Development of Evaluation Technology for Packed Bed Thermal Energy Storage System

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To realize carbon neutrality, it is important to decarbonize heat utilization processes that currently depend on fossil fuels, in addition to the spread of green power derived from renewable energy. A short-term approach to decarbonize heat utilization processes is to promote energy-saving equipment, while a medium- to long-term approach is to switch fuels that do not emit CO_2, electrify processes, and use green power. As an effort to promote energy saving, IHI has developed an evaluation technology for a system that recovers and stores the heat of high-temperature exhaust gas from a power plant and utilizes it. After conducting basic experiments using materials that can store high-temperature heat, such as crushed stones and steel balls, IHI conducted demonstration tests using exhaust gas from power generation equipment that was actually in operation, and confirmed the effectiveness of the system.

1. Introduction

As a social background, efforts toward carbon neutrality have been made worldwide, and the shift in energy sources from fossil fuels to renewable energies is accelerating. In Japan, the government declared that it will aim to achieve carbon neutrality by 2050, and in June 2021, the Green Growth Strategy was formulated mainly by the Agency for Natural Resources and Energy.

Renewable energy power supplies (photovoltaic power generation and wind power generation) serve as the core power supplies in a carbon-neutral society, and their power generation cost is declining rapidly owing to large-scale generation. However, renewable energy power supplies have the disadvantage of being dependent on regional characteristics, and the output and generating time fluctuate greatly. Therefore, the output of renewable energy power supplies needs to be stabilized before it can be utilized. Energy storage systems are useful for utilizing renewable energy power supplies. However, although energy storage systems are an essential element to achieve carbon neutrality, they are not common yet for various reasons.

At the same time, achieving carbon neutrality requires adopting green power and reducing CO_2 emissions by saving energy at existing facilities. In particular, reducing CO_2 emissions from industrial furnaces, boilers, and other facilities that consume fossil fuels is imperative. Utilizing thermal energy emitted from these facilities is one way of reducing CO_2 emissions from them. However, such thermal energy is wasted even though it can be used effectively in various situations. Major barriers to the effective utilization of thermal energy are that it is difficult to match the amount of heat, temperature, and timing of transmission and reception of heat between the waste heat source side and thermal energy user side. While at the same time, it is difficult to reduce the equipment cost to an affordable level with a reasonable investment recovery period.

Expectations for thermal energy storage technology are increasing as a technology to lower these barriers. Also, it can be said that the Japanese government's schemes to promote energy saving and green power, the global spread of carbon pricing (a scheme to price carbon, which is a main cause of climate change, to change the behavior of emitters), and other movements toward carbon neutrality are effective to lower the financial barrier to introducing waste heat utilization facilities.

Conventional thermal energy storage systems that have already been put to practical use or are under research and development use various thermal energy storage media, such as water (cold water, warm water, and hot water), heat transfer oil, molten salt, phase change materials, thermochemical materials, sand, rocks, and concrete, according to their temperature range and application. In this study, as an effort to promote energy saving, which is a short-term approach, we developed a packed bed thermal energy storage system, which allows us to recover high-temperature heat emitted from industrial furnaces, boilers, generators, and other facilities and utilize that heat when and where necessary. Since this system handles high-temperature heat, solids, which are stable even at high temperatures, were selected as the thermal energy storage media. Packed bed, fluidized bed and moving bed systems are used as solid thermal energy storage systems. In this study, in order to reduce the equipment cost and running cost, we adopted the packed bed system, which has excellent durability and maintainability without any moving parts in the thermal energy storage tank. A packed bed is a static solid particle bed formed by packing solid particles in a vessel to bring the solid and fluid into contact with each other.

This paper begins with the concept of thermal energy storage systems. As shown in **Fig. 1**, the thermal energy storage system consists of an interface with the heat source, heat exchanger, blower, and thermal energy storage tank from the upstream side of the system, and a heat exchanger and interface with the thermal energy user on the downstream side. There are two operating states: Charge mode and Discharge mode. In Charge mode, the heat of the exhaust gas from the heat source is recovered by the heat exchanger on the heat source side, and the recovered heat is stored in the thermal energy storage tank. In Discharge mode, air is supplied to the thermal energy storage tank to extract heat, and the extracted heat is utilized via the heat exchanger on the user side.

2. Experimental approach

2.1 Experimental system

We conducted basic experiments to establish a technology to evaluate the performance of packed bed thermal energy storage systems. The main evaluation items include the characteristics of heat transfer between the thermal energy storage medium and air and the heat loss of the thermal energy storage system.

Figure 2 is a schematic of the experimental system, and **Fig. 3** is a picture of the experimental system. **Table 1** shows the specifications of the experimental system. The experimental system consists of an air blower, flow meter,

