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A Feasibility Study of CO_2-Based Rankine Cycle Powered by Solar Energy

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Research Article

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The viability of a CO2-based Rankine cycle driven by solar energy was investigated via an experiment study. The suggested cycle, which comprises of evacuated solar tube collectors, a power producing turbine, a heat recovery system, and a feed pump, aims to accomplish cogeneration of heat and electricity. The system's Rankine cycle uses solar collectors to transform CO2 into a high-temperature supercritical state, which powers a turbine and generates electricity. Additionally, the cycle recovers thermal energy that may be used for a building's hot water supply, air conditioning system, refrigerator, and other applications. To examine the performance of the CO2-based Rankine cycle, a series of experimental setups was built. The findings demonstrate that the cycle has a high potential for using the CO2-based Rankine cycle driven by solar energy and can produce heat and electricity with reasonable thermodynamic efficiency. Additionally, this article will cover some research topics linked to the current work.

***Key Words*:** Rankine Cycle, Solar Energy, Supercritical Carbon Dioxide, Heat Recovery, Power Generation

Introduction

Nowadays, fossil fuel-powered electric power producing facilities provide most of the world's energy. These facilities generate electric energy using internal combustion or a traditional turbine steam process using fossil fuels like coal, oil, or gas. However, there are significant issues with the production of electricity from fossil fuels. When fossil fuels are used to produce electricity, several pollutants are produced as byproducts. Pollutants include NOx, carbon monoxide (CO), particulate matter (PM), SO2, organic hydrocarbons, and trace metals are released into the atmosphere during the combustion process. These pollutants cause major environmental problems such acid rain, ozone layer depletion, global warming, and more. Fossil fuels are simultaneously extracted and either transformed into usable industrial products or utilized to provide heat. Our impending major energy problem is caused by the depletion of fossil fuels due to resource constraints. As a result, several academics and industrial sectors are pursuing more environmentally friendly and renewable energy sources in place of fossil fuels. Renewable energy sources, including solar and wind power, are readily accessible, enormous sources of energy that are almost limitless and do not experience energy depletion.

The Kyoto Protocol is a legally binding agreement that calls for a 5.2% decrease in total greenhouse gas emissions during the five-year period of 2008–12 in comparison to 1990. By recycling or collecting these released gases, it is an effective method of lowering emissions of greenhouse gases like carbon dioxide, methane, nitrous oxide, HFCs, and so on. Therefore, since the 1990s, there has been a significant growth in interest in CO2 as a working fluid, and both industry and research have started a number of development and cooperation projects (1), (2). Carbon dioxide is a non-flammable, non-toxic working fluid that has less of an impact on the environment and individual safety than other working fluids (3). CO2 has a critical temperature of 31.1°C and a critical pressure of 7.38 MPa. Among these fluids, CO2 is more likely to reach the supercritical state since this critical temperature is much lower than that of other working fluids. Additionally, CO2 may be more suitable than other working fluids for use in thermodynamic cycles with mild temperatures between about 30

and 200 degrees Celsius due to its low critical temperature. Furthermore, there is no need to establish manufacturing capacity or distribution logistics since CO2 is readily available anywhere in the globe. In order to create a cogeneration system of heat and power with environmental preservation, a feasibility study of a Rankine cycle proposed by Yamaguchi et al. (4)—CO2-based Rankine cycle powered by solar energy—was conducted in this paper. This cycle uses both renewable energy (solar energy) and environmentally safe fluid (carbon dioxide). The paper will also highlight various research areas that resulted from this investigation.

Feasibility Study

CO_2-based Rankine cycle powered by solar en- ergy

Figure 1 shows a schematic diagram of the CO_2- based Rankine cycle. Evacuated solar collector is used to heat CO_2 contained in heating channels. The heating in the solar collector makes supercritical CO_2 high tem- perature state (Fig. 1, state 1). The high temperature su- percritical CO_2 drives the engine of the Rankine system, and power output can be available from the turbine gener- ator. The lower pressure carbon dioxide, which is expelled from turbine, is cooled in the heat recovery system. At the outlet of turbine, supercritical CO_2 still has a higher tem- perature (Fig. 1, state 2), which can be utilized to provide heat source for absorption refrigerating machine, boiling water or other uses, which can be achieved in the heat re- covery system. Or several heat recovery systems are set up to achieve heat collection at different temperatures si- multaneously. The heat recovery system is actually a heat exchanger. After leaving the heat recovery system (Fig. 1, state 3), CO_2 is pumped by the feed pump, back into the higher pressure condition (Fig. 1, state 4), and then the cy- cle recommences.

