

# **Operational Planning of an Engine Generator Using a High Pressure Working Fluid Composed of CO<sub>2</sub> Hydrate**

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## **Abstract**

An actuator system (gas-hydrate engine) using the dissociation and recombined continuous cycle of CO<sub>2</sub> gas hydrate was developed. The heat source temperatures required

for the operation of the proposed system are in the temperature range of green energy and low-quality exhaust heat. The energy flow of this proposed system was investigated by numerical analysis. From these results, for example, the entrance operating conditions of the recombination equipment are 9 °C and 1.2 MPa, and the exit conditions are 0 °C and 5 MPa. In the case of a heat source temperature of 20 °C of the recombination equipment, a heat source temperature of -5 °C of the dissociation equipment and the passing of a working fluid comprised of 1150 g/s of CO<sub>2</sub> and H<sub>2</sub>O about 5 kW of electric power can be obtained. Moreover, although the recombined speed was remarkably slow compared with dissociation, this study considered the relation of recombined speed between the physical conditions of the working fluid and the volume of the recombination equipment. Based on the results obtained in this study, a prototype will be developed next.

**Keywords:** CO<sub>2</sub> hydrate, Hydrate actuator, Hybrid power system, Operation planning, Working fluid.

## 1. Introduction

Hydrates have been examined for use in the transportation of natural gas and the submarine storage of CO<sub>2</sub>, for example [1-3]. Furthermore, the study used for storage of cold energy [4-6] and the study used for capture of CO<sub>2</sub> [7, 8] are investigated. Gas hydrate contains a gas molecule associated with a clathrate. It is thought that the recombined speed of gas hydrate has a strong influence on the gas solubility. For example, it is expected that, in the case of CO<sub>2</sub>, the hydrate clathrate is formed after the gas fully dissolves in water. However, a gas with a small solubility differs from the process in which a hydrate is recombined from CO<sub>2</sub>, as described above. The difference in the recombined process of a

hydrate is assumed to greatly influence the recombined speed of a hydrate and the dissociation speed of CO<sub>2</sub> gas. Gas hydrate has a large latent heat of recombination and dissociation; furthermore, the phase equilibrium state of recombination and dissociation produces a large pressure difference in response to a small temperature change. For example, if CO<sub>2</sub> hydrate is changed to 10 °C from 0 °C, then a pressure difference of about 3 MPa will arise on the phase equilibrium curve of the recombination and dissociation. A large amount of power can be obtained if the pressure difference of the dissociated gas of a hydrate is imposed on a fluid actuator. Thus, a system that attains gas dissociation and a hydrate recombination simultaneously is proposed using the two-set same reaction equipments [9]. In this proposal system, CO<sub>2</sub> gas dissociation from a hydrate and the recombination of the hydrate occur simultaneously. The reaction of CO<sub>2</sub> dissociation and hydrate recombination is replaced by exchanging the warm heat source and cool heat source of each reaction equipment after the end of the operation of the reaction equipment. The system continuously obtains high-pressure dissociated gas by the exchange of the heat sources. The permutation scheme (batch method) of the heat sources is a very simple. However, for obtaining the stable high power, it is necessary to develop the operation cycle into a continuation type from a batch type. Thus, in this paper, CO<sub>2</sub> gas hydrate was used as the working fluid, and the continuous cycle (gas-hydrate engine) of dissociation and recombination of a hydrate is proposed. Furthermore, the performance of the proposed system was evaluated by numerical analysis. By evaluating the performance of the proposed system using numerical simulation, an experimental model is examined in the next stage.

## **2. Outline of a Gas-hydrate Engine**

### **2.1 Composition of the Actuator System**

Figure 1 shows the CO<sub>2</sub> hydrate power generation system proposed in this paper. Positions from A to F in Fig. 1 show each position of the system. Moreover, the areas shown by the blue, orange, and pink lines show cooling, heating, and heat insulation, respectively. The proposed system consists of recombination equipment (Positions from A to B), dissociation equipment (Positions from C to D), a fluid actuator (Positions from D to E), and a buffer tank (Positions E to F). The recombination equipment consists of a high-pressure screw pump accompanied by a cooling device.

## 2.2 Hydrate Recombined by Recombination Equipment

The working fluid input into Position A consists of water in the liquid phase and CO<sub>2</sub> steam. This working fluid is sent to the exit B by high pressure after being cooled by the recombination equipment. The temperature of the working fluid after cooling is between -5 °C and +5 °C. The open air, green energy, and a freezer, for example, can be considered as candidates for the source of heat of cooling. When the temperature of the working fluid is 0 °C, the CO<sub>2</sub> hydrate is generated by pressurizing the working fluid at about 0.8 MPa or more with a screw pump. Generally, the recombined speed of the CO<sub>2</sub> hydrate is slower than the dissociation speed. For this reason, it is necessary to obtain the reaction time by increasing the volume of the recombination equipment. Furthermore, an electric motor is used for driving the screw pump of the recombination equipment. Power consumption of the electric motor is required for operation of the system, and this value greatly influences the power generation efficiency.

## 2.3 CO<sub>2</sub> Dissociation by Dissociation Equipment

The working fluid output from Position B has the form of a slurry containing many CO<sub>2</sub>

solid hydrates (5 to 15 wt%). This working fluid is supplied to the entrance (Position C) of the dissociation equipment. A stirrer and a heat exchanger are installed in the dissociation equipment, and CO<sub>2</sub> gas can be dissociated from a hydrate by a working fluid at about 15 °C . As a result, the pressure in the dissociation equipment rises rapidly. Heating sources of the working fluid using the dissociation equipment are assumed to be, for example, the open air, green energy, and low-temperature exhaust heat. From the exit (Position D) of the dissociation equipment, the high-pressure working fluid consists of water in the liquid phase and CO<sub>2</sub> steam output. By supplying this working fluid to an actuator, the power of a dynamo can be obtained through a crankshaft.

#### 2.4 Operation of the Actuator and Buffer Tank

There are many kinds of mechanisms for energy conversion equipment to obtain work from high-pressure fluid. The actuator shown in Fig. 1 consists of cylinders and pistons, connecting rods, a crank shaft with a flywheel, and a constant voltage AC generator. The electric power  $E_g$  is obtained from the constant voltage AC generator. The slurry output from the cylinder and piston (Position E) is supplied to a buffer tank. The buffer tank is prepared to absorb the pressure fluctuation of a working medium. The continuous operation of the proposed system is realized by supplying slurry (Position F) output from the buffer tank to the recombination equipment (Position A).

### 3. Change of State of Working Fluid

#### 3.1 Temperature and Pressure of the Working Fluid

- (1) Recombination equipment (Position A and Position B)

Figure 2 shows a model of the temperature, pressure, and phase change of the working fluid in each element of the proposed system. The details of the state of the working fluid in the figure are given in Section 3.2. The pressure of the working fluid that is inputted into the recombination equipment rises with a screw pump. The temperature of the section corresponding to Positions from A' to B in the figure is kept constant by the recombined latent heat of the hydrate. Therefore, a working fluid changes from water in the liquid phase and CO<sub>2</sub> steam to CO<sub>2</sub> hydrate, water in the liquid phase, and CO<sub>2</sub> steam.

