FIELD TEST OF NEWLY DEVELOPED TURBO HEAT PUMP FOR HOT WATER

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Abstract: This paper reports field test of a newly developed turbo heat pump for hot water of 80 degrees Celsius in an actual factory in order to achieve reduction of CO_2 emissions and to enhance energy saving. The heat pump is characterized by high efficiency and large amount of heat output, which approximately equals steam of 1,000 kg / hour, using a state-of-the-art turbo compressor. Low temperature heat source is required for the heat pump in order to achieve high efficiency. As a result of the field test, it was confirmed that the performance of the heat pump was nearly equal to that of design. The dynamic characteristics, such as fluctuation of the output water temperature and the time lapse from switch-on to full-load, were suitable for application in the factory. Primary energy consumption and CO_2 emission of the heat pump were calculated on the basis of the present results. Also, they were improved to match with those of the boilers.

Key Words: Heat Pump, Field Test, Hot Water, Turbo Compressor, Energy Saving

1 INTRODUCTION

Reduction of CO_2 emissions and energy saving are urgent issues in many fields of industry at present. Hot water, occupying a considerable energy consumption rate in the entire industry, is generally generated using combustion gas of higher than 1,000 degrees Celsius in the boilers. However, the temperature loss is large during boiler operation. Accordingly, we believed that energy saving could be accomplished if hot water could be generated using heat pumps. The present paper reports field tests of a newly developed turbo heat pump for hot water of 80 degrees Celsius in an actual factory. The heat pump is characterized by high efficiency and large amount of heat output. Primary energy consumption and CO_2 emission of the heat pump were calculated on the basis of the present results for comparison with those of the boilers.

2 NOMENCLATURE

C : CO_2 emission coefficient [kg-CO_2／kWh, kg-CO_2／m^3]	E : Primary energy ［J］
COP : Coefficient of performance of heat pump [－]	G : Mass flow rate [kg／s]
h : Enthalpy [J／kg]	$hour$: Hours of operation [hour]
M : Mass of CO_2 emission [kg]	Q : Heat value ［J／m3］
W : Thermal energy, Electric energy [J／s]	η : Efficiency [－]

Subscript

boiler : Boiler
gas : Gas
prim-boiler : Primary energy of boiler
prim-heatpump : Primary energy of heat pump
water-in : Water inlet to heat pump
elec-in : Electricity input
heatpump-out : Heat pump output
prim-elec : Primary energy of electricity
water : Water
water-out : Water outlet from heat pump

3 OUTLINE OF THE APPARATUS

3.1 Specifications of the heat pump for hot water

The heat pump was newly developed for hot water, as shown in Figure 1. The specifications are as shown in Table 1. The heat pump has the ability to produce hot water higher than 80 degrees Celsius continuously. Working fluid of the heat pump is HFC-134a. The compressor is a centrifugal type employing a two-stage impeller of the half close type. Input temperature of hot water is 75 degrees Celsius, as shown in Table 1. It is also possible to utilize water of a lower temperature than 75 degrees Celsius. The heat output of hot water by the heat pump can be calculated using Equation (1). The heat output of the full-load is 627 kW, which equals steam of approximately 1,000 kg/h. The heat exchanger, a brazing-plate type, was applied to both the condenser and the evaporator respectively, so as to obtain greater compactness. Electricity input to the heat pump is 400 V when the alternating frequency is 50 Hz and 440 V when the frequency is 60 Hz with three phase alternating current.

Figure1: Heat pump for hot water

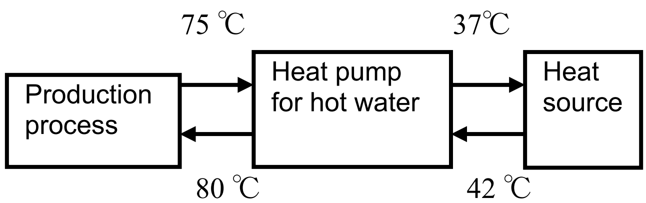

Figure 2: Facilities the heat pump

Table 1: Specifications of heat pump for hot water

Item	Specifications
Output temperature of hot water	80 ℃
Input temperature of hot water	75 ℃ for example
Flow rate of hot water	29.94 kg／s in the above condition
Input temperature of heat source water	45 ℃
Output temperature of heat source water	40 ℃
Flow rate of heat source water	23.58 kg／s
Heat output	627 kW
Coefficient of performance	4.5
Size	W:1.2m×D:2.2m×H:2.1m

