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Operation Performance of a Pilot-Scale Gasification/Melting Process for Liquid and Slurry-Type Wastes

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Abstract−A gasification/melting facility that can operate up to 10 bar and 1,550 °C with a maximum 1 ton/day capacity was developed for liquid and slurry-type combustible wastes. The main focus of the system development was minimal use of expensive fuel for maintaining the reaction temperature by replacing it with cheap waste oil for energy input. The carbon conversion obtained was 97% while the cold gas efficiency reached 77.6% for the refined waste oil. When the feed was refined oil mixed with fly ash from a municipal waste incinerator, the carbon conversion and cold gas efficiency were 93% and 71.9%, respectively, with a slag conversion ratio of 0.93. The slag produced from fly ash exhibited environmentally acceptable heavy-metal leaching values and thus can be applicable as road material and for other purposes. The optimal O_2/feed ratio was 0.9-1.0 when only the refined waste oil was gasified, whereas the O_2/feed ratio had to be higher than 1.2 when fly ash was mixed. In addition, data showed that gasifier temperature can be estimated by on-line methane concentration measurements.

Key words: Gasification, Melting, Combustible Wastes, Slag, Fly Ash

INTRODUCTION

Recently, the gasification process has received a good reception again in the energy and environmental fields. Among the many advantages of gasification technology, the most prominent one is the drastic reduction of SO_x and NO_x which have been some of the main obstacles in combustion-based processes. With higher recovery of clean energy by gasification from combustible waste feedstock that was considered too dirty to utilize in normal processes, the application area of gasification has broadened into waste treatment processes. In gasification, feeds containing high sulfur and heavy metals can be treated cleanly by producing elemental sulfur/sulfuric acid instead of polluting SO_x through the chemical mechanism of oxygen-deficient reduction environment and by converting heavy metals inorganic components of the feed into slag. Heavy metals are captured inside the intertwined melted structure of slag through the melting process of typically above 1,400 °C. The nitrogen components in the feed react to form mainly NH_3 during the gasification occurring in the oxygen-deficient environment instead of NO_x as in the combustion reaction, and thus they can be scrubbed easily in the gas-treatment step.

Moreover, current environmental concerns regarding the old-style coal-utilization and waste treatment technologies have prompted the development and application of gasification processes that produce far less pollutants like SO_x, NO_x, and dioxins while recovering energy mainly as a chemical energy of CO and hydrogen.

In Korea, waste incineration faces many challenges in proving its environmental cleanness, especially with respect to dioxins and the possibility of heavy metal leaching from the combustion ash. During the last decade, the application of gasification for coal has been quite successful in Korea [Yun et al., 2001], and researchers have started to implement the acquired technology into waste treatment. In the past, cost and system availability were the main obstacles for practical applications. However, wider application of the technology requires more stringent environmental regulations that will in turn stimulate the development of advanced processes. Also, a new energy approach has been proposed to improve the performance of coal IGCC (Integrated Gasification Combined Cycle) systems [Kim et al., 2001].

The objective of the study is to develop a gasification/melting process utilizing dirty and heavy metal loaded waste oil for energy source that is required in itself to be treated in an environmentally benign way. Table 1 illustrates the production and recovery of waste oil in Korea which require treatment. In 1999, 85.1% of the waste oil produced was recycled into low-quality fuel oil that was consumed in boilers for public-baths and other specific areas as required by law. The cement kiln is also a big consumer of waste oil, and fluidized-bed incinerators employ waste oil for auxiliary fuel [Gu et al., 2002]. The total amount of waste oil produced in Korea has more than doubled in five years from 206,000 tons in 1995 to 543,000 tons in 2000.

Since collecting a large quantity of feed in one spot is one of the most critical issues as in most wastes cases, the process is targeting the medium-size gasification/melting process of maximum 50 ton/day size by using not only waste oil but fly ash mixed waste oil to increase the profitability. The process is also targeting for simultaneous gasification and melting of waste oil as energy source instead of combustion-based melting. If dirty fuels like waste oil are employed and most of input energy can be converted into high quality syngas of CO and hydrogen for another purpose of economic value, the gasification/melting process can be more economical in certain areas. The combustion-based melting process of 5 ton/day for wastewater sludge has already been developed and reported else-

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Table 1. Amounts of produced and recovered waste oil in Korea (unit: k*l*)

	Year	1994	1995	1996	1997	1998	1999
Waste oil	Produced	196,828	206,275	212,562	237,504	229,323	198,427
	Recovered	120,416	147,735	174,902	226,139	215,173	168,776
	Recoverd ratio	61.2%	71.6%	82.3%	95.3%	93.8%	85.1%

Source: Korea Oil Recycling Association (2000.11)

where [Yun et al., 2001].