(2) Dissociation equipment (Position C and Position D)

The dissociation equipment raises the temperature of the working fluid with heating. Moreover, because CO<sub>2</sub> gas dissociates from a hydrate, the volume of the working fluid expands. However, because the expanded working fluid is sent to the actuator, the pressure of the working fluid is constant. The working fluid changes from CO<sub>2</sub> hydrate, water in the liquid phase, and CO<sub>2</sub> steam to water in the liquid phase and CO<sub>2</sub> steam.

(3) Cylinder and piston (Position D and Position E)

Mechanical work is obtained from the high-pressure working fluid supplied to the cylinder and piston (fluid actuator). Furthermore, the temperature and pressure of the working fluid decrease. The composition of the working fluid is the same as that of Position D (water in the liquid phase and CO<sub>2</sub> steam). Because the volume of an actuator changes, the pressure of the working fluid changes.

(4) Buffer tank (Position E and Position F)

If the capacity of the buffer tank is set up appropriately, then the change in the pressure of the working fluid will be stabilized. The buffer tank is heat-insulated, moreover, there is no phase change of the working fluid.

### 3.2 Operating Point of the Working Fluid

Figure 3 is a phase diagram of the CO<sub>2</sub> hydrate. The operating point of the proposed system and the solid-liquid phases of water are described in this figure. The temperature of the working fluid in the entrance A of the recombination equipment is high. The operating point A in Fig. 3 consists of liquid water and CO<sub>2</sub> steam. By installing a cooler in the recombination equipment, the working fluid of the operating point A is cooled to the operating point B. At operating between Point A and A', the working fluid consists of liquid water and CO<sub>2</sub> steam. Conversely, CO<sub>2</sub> hydrate is generated at operating between Point A' and B. The working fluid in this case consists of liquid water, CO<sub>2</sub> hydrate, and CO<sub>2</sub> steam. If the cooling temperature is further lowered to operating point B and the solid-liquid phase curve of water is passed, then the water in the working fluid will change to ice. When ice is generated, the recombined speed of a hydrate falls. Therefore, the problem of the blockade on the ice in piping occurs. Then, cooling of the working fluid is set up to remove the ice-point range.

CO<sub>2</sub> hydrate is heated within the dissociation equipment, and CO<sub>2</sub> gas is made to dissociate. Therefore, the hydrate composition decreases as the working fluid progresses from operating point C to D. Conversely, the amounts of liquid water and CO<sub>2</sub> steam increase. By supplying the working fluid of the operating point D to an actuator, part of the pressure changes to mechanical work, and the operating point of the working fluid moves to Point E. Furthermore, the working fluid of the operating point E reaches the entrance A of the recombination equipment through a buffer tank.

### 3.3 State of the Working Fluid

Figure 4 describes the state of the working fluid of the proposed system. The working fluids of the green and red areas consist of liquid water, CO<sub>2</sub> steam, and CO<sub>2</sub> hydrate and liquid water and CO<sub>2</sub> steam, respectively. The energy conversion of the cylinder and piston assumes heat insulation work. The recombination speed of CO<sub>2</sub> hydrate using the recombination equipment is slow compared to the gas dissociation speed using the dissociation equipment. Therefore, the magnitude of the mechanical work obtained from the proposed system is greatly dependent on the recombined speed of CO<sub>2</sub> hydrate by the recombination equipment.

#### 4. Relational Equations of Numerical Analysis

##### 4.1 Mechanical Work by the Cylinder and Piston

The working fluid of the inlet port (operating point D) of the cylinder and piston shown in Fig. 3 is liquid water and CO<sub>2</sub> steam. Then, the mechanical work of water and CO<sub>2</sub> steam is calculated as follows.

(1) CO<sub>2</sub> gas

The energy conversion of the cylinder and piston introduces the equation of the heat insulation work shown in Eq. (1).

$$P_{co_2} \cdot V_{co_2}^{\kappa} = \text{constant} \quad (1)$$

Here,  $P_{co_2}$ ,  $V_{co_2}$ , and  $\kappa$  are the pressure, volume, and ratio of specific heat of CO<sub>2</sub> gas, respectively. When changing from a state ( $P_D$ ,  $V_D$ ) to ( $P_E$ ,  $V_E$ ), CO<sub>2</sub> gas in the cylinder is assumed to be under adiabatic expansion. In this case, the CO<sub>2</sub> gas of  $P_D$  and  $T_D$  works

adiabatically to  $P_E$ . The temperature at the operating point E of CO<sub>2</sub> gas is calculated from the following equation:

$$T_E = T_D \cdot \left( \frac{P_E}{P_D} \right)^{(\kappa-1)/\kappa} \quad (2)$$

The work  $L_{CO_2}$  obtained by the expansion of gas is calculated using the following equation. Here,  $R_{CO_2}$  is the gas constant of CO<sub>2</sub>.

$$L_{CO_2} = \frac{R_{CO_2}}{\kappa-1} \cdot (T_D - T_E) \quad (3)$$

The work of vapor ( $L_{vp}$ ) and the calculation method described above can thus be found.

## (2) Liquid water

The high-pressure water of a state ( $P_D$ ,  $T_D$ ) is used to calculate the work  $L_{H_2O}$  in the case of changing to Position ( $P_E$ ,  $T_E$ ).

$$L_{H_2O} = m \cdot g \cdot h = w_{H_2O} \cdot \Delta t \cdot g \cdot \Delta P_{D-E} \cdot \frac{10.13}{0.1013} \quad (4)$$

Here,  $m$ ,  $g$ , and  $h$  are the mass of water, acceleration due to gravity, and head, respectively. Furthermore,  $w_{H_2O}$  is the mass flow rate of water,  $\Delta t$  is the sampling time interval, and  $\Delta P_{D-E}$  is the pressure difference of the operating points D and E.

The work  $L_{CP}$  output by the cylinder and piston is the sum of (1) and (2) described above, as shown in the following equations.  $L_{vp}$  of the right-hand side of Eq (5) is the heat insulation work by vapor.

$$L_{CP} = L_{CO_2} + L_{vp} + L_{H_2O} \quad (5)$$

$$W = L_{CP} \cdot \eta_a \cdot \eta_e \quad (6)$$

Here,  $\eta_a$  is the mechanical efficiency of the actuator without the dynamo, and  $\eta_e$  is the efficiency of the dynamo. Moreover,  $W$  is the electric power output of the system.

