CHARACTERISTICS OF THERMALLY DRIVEN PUMP IN SUPERCRITICAL CO_2 SOLAR RANKINE CYCLE SYSTEM

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Abstract- In this paper, basic characteristics of the thermally driven pump in supercritical CO_2 Rankine cycle system is studied. The thermally driven pump is a refrigerant (liquid CO_2)-circulations pump composed of two expansion tanks. Because of no mechanical movement and also no electric consumption, thermal pump is designed to be utilized on power sourcing device compared to feed pump. The experimental result of the thermal pump, flow rate at exit point, and also temperature and pressure, are verified and discuss in this study. It can be found that the flow rate of thermal pump is not stable flow. Though, thermal efficiency of system is higher than using feed pump.

Keywords- Solar Energy, Supercritical CO_2, Thermally Driven Pump, Rankine Cycle.

I. INTRODUCTION

Nowadays, more than 80% of energy consumption comes from fossil fuels. Due to the limited of energy source and environment impact, fossil energy is not the answer for sustainable energy. To solve the energy crisis which every countries are facing with, the renewable energy has been promoted for decades. The solar energy is one of the most cost-effectiveness way to deal with this problem. Solar energy is the biggest energy source and accessible to use.

Supercritical CO_2 Rankine cycle system was originally designed and constructed by Yamaguchi et al. in 2004. By combining the solar energy and CO_2 as working fluid, the efficiency becomes higher than ordinary solar cell. Moreover, CO_2 has low ozone potential and global warming potential (0 and 1 respectively), and also non-flammable and non-toxic. From the above reasons, CO_2 is the best candidate to use as working in supercritical Rankine system compared with other working fluids. CO_2 can change their state to be supercritical state easily, due to the low critical point 31.1°C and 7.38MPa of temperature and pressure, respectively. The operation temperature of the system is about 80°C to 200°C, by properties CO2, it has very high potential to operation.

From the ordinary Supercritical CO_2 Rankine cycle system which combine of solar collector, turbine, heat exchanger and feed pump, the mechanically feed pump itself has mechanically loss and also need to use electric energy to operation, that make the overall efficiency of system decrease. To avoid this problem, thermal pump is considered to be used, some studies show the possible of using thermal pump instead of mechanical feed pump. Thermally driving pump in supercritical CO_2 Rankine cycle system was originally invented, by using pressure difference between two points to feed the CO_2. The electric energy is not requiredin thermal pump operation, and no mechanical movement part in this thermal pump is necessary in construction.

Thermally driven pump can give higher pressure and temperature at the outlet of the pump compared with mechanically feed pump. It means that CO_2 in the system can be easier become supercritical state, which can be used to the turbine to generate electric energy. So, the thermally driven pump can improve the system, both on the performance and the ability. However, the time usage in thermally driven pump is longer than in feed pump that cause of non-continually flow at the thermal pump outlet, because of thermal pump has periodic nature and also required hot and cold heat source for using in the process.

In the present study, some fundamental estimation and the working principal are introduced together with experimental data obtained in the newly designed test system. The performance characteristics and effectiveness for the test system are discussed in the present investigation.

1.1 SYSTEM CONFIGURATION

The experimental setup is drawn in Figure 1, CO_2 is used as working fluid in Rankine cycle system which compose of solar collector①, expansion valve②, heat exchanger 1 ③and 2 ④, thermal pump⑩and also some data collector. Test section⑦is used instead of solar collector to heat CO_2 in this experiment to avoid the unstable of weather which has many factors to the supercritical CO_2Rankine cycle system. The mass flow meter ⑥, and also temperature and pressure sensors are installed to

measure in-time data for use in this study. The amount of 8kg of CO_2 is contained in this system and operation pressure is about 12MPa. Thermal driven pump in supercritical CO_2 solar Rankine cycle system consists with two expansion tanks (Figure 2). In each tank, the CO_2 tube is made of stainless steel SUS304 for endure a high working pressure with 23.6m of length. The CO_2 tube is covered by water tube to cooling/heating CO_2 (Figure 3). The diameter of CO_2 and water tube are 12.7mm and 25.4mm, respectively. The maximum value of CO_2 in each tank is 5.8L.

