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Carbon Dioxide Capture and Utilization for Gas Engine

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ABSTRACT

Sodium glycinate absorption and ethylene carbonate synthesis from a mixture gas of ethylene oxide and carbon dioxide are evaluated as carbon dioxide capture and utilization system for gas engine flue gas. The energy requirement for CO_2 capture is estimated at 3.3 GJ/tonne CO_2. The ethylene carbonate synthesis utilizes more than 90% of the captured CO_2 and supply 2.5 GJ/tonne CO_2 of thermal energy, which is 76% of the energy requirement for CO_2 capture. The thermal integration of the sodium glycinate absorption and the ethylene carbonate synthesis reduces the energy requirement for CO_2 capture from 3.3 GJ/tonne CO_2 to 0.8 GJ/tonne CO_2. The energy requirement for the CO_2 capture is supplied using the steam saturated at 0.78 MPa from the gas engine without its electric power reduction.

Keywords: Carbon Dioxide Capture; Carbon Dioxide Utilization; Carbonate Formation; Gas Engine

1. Introduction

Over the past decade, the global warming resulting from anthropogenic carbon dioxide (CO_2) has become one of the most important environmental matters. A quarter of the CO_2 emissions all over the world are exhausted from thermal plants. Post-combustion carbon dioxide capture is the technique that can be rapidly and safely employed for substantially reducing carbon dioxide emissions from existing and near future power plants [1]. The captured CO_2 is compressed, transported, and stored in depleted oil and gas fields [2].

A gas engine has been used as a combined heat and power system. The flow rate of carbon dioxide in its flue gas is short to carbon capture and storage, especially for transporting and storing captured carbon dioxide. Therefore, plant fertilization at a greenhouse is used to utilize the captured CO_2 from a gas engine [3]. However, the plant fertilization needs the large area and is not capable of supplying the heat of CO_2 capture.

North reported ethylene carbonate synthesis from dilute CO_2 and dilute ethylene oxide uses a gas-phase continuous flow reactor near conditions of ambient temperature and pressure. The synthesis is highly exothermic reaction and the rate of the reaction is high [4]. The ethylene carbonate synthesis from pure CO_2 was not estimated using a gas-phase reactor. Weiland reported sodium glycinate can remove CO_2 from the flue gas of a coal-fired thermal plant [5]. It was not estimated in the case of the flue gas of a gas engine, whose CO_2 concentration is much lower than that of a coal-fired thermal plant.

In this paper, we evaluated sodium glycinate absorption as CO_2 capture and ethylene carbonate synthesis as the captured CO_2 utilization and heat recovery for a gas engine.

2. Carbon Dioxide Capture and Utilizatio System

2.1. Gas Engine

Table 1 shows the specifications of the KV-18-V gas engine made by Kawasaki Heavy Industries, Ltd [6]. The KV-18-V gas engine has achieved a thermal efficiency of 49% on the basis of lower heating value and provide 7.8 MW of electric power, 2.3 MW of thermal power as steam saturated at 0.78 MPa, and 3.3 MW of thermal power as hot water at 88˚C. The fuel is city gas 13A [7] and the flow rate is 1412 Nm^3/h. The flue gas composition and flow rate are estimated under the assumptions; 1) air consists of oxygen (20.95%) and nitrogen (79.05%) [8], 2) the air-to-fuel ratio is 2.2 [9]. Those result in that the flue gas composition is a mixture of CO_2 (4.72%), H_2O (8.77%), O_2 (10.92%), and N_2 (75.59%) and the

Table 1. Specifications of KV-18-V gas engine.

Electric power	7800 kW
Electric efficiency	49.0%
Steam output[a]	14.4%
Hot water output[b]	20.6%
Fuel	City gas 13 A
Flow rate	1412 Nm^3/h
Composition	CH_4 (89.60%), C_2H_6 (5.62%), C_3H_8 (3.43%), C_4H_{12} (1.36%)
Lower heating value	40.6 MJ/Nm^3

[a]0.78MPa saturation, Inlet temperature: 60˚C; [b]Inlet/outlet temperature: 83˚C/88˚C.

flow rate of the flue gas is 34,857 Nm^3/h.

2.2. Carbon Dioxide Capture System

Figure 1 shows a carbon dioxide capture system. The system consists of an absorber, a rich-lean heat exchanger, a stripper, and a lean cooler. The flue gas enters the bottom of the absorber and an absorbing solvent enters the top of the absorber. The absorbing solvent selectively absorbs CO_2 from the flue gas. The CO_2 rich solvent from the bottom of the absorber passes through the rich-lean heat exchanger to preheat. The preheated CO_2 rich solvent enters at the top of the stripper. Then it is heated by the steam from a reboiler and desorbs CO_2. The desorbed CO_2 is separated from the steam at the top of the stripper. The CO_2 lean solvent from the bottom of the stripper is cooled using the rich-lean heat exchanger and the lean cooler. The cold CO_2 lean solvent is recirculated to the top of the absorber.

