Journal of Template

Vol. 00, No. 0, 0000

Research for Air Cooling System Using Vacuum-cooled Water Refrigerant*

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Abstract

An air-cooling system of a small capacity of several kilo-watts using only water refrigerant as a non-CFCs (Chlorofluorocarbon) technology is examined. The experimental device consists of two stages. The first stage is composed of a vacuum pump and a vacuum chamber of about 60 L in volume. The second stage has two heat exchangers (the exchanger located outside the vacuum chamber is a dummy cooling load) and a water circulating pump. An air-conditioner indoor unit or a heater is used as a dummy cooling load. The temperature and humidity characteristics are measured at each place. Consequently, the ability to cool the room air is ensured by an air-cooling system using only water refrigerant. A new vacuum pump, that can exhaust a large amount of water vapor, is developed and its properties are measured. It seems that the engine-based vacuum pump performance is sufficient to drive the air cooling system with water refrigerant.

Key words: Non-CFCs, Air-Cooling System, Water, Vacuum Pump, Heat

1. Introduction

Global environment problems such as global warming and ozone depletion are worrisome. Air-conditioners help increasing work efficiency and improve comfortable living environment. Alternatives to chlorofluorocarbon (HFC, etc.) used as refrigerant for air-conditioners don't destroy the ozone layer, but they are pointed out as greenhouse gas[(1)]. Although the collection at the time of the disposal is obliged, it is difficult to collect all the amount of refrigerant gas in each unit.

Water is one of the natural refrigerants like hydrocarbon (isobutane, propane), CO_2, ammonia, and air. Both its ODP (Ozone Depletion Potential) and GWP (Global Warming Potential) are zero and near to zero, respectively. Moreover, water exists in the natural world abundantly, doesn't have the toxicity and burn ability and is cheap.

International Committee of Weights and Measures in 1990 adopted an experimental formula about the saturation water vapor pressure P_s Pa which was reported by D. Sonntag in 1986[(2)]. The saturation water vapor pressure calculated by the experimental formula is shown in Fig. 1.

*Received XX Xxx, 200X (No. XX-XXXX)
[DOI: 00.0000/ABCDE.2006.000000]

When water is decompressed, it boils till the pressure equals to the saturation water vapor at the water temperature. The water temperature falls, since the boiling takes evaporative latent heat from the water. In other words, we can get coldness by decompressing the vacuum container with water. There are some applications of water decompression cooling, e.g. moist lettuce or cut flowers, where decompression takes heat of vaporization away from them rapidly [3], [4].

In resent years, Sanken Setsubi Kogyo Co. Ltd. (in Japan) and IDE technology Corporation (in Israel) cooperated to make water cooling systems that incorporated a steam turbo compressor [5], and sold them. The big cooling system with freezing capacity of more than 350 kW by IDE technology Corporation is used in a gold mine in Republic of South Africa. However, a small capacity water decompression cooling system of several kilo-watts such as for domestic use is not developed yet.

We aim at constructing a small and with a little environmental load air cooling system using water refrigerant and examine it experimentally. In this paper, the presently proposed system is an open loop refrigeration using vacuum-cooled water refrigerant. It consists of an evaporator and a vacuum pump. Using water instead of CFCs is easy on the environment. Abolition of the condenser leads to compactness and low cost of the system.

First, this paper aims at showing basic performance of the present system by theoretical work. For this purpose, a steady state model is developed and theoretical value of COP is simulated under ideal conditions.

Second, basic principle of the present system is validated through experiments. An experimental apparatus is constructed, and various data such as COP and local temperature are measured.

Fundamental data of the non-CFCs air-cooling system using only water refrigerant are offered.

