Heat recovery from low-temperature off-gas using micro-channel heat exchanger

Kazuaki KOBAYASHI[1*], Yuki KUWAUCHI[1 2], Yuji OGAWA1[1 3]

[1] Process Technology Div., Process Research Laboratories, NIPPON STEEL & SUMITOMO METAL CORPORATION, 20-1 Shintomi, Futtsu, Chiba, 293-0021 Japan.
[2] Now at NIPPON STEEL & SUMITOMO METAL U.S.A., INC., 1251 Avenue of the Americas, Suite 2320, New York, N.Y. 10020, U.S.A.
[3] Now at Steel Foundation for Environmental Protection Technology, 3-2-10 Nihombashikayabacho, Chuo-ku, Tokyo, 103-0025 Japan.

Abstract: In the COURSE50 project, a CO_2 separation and recovery system using an amine aqueous solution has been considered. In the system, the aqueous solution should be heated in a recovering process for the desorption of CO_2.The recovering temperature is less than 100 °C; thus, exhaust gases of steel plants can be utilized for heating. In this research, we first appraised the quantity of heat required in the project to recover 20 % of the CO_2 emitted from a representative steel works, designed a heat-recovering network to collect the heat from exhaust gas sources across the steel works, and found that pressured water was appropriate as the heat recovering medium. Second, we estimated the required efficiency of heat exchangers and realized that a heat exchanger with micro water vessels was appropriate because the flow rate of pressured water is much less than the gases. We designed and manufactured trial one and measured its efficiency in our laboratory using air and water. Finally, we experimentally measured the variation of its efficiency with time using real exhaust gas of a furnace of a steel plant.

1. INTRODUCTION

In the COURSE50 project, 30 % reduction of CO_2 emitted from all steel mills in Japan by 2050 is targeted. 10 % of the reduction will be achieved by reducing coke usage in blast furnaces, and 20 % will be carried out by capturing CO_2 emitted from blast furnace gas.

Chemical absorption process and physical adsorption process have been considered in the project as the CO_2 separation and recovery method. In the chemical process, the gas with rich CO_2 is dissolved into low-temperature amine aqueous solution, the aqueous solution including CO_2 is carried to recovery process, and is heated to separate and capture CO_2 gas from the solution.

As one of the accomplishments of the COURSE50 project, recovering temperature of the amine aqueous solution has been lowered to 95 °C and desorption calorie will be reduced to 1.6 GJ/ton-CO_2. For such low-temperature heating, exhaust gases from steel plants can be utilized as the heat sources.

Thus a technology to recover and transport the heat of unutilized low-temperature off-gas from steel mills is studied to provide the heat to the recover process in our research group.

In this article, we first appraised the quantity of heat required in the project to recover 20 % of the CO_2 emitted from a representative steel works. Second, we discussed the thermal medium which is appropriate for this heat recovering. Finally, we designed and manufactured a heat exchanger for heat recovering of low-temperature off-gas, and measured the variation of its efficiency.

2. REQUITED QUANTITY OF HEAT

Considering an integrated steel mill with 8 million ton/year of steel production and 1.9 ton-CO_2/ton-steel of CO_2 emission intensity, the CO_2 emission amounts to about 15 million ton/year. The CO_2 reduction target is 20 % of the emission; therefore it is nearly 3 million ton-CO_2/year.

The volume and temperature of off-gas emitted from a virtual integrated steel mill in Japan are shown in Fig. 1, and the layout of the mill is shown in Fig. 2.

In the COURSE50 project, both of chemical absorption process and physical adsorption process are availed to achieve the total amount of CO_2 capture, but the recovery share is studied in other research group based on economic rationality. However CO_2 amount recovered with utilizing off-gas specific heat is expected to around 2.4 million ton-CO_2/year. Therefore, heat recovery will amount about 3.9 PJ/year. Note that 115 °C saturated steam is required to heat the amine aqueous solution from the viewpoint of process design.

