A Feasibility Study of CO₂-Based Rankine Cycle Powered by Solar Energy

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An experiment study was carried out in order to investigate feasibility of CO₂-based Rankine cycle powered by solar energy. The proposed cycle is to achieve a cogeneration of heat and power, which consists of evacuated solar tube collectors, power generating turbine, heat recovery system, and feed pump. The Rankine cycle of the system utilizes solar collectors to convert CO₂ into high-temperature supercritical state, used to drive a turbine and produce electrical power. The cycle also recovers thermal energy, which can be used for absorption refrigerator, air conditioning, hot water supply so on for a building. A set of experimental set-up was constructed to investigate the performance of the CO₂-based Rankine cycle. The results show the cycle can achieve production of heat and power with reasonable thermodynamics efficiency and has a great potential of the application of the CO₂-based Rankine cycle powered by solar energy. In addition, some research interests related to the present study will also be discussed in this paper.

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

1. Introduction

In the modern age, the majority of electricity used in the world is provided by fossil fuel powered electric power generation facilities. These facilities use fossil fuels, such as coal, oil, or gas, in internal combustion or conventional turbine steam process to produce electric energy. However, fossil fuel powered electric power generation has serious problems. Many pollutants are generated as by products from the burning of fossil fuel to generate electricity. The combustion process releases pollutants, such as NOₓ, carbon monoxide (CO), particulate matter (PM), SO₂, organic hydrocarbons, and trace metals into the air, which leads to serious environmental pollution, such as acid rain, ozone layer depletion, and global warming and so on. At the same time, fossil fuels are excavated and used to generate heat or converted into useful industrial materials. Because of limitation of resources, exhausting fossil fuels leads to serious energy crisis we are about to face. Therefore, some forms of energy, instead of fossil fuels, which are renewable and more environmentally friendly, are being pursued by many researchers and industrial sections. Renewable energy, such as solar energy and wind energy, is easily available and very huge source of energy, which is a kind of inexhaustible supply and is not subject to energy depletion.

The Kyoto protocol is a binding agreement under which collective emissions of greenhouse gases (an average over the five-year period of 2008~12) will be reduced by 5.2% compared to the year 1990. It is a good way of reducing the emissions of greenhouse gases, such as carbon dioxide, methane, nitrous oxide, HFCs and so on by recycling or recovering these discharged gases. So the interests in CO₂ as a working fluid increased considerably from 1990s, and a number of development and co-operation projects were initiated by the industry and the research sector(1),(2). Among various working fluids, carbon dioxide is the non-flammable and non-toxic fluid and is little influence which it has on environment and personal safety than other working fluids(3). Its critical pressure and tem-
perature of CO₂ are 7.38 MPa and 31.1°C, respectively. Because this critical temperature is much lower than other working fluids, CO₂ is easier to become supercritical state among these fluids. And owing to the low critical temperature of CO₂, it is maybe better than other working fluids to be used in thermodynamic cycles of moderate temperature from about 30°C to 200°C. In addition, CO₂ is available in abundant quantities in all parts of the world, and production capacity or distribution logistics need not be developed.

Therefore, in this paper, a feasibility study was given to a Rankine cycle proposed by Yamaguchi et al.⁴—the CO₂-based Rankine cycle powered by solar energy, in which both renewable energy (solar energy) and ecologically safe fluid (carbon dioxide) are used in order to form a cogeneration system of heat and power with environmental preservation. In addition, some research fields stemming from this study will be discussed in the paper.

2. Feasibility Study

2.1 CO₂-based Rankine cycle powered by solar energy

Figure 1 shows a schematic diagram of the CO₂-based Rankine cycle. Evacuated solar collector is used to heat CO₂ contained in heating channels. The heating in the solar collector makes supercritical CO₂ high temperature state (Fig. 1, state 1). The high temperature supercritical CO₂ drives the engine of the Rankine system, and power output can be available from the turbine generator. The lower pressure carbon dioxide, which is expelled from turbine, is cooled in the heat recovery system. At the outlet of turbine, supercritical CO₂ still has a higher temperature (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 recovery system. Or several heat recovery systems are set up to achieve heat collection at different temperatures simultaneously. The heat recovery system is actually a heat exchanger. After leaving the heat recovery system (Fig. 1, state 3), CO₂ is pumped by the feed pump, back into the higher pressure condition (Fig. 1, state 4), and then the cycle recommences.