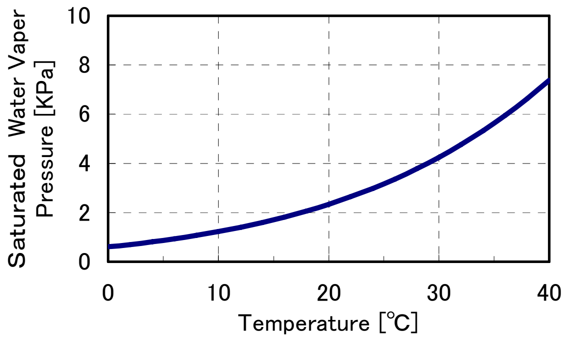

Fig. 1 A curve of the saturated water vapor pressure

2. Nomenclature

P_s : saturation water vapor pressure [Pa]
P_1 : pressure at the state number of 1 [Pa]
P_4 : pressure at the state number of 4 [Pa]
h : specific enthalpy [kJ/kg]
T : temperature [K]
T_1 : temperature at the state number of 1 [K]
q_L : quantity of cooling per unit mass of the refrigerant [kJ/kg]
w : compressing work by the vacuum pump per unit mass of the refrigerant [kJ/kg]
T_{vp} : temperature in the evaporator [K]
Φ : relative humidity [%]

X : absolute humidity [%]
V : specific volume [m^3/kg]
C_c : cooling capacity [kJ]
TCvw : primary cooling water temperature [℃]
TCci : air-conditioner indoor unit inlet water temperature [℃]
TCco : air-conditioner indoor unit outlet water temperature [℃]
TCai : room air temperature [℃]
TCao : cold air temperature from the air-conditioner indoor unit [℃]
P_{con} : electric power consumption [kWh]
S : volume flow rate [L/min]
P_k : pressure for k-th data [Pa]
P_{k+1} : pressure for (k+1)-th data[Pa]
V_C : volume of the vacuum chamber [L]
t : time interval [min]
ΔT : mean temperature difference [℃]
Q_1 : amount of heat at the first stage [kJ]
Q_2 : amount of heat at the second stage [kJ]
Δm : quantity of evaporation [kg]
Δq : flow rate of the circulating water [kg/s]
Subscripts :
inlet : inlet for the air-conditioner indoor unit
outlet : outlet for the air-conditioner indoor unit

3. Coefficient of Performance

In this work the theoretical COP for water refrigerant is calculated. The real refrigeration system is an unsteady system, but we replace it with a steady model and analyze simply. It is assumed that water is supplied continuously with constant flow rate and the whole system always keeps the steady state.

The model of the refrigeration system is shown in Fig. 2. The numbers in Fig. 2 show its each state. The COP as in the regular refrigeration system is decided as follows [(6)].

$$\mathrm{COP}_R = \frac{q_L}{w} = \frac{h_3 - h_2}{h_4 - h_3} \tag{1}$$

where q_L kJ/kg is the quantity of cooling per unit mass of the refrigerant, w kJ/kg is compressing work by the vacuum pump per unit mass of the refrigerant, and the pair of h and its subscript shows the specific enthalpy at each state.

We calculate the COP_R under the next conditions,

i) Intake: T_1=25℃, P_1=100 kPa

ii) Exhaust: P_4=100 kPa

where T_1 is the temperature at the state number of 1, the pair of P and its subscript shows the pressure at each state. The temperature T_{vp} in the evaporator varies from 5 to 30 ℃.

The COP_R is shown in Fig. 2. In the range of T_{vp}=5 - 30 ℃, we can see that the COP_R is around 3 and tends to go up with increasing T_{vp}.

