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Development of a compound energy system for cold region houses using small-scale natural gas cogeneration and a gas hydrate battery

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ABSTRACT

In this study, an independent energy system for houses in cold regions was developed using a small-scale natural gas CGS (cogeneration), air-source heat pump, heat storage tank, and GHB (gas hydrate battery). Heat sources for the GHB were the ambient air and geothermal resources of the cold region. The heat cycle of CO_2 hydrate as a source of energy was also experimentally investigated. To increase the formation speed of CO_2 hydrates, a ferrous oxide–graphite system catalyst was used. The ambient air of cold regions was used as a heat source for the formation process (electric charge) of the GHB, and the heat supplied by a geothermal heat exchanger was used for the dissociation process (electric discharge). Using a geothermal heat source, fuel consumption was halved because of an increased capacity for hydrate formation in the GHB, a shortening of the charging and discharging cycle, and a decrease in the freeze rate of hydrate formation space. Furthermore, when the GHB was introduced into a cold region house, the application rate of renewable energy was 47–71% in winter. The spread of the GHB can greatly reduce fossil fuel consumption and the associated greenhouse gases released from houses in cold regions.

1. Introduction

Various gases can form gas hydrates, in which gas molecules are trapped inside "cages" of hydrogen-bonded water molecules. Many industrial applications of the hydrates have been investigated, particularly of methane and carbon dioxide hydrates. With regard to methane hydrates, considerable research has focused on the highly efficient extractive technology of gas hydrate [1–3] and economical use of methane [4–7]. On the other hand, the methane hydrates also attract attention as a technologically highly efficient means for transporting natural gas. Study of natural-gas transportation is investigated by Javanmardi et al. [8], Hu et al. [9], and Kim et al. [10]. Studies have further investigated the use of gas hydrates for the storage of cold energy by Xie et al. [11], Bi et al. [12], Daitoku and Utaka [13], and capture of CO_2 by Aspelund et al. [14,15]. A prominent characteristic of gas hydrates is that the phase equilibrium condition of formation and dissociation occurs under large pressure differences with relatively small temperature changes. For example, on the phase equilibrium curve of formation and dissociation for CO_2 hydrate, a temperature change from 0 °C to 10 °C exhibits a corresponding pressure difference of about 3 MPa [16]. Therefore, when the pressure change caused by the dissociation expansion gas of a hydrate is released to an actuator, large amounts of power can be generated by a relatively small change in temperature. Furthermore, since gas hydrates can be easily stored, the combination of gas hydrates and an actuator can serve as an electric charge-and-discharge apparatus (gas hydrate battery: GHB). The large heat to power ratio makes this an important energy source for cold regions during winter where low cost and clean energy is essential. Therefore, the use of geothermal heat pumps, employing electric storage heaters for surplus power at midnight and early in the morning has become more common [17–19]. However, the technology described above requires electric power, and if fossil fuels are to be avoided, it means an increase in either

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thermal or nuclear power generation. The purpose of this study was, therefore, the development of a complex of cogeneration and the GHB system, using a small-scale natural gas engine [20,21] to reduce fossil fuel consumption for cold regions during winter, and subsequently greenhouse gases.

For this purpose, we use a carbon dioxide-based GHB, where the heat change was produced from low temperature of the ambient winter air in the cold region and high temperature of the heat medium, warmed by a geothermal heat exchanger. Power consumption is very small as the GHB is operated only by the circulating pump for the heat media. However, the capacity of gas hydrate generator and gas hydrate accumulator is large and requires repeated charge and discharge at regular intervals, as is common with all batteries. Therefore, in this paper we clarify the following: (1) the configuration and capacity of a small-scale natural gas CGS (cogeneration) and the GHB energy system for houses in cold regions; (2) the operation method for each piece of equipment constituting the system; and (3) the relation between heat to power ratio and fuel consumption of the proposed system. When these points are understood, the distributed energy can be improved drastically for cold regions, minimizing the accompanying winter heat demand and consumption of fossil fuels.

2. System configuration

2.1. System scheme

Fig. 1 shows the conventional and proposed distributed energy systems for houses in cold regions investigated in this paper. A conventional CGS for individual houses consists of the air heat-source heat pump, heat storage tank and heat supply by a natural-gas engine generator (Fig. 1a). The fuel consumption in System A (Fig. 1b) and the CGS in System B (Fig. 1c) is compared with the conventional CGS system (Fig. 1a). Heat on the demand side (space heating and hot water supply) in System A is supplied by the CGS exhaust heat and air heat-source heat pump, while heat for the dissociation process (electric discharge) of the GHB is supplied by an approximately 10–15 °C heat medium warmed by a geothermal heat exchanger. Moreover, for the formation processes (electric charge) of gas hydrates, ambient air, absorbed by a radiator, is used as a source of cold energy (yellow arrows (in the web version) in Fig. 1b and c). Alternatively, on the demand side in System B, heat is supplied by the CGS exhaust heat, air heat source heat pump, and partially supplied by the geothermal heat exchanger. An auxiliary boiler is operated when high temperature water supply is required in System A and System B; however, it is not further discussed in this paper. Moreover, the capacity of the geothermal heat exchanger is large in System B because geothermal heat provides part of the heat supply to the demand side (space heating and hot water supply), increasing the equipment cost of System B relative to System A. However, due to the large decrease in power consumption of the air heat source heat pump in System B, fuel consumption of the entire CGS system is expected drastically decrease.

