Evaluation of CO₂-capturing Power Generation Systems Utilizing Waste Heat from Ironworks

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Two kinds of CO₂-capturing power generation systems with and without regenerator are proposed which utilize saturated steam produced by making use of waste heat from ironworks, and their thermodynamic and economical characteristics were investigated. As an example of saturated steam, temperature and quantity was assumed to be 200°C and 10 t/h, respectively, by considering use of waste heat from a kiln at a pellet factory in an ironworks. Fundamental characteristics of the two proposed systems are estimated through computer simulation, such as power generation efficiency, energy saving characteristics, amount of CO₂ reduction, and economics. It was shown that the best system is attained for the proposed system without the regenerator when its turbine inlet temperature is set at 350°C. At this condition, the system was estimated to be economically feasible and to have following characteristics: repowering power generation efficiency 97.7 %, annual amount of saved energy 83.3 TJ, annual amount of CO₂ reduction 1 738 t-C, unit cost of generated power 6.42 yen/kWh, annual gross profit 25.4 million yen, and depreciation year 5.70. The proposed system could be adopted in many other waste heat emitting factories owing to its large CO₂ reduction characteristics and its economical profitability.

KEY WORDS: waste heat; ironworks; CO₂-capture; economic evaluation; turbine; efficiency.

1. Introduction

Large quantity of energy is consumed in making iron and steel and hence various kinds of innovative energy-saving technologies have been applied in this industry. So far, high temperature heat energy, generated in the process of iron and steelmaking, has been utilized such as for generating electric power. Low temperature heat energy, however, is not fully utilized, since it is difficult to raise the power generation efficiency and hence economics is not so good.

It is becoming more important to save energy to reduce CO₂ emission. Economical direct CO₂-capturing systems are also considered to be necessary in the near future for drastically decreasing the emission of CO₂. It is technologically easy to capture CO₂ from combustion gas if pure oxygen instead of the air is used to burn fuel. To produce pure oxygen, equipment for oxygen production and extra energy are required compared when no oxygen is produced. This deteriorates the efficiency of CO₂-capturing energy system and its economics.

If extremely high efficient system can be constructed, however, required amount of oxygen becomes small and economics of the resultant system is not so deteriorated. Based on this concept, CO₂-capturing power generation systems utilizing waste heat from factories were proposed by the author and its power generation characteristics were evaluated and it was shown that higher efficiency can be obtained than a large-scale power generation system without CO₂-capture.

It is a natural outcome in a sense, however, that energy systems utilizing waste heat have high efficiency, since the systems use waste heat. It is necessary to show, therefore, that the systems have economical feasibility. It has been shown that the proposed system could have the possibility of economical feasibility as for a case of using the waste heat from a garbage incineration plant.

The quality and quantity of waste heat, however, differ greatly according to its source. CO₂-capturing power generation systems proposed by the author are based on gas turbine technology, so that various systems with different cycle can be constructed such as a system with regenerative cycle other than Brayton cycle, and thermodynamic characteristics and economics of the system also differ greatly according to its cycle.

Hence it is considered to be important to investigate specifically the possibility of economical realization of each system using waste heat from ironworks and how much CO₂ reduction effect the system using it really has, if the system is economically feasible.

In this paper, by taking an example of utilizing low temperature waste heat from ironworks, two kinds of CO₂-capturing power generation systems with and without the regenerator are investigated, and their thermodynamic and economical characteristics are evaluated together with those of a conventional power generation system.
2. Structure of Power Generation Systems Utilizing Waste Heat of Factories

It has been assumed that saturated steam is produced by utilizing waste heat from ironworks and used for generating electric power in this research.

2.1. Conventional System

For generating power by using saturated steam produced by utilizing waste heat from factories, a steam turbine power generation system, whose structure is shown in Fig. 1, is adopted so far. Power generation efficiency of steam turbine system using saturated steam produced by utilizing waste heat is usually low, less than 10% as will be shown in the following. This is because steam condition is bad.