In a typical municipal waste incinerator, ash components go to bottom ash by 90% and fly ash by 10% in general. Although bottom ash is relatively easy to melt to reduce the size in reclamation, fly ash is known to be one of the most difficult feedstocks to melt because of its fine powder and high content of heavy metal components exhibiting low melting point. Reclamation of fly ash and bottom ash at the waste-dumping site has recently become increasingly difficult and expensive; thus an efficient and reliable process to treat fly ash is in great demand. There are many technological approaches, such as thermal plasma [Ahn et al., 2001], electrical arching, and thermal melting, to convert fly ash to slag that is known to be one of the safest ways from an environmental point of view. The nuclear waste treatment field has been active in applying plasma and glass vitrification technologies to melt, vitrify, and reduce the volume of the wastes [Song et al., 1998] since operating cost can be covered in this case. As can be expected, high operating cost involved in the plasma and arching approaches has been a bottleneck for wider applications. For the large volume of fly ash from municipal incinerators, these expensive technologies have a limit in application. Melting the fly ash with waste oil can be one hopeful candidate to overcome the problems regarding operating costs.

For the process development, an accumulated process database in melting for coal and wastewater sludge was first utilized in the basic design of the process and, with additional support of computer simulation on the detailed design, three prototype pilot plants were built and tested with actual feed during the two year period from 2001 to 2002. Based upon the data regarding the reaction characteristics of waste oil obtained from the first prototype that was a small one-stage reactor, the second prototype of 1 ton/day capacity has been built and tested. The third prototype of 1 ton/day size contains more elaborate feeding systems in addition to the internal plate whose purpose is to increase the residence time of the reactants in the reactor. In this study, the gasification/melting results obtained from the third upgraded pilot plant are discussed in terms of syngas composition and effects of key operational variables. Related gasification/melting results for coal and wastewater sludge can be found elsewhere [Yun et al., 2001, 2002], and thermodynamically simulated results for waste oil and refined oil have been published elsewhere [Lee et al., 2002].

EXPERIMENTAL

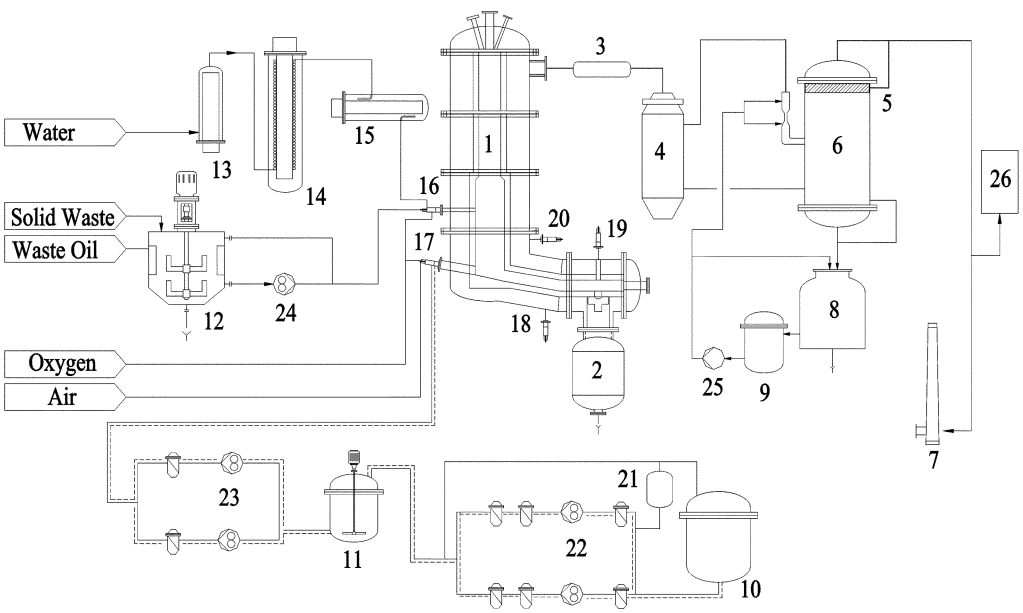

Fig. 1. Process flow diagram of waste-oil gasification/melting system.

1. Melting furnace
2. Slag receiver tank
3. Condensor
4. Water spray chamber
5. Demister
6. Scrubber
7. Flare stack
8. Water tank
9. Bag filter
10. Waste oil storage tank
11. Waste oil service tank
12. Solid waste and waste oil feeder
13. pre-Heater
14. Main steam heater
15. Service steam heater
16. Slurry feed burner
17. Waste oil feed burner
18. 19. Oxygen supply burner #1, #2
20. Pilot burner
21. Washing water tank
22. Waste oil transfer pump #1, #2
23. Waste oil feed pump #1, #2
24. Slurry feed pump
25. Recycle water feed pump
26. On-line gas analyzer

Fig. 1 shows the process flow diagram of the 1 ton/day gasification facility that was developed from March 2000 for the liquid or slurry type combustible wastes. Maximum pressure and temperature for the operation are 10 bar and 1,550 °C, respectively. This system consists of a feeding apparatus, a gasification/melting reactor, a gas treatment facility, and a flare stack.