The solar collector is the heart of the CO_2-based

Rankine cycle system. Its characteristics play an impor- tant role in the successful operation of such systems. For example, the CO_2 temperature at the outlet of the solar collector is an important performance parameter in achiev- ing a good heat collection and power generation from the Rankine cycle. A higher temperature of CO_2 in the cy- cle will make it easy to collect heat from the cycle, and a

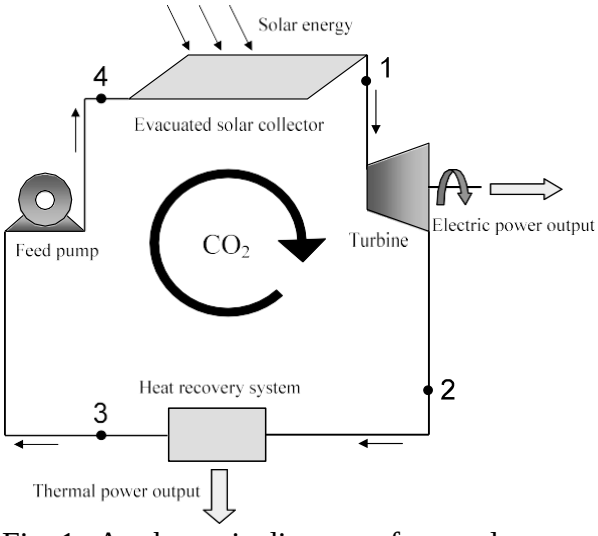


Fig. 1 A schematic diagram of a novel concept—CO_2-based Rankine cycle powered by solar energy

the cycle temperatures and pressures etc. to study the fea- sibility of the solar energy powered Rankine cycle using carbon dioxide.

Experimental facility and procedure

A schematic design of the built experimental facility is shown in Figure 2. Evacuated solar collector arrays, a pressure relief valve, heat exchangers, a liquid CO2 feed pump, and a cooling tower make

up the majority of the experimental facility. A mechanism for measuring and gathering data is also included. The physical characteristics of supercritical CO2 are really halfway between those of a liquid and a gas. Therefore, it is challenging to determine whether a gas or liquid turbine should be employed for such a Rankine cycle employing supercritical CO2. To put it another way, there isn't yet a turbine for supercritical CO2. In order to examine the cycle performance, a pressure relief valve was used in the experiment rather of a turbine. In order to simulate the pressure drop that would occur in a real turbine, the pressure relief valve may open the cycle loop to different degrees. This allows for the achievement of a thermodynamic cycle. Although we are aware that the outlet temperature and thermo-physical characteristics differ between the actual turbine condition and the current condition, basic cycle performance for the power/heat production can be known based on thermodynamic estimations even though no electricity power is output during the test. The CO2-based Rank-ine cycle in the current research was assumed to employ a gas microturbine in order to estimate cycle performances. The power production from the turbine is calculated using the thermodynamic equation (5) that follows:

Increased CO2 pressure helps power turbines that generate electricity. In order to comprehend the operation of the CO2-based Rankine cycle, this study

$$W_{power} = m_c \eta_{is} \eta_{gen} \frac{k}{k-1} RT_2 \left[1 - \left(\frac{P_1}{P_1}\right)^{\frac{k-1}{k}}\right] \quad (1)$$

powered by solar energy, efforts were made to measure where m_c is the mass flow rate of CO_2, R is the gas con-

Fig. 2 A schematic diagram of the experimental set-up

Pump

stant, k is the ratio of the specific heat at constant pressure

$$\eta = W_{power} \quad (3)$$

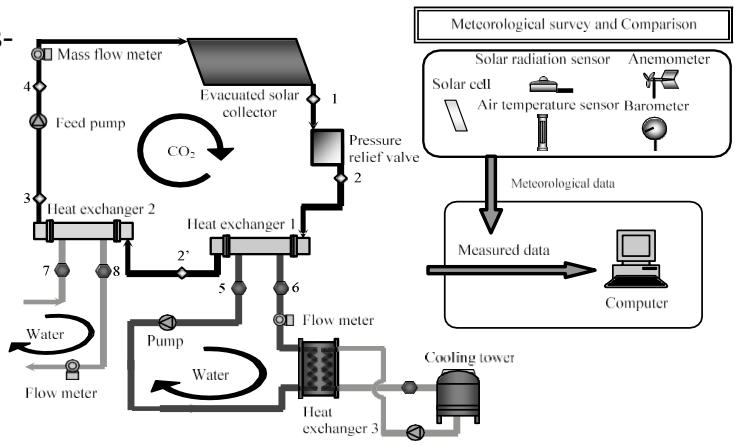
and constant volume, T, P

are the temperature and pres-

Power

$\overline{Qin}$

1 1



sure at the turbine inlet, P_2 is the pressure at the turbine outlet, η_{gen} is generator efficiency, a value of 0.95 is used

