

# EVALUATION OF ENERGY CONSERVATION BY USING HOT WATER CENTRIFUGAL HEAT PUMP WITH INVERTER MOTOR DRIVE

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**Abstract:** In terms of greenhouse gas reduction, it is indispensable to develop high performance equipment for energy conservation. The high performance hot water heat pump using a centrifugal compressor with inverter drive has been developed. The heat pump supplies continuous max 90°C hot water by using an exhaust heat source water temperature range from 35 to 50°C. These performance characteristics have been verified on a customer's factory for more than one year examining the durability of the heat pump, following the capability of hot water leaving temperatures, control stability by fluctuating heat load and heat source water entering temperature. The reduction amount of CO<sub>2</sub> emissions and running costs have been calculated using the heat load pattern of a general factory with measured performance. Reductions of about 47% of the annual running cost and about 59% of the CO<sub>2</sub> emission by replacing of the boiler with the hot water heat pump, are shown in this report.

**Key Words:** heat pump, centrifugal chiller, inverter drive, hot water

## 1 INTRODUCTION

For the prevention of global warming, the reduction of the greenhouse gases, especially the reduction of CO<sub>2</sub> emissions that account for 95% of the greenhouse gases, is a main subject of environmental problems. The CO<sub>2</sub> emissions in Japan are 1214 million tons in FY 2009 Annual Energy Report and CO<sub>2</sub> emissions have been increasing from 1144 million from 1990 which is the base year for emissions specified in Kyoto Protocol. Reduction of CO<sub>2</sub> emissions especially from the industrial sector such as factories etc. that account for 40% of the total CO<sub>2</sub> emissions have been important.

The total ratio in energy source consumed by the burning of fossil fuels such as oil and coal which account for a large part of the CO<sub>2</sub> emissions is 73% in The GHGs Emissions Data of Japan (1990-2008). Therefore we urgently need the effective use of energy and large-scale conversion of energy source.

There is a wide variety of usage of hot water for industrial use such as heating of hot pure water for cleaning semiconductors, heating and sterilizing processes in beverage factories, food factories and drying in painting process etc. The temperature range for cleaning is about 30°C to 60°C for heating and sterilizing is about 80°C to 125°C and for drying is about 65°C to 180°C. Hot water is usually supplied by boiler in conventional systems with fossil fuels.

Hot water of 80°C is cooled to 35°C to 40°C at the cleaning process in the semiconductor factory etc. Because the water within the range of this temperature is not useful for other

processes and is usually cooled with the cooling tower and discharged into drainage, this accordingly leads to a waste of energy. Therefore heat pump technologies which recover exhaust heat to use it effectively for air conditioning use etc. are getting a lot more attention and becoming popular.

Because of these factors, the heat pump has been developed which equips a high efficiency two-stage compression centrifugal compressor as a device which is able to continuously supply hot water of max. 90°C which is useful for plant process by using the exhaust heat which had been discharged from cooling towers and heat of 35°C to 50°C generated at incinerator etc. as heat source.

## 2 FEATURES

The basic principle of the heat pump is shown in Figure 1.

As a base configuration, this heat pump system consists of a centrifugal compressor installed with two impellers, an evaporator, condenser and an economizer which are plate heat exchangers.

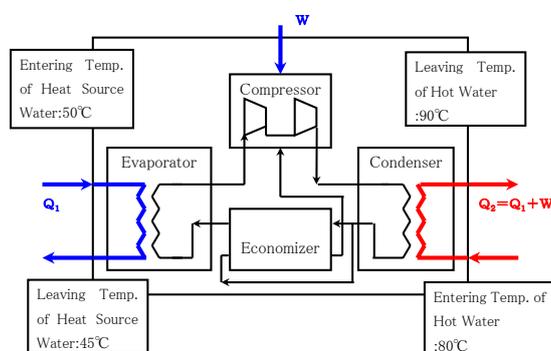


Figure 1: Heat Cycle of Heat Pump

There are two models of heat pump: HP1 is suitable for a case when the heat source water entering temperature is high and a lot of heat output is necessary and HP2 can output hotter hot water. The maximum output temperature of HP1 is 80°C, and HP2 is 90°C. The temperature range of heat source water for HP1 is from 35°C to 50°C, and HP2 is from 10°C to 50°C. The heat source water temperature for HP2 is from 35°C to 50°C to output 90°C. The heating capacity of HP1 is 627kW, and HP2 is 547kW.