The solar collector is the heart of the CO₂-based Rankine cycle system. Its characteristics play an important role in the successful operation of such systems. For example, the CO₂ temperature at the outlet of the solar collector is an important performance parameter in achieving a good heat collection and power generation from the Rankine cycle. A higher temperature of CO₂ in the cycle will make it easy to collect heat from the cycle, and a higher pressure of CO₂ is helpful to drive turbine in producing electric power. In this paper, as a first step of understanding the performance of the CO₂-based Rankine cycle powered by solar energy, efforts were made to measure the cycle temperatures and pressures etc. to study the feasibility of the solar energy powered Rankine cycle using carbon dioxide.

2.2 Experimental facility and procedure

Figure 2 shows a schematic diagram of the experimental facility constructed. The experimental facility is mainly comprised of evacuated solar collector arrays, a pressure relief valve, heat exchangers, liquid CO₂ feed pump and cooling tower. In addition, a measurement and data acquisition system is also included. Supercritical CO₂ actually has physical properties somewhere between those of a liquid and a gas. So it is difficult to decide whether a turbine of a gas or a liquid type is used for such a Rankine cycle using supercritical CO₂. In other words, to date there is no turbine available for supercritical CO₂. Therefore, in the experiment, a pressure relief valve was used, instead of a turbine, in order to study the cycle performance. The pressure relief valve can provide various extents of opening for the cycle loop in order to simulate pressure drop occurring in realistic turbine condition and consequently a thermodynamic cycle can be achieved. No electricity power is outputted in the test, but basic cycle performance for the power/heat production can be known based on thermodynamic estimations, although we are aware that the outlet temperature and thermo-physical properties are different between the true turbine condition and the present condition. In present study, in order to estimate the cycle performances, an assumption was made that a gas microturbine was used in the CO₂-based Rankine cycle. The following thermodynamic equation⁵ is used to calculate the power generation from the turbine:

\[ W_{\text{power}} = m_c \eta_t \eta_{\text{gen}} \left( \frac{k}{k-1} \right) R T_1 \left[ 1 - \left( \frac{P_2}{P_1} \right)^{\frac{k-1}{k}} \right] \]  \hspace{1cm} (1)

where \( m_c \) is the mass flow rate of CO₂, \( R \) is the gas con-

Fig. 1 A schematic diagram of a novel concept—CO₂-based Rankine cycle powered by solar energy
stant, \( k \) is the ratio of the specific heat at constant pressure and constant volume, \( T_1, P_1 \) are the temperature and pressure at the turbine inlet, \( P_2 \) is the pressure at the turbine outlet, \( \eta_{\text{gen}} \) is generator efficiency, a value of 0.95 is used in the paper, and \( \eta_{i} \) is isentropic efficiency, defined as the ratio of the enthalpy change at isentropic conditions and the actual enthalpy change:

\[
\eta_{i} = \frac{h_1 - h_2}{h_1 - h_{i,\text{ss}}}
\]

the value of the isentropic efficiency can determined through experiments, where the temperatures and pressures are measured. Note that \( k \) varies with temperature, and in the present study, the value of \( k \) is taken as the average 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 condition. 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 \( \eta_{\text{power}} \) and heat recovery efficiency \( \eta_{\text{heat}} \):

\[
\eta_{\text{power}} = \frac{W_{\text{power}}}{Q_{in}}
\]

\[
\eta_{\text{heat}} = \frac{Q_{out}}{Q_{in}}
\]

where \( Q_{in} \) is the heat quantity absorbed into CO\(_2\) in the solar collector, and \( Q_{out} \) is the heat quantity recovered from the cycle. The performance parameters related to the cycle can be calculated,

\[
Q_{in} = m_c(h_1 - h_4)
\]

\[
Q_{out} = m_c(h_2 - h_3)
\]

\[
W_{\text{pump}} = m_c(h_4 - h_3)
\]

where \( W_{\text{pump}} \) 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 provided by Showa Denko. K.K. A sketch of the solar collectors is shown in Fig. 3. These collectors consist of a glass envelope over a glass tube coated with a selective solar absorber coating. This coating with a high solar absorbance 0.927 and a low emissivity 0.193, is applied on the vacuum side of the inner glass tube. The absorbed heat is conducted through the inner glass tube wall and then removed by heat removal fluid in a metal U-tube inserted in the inner tube with a fin (thickness 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.
area of the solar collectors used in the Rankine cycle is about 9.6 m².