$\eta heat = \frac{Qout}{Qin}$ (4)

in the paper, and η_{is} is isentropic efficiency, defined as the ratio of the enthalpy change at isentropic conditions and the actual enthalpy change:

where Q_{in} is the heat quantity absorbed into CO_2 in the so- lar collector, and Q_{out} is the heat quantity recovered from the cycle. The performance parameters related to the cycle

ηis

$\frac{h_1 - h_2}{= h_1 - h_2 is}$ (2)

can be calculated,

$Q_{in} = m_c(h_1 - h_4)$ (5)

the value of the isentropic efficiency can determined through experiments, where the temperatures and pres- sures are measured. Note that k varies with temperature, and in the present study, the value of k is taken as the av- erage of the inlet and the outlet of the turbine. It should be mentioned here that although Eq. (1) is suitable to perfect gas, it is used in the present study to approximately model the work performed during the expansion process, because CO_2 working temperature is very high. In addition, the work estimated represents a minimum value, which just represents the loss throughout the valve, because there is no turbine in the experiment. And using the pressure relief valve instead of turbine artificially reduces the CO_2 flow rate in the loop, and the CO_2 flow rate under the turbine condition should be larger than that of the present condi- tion. Therefore, the work in the true turbine condition may be larger than the values estimated in the present analysis.

In addition, the following efficiencies are defined to

describe the performance of the Rankine cycle, power generation efficiency η_{power} and heat recovery efficiency $\eta heat$:

$Q_{out} = m_c(h_2 - h_3)$ (6)

$W_{pump} = m_c(h_4 - h_3)$ (7)

where W_{pump} is the power consumption of the CO_2 feed pump.

All-glass evacuated solar collectors with a U-tube heat removal system are used in the present experiment facility, which is a commercial product developed and pro- vided by Showa Denko. K.K. A sketch of the solar collec- tors is shown in Fig. 3. These collectors consist of a glass envelope over a glass tube coated with a selective solar ab- sorber coating. This coating with a high solar absorbance 0.927 and a low emissivity 0.193, is applied on the vac- uum side of the inner glass tube. The absorbed heat is conducted through the inner glass tube wall and then re- moved by heat removal fluid in a metal U-tube inserted in the inner tube with a fin (thichness is 0.2 mm) connecting the outlet arm of the U-tube to the inner glass tube. The every U-shaped heat removal fluid tube used is 3.6 m long and 0.005 m internal diameter, shown in Fig. 3. Efficient

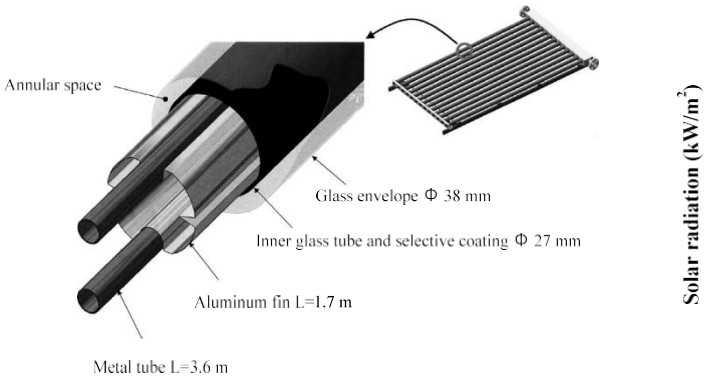


Fig. 3 A sketch of the evacuated solar collector used in CO_2-based Rankine cycle

area of the solar collectors used in the Rankine cycle is about 9.6 m^2.

The two shell and tube heat exchangers are used for achieving simultaneous heat recovery of both higher- temperature and lower-temperature, with tube side of CO_2 and shell side of water. As shown in Fig. 2, the higher- temperature water and lower-temperature water are re- spectively provided to the heat exchanger 1 and 2 to simu- late the heat recovery processes. The total heat exchanger area utilized is about 0.76 m^2. In higher-temperature heat recovery system, a mechanical-draft water cooling tower with a cooling capacity of 22 kW is used as a heat sink, dissipating heat recovered from the Rankine cycle section into the ambient.

A high-accuracy measurement and data acquisition system is used to achieve real-time data measurement, data acquisition, and processing. Meteorological data, such as solar radiation, atmospheric temperature values, can be acquired through the meteorological instruments installed in the experiment system, as shown in Fig. 2. Ac-
curacies of sun radiation sensor and air temperature gauge are ±0.3% and ±0.15 + 0.002|t|°C, respectively. In addi- tion, 5 thermal couples and 5 pressure transmitters are
mounted in the CO_2 loop to measure CO_2 temperatures and pressures, respectively, with accuracy of ±0.1°C for temperature measurement and ±0.2% for pressure mea- surement. There are 5 platinum resistor temperature sen-
sors mounted to measure water temperatures at the in- lets and outlets of the heat exchangers with accuracy of
±0.15 + 0.000 2|t|°C. CO_2 mass flow meter is mounted at the downstream of pump exit with accuracy of ±0.1% and two water flow meter mounted in the heat recovery sys-