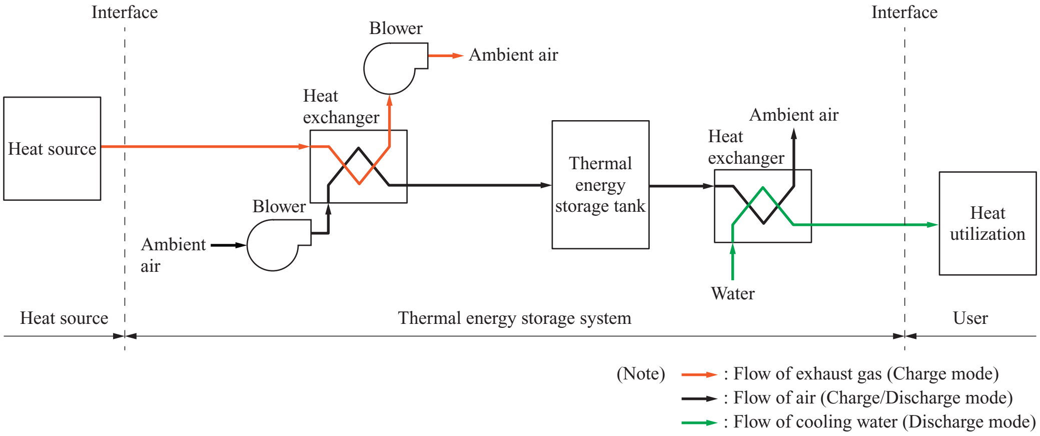


Fig. 1 Concept of thermal energy storage system

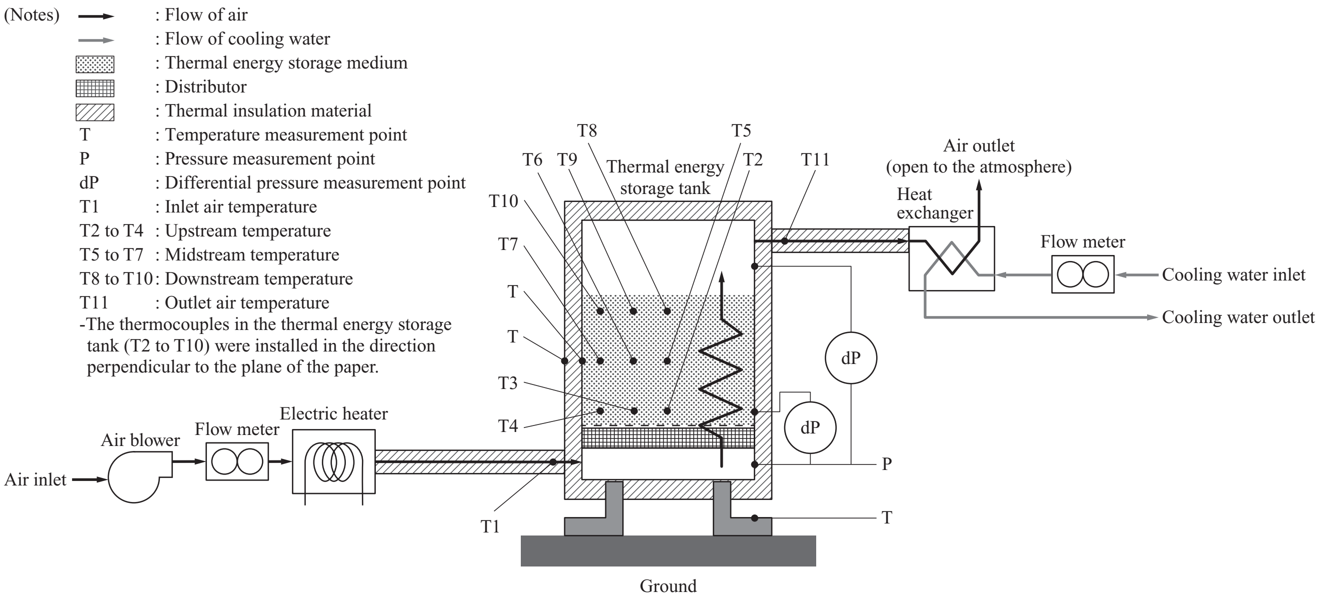


Fig. 2 Schematic diagram of packed bed thermal energy storage system

Fig. 3 Picture of packed bed thermal energy storage system

Table 1 Specifications of packed bed thermal energy storage system

Component	Specifications
Overall dimensions	Width 2 m, Depth 5 m, Height 1 m
Thermal energy storage tank	Dimensions : Volume 0.136 m^3, Inside diameter 0.498 m, Height 0.7 m Material : SUS304
Air piping	Material : SUS304, Nominal thickness : Sch10, Nominal diameter : 100 A
Thermal insulation material	Material : Rock wool, Thickness: 50 mm

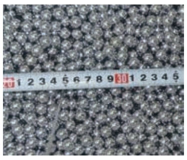
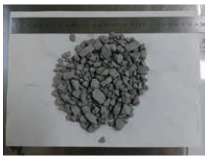
and electric heater (heat source) on the upstream side of the thermal energy storage tank, and a heat exchanger and exhaust duct on the downstream side of it. The thermal energy storage tank has distributors arranged at the bottom so that air flows evenly around the thermal energy storage medium that fills the tank. The outer surface of the thermal energy storage tank is covered by thermal insulation material. In Charge mode, air is heated with the electric heater and sent into the thermal energy storage tank to store the heat in the thermal energy storage medium. In Discharge mode, the electric heater is not used, and air of ambient temperature is supplied into the thermal energy storage tank to deprive the hot thermal energy storage medium of heat and utilize the heat with the heat exchanger.

Table 2 shows the thermal energy storage media used for the basic experiments, and **Table 3** shows the experimental conditions. As thermal energy storage media, steel balls, which have a high heat capacity and a uniform shape, and crushed stones, which have a smaller heat capacity than steel balls and large surface areas with non-uniform shapes, were used. Steel balls and crushed stones are inexpensive and easily available, so they are suitable from an economic perspective. The air temperature was measured at the inlet and outlet of the thermal energy storage tank. In addition, the temperature in the packed bed of the thermal energy storage tank was measured by inserting a total of nine thermocouples at three points in the radial direction (tank center, midpoint, and around the tank wall) of three cross sections (upstream, midstream, and downstream) perpendicular to the principal flow direction.

