



13th IEA Heat Pump Conference
April 26-29, 2021 Jeju, Korea

Energy Performance Estimation and Verification of an Industrial Waste Heat Recovery Heat Pump

Toshihiko OKUNO^a, Takashi KUWABARA^a, Akira KOYAMA^a,
Jun SHISHIDO^b and Katsumi HASHIMOTO^{c*}

^a Sales Dept., Science Inc., Saitama-Shi, Saitama, 331-0812, Japan

^b Research and Development Center, Tohoku Electric Power Co., Inc., Sendai-shi, Miyagi, 981-0952, Japan

^c Energy Innovation Center, Central Research Institute of Electric Power Industry, Yokosuka-shi, Kanagawa, 240-0196, Japan

Abstract

Aiming to save primary energy, reduce greenhouse gas, and save running cost, it is important to construct systems in industrial factories more efficient by utilizing heat from warm wastewater. To realize more efficient water heating system, it is essential to develop and evaluate affordable direct heat-recoverable heat pump which has direct recoverable evaporator. An experimental performance evaluation and an estimation based on the results have been conducted. According to the evaluation, developed heat pump achieved a COP of 4 or more, with a warm wastewater temperature of 35°C. Verification of the estimation was conducted by the field measurement. A problem, performance degradation according to fouling of the evaporator. A solution was developed, and availability was validated through the field measurement.

Keywords: wastet heat recovery, heat pump, direct recoverable evaporator, experimental performance evaluation, verification

1. Introduction

Heat pumps are expected to penetrate significantly due to their high energy conservation and greenhouse gas mitigation effects and have already established themselves as key components in air-conditioning equipment for residential and commercial buildings. Conversely, although penetration into the industrial sector is also now developing, due to exceptional energy conservation and greenhouse gas mitigation potential [1], some hindrances remain, for example, the high initial cost and the lack of awareness.

Heat recovery water-heating heat pumps capable of heating water up to high temperatures efficiently powered by waste heat from industrial processes are expected to spread because they use renewable energy (it is waste heat) efficiently, reduce primary energy input and offer high generality. Most conventional systems, however, were inefficient and involved high running costs because of their indirect construction, which meant an extra circulation loop was needed to recover heat from waste heat. Accordingly, commercialization of a “direct heat-recoverable heat pump”, capable of recovering heat directly in the evaporator (“direct heat-recoverable evaporator”) from waste heat, has been expected, which could conserve primary energy, reduce greenhouse gas, save on initial and running costs and reduce footprint. Many issues, however, remain when it comes to developing the “direct heat-recoverable evaporator”, for example, separating it from the heat pump, its ability to withstand various chemical species and impurities, anti-fouling performance and so on. Kuwabara et al. [2] reported the shell-and-coil type heat exchanger as a possible solution and a direct heat-recoverable heat pump is also being developed.

In this report, the direct heat-recoverable heat pump using a shell-and-coil type evaporator is evaluated in a performance evaluating facility and through field measurement. Degradation of heating capacity due to fouling accumulation and its fixing using self-cleaning found on the field measurement are also reported.

* Corresponding author. Tel.: +81-70-65-68-94-48;
E-mail address: hashimo@criepi.denken.or.jp.

2. Experimental performance evaluation and modeling of efficiency

2.1. Heat pump to be tested

The direct heat-recoverable heat pump water heater is selected for testing, with specifications as in Table 1 and the following features [2]: (1) The evaporator can be settled separately from the main body (see Figure 1) and the maximum separation distance is 10 m, (2) it has a fixed speed compressor and (3) the outlet temperature can be controlled using a water-control valve.