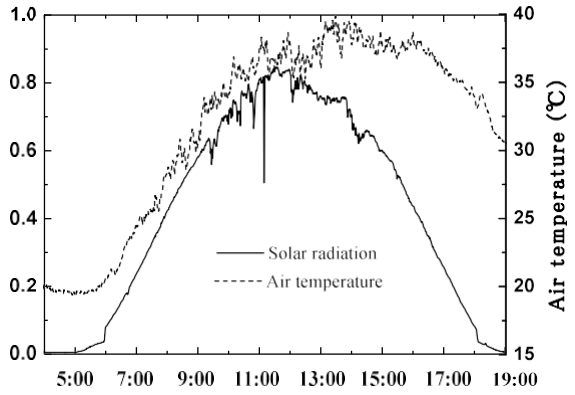


Fig. 4 Variations of solar radiation and air temperature measured with time

tems with accuracy of ±0.5%. Therefore, accuracies of the cycle parameters defined in the equations above are calculated to be less than ±1.0%. The measuring points of all the sensors are shown in the Fig. 2.

During a typical experiment, water pumps are first turned on and the rates of incoming water flows in the heat recovery systems are adjusted. Then the CO_2 feed pump is switched on and the opening of pressure relief valve is adjusted to the expected extent. When finishing test, the CO_2 pump is turned off only after the pressure relief valve is adjusted to a state of full open. At last the water pumps are turned off. During the test, temperatures, pressures etc. attached to the Rankine cycle are measured and transported through the computerized data acquisition equipment to record data as function of time. Thermal in- sulation coating is installed for all the carbon dioxide and water loops to reduce heat losses from the piping.

Experimental results and discussion

The CO_2-based Rankine cycle performance was tested in August, 2004, in Kyoto of Japan. The experi- ment was conducted from about 10:00 in the morning to 5:00 in the afternoon, through the whole daylight for a to- tal of almost 7 hours. The total amount of CO_2 of about 6.0 kg was charged into the CO_2 loop of the experimental facility.

Figure 4 shows solar radiation and air temperature measured with a function of time. The solar radiation in- creases with time from 5:00 until it reaches a maximum value of around 0.83 kW/m^2 at 12:30. Then, the solar ra- diation begins to decrease with time. The time-averaged solar radiation and air temperature measured are about 0.50 kW/m^2 and about 32.5˚C, respectively. The mea- sured water temperatures and flow rates in the heat recov- ery systems are shown in Fig. 5. It can be seen that during the most time of the test, the inlet water temperature and flow rate for the heat exchanger 1 are respectively con- trolled at 30.2˚C and 835.0 L/h and for the heat exchanger 2 at 9.0˚C and 200.0 L/h. The time-averaged outlet water temperatures of the heat exchanger 1 and 2 are respec- tively about 33.1˚C and 19.3˚C, respectively.

Figure 6 shows the measured CO_2 temperatures at the monitoring points of the Rankine cycle loop, as shown in Fig. 2, in which the CO_2 flow rate measured is also in- cluded. During the test hours, the pressure relief valve was adjusted to a state of one-third open. It can be seen

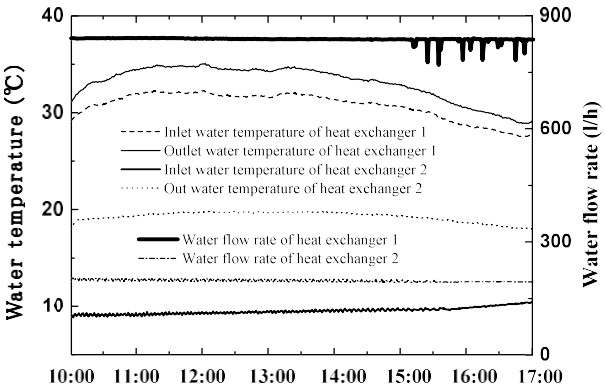


Fig. 5 Variations of inlet and outlet water temperatures and flow rates measured in the heat exchanger 1 and 2

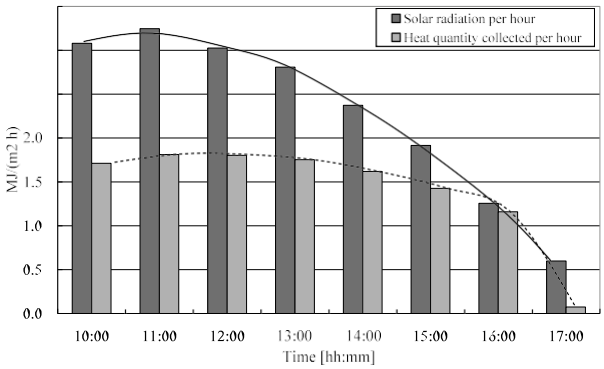


Fig. 7 The amount of solar radiation and heat quantity collected in the solar collector per area and per hour

machine and air conditioning etc. It should be mentioned here that in the real turbine condition, the temperature at the turbine outlet may be lower than the present value of 160.0℃.