The rated specifications of this heat pump are shown in Table 1. COP(Coefficient of Performance) of HP1 is 4.5, and HP2 is 3.7. The power consumption used to calculate COP contains all electric powers of the inverter input, the oil pump, the oil heater, the control power, and other operation motors.

Table 1: Specifications of Heat Pump

item	Specification	Specification
Type	HP1	HP2
Heating Capacity	627 kW	547 kW
Hot Water Temp.	75°C in / 80°C out	80°C in / 90°C out
Hot Water Flow Rate	107.8 m <sup>3</sup> /h	48.4 m <sup>3</sup> /h
Heat Source Water Temp.	45°C in/40°C out	50°C in / 45°C out
Heat Source Water Flow Rate	84.9 m <sup>3</sup> /h	70.9 m <sup>3</sup> /h
Inverter Input	136.2 kW	147.6 kW
COP	4.5	3.7
LxWxH	2.2m x1.2m x2.1m	1.55m x1.2m x2.0m
Shipping Weight	3150kg	2400kg
Operating Weight	3610kg	2700kg
Refrigerant	HFC-134a	HFC-134a

The miniaturization technology of boilers has been advanced, so therefore miniaturization of heat pumps is also needed to apply for the replacement demand of a boiler. The appearance of a heat pump is shown in Figure 2.



**Figure 2: Appearance of Heat Pump (HP1)**

(1) Downsizing of compressor

- A centrifugal compressor of which suction gas volume per unit volume is larger than that of a screw compressor is adopted.
- The increasing gear and ball bearings are downsized by a small torque construction with a high speed motor for inverter.

(2) Downsizing of heat pump unit

- The oil tank and the oil pump are separated from the compressor to be put in the unit to minimize the volume of the unit.
- The inverter panel is installed in the heat pump unit..
- Adopting plate heat exchangers for all heat exchanger.
- Optimizing the inverter and the compressor arrangement.

The installation area of HP1 is 1.86m<sup>2</sup>, and HP2 is 2.64m<sup>2</sup>, which is similar to the level of the installation size of general boilers with 1ton/h.

### **3 HIGH-PERFORMANCE DESIGN**

To achieve high efficiency, the following element technologies are adopted.

- Two-stage compression two-stage expansion cycle
- High-efficiency and accuracy machined impellers
- Low-loss speed increasing gear, low-loss bearings
- First vane control mechanism for capacity control.
- Variable speed control using an inverter for fluctuation of entering temperature of both the hot water and the heat source water.

The temperature of the refrigerant gas is 50°C or more higher compared with the chiller for air-conditioning so that the heat pump can output the 90°C hot water. Therefore, it has been analyzed how the tip clearance between the impeller blade and shroud changed depending on heat with the temperature rising to prevent leakage loss. The thickness of blades is

reduced and the performance is better at view of the gas blockage, and is worse at the view of the clearance slightly. Blade angle distributions are changed and flow patterns and blade surface speed distributions were confirmed through a viscous 3-dimensional fluid dynamics analysis. The analysis throughout suction to exhaust point of the compressor is able to indicate a certain performance value before a bench test.

The fluid distortion analysis bases on an integrated analysis of the impeller and diffuser is performed because it is not possible to accurately grasp the performance of the compressor by only a single impeller. By this viscous 3-dimensional analysis on an entire stage, it is possible to evaluate how a flow in the impeller affects a flow in the downstream diffuser.

#### 4 CONTENTS OF VERIFICATION TEST

The verification test was performed per 5°C from 25°C to 50°C at the heat source water entering temperature and from 50°C to 80°C at the hot water leaving temperature to confirm heating capacity, COP, safety operation and reliability. The performance data was measured for ten times at intervals of two seconds and the heating capacity and COP were calculated by its average value. Calibrated measurement devices were used.