The steam turbine power generation system using saturated steam is referred to the conventional system in the following.

2.2. Proposed Two Systems

In this research, two systems shown in Figs. 2 and 3 are investigated as CO₂-capturing power generation systems.

Figure 2 shows the schematic structure of a new proposed system, in which low temperature steam produced by utilizing waste heat is fed to a gas turbine combustor and its temperature is raised by combusting fuel, injected together with oxygen. High temperature gas, composed mainly of H₂O and CO₂ gas, is used for driving gas turbine generator. Turbine outlet gas is cooled in a condenser, thus the most of steam is condensed and condensed steam is reused for producing low temperature saturated steam. CO₂ gas, generated as the result of combustion reaction of the fuel, can be easily separated from liquid condensate and captured. The captured CO₂ gas is liquefied with liquefaction equipment for volume reduction. The liquefied CO₂ will be dumped into deep sea bottom, or reused as carbon resource for producing chemicals such as methanol from hydrogen if it can be inexpensively obtained by way of electrolysis of water by using electric power generated from photovoltaic cells in the future.6)

The proposed system uses H₂O as working fluid of gas turbine and pressure of H₂O is made high when it is in the state of liquid, so that compressing work of working fluid gas is not required, being different with conventional gas turbine in which a large amount of air is compressed with air compressor and approximately two third of turbine axial power output is consumed in this compression process. This feature together with making use of waste heat energy makes the efficiency of fuel use significantly high. The fuel is burned by using oxygen, so that combustion reaction is taken place in the combustor without N₂ gas, so that no thermal NOₓ is generated in the system. The system is referred to a H₂O turbo system or H₂O turbo-S in the following. H₂O turbo system is expected to have the following feature that its power output and CO₂ reduction effect are small.

Figure 3 shows the structure of the other proposed system in which a regenerator is incorporated into the H₂O turbo system to superheat the inlet saturated steam by using turbine exhaust gas to improve efficiency. This system is referred to a regenerative system or Regen-S, for simplicity, in the following. The regenerative system is expected to have the following feature that its power output and CO₂ reduction effect are large.

3. Estimation of Power Generation Characteristics

3.1. Precondition

Partly modified simulation models which were proposed by the author, have been employed to estimate power generation characteristics of the systems investigated.7) Major exogenous variables and parameters used for estimation are listed in Table 1. The values in the tables are based on previous analyses performed by the author on a variety of power generation systems,2–5) and are considered to be realizable by applying present technologies.

As shown in Table 1, temperature and flow of steam produced by waste heat are assumed to be 200°C and 10 t/h, respectively, adopting a case of producing saturated steam with waste heat recovering boiler by utilizing waste heat
emitted from a kiln at a pellet factory in an ironworks. Since the pressure of the saturated steam with temperature 200°C is 1.55 MPa, we can see that the steam condition is worse compared to the case of utilizing the waste heat from a garbage incineration plant where steam temperature could be assumed to be 275°C and pressure 2.16 MPa.

In evaluating the conventional system, condenser outlet pressure gives a great influence on its efficiency, so it was changed from 4.9 kPa by 4.9 kPa and the optimal value was searched in the meaning that the highest efficiency is attained. It was imposed that the dryness of steam at turbine outlet should be higher than 89% from the technological reason for steam turbine. In evaluating the proposed systems, turbine inlet temperature (TIT) gives a great influence on system efficiency, so it was changed from 250 to 1300°C by 50°C and the optimal value was searched. In the following, however, simulation results changed up to 1500°C are discussed, for seeing the effect of raising TIT that can be expected to be realizable in the future. This is because the gas turbine with TIT of 1500°C class has already been developed for large scale power plants, and these technologies on raising TIT for large scale gas turbines can be applied to middle or small scale one.

As for condenser outlet pressure, it can be expected that the lower the pressure the larger the power output. Considering that turbine exhaust gas includes CO2 gas formed by combustion reaction, it was assumed to be 9.81 kPa. Condenser outlet temperature was assumed to be 32.6°C.