Furthermore, the solar collector efficiency is defined to describe the performance of collecting heat using super- critical CO_2 in the collector,

$$\eta collector = \frac{\int_0^{t} m_c(h_1 - h_4)dt}{\int_0^{t} IAdt} \quad (8)$$

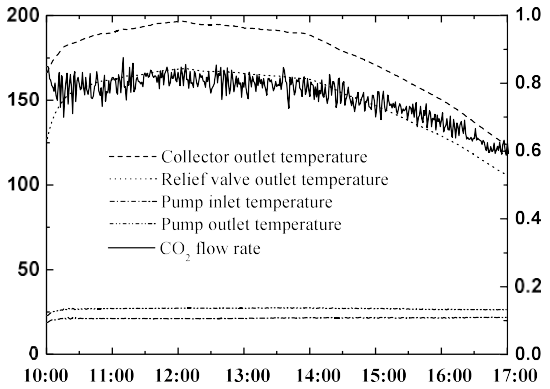


Fig. 6 The measured CO_2 temperatures and flow rate in the CO_2-based Rankine cycle loop

where h_1, h_4 are enthalpy values of CO_2 respectively in the outlet and inlet of the turbine, which can be obtained based on the measured temperatures and pressures, I is the solar radiation striking the collector surface, A is the efficient area of the solar collector, $\int_0^{t} m_c(h_1 - h_4)dt$ represents the heat quantity absorbed into carbon dioxide in the collector from Fig. 6 that the CO_2 flow rate achieved in the cycle

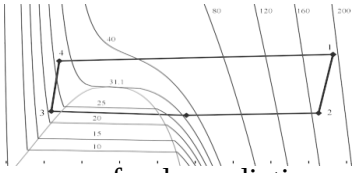
, *t*

loop is about 0.8 kg/min, which is kept throughout most of the daylight time. It can also be seen that the CO_2 tem- perature at the outlet of the solar collector increases with

during a time period of *t*, $\int_0^{,t} IAdt$ is the total amount of the solar radiation striking the collector surface.

elapsed time, and at 12:00, the CO_2 temperature reaches up to about 194.0°C. After that, the temperature tend to

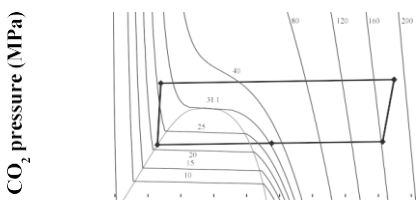
Figure 7 shows the calculated $\int_0^{,t} IAdt$ and



drop gradually with time, which may be due to the nat- ural decreases of solar radiation and air temperature, as shown in Fig. 4. The averaged temperature at the outlet of solar collector from 10:00 to 17:00 is about 185.0°C, which is encouraging, since such a high average temperature of 185.0°C achieved make it easy to collect thermal energy from the cycle and achieve power generation in the turbine.

It can also be seen that there is a temperature differ- ence of about 35.0°C between the inlet and outlet of the pressure relief valve during the test hours which is contributed to the pressure drop throughout the pressure relief valve. As shown in the figure, the CO_2 temperature at the outlet of the valve is about 160.0°C, still a relatively high temperature, and such a heat source can be possible to be utilized for boiling water, absorption refrigerating

$\int_0^{,t} m_c(h_1 - h_4)dt$ per collector area and per hour from 10:00 to 17:00 based on the measured data. It can be seen that the variation of the heat quantity absorbed into CO_2 in the collector with time is similar to the variation of the amount of solar radiation, as shown in solid and dash lines, repectively in Fig. 7. During the time period, the averaged amount of solar radiation is about 2.29 MJ/($m^2 \cdot h$) and the averaged heat quantity collected in the collector is about 1.42 MJ/($m^2 \cdot h$). An average collector efficiency is calculated at 62.0%. The efficiency of 62.0% shows that the collector used is effective in collecting heat using supercritical CO_2, which may explain to a certain extent why a relatively high temperature of 185.0°C is achieved at the collector outlet. Furthermore, the collector efficiency becomes more and more higher with time. We think the reason given to this phenomenon may be that the