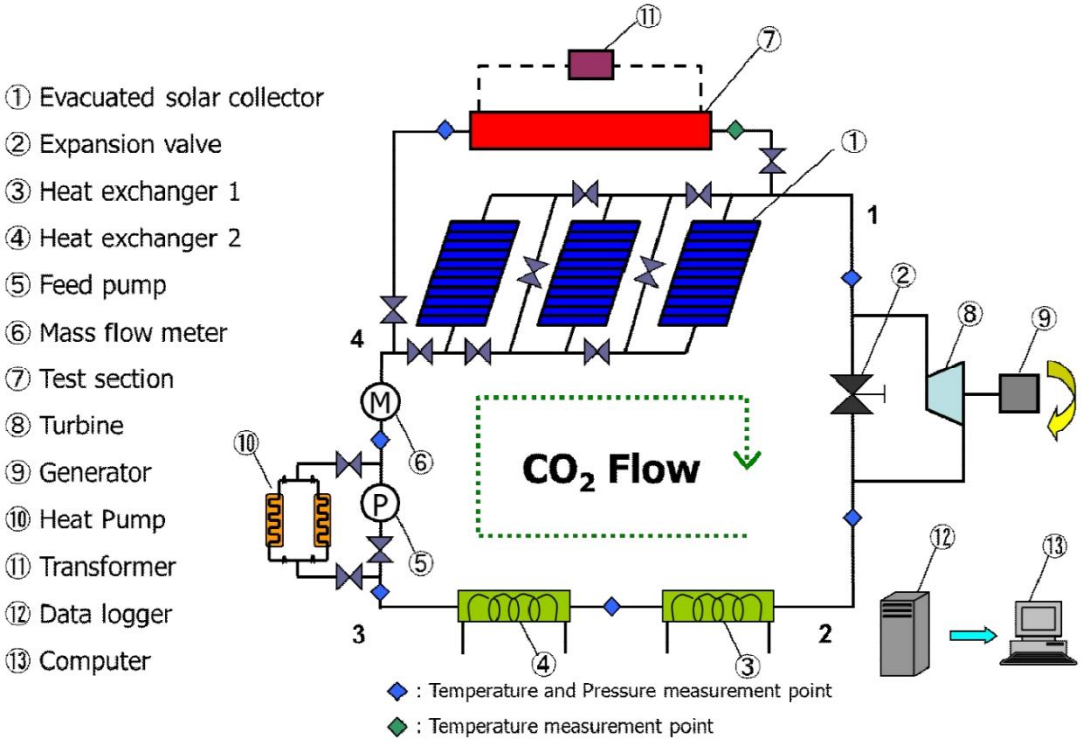

Figure 1 Experimental setup

II. WORKING PRINCIPLE AND PROCESS DESCRIPTION

In the ordinary supercritical CO_2 solar Rankine cycle system, feed pump (5) raise pressure of CO_2 to higher pressure and feed back to solar collector which obtain the heat from solar radiation and its temperature becomes higher. The high pressure and high temperature state CO_2 turn to supercritical phase and expands to push the turbine to generate energy. At the exit of turbine, CO_2 become lower temperature and pressure. Through to the heat exchanger for absorb waste heat from CO_2 to household usage. Then, CO_2 is pumped back again to high pressure state. The P-h diagram and CO_2 state of ordinary supercritical CO_2 Rankine cycle system is drawn in Figure 4(a).

