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Performance Comparison of Rankine Cycle using Solar Energy and Supercritical CO_2 over Basic Rankine Cycle

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ABSTRACT

The rankine cycle to convert heat into useful work has been investigated for many years. Use of solar energy and CO_2 is of great importance in reducing energy shortage and environment problems such as global warming, ozone depletion, and atmospheric pollution. A solar powered rankine cycle using supercritical CO_2 shows a higher potential than a basic rankine cycle, when considering heat source as solar collector and the heat transfer between heat source and working fluid (carbon dioxide) in the main heat exchanger. This is mainly due to better temperature glide matching between heat source and working fluid. The solar powered CO_2 cycle also shows no pinch limitation in the heat exchanger. This study compare the performance of solar powered rankine cycle with supercritical CO_2 recovering heat (high temperature heat and low temperature heat), which could be used for refrigeration, air-conditioning, hot water supply etc. in comparison to rankine cycle .The results obtained show that the solar powered rankine cycle using CO_2 works stably in a transcritical region, estimated power generation efficiency is 0.25 and heat recovery efficiency is 0.65.

***Keywords*—** CO_2; Efficiency;Rankine cycle; solar powered Rankine

I. INTRODUCTION

In recent years, the increasing consumption of fossil fuels has led to more and more environmental problems such as global warming, ozone depletion, and energy shortage. Due to all these reasons, utilizing the renewable energy (solar and wind power), high and low grade waste heat, heat and CO_2 for combined production of electricity and thermal energy. When utilizing low grade waste heat, the traditional rankine cycle[1] (figure 1) does not give a satisfactory performance due to its low thermal efficiency and large volume flow. However, due to high thermal efficiency solar heated thermodynamic cycle (figure 2) [1] is able to provide low grade thermal energy to drive other application as water or space heating as well as thermal energy at higher temperature for driving an absorption chiller, sea-water distiller.

[1] Preferred for high temperature power plant

Nomenclature

BRC	Basic Rankine Cycle
CO_2	Carbon Dioxide
EMI	Exergy Merit Index
Q_{in}	heat quantity absorbed into CO_2 in the heat collector
Q_{out}	heat recovery in rankine cycle
W_{power}	power generation of the rankine cycle
m_e	CO_2 mass flow rate, kg/s
η_{power}	power generation efficiency
η_{heat}	heat recovery efficiency
η_{gen}	generator efficiency

Subscripts

1-4	points of cycle route

TABLE I

CHARACTERISTICS OFSOME WORKING FLUIDS

	R-12	R-22	R-134a	R-407C	R-410A	R-717	R-290	R-744
ODP/GWP	1/ 8500	0.05/ 1700	0/ 1300	0/ 1600	0/ 1900	0/0	0/3	0/1
Flammability/ toxicity	N/N	N/N	N/N	N/N	N/N	Y/N	Y/N	N/N
Molecular mass (kg/kmol)	120.9	86.5	102	86.2	72.6	17	44.1	44
Critical pressure (MPa)	4.11	4.97	4.07	4.64	4.79	11.42	4.25	7.38
Critical temperature (°C)	112	96	101.1	86.1	70.2	133	96.7	31.1
Reduced pressure[a]	0.07	0.1	0.07	0.11	0.16	0.04	0.11	0.47
Reduced temperature[b]	0.71	0.74	0.73	0.76	0.79	0.67	0.74	0.9
Refrigeration capacity[c] (kJ/m³)	2734	4356	2868	4029	6763	4382	3907	22545

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R-12: dichloro difluoro methane; R-22: chloro difluoro methane; R-134a: tetra fluoro ethane; R-407C: ternary mixture of Difluoro methane /penta fluoro ethane/tetra fluoro ethane (23/25/52, %); R-410A: binary mixture of Difluoro methane /penta fluoro ethane (50/50, %); R-717: ammonia; R-290: propane; R-744: carbon dioxide. [a] Ratio of saturation pressure at 0^{o}C to critical pressure. [b] Ratio of 273.15 K (0^{o}C) to critical temperature in Kelvin. [c] Volumetric refrigeration capacity at 0^{o}C.Ref.[1].

