power

By testing this engine, we have demonstrated that this engine can be operable in significantly wide range of heating value of fuel gases (6MJ/Nm^3-25MJ/Nm^3) with almost constant electrical output (55kW) and thermal efficiency (30%). The emissions of NOx and CO are also very low (less than 20ppm). By installing several units in parallel, we can easily increase the power output level.

5.3 Commercial systems of the STAR-MEET system

The STAR-MEET systems can be applicable to small to medium sized plant (1ton-100tons/day scale) for power generation from various kinds of burnable solid wastes. We have constructed two commercial STAR-MEET units.

5.3.1 Power generation from chicken manure using a Stirling engine

Figures 12 and 13 show the system flow and the photograph of the commercial small-scale STAR-MEET system installed in Japan. The system utilizes about 100 kg/hour of chicken manure as a fuel which is pre-dried by the hot air produced by recovering body heat of chickens. The system is mainly composed of an air-blown updraft type fixed bed gasifier, a reformer, gas purification components and a Stirling engine. The reformed gas is premixed with LPG to increase the heating value up to the required value and is injected into the Stirling engine. Hot water generated from the heat exchanger installed in the Stirling engine is used for drying chicken manure. The electrical output of this Stirling engine is 55 kW (1,800 rpm) at 60 Hz.

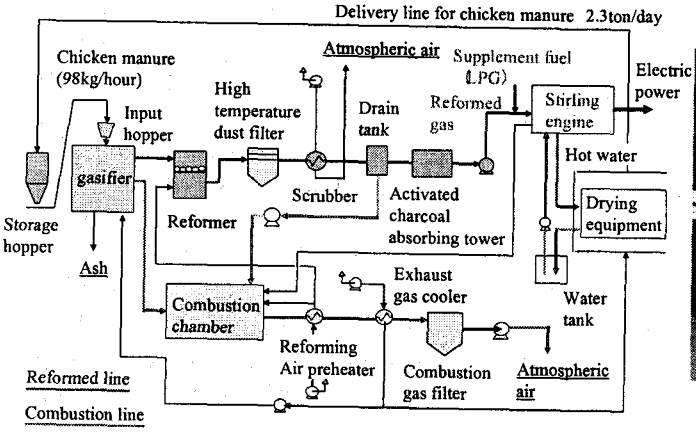


Fig.12 System flow of the small-scale STAR-MEET system

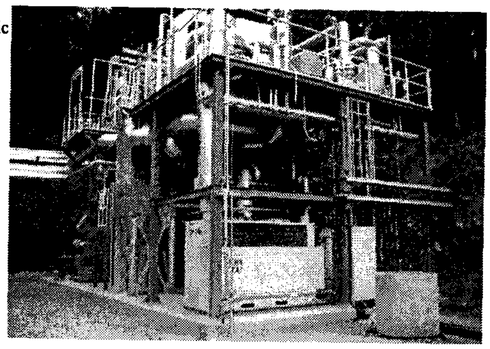


Fig.13 Photograph of the small-scale STAR-MEET system

5.3.2 Power generation from MSW using dual fueled diesel engines

Figures 14 and 15 show the system flow and the photographs of the commercial medium-scale STAR-MEET system installed in a local town in Japan, where 900 kW electric power is generated from 20tons/day of mixture of municipal solid wastes (MSW) and meat & bone meals of cows using six dual fueled diesel engines.

Mixture of MSW and meat & bone meals is fed into a gasifier (shaft-kiln) where it is carbonized by hot oxygen free combustion gas supplied from a melting furnace and then is fed into the melting furnace where the carbide will be completely combusted and the ash will be melted and extracted. The pyrolysis gas produced in the gasifier is introduced into the reformer, where tar and soot components in the pyrolysis gas are reformed into gaseous components by the reaction with high temperature (1000C) steam/air mixture under the condition of high temperature over 800C. Main components of the reformed gas are H_2, CO, CO_2, N_2, CH_4 and gaseous hydrocarbons such as C_2H_2. The thermal energy of the reformed gas is used for making saturated steam. Dusts in the reformed gas are removed by the bag filter, and impurities such as HCl, H_2S, etc. in the reformed gas are removed in the wet type scrubber. The recovered fly ashes are supplied into the gasifier again, and the condensed water originated from the moisture in the solid fuels and the steam supplied for reforming is adequately treated and discharged. Finally this purified fuel gas is pressurized by a suction blower and is used as a fuel for dual fueled diesel engines with power generators and for the low-BTU gas burning furnaces with heat exchangers to produce hot air for the melting furnace and high temperature steam/air mixture for the reformer.