In the new process of system, mechanically feed pump is replaced by thermal pump. The working process of thermal pump is shown in Figure 5. There are upper and lower valves on the each tanks to control the inlet and outlet flow of thermal pump. The lower valves are opened to collect CO_2 from the heat exchanger (Figure 5(a)), when each tank is fulfilled with CO_2, lower valves are closed and hot water supply to each tank for heat CO_2 (Figure 5(b)). CO_2 is heated up to be high pressure and temperature state (around 9MPa in this experiment), the upper valve is opened (Tank A in Figure 5(c)), CO_2 expand to solar collector by pressure different of two point. After CO_2 flow out from the tank, cold water supply and cool down the tank (pressure inside is also decreased) and lower valve is opened again to fulfil tank by CO_2, while another tank achieve the high pressure and temperature state of CO_2 upper valve is opened and follow the same way of first loop (Tank B in Figure 5(d)). Both tanks are continue processing by heating and cooling CO_2 by hot and cold water to archive high temperature and pressure state CO_2, and also decrease pressure in the tank for ready to charging of CO_2 from heat (Figure 5(e) and 5(f)). The P-h diagram of this process is shown in Figure 4(b).

Comparing the ordinary process with mechanically feed pump and new process with thermal pump, there is no mechanical loos in term of thermal pump and also no need outsource electric supply for driving pump comparing with feed pump. To heating and cooling CO_2 in thermal pump, it induce the pressure difference between the point of thermal pump inlet and heat exchanger outlet, thermal pump outlet and solar collector inlet vice versa. Another benefit is higher pressure and temperature at the outlet of thermal pump compared with feed pump, so that make CO_2 become supercritical state since the outlet of thermal pump.

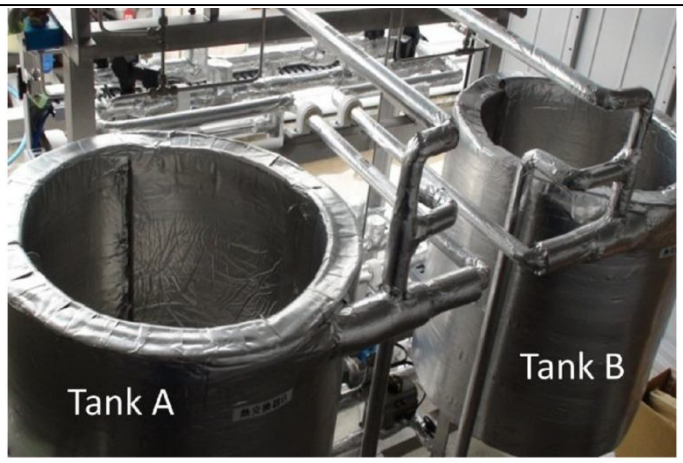

Figure 1 Thermally driven pump.

III. EXPERIMENTAL EVALUATIONS

To prevent other factors which affect with thermally driven pump in supercritical CO_2 solar Rankine cycle system from the weather, the heater test section⑦ is used instead of solar collector① to have the similar heat source for solar radiation, and turbine⑧ is replaced by expansion valve②. The heat source for this experiment is produced by water heater to control the temperature and flow rate of hot water. The pressure of inlet of CO_2 in thermal pump is about 5MPa and be raised up to 9 MPa before valve open through to heater test section. Due to the pressure difference for charging CO_2 in thermal pump, the pressure inside the tank during the cooling stage is reduced to 5MPa by cold water supply. The temperature and flow rate of hot water in heating stage are very important factors of the performance in thermal pump, this is discussed in section 4.

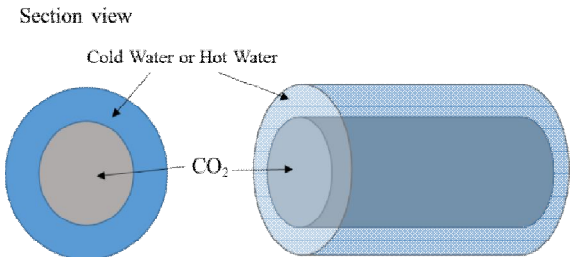

Figure 2 Section view of CO_2 inside thermal pump.