Table 1. Specifications of heat pump to be tested

Heating capacity	50 kW
Refrigerant	R410A
Output temperature	50 – 65 °C
Upper limit of heat source temperature	53 °C
Maximum distance to evaporator	10 m

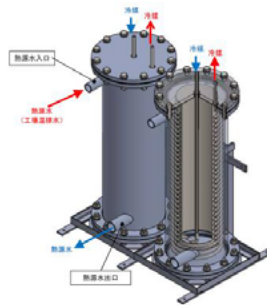


Figure 1 Schematic diagram of direct recoverable evaporator in the heat pump [2]

2.2. Performance evaluating facility

The performance evaluation facility is in the Central Research Institute of Electric Power Industry and Hashimoto et al. [3] reported on the design and performance of the facility, within which the heat pump to be tested is installed (see Figure 2). To measure performance, the hot water volumetric flow rate, hot water inlet and outlet temperature, heat source water volumetric flow rate, heat source water inlet and outlet temperatures and electricity consumption were measured highly accurate, with particular focus on ensuring accurate temperature measurement. A highly accurate resistance thermometer and highly accurate logger (NETSUSHIN NX1000) were used.

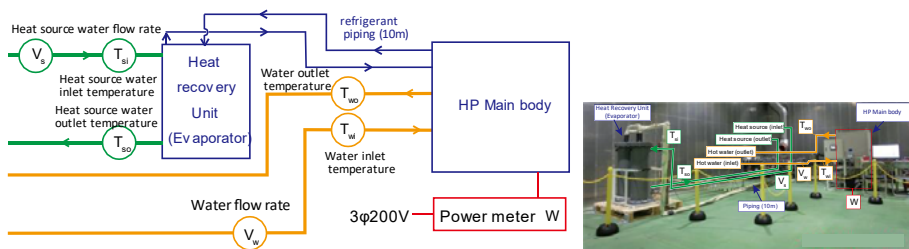


Figure 2 Photograph of the heat pump in the evaluating facility

2.3. Definitions of evaluation indexes

Water heating capacity, or Q_w , is defined as the following equation:

$$Q_w = \frac{60 V_w(T_{wo}-T_{wi})}{860} \tag{1}$$

Here, V_w , T_{wi} and T_{wo} constitute the hot water volumetric flow rate (L/min), hot water inlet temperature (°C) and hot water outlet temperature (°C), respectively. And density of water assumed to be 1kg/L.

Coefficient of performance of water heating, or COP_w , is defined as the following equation:

$$COP_w = \frac{Q_w}{W} \tag{2}$$

Here, W is electricity consumption (kW).

2.4. Result of evaluation

(a)Rating condition

Table 2 shows the result of the performance in terms of the rating condition. Assuming that the heat pump is used for preheating boiler feedwater, that is inlet temperature T_{wi} is 17 °C and target outlet temperature T_{wo} is 65 °C, and using warm waste water as a heat source, that is heat sink inlet temperature T_{si} is 30 °C, the conditions shown in the notation were used as rated conditions. As a result of the measurement, A was 64.89 °C, that is almost equal to the target of 65 °C, and the heating capacity was 53.59kW and COP_w was 3.84.

Table 2 Performance in rating condition. (Run 65-1-1)

Title	Setpoint	Title	Results
T_{wi} (°C)	17	Q_w (kW)	53.59
T_{si} (°C)	30	V_w (L/min)	16.09
		W (kW)	13.95
		COP_w (-)	3.84
T_{wo} (°C)	65	T_{wo} (°C)	64.89

(b)Performance map

The water-heating capacity map (Figure 3) is obtained using the hot water inlet temperature and the heat source water inlet temperature as parameters.

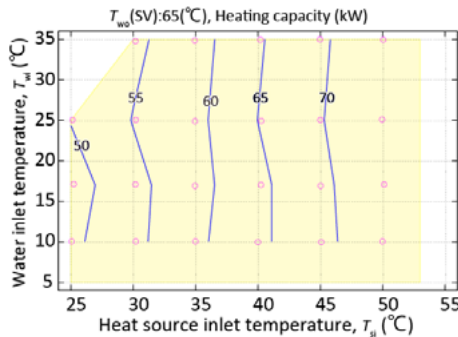


Figure 3 Performance map (T_{wo} (SV) = 65 °C)

2.5. Modeling of efficiency

Performance measurements are used to obtain a modeling equation. Assuming a hot water outlet temperature of 65 °C, the water heating COP is modeled as per Equation (3).

$$COP_w = 0.065 T_{si} + 1.95 \quad (3)$$

Here, T_{si} is heat source water inlet temperature. Since the influence of T_{wi} is very weak, it is ignored.