#### 4.2 Amount of Heat of Cooling of a Working Fluid using Recombination Equipment

When the working fluid moves to the exit operating point B from the inlet-port operating point A of the recombination equipment, a phase change of the working fluid occurs. That is, although the working fluid consists of liquid water and CO<sub>2</sub> steam from the operating point A to A', CO<sub>2</sub> hydrate is added to the operating point A' to B. Then, the amount of heat of cooling of the working fluid required for the recombination equipment is obtained from the amount of sensible heat and the amount of latent heat of each working fluid composition, as shown in Eqs. (7) to (10).

$$Q_{sh1} = \sum_{i=1}^{N_m} (w_{wf,lg,i} \cdot c_{wf,lg,i} \cdot (T_A - T_{A'})) \quad (7)$$

$$Q_{sh2} = \sum_{i=1}^{N_m} (w_{wf,s,i} \cdot c_{wf,s,i} \cdot (T_{A'} - T_B)) \quad (8)$$

$$Q_{sh3} = \sum_{i=1}^{N_m} (w_{wf,lg,i} \cdot c_{wf,lg,i} \cdot (T_{A'} - T_B)) \quad (9)$$

$$Q_{lh} = \sum_{i=1}^{N_m} (w_{wf,s,i} \cdot l_{wf,i}) \quad (10)$$

Here,  $N_m$  is the total number of working fluid compositions, and  $w_{wf,i}$  is the mass flow rate of a composition  $i$  of the working fluid. Moreover,  $c_{wf,i}$  is the specific heat of the composition  $i$  of the working fluid.  $w_{wf,s}$  and  $c_{wf,s}$  are the mass flow rate and specific heat of the CO<sub>2</sub> hydrate, respectively, and  $w_{wf,lg}$  and  $c_{wf,lg}$  are the mass flow rate and specific heat, respectively, of each of liquid and gas of the working fluid.

$Q_{sh1}$  is the amount of sensible heat for cooling the working fluid from the operating point A to A'. Moreover,  $Q_{sh2}$  is the amount of sensible heat for cooling CO<sub>2</sub> hydrate in the working fluid from the operating point A' to B.  $Q_{sh3}$  is the amount of sensible heat for cooling the liquid and gas composition of the working fluid from the operating point A' to B. Furthermore,  $Q_{lh}$  is the amount of latent heat required for the recombination of CO<sub>2</sub> hydrate. Therefore, the amount of heat of cooling of the working fluid by the recombination equipment can be calculated by the following equations.

$$Q_{RE} = Q_{sh1} + Q_{sh2} + Q_{sh3} + Q_{lh} \quad (11)$$

#### 4.3 Heat Quantity of a Working Fluid by Dissociation Equipment

By heating the working fluid between the entrance operating point C and the exit operating point D of the dissociation equipment, the phase change of the working fluid occurs in conjunction with the dissociation of CO<sub>2</sub> gas. Therefore, the quantity of heat required of the dissociation equipment is the sum of the sensible heat of the working fluid and the gas heat of dissociation (latent heat) of CO<sub>2</sub> hydrate. Then, the amount of sensible heat and the amount of latent heat are calculated (Eq. 14) by adding the results of Eqs. (12)

and (13). The quantity of heat required for the dissociation equipment is obtained from these results.

$$Q_{sh,CD} = \sum_{i=1}^{N_m} (w_{wf,lg,i} \cdot c_{wf,lg,i} \cdot (T_D - T_C)) \quad (12)$$

$$Q_{lh,CD} = \sum_{i=1}^{N_m} (w_{wf,s,i} \cdot l_{wf,i}) \quad (13)$$

$$Q_{DE} = Q_{sh,CD} + Q_{lh,CD} \quad (14)$$

#### 4.4 Recombination Speed of CO<sub>2</sub> Hydrate

CO<sub>2</sub> is dissolved in the water of the working fluid, and the amount of dissolution is dependent on the temperature and pressure of this working fluid. The recombined speed of CO<sub>2</sub> hydrate at the ice melting point is early compared with the recombined speed at other temperature and pressure conditions. The characteristic of the recombined speed of CO<sub>2</sub> hydrate was reported by Kawamura et al. in 2002 [10]. Figure 5 shows the result of the recombined speed of CO<sub>2</sub> hydrate on the ice melting temperature proposed by Kawamura et al. In the analysis of this study, the recombined speed of CO<sub>2</sub> hydrate in the recombination equipment was calculated by modeling the result of Fig. 5.

#### 4.5 Volume of Buffer Tank

As shown in Fig. 6, it is assumed that the pressure  $P_E$  of the entrance E of the buffer tank shows a change of  $\pm\Delta P$  compared to the average pressure  $\overline{P_E}$  due to the volume fluctuation of the actuator. The volume of the buffer tank used to absorb the pressure fluctuation of CO<sub>2</sub> steam is calculated. Equation (15) is obtained from the quantity of the pressure, temperature and volume in the buffer tank and operating point E. Here, if it is

assumed that  $T_E$  and  $T_{BT}$  are equal, then the volume  $V_{BT}$  of the buffer tank can be calculated using Eq. (16). However,  $\varphi_{BT}$  in the formula is a safety factor of the design. Although  $V_{BT}$  changes as  $+\Delta P$  or  $-\Delta P$ , a value  $V_{BT}$  with a large absolute value is adopted.

$$\frac{\overline{P}_E \cdot V_E}{T_E} = \frac{P_{BT} \cdot V_{BT}}{T_{BT}} \quad (15)$$

$$V_{BT} = \frac{\overline{P}_E}{P_{BT}} \cdot V_E \cdot \varphi_{BT} = \frac{\overline{P}_E}{P_E \pm \Delta P} \cdot V_E \cdot \varphi_{BT} \quad (16)$$

## 5. Numerical Simulation

To evaluate the engine performance of the proposed system, a numerical simulation was done according to the following procedures.

### 5.1 Calculation of the Work of Actuator $L_{CP}$

Once the heat source of high and low temperatures used for the proposed system is defined, the operating point of the generation temperature of CO<sub>2</sub> hydrate by the recombination equipment shown in Fig. 3 and the gas dissociation temperature by the dissociation equipment will be decided. However, the recombined pressure of CO<sub>2</sub> hydrate is determined by the ice dissolution phase, and the gas dissociation pressure is set as the highest pressure of the system. As a result, the compression pressure  $\Delta P_{A-B}$  required for a screw pump is decided. Furthermore, if the flow of the working fluid  $w_{wf}$  is given, the heat of cold energy and warm energy required for the recombination equipment and the dissociation equipment will be obtained. The amount of dissolution of CO<sub>2</sub> and the amount of recombination of CO<sub>2</sub> hydrate can be obtained from the conditions of the mass flow rate of

the working fluid, temperature and pressure, and the results are described above. Next, the work  $L_{H_2O}$ ,  $L_{vp}$ ,  $L_{CO_2}$  of each working fluid composition is calculated using Eqs. (1) to (4) described in Section 4.1. Furthermore, the work  $L_{CP}$  output from the actuator is obtained by Eq. (5).

## 5.2 Pressure-Volume Diagram of the Working Fluid

Figure 7 shows an example of the operating point on the pressure-volume diagram of the working fluid used for the numerical simulation. In the analysis example shown in Fig. 7, the entry conditions of the recombination equipment are 9 °C and 1.2 MPa, and the exit conditions are 0 °C and 5 MPa. The entry conditions of the dissociation equipment are 0 °C and 5 MPa, and the exit conditions are 15 °C and 5 MPa. The working fluid is pressurized with a screw pump from 1.2 MPa to 5 MPa.