The measurement results of heating capacity and COP are respectively shown in Figure 3. The diagonal lines with numbers in the box are specification values. COP of 4.64 is confirmed under the operating condition of the heat source water entering temperature of 46.3°C, hot water leaving temperature of 80.0°C, and heating capacity of 618KW (98.5% capacity against 627KW) This test result indicates that the target COP 4.5 was exceeded at the rated specification. Shaded areas at the bottom right are areas outputting larger capacity, but lower COP, than the planned capacity.

As shown in Figure 3, the higher the heat source temperature, the smaller the specific volume of compressor suction gas, therefore holding heat amount per unit volume of refrigerant gas increases and heating capacity becomes larger. The measurement point of A to C is a reference area outside the range of specification. At point D, the targeted hot water leaving temperature of 80°C was achieved. The lower limit of heat source entering temperature for the heat pump to output the hot water of 80°C is 40°C.

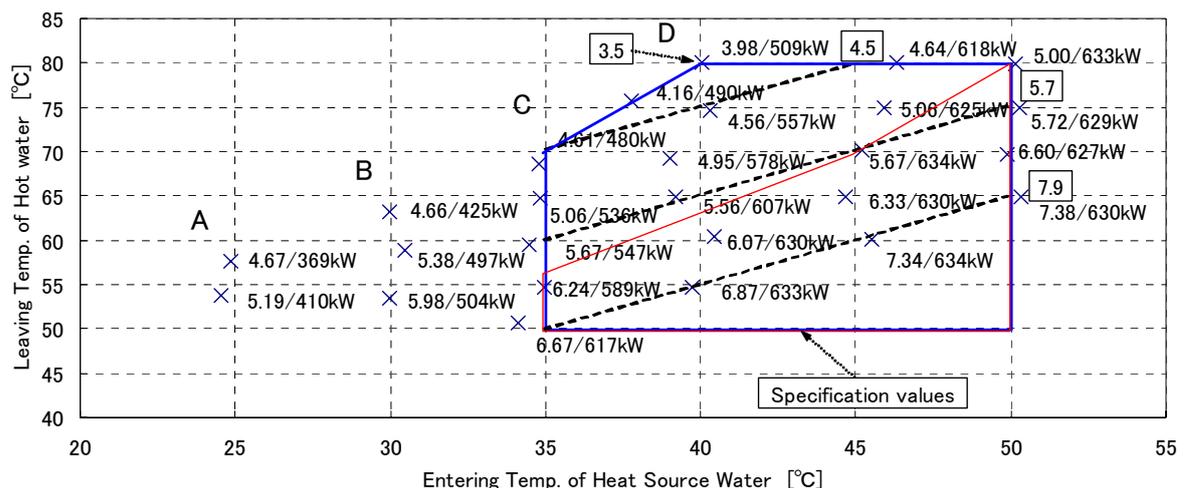


Figure 3: Measurement Results of Heating Capacity and COP

The verification test equipment has a flow measurement device for performance measurement of the compressor. Therefore performance degradation occurs due to pressure drop. If the device is removed, COP increases by 2.5% from the plot value in Figure 3.

The smaller a difference between the hot water leaving temperature and the heat source water entering temperature, the less the rotation frequency of compressor for sucking the

same air volume, and then losses of bearing etc. and powers of motors decrease in proportion to the square to cube of the rotation frequency. Accordingly, COP increases up to 8.0 because the inverter input required for outputting the same amount of heat decreases.

For the load control of this heat pump, the following three controls are combined as the conventional centrifugal chiller to achieve an optimum operation.

- Compressor suction air volume control by a suction vane control
- Compressor rotation frequency control by an inverter device
- Hot gas by-pass valve control which prevents a surging area by increasing the suction air volume to the compressor by circulating the refrigerant gas

By these controls, a continuous control is applied from a load of 100% to the minimum load of 20%. For previous boilers, three-position control of applied load is 100%-75%-50%-0% is common and the control switches to ON/OFF control in the area below 50%. Therefore frequent start/stop decreases the efficiency. Compared with that, reduction of energy consumption in the part load area is possible.

As shown in Figure 3, the higher the heat source water temperature or the lower the hot water leaving temperature, the higher the COP.

The following results were obtained by this verification test.

(1) At the heat source water entering temperature of 25°C to 50°C, safety operation of the equipment to the hot water leaving temperature of 50°C to 80°C was confirmed.