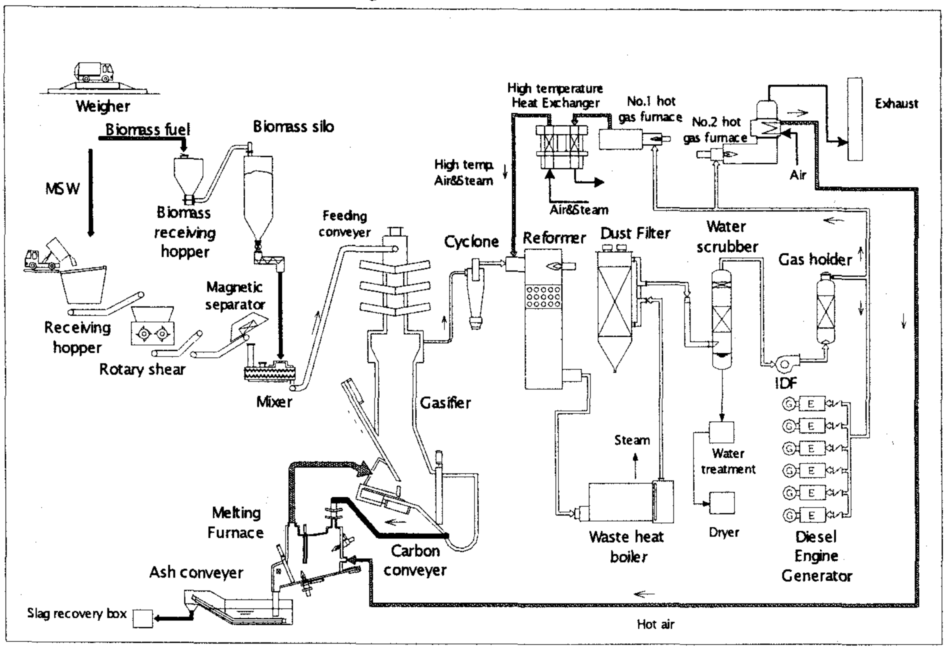
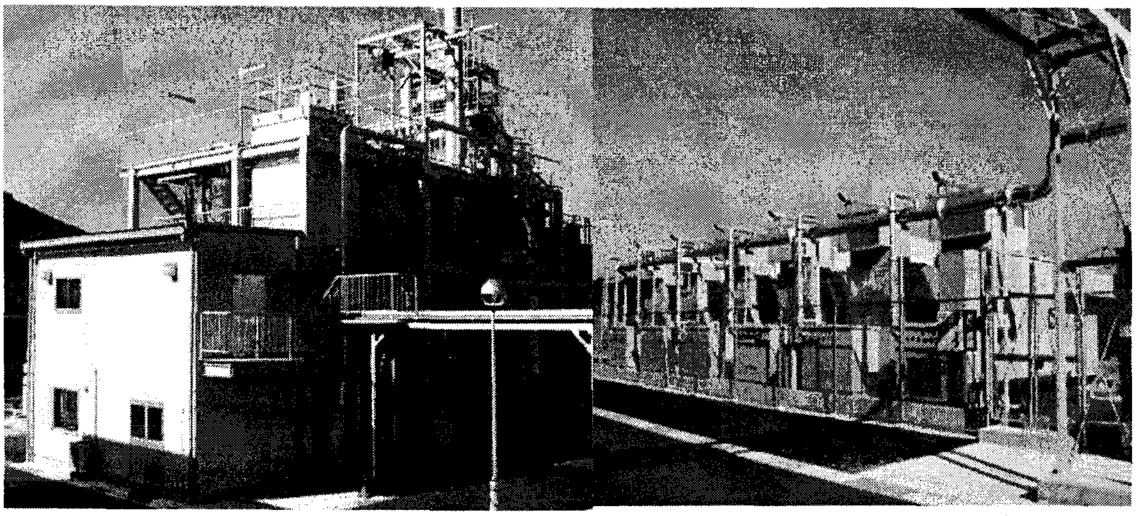


Fig.14 System flow of the medium-scale commercial STAR-MEET system



Gasification part　　　　　　　　　　Power generation part

Fig.15 Photographs of the medium-scale commercial STAR-MEET system

5.4 Medium-BTU gas production

The STAR-MEET system is one of air-blown gasification systems, so the nitrogen contained in air will be mixed into the fuel gas which lowers the heating value of the fuel gas down to about 4MJ/Nm^3. Thus the use of this low-BTU gas is limited only to power generation. In order to avoid nitrogen mixing into the fuel gas, two systems are developed named as REPRES and HyPR-MEET systems. The main component of the fuel gas produced by these systems are H_2, CO and CO_2, whose heating value is about 10-20 MJ/Nm^3, and can be utilized as a gaseous fuel alternative to natural gas. If we will increase the concentration of H_2, we can produce hydrogen which is expected to be a next generation energy media alternative to petroleum.