To treat feeds of high viscosity like vacuum residual oil, an electrical heater was installed around the waste-oil feed tank 12 and to the supply line as far as the slurry feed burner 16. The main waste oil feed for the reactor is provided through the waste-oil feed burner 17 starting from the waste-oil tank 10 through two parallel pumping and filtering lines. Burner 17 provides most of the heating energy to sustain the melting temperature at the bottom part of the melting furnace 1, whereas burner 16 works as a feeding port for solid wastes mixed with waste oil. Waste oil to burner 17 reacts with oxygen and air while waste oil through burner 16 is being mixed with steam and oxygen to be injected into the reactor. The parallel line is used interchangeably when one line is clogged by particulates that reside in waste oils. Solid wastes like fly ash are mixed with waste oil in stirrer vessel 12 and injected into the gasifier through the nozzle with superheated steam that works as a feed carrier as well as a reactant. The steam supply system consists of a constant flow water pump, pre-heater 13, and two consecutive steam generators 14 and 15 for superheated steam generation. Steam works as a reactant in the carbon-steam and water-gas-shift reactions. Superheated steam has been used so that the gasification reaction will not be quenched that occurs at high temperature.

Molten slag flows through the horizontal melting furnace section of the reactor to ensure enough melting residence time and drops into slag receiver tank 2 half-full of water. Hot syngas (>1,200 °C) is cooled in condenser 3 and passes through scrubbers 4 and 6. Scrubbers eliminate soot that resides in the syngas produced with additional demister filter 5. Soot is finally captured at the metal bag filter 9, and the cleaned water is recycled for scrubbing through pump 25. On-line gas analyzers provide an instantaneous gas composition of CO, CO_2, H_2, CH_4 to help in accessing the reaction status. Additional on-line gas chromatography (MTI Analytical Instrument, P200H) provides more precise quantitative gas composition with a 3 minute interval. Combustible syngas with explosive characteristics is combusted in a flare stack 7. The picture of the plant can be found in an earlier report [Yun et al., 2002].

In this study, refined oil vacuum-distilled from automobile waste oil, has been used to determine the performance of the gasification system. Furthermore, the melting system has been verified through the tests with fly ash/refined oil mixed feed. The elemental analysis data of refined oil are presented in Table 2. Table 3 shows the analysis result of fly ash obtained from a commercial municipal waste incineration plant in Gyunggi province, Korea. Inorganic compositions of fly ash analyzed by XRF are also shown in Table 3.

Feeding conditions for the gasification/melting of the waste oil/fly ash feed were 13 kg/hr refined waste oil through the waste oil feed burner 17, and 10.4 kg/hr fly ash mixed with 20 kg/hr waste oil through the slurry feed burner 16 as shown in Fig. 1. Since the process employs an entrained flow type, particle size distribution of fly ash is one of the key parameters for a high yield operation. Particle size distribution data of the fly ash is shown in Fig. 2 in which most of the particles are in the 10-200 μm range. However, a SEM (Scanning Electron Microscopy) picture in Fig. 3 for the fly ash demonstrates a shape of congregates in much smaller pieces to form a bigger size as determined by the particle size analyzer (Malvern Mastersize 2000).

Table 2. Analysis data of refined oil

Ultimate analysis (wt%)						Higher heating value (kcal/kg)
C	H	O	N	S	Ash	
87.6	11.31	0.53	0.18	0.21	0.17	10953

Table 3. Analysis data of fly ash

Ultimate analysis (wt%, as received)						Ash fluid temperature (°C)
C	H	O	N	S	Ash	
0.18	0.07	0.09	0.0	0.99	98.67	1240
Inorganic ash composition (wt%)						
Al_2O_3	SiO_2	CaO	Fe_2O_3	K_2O	MgO	MnO	Na_2O
1.02	2.85	24.3	4.21	1.65	5.0	0.04	4.75
P_2O_5	TiO_2	Cl	ZnO	PbO	CuO	Cr_2O_3	Others
21.21	0.07	1.47	24.95	1.78	2.65	0.24	3.81

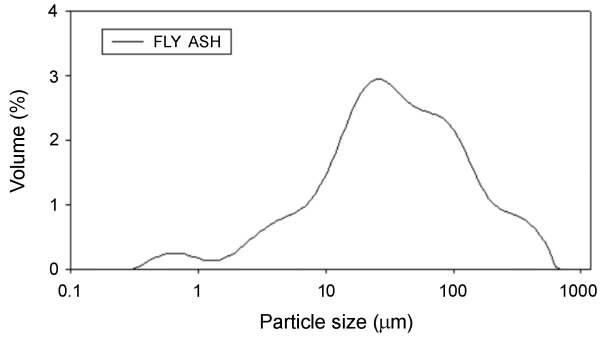

Fig. 2. Particle size distribution of fly ash obtained from municipal waste incinerator.