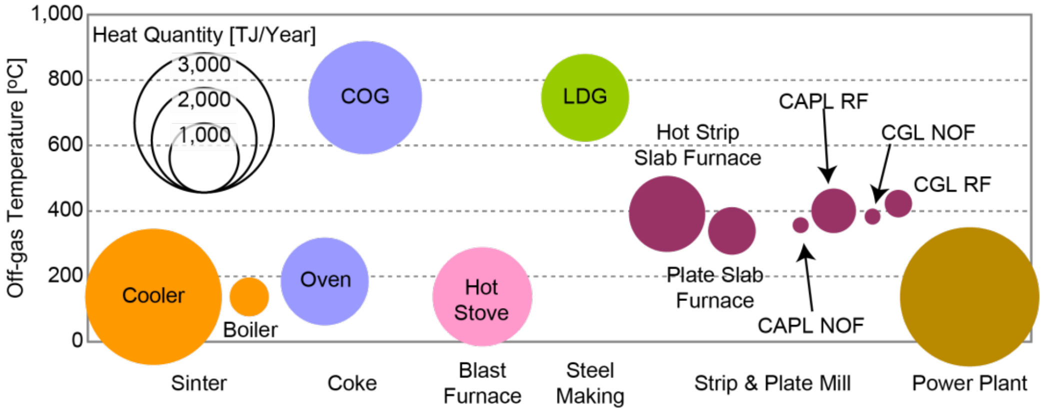

Figure 1. Off-gas volume and temperature of a model integrated steel mill.

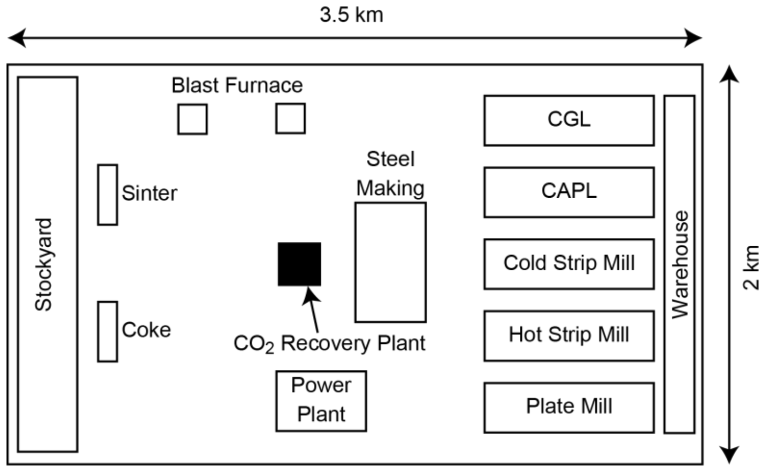

Figure 2. Plant layout of a model integrated steel mill.

3. THERMAL MEDIA

In this section, we discuss which thermal media can be applied for heat recover from off-gases and heat transporting from heat emission sources to the recovering process.

Solid, liquid, gas and electricity are considered as thermal media. Here, solid is generally difficult to carry, so it is excluded from consideration. Moreover, the efficiency of power generation using low-temperature gas is around 10 % of input energy, so it is also excluded from consideration.

Off-gas itself, air, steam, oil and compressed water are discussed as thermal media, and amount of recovered thermal energy available at recovery process is calculated. The calculation condition is shown in Fig. 3.

A case with oil used as the heat recovery carrier is explained below as an example. First, off-gas calorie is recovered using oil. In this heat recovering procedure, the temperature deference of pinch point for heat exchange is assumed to be 20 °C. However, maximum temperature of oil is confined to be 300 °C. Secondly, the oil is transported through a pipe line to the recovery process. Here, 2 m/s of economic transport velocity is adopted as the transport rate of oil, and 80 mm thickness of heat insulator is wrapped around the line pipe. Next, steam is generated in a boiler using the thermal energy of the oil. The pinch point is also assumed to be 20 °C, and steam generation loss is assumed to be 10 %, thus 90 % of energy transferred from the oil to boiled water is actively used. Finally, the oil is transported back to the heat source.

---

[*] Corresponding author. E-mail: kobayashi.6cq.kazuaki@jp.nssmc.com, telephone: + 81-80-4602-1501.

In addition to the above description, maximum temperature of compressed water is limited to 180 °C and steam is generated in a flash tank with its efficiency being also 90 % in the compressed water case, and economic transport velocity for gas and steam is assumed to be 20 m/s.

