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Experimental and theoretical study on the characteristics of vacuum residue gasification in an entrained-flow gasifier

Young-Chan Choi[†], **Jae-Goo Lee, Sang-Jun Yoon and Moon-Hee Park***

Fossil Energy & Environment Dept., Korea Institute of Energy Research, Daejeon 305-343, Korea
*Daesung Institute for Clean Energy, Daegu 703-090, Korea
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Abstract−About 200,000 bpd (barrel/day) vacuum residue oil is produced from oil refineries in Korea. These are supplied to use asphalt, high sulfur fuel oil, and upgrading residue hydro-desulfurization units. High sulfur fuel oil can be prepared by blending oil residue with light distillate to bring fuel oil characteristics in the range of commercial specifications, which will become more stringently restrictive in the near future in Korea. Vacuum residue oil has high energy content; however, due to its high viscosity, high sulfur content and high concentration of heavy metals are representative of improper low grade fuel, which is considered difficult to gasify. At present, over 20 commercial scale IGCC (Integrated Gasification Combined Cycle) plants using feedstocks with vacuum residue oil for gasification are under construction or operating stage worldwide. Recently, KIER (Korea Institute of Energy Research) has been studying the vacuum residue gasification process using an oxygen-blown entrained-flow gasifier. The experiment runs were evaluated under a reaction temperature of 1,200-1,250 °C, reaction pressure of 1.0 kg/cm^2, oxygen/V.R ratio of 0.8-1.2 and steam/V.R ratio of 0.4-0.7. Experimental results show a syngas composition (CO+H$_2$), 77-88%; heating value, 2,300-2,600 kcal/Nm^3; carbon conversion, 95-99, and cold gas efficiency, 68-72%. Also, equilibrium modeling was used to predict the vacuum residue gasification process and the predicted values reasonably well agreed with experimental data.

Key words: Gasification, Syngas, Vacuum Residue, Entrained-flow

INTRODUCTION

The recent energy consumption in South Korea shows that the consumption of light oil such as gasoline has increased consistently due to the economic growth and the development of car industries. As the consumption of low grade heavy oils is regulated in order to prevent air pollution in cities; however, high sulfur bunker-C oils are being replaced with clean fuels such as light oil or gas. The continuous increase in the consumption of clean fuels and the decrease in the consumption of heavy oils are accelerating imbalance between the supply and demand of heavy and light oil. So, oil refineries in Korea have been increasing the yield of light oil by applying thermal cracking, catalytic cracking, hydrocracking, partial oxidation methods to atmospheric residue, by-product after refining, or vacuum distillation method, those of which are not apart from simple atmospheric distillation [Kim et al., 2001].

As global pressure is expected to increase to resolve recent steep increases in oil price due to the Iraq war, terror risks, and global warming, some advanced countries are actively developing clean energies by improving the efficiency of electric power generation and gasifying low grade oil sources. According to the Peak-oil theory [Park et al., 2002] that has been discussed among energy specialists and geologists after the 1970s, oil production is not only expected to decrease rapidly but also the oil price is expected to skyrocket due to the decrease in oil reserves, population increase, economic problems, and other complicated social factors. Therefore, the development of ultra heavy oil including Orimulsion that uses oil shell, tar sand, and bitumen as raw materials is expected to mitigate the consistent oil crisis. Considering that CO$_2$ emissions from burning of ultra heavy oil are 4-6 times [Park, 2005] more than those from existing fuel burning, the development of clean energy technologies of ultra heavy oil is urgently required.

Vacuum residue gasification technology using Texaco type gasification process that can solely gasify liquid hydrocarbon fuel is the one of the technologies to expand the demand for excessive by-products that are generated from the producing process of high quality petroleum. The expansion of the demand for heavy oil may resolve the imbalance between light and heavy oil consumption. This technology is also expected to be an essential alternative to maintain stability of the domestic energy supply and demand and resolve environmental problems not only because energy and electricity are produced with syngas, which is generated by gasifying a variety of raw materials that are solid or liquid, but also because new processes with polygeneration concepts that produce hydrogen and synthesize methanol and DME can be developed.

