[*Technical Paper*]

Development of Bench-Scaled Adsorption Type Steam Recovery System for Generating High Temperature Steam from Hot Waste Water*

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ABSTRACT

The system to generate steam from low-grade waste heat is therefore required for the effective utilization of energy. In this study, a novel steam generation process using a direct heat exchange system with adsorbent-water pair is proposed. Contacting water with adsorbent makes excess water evaporate due to the release of adsorption heat from adsorbent. Because this system does not require any heat exchangers, increment in packing density of adsorbent particles in the reactor is expected. The bench-scaled adsorption type steam recovery system of the steam generators for 10-45 kg-adsorbent/unit was developed. Operation condition of the steam generation process and the regeneration process of this system were investigated using this equipment of the one or three generator units. As a result, the steam at 170 °C (maximum) and 150 °C (average) could be generated continuously using the bench-scaled equipment of three steam generators.

1. Introduction

The efforts for energy conservation are requested because of the limitation of fossil fuel and the environmental issue of global warming. Petrochemical and Steel industries are especially the largest energy-consuming manufacturing industries. While large amount of hot waste water with the range of 60-90 °C is released from these industrial processes, steam is demanded and large quantities of fossil fuel are generally consumed. The system to generate steam from low-grade waste heat is therefore required for the effective utilization of energy.

In this study, a novel steam generation process using a direct heat exchange system with adsorbent-water pair is proposed. Contacting water with adsorbent makes excess water evaporate due to the release of adsorption heat from adsorbent. Because this system does not require any heat exchangers, increment in packing density of adsorbent particles in the reactor is expected. The purpose of this study is to investigate the novel steam generation system using adsorbent-water pair. Cycle operation which consists of steam generation process and regeneration process of this system has been studied experimentally and numerically using laboratory-scaled equipment of steam generator for 0.3 kg-adsorbent/unit[1-6]. Based on this basic study, bench-scaled adsorption type steam recovery system of the steam generators for 10-45 kg-adsorbent/unit was manufactured. Operation condition of the steam generation process and the regeneration process of this system were investigated using bench-scaled equipment of one steam generator. And more, continuous steam generation operation was examined using this equipment of the three generator units.

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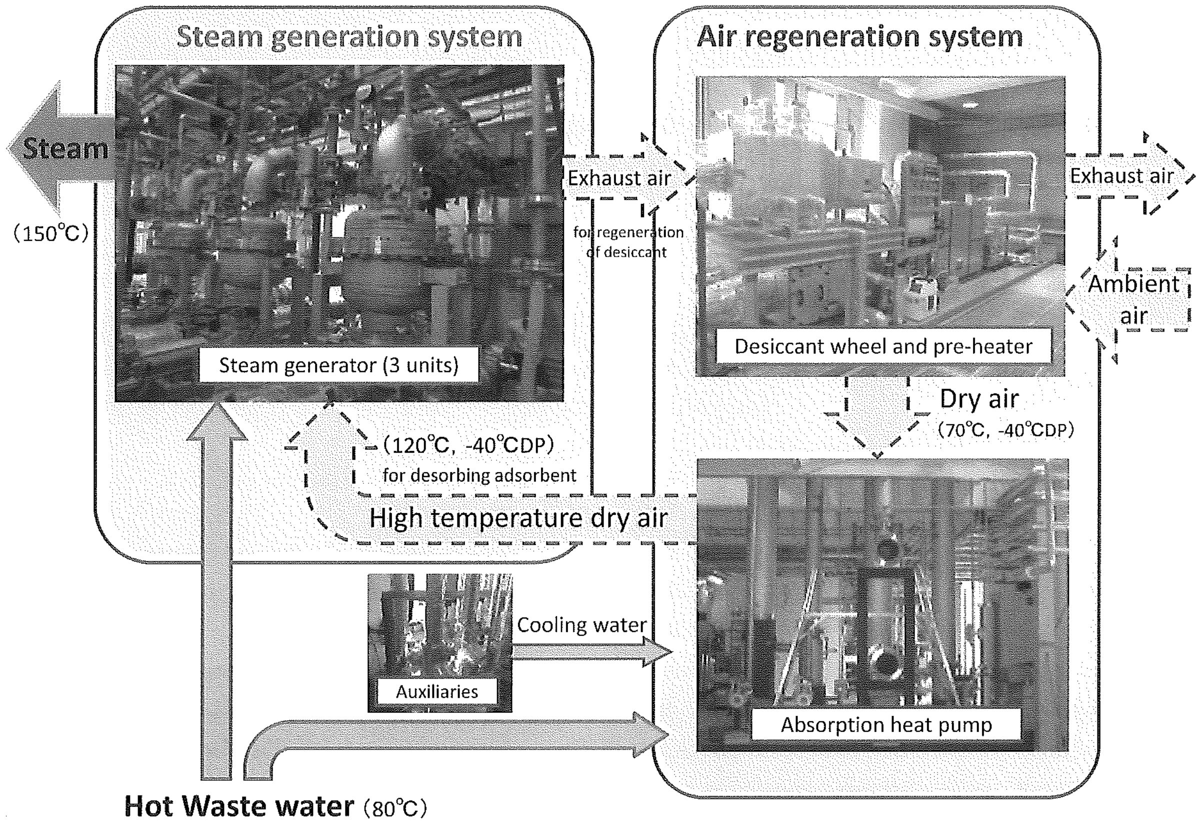