(2) The planned COP 4.5 at the rated points was achieved. In addition, to the planned heat output on each temperature condition other than the rated points, the planned COP was most often achieved.

(3) The motor stator coil temperatures were below 70°C in operation under each condition as against the allowable maximum temperature of 115°C and its reliability was confirmed. In addition, stability of the bearing temperature was confirmed within the allowable range.

## **5 OPERATING PERFORMANCE IN THE FIELD**

The verification operation of the hot water heat pump HP1 was performed for about one year in the actual field of a semiconductor factory (The daily operating data is shown in Figure 4). The hot water leaving temperature is set at 80°C and it keeps almost 80°C despite disturbances such as fluctuation of the heat source water entering temperature. Thermal capability fluctuates with fluctuation of the heat source water entering temperature. However, COP stably keeps about 4.1 at an average daily heat source water temperature of about 43°C. In addition, the parameter of the control software was adjusted to follow to the change of the heat source and hot water entering temperature, big trouble was not found, and either the stability driving was able to be done though the field test was executed for about one year. Moreover, the inside temperature of the heat pump and the temperature of bearings were under the designed temperature and reliability was able to be confirmed.

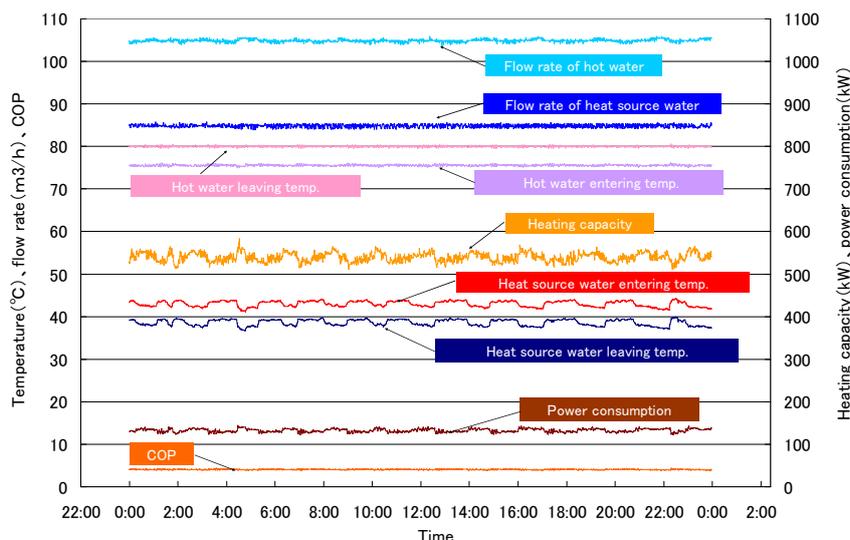


Figure 4: The Daily Operating Data in The Field

## 6 COMPARISON OF CO<sub>2</sub> EMISSIONS AND ECONOMY

### 6. 1 Comparison of a boiler and the heat pump

The equipment using (gas firing) boilers is compared with the equipment using heat pumps in amount of CO<sub>2</sub> emissions and economical point of view. The system diagrams of the equipment are shown in Figure 5.