Currently, about 200,000 bpd vacuum residue is produced from five oil refineries in Korea. Some of them are supplied to use asphalt or sulfur fuel oil and others are supplied for upgrading at the residue hydro-desulfurization process. The basic principle of this technology is to change heavy hydrocarbon, which has high boiling point in crude oil, to light hydrocarbon under the catalyst in hydrogen atmosphere or to desulfurize in the form of H$_2$S by reacting sulfur with hydrogen. However, as most processes that change heavy oil to light oil spend large amounts of hydrogen, new technologies, with which hydrogen can be produced more easily, are simultaneously

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[†] To whom correspondence should be addressed.
E-mail: youngchan@kier.re.kr

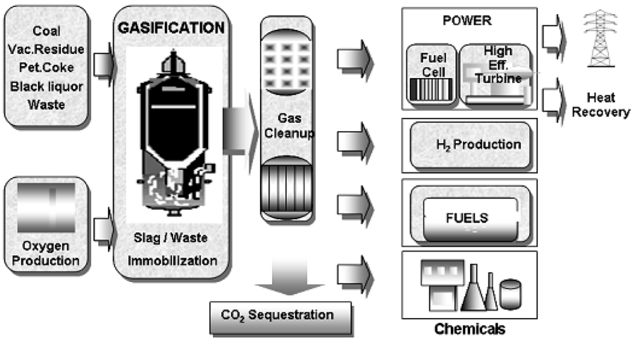

Fig. 1. PFD of polygeneration system.

being developed [Park et al., 2002].

Methods to produce hydrogen in the oil refining process are divided into the Methane Reforming Method and the Partial Oxidation Gasification Method. The gasification technology with non-catalyst, partial oxidation, and steam reaction produces gas that is composed of H_2 and CO through partial oxidation reactions and endothermic gasification reactions. Fig. 1 shows PFD of the polygeneration system related to entrained-flow gasification of low grade hydrocarbon fuels including vacuum residue.

As the operating condition of gasification reactor requires a very high temperature of more than 1,200 °C, incombustible matters such as ash are melted and discharged in the form of slag. Because toxic heavy metals are included in slag when slag is solidified, it is possible to treat them in a stable condition. In addition, the amount of product gas is much smaller compared to that of a combustion or incineration system, so the gas refining system, which treats reductive pollutants such as H_2S, NH_3 produced during gasification process, can be smaller. That means it can be an easier technology to accomplish clean energy.

Kidoguchi et al. [2003] at the Central Research Institute of Electric Power Industry (CRIEPI) in Japan developed and verified the technique, “Research Gasifier for Liquid Fuel” for liquid fuels such as extra heavy oil to establish technology for supporting rational design and operation of a gasifier, in order to clarify significant phenomena in a gasifier. In this research, the effect of steam feed rate to a gasifier on gasification characteristics was quantitatively examined. Futhermore, heat and material balance calculation was done based on the data obtained from the gasification tests.

In this study, for IGCC, hydrogen production process, and the conversion of syngas to clean liquid fuel, we try to understand gasification characteristics of vacuum residues that are produced by domestic refineries and problems related to operations by using an entrained-flow gasifier. The entrained-flow gasifier not only has a simple process but also fast gasification reaction time that responds sensitively to the load changes. Experimental results are compared with the composition of product gas, calorific value, etc., which are calculated through the theoretical analyses about vacuum residue gasification by using the equilibrium model. The results will be applied to a future power generation system from vacuum residue and the design and construction of hydrogen production process.

THEORETICAL ANALYSIS

On the basis of experimental know-how acquired through coal gasification study using an entrained-flow gasifier, KIER performs a vacuum residue gasification study. Generally, when particles of coal or vacuum residue flow in a high temperature gasifier, particles are heated and water is evaporated very quickly. If the temperature rises higher, volatile matter in particles is devolatilized and flames are made by reacting to oxygen with char. They go through the process of combustion and gasification. Each particle in a gasifier goes through complicated chain reactions with very short residence time and very fast heating rate which also affects the temperature, reaction rate, and composition of produces gas in a gasifier. By using the equilibrium model [Himmelblau, 1996], which hypothesizes thermodynamic equilibrium in these very complicated coal and vacuum residue activities, product gas and calorific value as per the condition of gasification agent input can be analyzed. Table 1 shows the chemical properties of the vacuum residue produced in domestic S company which are used for theoretical analyses and experiments of this study.