3. Verification by field measurement

3.1. Outline of the field measurement

A field measurement is conducted in a cleaning factory located near Sendai City, Miyagi prefecture (in the Tohoku region of Japan). Figure 4 shows a schematic diagram of the field measurement. This factory uses about 70 tons of steam per day, and all of which is supplied by a steam boiler fueled with A-type heavy oil.

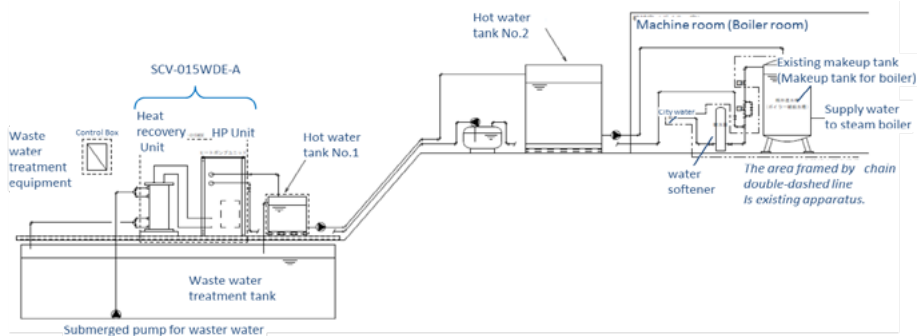


Figure 4 Schematic diagram of the field performance evaluation.

The overall amount of warm effluent wasted from all the cleaning processes in the factory constitutes about 300 tons per day, which is collected in a waste water treatment tank and then discarded as sewage after purification and pH adjustment. The warm wastewater contains fiber waste, dust, detergent components, soap scum and so on.

The heat pump to be tested is installed on top of the wastewater treatment tank and the warm wastewater is propelled to the heat pump by the pump, whereupon heat is recovered from the same and the wastewater is returned to the wastewater treatment tank.

The standard specification of the evaporator shell is made of PVC, but was made of acrylic for the field measurement to visualize the fouling inside the evaporator. The distance between the heat pump main body ("HP Unit") and the heat-recoverable evaporator ("Heat Recovery Unit") is set at 5 m.

There are two hot water tanks. Tank 1, volume of 2m³, is located on the wastewater treatment tank, while Tank 2 is located near the steam supplying boiler in the mechanical room. The distance between the two tanks is 140m and they are connected by well-insulated hot water piping. The existing replenishing tank (makeup tank) and Tank 2 are also connected by piping.

In the field measurement, the following two type of tests are conducted:

1. Non-load test:
Heat is recovered from warm wastewater to generate hot water, and the hot water is discharged into a wastewater treatment tank.
2. Full-scale load test:
Hot water generated by recovering heat from warm wastewater is supplied to the replenishing tank to be used for preheating replenishing water.

Field measurements are conducted from July 2017 to February 2018. The no-load test lasted for about 6 months from July 2017 to January 2018, while the full-scale load test lasted for two weeks from February 5 to 16, 2018. The factory does not operate at weekends.

Well water (temperature 12 - 16 °C) is used as a heated medium to generate hot water, and the target hot water outlet temperature was set to 65 °C.

3.2. Field measurement result and the verification of the modeling

The heating capacity is degraded due to cumulative fouling in the field measurement, which is mitigated by daily self-cleaning. Details will be described in Section 4 and the following description is based on the result after conducting self-cleaning.

Figure 5 shows the daily average heating COP by field measurement (hereinafter referred to as heating COP (field), indicated as “Field test” in figure 5) from February 5 to 16 and heating COP (lab) calculated from Equation (3). The heated COP (field) on February 5 is about 10% higher than the heated COP (lab), which is presumably attributable to the length of the refrigerant pipe between the evaporator and main body.