2.2. Energy flow and energy balance equation

The energy flow and energy balance of each system are described below by Fig. 1a–c. Green, red, blue, and yellow arrows (in the web version) in Fig. 1 are natural gas fuel, electricity, heat, and the formation process of gas hydrates, respectively. The symbols q_f, p, and h in Fig. 1 refer to fuel flow rate, electricity, and heat based on the calorific value, respectively, while η, T, and COP (coefficient of performance) refer to efficiency, temperature, and the performance coefficient of the heat pump. The subscript t is sampling time, θ_{cgs} is the heat to power ratio of the CGS output, and H_{st} is the heat storage quantity.

2.2.1. Conventional system (Fig. 1a)

Electricity output is obtained from the CGS alone and is supplied to the demand side and air heat source heat pump (Eq. (1)). The heat output from the CGS is calculated using Eq. (2), with heat storage ($H_{st,t}$) obtained from Eq. (3) using heat storage start and finish times, hss and hse, respectively. The heat released from the heat storage tank is calculated using Eq. (4), which introduces the efficiency of thermal storage ($\eta_{hst,t}$) into each sampling time from the start (ohs) to finish (ohe) of heat output. The thermal power ($h_{ahp,t}$) of the air heat source heat pump is obtained from $\mathrm{COP}_{ahp,t} \cdot p_{ahp,t}$ by giving the electricity ($p_{ahp,t}$) to the heat pump (Eq. (5)). The heat demand ($h_{demand,t}$) is the sum of the thermal power of the heat storage tank and heat pump, as shown in Eq. (6).

$$\frac{1}{\theta_{cgs,t}+1}\cdot q_{f,t} = p_{cgs,t} = p_{demand,t} + p_{ahp,t} \quad (1)$$

$$h_{cgs,t} = \frac{\theta_{cgs,t}}{\theta_{cgs,t}+1}\cdot q_{f,t} \quad (2)$$

$$H_{st,t} = \sum_{t=hss}^{hse} h_{cgs,t} \quad (3)$$

$$h_{hst,t} = \sum_{t=ohs}^{ohe} \left(\eta_{hst,t}\cdot h_{st,t}\right) \quad (4)$$

$$h_{ahp,t} = \mathrm{COP}_{ahp,t}\cdot p_{ahp,t} = h_{amb,t} + p_{ahp,t} \quad (5)$$

$$h_{demand,t} = h_{hst,t} + h_{ahp,t} \quad (6)$$

2.2.2. System A (Fig. 1b)

Since electricity of System A is output from the CGS ($p_{cgs,t}$) and GHB ($p_{ghb,t}$), the balance equation of electricity is shown by Eq. (7). Furthermore, as the amount of GHB electric discharge is dependent on the dissociation temperature of the gas hydrate, as displayed in Figs. 2 and 3, the function $\psi(T_{ghb})$ of dissociation temperature is introduced. The GHB electric discharge is calculated by Eq. (8) using the heat ($h_{gth,ghb,t}$) of the heat medium supplied to the GHB via the geothermal heat exchanger. Although the heat medium is circulated with a pump between the geothermal heat exchanger and the GHB, the power consumption ($\Delta p_{pump,t}$) in the circulation pump is calculated by Eq. (9), where ρ_w, $Q_{w,t}$, η_{pump}, and H represent density of the heat medium, volumetric flow, pump efficiency, and total head of actual pump head and loss head, respectively. Although thermal power of the CGS is the same as previously described in Eq. (2), the exhaust heat ($h_{cgs,t}$) of the CGS and the thermal power ($h_{ahp,t}$) of air heat source heat pump (Eq. (5)) are stored in a heat storage tank ($H_{st,t}$), as shown in Eq. (10). Moreover, the thermal power from the heat storage tank supplied to the demand side ($h_{demand,t}$) is calculated by Eq. (11). The heat ($h_{hst,ghb,t}$) to the GHB is supplied by controlling the flow of the heat medium by the geothermal heat exchanger. In Fig. 1b and c, the energy flow (yellow arrows (in the web version)) is provided for the charging operation of the GHB in which gas hydrates are formed. Cold energy ($h_{ahb,amb,t}$), required for the generation process of gas hydrates, is absorbed from the ambient air using a radiator.