From the Table I, it can be seen that carbon dioxide (CO_2, R-744) is non-flammable, non-toxic and friendly to environment. In addition, vapour pressure of CO_2 is much higher than rankine cycle. Also, its volumetric refrigeration capacity (22545kJ/m^3 at 0^{o}C) is 3-10 times higher than CFC, HCFC, and HFC fluids. Thus, with the use of CO_2, the system volume would be smaller and working fluid amount would be lower; and CO_2 thermodynamic and transport properties seems to be favorable in terms of heat transfer and pressure drop.

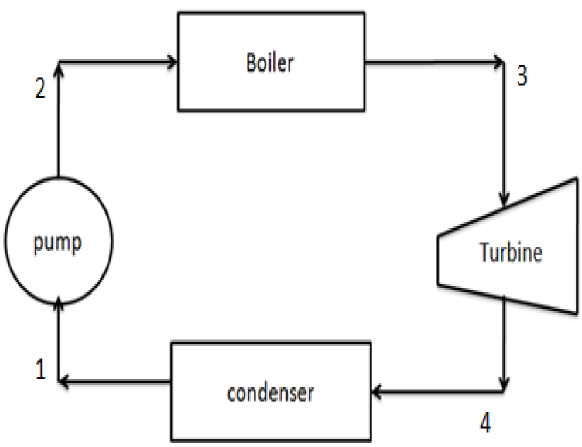

Figure 1: (a) Rankine cycle system layout

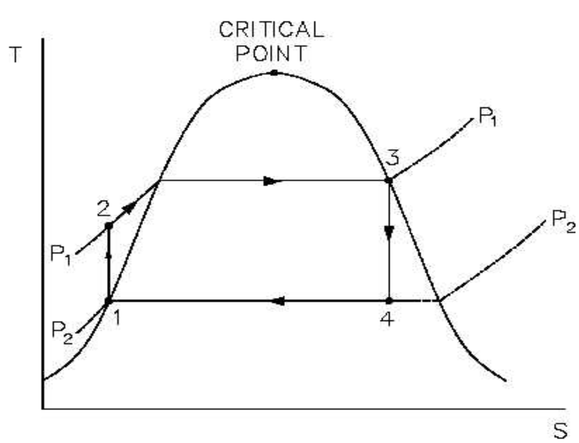

Figure 1:(b) T-S diagram of rankine cycle

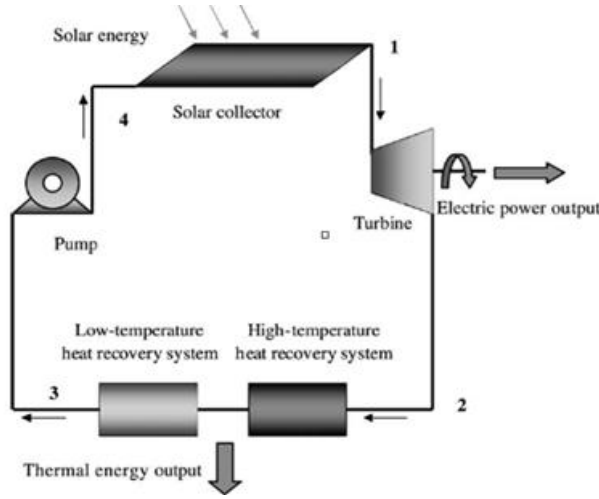

Figure 2: Solar powered rankine cycle system layout

[2] Temperature change during take-up of heat energy

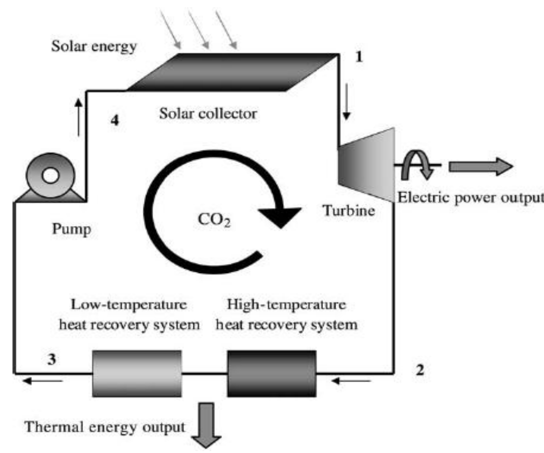

Figure 3:(a) System layout of solar powered rankine cycle with supercritical CO_2