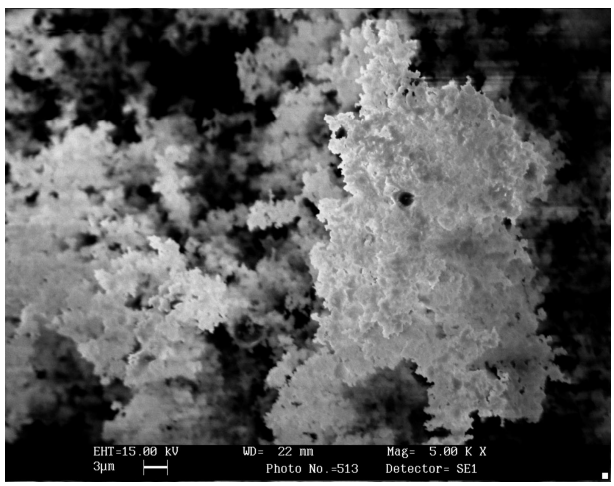

Fig. 3. SEM picture of fly ash from municipal waste incinerator (×5,000).

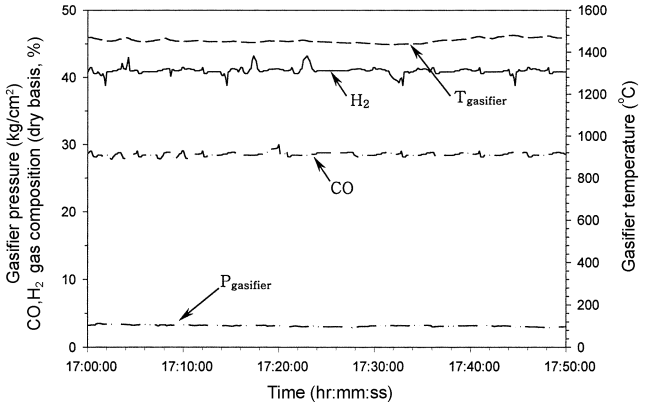

Fig. 4. Typical profiles of operating temperature, pressure, and gas compositions of the produced gas with time.

RESULTS AND DISCUSSION

Fig. 4 illustrates typical operating profiles of gas composition, temperature, and pressure with time when refined oil was gasified in the system. In this case, the reactor pressure was controlled around 3.5 bar, and the reactor temperature measured at the mid-position between feed burners 16 and 17 in Fig. 1 was maintained around 1,480 °C. Gas compositions exhibit around 42% hydrogen and 28% CO. Other gas components include about 14% CO_2 while the rest of the gas is nitrogen that was introduced into the reactor with air utilized for maintaining the suitable burner feeding velocity at the burner tip. The nitrogen was also employed as a spraying medium gas at the water spray chamber. There is about ±1-2% fluctuation in gas compositions, particularly in H_2 concentration that occurred by a mechanical hunting in the steam generator. The amount and quality of steam is critical in determining H_2 concentration because of the steam's role in water-gas shift reaction. A certain range of fluctuation in gas composition can be dealt with by the syngas combustor unless the flame itself is turned off by the fluctuation. From the experimental observation, flame was possible to be lit and maintained when CO concentration is above 20%, preferably above 25%.

In order to obtain the data on the treatable feed amount in a fixed reactor volume, refined oil amount was varied from 15 kg/hr to 30 kg/hr at the O_2/feed mass ratio range of 1.23-1.41. Fig. 5 shows the effect of varying feed amount upon the reactor temperature. In the figure, the horizontal dotted line at the left corner is for 15 kg/hr case while the horizontal dotted line at the right middle corner shows the 30 kg/hr feeding case. Each step represents an increase of 5 kg/hr feeding amount. Steam supply for the gasification reaction was maintained above 0.5 steam/feed weight ratio. For comparison, commercial gasifiers using fuel oil or vacuum residual oil employed a typical steam/oil ratio of 0.41-0.51. Here, reactor temperature is important because it should remain below the serviceable refractory temperature and also be high enough to sustain fast reaction and melting of inorganic components. This temperature is known to be around 1,300 °C in many oil gasification plants. In Fig. 5, when the feeding amount represents 15 kg/hr, the gasifier temperature remains at 1,320 °C. The second step of 20 kg/hr illustrates that the temperature stabilizes at 1,340 °C in less than 10 min. However, at the third step change to 25 kg/hr, the temperature increased to above 1,400 °C after 15 min, which suggests that a reduced amount of O_2 should be employed above 25 kg/hr range if the conversion level is already high enough and able to sustain.

For each step of feeding amount, the syngas composition produced is shown in Fig. 6. At each oil feeding rate, O_2/feed mass ratio was adjusted in the range of 1.23-1.41 for the maximum CO and H_2 content. At 15 kg/hr feeding condition, gas compositions of H_2, CO, CO_2 remain in the 20-25% range altogether. When the feeding amount is increased to 30 kg/hr, H_2 and CO_2 compositions exhibit rapid increase and drop while CO concentration shows a relatively small increment. At the 30 kg/hr condition, the H_2/CO ratio obtained was 1.73, which is close to 1.75 that is obtainable in the commercial gasifiers using natural gas without steam addition. The results illustrate that more proper gasification reactions occur with the increase in oil feeding rate until it reaches 30 kg/hr since most of the feeding oil would be consumed to maintain the reactor temperature when the feeing oil amount is small. Typical commercial-scale fuel oil gasification under conditions of steam/fuel ratio 0.51 and O_2/feed ratio 1.05 produces syngas containing H_2/CO ratio of 0.94. Higher H_2 content can be more competitive in market value if syngas is utilized as a chemical feedstock instead of generating electricity through gas turbine. For power generation, the produced