Table 3 Experimental conditions

Item	Unit	Test conditions
Operation mode	—	Charge, Discharge
Thermal energy storage medium	—	Steel balls, No. 4 crushed stones, No. 6 crushed stones
Air flow rate	Nm^3/h	30 to 330
Air temperature	°C	20 to 250
Air heating power	kW	9 to 17

Table 2 Thermal energy storage media

Item	Unit	Steel balls	No. 4 crushed stone	No. 6 crushed stone
Material	—	Carbon steel	No. 4 crushed stone for concrete (JIS A 5001)	No. 6 crushed stone for concrete (JIS A 5001)
Density	kg/m^3	7 860	2 668	2 640
Reference diameter	mm	11	20 to 30 (26.6 to 28.2)*1	5 to 13 (9.5 to 10.6)*1
Filling weight	kg	674	208	214
Filling rate	—	0.63	0.55	0.58
Picture	—			

(Note) *1 : Measured value obtained by image analysis in **Section 3.1**

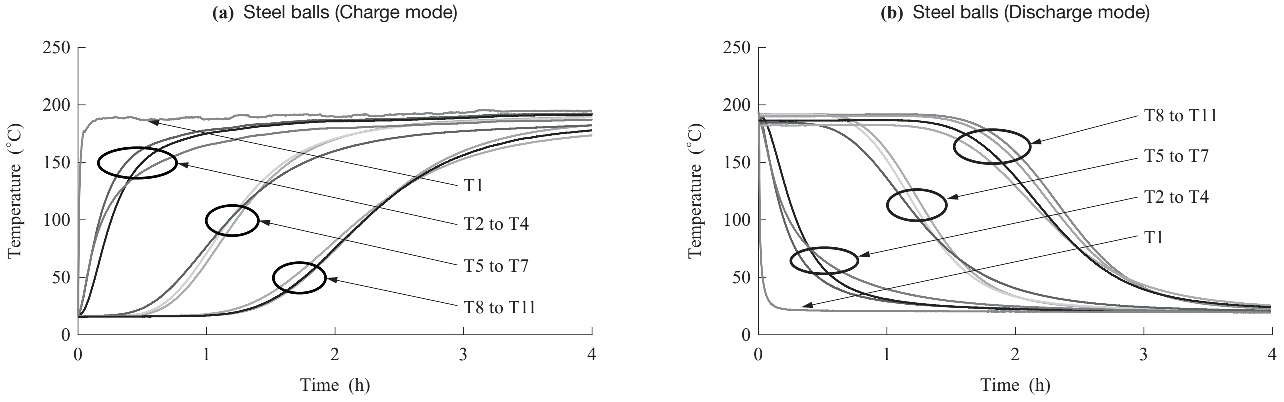
As for the pressure loss, the system was designed by using Nakajima's equation(1) for the distributors, and Ergun's equation(2) for the packed bed.

2.2 Experimental results with different thermal energy storage media

Figure 4 shows the temperature history of air at the inlet and the inside of the thermal energy storage tank (at nine points). In all graphs, the inlet air temperature changes first. After that, the temperature changes at the three upstream points, at the three midstream points, and at the three downstream points in this order. The results obtained from the experiment are as follows:

- In Charge mode and Discharge mode, the temperature change over time increases in Charge mode and decreases in Discharge mode.
- Steel balls have a slower thermal response than crushed stones because steel balls have higher heat capacity.
- Compared with No. 4 crushed stones, No. 6 crushed stones have a rapid temperature rising and falling curve. Therefore, the temperature gradient region (thermocline) between the high-temperature side and the low-temperature side in the thermal energy storage tank is narrower.

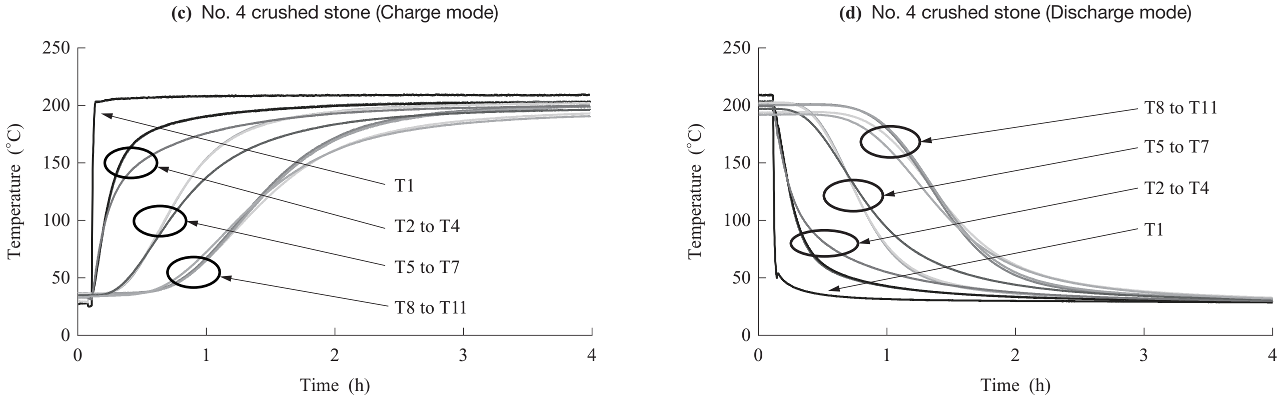
Crushed stones have a quicker thermal response because


(a) Steel balls (Charge mode)

(b) Steel balls (Discharge mode)

(Note) Air flow rate : 130 Nm^3/h

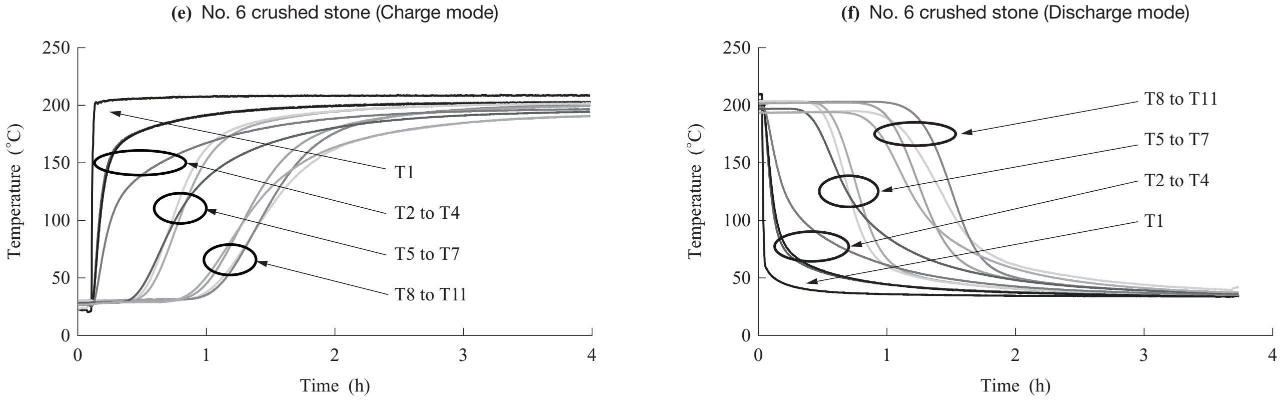
(Note) Air flow rate : 132 Nm^3/h


(c) No. 4 crushed stone (Charge mode)