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 CO₂ and shell side of water. As shown in Fig. 2, the higher-temperature water and lower-temperature water are respectively provided to the heat exchanger 1 and 2 to simulate the heat recovery processes. The total heat exchanger area utilized is about 0.76 m². 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. Accuracies of sun radiation sensor and air temperature gauge are ±0.3% and ±0.15 + 0.002°/°C, respectively. In addition, 5 thermal couples and 5 pressure transmitters are mounted in the CO₂ loop to measure CO₂ temperatures and pressures, respectively, with accuracy of ±0.1°C for temperature measurement and ±0.2% for pressure measurement. There are 5 platinum resistor temperature sensors mounted to measure water temperatures at the inlets and outlets of the heat exchangers with accuracy of ±0.15 + 0.0002/°F. CO₂ 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 systems 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 CO₂ feed pump is switched on and the opening of pressure relief valve is adjusted to the expected extent. When finishing test, the CO₂ 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 insulation coating is installed for all the carbon dioxide and water loops to reduce heat losses from the piping.

2.3 Experimental results and discussion

The CO₂-based Rankine cycle performance was tested in August, 2004, in Kyoto of Japan. The experiment was conducted from about 10:00 in the morning to 5:00 in the afternoon, through the whole daylight for a total of almost 7 hours. The total amount of CO₂ of about 6.0 kg was charged into the CO₂ loop of the experimental facility.

Figure 4 shows solar radiation and air temperature measured with a function of time. The solar radiation increases with time from 5:00 until it reaches a maximum value of around 0.83 kW/m² at 12:30. Then, the solar radiation begins to decrease with time. The time-averaged solar radiation and air temperature measured are about 0.50 kW/m² and about 32.5°C, respectively. The measured water temperatures and flow rates in the heat recovery 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 controlled 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 respectively about 33.1°C and 19.3°C, respectively.

Figure 6 shows the measured CO₂ temperatures at the monitoring points of the Rankine cycle loop, as shown in Fig. 2, in which the CO₂ flow rate measured is also included. During the test hours, the pressure relief valve was adjusted to a state of one-third open. It can be seen
Variations of inlet and outlet water temperatures and flow rates measured in the heat exchanger 1 and 2.

The measured CO₂ temperatures and flow rate in the CO₂-based Rankine cycle loop from Fig. 6 that the CO₂ flow rate achieved in the cycle loop is about 0.8 kg/min, which is kept throughout most of the daylight time. It can also be seen that the CO₂ temperature at the outlet of the solar collector increases with elapsed time, and at 12:00, the CO₂ temperature reaches up to about 194.0°C. After that, the temperature tends to drop gradually with time, which may be due to the natural decrease 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 makes 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 difference 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 CO₂ 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 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°C.

Furthermore, the solar collector efficiency is defined to describe the performance of collecting heat using supercritical CO₂ in the collector,

\[ \eta_{\text{collector}} = \frac{\int_0^t m_v(h_1 - h_4)dt}{\int_0^t IAdt} \quad (8) \]

where \( h_1, h_4 \) are enthalpy values of CO₂ 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, \( \int_0^t m_v(h_1 - h_4)dt \) represents the heat quantity absorbed into carbon dioxide in the collector during a time period of \( t \), \( \int_0^t IAdt \) is the total amount of the solar radiation striking the collector surface.

Figure 7 shows the calculated \( \int_0^t IAdt \) and \( \int_0^t m_v(h_1 - h_4)dt \) 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 CO₂ in the collector with time is similar to the variation of the amount of solar radiation, as shown in solid and dash lines, respectively in Fig. 7. During the time period, the averaged amount of solar radiation is about 2.29 MJ/(m²·h) and the averaged heat quantity collected in the collector is about 1.42 MJ/(m²·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 CO₂, 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
CO₂ 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 CO₂ 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 CO₂-based solar collector works.