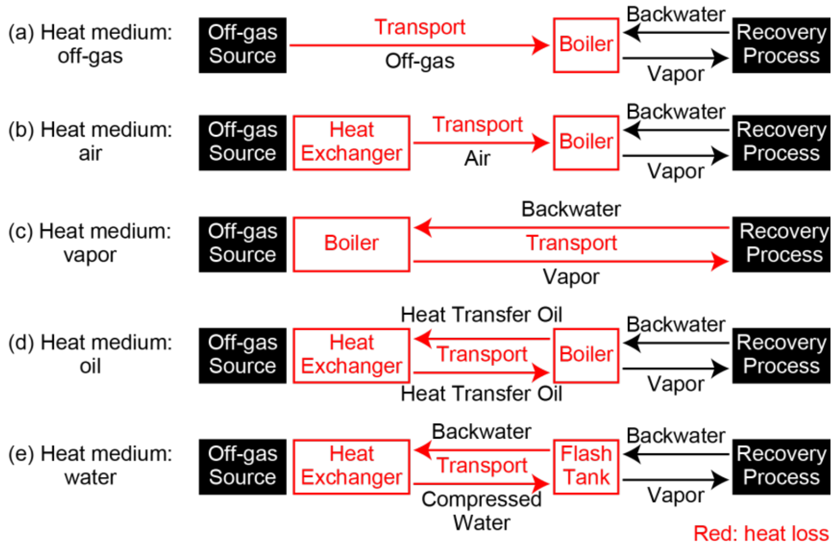

Figure 3. Heat recovering carriers and heat loss source.

Steam calorie available at the recovery process is calculated under the above assumption in Fig. 4.

In Fig. 4, we can see that heat dissipation loss at transporting in off-gas and air cases are large. We can also see that heat exchanging loss in air and oil cases are sizable because heat exchange is done twice. Therefore, steam and compressed water are seemed preferable for the project as the heat carrier because both of transporting and heat exchanging loss are small. Furthermore, the loss of compressed water is slightly smaller than that of steam, thus compressed water is adopted as the heat carrying medium.

4. HEAT EXCHANGER FOR LOW-TEMPERATURE OFF-GAS HEAT RECOVERY

Thermal efficiency of heat exchangers to recover the required quantity of heat is discussed in this section. Thermal efficiency of high-temperature fluid η_{h} and water equivalent ratio r_{weq} are used to express the performance of heat exchangers.

$$\eta_{\mathrm{h}} = \frac{T_{\mathrm{hi}} - T_{\mathrm{ho}}}{T_{\mathrm{hi}} - T_{\mathrm{ci}}} \qquad (1)$$

$$r_{\mathrm{weq}} = \frac{\dot{m}\, C_{\mathrm{p}}|_{\mathrm{h}}}{\dot{m}\, C_{\mathrm{p}}|_{\mathrm{c}}} \qquad (2)$$

C_{p} [J/(kg · K)]: specific heat, T [°C]: fluid temperature, $\dot{m}$ [kg/s]: mass flow rate,
h: high-temperature side, c: low-temperature side, i: inlet side, o: outlet side.

The relation between amounts of CO_2 separated using recovered heat and thermal efficiency of heat exchangers are shown in Fig. 5. We can see the target thermal efficiency is 66 %.

Note that water equivalent ratio is within a certain range. First, water equivalent ratio should be set small so that the compressed water temperature does not exceed 180 °C for the off-gas heat source above 180 °C. Secondly, the ratio should be set to 1.0 in order to obtain the water as high as possible for the heat source less than 180 °C. 1.0 of water equivalent ratio means that volume ratio of gas and water is over 1,000, therefore it is necessary to adopt micro channels as water vessels in order to make the heat exchanger compact.

A schematic diagram of the micro heat exchanger developed in this project for low-temperature off-gas and water heat recovery is shown in Fig. 6. S-shape fins [1] were adopted for water micro channels to improve efficiency, and corrugate fins were selected for gas channels to reduce dust adhesion.

An experimental result of thermal efficiency of the developed micro heat exchanger in our laboratory is show in Fig. 7. Hot air and cold water were used in the experiment as high and low-temperature fluid. We can see that the performance of the developed exceeds the target thermal efficiency of 0.66 (66 %) under wide water equivalent ratio. In Fig. 7, the efficiency of a conventional fin-tube type heat exchanger is also shown. Comparing both results, we can notice that the performance of the developed heat exchanger is better than that of the conventional one.