Fig. 1 Bench-scaled adsorption type steam recovery system

2. Experimental System

2.1 Apparatus

An outline of the bench-scaled adsorption type steam recovery system is shown in **Fig.1**. This system is composed of steam generation system, air regeneration system, and their auxiliaries. The steam generation system generated steam from absorbing zeolite pellet as the adsorbent, at the steam generation process. The air regeneration system produced high temperature dry air for desorbing zeolite pellet at the regeneration process. The steam generation system is composed of cylindrical steam generators, a feeding pump of water, a vacuum pump, a compressor of air, and a water tank for hot water. An outline of the steam generator is shown in **Fig.2**. The steam generator was made of stainless steel with the height of 565 mm and the inner diameter of 498 mm. Zeolite pellet was packed into the steam generator for 10-45 kg/unit. The air regeneration system is composed of a blower, a desiccant wheel, a pre-heater, and LiBr/H_2O absorption heat pump to heat up dry air.

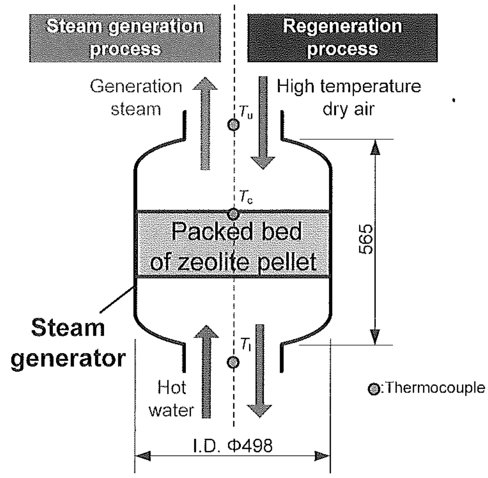

Fig. 2 Steam generator

2.2 Operation methods

The steam generation process and the regeneration process are shown in **Fig.3**. Operation methods of each process were determined from results of the labo-scale experimental system[4]. In the steam generation process, air in the steam generator was removed by the vacuum pump (step 1). Hot water of 80 °C was introduced to the steam generator from the water tank through the feeding pump. Low-pressure vapor which evaporated from hot water was adsorbed zeolite. Adsorption heat was generated, to raise the temperature of the zeolite (step 2). After that, hot water contacted the zeolite. Steam was then generated by adsorption heat (step 3-4). The steam generation process was terminated when water interface reached the top of packed bed of zeolite pellet (step 5). After the steam generation process, it is changed to the regeneration process. Remained water was drained from the bottom of the steam generator by compressed air from the compressor (step 6). The high temperature dry air was introduced to the generator. Water is desorbed from zeolite, and zeolite return to the initial condition (step 7). The high temperature dry air with dew point of -40 °C was produced from ambient air by the desiccant wheel. The high temperature dry air was heated up to 70 °C by the pre-heater, and more, heated up to 125 °C by the LiBr/H_2O absorption heat pump. Air exhausted from the steam generator was recycled to use heat source of the desiccant wheel.