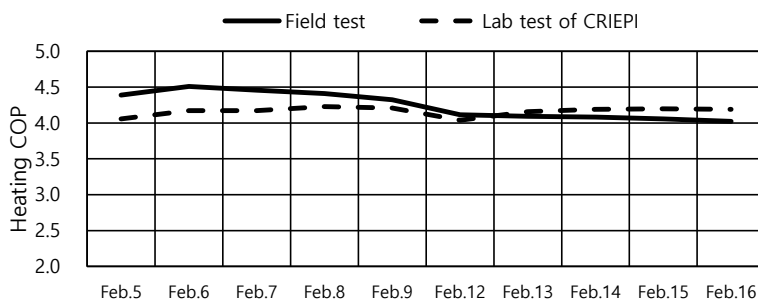


Figure 5 Performance comparison between field measurement and modeling by lab evaluation

From February 6 to 12, the heating COP (field) is on a downward trend, which implies that daily self-cleaning cannot completely remove the fouling from the coil surface of the evaporator. Conversely, since the decreasing trend of heated COP (field) after February 12 has been alleviated, self-cleaning is considered effective in preventing any reduction in heated COP.

3.3. Estimation of the installation effect

Figure 6 shows the estimated reduction in daily A-type heavy oil and increase in daily electricity consumption based on the field measurement. The average reduction in A-type heavy oil was about 88L, and the average increase in electricity was about 194kWh.

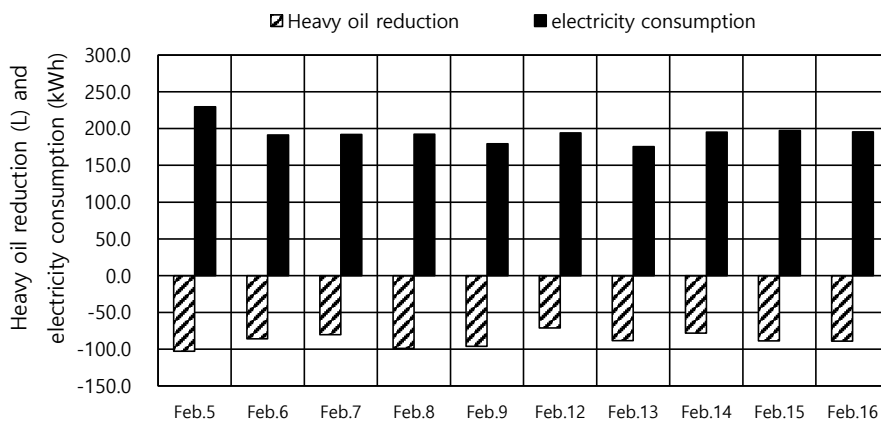


Figure 6 Daily variation of estimated electricity consumption and A-type heavy oil reduction effects.

The annual introduction effect is estimated based on this result. Assuming 262 working days per year, a primary energy reduction effect of 395 GJ and a CO₂ emission-reduction effect of 36 ton- CO₂ can be expected. Here, the grid power primary energy conversion factor, A-type heavy oil calorific value, grid power CO₂ emission intensity (2015) and A-type heavy oil CO₂ emission intensity are assumed at 9.97 MJ / kWh, 39.1 MJ / L, 0.53 kg- CO₂ / kWh and 2.71 kg- CO₂ / L, respectively.

With regard to the CO₂ emission-reduction effect, further intensification can be expected as the decarbonization of grid power progresses.

4. The cumulative fouling on the coil of evaporator and the effect of self-cleaning

Figure 7 shows the water-heating-capacity and heat source temperature at the inlet of the evaporator (denoted as “draining temp”) under operation. A decline in heating capacity is observed as shown in the graph denoted as “no cleaning” (from February 14 to 16), at a rate estimated at 094 MJ/h. Based on the virtually constant heat source temperature and the accumulation of cotton-lint fouling observed, it was suggested that the latter fouling may explain the deterioration, something supported by the significant fouling adhesion on the first day and the concurrent significant decline.