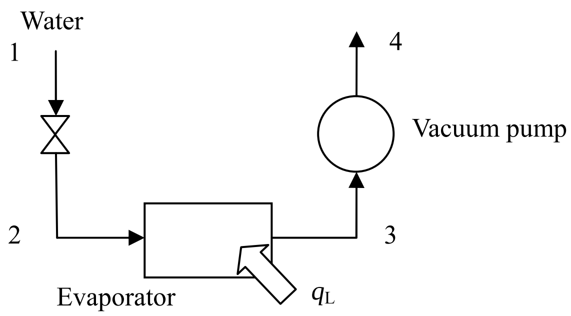

Fig. 2 The model of the refrigeration system

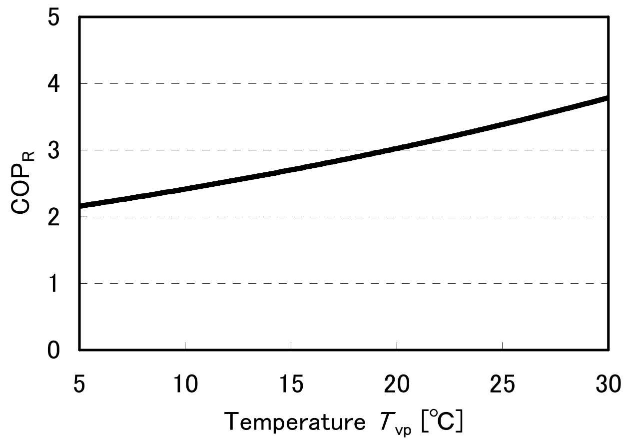

Fig. 3 COP_R for temperature T_{vp} in evaporator

COP in this experiment using an air-conditioner indoor unit is calculated as follows.

First, the relative humidity Φ is measured. Using the saturation water vapor pressure P_s, the relative humidity Φ is converted into the absolute humidity X[7), (8)].

$$X = 0.622 \times \frac{\Phi P_s}{1.013 \times 10^5 - \Phi P_s} \quad (2)$$

where 0.622 is the ratio of molecular weight of steam/air.

Next, using eq. (2), the specific enthalpy[(6)] h kJ/kg is calculated by

$$h = 1.005 \times T + (2447 + 1.846 \times T) \times X \quad (3)$$

where the specific heat at constant pressure of dehydration air is 1.005 kJ/(kg(DA)･K) [(7)], T K is the temperature, the evaporative latent heat of water is 2447 kJ/kg at TCao = 22.0 ℃ [(9)], and the specific heat at constant pressure of water vapor is 1.846 kJ/(kg・K) [(7)]. The specific volume V m^3/kg is calculated by the ideal gas equation by

$$V = \frac{(287.1 + X \times 461.7) \times T}{(1 + X) \times 1.013 \times 10^5} \quad (4)$$

where the gas constants of dry air and water vapor are 287.1 and 461.7 J/(kg･K) [(10)], respectively.

Therefore, the cooling capacity C_c kW for unit time at the quantity of wind 0.12 m^3/s from the air-conditioner indoor unit is[7],

$$C_c = \frac{h_{inlet} - h_{outlet}}{V} \times 0.12 \tag{5}$$

Then, COP for unit time is obtained by[6]

$$\mathrm{COP} = \frac{\text{Cooling capacity kW}}{\text{Integrated power for unit time kW}} \tag{6}$$

4. Experimental Setup and Method

4.1. Cooling Experiment Using Air-conditioner Indoor Unit

Experimental setup is shown in Fig. 4. The experimental device consists of two stages, the first stage is composed of a vacuum pump and a vacuum chamber of about 60 L in volume, and the second stage has two heat exchangers and a water circulating pump.

In the first stage, the primary cooling water of 5.0 L is located in the vacuum chamber. A heat exchanger is located in the primary cooling water in a plastic container which is thermally isolated with the stainless vacuum chamber. When the vacuum chamber is decompressed by the water ring vacuum pump, the temperature of the primary cooling water falls down so that thermal energy is taken as latent heat. In the second stage, the water cooled by the heat exchanger inside the vacuum chamber is flowing into the other air/water heat exchanger (produced by Corona Co., CSH-ES282-W) for the indoor unit of air-conditioner with flow rate of 2.6 L/min by the circulating pump. Total amount of the secondary circulating water is 5.0 L. The room air exchanges the heat and the cooled air is supplied through the outlet of the air-conditioner indoor unit. The cooled air is isolated from the room air by a plastic sheet which is located at the outlet of the air-conditioner indoor unit.

The characteristics of each place, i.e. the primary cooling water temperature TCvw, the air-conditioner indoor unit inlet water temperature TCci, the outlet temperature TCco, the room air temperature TCai, and the cold air TCao, are measured by thermocouples (TC-K-F).

The thermocouple soldered with two copperplates of 10 mm ×10 mm is placed in the circulating water pipe diagonally at about 10 degrees and measures the average temperature.

In addition, both the room air humidity and the air humidity at the outlet of the air-conditioner indoor unit are measured by humidity sensors (HIOKI 9653). The absolute humidity and specific enthalpy are calculated in eqs. (2) and (3). Electric power consumption by the water ring vacuum pump and the circulating water pump are measured by each wattmeter. The COP is calculated in eq. (6).