3.2 Facilities for field test of the heat pump

Facilities for field testing of the heat pump are shown in Figure 2. Testing was conducted in an actual operating factory producing semiconductors. The heat source water was supplied from a hot water header to the heat pump. Hot water produced by the heat pump was introduced to a heat recovery header. One heat pump was installed at the facility.

4 METHOD OF FIELD TEST

The conditions of field tests are shown in Table 2. Hot water output temperatures ranged between 55 degrees Celsius and 80 degrees Celsius with the load of 100 % under conditions 1 to 4. The temperature difference between inlet water and outlet water was set at 5 degrees Celsius in the case of full load. The load ranged between 28 % and 80 % with the hot water output temperature of 80 degrees Celsius under conditions 5 to 8. The hot water output temperature ranged between 55 degrees Celsius and 80 degrees Celsius at a load of 100 %. The heat source water flow rate was 50 % under conditions 9 to 12. The tests began in November and ended in December of the following year.

Table 2: Experimental conditions

Cond-itions	Output temperature of hot water	Load	Flow rate of hot water	Input temperature of heat source
1	80 ℃	100 %	100 %	42 ℃±1℃
2	70 ℃	100 %	100 %	42 ℃±1℃
3	60 ℃	100 %	100 %	42 ℃±1℃
4	55 ℃	100 %	100 %	42 ℃±1℃
5	80 ℃	80 %	100 %	42 ℃±1℃
6	80 ℃	60 %	100 %	42 ℃±1℃
7	80 ℃	40 %	100 %	42 ℃±1℃
8	80 ℃	28 %	100 %	42 ℃±1℃
9	80 ℃	100 %	50 %	42 ℃±1℃
10	70 ℃	100 %	50 %	42 ℃±1℃
11	60 ℃	100 %	50 %	42 ℃±1℃
12	55 ℃	100 %	50 %	42 ℃±1℃

We obtained the following data on average at one-minute intervals using a Web data-capturing system; namely, the inlet temperature of the heat source water and its outlet heat temperature and flow rate, the inlet temperature of the hot water and its outlet heat temperature and flow rate, the compressor discharge pressure, the compressor inlet pressure, the compressor discharge temperature, the feed oil pressure and temperature, the first impeller discharge pressure, the oil tank temperature, main motor current, the bearing temperature, and the atmospheric air temperature.

The output heat value of the heat pump was calculated using Equation (1) based on the measurement data of each condition mentioned in Table 2. Then, the COP of the heat pump was calculated using Equation (2). Evaluations of the dynamic characteristics were also conducted such as the temperature fluctuations of the heat pump output water when heat source water inlet temperature fluctuated, the time required from switch-on to start, the time taken from switch-off to stop.

$$W_{heatpump-out} = \left(h_{water-out} - h_{water-in}\right) \cdot G_{water} \tag{1}$$

$$COP = \frac{W_{heatpump-out}}{W_{elec-in}} \tag{2}$$

5 RESULTS OF FIELD TESTS

5.1 Measurement data of the heat output and the COP

Table 3: Experimental results of heat output and coefficient of performance

Cond-itions	Measured value／planned value of coefficient of performance	Measured value／planned value of heat output	Deviation of output temperature of hot water in one day
1-①	1.02～1.16	1.01～1.08	79.7～80.0 ℃
1-②	1.00～1.02	0.97～1.00	80.0 ℃
2	0.95～0.98	0.99～1.03	69.9～70.0 ℃
3	0.95～1.00	1.00～1.03	60.0 ℃
4	1.03～1.05	0.99～1.01	55.0 ℃
5	1.03～1.09	0.97～1.01	80.0 ℃
6	0.90～0.94	1.00～1.04	80.0 ℃
7	0.95～0.99	1.04～1.07	80.0 ℃
8	—	—	80.0 ℃
9	1.02～1.08	1.06～1.10	79.2～79.8 ℃
10	0.98～1.04	0.92～1.06	69.7～70.0 ℃
11	0.93～1.05	0.97～1.05	59.4～59.8 ℃
12	0.95～1.05	0.88～1.00	54.3～54.5 ℃