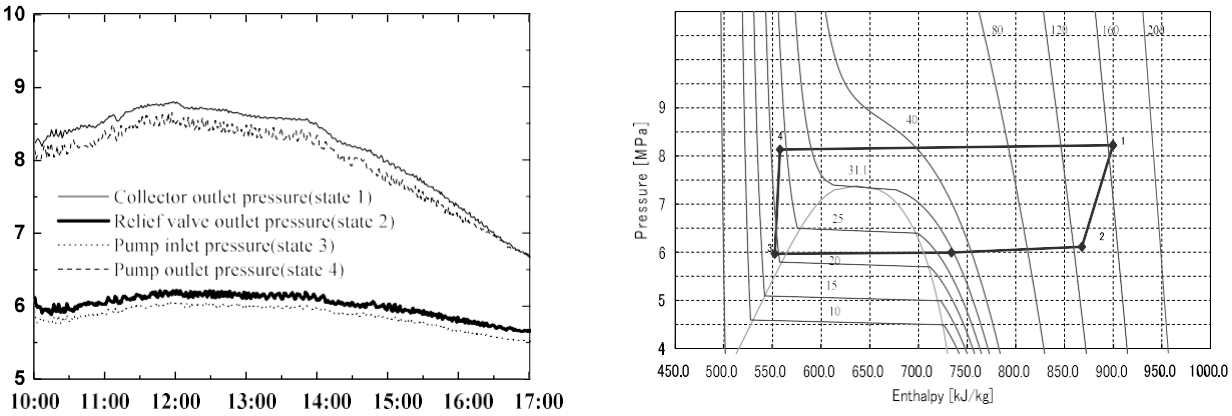


Fig. 8 Variations of CO_2 pressures measured with time in the cycle loop

CO_2 flow becomes more and more turbulent with solar heating in the collector tube in the present stage. But another analysis is necessary to confirm this phenomenon precisely. Based on the present results, supercritical CO_2 seems good fluid to absorb heat in the solar collector. Solar energy may be utilized effectively using the present method. But the future detailed study has to be done to investigate how the CO_2-based solar collector works.

Figure 8 shows the CO_2 pressures measured during the test hours in the cycle loop. It can be seen that there appears a big pressure difference (about 2.2 MPa) between state 1, 4 and state 2, 3. The supercritical high-pressure side and subcritical low-pressure side of the CO_2-based Rankine cycle can be obviously observed in this figure. The high pressures reach up to 8.2 MPa and low pressures are about 6.0 MPa. The results show that during the most time of the test, the CO_2-based prototype works in a tran- scritical Rankine cycle.

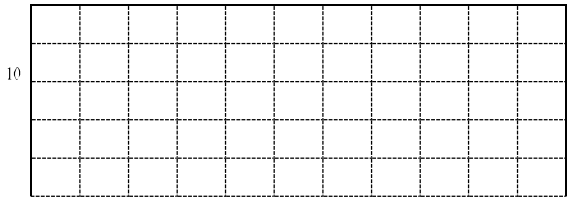
Furthermore, the CO_2-based cycles at 10:00, 12:00 and 14:00 are respectively shown in the *p–h* diagram in Fig. 9 (a), (b) and (c), in which thermodynamic and trans- port properties of CO_2 were calculated based on the mea- sured temperatures and pressures using a Program Pack- age for Thermophysical Properties of Fluids database ver- sion 12.1 (PROPATH 12.1). From the figures, it can be clearly seen that these working cycles are used for simul- taneous heating and heat recovery in the temperature from

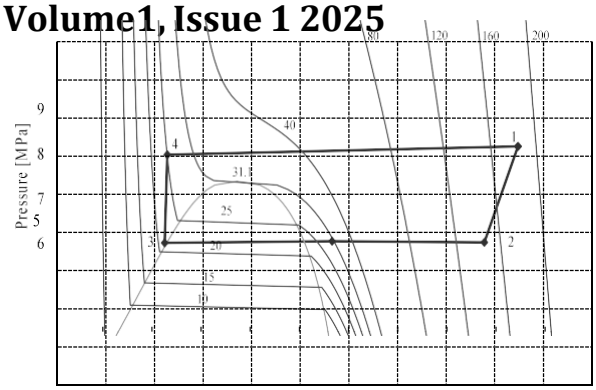
about 25.0˚C to 185.0˚C for the heating process in the so- lar collector and about 145.2˚C to 22.0˚C for heat recov- ery. Most time of the heating processes in these Rankine

cycles are in the supercritical region for CO_2. In other words, under the supercritical state, CO_2 is heated by the absorber surface in the solar collector. It is also seen from Fig. 9 that the CO_2-based Rankine cycle can work stably through the daytime in the transcritical regions.