When vacuum residue is presented by rational formula only with C and H on the basis of Table 1, it is $C_{81.85/12}H_{10.03}$. Simply, it can be expressed as $CH_{1.47}$ and its molecular weight is 13.47.

The global gasification reaction equation of vacuum residue can be shown as follows:

$$CH_{1.47}+wH_2O+mO_2=x_1H_2+x_2CO+x_3CO_2+x_4H_2O+x_5CH_4 \tag{1}$$

The material balance equations of global gasification reaction can be established as follows:

$$\text{Carbon balance: } 1=x_2+x_3+x_5 \tag{2}$$

$$\text{Hydrogen balance: } w+0.735=x_1+x_4+2x_5 \tag{3}$$

$$\text{Oxygen balance: } w+2m=x_2+2x_3+x_4 \tag{4}$$

If the status of equilibrium regarding gasification process is assumed, the energy balance equation is as follows:

$$\begin{aligned} H^o_{f,\,V.R}(T_i)+wH_{H_2O(l)}(T_i)&=x_1H_{H_2}(T_o)+x_2H_{CO}(T_o)\\ &\quad+x_3H_{CO_2}(T_o)+x_4H_{H_2O(v)}(T_o)+x_5H_{CH_4}(T_o) \end{aligned} \tag{5}$$

where, T_i=298.15 K, T_o=process parameter

$$H_i(T_o)=H^o_{f,\,i}+\Delta H_i,\ \Delta H_i=(T_o-T_i)(C_{p,\,i})$$
$$H_{H_2O(l)}(T_i)=H^o_{f,\,H_2O(l)}+H_{(vap)}=-241{,}865\ \text{kJ/kmol}$$
$$H_{H_2O(v)}(T_o)=H^o_{f,\,H_2O(v)}+\Delta H_{H_2O(v)}$$

The equilibrium model can be analyzed under the assumption that all reactions are thermodynamically in equilibrium. The methane formation, water gas shift reaction and equilibrium constant are as follows [Zainal et al., 2001]:

$$C+2H_2=CH_4 \tag{6}$$

Table 1. Elemental analysis of vacuum residue

Sample no.	Carbon (wt%)	Hydrogen (wt%)	Oxygen (wt%)	Nitrogen (wt%)	Sulfur (wt%)	Ash (wt%)	H.H.V (kcal/kg)
V.R.	81.85	10.03	2.20	0.20	5.72	0.96	10,010

$$CO+H_2O=CO_2+H_2 \qquad (7)$$

$$K_1=\frac{P_{CH_4}}{(P_{H_2})^2} \qquad (8)$$

$$K_2=\frac{P_{CO_2}P_{H_2}}{P_{CO}P_{H_2O}} \qquad (9)$$

Therefore, Eqs. (8) and (9) can be explained with functions of the concentration and temperature of global gasification reaction equations, as follows:

$$\text{Methane formation: } K_1(T_o)=\frac{x_5}{(x_1)^2} \qquad (10)$$

$$\text{Shift reaction: } K_2(T_o)=\frac{x_1x_3}{x_2x_4} \qquad (11)$$

$$\text{Where, } K_1(T)=T^{-6.567}\text{Exp}\Big(\frac{7082.848}{T}+\frac{7.466\times10^{-3}}{2}T -\frac{2.164\times10^{-6}}{6}T^2+\frac{0.701\times10^5}{2T^2}+32.541\Big),$$

$$K_2(T)=T^{1.86}\text{Exp}\Big(\frac{5872.373}{T}-\frac{2.7\times10^{-4}}{2}T -\frac{58200}{T^2}-18.013\Big) \text{ [Kim et al., 2002]}$$