As for fuel, liquefied petroleum gas (LPG) composed of 50% of C3H8 and 50% of C4H10, which is used in an ironworks, was assumed to be used.

### Table 1. Major exogenous variables and parameters used for estimating systems’ characteristics.

| Item | Conventional system | Proposed systems |
|------|---------------------|-----------------|
| (a) Exogenous variables | | |
| Temperature of steam produced by waste heat (°C) | 200 | As at left |
| Flow of steam produced by waste heat(t/h) | 10 | As at left |
| Turbine inlet temperature (°C) | — | 250-1300 |
| Condenser outlet pressure (kPa) | Optimal value searched | 9.91 |
| Condenser outlet temperature (°C) | — | 32.55 |
| Fuel gas and its volume composition (%) | — | C3H8: 50 and C4H10: 50 |

### Table 2. Estimated characteristics of the steam turbine system.

| Item | Value |
|------|-------|
| Condenser outlet pressure (MPa) | 0.167 |
| Dryness of turbine outlet steam (%) | 89.0 |
| Generated power (kW) | 905 |
| Net generated power (kW) | 860 |
| Steam-base power generation efficiency (%) | 11.1 |
| Annual saved energy quantity (TJ/year) | 52.0 |
| Annual CO2 reduction quantity (t-C/year) | 778 |
| Facility cost (10^6 yen) | 90.5 |
| Depreciation cost (10^6 yen) | 9.14 |
| Maintenance cost (10^6 yen) | 4.53 |
| Steam cost (10^6 yen) | 42.0 |
| Annual power generation cost (10^6 yen) | 55.7 |
| Value of annually generated power (10^6 yen) | 57.8 |
| Unit cost of power (yen/kWh) | 7.71 |
| Annual gross profit (10^9 yen) | 2.11 |
| Depreciation year (year) | 10.5 |

### 3.2. Estimated Characteristics of Conventional System

As the condenser outlet pressure was made lower in the conventional system, the dryness of turbine outlet steam was estimated to become lower, the generated power greater, and power generation efficiency higher. As shown in Table 2, the maximum power output and power generation efficiency has been estimated to be 860 kW and 11.1%, respectively, when the dryness of steam at turbine outlet has the lowest value of 89%.

### 3.3. Estimated Characteristics of Proposed Systems

Figure 4 shows estimated results of power generation characteristics of the proposed systems. In H2Oturbo-S, results are not shown in the region where TIT is lower than 350°C. This is because steam dryness at turbine outlet has been estimated to become lower than 89% for temperature range from 250 to 300°C, and H2Oturbo-S becomes technologically infeasible for these temperature range. In Regen-S, results are not shown in the region where TIT is lower.
than 850°C. This is because temperature at turbine outlet must be higher than that of the inlet saturated steam for the Regen-S to operate properly, and hence TIT higher than 800°C was required for Regen-S.

Figure 4(a) shows estimated net generated power. Here, the net generated power is defined as the power which is obtained by subtracting the total inhouse power from the generated power at the generator. Note that the total inhouse power of the proposed system includes the power needed for production and compression of oxygen, for liquefaction of captured CO$_2$. In this research, all the calculation of power generation efficiency relevant to the fuel was done by using lower heating value (LHV) of the fuel.

As shown in Fig. 4(b), the fuel-base power generation efficiency is estimated to become lower as the TIT becomes higher. This is because the higher the TIT the larger the ratio of fuel energy to the total input energy for generating electric power. The maximum value of the fuel-base power generation efficiency is estimated to be 172% for H$_2$O-turbo system when the TIT is 350°C.