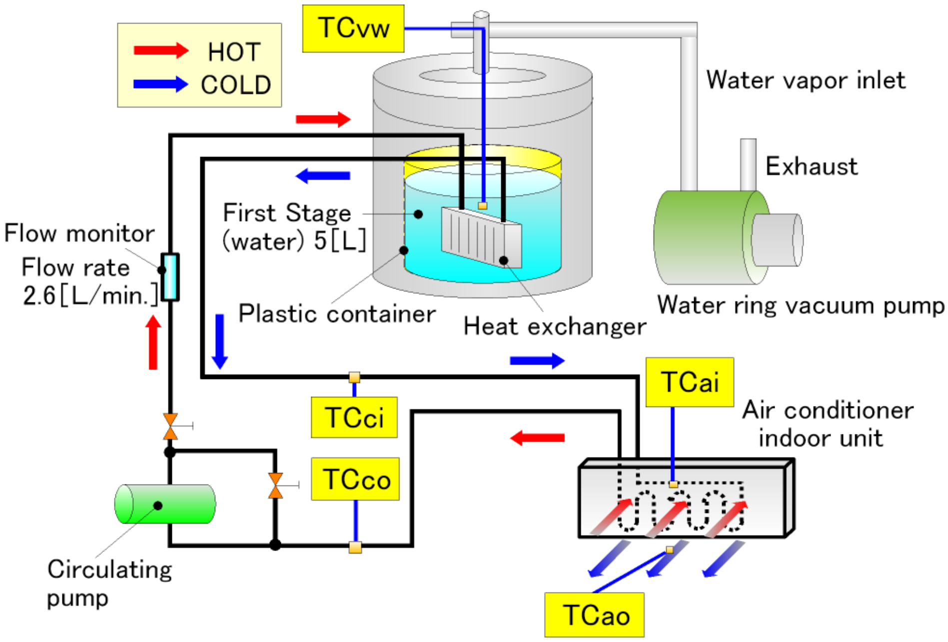

Fig. 4 Experimental setup

4.2. Cooling Experiment Using Dummy Cooling Load

We try to find the exact COP of the amount of heat with dummy cooling load. Instead of the cooling load for the air-conditioner indoor unit, a heater of 0.24–1.33 kW is used. The total amount of the primary cooling water is 5.0 L, the total amount of the secondary circulating water is 5.0 L with a flow rate of 3.0 L/min. The electric power consumption (the denominator of eq. (6)) and all refrigerant water temperature shown in Fig. 4 are measured. The quantity of the primary cooling water is measured by a weight meter (A&D Co. LTD, FT-100KA1).

4.3. Performance Characteristics of Engine Vacuum Pump

In previous sections 4.1 and 4.2, a water ring vacuum pump (WRVP) is employed to decompress the vacuum chamber. Since this vacuum pump can’t evacuate water vapor over the pressure of saturation water vapor of the water seal, the vacuum pump needs ice of about 15 kg per hour to keep the temperature of water seal with about 2 ℃. We tried to use an oil-sealed rotary pump, and considered an oil free vacuum pump and etc.[11], but they don't have ability to exhaust ~~a~~ large amount of water vapor (about 10 % per hour for the weight of the primary cooling water).

Therefore, the development of a new type of vacuum pump which can exhaust large amount of water vapor and can evacuate up to about 1 kPa is needed. In our laboratory, a new type of vacuum pump (a kind of piston type vacuum pumps and we call it "the engine vacuum pump") has been developed.

The engine vacuum pump is shown in Fig. 5. An engine of a car is used as it is, and the modified cylinder head which has two reverse-check valves for each cylinder head can exhaust gas by the pressure difference between the internal and external automatically. The reverse-check valve is made of a 0.3 mm thick FRP sheet. The engine vacuum pump has a simple structure, it is cheap, and its construction is easy.

The air intake is connected to the vacuum chamber, and water vapor is injected in the first stage cylinder. The second stage piston inspires water vapor from the first stage cylinder at the same time as the first stage piston works with a compression process. In the compression process of the second stage piston, the water vapor is exhausted into air.