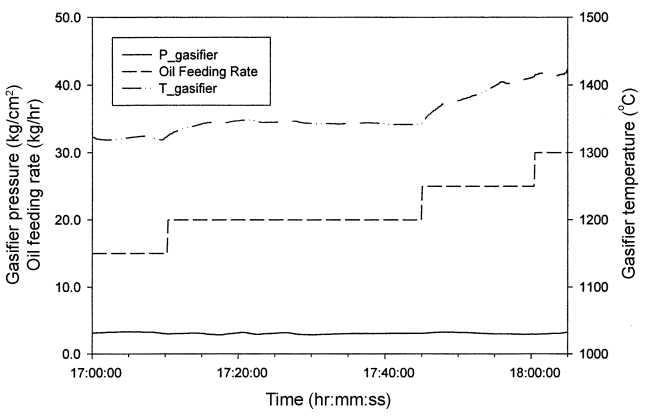

Fig. 5. Effects of feeding amount on the gasifier temperature at the O_2/feed ratio of 1.23-1.41.

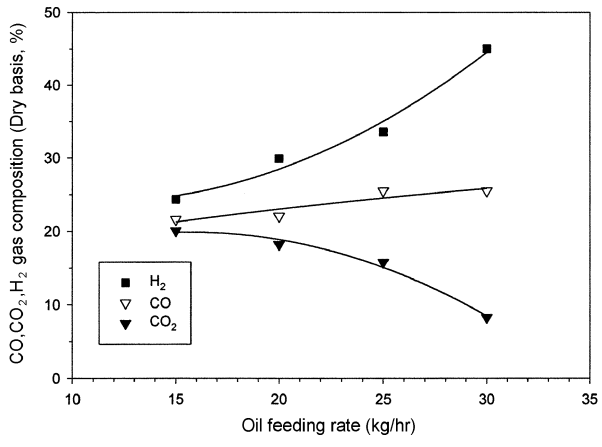

Fig. 6. Syngas compositions with varying feed amount at the O_2/feed ratio of 1.23-1.41.

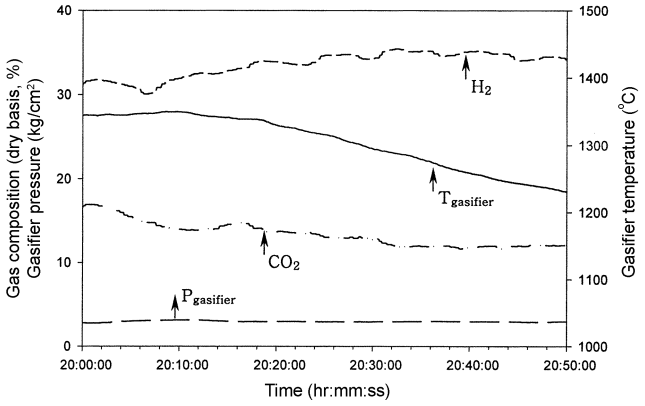

Fig. 7. Sensitivity of gasifier with decreasing oxygen feed amount from 25.5 kg/hr to 12.7 kg/hr at 20 kg/hr refined oil feeding condition.

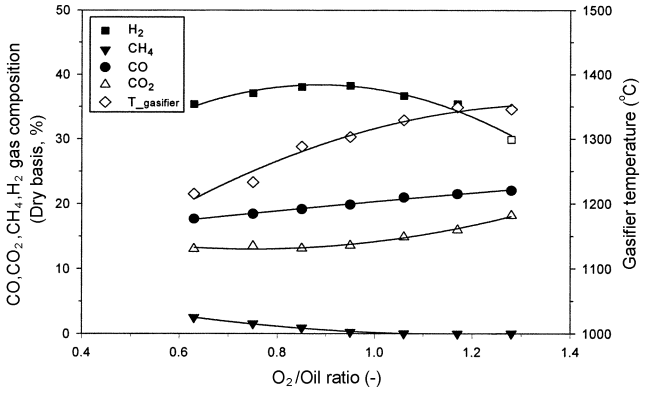

Fig. 8. Effect of O_2/feed mass ratio upon the syngas composition and gasifier temperature at 20 kg/hr oil feeding condition.

syngas has to be combusted. Thus H_2/CO ratio is not an important factor because of their similar heat of combustion. Rather, total syngas heating value is important when the syngas is used as fuel for power generation. For the entrained-bed type gasification system, reaction time is normally less than 4-5 sec requiring fast monitoring of the reaction. Among the important operating parameters, oxygen feeding amount is the most important one because it determines the reactor temperature, hence the reaction time at the fixed reactor volume. If the temperature was not high enough, a large amount of unburned soot would be formed to undermine the conversion.