(d) No. 4 crushed stone (Discharge mode)

(Note) Air flow rate : 129 Nm^3/h

(Note) Air flow rate : 136 Nm^3/h


(e) No. 6 crushed stone (Charge mode)

(f) No. 6 crushed stone (Discharge mode)

(Note) Air flow rate : 127 Nm^3/h

(Note) Air flow rate : 136 Nm^3/h

Fig. 4 Temperature history of experimental results crushed stones, which have irregular surfaces, have a larger surface area than steel balls. The irregular surfaces of crushed stones are presumed to produce turbulence of air around them, thereby providing enhanced heat transfer. Therefore, steel balls are better suited to reducing the size of the thermal energy storage tank while maintaining the same amount of heat. On the other hand, crushed stones are more suitable when a quick thermal response is required.

The thermocline is narrow probably because of the following two reasons, which are attributable to the fact that No. 6 crushed stones have a smaller particle size:

(1) The large total heat transfer area enhances heat transfer on the upstream side of the thermocline (heat is sufficiently exchanged).

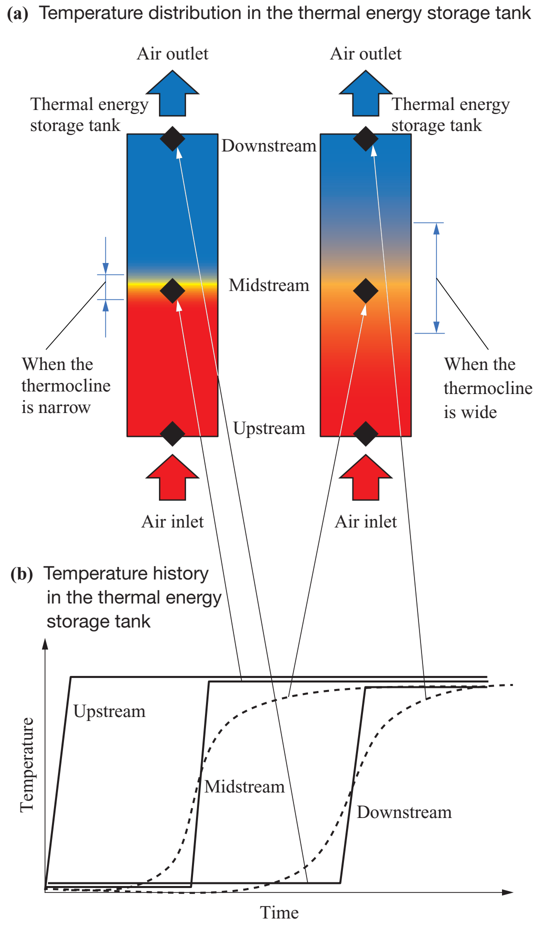
(2) The number of contact of particles per unit length increases, and the thermal resistance increases, which decreases the apparent thermal conductivity in the entire thermal energy storage medium. For these reasons, it is presumed that heat diffusion is suppressed in the packed bed, producing a rapid temperature change in a narrow area in the principal flow direction.

The width of the thermocline is important in evaluating the performance of the packed bed thermal energy storage tank. **Figure 5-(a)** shows the temperature distribution of the thermal energy storage tank, and **-(b)** shows the temperature history in Charge mode. When a narrow thermocline is formed, in the final phase of Charge mode, the outlet air temperature does not increase until the thermal energy storage medium on the downstream side of the thermal energy storage tank gets hot. As a result, the amount of heat taken away by the exhaust air decreases, providing better thermal energy storage performance. However, when a wide thermocline is formed, the outlet air temperature increases before the thermal energy storage medium downstream of the thermal energy storage tank gets hot, and heat is taken away by the exhaust air, resulting in worse thermal energy storage performance. In **Fig. 5-(b)**, the width of the thermocline is represented as the transition time before and after Charge mode or Discharge mode. This means that the more rapid the temperature change, the narrower the thermocline.

Also, because of the effect (2), the temperature dispersion tends to be larger in each of the measurement cross sections upstream, midstream, and downstream. In designing a thermal energy storage tank, there is a need to ensure that a good thermocline is formed and predict the temperature distribution of the inside of the thermal energy storage tank in the radial direction (direction perpendicular to the principal flow) in consideration of the distributors and external heat radiation.

3. Calculation approach

3.1 Thermal model


(a) Temperature distribution in the thermal energy storage tank

(b) Temperature history in the thermal energy storage tank

Fig. 5 Image of thermocline of packed bed thermal energy storage tank

To predict and evaluate the performance of the packed bed thermal energy storage system, we developed a thermal model at the same time as conducting basic experiments. For the thermal calculation, we used a general-purpose tool using a thermal network model. **Figures 6 and 7** are schematics of the thermal model. Rans-Marshall's equation⁽³⁾ for the heat transfer coefficients used for the packed bed was corrected to reflect the results of the present experiment, and the corrected values were used as the heat transfer coefficients of air and thermal energy storage media. The correction factors, or factors to be multiplied by the product of the heat