The global gasification reactions have eight parameters (x_1, x_2, x_3, x_4, x_5, w, m and T); with these parameters, six equations for material balance and equilibrium reaction are explained. Among the parameters, x_1, x_2, x_3, x_4 and x_5, which represent the concentration of products, are unknown parameters and the quantity of H_2O and O_2, which are put in as reactants, and reaction temperature are process parameters. Therefore, by fixing reaction temperature (process parameter) and determining the quantity of H_2O as the quantity that is put in the process, the quantities of O_2 and produces gas, which are necessary for reaction, can be calculated by combining the previously defined six equations. The previously defined six simultaneous equations can be solved by the Newton-Raphson method with repetitive calculations under a tolerance of 10^{-6}. The detailed process for calculation is in Reference [Himmelblau, 1996]. Constants, ΔG^o_{298}

Table 2. Constants of heat capacities, Gibbs functions and heats of formation at 298.15 K (kJ/kmol)

Formula	Phase	Constants of heat capacities*					$\Delta G^o_{298.15}$	$\Delta H^o_{298.15}$
		T_{max}	a	10^3b	10^6c	10^{-5}d		
CH_4	g	1,500	1.702	9.081	−2.164	-	−50,460	−74,520
H_2	g	3,000	3.249	0.422	-	0.083	0	0
CO	g	2,500	3.376	0.557	-	−0.031	−137,169	−110,525
CO_2	g	2,000	5.457	1.045	-	−1.157	−394,359	−393,509
H_2O	g	2,000	3.470	1.450	-	0.121	−228,572	−241,818
H_2O	*l*	-	-	-	-	-	−237,129	285,830
O_2	g	-	-	-	-	-	0	0
C	s	2,000	1.771	0.771	-	−0.867	0	0
$CH_{1.895}O_{0.363}$	s		-	-	-	-	-	−86,913*

*Equation of heat capacities is $C^{ig}_{p,i}/R=a+bT+cT^2+dT^{-2}$.
*From Hess' law.

Table 3. Function of equation with operation temperature

Temp. (°C)	K_1	K_2	H_{H_2}	H_{CO}	H_{CO_2}	$H_{H_2O(v)}$	H_{CH_4}
1,500	0.000831	0.276987	45395.045	−62122.430	−315975.574	−180568.712	28408.989
1,400	0.001207	0.310618	42086.932	−65726.341	−321980.061	−186088.942	19327.878
1,300	0.001835	0.354680	38813.608	−69283.832	−327893.377	−190926.834	10399.713
1,200	0.002952	0.414078	35575.013	−72794.882	−333714.685	−195643.655	1660.474
1,100	0.005084	0.496936	32371.070	−76259.460	−339442.899	−200239.289	−6853.853
1,000	0.009516	0.617446	29201.676	−79677.530	−345076.596	−204713.590	−15107.286
900	0.019749	0.802020	26066.694	−83049.039	−350613.865	−209066.357	−23063.842
800	0.046687	1.103809	22965.936	−86373.917	−356052.083	−213297.315	−30687.539
700	0.130467	1.640704	19899.137	−89652.066	−361387.551	−217406.078	−37942.393
600	0.454412	2.708997	16865.909	−92883.341	−366614.873	−221392.082	−44792.420
500	2.133903	5.186766	13865.666	−96067.522	−371725.863	−225254.470	−51201.639
400	15.27186	12.33779	10897.470	−99204.259	−376707.469	−228991.878	−57134.066
300	204.1649	41.00937	7959.733	−102293.960	−381537.533	−232601.987	−62553.719
200	7362.538	236.6885	5049.521	−105333.528	−386175.159	−236080.522	−67424.613
100	15097153	3714.992	2160.755	−108321.693	−390535.621	−239418.621	−71710.767
25	6.93×10^8	103260.8	0.000	−110525.000	−393509.000	−241818.000	−74520.000