Figure 8 shows the CO₂ 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 CO₂-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 CO₂-based prototype works in a transcritical Rankine cycle.

Furthermore, the CO₂-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 transport properties of CO₂ were calculated based on the measured temperatures and pressures using a Program Package for Thermophysical Properties of Fluids database version 12.1 (PROPATH 12.1). From the figures, it can be clearly seen that these working cycles are used for simultaneous heating and heat recovery in the temperature from about 25.0° to 185.0° for the heating process in the solar collector and about 145.2° to 22.0° for heat recovery. Most time of the heating processes in these Rankine cycles are in the supercritical region for CO₂. In other words, under the supercritical state, CO₂ is heated by the absorber surface in the solar collector. It is also seen from Fig. 9 that the CO₂-based Rankine cycle can work stably through the daytime in the transcritical regions.

The CO₂-based thermodynamic cycles are important in understanding of the cycle performance. Following is a further thermodynamic analysis made, in which the time-averaged CO₂ temperatures and pressures during the test are calculated and the Rankine cycle based on the average 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 addition, the pump work (power input of the cycle) was estimated to be about 0.15 kW and the heat recovery achieved is about 4.20 kW. The power generation efficiency \( \eta_{power} \) is
is estimated at 0.16 and the heat recovery efficiency $\eta_{\text{heat}}$ 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 passing 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 generation, 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. Furthermore, 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. Compared 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 problems 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 advantages 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 estimate its market feasibility. In general, the proposed solar Rankine cycle using CO$_2$ has a great potential of achieving 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, hospitals, office buildings, multifamily dwellings, and other facilities that can benefit from an independent source of power and heat.

3. Some Research Interests

In addition, several research interests may be related to the concept—forming a Rankine cycle using both solar energy and carbon dioxide. An understanding of flow and heat transfer of supercritical CO$_2$ (occurring in the solar collector tubes) is important for further increasing the Rankine cycle performance. Flow and heat transfer characteristics at sub-critical flow conditions have received considerably, in-depth study by many investigators. Flow and heat transfer at supercritical conditions, however, has not been investigated to a similar degree. Comprehensive reviews on previous works associated with variable-property heat transfer and supercritical heat transfer are given by Refs.$^{(7)}$–$^{(10)}$. It is generally agreed that the correlations do not show sufficient agreement with experiments to justify their use except in very limited conditions. Also an evacuated solar collector, which is specially designed for supercritical CO$_2$, is needed to be developed. Although the collector efficiency was obtained, as shown in Fig. 7, a complete nature for flow and heat removal by supercritical CO$_2$, which occurs in the collector, is still not known based on the existing references. In the future, engineering design and optimization work are necessary to be carried out on the evacuated solar collectors using supercritical CO$_2$ as the working fluid. Another interest may be a new development of turbine suitably driven by supercritical CO$_2$. The new turbine should be different from traditional liquid and gas turbine, because the physical properties of supercritical CO$_2$ near its critical point exhibit extremely rapid variation with change in temperature and pressure. The new turbine should be designed to be effectively driven by supercritical CO$_2$.

4. Concluding Remarks

A feasibility study was conducted for solar energy
powered Rankine cycle using supercritical carbon dioxide. The cycle is a combination of using renewable energy (solar energy) and pure natural working fluid (carbon dioxide). The CO₂-based Rankine cycle can not only produce electrical power but also provide heat collections of different temperatures. The obtained results show supercritical CO₂ can effectively collect heat in the evacuated solar collector and CO₂ temperature in the solar collector can reach about 185.0°C, which help to achieve heat recovery and power generation. And the CO₂-based Rankine cycle works in the trans-critical region throughout the most of the test hours. The thermodynamic analyses based on the measured data show that the CO₂-based Rankine cycle can achieve heat collection and electricity generation with a reasonable thermodynamic efficiency of the power generation efficiency \( \eta_{\text{power}} \) is 0.16 and the heat recovery efficiency \( \eta_{\text{heat}} \) is 0.82. The study shows the potential of the application of the CO₂-based Rankine cycle powered by solar energy. In the future a turbine condition is needed to further investigate the CO₂-based Rankine cycle. In addition, the objective of the paper is only to give a feasibility study and more experimental data is also needed to study the Rankine cycle.

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