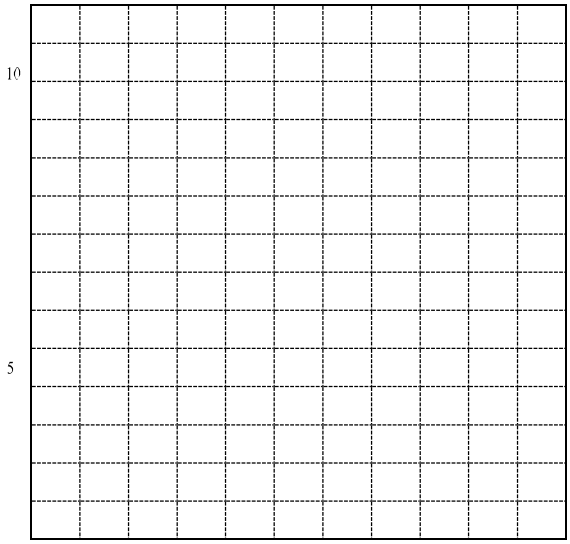
The CO_2-based thermodynamic cycles are important in understanding of the cycle performance. Following is a

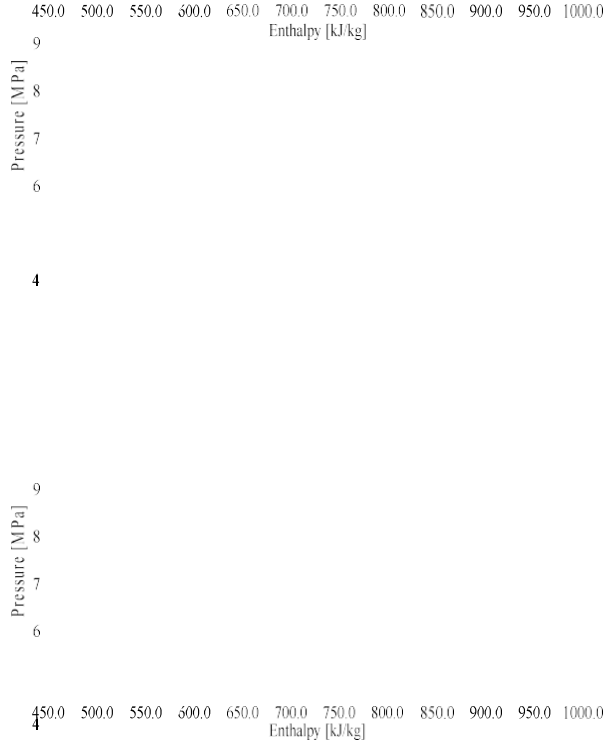
(a)





(b)

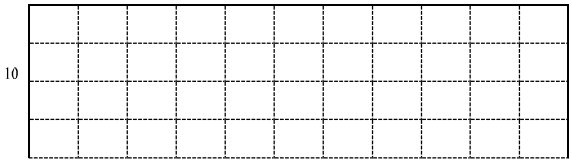




(c)

Fig. 9 The CO_2-based Rankine cycle achieved in the test,
(a) 10:00; (b) 12:00; (c) 14:00

further thermodynamic analysis made, in which the time- averaged CO_2 temperatures and pressures during the test are calculated and the Rankine cycle based on the aver- age levels of temperatures and pressures is analyzed. The averaged Rankine cycle is shown in Fig. 10 in the *p–h* diagram. The thermodynamic estimation shows that the power output is about 0.82 kW, which is obtained based on Eq.(1) using the time-averaged parameters. In addi- tion, the pump work (power input of the cycle) was esti- mated to be about 0.15 kW and the heat recovery achieved is about 4.20 kW. The power generation efficiency η_{power}



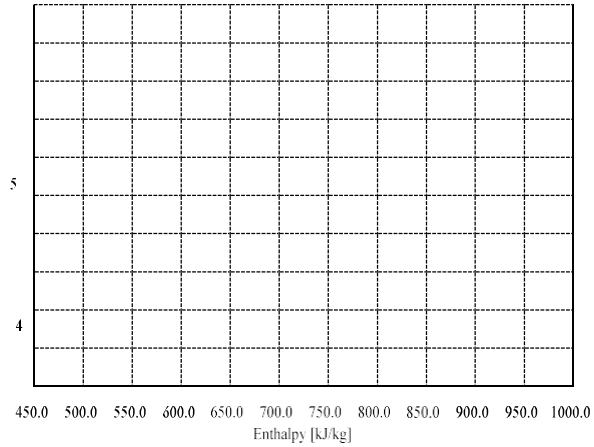


Fig. 10 The CO_2-based Rankine cycle based on the time- averaged temperatures and pressures measured in the cycle loop during the test

is estimated at 0.16 and the heat recovery efficiency η_{heat} is 0.82, which is comparable with the total efficiency of cogeneration by natural gas generator. It is noted that the pump work was high in the test, and maybe in the future a higher efficient pump is considered in the cycle, because the feed pump used in the test is originally designed for water. Or a solar energy powered pump can also be considered in the future design. It is also noted that the power generation estimated almost equals to throttling loss pass- ing the valve, which does not represent the power output, because no turbine was used in the test. If a turbine is used, the actual power output should be much larger than this value of the loss (0.80 kW). In addition to power genera- tion, the advantage of the CO_2-based Rankine cycle more stems from the thermal energy collected from the cycle, which is much higher than electrical power obtained.