5.4.1 REPRES system

Figures 16 and 17 shows the system flow and the photograph of the REPRES system. Solid wastes are supplied into the rotary-kiln type gasifier, where they are pyrolyzed by external heating of combustion gas of a part of produced fuel gas and residual char. So there is no mixing of air into the pyrolysis gas. The pyrolysis gas then flows into the reformer, where tar components in the pyrolysis gas are reformed into gaseous components in the char bed which is electrically heated up to about 1000C. So there is no mixing of air into the reformed gas also. The reformed gas is purified by bubbling into a water bath, and will be utilized as a fuel gas for power generation, external heating of the rotary-kiln and other usages. The residual char is recovered and burned to use as a heat source for the external heating of the rotary-kiln. A 20 tons/day commercial plant is recently installed and now under operation in a private company for power generation from construction scraps. The combination of MMCS and REPRES successfully demonstrated production of medium-BTU gas (about 16MJ/Nm^3) from MSW produced in a local town in Japan.

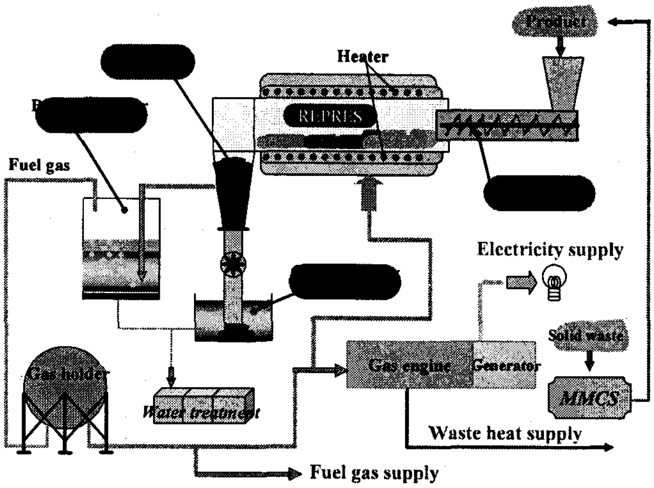


Fig.16 System flow of the REPRES system

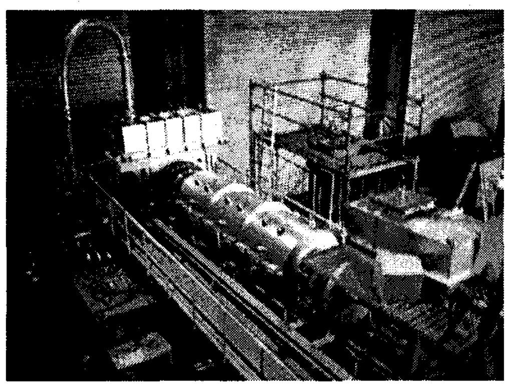


Fig.17 Photograph of the REPRES system

5.4.2 HyPR-MEET system

We have started a new research project aiming at gasifying solid wastes including biomass resources with high temperature steam heated up to about 1000-1300C by using a high temperature heat exchanger and at producing medium-BTU gases whose main components are H_2 and CO. This system is named as the HyPR-MEET whose flow diagram is shown in Fig.18.

Solid wastes and/or biomass resources are fed from the top of the fixed bed type gasifier, and are decomposed to produce a fuel gas and chars with super high temperature steam heated up to about 1300C supplied from the bottom of the gasifier. The fuel gas including tar is led to the reformer and partially combusted by oxygen gas, so we can increase the temperature inside of the reformer up to 800C-1000C. Tar content in the fuel gas is reformed with steam under this high temperature in the reformer and is decomposed to H_2 and CO. A part of tar converts into small soot, so this soot is removed by the high temperature dust filter which is installed downstream of the reformer. Removed soot is recycled into the gasifier as a fuel with solid fuels. With this process, we can produce a clean medium-BTU gas with the heating value of about 8-12 MJ/Nm^3, which is cooled and purified after the sensible heat of the reformed gas is recovered by air preheating and steam generation. At the same time, char remaining in the gasifier is transported into the melting furnace and combusted by preheating air to produce molten slag. High temperature combustion gas with the temperature above 1300C is generated and molten slag exists as a lot of dust in the combustion gas. This combustion gas is cooled to about 1000C by injecting fresh air and solidified molten slag is removed in the high temperature dust filter. Because the combustion gas flowing out of the high temperature dust filter contains lot of oxygen, we can reheat the combustion gas again by injecting a part of produced medium-BTU gas and obtain 1400-1600C combustion gas containing little dust. This high temperature combustion gas is introduced into high temperature steam heater which produces high temperature steam heated up to about 1300C as a gasifying agent. The produced medium-BTU gas is used for driving a gas engine generator, used as a fuel for molten carbonate type fuel cells or used as a feed stock gas for extracting hydrogen because hydrogen concentration in the fuel gas is higher than that in the fuel gas produced by the REPRES system. The HyPR-MEET system is now under development stage, and the photograph of its demonstration plant installed in Japan is shown in Fig.19.