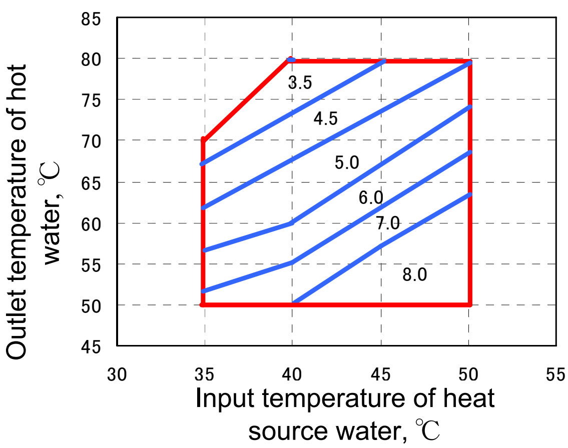

Figure 3: Performance curve of heat output

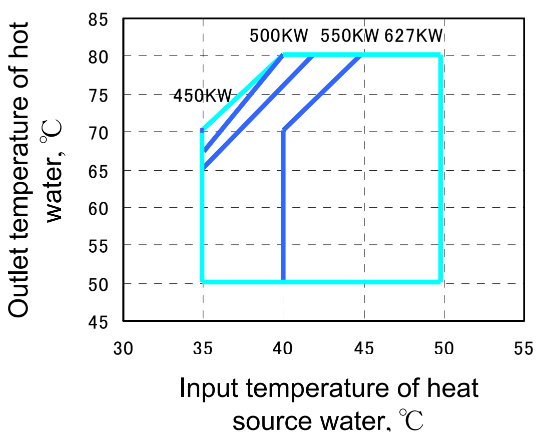

Figure 4: Performance curve of coefficient of performance

The experimental results are shown in Table 3. No values are given for condition 8, because no planned values exist. It was found that the measurement data of heat output and that of COP are highly consistent with the planned values, while the measurement data COP were slightly lower than the planned values in a few conditions. Therefore, planned values were revised considering the measurement data. Next, the performance curve of heat output and that of COP were obtained, as shown in Figures 3 and 4.

Measurements were conducted twice at intervals of several months in condition 1. As a result, heat pump performance in the first measurement was almost the same as that of the second performance. The water outlet temperature was slightly lower than 80 degrees Celsius, the target value in condition 9. We believe that this was caused by the fact that the water inlet temperature was lower than 70 degrees Celsius, the target value.

The bearing temperature of the heat pump was 82.0 degrees Celsius at maximum. This was lower than the allowance temperature of 85 degrees Celsius. The main body temperature of the heat pump was 43.7 degrees Celsius at maximum under conditions of atmospheric air temperature of 34.7 degrees Celsius and a room temperature of approximately 37.7 degrees Celsius existed in August. This was also lower than the allowance temperature of 50 degrees Celsius. The heat pump was able to operate for a period of 8,712 hours discounting times the heat pump had to be stopped for brief inspections. No major problems were encountered. Accordingly, we believe that the reliability was confirmed.

5.2 DYNAMIC CHARACTERISTCS

Table 4: Fluctuations of output temperature of hot water regarding fluctuation of input temperature of heat source water

Conditions	Fluctuations of input temperature of heat source water	Fluctuations of output temperature of hot water
1-①	± 3 ℃	± 0.6 ℃
1-②	± 3 ℃	± 0.6 ℃
2	± 3 ℃	± 0.3 ℃
3	± 3 ℃	± 0.2 ℃
4	± 3 ℃	± 0.5 ℃
5	± 3 ℃	± 0.3 ℃
6	± 3 ℃	± 0.3 ℃
7	± 2 ℃	± 0.2 ℃
8	± 3 ℃	± 1.5 ℃
9	± 3 ℃	± 1.0 ℃
10	± 3 ℃	± 1.0 ℃
11	± 3 ℃	± 1.5 ℃
12	± 3 ℃	± 1.7 ℃