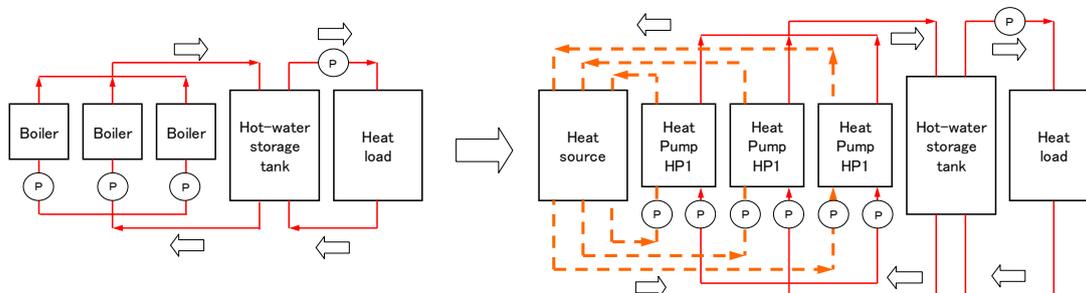
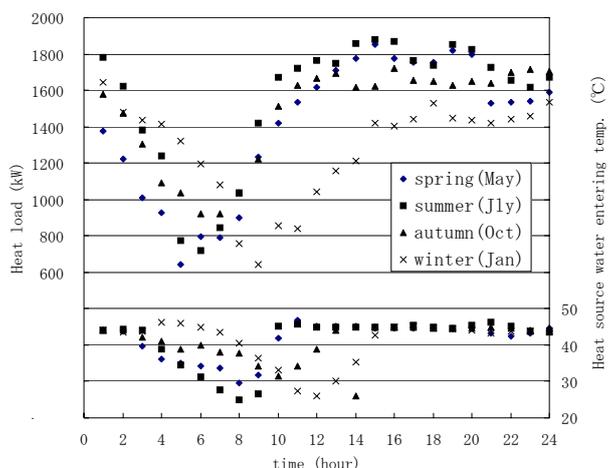


Figure 5: System Diagrams of Boilers and Heat Pumps

For the equipment using boilers, it consists of three boilers and the maximum amount of heat output per one boiler was 627kW which is equivalent to that of a 1ton boiler. Then maximum amount of heat output of equipment was  $627 \times 3 = 1881 \text{ kW}$  and the efficiency of boilers was 95%. For the equipment using heat pumps, it consists of three heat pumps (HP1), to which, a certain amount of the high temperature heat source water of 30°C to 45°C was supplied continuously. They have large amount of heat output and high efficiency in the high temperature zone of the heat source water. For the hot water, the entering temperature was 70°C, the leaving temperature was 80°C and the temperature difference was 10°C. In addition, the quarterly amount of boiler heat and heat source water temperature of a certain factory in Tokyo area were used for the data of the hot water side load and the heat source water and were calculated as all-year continuous running. The data of heat load and heat source water temperature is shown in Figure 6.



**Figure 6: Heat Load and Heat Source Water Temp. data**

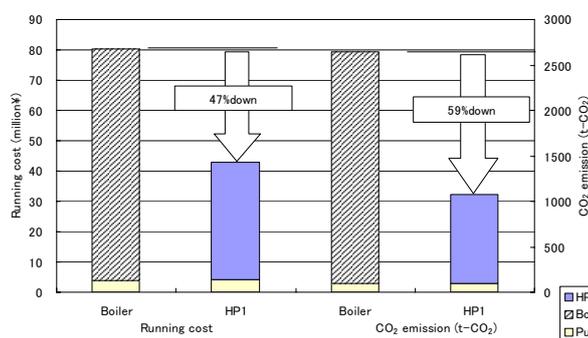
Power consumption per one pump conveying hot water and heat source water is from 5.5 kW to 18.5kW and the reduction of this auxiliaries power also contributes to the overall efficiency improvement. For the heat pump operation, the variable flow control by inverter devices which increases or decreases flow rates applied to pumps conveying hot water and heat source water.

The data of CO<sub>2</sub> emission intensities and charges used for calculating the economy is shown in Table 2.

**Table 2: CO<sub>2</sub> Emission Intensities and Charges**

	CO <sub>2</sub> emission intensity kg-CO <sub>2</sub> /kWh	Charge
Electricity	0.324	12.9 yen/kWh
City gas (13A)	2.19	59.05 yen/m <sup>3</sup>

The comparison of annual running cost and CO<sub>2</sub> emissions estimated on the above condition is shown in Figure 7.



**Figure 7: Comparison of Running Cost and CO<sub>2</sub> Emission**

By changing the boiler to this heat pump, significant reductions of the annual running cost, about 47% reduction for the boiler, are expected. As well as the running cost, significant reductions of the CO<sub>2</sub> emission of about 59% are expected.