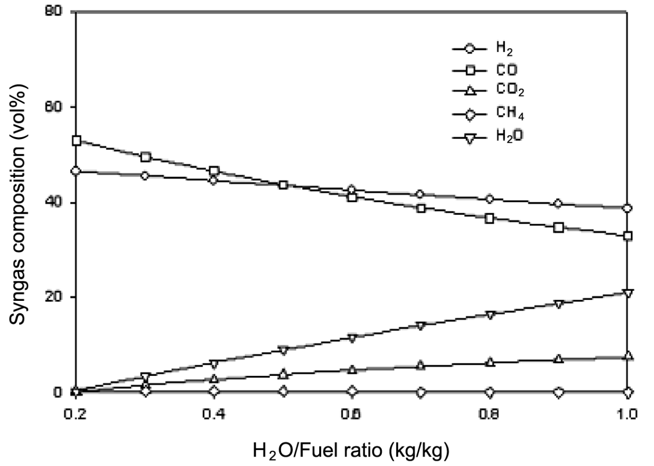

Fig. 2. Effect of H_2O/fuel ratio on gas composition at 1,200 °C.

and ΔH^o_{298}, which are necessary to make energy balance equations for the gasification process, are calculated and shown in Table 2, while coefficient values related to Eqs. (10) and (11) whose coefficient values change according to temperature changes are calculated and shown in Table 3.

When the inner temperature of the reactor is kept at 1,200 °C by using the equilibrium model, the production of gas, according to H_2O/fuel ratio of vacuum residue, is shown in Fig. 2. Also, as seen in Fig. 2, the more H_2O/fuel ratio increases, the more H_2O, which fails to react and is discharged, increases, and the concentration of syngas (H_2+CO) is maintained at 98-71%. In addition, H_2 and CO decrease when H_2O/fuel ratio increases. Especially, the decreasing ratio of CO is significant. When the inner temperature of the reactor remains at 1,200 °C, H_2O/fuel ratio increases and the H_2O surplus that is supplied to the inside of the reactor also increases. That reduces the temperature of the reactor. In order to remain at 1,200 °C consistently, additional combustion through additional supply of oxygen is necessary. The additional combustion causes additional consumption of combustible components in vacuum residue. Then, CO_2 increases through complete combustion as H_2O/fuel ratio increases and gasification reactions ($C+H_2O \rightarrow CO+H_2$), that is, endothermic reactions, decrease. Especially, the reason for the greater decreasing ratio of CO in comparison with that of H_2 is considered to be the additional consumption of CO by water gas shift reactions. According to the theory analysis, it is calculated that methane is scarcely produced.

When the temperature of the reactor and H_2O/fuel ratio are kept at 1,200 °C and 0.4, respectively, the composition and quantity of product gas to 1.0 kmol of vacuum residue is shown in Table 4. H_2O/fuel ratio was decided as 0.4 which is used in a general Texaco type vacuum residue gasification plant.

Table 4. Composition and flow rate of syngas (1,200 °C, H_2O/fuel ratio=0.4)

Produced gas	Quantity (kmol)	Composition (vol%)
H_2	0.903	44.5
CO	0.943	46.5
CO_2	0.055	2.7
CH_4	0.002	0.1
H_2O	0.127	6.2
Total	2.030	100

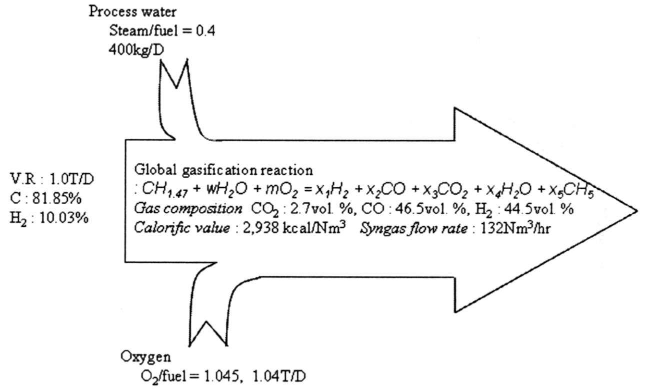

Fig. 3. Material balance for vacuum residue gasification process.

The material balance of vacuum residue gasification is shown in Fig. 3 when the temperature of the reactor and H_2O/fuel ratio are kept at 1,200 °C and 0.4, respectively, with 1.0T/D of vacuum residue supply on the basis of Table 4 (Table 4 is calculated based on 1 kmol of vacuum residue whose molecular weight is 13.7). As seen in Fig. 3, in the theory analysis using the equilibrium model, the flow rate and the calorific value are calculated at 132 Nm^3/hr and 2,938 kcal/Nm^3, respectively. After the reaction temperature and H_2O/fuel ratio are fixed, O_2 flow rate can be calculated. H_2O/fuel ratio is 1.045 at the conditions of reaction temperature of 1,200 °C and H_2O/fuel ratio of 0.4.