3. Results

3.1 Cycle Operation using one steam generator

Cycle operation conditions of the steam generation process and the regeneration process were confirmed

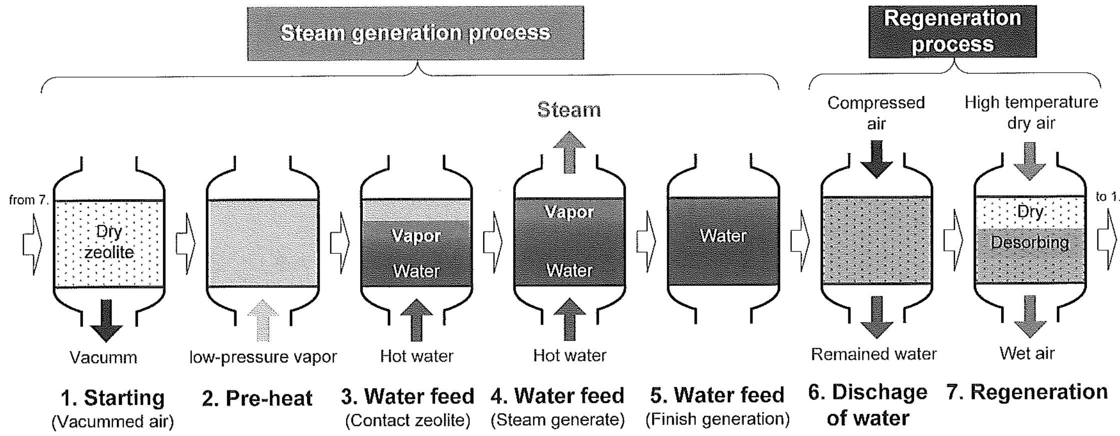

Fig. 3 Steam generation process and regeneration process

Table 1 Operation conditions using one steam generator

Steam generator		Steam generation process		Regeneration process	
Number of units	1 unit	Process time	810 sec	Process time	1,200 sec
Weight of zeolite pellet per unit	10 kg/unit	Inlet temperature of hot water	80 °C	Inlet temperature of high temperature dry air	125 °C
				Inlet dew point of high temperature dry air	-50 °C
				Flow rate of high temperature dry air	1,050 $Nm^3/(h\cdot unit)$