## 5.3 Recombined Speed of the Hydrate and Volumetric Flow of the Recombination Equipment

For the recombination speed of CO<sub>2</sub> hydrate, the results of Kawamura et al. in 2002 [10], which are described in Section 4.4, are used. From the experimental results shown in Fig. 5, the CO<sub>2</sub> hydrate recombination speed in the temperature range of -5 °C to 5 °C is about 1.17 times larger than the speed in the range of 1 °C to -1 °C .

## 5.4 Amount of Cold Energy and Warm Energy Heat Supplies

The mass flow rate of the working fluid, the efficiency of each piece of equipment, and the latent heat of CO<sub>2</sub> hydrate used in the numerical simulations are shown in Table 1. The temperature of the source of cold energy and warm energy was set to 5 °C differences in temperature for the working fluid. For example, the hydrate generation temperature and

gas dissociation temperature of the heat-source temperatures of 0 °C and 15 °C are -5 °C on the low temperature side and 20 °C on the high temperature side. However, the heat supply to the recombination equipment and dissociation equipment changes with the setting of the difference in temperature of each heat source and the working fluid as described above.

## **6. Analysis Results and Discussion**

### **6.1 Energy Flow**

Figure 8 shows the analysis results of the energy flow when the proposed system is operated according to the heat cycle shown in Fig. 7. If a warm energy and cold energy of 140 kW and 114 kW are supplied to the dissociation equipment and recombination equipment, respectively, then 5.14 kW of power output from the dynamo can be obtained. Because the latent heat of the phase change of CO<sub>2</sub> hydrate is large, there is a large quantity of warm energy and cold energy supplied to the system. However, the proposed system is driven with green energy, and the low-temperature exhaust heat is hardly used. Conversely, the energy consumption of the screw pump and the loss of the actuator and the dynamo are 3.8 kW and 17.1 kW, respectively.

### **6.2 Influence of Differences in the Heat-Source Temperature**

#### **(1) The conditions of a cycle**

If, for example, green energy and the open air are used for the heat source of the system, frequent fluctuations from a target temperature will be expected. Thus, in this study, the relation of the temperature change of a cooled heat source and the energy flow of the system were investigated. The engine performance at the time in which the temperature-pressure

conditions of the proposed system shown in Fig. 7 were changed into each condition shown in Fig. 9 was evaluated. The heat cycle shown in Fig. 7 (proposed system, recombination temperature = 0 °C), recombination temperature = -5 °C, and recombination temperature = +5 °C are shown in Fig. 9. The dissociation temperature of the heat cycle was set to 15 °C.

(2) The results of the energy flow

Figures 10 (a) and (b) are the analysis results of the energy flow in the case where the recombination temperature was -5 °C and +5 °C. The generator output at the time of the recombination temperature of -5 °C is 5.57 kW. But, the generator output at the time of the recombination temperature of +5 °C is 3.41 kW. Therefore, the difference in the generation of electrical energy is 2.16 kW (5.57 kW-3.41 kW) for a 10 °C (from -5 °C to +5 °C) difference in the temperature of recombination. Furthermore, the heat transfer area of the dissociation equipment and recombination equipment of "Figs. 10 (a) and (b) was measured. Figure 10 (a) shows an increase from 110% to 160% compared to Fig. (b) because the difference in the entrance temperature  $T_C$  of the dissociation equipment (specifically, the outlet temperature  $T_B$  of the recombination equipment) and the outlet temperature  $T_D$  of the dissociation equipment is large at a recombination temperature of -5 °C.

Each power generation efficiency of a cold energy basis of Figs. 10 (a) and (b) is 4.2% and 3.4%. These efficiencies are the cases of supply of atmospheric air to dissociation equipment, and supply of production cold energy to recombined equipment. However, when the cold energy by the difference in temperature of day and night and green energy such as snow ice is used, the power generation efficiency will increase.

### 6.3 Capacity of Recombination Equipment

The speed of recombination is remarkably small compared to the dissociation speed. The system performance depends on the space velocity of the recombination equipment of the working fluid. Therefore, it is necessary to determine the capacity of the recombination equipment from the system performance target and recombination speed.

For example, the quantity of flow of the working fluid given in Table 1 leads to a CO<sub>2</sub> hydrate recombination target in the recombination equipment of 15 wt%. (The value on the vertical axis in Fig. 5 is about 0.07.) However, if the target amount of CO<sub>2</sub> hydrate recombination is set even smaller, then an even larger hydrate recombination speed can be obtained because the amount of recombination is proportional to the sampling time if the target amount of CO<sub>2</sub> hydrate recombination is small (the value of the vertical axis of Fig. 5 is about 0.047 (10 wt%)). However, if the value of the vertical axis of Fig. 5 exceeds 0.047, the relation between the amount of recombination and the sampling time will follow the second-order curve (the curve of the broken line in Fig. 5). If there is little target recombination of the hydrate, the capacity of the recombination equipment will become large. Accordingly, because the recombination speed of a hydrate is slow, it is necessary to obtain the reaction time required for the recombination of a hydrate by determining the capacity of the recombination equipment. Thus, in this paper, the number of times in which the working fluid was replaced compared to the capacity of the recombination equipment required for obtaining the target amount of CO<sub>2</sub> hydrate recombination was investigated. If there is a large number of a replacement, then the capacity of the recombination equipment must be changed into large volume. Fig. 11 shows the relationships between the target amount of CO<sub>2</sub> hydrate recombination, the recombination temperature, and the number of replacements of the working fluid. Based on the relation of the recombination speed and the amount of recombination of CO<sub>2</sub> hydrate shown in Fig. 5, when the amount of target

recombination is large (15 wt% in Fig. 11), the recombination speed falls. As a result, the number of replacements of the volume of recombination equipment to the volume of working fluid increases greatly. Therefore, it is necessary to constrain the target amount of CO<sub>2</sub> hydrate recombination to less than 10 wt%. If the target amount is set to less than 10 wt% when the temperature of recombination is  $\pm 5$  °C, the capacity of the recombination equipment is half of the capacity of the case of 15 wt%.

## 7. Conclusions

An actuator system (gas-hydrate engine) designed to realize the continuous dissociation and recombination of a hydrate was proposed using a CO<sub>2</sub> gas hydrate as the working fluid. The following conclusions were obtained by investigating the performance of this proposed system by numerical analysis.

(1) The energy flow of the proposed system was clarified. For example, with entry conditions of the recombination equipment of 9 °C and 1.2 MPa and exit conditions of 0 °C and 5 MPa, a heat-source temperature of the recombination equipment of -5 °C, a heat-source temperature of the dissociation equipment of 20 °C, and a working fluid composed of CO<sub>2</sub> and H<sub>2</sub>O that is passed at 1150 g/s, about 5 kW of electric power can be obtained.