EXPERIMENT

1. Experimental Apparatus [Choi et al., 2001a, b, c]

The gasifier, an entrained gasifier that supplies preheated 99.9% oxygen, a mixture of vacuum residue, and high pressure steam, is designed following the top-down firing method to have allowable pressure of 25 atm and allowable temperature of 1,800 °C. On the

Fig. 4. Overview of 1.0 T/D vacuum residue gasifier in KIER.

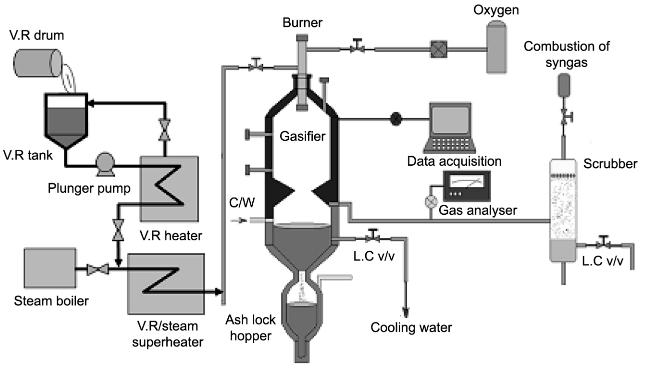

Fig. 5. Schematic diagram of 1.0 T/D vacuum residue gasifier in KIER.

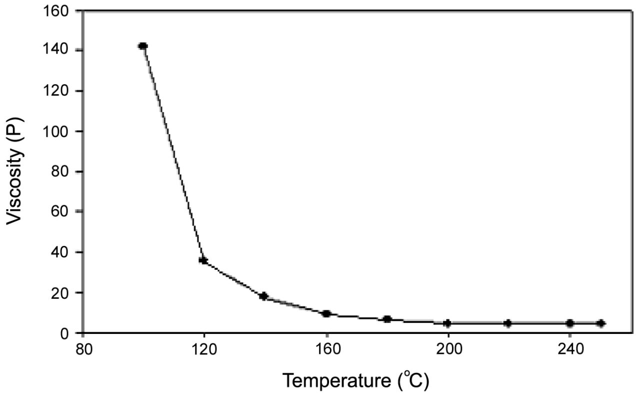

Fig. 6. Viscosity of vacuum residue related to the gasifier temperature.

upper part of the gasifier, a special burner for oxyfuel combustion is installed. Fig. 4 and Fig 5 show the overview and the schematic diagram of 1.0T/D entrained-flow gasifier in KIER.

The inner part of the gasifier is composed of a heat resisting and insulating materials. A mixture of vacuum residue, high pressure steam, and oxygen produces syngas such as CO, H_2, CO_2, CH_4, H_2S, COS, etc., through partial oxidization reaction within the reaction temperature range of approximately 1,100-1,300 °C. On the wall of the gasifier, one R-type thermocouple is installed to measure the inside temperature of gasifier and 12 K-type thermocouples measure the temperature distribution and heat loss from the wall of gasifier. At the lower side of the gasifier, there is a cooling water level control system to rapidly cool hot gas and the produced unreacted carbon. Cooling water and unreacted carbon are discharged to the lower part while syngas is supplied to the gas refining system (1st and 2nd carbon scrubber) through the downcomer. In order to maintain the optimal gasification reaction, an IR (Infra-red) analyzer automatically analyzes syngas composition every second. The flow, temperature, pressure, steam, and V.R. supplying flow of syngas are put into an automatic recording equipment by connecting with the main computer, and then the operating status and results are analyzed. After unreacted carbon in syngas, which is discharged from gasifier, is removed by the 1st and 2nd gas refining system, which contain packing material, syngas is burned in a flare stack though flowmeter.