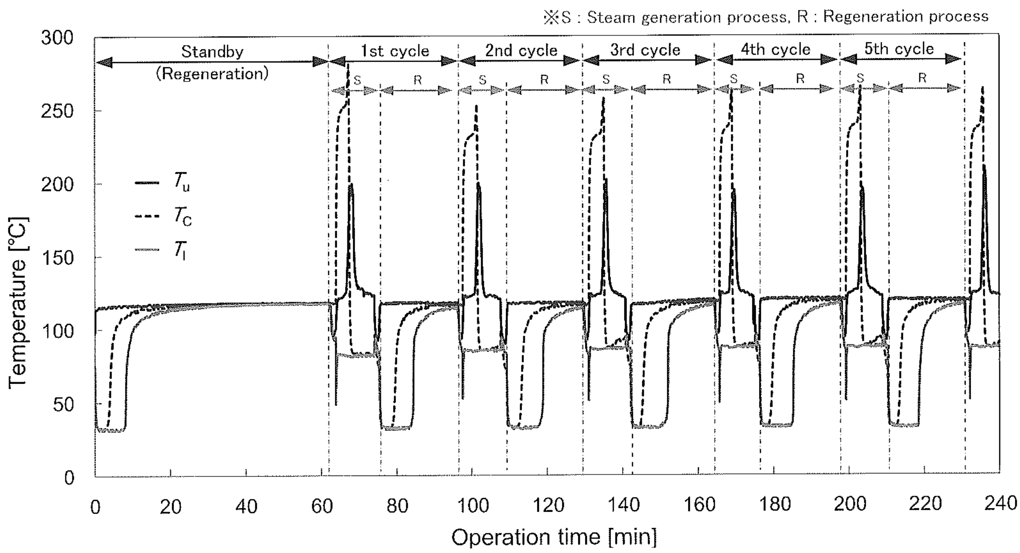

Fig. 4 Results of cycle operation using one steam generator

experimentally using the bench-scaled equipment of one steam generator. In these experiments, the amount of zeolite packed in the steam generator was 10 kg/unit. The experimental conditions are shown in **Table 1**.

The experimental results are shown in **Fig.4**. By the experimental results at the steam generation process, superheated steam whose temperature was 200 °C (T_u) was generated from the hot water at 80 °C (T_l). The peak temperature in the packed bed reached 260 °C (T_c). The mass of steam generated per unit mass of zeolite was 0.09 kg-steam/kg-zeolite/cycle. In addition, the results after the second cycles depict good agreement in thermal response. It was shown that the proposal operation methods are effective for stable continuous steam generation.

3.2 Cycle Operation using three steam generators

Cycle operation condition for continuous steam generation was confirmed using the bench-scaled equipment of the three generator units. The amount of zeolite packed per steam generator was 45 kg/unit. The operation methods and the operation condition are shown in **Fig.5** and **Table 2-3**, respectively. Steam was generated by turns in the three generators (unit A, B, C). For example, when the unit A was on the stage of the steam generation process, the unit B and C were at the regeneration process. After the end of steam generation process at A, the unit B was turned to the steam generation process, and then unit C and A were at the regeneration process. Furthermore, after the end of steam generation process at B, the unit C was turned to the steam generation process. In these experiments, each process time was determined by the experimental results using one steam generator in which the steam generation process time and the regeneration process time were decided to be 1,500 sec and 3,000 sec, respectively.