In order to determine how the change in oxygen feed affects the overall gasifier performance, the oxygen amount was gradually reduced from 25.5 kg/hr up to 12.7 kg/hr while the amount of refined oil was maintained at 20 kg/hr, which corresponds to the O_2/feed mass ratio of 0.635-1.275. The result is illustrated in Fig. 7, in which gasifier temperature, pressure, and H_2/CO_2 compositions are shown. As expected, the gasifier temperature drops from 1,350 °C to 1,230 °C when the O_2/feed mass ratio changes half from 1.275 to 0.635 whereas the CO_2 concentration decreases while the H_2 concentration increases. The CO_2 concentration is reduced from 18% to about 14% directly because the temperature was lowered. It should be noted here that gas composition is not directly related to the total carbon conversion value. At a lower gasifier temperature below 1,300 °C when the oxygen amount was reduced to less than about 0.8, the carbon conversion value would become a few percent lower than the optimal gasifier condition. The meaning of Fig. 7 is that, even with a sudden obstruction of oxygen that is the most important adjustable parameter in the gasifier operation, if the obstruction lasts for a relatively short period of time, the gasifier operation can be maintained probably only with some loss in carbon conversion. But, a sudden increase of oxygen above the optimal condition can pose a serious damage to the refractory lining inside the reactor. The operating experience shows that sudden increase in oxygen of more than about 50% of optimal required oxygen amount can bring about an increase in temperature above 1,550 °C in a few minutes. Thus, the system design should be cautious in preventing any source of sudden increase in the amount of oxygen feeding.

Fig. 8 shows the effect of varying oxygen amount at the fixed feeding amount of 20 kg/hr. Compared to the case where O_2/feed mass ratio was 1.23-1.41 in Fig. 6, the oxygen amount was varied at the lower level of 0.6-1.3. In this case, the optimal O_2/feed weight ratio appears to be around 0.9-1.0 from the convex peak of H_2 where the gasifier temperature is around 1,300 °C. If the feed contains inorganic components that need to be melted to slag, the gasifier operation temperature should be, in general, about 100 °C higher than the fluid temperature of measured ash melting temperature under the reducing environment. From this point of view, to melt the inorganic component in the ash sample showing 1,240 °C fluid temperature, a temperature higher than 1,340 °C would be necessary even though there would be a sacrifice in gas quality, especially a sharp drop in the H_2 concentration. In the case of gasifying only the waste oil that contains no inorganic components to melt, the optimal O_2/feed mass ratio would be 0.9-1.0. On the other hand, if melting of inorganic components were necessary, the melting temperature would determine the operating temperature range first of all.

In contrast to the shape of the H_2 concentration, the increasing amount of the CO concentration is relatively small. With an increase in the O_2/feed mass ratio, the gasifier temperature monotonously increases, and the CO_2 concentration starts to increase rapidly above 0.95 O_2/feed ratios. Thermodynamic estimation also predicts a similar change pattern in gas composition with the O_2/feed ratio for oil gasification [Lee et al., 2002]. On the other hand, methane concentration drops rapidly with the increasing temperature. Methane pro-

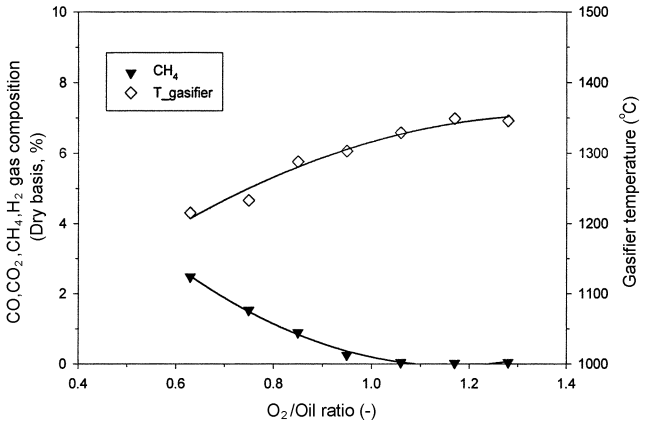

Fig. 9. Relationship between methane concentration and gasifier temperature.

file with temperature is enlarged in Fig. 9.

At high temperatures above 1,400 °C, structural damages in thermocouples that are located on the inner diameter surface of the gasifier are inevitable in the long run. Actual reaction zone temperature can reach above 1,600 °C, and thus flame in the reaction zone should be maintained to minimize any direct hit on the refractory by a proper design and alignment of the feeding nozzle. In operating the entrained-bed type gasifier system, reaction time is just a few seconds, and there is high possibility of refractory damage in a short time of minutes order if the gasifier temperature stays above 1,600 °C. Thus, for safe and reliable operations, immediate knowledge regarding the gasifier temperature of the reacting zone is a critical factor. In commercial gasifiers, most thermocouples are located a few inches inside the gasifier refractory while some thermocouples are directly contacting the reacting gases that are in a reducing and corrosive environment. The directly contacting thermocouple is most prone to corrosion and thermal melting during long operation. Therefore, an indirect way of measuring the gasifier temperature is a very important issue.