Table 2 shows the design conditions of the CO_2 capture system. The absorbing solvent is 45 wt% Sodium Glycinate. The absorber inlet temperatures of the flue gas and the cold lean solvent are 40˚C. A temperature of approach of 4˚C is chosen for the rich-lean heat exchanger. The absorber and stripper have 18 m and 9 m height beds using Sulzer Mellapak M250.X structured packing, respectively. They are sized for 50% of flood. The operation pressure of the stripper is 200 kPa. The carbon dioxide capture system is simulated using the ProTreat® software (Optimized Gas Treating, Inc.).

2.3. Ethylene Carbonate Synthesis System

Figure 2 shows an ethylene carbonate synthesis system. The ethylene carbonate synthesis system consists of a heat exchanger and a Gibbs reactor, for which the reaction equilibrium is calculated by minimizing the Gibbs free energy at specified temperature and pressure.

An equimolar mixture gas of the captured CO_2 and ethylene oxide (EtO) enters the heat exchanger at 40˚C and is preheated. The preheated mixture enters the Gibbs reactor and forms ethylene carbonate ($EtCO_3$) from CO_2

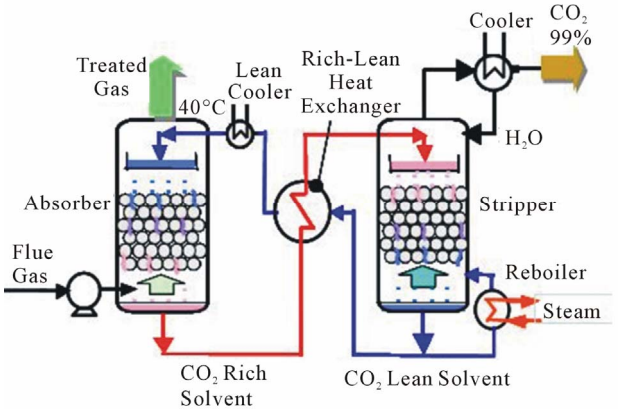

Figure 1. Carbon dioxide capture system.

Table 2. Design conditions of CO_2 capture system.

Solvent	Sodium Glycinate	45 wt.%
Absorber	Packing	Sulzer Mellapak M250.X
	Packing Height	18 m
	Flood	50%
	Solvent Inlet Temperature	40˚C
	Flue gas Inlet Temperature	40˚C
Stripper	Packing	Sulzer Mellapak M250.X
	Packing Height	18 m
	Flood	50%
	Cooler Exit Temperature	40˚C
	Cooler Exit Pressure	200 kPa
	Reboiler Operating Pressure	200 kPa
Rich-Lean Heat Exchanger	Approach Temperature	4˚C

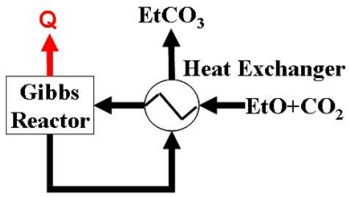

Figure 2. Ethylene carbonate synthesis system.

and ethylene oxide exothermically. The synthesized ethylene carbonate is cooled in the heat exchanger. A temperature of approach of 10˚C is chosen for the heat exchanger. The ethylene carbonate synthesis system is simulated using the VMGSim® software (Virtual Material Group Inc.) with Advanced Peng-Robinson property package. The temperature of ethylene oxide at the heat exchanger exit is higher than 40˚C, which is higher than the melting point of ethylene carbonate (34˚C - 37˚C).

3. Results and Discussion

3.1. Carbon Dioxide Capture

Figure 3 shows a plot of CO_2 recovery ratio as functions of the flow rate of the CO_2 lean solvent and the reboiler duty. The CO_2 recovery ratios at the different reboiler duty have peaks at the flow rate of the CO_2 lean solvent of 60 tonne/h (t/h).

Figure 4 shows a plot of the energy requirement for CO_2 capture (CO_2 recovery energy) as a function of the CO_2 recovery ratio at 60 t/h of the flow rate of the CO_2 lean solvent. The CO_2 recovery energy increases linearly with the CO_2 recovery ratio.

We aimed for 0.098 $kgCO_2/kWh$ of carbon dioxide emission factor, which is equal to that of a coal-fired thermal plant with 90% of CO_2 recovery on the basis of gross power [10]. This results in 76.5% of CO_2 recovery from the flue gas of the KV-18V gas engine and indicates 3.3 GJ/tonne CO_2 (GJ/tCO_2) of the CO_2 recovery energy. The KV-18V gas engine can supply 3.2 t/h of the steam saturated at 0.78 MPa, whose energy is equal to the 3.3 GJ/tCO_2 of the CO_2 recovery energy.

3.2. Ethylene Carbonate Synthesis

Figure 5 shows a plot of degrees of CO_2 conversion by ethylene carbonate synthesis against reaction temperatures at 101.3 kPa. The degree of conversion decreases stepwise at temperature of 133˚C and above. The vapor pressures of ethylene carbonate are lower than the partial pressures of that at the equilibrium state of the reaction which produces ethylene carbonate at temperature of 133˚C and below. It results in the liquefaction of ethylene carbonate and more than 90% of the conversion.