The experimental results are shown in **Fig.6**. By the

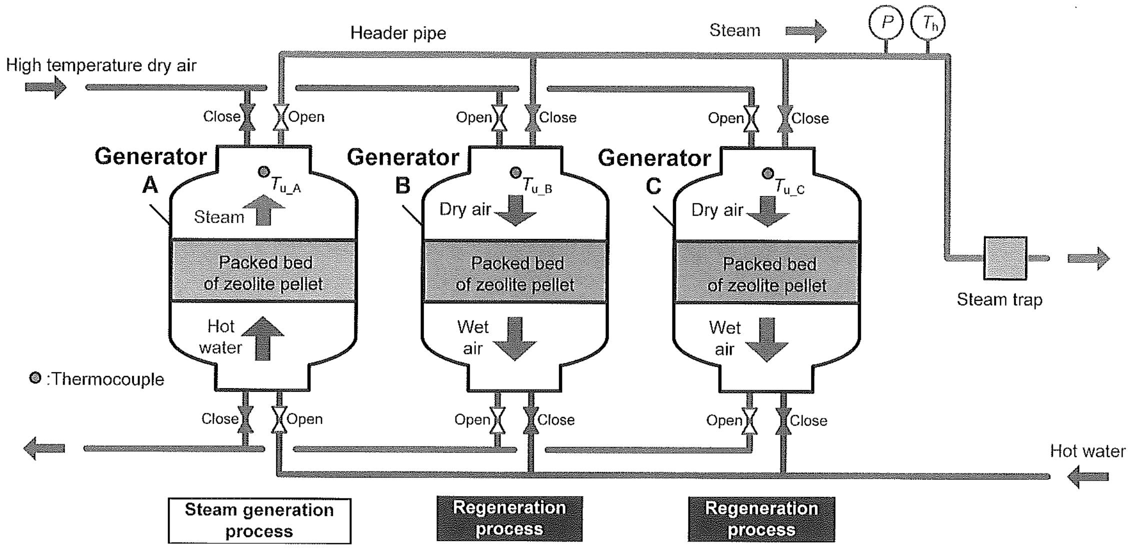

Fig. 5 Operation methods and schematic diagram of equipment using three steam generators (1st cycle)

Table 2 Operation methods using three steam generators (each unit)

Unit name	1st cycle	2nd cycle	3rd cycle	4th cycle
Generator A	**Steam generation**	**Regeneration**	**Regeneration**	**Steam generation**
Generator B	**Regeneration**	**Steam generation**	**Regeneration**	**Regeneration**
Generator C	**Regeneration**	**Regeneration**	**Steam generation**	**Regeneration**

Table 3 Operation conditions using three steam generators

Steam generator		Steam generation process		Regeneration process	
Number of units	3 units	Process time	1,500 sec	Process time	3,000 sec
Weight of zeolite pellet per unit	45 kg/unit	Inlet temperature of hot water	80 °C	Inlet temperature of high temperature dry air	128 °C
				Inlet dew point of high temperature dry air	-62 °C
				Flow rate of high temperature dry air	600 $Nm^3/(h\cdot unit)$

experimental results, the generated steam whose temperature was 130-170 °C and pressure was 0.24-0.94 MPa (150 °C and 0.48 MPa on the average) was obtained continuously from the three generator units, and was supplied to the header pipe.

4. Conclusion

A novel steam generation process using a direct heat exchange system with adsorbent-water pair is proposed. The bench-scaled adsorption type steam recovery system of the steam generators was developed. Operation condition of the steam generation process and the regeneration process of this system were investigated using the bench-scaled equipment of the steam generators. The results supported the following conclusions.

1) The steam at 260 °C (peak) and 0.09 kg-steam /kg-zeolite/cycle could be generated from the hot water of 80 °C using the bench-scaled equipment of one steam generator.
2) The steam at 170 °C (maximum) and 150 °C (average) could be generated continuously using the bench-scaled equipment of three steam generators.