If the engine vacuum pump is composed by one cylinder, it cannot exhaust a lot of the water vapor continuously since the inspired water vapor is condensed into water in a compression process and the condensed water evaporates by the next expansion process.

The pressures P_k and P_{k+1} at specified time intervals in the vacuum chamber are measured, and the volume flow rate S L/min [12] is calculated by the pressure difference (P_k, P_{k+1}), using the next equation.

$$S = \frac{V_C}{t} \log_e \frac{P_k}{P_{k+1}} \tag{7}$$

where V_C L is the volume of the vacuum chamber and t, given in minutes, is the time interval between the pressures P_k Pa and P_{k+1} Pa. The sampling interval is 10 s.

The primary cooling water of 1-5 L is evacuated by the engine vacuum pump with the first stage in Fig. 4. The temperature of the primary cooling water is measured, and the quantity of the primary cooling water suited for the ability of the engine vacuum pump is examined.

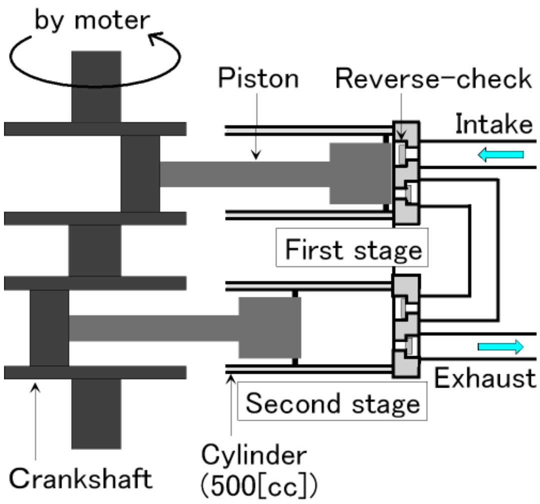

Fig. 5 Schematic diagram of the engine vacuum pump

5. Experimental Results and Discussions

5.1. Experimental Results for Air-conditioner Indoor Unit

The temperature of each place and the electric power consumption are shown in Fig. 6. During the experiment, TCai is kept at almost the same temperature of 29 ℃. Just after the experiment starts, TCvw decreases suddenly, and the others are decreasing gently. The driving of the experimental setup has become a steady state 20 minutes after the experiment starts. In the steady state between 20-60 minutes, the mean temperature difference (dry-bulb temperature) between TCai and TCao is about 7.2 ℃.

Relative humidity at the room air inlet and the cold air outlet are shown in Fig. 7. The relative humidity of the inlet is approximately constant, but the relative humidity of the outlet rises, and the characteristic becomes almost constant 20 minutes after the experiment starts.

The reason seems to be that the relative humidity is defined as the quantity of water vapor for unit volume divided by the saturation water vapor density at the temperature. The saturation water vapor density depends on the temperature decreasing, but the quantity of the water vapor is almost the same.

The relative humidity is converted by eq. (2) to the absolute humidity. Using eq. (3), the specific enthalpy is calculated and the COP is shown in Fig. 8. The COP shows low value at the time of the vacuum pump starting, but it shows about 1.0 for the steady state.

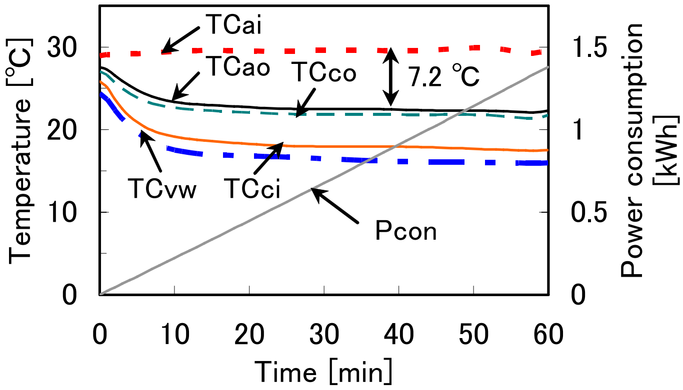

Fig. 6 Characteristics of temperature and electric power consumption

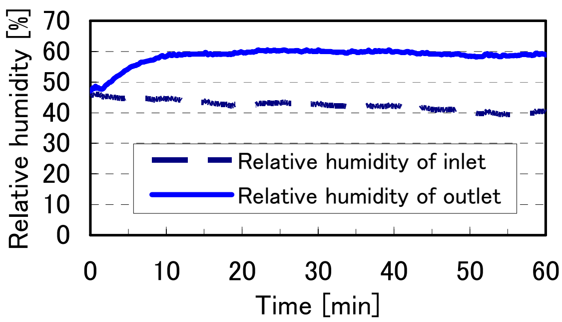

Fig. 7 Relative humidity (Primary cooling water of 5.0 L)