(2) To investigate the relation between the difference in the heat-source temperature and the performance of the proposed system, the energy flow in the case of a recombination temperature of -5 °C and +5 °C was analyzed. As a result, it was found that the difference in the temperature of recombination greatly influences the generation of electrical energy. Furthermore, the heat transfer area required for the recombination equipment and the dissociation equipment reached a maximum increase of 160%.

(3) Because the recombination speed is remarkably slow compared to the dissociation speed, it is necessary to obtain the reaction time of a working fluid by increasing the volume of the recombination equipment. Then, the capacity of the recombination equipment is calculated from the recombination speed obtained in the past experiment. As a result, it was clearly shown that the volume of the recombination equipment decreases by appropriately setting the amount of CO<sub>2</sub> hydrate recombination contained in a working fluid.

(4) Because the latent heat of CO<sub>2</sub> hydrate is large, the warm energy and cold energy required for the operation of the proposal system are large. However, the proposed system can use green energy and unused low-temperature exhaust heat.

Based on the results described above, a prototype will be developed as part of the future work of this project.

## Nomenclature

$c$	: Specific heat [J/(g·K)]
$g$	: Acceleration of gravity [m/s <sup>2</sup> ]
$h$	: Head of water [m]
$L$	: External work [Nm]
$l$	: Latent heat [J/g]
$L_{CP}$	: External work of cylinder and piston [Nm]
$m$	: Mass of water [kg]
$N_m$	: The number of working fluid compositions
$P$	: Pressure [MPa]
$\bar{P}$	: Mean pressure [MPa]
$\Delta P$	: Differential pressure [MPa]
$Q_{lh}$	: Latent heat of working fluid [W]
$Q_{sh}$	: Sensible heat of working fluid [W]
$T$	: Temperature [°C]
$\Delta t$	: Time interval of sampling [s]
$V$	: Volume [m <sup>3</sup> ]

$W$  : Power output of system [W]

$w$  : Mass flow rate [kg/s]

Roman character

$\varphi$  : Safety factor

$\eta_a$  : Efficiency of the actuator [%]

$\eta_e$  : Efficiency of the engine generator [%]

$\kappa$  : Ratio of specific heat

Subscript

$BT$  : Buffer tank

$lg$  : Composition of working fluid liquid, vapor and gas

$RE$  : Recombination equipment

$s$  : Composition of working fluid hydrate

$wf$  : Working fluid

**References**

[1] Xuemei Lang, Shuanshi Fan, Yanhong Wang, Intensification of methane and hydrogen storage in clathrate hydrate and future prospect, *Journal of Natural Gas Chemistry*, 2010, 19(3), 203-209.

[2] Nam-Jin Kim, Jeong Hwan Lee, Yil Sik Cho, Wongee Chun, Formation enhancement of methane hydrate for natural gas transport and storage, *Energy*, 2010, 35(6), 2717-2722.

[3] Jorge Gabitto, Costas Tsouris, Dissolution mechanisms of CO<sub>2</sub> hydrate droplets in deep seawaters, *Energy Conversion and Management*, 2006, 47(5), 494-508.

[4] Yingming Xie, Gang Li, Daoping Liu, Ni Liu, Yingxia Qi, Deqing Liang, Kaihua Guo, Shuanshi Fan, Experimental study on a small scale of gas hydrate cold storage apparatus, *Applied Energy*, 2010, 87(11), 3340-3346.

[5] Yuehong Bi, Tingwei Guo, Liang Zhang, Lingen Chen, Fengrui Sun, Entropy generation minimization for charging and discharging processes in a gas-hydrate cool storage system, *Applied Energy*, 2010, 87(4), 1149-1157.

[6] Tadafumi Daitoku, Yoshio Utaka, Separation characteristics of clathrate hydrates from a cooling plate for efficient cold energy storage, *Applied Energy*, 2010, 87(8), 2682-2689.

[7] Audun Aspelund, Truls Gundersen, A liquefied energy chain for transport and utilization of natural gas for power production with CO<sub>2</sub> capture and storage - Part 4: Sensitivity analysis of transport pressures and benchmarking with conventional technology for gas transport, *Applied Energy*, 2008, 86(6), 815-825.

[8] Audun Aspelund, Truls Gundersen, A liquefied energy chain for transport and utilization of natural gas for power production with CO<sub>2</sub> capture and storage - Part 1, *Applied Energy*, 2009, 86(6), 781-792.

[9] Shin'ya OBARA, Development of a hybrid compressed gas engine/PEFC power system using the dissociation expansion characteristics of gas hydrate, *International Journal of Hydrogen Energy*, 2010, 35(19), 10604-10612.

[10] T. Kawamura, T. Komai, Y. Yamamoto, K. Nagashima, K. Ohgaa, K. Higuchia, Growth kinetics of CO<sub>2</sub> hydrate just below melting point of ice, *Journal of Crystal Growth*, 2002, 234, 220-226.

## Captions

Fig. 1 CO<sub>2</sub> hydrate power generation system.

Fig. 2 Model of the change of state of the working fluid.

Fig. 3 System operation in a pressure-temperature diagram.

Fig. 4 Conditions of the working fluid.

Fig. 5 Experimental data in the early period of CO<sub>2</sub> hydrate growth.

Fig. 6 Buffer tank.

Fig. 7 Pressure-volume diagram of the working fluid.

Fig. 8 Analysis results of the energy flow. The recombination temperature was 0 °C. Conditions: water at a flow rate of 0.001 m<sup>3</sup>/s and a CO<sub>2</sub> to hydrate weight percent of 10 wt%.

Fig. 9 System operation in a pressure-temperature diagram.

Fig. 10 Analysis results of the energy flow. The recombination temperatures were -5 °C and +5 °C. Conditions: working flow using water of 0.001m<sup>3</sup>/s and CO<sub>2</sub> weight percent to hydrate of 10 wt%.

(b) Temperature of recombination: +5 °C

(a) Temperature of recombination: -5 °C

Fig. 11 Analysis results of the working fluid replacement rate in the recombination equipment.

Table 1 Analysis conditions of the proposed system.