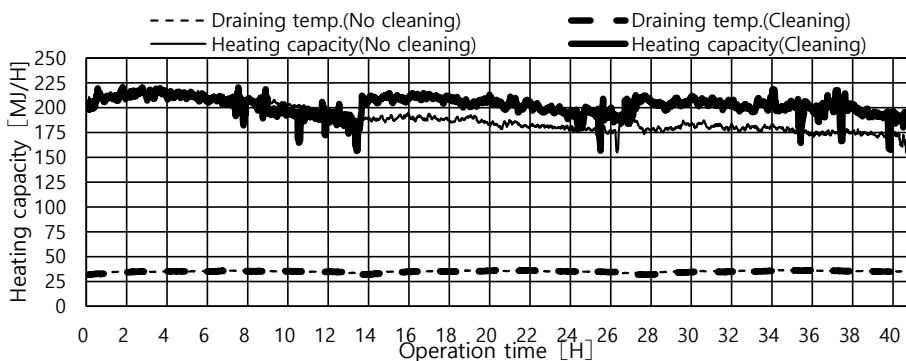


Figure 7 Decreasing heating capacity with adherence onto coil surface and recovery by the self-cleaning

There has been concern about the decline in the evaporator heating capacity due to cumulative fouling on the evaporator coil surface since the project started. Annual chemical cleaning and disassembly cleaning (once every two to three years) are being considered and urgent measure to counter daily performance degradation are required due to cumulative fouling beyond expectations.

Self-cleaning using discharge heat source water from the evaporator is carried out as an urgent measure. To realize the self-cleaning, a discharge valve is installed on the piping on the evaporator outlet. Random bubbling from the discharge valve helps to clean more effectively.

Figure 7 also shows the heating capacity and heat source temperature at the evaporator inlet after self-cleaning, the results of which are shown as “cleaning” (from February 14 to 16). The self-cleaning is conducted daily just after stopping operation. It is confirmed that the visual impact of the cumulative fouling was eased and the heating capacity recovered after the self-cleaning.

5. Conclusion

A heat-recoverable water heating heat pump is evaluated in two ways, via a performance measurement facility and field measurements and its high performance due to a direct heat-recoverable evaporator was confirmed, despite being designed as an affordable heat pump.

In addition, a problem of fouling on the surface of the evaporator coil is solved by using a new heat exchanger cleaning method (daily self-cleaning) and it was confirmed that performance recovered after this cleaning. It is also understood that the length of the separation pipe between the main body and evaporator impacted on performance.

Aiming to conserve more primary energy in the industrial sector, it is important not only to improve heat pump efficiency but also to improve the total design of the hot water supply system and system operation. We will continue to challenge these improvements.

Nomenclature

COP	: Coefficient of Performance, -	W	: Electricity consumption, $\text{kJ} \cdot \text{s}^{-1}$
\underline{Q}	: Heating capacity, $\text{kJ} \cdot \text{s}^{-1}$	w	: (subscript) hot water (heat sink)
T	: Temperature, $^{\circ}\text{C}$	s	: (subscript) heat source water
V	: Volumetric flow rate, $\text{L} \cdot \text{min}^{-1}$	i,o	: (subscript) inlet, outlet

References

- [1] Heat pump and thermal storage center of Japan, Primary energy saving and CO2 reduction effect by increasing diffusion of Heat Pump, News release, 4th Aug. 2017
- [2] Kuwabara T. and Shishido J., Development of Hot Water Supplying System by Direct Expansion-type Water Source Heat Pump for Exhaust Heat Recovery, *Electro-Heat*, 213 (2017), pp. 66-69. (in Japanese)
- [3] Hashimoto K. et al., kkkkDevelopment of Large-Capacity Heat Pump Performance Evaluationg Apparatus, Proceedings of the 11th Heat Pump Conference, (2019), P.4.7