Another attractiveness of the solar energy powered Rankine cycle using CO_2 is in the environment aspect. An analysis of energy conversion was conducted based on the

U.S Electric Power Annual[6]. It is assumed that 10,000 set of the CO_2-based Rankine machines are produced and equipped for buildings in Japan per year. The petroleum of 30,000 kL was saved per year if the Rankine machine is used instead of a petroleum-fired power plant. Further- more, CO_2 emission of about 85,000 ton can be reduced per year not only due to the usage of renewable energy, but also consuming CO_2 by the system itself.

In this paper, an economic analysis is not intended to be presented, mainly because the experimental facilities are much higher than that in large production, at the same time, it is also difficult to consider environmental profits into the cost, which may reduce the cost greatly. Com- pared to other fluids, carbon dioxide is inexpensive and its price on a mass basis is two orders of magnitude lower than that of HFC-134a. Due to the lower liquid density and smaller system volume, the charged amount would be lower with CO_2, further reducing the cost. And recycling or recovery of CO_2 would not be necessary, either for environmental or for economic reasons. CO_2 is also thermally stable and behaves inertly, thus eliminating material prob- lems or chemical reactions in the system. A high pressure used for the operation of the CO_2-based Rankine cycle may increase its cost to a certain extent. But all advan- tages of these above may reduce system costs to the point where mass production becomes feasible. In the future, an exactly economic analysis needs to be made to further es- timate its market feasibility. In general, the proposed solar Rankine cycle using CO_2 has a great potential of achiev- ing a cogeneration of heat and electricity with reasonable thermodynamic cycle efficiencies, effectively reduce the CO_2 emission and avoid the toxicity or flammability risks of ammonia and hydrocarbons. Its market may be for the energy loads of commercial facilities, hotels, schools, hos- pitals, office buildings, multifamily dwellings, and other facilities that can benefit from an independent source of power and heat.

Some Research Interests

Additionally, the idea of creating a Rankine cycle utilizing both solar energy and carbon dioxide may be relevant to a number of academic areas. To further improve the Rankine cycle efficiency, it is crucial to comprehend the flow and heat transfer of supercritical CO2 (occurring in the solar collector tubes). Many researchers have studied flow and heat transmission characteristics at sub-critical flow regimes in great detail. However, supercritical flow and heat transmission have not been studied to the same extent. Refs. (7) through (10) provide thorough reviews of earlier research on variable-property heat transfer and supercritical heat transfer. It is widely acknowledged that, outside from very specific circumstances, the correlations do not demonstrate enough agreement with experiments to support their usage. Additionally, the development of an evacuated solar collector specifically designed for supercritical CO2 is required. Even if the collector efficiency was achieved, as Fig. 7 illustrates, the whole nature of the flow and heat removal by supercritical CO2 that takes place in the collector is still unknown based on the references that are now available. In the future, the evacuated solar collectors employing supercritical CO2 as the working fluid will need engineering design and optimization effort. A novel turbine that is appropriately powered by supercritical CO2 would be of further interest. Because the physical characteristics of supercritical CO2 at its critical point display extraordinarily fast variation with changes in temperature and pressure, the novel turbine should vary from conventional liquid and gas turbines. Supercritical CO2 should be able to power the new turbine efficiently.

Concluding Remarks

Supercritical carbon dioxide was used in a feasibility study for a Rankine cycle fueled by solar energy. The cycle combines the use of pure natural working fluid (carbon dioxide) with sustainable energy (solar energy). In addition to producing electricity, the CO2-based Rankine cycle may generate heat collections at various temperatures. The obtained findings demonstrate that supercritical CO2 can efficiently collect heat in the evacuated solar collector and that the CO2 temperature in the solar collector may reach around 185.0◦C, which aids in power production and heat recovery. Additionally, during the majority of the test hours, the CO2-based Rankine cycle operates in the trans-critical area. The CO2-based Rankine cycle may generate electricity and collect heat with an acceptable thermodynamic efficiency of 0.16 for power production and 0.82 for heat recovery, according to thermodynamic studies based on collected data. The research demonstrates the possibilities of using a solar-powered CO2-based Rankine cycle. Future research on the CO2-based Rankine cycle will need a turbine condition. Furthermore, the paper's goal is just to provide a feasibility analysis; further experimental data is required to fully understand the Rankine cycle.

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