Figure 6 shows a plot of the generated heat per the captured CO_2 against the reaction temperatures at 101.3 kPa. The reaction heat of the synthesis is almost the same among the reaction temperatures and the total amount of heat generated by the synthesis increases with the degree of conversion. That results in the similar trend between the degree of conversion and the generated heat per the captured CO_2. The synthesis generates 2.5 GJ/tCO_2 of thermal energy at temperature of 133˚C and below.

Figure 7 shows a plot of maximum reaction temperatures of nonequilibrium state as a function of reaction pressures. The degree of conversion at the state of nonequilibrium is more than 90%. The maximum reaction temperature is higher than 120˚C of the operation temperature of the reboiler.

The ethylene carbonate synthesis can supply 76% of the CO_2 recovery energy and utilize more than 90% of the captured CO_2. The thermal integration of the sodium glycinate absorption carbon capture and the ethylene carbonate synthesis systems reduces the CO_2 recovery energy from 3.3 GJ/tCO_2 to 0.8 GJ/tCO_2.

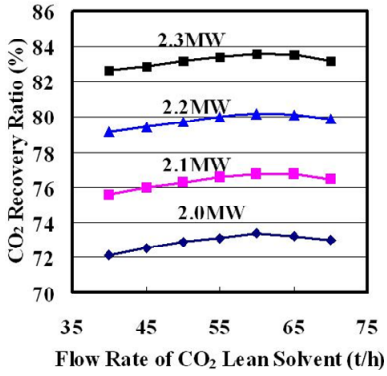

Figure 3. CO_2 recovery ratio as functions of flow rate of CO_2 lean solvent and reboiler duty.

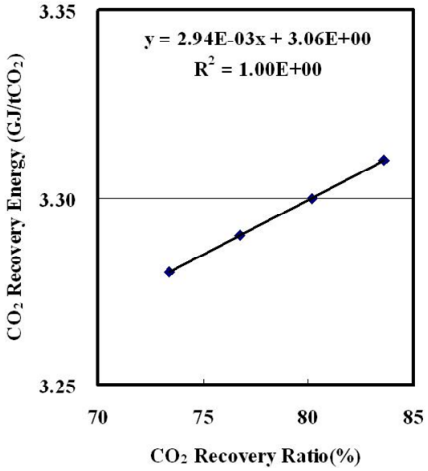

Figure 4. CO_2 recovery energy a function of CO_2 recovery ratio.

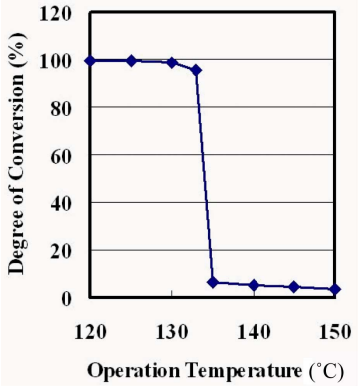

Figure 5. Degree of conversion as a function of operation temperature at 101.3 kPa.

4. Conclusion

The ethylene carbonate synthesis using the carbon dioxide recovered from the gas engine flue gas can supply 76% of the energy requirement for CO_2 capture and utilize more than 90% of the captured CO_2. The thermal integration of the sodium glycinate absorption and the

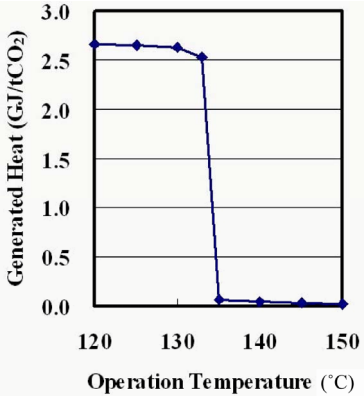

Figure 6. Generated heat as a function of operation temperature at 101.3 kPa.

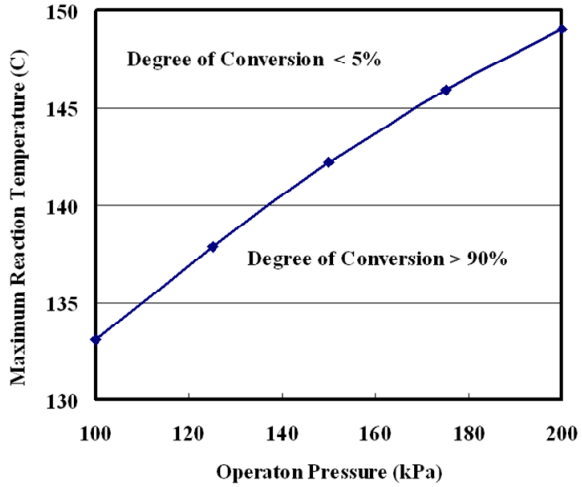

Figure 7. Maximum reaction temperature as a function of operation pressure.

ethylene carbonate synthesis reduces the energy requirement for CO_2 capture from 3.3 GJ/tCO_2 to 0.8 GJ/tCO_2. The energy requirement for the CO_2 capture can be supplied by 0.78 MPa saturation steam from the gas engine without its electric power reduction.

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