We will experiment the developed micro heat exchanger in a steel plant to make long-term evaluation.

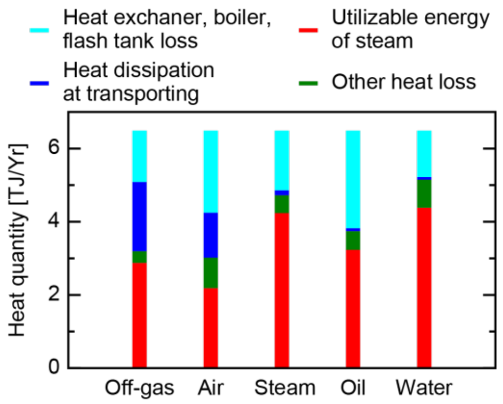

Figure 4. Utilizable heat quantity and heat loss of off-gas.

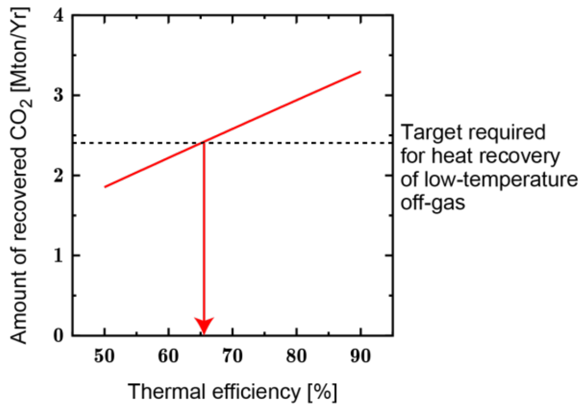

Figure 5. Relation of CO2 recovery amount and thermal efficiency.

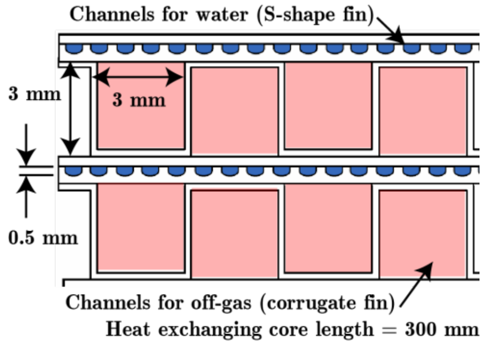

Figure 6. Schematic diagram of the developed micro heat exchanger for low-temperature off-gas and water.

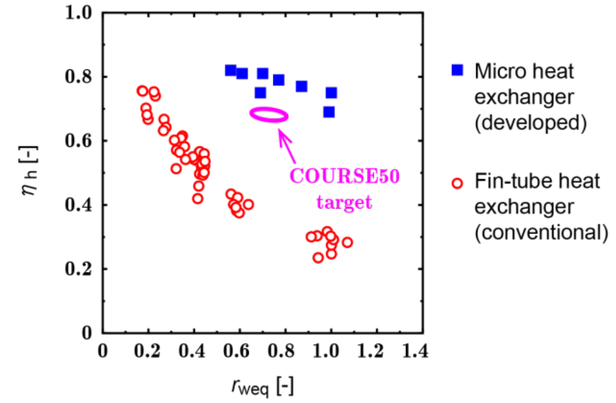

Figure 7. Experimental result of thermal efficiency of the developed micro heat exchanger.

5. CONCLUSION

Heat recovery technology for low-temperature off-gas from steel plants was studied in order to supply the heat for recovery plants of chemical CO_2 absorption process. The target of the heat recovery quantity was specifically discussed and compressed water was selected as the thermal carrying medium. A micro heat exchanger with S-shape fins for water channels and corrugate fins for gas channels was developed for the heat recovery. The performance of the developed micro heat exchanger was experimentally measured and it exceeded the objective thermal efficiency of 0.66.

Acknowledgements: This article is based on results obtained from "Development of technologies for environmentally harmonized steelmaking process, 'COURSE50'" project commissioned by the New Energy and Industrial Technology Development Organization (NEDO).

REFERENCES

[1] Tsuzuki, N., Kato, Y., Nikitin, K., and Ishizuka, T., J. Nucl. Sci. Technol., 46 (2009), 403–412.