As vacuum residue is solid at normal temperature, the temperature of vacuum residue should be kept at 150-250 °C in order to maintain optimal viscosity so that it can be supplied into the gasifier. For it, a preheating system using Shell Thermia oil B is established. Maintaining optimal viscosity through preheating is one of the very important factors. For it, most vacuum residue supplying lines are made with double pipes, and a super heater for heating a mixture of steamed vacuum residue is installed to facilitate supply and improve reactivity. In order to achieve stable partial oxidization for gasification, the inner temperature of the gasifier should be kept at 1,200 °C by preheating for sufficient time enough to accumulate appropriate heat on a heat resisting and insulating material in gasifier by using LPG and air before supplying a mixture of steamed vacuum residue and oxygen. When the inner temperature of the gasifier becomes stable, a steam mixture of vacuum residue and oxygen is supplied after blocking LPG and gasification reaction can proceed with stable flames.

2. Experimental Results

Vacuum residue used for the experiment is the product of domestic S oil refinery and its values of elementary analysis and calorific value analysis show very low content of hydrogen (10%), very high contents of carbon (81.8%), and sulfur (5.7%), respectively. So, it is difficult to use it as fuel oil under current domestic environmental regulations. The change of vacuum residue viscosity to temperature is one of the very important factors related to the transfer of vacuum residue. As shown in Fig. 6, there is no problem in transferring vacuum residue because the viscosity of the vacuum residue remains about 30P at more than 120 °C.

In the gasification experiment, the inner temperature of reactor is controlled, keeping 32 kg/hr of vacuum residue supply and 30-34 Nm^3/hr of oxygen flow. The operating conditions and results of gasification experiment are shown at Table 5 and the reaction temperature and reaction pressure are maintained 1,200-1,250 °C and 1.0 kg/cm^2ab, respectively. Results of the gasification experiment are stored in real time. Fig. 7 shows the changes in the product gas composition of vacuum residue, oxygen, and steam flow. As in Fig. 7, the production of syngas (CO+H_2) is analyzed to be 77-80% and calorific value of 2,300-2,600 kcal/Nm^3. Also, there is not a big change in syngas composition related to oxygen and steam flows. However, if steam flow increases, oxygen supply should increase to keep the temperature of the gasifier. As a result, the production of CO_2 increases gradually. Carbon conversion is calculated by the analysis of the product gas, such as gas composition (CO, CO_2 and CH_4)

Table 5. Operating conditions and experimental results

V.R feed rate (kg/hr)	32
O_2 feed rate (kg/hr)	30-34
Steam feed rate (kg/hr)	15-23
Reaction temperature (°C)	1,200-1,250
Operating pressure (kg/cm^2ab)	1
Syngas composition (%)	77-80
Heating value (HHV, kcal/Nm^3)	2,300-2,600
Carbon conversion (%)	95-99
Cold gas efficiency (%)	68-72

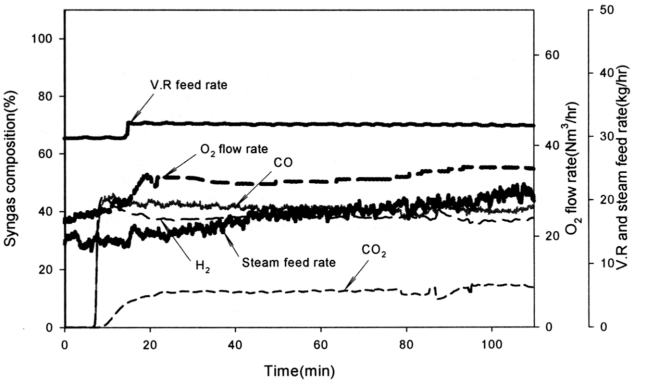

Fig. 7. O_2, steam and VR feed rate vs. syngas composition.

Table 6. Comparison of results between experiment and theoretical calculation (1,200 °C, H_2O/fuel ratio=0.4)

		Calculation	Experiment	Commercial Texaco plant [Quintana, 1990]
Produced gas (%)	H_2	44.5	37.5	38.7
	CO	46.5	42.4	40.8
	CO_2	2.7	12.2	6.4
	CH_4	0.1	0.08	-
Calorific value (kcal/Nm^3)		2,938	2,306	2,288
Carbon conversion (%)		100	99.0	95.2

and syngas flow rate. In the experiment, the calculated carbon conversion is more than 95%, and this high carbon conversion can be verified as almost no unburned carbon is collected from unburned carbon recovery basin. Also, the result of H_2S analysis during the experiment is measured as 5,000-6,000 ppm.