Performances of present Supercritical CO_2 solar Rankine cycle system with using thermally driven pump are evaluated by investigating the variations of the CO_2 flow rate in the system loop, pressures and temperatures at the outlet difference against times, and the system thermal efficiency. The system thermal efficiency can be calculated by two condition, ideal condition and practically condition. By ideal condition, both of feed pump and turbine efficiency are 100% (η_{Pf} and η_{Pt}, respectively). The efficiencies of feed pump η_{Pf} and turbine η_{Pt} are 50% and 70%, respectively in the case of practically condition.

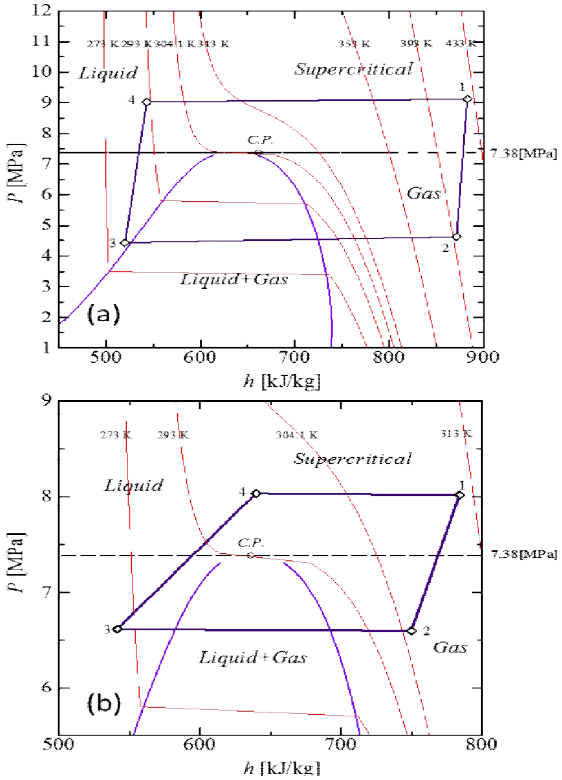

Figure 3 P-h diagram of supercritical CO2 Rankine cycle system with using feed pump (a) and thermal pump (b).

The above thermal efficiency is determined as that of feed pump (η_{thf}) and turbine (η_{tht}) in the system. In case of thermal pump, there is no extra power input. Physical properties of CO2 are calculated using database PROPATH V13.2. The system efficiencies are calculated as

$$\eta_{thf} = \frac{\left(h_{e,1} - h_{e,2}\right) - \left(h_{e,4} - h_{e,3}\right)/\eta_{Pf}}{h_{e,1} - h_{e,4}} \qquad (1)$$

and

$$\eta_{tht} = \frac{\left(h_{e,1} - h_{e,2}\right)\eta_{Pt}}{h_{e,1} - h_{e,3}} \qquad (2)$$

For the system with feed pump and thermal pump, respectively. By h is specific enthalpy (J/kg) on each

position of process in the system (see Figure 1), $h_{e,1}$-$h_{e,2}$, $h_{e,4}$-$h_{e,3}$, $h_{e,1}$-$h_{e,3}$ and $h_{e,1}$-$h_{e,4}$ are the heat drop of turbine, and net heats collected by the system with the thermally driven pump and feed pump, respectively.