Figure 4(c) shows estimated repowering power generation efficiency in short. Here, the repowering efficiency, denoted $\eta_r$, is the efficiency which is calculated by the following equation:

$$\eta_r = \frac{E_g - E_s}{Q_f} \times 100\%$$ ............................(1)

where $E_g$ is the net generated power in the system, $E_s$ is the net generated power that can be generated by using the saturated steam, and $Q_f$ is the input fuel energy. $\eta_r$ designates the net efficiency how efficiently the input fuel energy is converted to electrical power energy when the input steam energy to the system is also taken into account. It can be seen that the maximum value of the repowering efficiency is estimated to be 97.7% for H$_2$O-turbo system when the TIT is 350°C, that is, even when generated CO$_2$ should be captured and liquefied, the proposed H$_2$O-turbo system can generate electric power with the repowering efficiency higher than 90% by utilizing waste heat from the ironworks.

It can also be seen that at the same TIT the value of $\eta_r$ in the Regen-S is higher than that of H$_2$O-turbo system, that is, the Regen-S is more efficient than H$_2$O-turbo system.

4. Evaluation of Saved Energy and CO$_2$ Reduction Amounts

4.1. Presumption

Annual saved energy and CO$_2$ reduction quantities have been estimated for the conventional system and the proposed systems. In estimating annual saved energy and CO$_2$ reduction quantities, it was assumed that the same net power should be generated in a conventional large-scale thermal power plant whose power generation efficiency is 50%, and the estimated fuel and generated CO$_2$ quantities were compared with those of the conventional system and the proposed systems, respectively.

4.2. Conventional System

Estimated annual saved energy and CO$_2$ reduction quantity of the conventional system are shown in Table 2. As seen from Table 2, annual saved energy and CO$_2$ reduction quantity were estimated to be 52.0 TJ and 778 t-C, respectively. It should be noted, however, that the possibility this is actually realized has little chance on account of economical reason as will be shown in the following section.
4.3. Proposed Systems

Figure 5(a) shows estimated annual saved energy quantities of the proposed two systems. The maximum value of the annual saved energy is estimated to be 123 TJ for the Regen-S when the TIT is 1 500°C. Figure 5(b) shows estimated annual CO2 reduction quantities of the proposed two systems. As seen from Fig. 5(b), it is estimated that the higher the TIT, the larger the CO2 reduction quantity and that its value in each system has little difference at the same TIT, since the generated net power is nearly equal. The maximum value of the annual CO2 reduction quantity is estimated to be 6085 t-C for the H2O turbo system when the TIT is 1 500°C.

5. Evaluation of Economics

5.1. Presumption for Economic Evaluation

Various indices have been proposed for economic evaluation of power generation systems so far. Unit power cost, annual gross profit and depreciation year were adopted in the present research. As for the definition of these indices, see Ref 9).

Table 3 shows the values assumed for economic evaluation. As for the unit cost of power generation equipment, it is assumed to be 100 000 yen/kW regardless of system construction, based on the present actual value of both the steam turbine and gas turbine power generation equipment is 50 000 yen/kW for large scale plants in Japan, and taking into account that the proposed systems are new and small scale. Steam cost is assumed to be 500 yen/ton and fuel cost 0.762 yen/MJ. The generated power is assumed to have the economical value of 8 yen/kWh. The values of these data were determined by the author based on the present economical status in iron and steelmaking industry in Japan.

5.2. Results of Conventional System

Estimated results of economic evaluation of the conventional system are shown in Table 2. As shown in Table 2, unit cost is estimated to be 7.71 yen/kWh, annual gross profit 2.11 million yen, and depreciation year 10.5 year. Thus, the system is economically feasible, but the depreciation year is over 10 year and it would be concluded that this system is difficult to be realized for economical point of view. The main reason why the economical condition is not so favorable can be attributed to the high cost of the steam. This is considered to be the major reason why low temperature heat energy from kilns is not utilized in many ironworks and emitted to the atmosphere as waste heat.

5.3. Results of Proposed Systems

Figure 6(a) shows the estimated unit power cost of the proposed systems. As seen from Fig. 6(a), the minimum value of unit power cost 6.42 yen/kWh is attained when the TIT is set at 350°C for H2O turbo-S. Figure 6(b) shows the estimated annual gross profit of the proposed systems. As seen from Fig. 6(b), the maximum value of annual gross profit 35.8 million yen is attained when the TIT is 1 500°C for Regen-S. Figure 6(c) shows the estimated depreciation year of the proposed systems. As seen from Fig. 6(c), the minimum value of depreciation year, 5.70 year, is attained when the TIT is 350°C for H2O turbo-S.