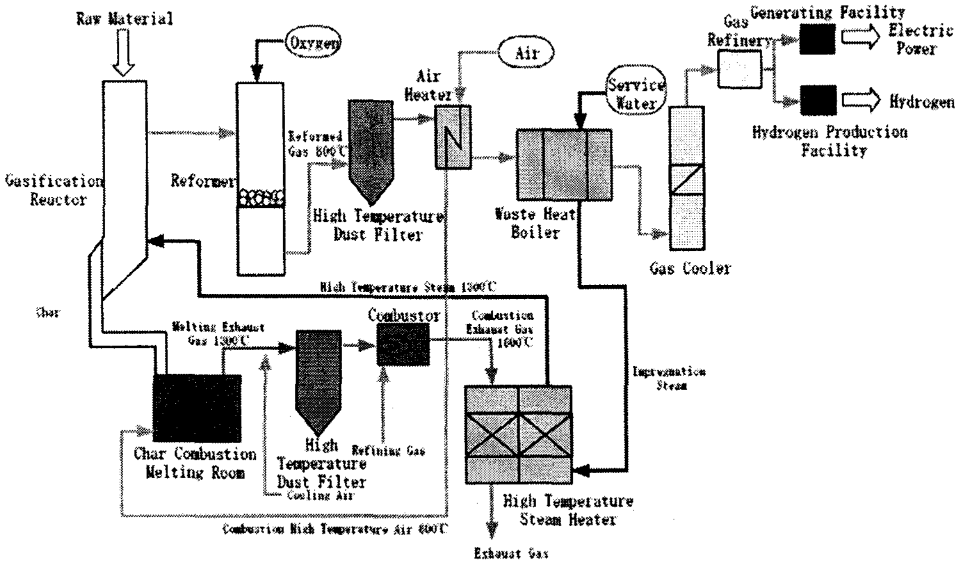


Fig.18 System flow of the HyPR-MEET system

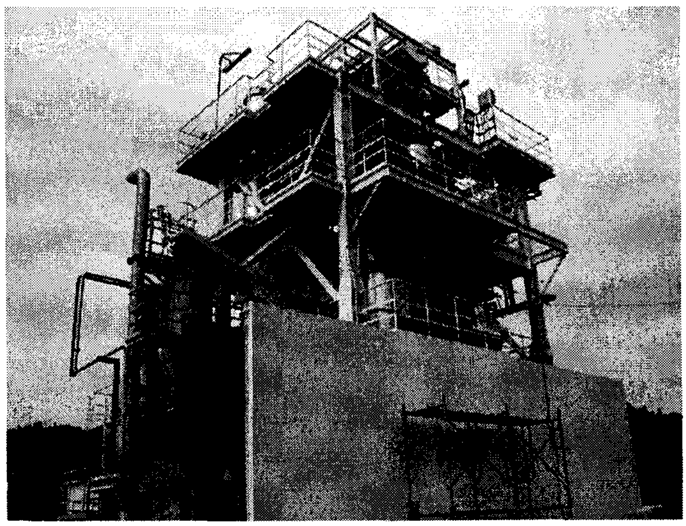


Fig.19 Photograph of the demonstration plant of the HyPR-MEET system

6. Summary

The main feature of these total technologies is that we can constitute the optimum treatment scheme fitting to the property of wastes, amount of wastes and energy requirement. For high moisture content wastes or biomass resources, high pressure steam process (MMCS) for crush, dry and deodorize wastes to produce high quality fertilizer or fuel is most appropriate. For dry or semi-dry solid wastes, the STAR-MEET system can be applied to produce low-BTU gases for power generation using duel fueled diesel engines or Stirling engines, and the REPRES and HyPR-MEET systems can be applied to produce hydrogen rich medium-BTU gas. For waste plastics and oils, liquefaction technology is best fit to produce light oil or kerosene equivalent fuel oils. These total technologies are completely different from the existent waste treatment technologies based on land-filling or incineration, and are expected to disseminate all over the world in the near future.