As for the replacement of the boiler with HP1, the heat source water at the sufficiently-high temperature can be supplied and it can be used in the range that the performance of HP1

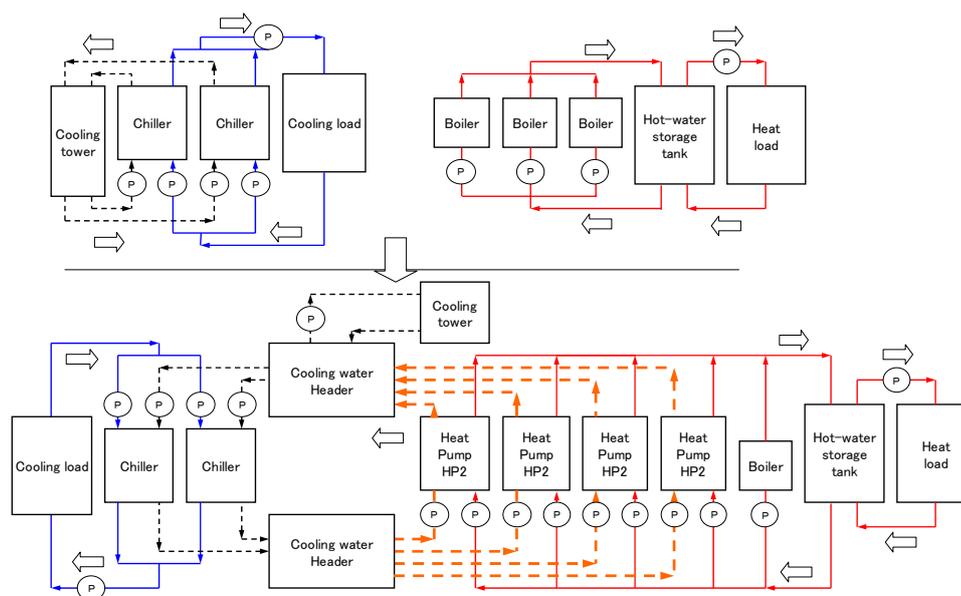
does not decrease. Moreover the equipment can run with very high efficiency and the annual average COP is 4.1. Therefore it is considered that the significant reductions of the CO<sub>2</sub> emissions and running cost described above can be achieved.

In addition, the reduction of the power consumption of pumps for water by variable flow control by inverter device is small because the average load factor of the heat pump is 83% which is high and the time exceeding 80% of the load factor is about 70% of the total operation period.

By using HP1, a pump for heat source water was required so therefore more pumps were required and the auxiliary's power stayed much the same.

## 6.2 Comparison of boilers with constant speed centrifugal chillers and heat pumps with variable speed centrifugal chillers

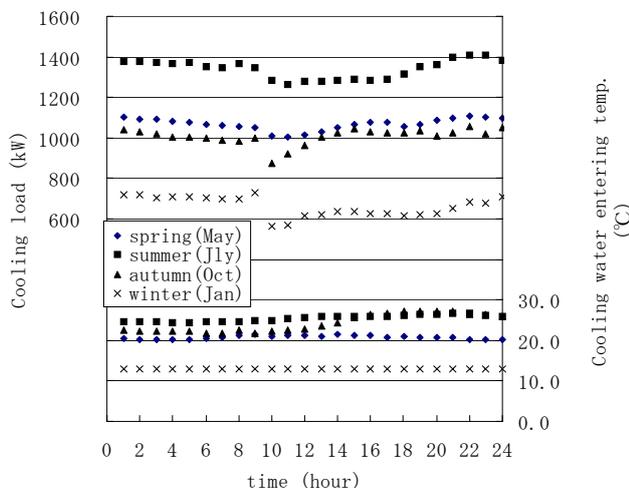
CO<sub>2</sub> emissions and running cost were compared between the equipment for heat load by using boilers and for cooling load by using fixed speed centrifugal chillers at the same time and the equipment by using heat pumps and variable speed centrifugal chillers with the inverter motor drive. The system diagrams of the equipment are shown in Figure 8.