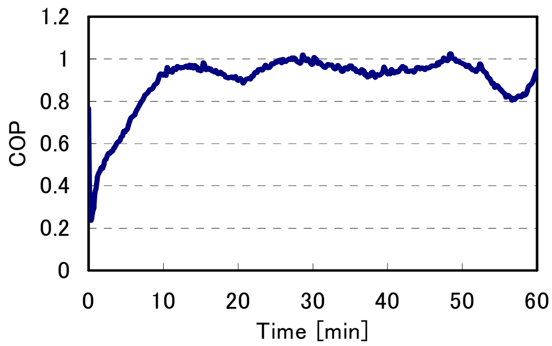

Fig. 8 COP (Primary cooling water of 5.0 L)

5.2. Experimental Results for Dummy Cooling Load

The secondary circulating water is supplied from a constant dummy cooling load (1.03 kW) instead of the air-conditioner indoor unit in Fig. 4, and the temperatures and the weight of the primary water are shown in Fig. 9. The driving of the experimental setup has become a steady state 40 minutes after the experiment starts. In the steady state between 50-70 minutes, the temperature difference ΔT between heater inlet and outlet is about 4.7 ℃.

The quantity of the primary cooling water is shown on the right axis in Fig. 9. The primary cooling water of 5 L is decreasing linearly, and the quantity decreases about 15% for 90 minutes.

The dummy cooling load supplied by the heater, i.e. the cooling capacity C_c for unit time, is determined from the amounts of heat Q_1 at the first stage and Q_2 at the second stage by[10],

$$C_c = Q_1 = 2447 \times \Delta m \tag{8}$$

$$Q_2 = 4.2 \times \Delta T \times \Delta q \tag{9}$$

where the evaporative latent heat of water is 2447 kJ/kg at TCvw= 22 ℃ [9], Δm kg is the quantity of evaporated water, the specific heat of liquid water is 4.2 kJ/(kg・K) [10], and Δq kg/s is the flow rate of the circulating water. The difference, i.e. Q_1 - Q_2, is the thermal leak from the vacuum chamber and it depends on the temperature difference between the room temperature and the primary cooling water.

The electric power of about 1.3 kW and C_c in eq. (8) are substituted for eq. (6), the COP is 0.83 for the steady state as an average of Δm for 10 seconds. The maximum COP is 1.04 for the dummy cooling load of 1.3 kW.

Consequently, in air-cooling system using only water refrigerant, a certain heat capacity has been handled. The experimental value of the COP is about one third of the theoretical value. It is considered that loss of work in the vacuum pump and imperfectness of heat transfer in the evaporator are not negligible. The performance of these elemental apparatuses should be enhanced in order to use the present system in practical situation.

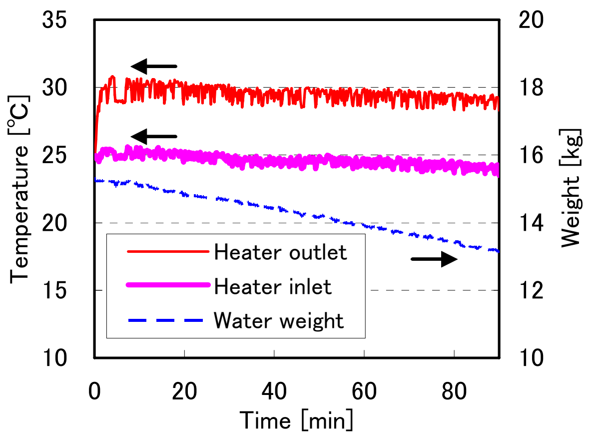

Fig. 9 Variations of temperature and weight (dummy cooling load of 1.03 kW)

5.3. Experimental Results for the Engine Vacuum Pump

Relations between the volume flow rate and the ultimate pressure of the air evacuated by the engine vacuum pump are shown in Fig. 10. The curves are discontinuous when the volume flow rate falls down, since the sampling time of 10 s is short and the pressure difference is little. The ultimate pressure evacuated by the engine vacuum pump with over 400 rpm is lower than that of the water ring vacuum pump and the pressure achieves about 1 kPa of our expected value.