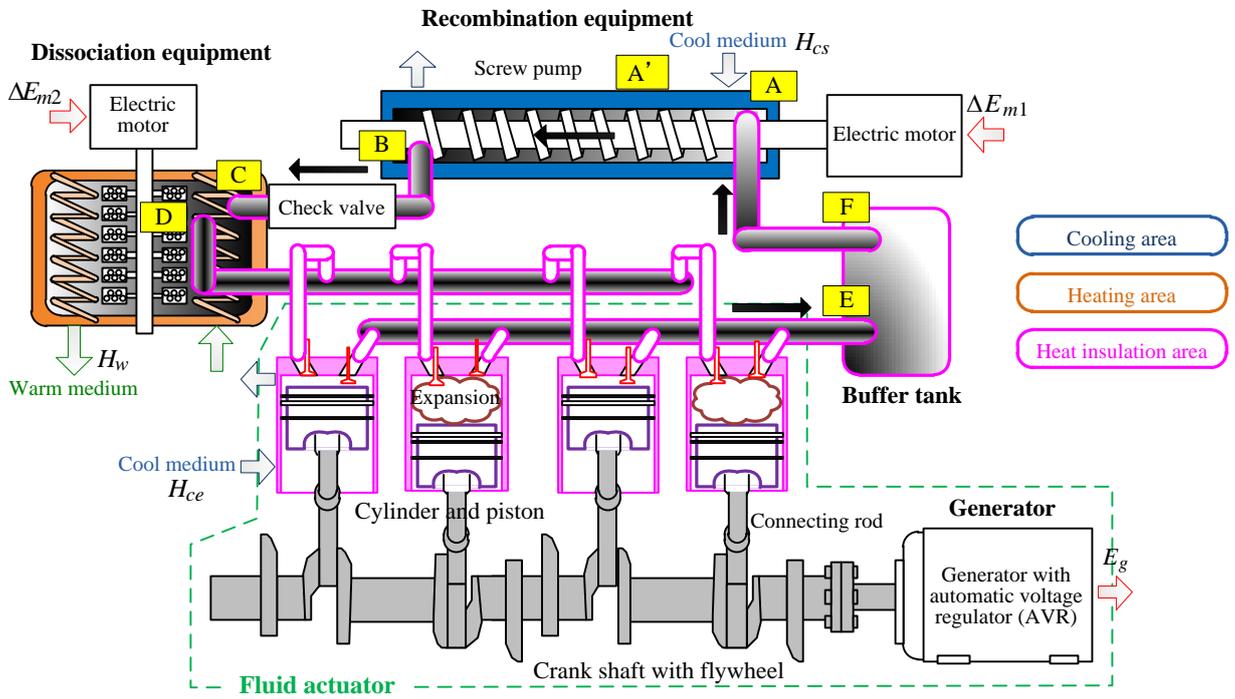


Fig. 1 CO<sub>2</sub> hydrate power generation system

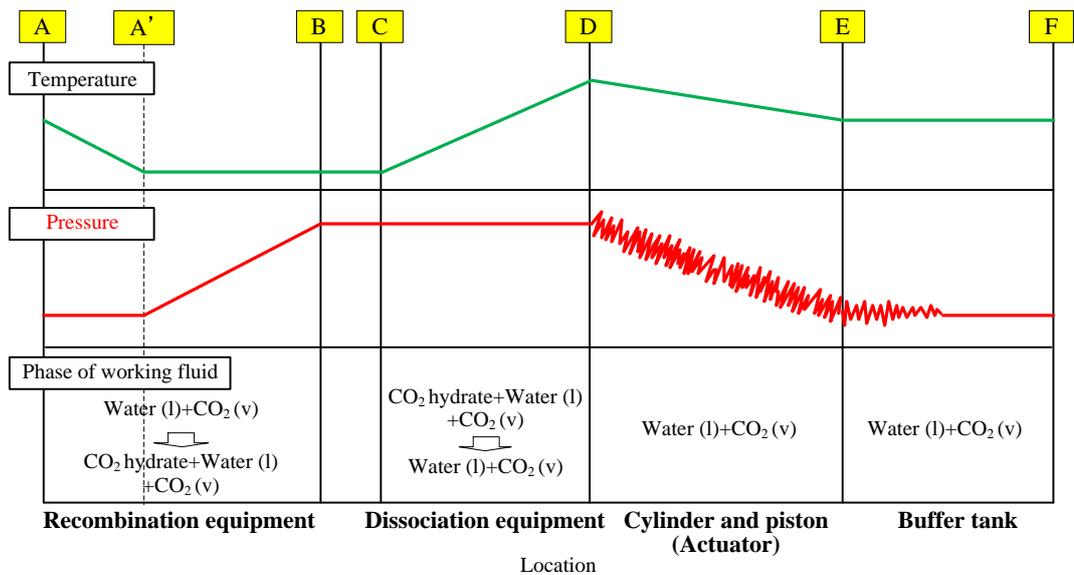


Fig. 2 Model of the change of state of the working fluid.

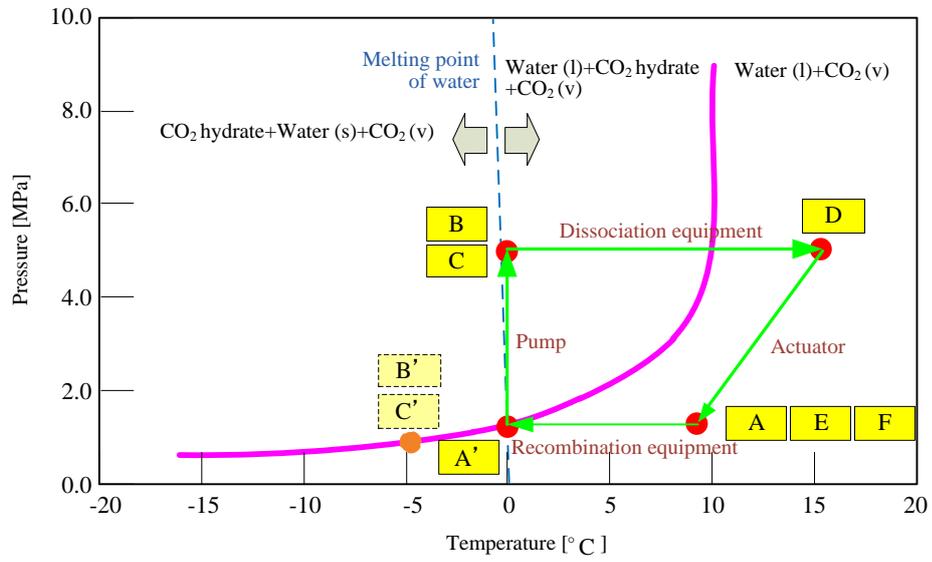


Fig. 3 System operation in a pressure-temperature diagram.

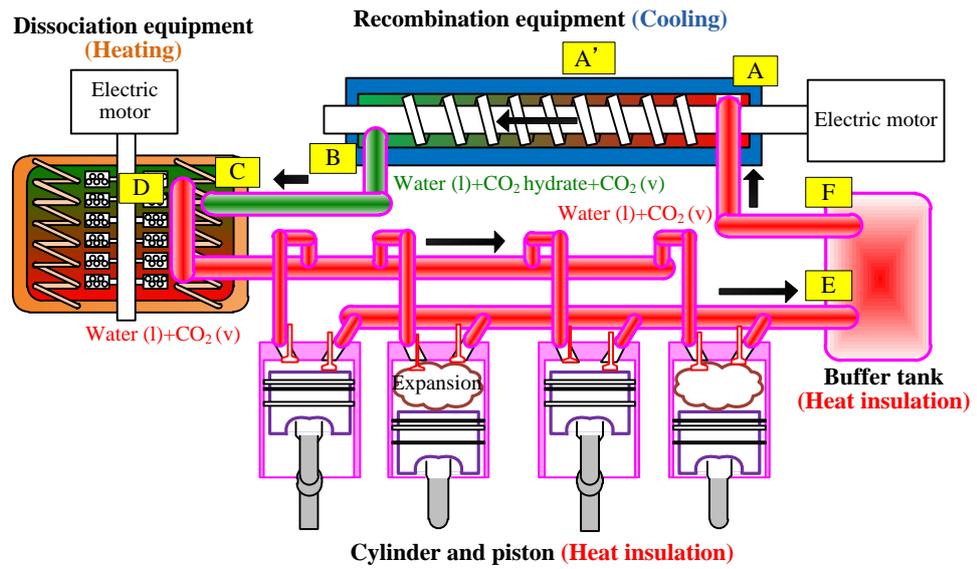


Fig. 4 Conditions of the working fluid.