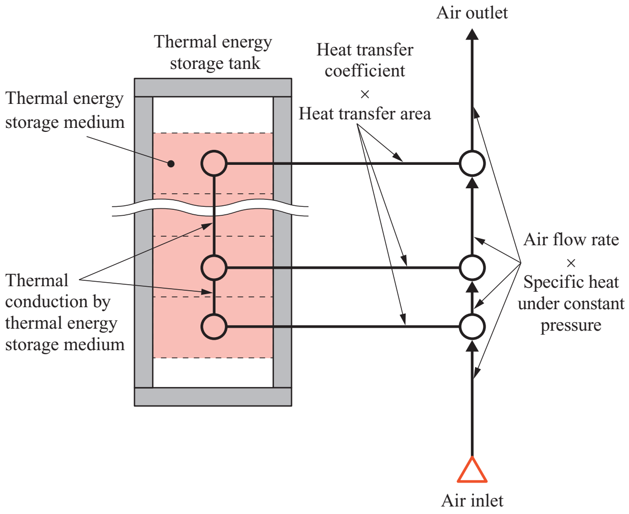
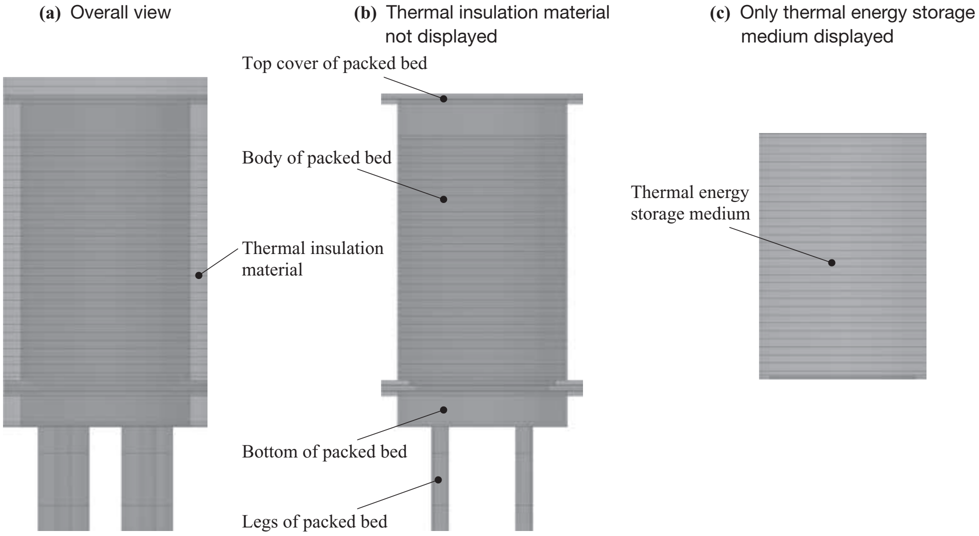


Fig. 6 Thermal model of thermal storage tank


(a) Overall view

(b) Thermal insulation material not displayed

(c) Only thermal energy storage medium displayed

Fig. 7 Components of thermal model

transfer coefficient and surface area, were 1.0 and 3.0, which were used for the steel balls and crushed stones, respectively. The correction factor for crushed stones takes into consideration both the increase in the heat transfer area due to surface irregularities of crushed stones and the increase in the heat transfer coefficient due to increased turbulence in the air flow. The average particle size of crushed stones was obtained by taking a picture of a projection of crushed stones as shown in **Fig. 8**; obtaining the area of each crushed stone in the projection by image analysis; and calculating the average value with a statically sufficient sample size of 400 or more. As a result, the following measured values were obtained:

- Average particle size of No. 4 crushed stones: ϕ 26.6 to 28.2 mm
- Average particle size of No. 6 crushed stones: ϕ 9.48 to 10.6 mm

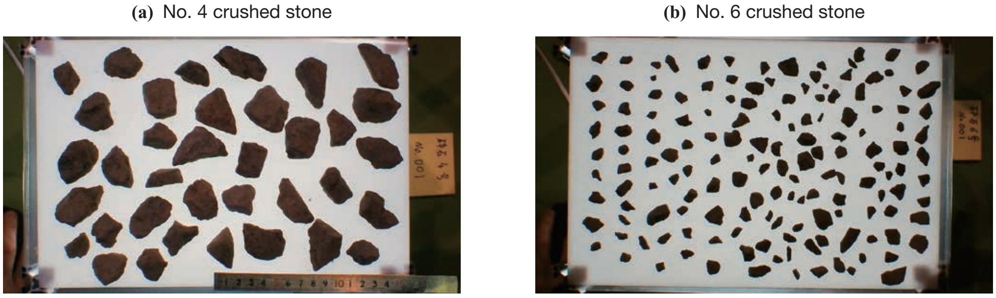
The apparent thermal conductivities of the thermal energy storage medium that fills the thermal energy storage tank in the radial direction and height direction were obtained by using Yagi and Kunii's equation(4). The effective thermal conductivity in the radial direction represents the value with the fluid stationary in the packed bed. However, the effective thermal conductivity in the height direction represents the value with the fluid flowing in the packed bed, and is larger than the effective thermal conductivity in the radial direction.

3.2 Comparative verification of experimental and thermal calculation results

Figure 9 compares the outlet air temperature history of the thermal energy storage tank between the experimental and calculation results. The outlet air temperature history is qualitatively consistent both in Charge mode and Discharge mode. Then, we quantitatively evaluated the outlet air temperature of the thermal energy storage tank, considering that it can be used to evaluate the temperature history in the entire tank. We set the duration during which the temperature changes by 99% before and after Charge mode and Discharge mode as the reference time as shown in **Fig. 10**, and evaluated the average value of the temperature difference (absolute value) during this period. Under the experimental conditions applied here, as shown in **Fig. 11**, while the stable temperature difference is approximately 150 to 220°C, the average temperature difference between the experimental and calculation results is mostly within 5%, showing that the prediction accuracy is adequate.