As illustrated in Fig. 9, when the thermocouple gets damaged, the methane concentration can be used as an indirect indicator of gasifier temperature. The temperature in Fig. 9 was measured by a direct contacting thermocouple with the reacting gas. The R-type thermocouple was used with a ceramic tip on the gas-contacting area. When temperature gets higher, methane concentration drops rapidly. At a gasifier temperature of 1,200 °C, methane concentration shows about 2.5% value. When the temperature reaches above 1,320 °C, methane concentration level drops below 1,000 ppm level. Normally a coal gasifier operation requires less than a few hundreds ppm of methane level for smooth slag formation and discharge through the slag tap hole. However, since each feed sample shows different response according to its inherent composition and decomposing behavior, independent tests under actual temperature and pressure conditions must be performed to obtain the relationship data of methane concentration versus temperature.

Gasifier performance can be summarized by two parameters of carbon conversion and cold gas efficiency. Cold gas efficiency is defined as the ratio of heating value in the produced syngas to the heating value of total input feed. From the test utilizing refined waste oil, maximum carbon conversion and cold gas efficiencies were 97% and 77.6%, respectively, with typical gas compositions of 21.2% CO, 49.0% H_2, 16.9% CO_2, 0.19% CH_4, 0.01% NH_3, 0.06% O_2, and 12.7% N_2. A simulation study reported that a feed containing higher heating value yields higher cold gas efficiency [Wallman et al., 1998], in that cold gas efficiency of 40-50% was predicted for the municipal solid wastes of 2,390 kcal/kg higher heating value (HHV) while a feed of 9,560 kcal/kg HHV yielded cold gas efficiency of 74-78%. Considering the HHV of the refined waste oil employed in this study, which was 10,953 kcal/kg, the 77.6% value of cold gas efficiency appears to be in the reasonable range approaching the simulation result.

When the mixed feed of refined oil and fly ash was tested, carbon conversion and cold gas efficiency showed 93% and 71.9%, respectively, with a typical gas composition of 28.9% CO, 41.6 H_2, 10.4% CO_2, 0.38% CH_4, 0.015% NH_3, 0.067% H_2S, 0.03% O_2, 18.7% N_2. Based upon the captured fines amounts through the process after the gasifier, the slag conversion ratio was estimated to be 93.1% in single loop, and the rest was carried over from the gasifier. The carryover fines are recycled in the continuous operation.

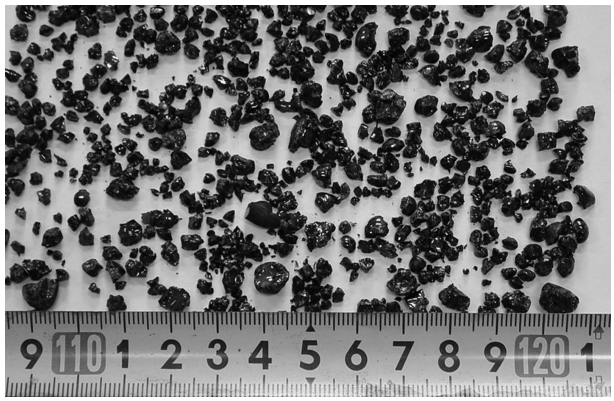

Fig. 10. Size and shape of produced slags after the gasification of the fly ash with refined waste oil (unit: cm).

A similar design of reactor technology was also successfully applied in a 5 ton/day-scale plant for melting wastewater sludge [Yun et al., 2002]. In this case, the system based upon combustion at atmospheric pressure instead of gasification resulted in a once-through slag recovery ratio of above 90%. The size of slags produced shows a diameter from a few millimeters to the maximum of 1.5 cm, depending upon the adjusted silica ratio of ash. In Korea's case, this melting furnace system will be commercially attractive when ocean dumping of wastewater sludge becomes prohibited by 2005 as expected. Currently, land reclamation and ocean dumping are allowed because of the huge amount of sludge and the cost involved when the incineration or melting technologies will be applied.

One of the reasons for applying gasification technology in wastes is its capability to convert heavy metal loaded wastes into environmentally benign products like slag. From the refined oil/fly ash, the produced slag exhibits a few millimeter sizes as shown in Fig. 10, which is quite similar to slags obtained from coal and wastewater sludge at least in size and shape. The incinerator fly ash feed contains a high concentration of fluxing components like 24.3% CaO and 5% MgO, which work to reduce the melting temperature [Yang et al., 1997], and thus exhibit a fluid temperature of 1,240 °C, which is quite a bit lower than the usual incinerator ash fluid melting temperature above 1,500 °C. The gasifier temperature of 1,480 °C was sufficient to melt the fly ash continuously. Although slag composition would vary with feed by its original inorganic composition, it appears that the cooling method for hot molten slag determines the shape and size of the slag produced. In this case, a quenching method in which molten slag drops directly into the water pool was applied as in the cases for coal and wastewater sludge. Bigger slag of 5-7 mm diameters shown in Fig. 10 is easy to break with just a fingertip grip when the quenching method is used. Normally, harder and denser slags can be obtained by a slow cooling method such as cooling under air.