Table 4 shows the summary of estimated characteristics of the proposed systems when the unit power cost is estimated to be minimum under the condition that the TIT is lower than or equal to 1 300°C.

It can be concluded that the most favorable system from economical point of view is the H2O turbo system whose TIT is set at 350°C. It should be noted, however, that the regenerative system is considered to be favorable when constraints on CO2 emission are imposed such as CO2 tax, since its CO2 reduction effect is large.

5.4. Case Study When Oxygen Produced in Ironworks Can Be Used

As can be seen from Table 4, the ratio of cost of depreciation for oxygen production equipment is relatively high in the proposed systems. Oxygen is usually produced and used
in most ironworks, so instead of installing the equipment for oxygen production in the proposed systems, making use of oxygen produced in the ironworks is considered to be possible. In this section this case is investigated, assuming that economical value or the buying cost of oxygen is 5.6 yen/Nm³, based on the unit power cost is 8 yen/kWh, and the other conditions are same.

Table 5 shows the estimated results when unit power cost becomes minimum for each proposed system in the case of buying oxygen. Compared with the results shown in Table 4, it can be seen that the net generated power is estimated to become larger and thus the value of annually generated power is larger than the case of installing oxygen production equipment. It is estimated, however, that annual gross profit becomes smaller than the case of installing oxygen production equipment, since the oxygen buying cost becomes higher than the depreciation cost of oxygen production equipment. Hence unit cost of power is estimated to become higher and annual gross profit smaller. It can also be seen that depreciation year becomes shorter than that in the case of installing oxygen production equipment, since the depreciation cost of oxygen production equipment is unnecessary and the total depreciation cost becomes smaller.

It can be said based on the obtained results that making use of oxygen produced in the ironworks is more desirable in a case when investing money is not abundant and the need of prompt recovery of invested money is strong.

6. Conclusion

Power generation characteristics and economics of the proposed two kinds of CO₂-capturing power generation systems for utilizing waste heat emitted from ironworks have been evaluated, as well as those of a conventional steam turbine system. In evaluation, 10 t/h of saturated steam with temperature 200°C was assumed to be used.

For the case of using the conventional steam turbine sys-
tem, it was estimated that this system was economically not favorable under the assumed conditions.

For the two proposed systems, H₂Oturbo system and regenerative system, power generation characteristics, fuel saving characteristics, CO₂ reduction effects, and economics have been estimated by changing turbine inlet temperature (TIT) from 250°C through 1300°C by 50°C. Fuel-base power generation efficiency and repowering power generation efficiency have been adopted in evaluating power generation characteristics, and unit power cost, annual gross profit and depreciation year in evaluating economics.

It has been estimated that the H₂Oturbo system, whose TIT is set at 350°C, is favorable from energy saving and economical points of view. This system has been estimated to have the following characteristics: fuel-base power generation efficiency is 172%, repowering power generation efficiency 97.7%, annual energy saving amount 83.3 TJ, annual CO₂ reduction quantity 1738 t-C, unit power cost 6.42 yen/kWh, annual gross profit 25.4 million yen, and depreciation year 5.70.

It has also been shown that the regenerative system is considered to be favorable when constraints on CO₂ emission were imposed such as CO₂ tax in the future, since CO₂ reduction effect is estimated to be 2.8 times greater than that of the H₂Oturbo system. It has further been shown that making use of oxygen produced in the ironworks is more desirable in the case when investing money is not abundant and the need of prompt recovery of invested money is required, since depreciation year becomes shorter than the case of installing oxygen production equipment.

It could be expected that the proposed systems can be widely applied to utilize waste heat from factories other than ironworks, since the systems are estimated to have high energy saving and CO₂ reduction characteristics together with economical feasibility.

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