The water temperature by exhausting water vapor is shown in Fig. 11. For a few minutes after starting to evacuate water vapor, the water boils intensely and the water temperature suddenly corrupts, and then the temperature is decreasing. The temperature fall is as the earlier with the less quantity of primary cooling water. The temperature of the primary cooling water should be lower than 20 ℃ to get the air cooled. It seems that about 3 litters of primary cooling water are suitable for the experimental setup, because the heat exchanger in the vacuum chamber should be put in the primary cooling water enough.

Consequently, it is clear that the engine vacuum pump can work enough for the air cooling system using water refrigerant.

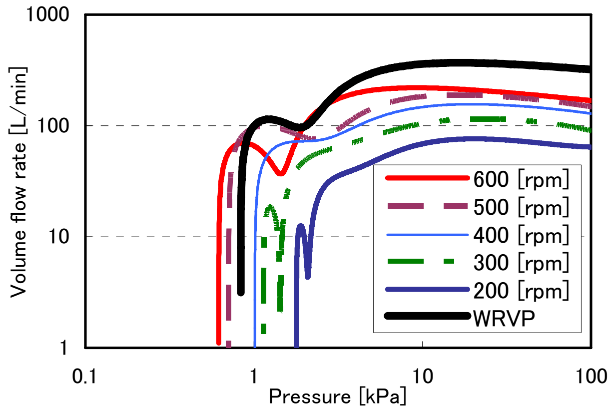

Fig. 10 Volume flow rate and ultimate pressure for the engine vacuum pump and water ring vacuum pump

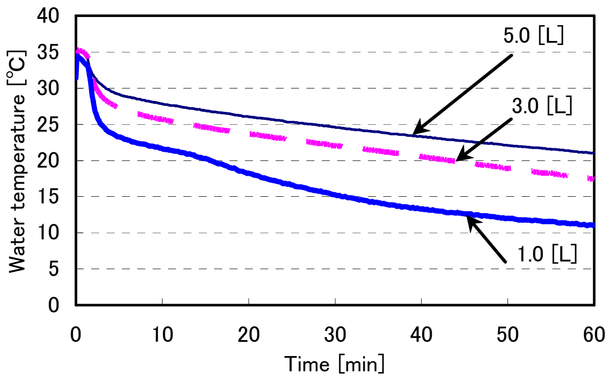

Fig. 11 Vacuum-cooling by the engine vacuum pump (No dummy cooling load)

6. Conclusions

A small capacity air-cooling system of several kilo-watts using only water refrigerant as a non-CFCs technology was examined.

The decompression cooling could cool down the room air with about 7.2 ℃ for the ambient temperature of 29 ℃. The COP was about 1.0. In the measurement using a heater as dummy cooling load, the COP was also about 1.0. Consequently, the water was cooled by decompression cooling, and the circulation exchanged cold energy to the room air.

A new vacuum pump which can exhaust a large amount of water vapor was designed and produced. The ability of the engine vacuum pump was measured. The ultimate pressure of the engine vacuum pump achieved is about 1 kPa at 400 rpm. It seems that the engine vacuum pump can work enough for the air cooling system using water refrigerant.

Fundamental data of the non-CFCs air-cooling system using only water refrigerant were offered. Experimental model showed COP corresponding to roughly one third of the theoretical value. It was suggested that the vacuum pump and the evaporator should be refined for practical use. However, the experimental data verified the basic concept of the vacuum-cooled water refrigerant. A detail analysis is needed in order to improve performance in the next stage of the present study.

Acknowledgements

The authors are grateful to Dr. Katsumi Moroga for many useful discussions and his advices.

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