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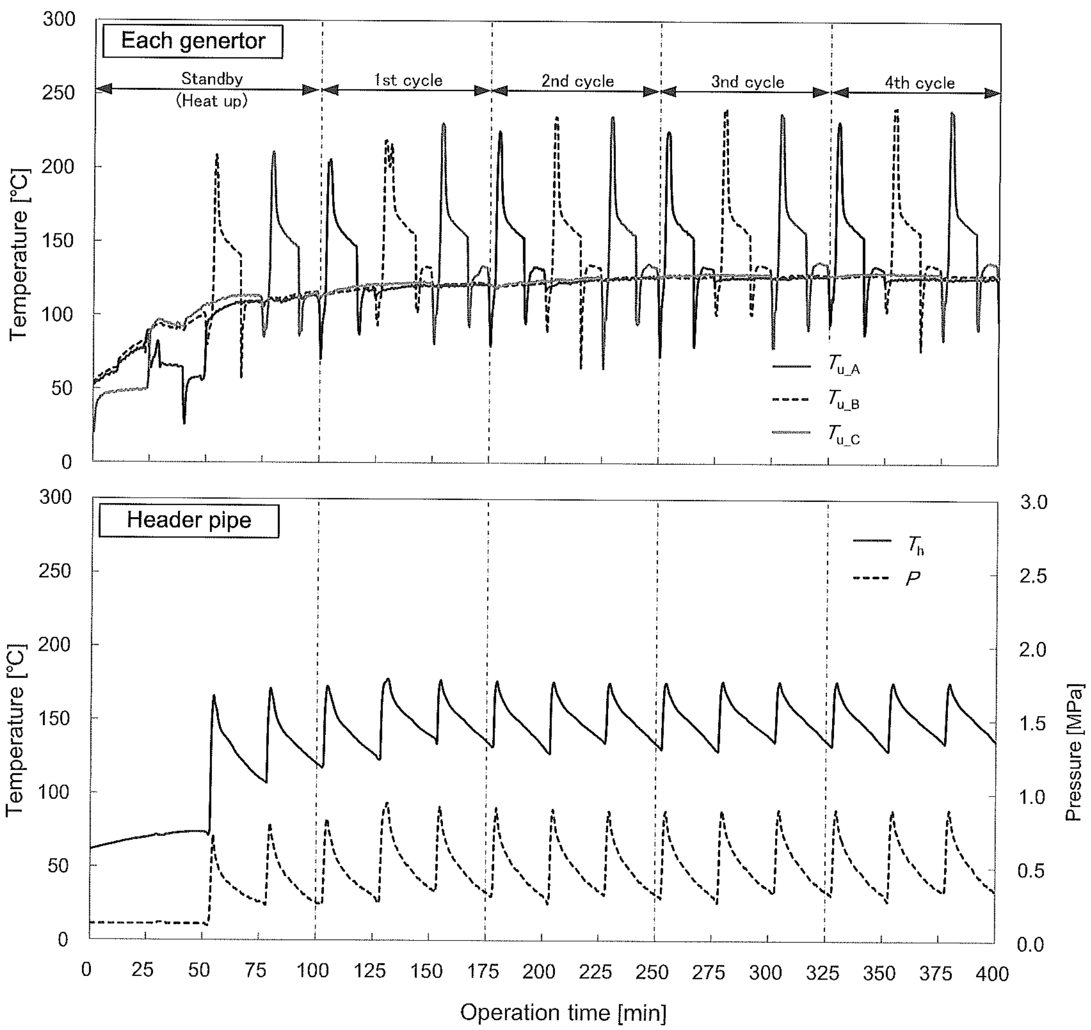

Fig. 6 Results of cycle operation using three steam generators

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付 記

要 約

エネルギーの有効利用のために，低質な排熱から蒸気を生成するシステムが求められている．本研究では，吸着剤／水の直接熱交換による新たな蒸気生成方式を提案する．吸着剤へ水を接触させることで，吸着剤からの吸着熱が放出され余剰水の蒸発させる．本方式は熱交換器を必要としないため，反応容器内の吸着剤粒子の充填密度の向上（容器構造の簡略化）が期待できる．吸着材としてゼオライトを 10-45[kg/台]充填できる蒸気生成器で構成されたベンチスケール規模の蒸気回生システムを製作した．このシステムの運転を構成する「蒸気生成工程（ゼオライト充填層に温排水を接触させ，蒸気を生成させる工程）」と「再生工程（湿潤状態のゼオライト充填層に高温低湿空気を供給して乾燥させる工程）」の運転条件について，1 台または 3 台の蒸気生成器を用いて検討した．その結果，3 台の蒸気生成器によるベンチスケール装置から，最大 170℃，平均 150℃の蒸気を連続的に生成することができた．

特に，鉄鋼分野や化学産業分野のような大量のエネルギーを消費する産業部門において，更なるエネルギーの消費量削減と有効利用は緊迫の課題である．その方策として，製造プロセスから排出される未利用の低温排温水（60～90℃）から，本方式のように直接回生して蒸気で活用できる技術の開発・実用化は極めて重要である．

本研究では，1 台のベンチスケール装置の蒸気生成器を用いて，80℃の排温水から最大温度で 260℃の蒸気が発生し，0.09 [kg-蒸気 /kg-ゼオライト/サイクル] の蒸気生成量を得られた．そして 3 台の蒸気生成器を用いてシステムを運転した場合，最大 170℃，平均 150℃の蒸気を連続的に生成し，上述の産業分野における実現可能性を確認できた．

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