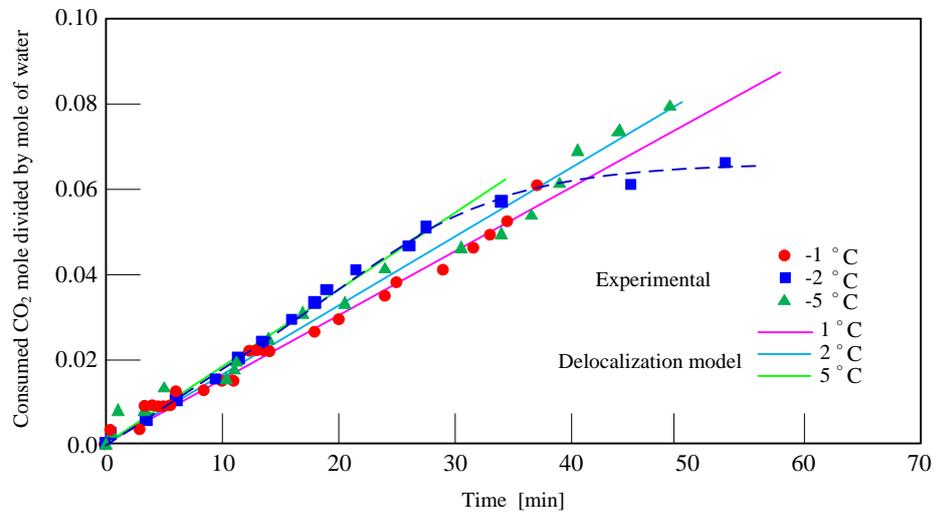


Fig. 5 Experimental data in the early period of CO<sub>2</sub> hydrate growth.

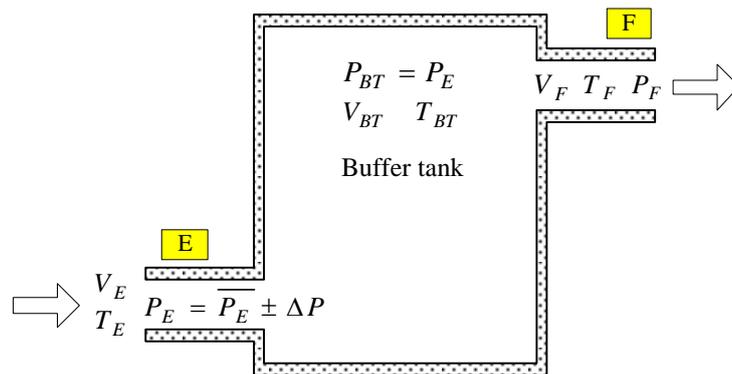


Fig. 6 Buffer tank.

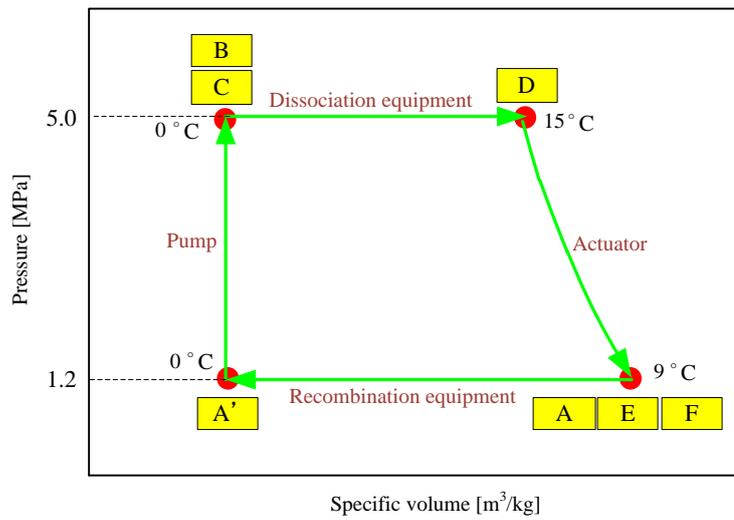


Fig. 7 Pressure-volume diagram of the working fluid.

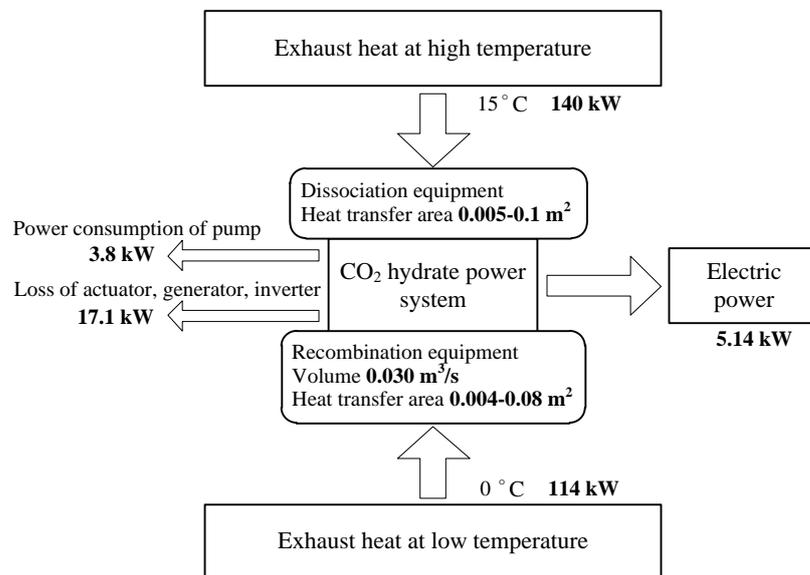


Fig. 8 Analysis results of the energy flow. The recombination temperature was 0°C. Conditions: water at a flow rate of 0.001 m<sup>3</sup>/s and a CO<sub>2</sub> to hydrate weight percent of 10 wt%.