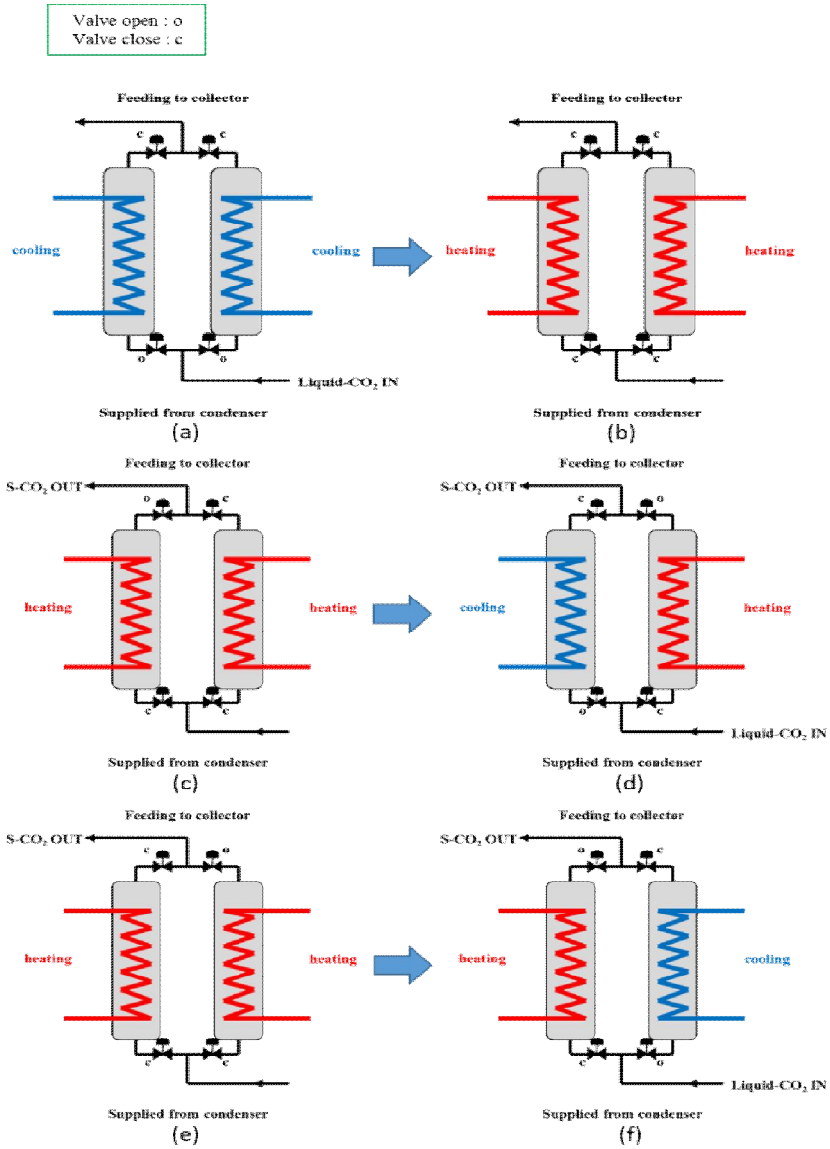

Figure 4 Working process of thermal pump.

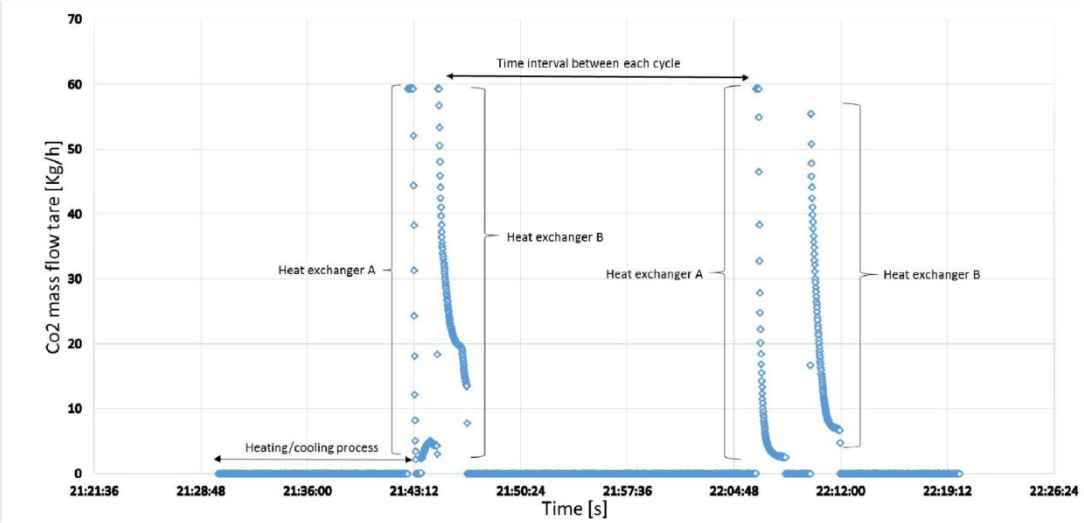

Figure 6 CO_2 mass flow rate in the thermal pump.