4. Demonstration test

We conducted a demonstration test of the thermal energy storage system by using exhaust gas from a power generation facility in operation (4-MW gas engine, manufactured by IHI Power Systems Co., Ltd., in Yokohama Works of IHI Corporation(5)). **Figure 12** shows the details of the test

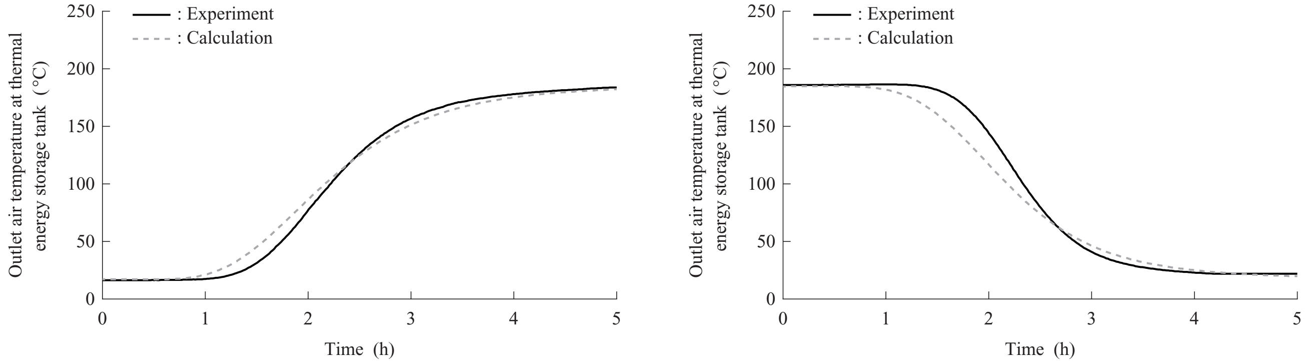

(a) No. 4 crushed stone

(b) No. 6 crushed stone

Fig. 8 Picture of crushed stones

(a) Steel balls (Charge mode)

(b) Steel balls (Discharge mode)

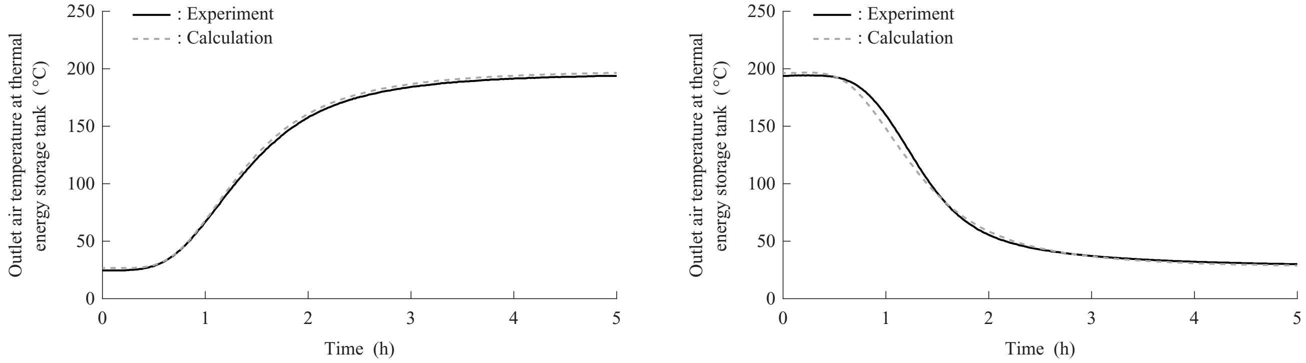


(Note) Air flow rate : 129.5 Nm^3/h

(Note) Air flow rate : 131.9 Nm^3/h

(c) No. 4 crushed stone (Charge mode)

(d) No. 4 crushed stone (Discharge mode)

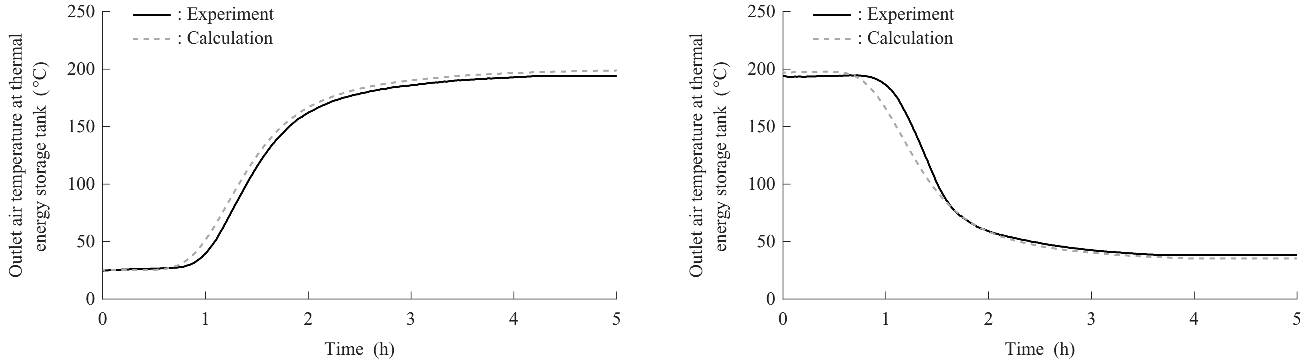


(Note) Air flow rate : 126.4 Nm^3/h

(Note) Air flow rate : 135.1 Nm^3/h

(e) No. 6 crushed stone (Charge mode)

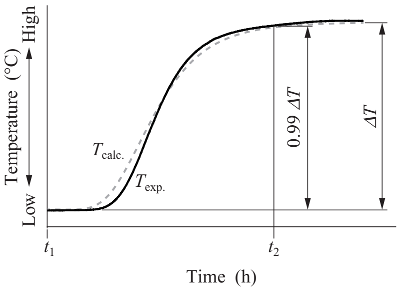
(f) No. 6 crushed stone (Discharge mode)



(Note) Air flow rate : 127.2 Nm^3/h

(Note) Air flow rate : 135.8 Nm^3/h

Fig. 9 Comparison results of outlet air temperature history at thermal storage tank between experiments and calculations