The SEM picture in Fig. 11 on the inner surface of slag demonstrates a dense structure formed by melted inorganic components, which suggests that a finely ground slag might be a good candidate for replacing sand for construction or road construction filler. One of the most important issues regarding waste treatment nowadays is related to methods of converting all the components in wast-

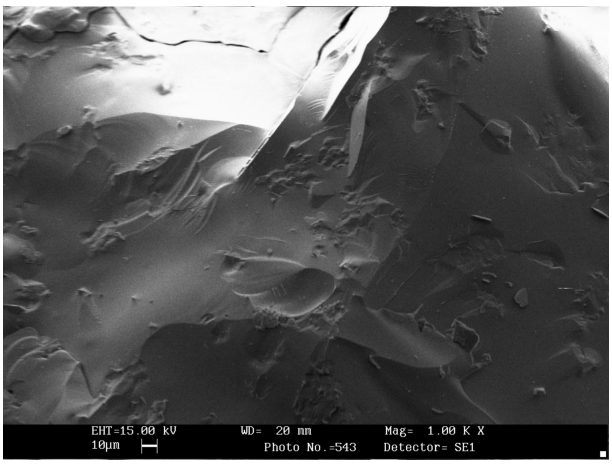

Fig. 11. Inner surface SEM picture of slag produced from the gasification/melting plant for the feed of municipal incinerator fly ash mixed with refined waste oil (×1,000).

es into reusable products of economic value in an environmentally benign way. To verify the safety of slag, effluent tests were conducted to confirm that no effluent would cause leaching of heavy metals. There is a Korean regulation for the allowable leaching concentration of heavy metals Hg, Cd, Pb, Cr^{+6}, As, and CN^- as illustrated in the right-hand column of Table 4. The Korean regulation will become more stringent following the current Japanese regulation standard so that only one-tenth level of above heavy metals are allowed. Considering the trend toward stronger environmental regulation on heavy metal leaching that can contaminate the underground water from ash reclamation sites, melting technology would soon come into the market to replace the current direct reclamation and incineration methods at least for the ash containing high concentration of heavy metals.

Effluent results in Table 4 illustrate that the effluent from untreated incinerator ash leaches a high concentration of Hg, Cd, Zn, Fe, and especially, Pb. The leaching concentration of Cd is more than 200 times above the regulation. Note that Cr in Table 4 measured the total Cr concentration, not the Cr^{+6}. When the ash was treated by the newly developed gasification/melting method, the slag produced exhibited a heavy metal leaching level well below the regulation standards, even below the ten times more stringent standards of the future. Thus, the slags produced by gasification/melting can be utilized safely as a road material and for other purposes.

Table 4. Comparison of heavy metal contents in fly ash, slag, and their effluents from water extraction

Item	Incinerator fly ash		Slag from fly ash		Korean standard
	Total	Effluent	Total	Effluent	Effluent
	wt%	mg/*l*	wt%	mg/*l*	mg/*l*
Hg	0.0009	0.2090	N.D.	N.D.	0.005
Cd	0.0694	64.8680	0.0008	0.001	0.3
Pb	0.2121	2.0960	0.0148	0.008	3.0
Cu	0.0541	1.490	0.0239	0.018	3.0
Cr	0.0531	0.7180	0.0143 (Total Cr)	0.088 (Total Cr)	1.50 (Cr^{+6})
As	0.0051	0.0670	0.0019	0.001	1.0
CN^-	-	-	-	N.D.	1.0
PCB	-	-	-	N.D.	
Zn	0.7385	35.359	0.0527	0.056	
Ni	0.0088	0.1950	0.0020	0.006	
Fe	0.2793	20.8130	0.1299	0.322	
Mn	0.0241	2.6250	0.0072	0.007	

(N.D.: Not detected).

CONCLUSIONS

A gasification/melting process utilizing the calorific value of waste oil as a heating energy in melting has been installed and tested. The feed of fly ash was converted into environmentally benign slag products while minimizing extra fuel cost. Overall efficiencies were verified to be above 90% in carbon conversion and above 70% in cold gas efficiency. Tests varying feeding amounts yielded a maximum H_2/CO ratio of 1.73, which is close to the commercial gasification results with natural gas. As one of the most important parameters in the gasifier operation, an optimal O_2/fuel mass ratio for refined waste oil was found to be in the range of 0.9-1.0. However, if the inorganic components in the feed need to be converted to slag, the fluid melting temperature of the feed determines the operation temperature. For the sample of fly ash mixed with waste oil in the study, an O_2/fuel ratio of above 1.2 was necessary in order to sustain the reactor temperature.

The effects of reducing the oxygen amount were tested to verify the response upon gasifier temperature and upon the produced syngas compositions. In addition, results clearly illustrated that methane content in the product gas can be utilized for indirect temperature estimation inside the reactor, which is useful in considering the frequent breakdown of thermocouples under the hostile condition of reducing high temperature in gasification.

Gasification slags were confirmed to be environmentally safe in the aspect of heavy metal leaching even with the ten times more stringent future regulation standards, demonstrating also a dense structure suitable for sand replacement or fillers in construction.

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