**Figure 8: System Diagrams**

For the equipment with the boilers and the fixed speed centrifugal chillers, three boilers (which are the same as the previous section) were used and the maximum amount of heat output was 1881kW. Two fixed speed centrifugal chillers with a chilled water entering temperature of 12°C and leaving temperature of 7°C having cooling capacity of 703kW were installed and the total cooling capacity was 1406kW. As for the equipment with the heat pumps and the variable speed centrifugal chillers, HP2 was adopted for the heat pumps to be able to output the hot water of 80°C even when the cooling water temperature at the chiller side, or the heat source water entering water temperature, decreases when the outside air temperature decreases. For the hot water, entering temperature was 70°C and leaving temperature was 80°C. The temperature difference was 10°C. If the cooling load is minimal, the exhaust heat from the chiller side is small. To ensure the hot water leaving temperature even in high load condition the heating load is high on that occasion, four heat pumps and one boiler were installed in parallel. The data with the hot water side load is the

same as the previous section. For the chilled water side load data, the quarterly cooling load data of a certain factory was used as a reference.

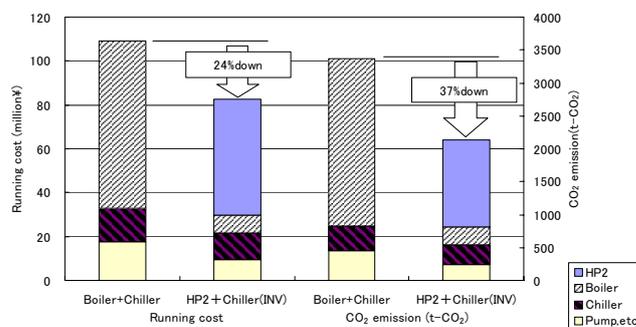


**Figure 9: Cooling Load and Cooling Water Entering Temp. Data**

The cooling water temperature was estimated from the wet-bulb temperature measurement data of Tokyo area of 2010. The cooling water temperature of the lower limit was 13°C to stably run the chillers. The cooling load data and the cooling water entering temperature are shown in Figure 9.

The variable flow control by inverter device was applied to the conveying pump for the variable speed centrifugal chillers and the heat pumps as the previous section. And the power of the cooling tower decreased as the heat discharge decreased.

Comparison of annual running cost and the CO<sub>2</sub> emissions is shown in Figure 10.



**Figure 10: Comparison of Running Cost and CO<sub>2</sub> Emission**

By the combined use of the heat pumps and the centrifugal chillers with the inverter motor drive, the annual running cost and the CO<sub>2</sub> emission reduced by 24% and 37%, respectively. As for the comparison of the power consumption of fixed speed/variable speed centrifugal chillers is about 20% reduction of the power consumption was achieved due to the effect of the power drop because of a decrease of the rotation speed of compressor when the cooling water temperature decreased. As for auxiliaries power, though the total power consumption became large because more pumps were installed, the average load factor of the heat pump was below 70% and never exceeded 80% of the load factor. Therefore the power consumption was able to be reduced by 46% because the power drop by the variable flow

control was large. As for the effect of the replacement of the boiler with the heat pump, the same energy conservation as the previous section was not achieved. For the case study in the previous section, entering temperature of heat source water is from 30°C to 45°C however, in this case, the heat source was the cooling water of the chiller and the cooling water temperature was decreased for operating the chiller efficiently. Accordingly, the heat source water temperature decreased and the average COP of the heat pump became 2.9. In addition, if the cooling water is increased to improve the efficiency of the heat pump, COP of the chiller side decreases. Therefore the economy and the CO<sub>2</sub> emission stayed pretty much the same. As a result, for the combination of the centrifugal heat pump with the inverter motor drive and the centrifugal chiller, changes in the cooling water temperature at the middle temperature side, or the heat source water temperature, do not affect the performance if the chilled water leaving temperature at the low temperature side and the hot water leaving temperature at the high temperature side are constant.

## **7 CONCLUSION**

- The high performance hot water heat pump using a centrifugal compressor with inverter drive has been developed.
- On the verification test on a test model, COP and the amount of heating capacity on each temperature condition have been measured and they met the planned values.
- On the field test, the capability of the heat capacity and leaving temperature of hot water even if the water side condition is changed.
- On the case study of the replacement of the boiler with the heat pump, significant reductions of about 47% of the annual running cost and about 59% of the CO<sub>2</sub> emission, are expected.
- On the case study of the replacement with the heat pumps and the centrifugal chillers with the inverter motor drive, significant reductions of about 24% of the annual running cost and about 37% of the CO<sub>2</sub> emission, are expected.

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