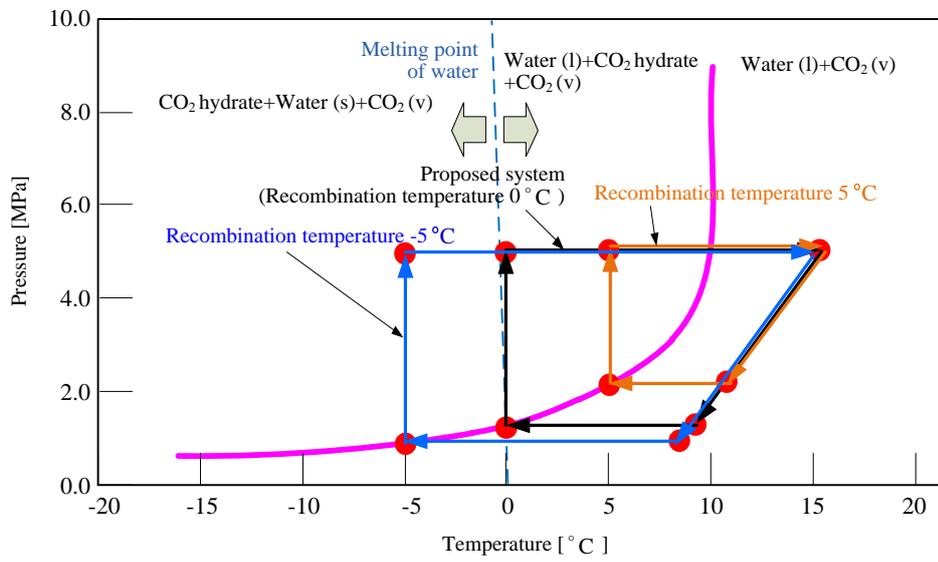
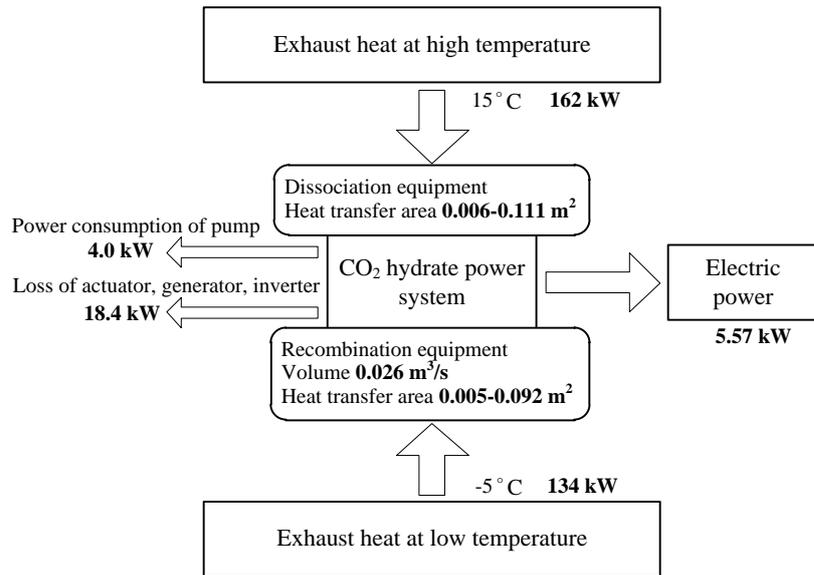
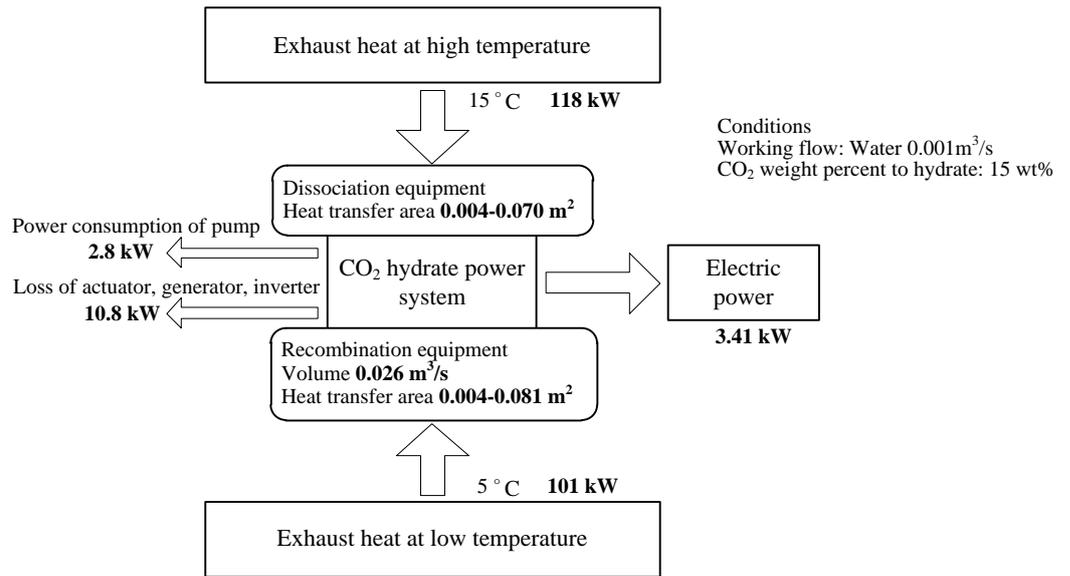


Fig. 9 System operation in a pressure-temperature diagram.



(a) Temperature of recombination:  $-5^{\circ}\text{C}$



(b) Temperature of recombination:  $+5^{\circ}\text{C}$

Fig. 10 Analysis results of the energy flow. The recombination temperatures were  $-5^{\circ}\text{C}$  and  $+5^{\circ}\text{C}$ . Conditions: working flow using water of  $0.001\text{m}^3/\text{s}$  and  $\text{CO}_2$  weight percent to hydrate of 10 wt%.

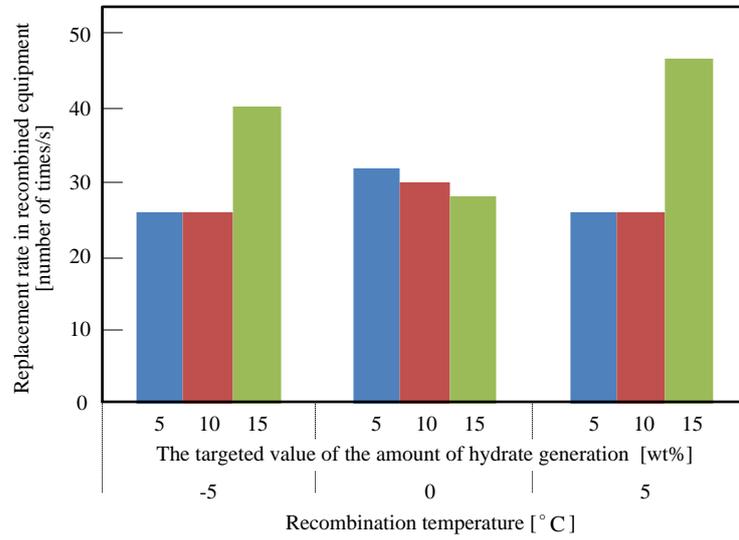


Fig. 11 Analysis results of the working fluid replacement rate in the recombination equipment.

Table 1 Analysis conditions of the proposed system.

Mass quantity of working fluid: H <sub>2</sub> O 1000 g/s, CO <sub>2</sub> 150 g/s (15 wt%)	
Efficiency of actuator	80 %
Efficiency of pump	80 %
Efficiency of generator	85 %
Latent heat of CO <sub>2</sub> hydrate generation	500 kJ/kg