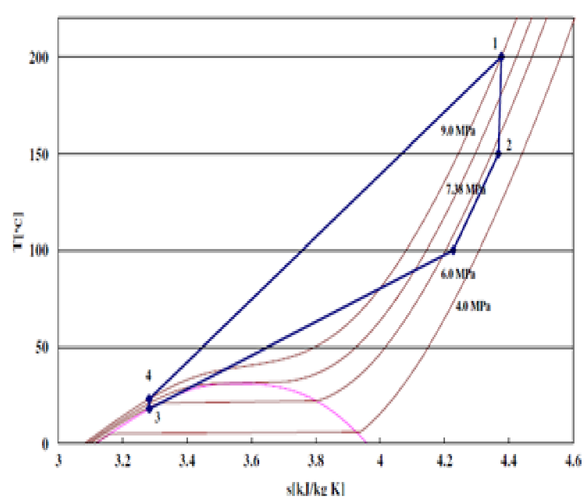

Figure 3:(b)T-S diagram of solar powered rankine cycle with supercritical CO_2 [1]

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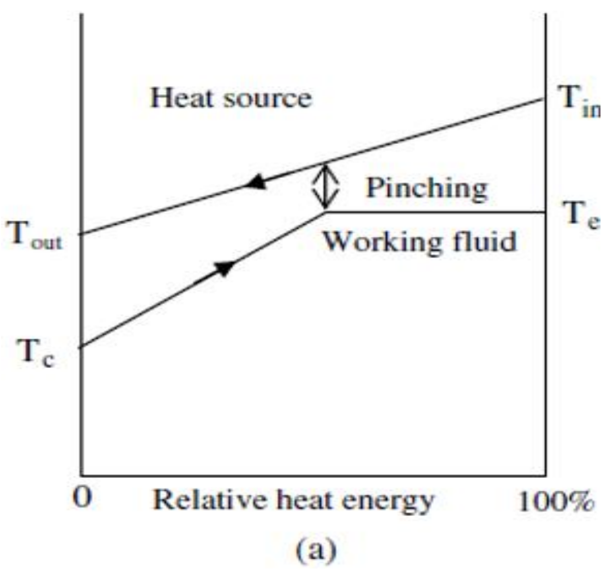
II. THERMODYNAMIC ANALYSIS OF CYCLE'S POTENTIAL IN WASTE HEAT RECOVERY

Compared with the basic rankine cycle, the solar powered with supercritical CO_2 (figure 3)[1] cycle has a higher potential in making use of the energy in a waste heat with gradient temperature, such as exhaust gases. The temperature ''glide''[2]for solar powered CO_2 above the critical point allows for a better matching to the heat source (as solar collector) temperature glide than any basic rankine working fluid working below the critical point. Therefore, the so-called pinching problem, which may occur in basic rankine cycle's counter current heat exchanger, can be avoided by solar powered with carbon dioxide cycle. [4] This may be graphically represented as Figure.4. When utilizing the energy in high-grade heat source and low grade heat source, the enthalpy of the heat source fluid will drop with a gliding temperature profile in the main heat exchanger during the energy transfer process. For a cycle that uses waste heat at a moderate inlet temperature (80^0C–200^0C) as heat source,[4] the best efficiency and highest power output is usually obtained when the working fluid temperature profile can match the temperature profile of the heat source fluid. Therefore, if the heat transfer between the power cycle and the heat source is taken into account properly, the CO_2transcritical power cycle ought to outperform the BRC, since the supercritical ''temperature glide'' of the working fluid allows for a better matching to the heat source fluid's temperature changes.



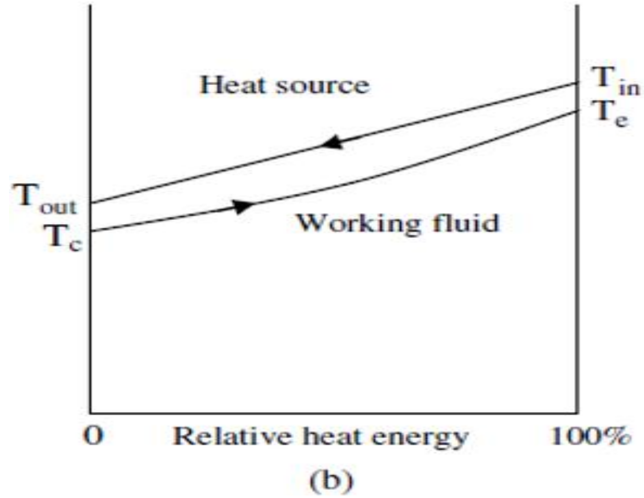


Figure 4: Schematic representation chart of the heat transfer between waste heat and working fluid in the high temperature main heat exchanger (a) organic rankine cycle; (b) solar powered with supercritical CO_2 cycle. [4]