(Note) Average temperature difference between calculation and experimental values

$$: \frac{\int_{t_1}^{t_2} \left| T_{calc.} - T_{exp.} \right| \mathrm{d}t}{t_2 - t_1}$$

Fig. 10 Average temperature difference of outlet air at thermal storage tank between experimental results and calculation results

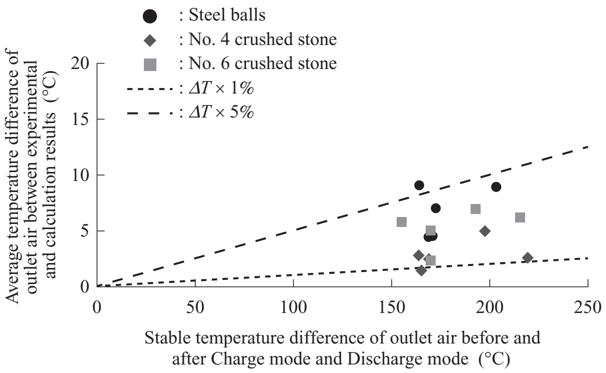
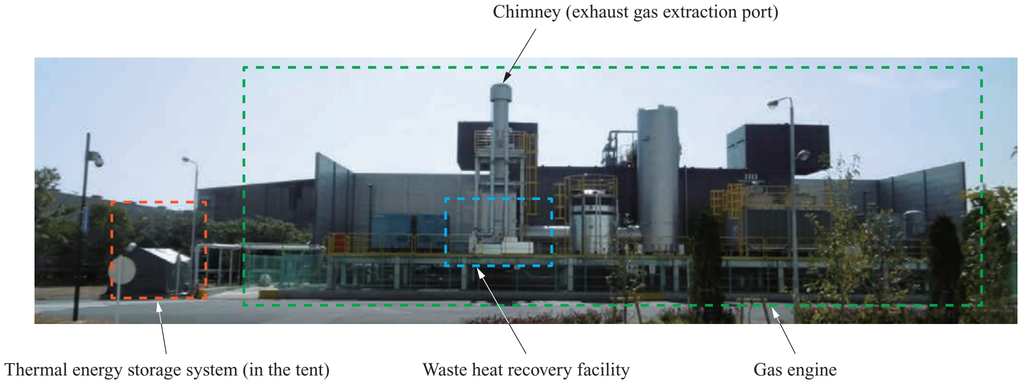


Fig. 11 Evaluation of prediction accuracy by comparing experimental results and calculation results

(a) View of entire gas engine and thermal energy storage system



(b) Thermal energy storage system (in the tent) **(c)** Waste heat recovery facility

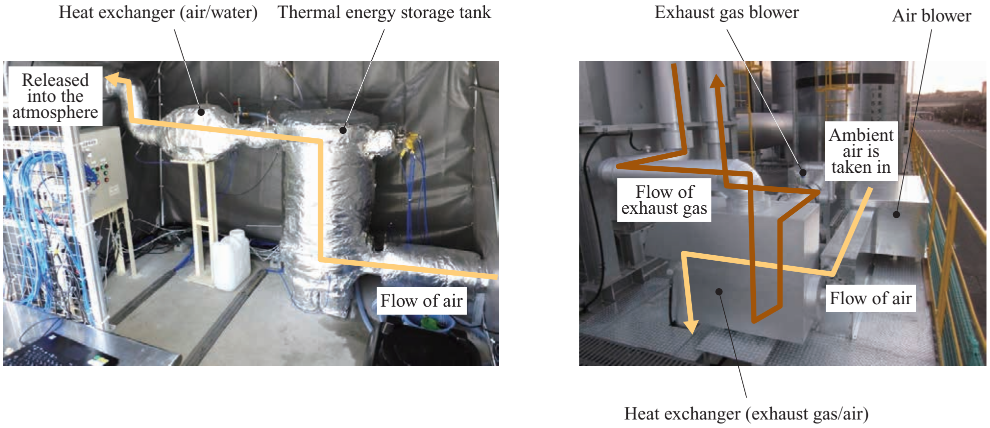


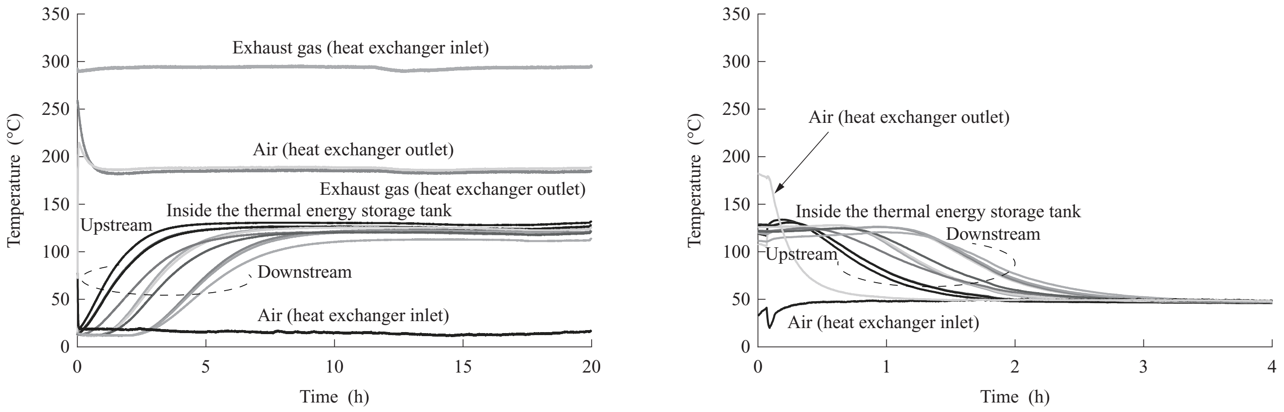
Fig. 12 Details of test facility

facility, and **Table 4** shows the specifications of the exhaust gas test. To change the heat source of the experimental system shown in **Chapter 2** from an electric heater to exhaust gas, we added a heat exchanger, duct, and blower, for waste heat recovery. As a thermal energy storage medium, steel balls were adopted in consideration of their high heat capacity and workability.