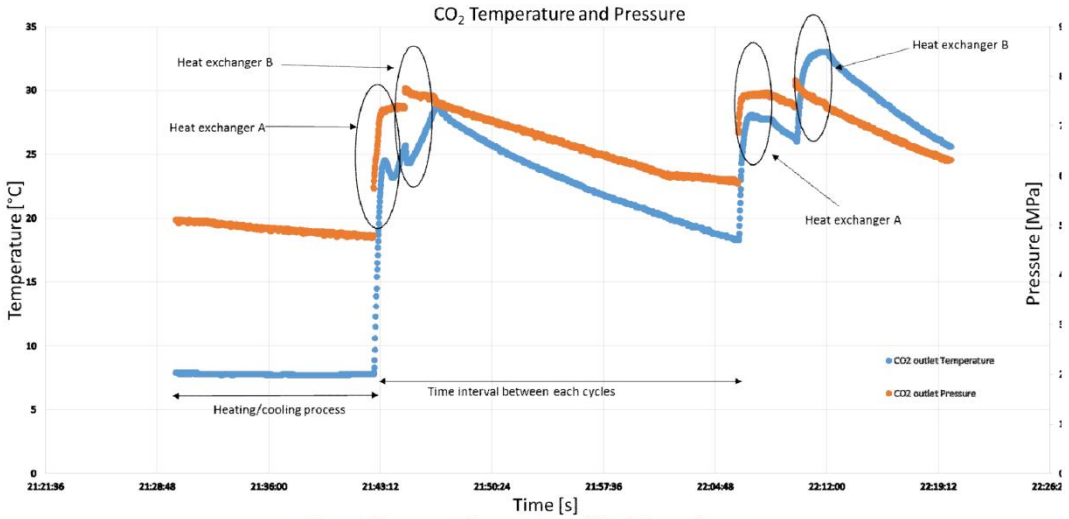

Figure 7 Pressure and temperature of CO_2 in thermal pump.

IV. RESULT AND DISCUSSION

The experimental in this study is operated by using test section heater instead of solar collector to avoid the impact from the weather-season that make system can be operated anytime to do the experimental. Figure 6 and 7 show the experimental result on outlet flow of thermal pump, and pressure and temperature at the exit point of thermal pump, respectively. The system was operated on 4th of December2013 in the night time. The operation condition as follow: 5MPa of inlet $CO_2$from heat exchanger, 50 °C of inlet hot water with 0.42 L/min of flow rate and 15 °C of cold water inlet.

The CO_2 is raised up from 5 MPa to 8 MPa, which valve is set toopen to let high pressure and temperature CO_2 flow to solar corrector by pressure difference created between tanks of thermal pump and the solar collector. In the other hand, the pressure difference is also created between tanks of thermal pump and heat exchangers through the alternative heating and cooling processes of thermal pump using heat and cold sources from the system itself. In Figure 6, the outlet flow of CO_2 can be up to 60 kg/h. Therefore, the peak point of outlet flow is occurred in very short period of time, and also time interval between each loop of thermal pump is quite long. Due to these reasons, the flow rate of outlet flow is not continuous. The temperature and pressure at the outlet point of thermal pump from the same experimental are shown in Figure 7.

At the peak point of outlet flow, CO_2 is above its critical point (31.1 °C of temperature and 7.39 Mpa of pressure), so it becomes supercritical CO_2 before going to solar collector, that makes the system has more efficiency (Figure 4(b)). In the process of thermal pump, it is found that the time for heating CO_2 in thermal pump is reduced due to the small diameter tube in thermal pump. The thermal pump still has no continually of outlet flow. To archive the aim of replacing feed pump with thermal pump, it is expected that more tank units should be installed in order to get more efficiency and reduce the time usage in thermal pump.