[3]The ratio of the work generated by the saved steam to the exergy supplied by the solar heat

III. CYCLES' PERFORMANCES COMPARISON

In the current work rankine cycle, solar powered rankine cycle, and solar powered rankine with CO_2 cycle are considered. Taking the ambient temperature as 25^0C (298K) and assuming the average temperature difference for heat transfer in heaters as 10^0C, two cases are investigated. In case 1, we are assuming that normal flat plate solar collector is used, and 110^0C liquid is produced. In case 2, we are assuming that some advanced solar collector (may be with concentrator) is used and 286^0C hot liquid is produced.If low temperature thermal energy is used as the heat source to heat the feed water in the regenerative Rankine cycle, the value of EMI[3] (Exergy Merit Index) is high. If we just use the simplest collector, the flat plate collector, which yields hot fluid to 110^0C, the EMI is pretty high and when employing a high temperature solar collector, (286^0C) 30.04% extra work can be generated and the EMI still exceeds unity. [5]

In order to compare solar powered rankine cycle to solar powered rankine with CO_2 cycle under equal operating conditions, it is common to use the same boiling and condensing temperatures in these cycles. The evacuated solar collector of 29.0 m^2 is used, which has a maximum allowable work pressure of 12 MPa, and a maximum working temperature of 250^0C. Furthermore, the feed pump can provide a maximum operating pressure of 12 MPa and flow rate of 0.03 kg/s, respectively.

The total amount of CO_2 for the maximum efficiency and safe operation is 5.5 kg and generator efficiency η_{gen}

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= 0.92 is used to calculate the produced electric power. The CO_2 temperature at the collector outlet reaches up to about 165^{0}C. At the same time, the water temperatures of the heat recovery systems also increase with time, which is due to increase of CO_2 temperatures. Moreover, CO_2 temperature in the collector depends on the CO_2 flow rate m_c and the heat input Q_{in}.

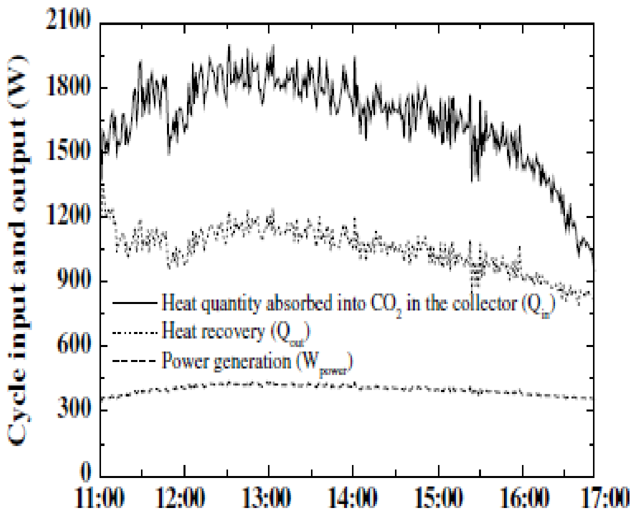

Figure 5: variations of the cycle outputs and the heat quantity absorbed into CO_2 in the collector with time

The energy outputs from the CO_2-based Rankine cycle (power generation W_{power} and heat recovery Q_{out}) and heat quantity absorbed into CO_2 in the collector Q_{in} are shown in Figure 5[1].The temperature and pressure values are obtained experimentally, including CO_2 flow rate. Further enthalpy values at different monitoring points are calculated based on the measured temperature and pressure values using a Program Package for Thermo physical Properties of Fluids database version 12.1 (PROPATH 12.1). From Figure 5, it is seen that variation of Q_{in} with time is similar to that of solar radiation measured with time to a certain extent. The time-averaged Q_{in} is estimated at 1610.2 W. The power generation W_{power} and heat recovery Q_{out} are found to be relatively stable throughout the test hours. The time-averaged W_{power} and Q_{out} are estimated at 401.1 W and 1050.4 W, respectively. The total output from the cycle is about 1451.5 W. The power generation of 401.1 W was obtained based on some assumptions described above. The power generation efficiency η_{power} and heat recovery efficiency η_{heat} of the Rankine cycle with CO_2 are shown in Figure. 6. In the figure, the time-averaged η_{power} is found to be 0.25 and η_{heat} is 0.65. [1]