Figure 13 shows the results of the demonstration test. **Figure 13-(a)** shows that in the heat exchanger for waste

Table 4 Specifications of actual exhaust gas demonstration of thermal energy storage

Item	Specifications
Gas engine	12V28AGS (IHI Power Systems Co., Ltd.), Output 4 000 kW, City gas (13A)
Exhaust gas temperature	330 to 360°C
Exhaust gas pressure	Atmospheric pressure
Amount of heat of exhaust gas	3 880 MJ/h (16 000 Nm^3/h)
Operation time	24 hours during weekdays



(a) Steel balls (Charge mode) **(b)** Steel balls (Discharge mode)

(Note) Air flow rate : 74 Nm^3/h

(Note) Air flow rate : 306 Nm^3/h

Fig. 13 Result of thermal energy storage test

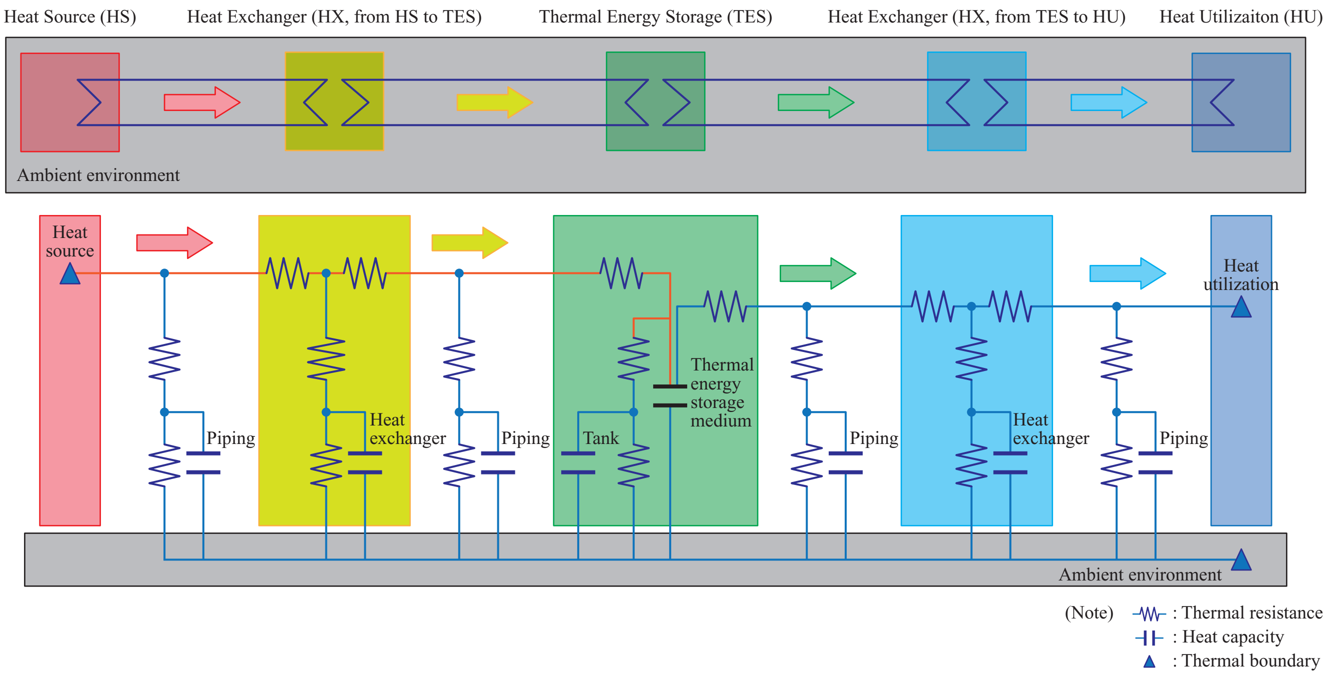


Fig. 14　**Proposal material image of thermal energy storage system**

heat recovery, the exhaust gas inlet and outlet temperatures are approximately 300°C and 180°C, respectively. At the same time, the air temperature increased from ambient temperature to 180°C. The air heated by the heat exchanger raised the temperature of the heat storage material to about 130°C. **Figure 13-(b)** shows that after air at ambient temperature flowed in, the temperature decreased from the upstream side to the downstream side of the thermal energy storage tank.

In equipment design for this demonstration test, we used the evaluation technology established through the aforementioned basic experiments and thermal model development. Through this demonstration test, we confirmed that a series of processes for recovering, storing, and utilizing heat from high-temperature exhaust gas can be performed as designed. From this result, we confirmed the effectiveness of the evaluation technology for packed bed thermal energy storage systems.

5.　Conclusion

Through the basic experiments and thermal model development, we established an evaluation technology for packed bed thermal energy storage systems. Then, using the established evaluation technology, we designed a demonstration test system that uses exhaust gas from an actual power generation facility and conducted a demonstration test, where the expected performance could be achieved. From this result, we confirmed the effectiveness of the evaluation technology for packed bed thermal energy storage systems, and are now ready to make contributions to designing adequate packed bed thermal energy storage systems for energy saving with waste heat recovery, whose demand is rising in various situations. Currently, we are developing a tool, the concept of which is shown in **Fig. 14**, in order to propose a thermal energy storage system that satisfies the specifications required by the heat source side and thermal energy user side. Using this tool, we will study specifications for scaled-up systems and estimate their cost. Also, we are considering using this tool for proposal activities for customers to introduce thermal energy storage systems as an option to promote their energy savings.

With the results obtained this time, the IHI Group will offer technical consultation to customers who need thermal energy storage, thereby contributing to promoting energy saving and realizing a decarbonized society.

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