The system thermal efficiencies of supercritical CO_2 Rankine cycle system with feed pump and thermal pump in the ideal condition varying with the outlet temperature of solar collector unit at two different pressures P = 8.0 and 10.0Mpa and two temperatures T = 100 and 200°C are estimated with outlet temperature of heat exchanger (condensation temperature), based on the cycle diagram in Figure 4 (a) and (b), assuming the system under the given conditions in equations (1) and (2) as mentioned above.

The results of estimates are shown in Figure 8 for feed pump and Figure 9 for thermal pump. Same as Figure 4(b), the system thermal efficiency of the supercritical CO_2 solar Rankine cycle system increases with pressure.

However, the effect of the outlet temperature of solar collector on the system thermal is small, as observed from Figure 8 and 9. The outlet temperature from heat exchanger has a significant effect on the system thermal efficiency.

With temperature increasing, the system thermal efficiency decreases. Compared the efficiency of feed pump and thermal pump from Figure 8 and 9, supercritical CO_2 Rankine cycle system with thermal pump has higher thermal efficiency than using feed pump in all operate condition, by the highest thermal efficiency is with condition of 10.0MPa and 200°C of pressure and temperature, respectively.

From the result above, it can imply that suitable heat sink with adequately low temperature is an important factor to achieve and improve efficient operation of the present supercritical CO_2 Rankkine cycle system.

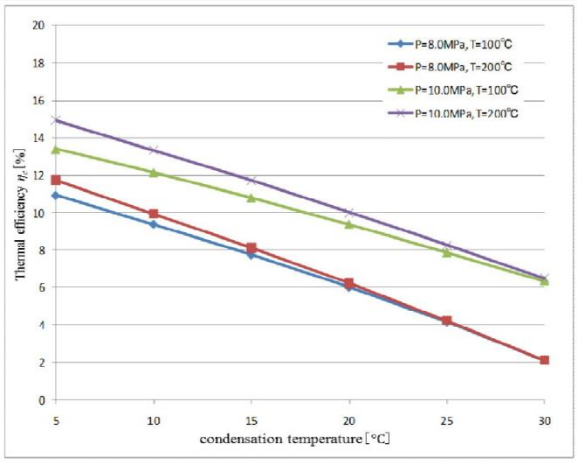

Figure 8 System thermal efficiencies of system with feed pump.

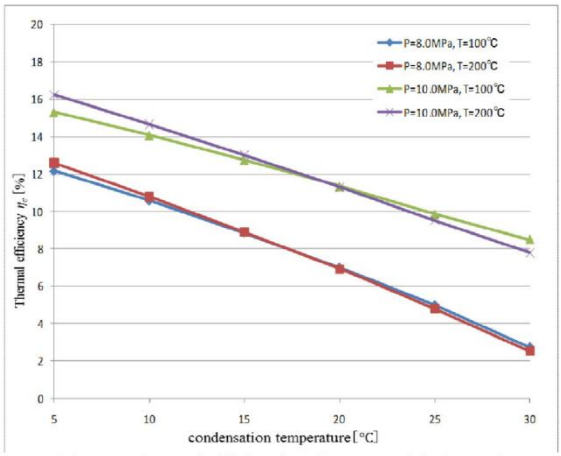

Figure 9 System thermal efficiencies of system with thermal pump.

CONCLUSIONS

In this present study, mechanically feed pump is replaced by thermally driven pump, in order to implement the electric power usage and efficiency loss of feed pump in the supercritical CO_2 Rankine cycle system. Thermally driven pump works well in supercritical CO_2-based cycle, and itis speculated that thermal efficiency of the system can be also improved compared with using feed pump. However, the flow rate of CO_2 when using thermal pump is not stable. In addition, the efficiency of the system with thermal pump strongly depend on CO_2 inlet temperature itself and also little depend on the solar collector outlet temperature.

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