The temperature fluctuations of the heat pump output water were controlled so as to remain as constant as possible when the heat source water inlet temperature fluctuated as shown in Table 4. The temperature fluctuations of the heat pump output water were in the range between ±0.2 to ±0.6 degrees Celsius under the condition that heat source water inlet temperature fluctuated within ±3 degrees Celsius in conditions 1 to 7. The temperature fluctuations of the heat pump output water were larger than those of conditions 1 to 7 when the hot water flow rate was 50 percent in conditions 9 to 12. The reason is considered to be related to the fact that temperature difference between inlet hot water and outlet hot water grows larger and that heat transmission in the condenser becomes unstable in some extent.

Consequently, the temperature fluctuations of the heat pump output water grew comparatively larger under on condition 8, of which the load was 28 percent.

The time that hot water temperature reached 70 degrees Celsius from switch-on was approximately 30 minutes at first. The control method of the bypass-valve, which connected the hot water inlet to the hot water outlet, was improved. As a result, the time was able to be shortened to approximately 13 minutes. The time taken from switch-off to stop was approximately 2 minutes.

6 DISCUSSIONS

The actual values of the heat pump performance were obtained in performance tests and the application studies. The primary energy and CO_2 emission of the heat pump were calculated based on the results. These values were compared with those of thermal supply by the boilers.

6.1 Calculation of primary energy consumption of heat pump

Annual primary energy consumption of the heat pump was calculated to be 4,486 GJ using Equation (3), under condition that the conversion coefficient of electricity to primary energy was 36.9 %(1), COP of the heat pump was 4.5, and annual operation time was 3300 hours.

$$E_{prim-heatpump} = \frac{W_{heatpump-out} \cdot hour \cdot 3600}{COP \cdot \eta_{prim-elec}} \tag{3}$$

On the other hand, the annual primary energy consumption of boilers was calculated to be 8,276 GJ using Equation (4), under condition that the same thermal value was supplied by the boilers, of which the efficiency was 90 %.

$$E_{prim-boiler} = \frac{W_{heatpump-out} \cdot hour \cdot 3600}{\eta_{boiler}} \tag{4}$$

It was found that the primary energy consumption of the heat pump was approximately 54 % of that of the boilers.

6.2 Calculation of CO_2 emission of heat pump

Annual CO_2 emission of the heat pump was calculated to be 161.7 t using Equation (5), under the condition that the CO_2 emission coefficient of electricity was 0.351 kg-CO_2/kWh(2).

$$M_{CO2} = \frac{W_{heatpump-out} \cdot hour \cdot C_{elec}}{COP} \tag{5}$$

On the contrary, annual CO_2 emission of the boilers was calculated to be 402.8 t using Equation (6), under condition that the CO_2 emission coefficient of fuel gas was 2.19 kg-CO_2/m^3N[1] and heat value of the gas was 45 MJ/ m^3N.

$$M_{CO2} = \frac{W_{heatpump-out} \cdot hour \cdot 3600 \cdot C_{gas}}{\eta_{boiler} \cdot 1000 \cdot Q_{gas}} \tag{6}$$

It was found that the CO_2 emission of the heat pump was approximately 40 % of that of the boilers.

7 CONCLUSIONS

Field testing of the newly developed heat pump had been conducted over one year. As a result, it was confirmed that the measurement values of heat pump output and the COP almost the same as the planned values, and dynamic characteristics posed no problem regarding factory application. Also, it was found that the heat pump showed energy-saving promise together with a reduction of CO_2 emissions. The heat pump is expected to continue stable operation with high performance in the future. We will continue to confirm the usefulness of the heat pump by obtaining not only further data of the present testing but also data of applications for other factories.

8 REFERENCES

[1] Agency for Natural Resources and Energy, Ministry of Economy, Trade and Industry, 2008, "Energy Conservation Law".
[2] Ministry of the Environment, 2010.12, "Press release of the CO_2 emission coefficient of electricity ".