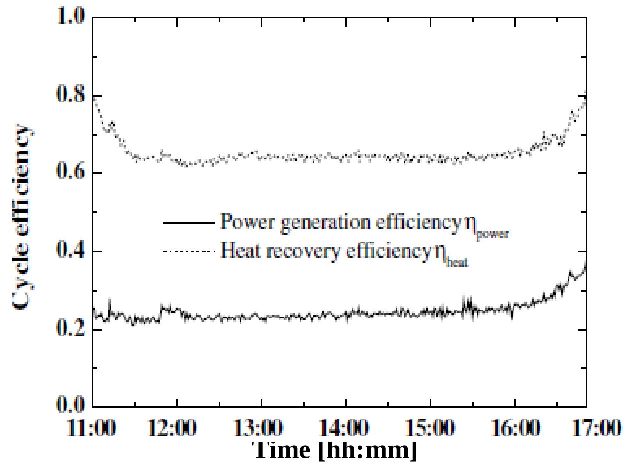

Figure 6: Variations of the power generation efficiency and heat recovery efficiency with time

An analysis of energy conversion was conducted based on the US Electric Power Annual. If solar powered rankine cycle with supercritical CO_2 plant is used instead of a petroleum-fired power plant, the saved petroleum M_p and the reduced CO_2 emission M_e per year can be simply estimated as:

$$M_p = 365 t_o a_1 (W_{power} + Q_{out} - W_{pump})$$

$$Me = 365 t_o a_2 (W_{power} + Q_{out} - W_{pump})$$

where t_o is operating time per day, a_1 is the amount of petroleum consumed to produce 1 kWh of electrical energy and a_2 is the amount of CO_2 emission if 1 kW h of electrical energy is produced by a petroleum fired power plant. In this paper, t_o = 7.0 h, a_1 = 0.266 l/kW h, and a_2 = 0.894 kg/kW h are used. [1]

TABLE II

ECONOMICS ESTIMATION OF SOLAR ENERGY POWER RANKINE CYCLE USING CO_2

	Estimation results
M_p(saved petroleum)	8.5kl/year
M_e(reduced CO_2 emission)	28,237.0 kg/year
Cost(for total energy)	US$0.047/kWh
Cost(for electric energy)	US$0.176/kWh

Ref. [1]

Table II shows the economic estimation results. The petroleum of M_p = 8.5 kl can be saved per year, and furthermore, the CO_2 emission of about Me = 28237.0 kg can be reduced per year. Here, it is assumed that 10,000 set of machine systems were manufactured per year and the capital investment for users can be paid back within5

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years. Therefore, a cost of US$0.047 per kW h for the total energy output and US$0.176 per kWh for electric energy is obtained.

IV. CONCLUSION

In this work, basic rankine cycle, solar powered rankine cycle and solar powered rankine cycle with supercritical CO_2 have been compared with respect to their abilities to convert energy from low grade and high grade waste heat to useful work. 30.04% extra work can be generated when employing a high temperature solar collector at ambient temperature (25^0C).In addition, at the average temperature difference for heat transfer in heat exchanger is 10^0C. When solar powered rankine cycle and solar power rankine cycle with CO_2 are compared under equal operating condition, it is common to use at the same boiling and condensing temperature. The results show that CO_2 temperature in solar collector can reach about 165^0C and CO_2 based cycle can work in transcritical region and can produce electricity with heat collection. The power generation efficiency is 25% and heat recovery efficiency is 65%.

The economic result shows that 8.5 kl/year petroleum can be saved and 28,237.0 kg/year CO_2 emission can be reduced by using 1451.5W capacity of solar powered rankine cycle with CO_2 plant. Moreover, total energy cost US$0.047/kWh and cost for electric energy US$0.176/kWh can be achieved by using solar powered rankine cycle with supercritical CO_2.

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