In order to compare with the result of theoretical analysis using the equilibrium model, the experimental condition of vacuum residue sets up the supply of vacuum residue to be 32 kg/hr, and other experimental conditions are shown in Table 6. As operating conditions for the experiment, the temperature of reactor, the pressure of reaction and H_2O/fuel ratio are 1,200-1,250 °C, 1.0 kg/cm^{2}ab and 0.4, respectively. In this paper, considering the difficulty of parametric study in process development research, representative experimental results (1,200 °C, H_2O/fuel ratio=0.4) were compared with theoretical values.

As shown in Table 6, the syngas (CO+H_2) composition from the result of calculation is higher than that from the result of the experiment. In the results of calculation, the heat loss through the gasifier wall is disregarded. It means that the quantity of oxygen supply to maintain the temperature of the reactor and the heat supply for gasification reaction ($C+H_2O \rightarrow CO+H_2$) by combustion reaction ($C+O_2 \rightarrow CO_2$) is less required. As a result, the theoretical value of produced gas shows a decrease in CO_2 and increase in syngas (H_2+CO). In order to evaluate results of the experiment, the production of produced gas, calorific value, and carbon conversion are compared with those of an Italian Texaco plant, which is commercially operating to perform vacuum residue gasification through IGCC (Integrated Gasification Combined Cycle). As both results are very similar, the excellence of the experiment can be verified.

CONCLUSION

With an entrained-flow gasifier, the gasification of vacuum residue is performed. In order to predict the gasification process by using the equilibrium model, experimental and calculated values on produced gas composition and calorific value are compared and analyzed. A summary of the results is as follows:

1. The gasification experiment is performed in the range of the vacuum residue quantity of 0.8 T/D, reaction temperature of 1,200-1,250 °C and reaction pressure of 1.0 kg/cm^{2}ab.
2. The calorific value of syngas is 2,300-2,600 kcal/Nm^3. Syngas production is 77-80%. Carbon conversion is 95-99%. H_2S content in syngas is analyzed to be 5,000-6,000 ppm.
3. With the equilibrium model, the changes of gas composition and calorific value are predicted in accordance with the conditions of gasification agent input. The syngas composition from the result of calculation is higher than that from result of experiment. In the results of calculation, as the heat loss of gasifier is disregarded, combustion reaction to supply heat to maintain the temperature of reactor is less required. As a result, the theoretical value of produced gas shows a decrease in CO_2 and increase in syngas (H_2+CO).
4. For stable operation of the gasification process with vacuum residue, the experimental results of this study are compared and analyzed with those of a Texaco IGCC plant, which is commercially operating, and the excellence of this study can be verified. After long term operation and a review of the operational problems, the commercial usability of this study will be evaluated.

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NOMENCLATURE

w : amount of water per kgmol of vacuum residue
m : amount of oxygen per kgmol of vacuum residue
x_1 : coefficient of hydrogen in the product gas
x_2 : coefficient of carbon monoxide in the product gas
x_3 : coefficient of carbon dioxide in the product gas
x_4 : coefficient of water in the product gas
x_5 : coefficient of methane in the product gas
$H^o_{fV.R}$: heat of formation of V.R
$H^o_{fH_2O(l)}$: heat of formation of liquid water
$H_{(vap)}$: heat of formation of water vapor
H^0_{fCO}, $H^0_{fCO_2}$, $H^0_{fCH_4}$: heat of formation of gaseous products
C_{PH_2}, C_{PCO}, C_{PCO_2}, C_{PH_2O}, C_{PCH_4} : specific heats of gaseous products
T_1 : ambient temperature
T_2 : gasification temperature at the reaction zone
ΔG^0 : standard Gibbs function of formation
ΔA, ΔB, ΔC, ΔD : coefficients for determining specific heat

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