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Performance Evaluation of a Thermosyphon Solar Water Heater Using Supercritical CO_2 as Working Fluid

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Abstract—An experimental study was performed to investigate the performance of thermosyphon solar water heating (SWH) system using R744 (CO_2) as the working fluid. An experimental setup in which 1.15m^2 evacuated tube (U-pipe) solar collector acting as a source as well as an evaporator for the refrigerant was designed and tested. The influence of various operating and design parameters on the overall performance of a CO_2 assisted SWH system was also investigated. The experimental results had indicated that it is possible to induce the natural convective flow even during solar-adverse conditions. The time-averaged collector and heat recovery efficiencies for summer were about 59% and 45%, respectively.

Keywords— Solar Water Heating, R744, Evacuated Tube Collector, Heat Recovery Efficiency

I. INTRODUCTION

COST effective energy acquisition and consumption will forever be an essential for a nation's economic prosperity and growth. Energy can be obtained from many sources, but in the past, fossil fuels have been the most profitably gathered and consumed source. However, the destructive environmental consequences of fossil fuel consumption were not fully understood or fully addressed. As technology and awareness have grown and evolved, society is now better able to work towards a solution to the problem generated from fossil fuel consumption. The solution steps need to maintain profitability and feasibility. But in the end, an import-independent, inexhaustible, and clean energy acquisition method needs to be developed for the betterment of the humanity.

In the United States, water heating accounts for 20% of all household energy use [1]. There are several types of water heating systems, but the most predominately used is the conventional water heater. The majority of conventional water heaters are powered by electricity derived from fossil fuels. One emerging alternative water heating method is solar water heating (SWH). Solar power is import-independent, inexhaustible, clean, and is one of the best candidates for fossil fuel replacement.

The growing popularity of SWH systems is fueled by their environmentally friendly operations with minimal system maintenance and operation costs as compared to conventional water heating systems [2]. Extensive investigations were done both as theoretical and experimental studies to improve the thermal efficiency of the SWH system [3-18]. Most of the conventional SWH systems utilize water as the heat transfer fluid which cannot be used in solar-adverse regions. This is due to the fact that water-based collectors are susceptible to freezing.

The selection of a working fluid plays a very significant role in the development of an efficient and environmentally friendly SWH system that can function even when exposed to low ambient conditions. Several conventional refrigerants have been taken into consideration, but in many cases these refrigerants are toxic, cause pollution, and are damaging greenhouse gases. There is a growing demand in technology based on ecologically safe "natural" refrigerants, like ammonia, hydrocarbons, carbon dioxide, water, and air. Among these, carbon dioxide (CO_2) is the only one which is non-flammable, non-toxic, and can also operate in a vapor compression cycle below 0 °C [19]. Therefore CO_2 was chosen as a working fluid for the current study. Table I compares the properties of CO_2 with other working fluids. As mentioned in the Table I, one property of CO_2 which distinguishes it from other refrigerants is its low critical point (31.1 $^{\circ}$C at 7.3 MPa). These properties make CO_2 an ideal working fluid to be used in sub-zero temperatures with low solar radiation.

Several studies have been initiated utilizing CO_2 as the working fluid [20-26]. In this study, an attempt has been made to investigate the performance of a thermosyphon based SWH system. Experimental investigations are conducted to study the system's basic characteristics, including CO_2 temperature, CO_2 pressure, collector performance and heat recovery efficiency. The results were also used to study the influence of various design parameters on the overall system performance.

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TABLE I
ENVIRONMENTAL BENEFITS OF CO_2 [19]

Refrigerant Type	R-134A	R-404A	Ammonia	R-744
Naturally Occurring	No	No	Yes	Yes
ODP	0	0	0	0
GWP	1300	3260	0	1
Critical Point Temp	101.1°C	71.7°C	132.2°C	31.1°C
Critical Point Pressure	4.07 MPa	3.73 MPa	11.3 MPa	7.37 MPa
Triple Point Temp	-103°C	-100°C	-77.8°C	-56.6°C
Triple Point Pressure	40 MPa	2.8 MPa	6.0 MPa	518 MPa
Flammable/ Explosive	No	No	Yes	No
Toxic	No	No	Yes	No

II. EXPERIMENTAL SET-UP

In this study, the SWH system was designed and constructed to harness solar energy effectively and efficiently for heating applications in solar-adverse regions like Fargo, North Dakota. A system diagram of the SWH system using CO_2 as a working fluid is shown in Fig.1. The system consists of an evacuated tube collector (ETC) as heat collecting source, a hot water storage tank with an immersed heat exchanger (HX), valves, and data acquisition system.

In the present experimental set-up, an evacuated tube solar collector (Fig. 2) consisted of 6 evacuated glass tubes mounted on an aluminum base, which provided the angle of inclination of 45° N (latitude of Fargo, ND). The evacuated glass tubes have high solar absorbance ranging between 0.90-0.92 and possess a low emissivity value of 0.193. The absorbed heat from the glass tubes was conducted through the inner glass tube wall and removed by the heat removal fluid through copper tubing fabricated into the "U-tube" configuration. The dimensions of the copper tubing in the "U-tubes" were an outer diameter of 6.35 mm and an inner diameter of 3.175 mm. These dimensions were based on pressure rating of 12 MPa and an operational temperature range of -15 to 90^{o} C. Further details of the collector been summarized are listed in Table II.

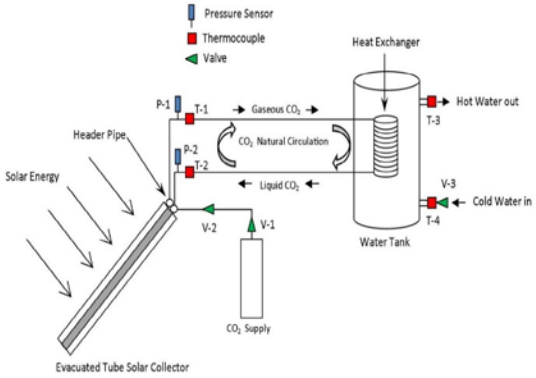

Fig. 1 Schematic diagram of a simple Thermosyphon SWH System

The volume of the storage tank used in the SWH system depends largely on the collector area. Therefore, for the given collector area (1.15 m^2), a 55 Liter storage steel tank was chosen. The heat output from the ETC is delivered to the insulated 55 L capacity storage tank through an immersed helical shaped heat exchanger. The heat exchanger immersed is made up of copper coil consisting of 12 turns of the "header" copper tubing, which has a surface area of 0.0506 m^2.

TABLE II
PARAMETERS FOR THE GLASS EVACUATED TUBE SOLAR COLLECTOR

Material	Parameters	Value
Absorbing coating	Absorptivity	0.92
	Emissivity	0.193
Outer glass tube	Outer diameter (m)	0.047625
	Inner diameter (m)	0.0381
	Thickness (m)	0.0015875
Copper fin	Thickness (m)	0.0006
	Conductivity (W/mK)	307
U-tube	Outer diameter (m)	0.00635
	Inner diameter (m)	0.003175
	Thickness (m)	0.015875
Tubular collector	Length (m)	3.6576 m

As shown in Fig.1, three valves are utilized in the system to control the systems operation. Valve 1 is a venting valve, and was installed at the CO_2 filling loop to empty the CO_2 from the system. Valve 2, is a high pressure needle valve which was installed at the inlet of the solar collector to charge the system from the CO_2 supply. To control the flow of water, valve 3, an automatic valve, was integrated to the inlet of the storage tank.

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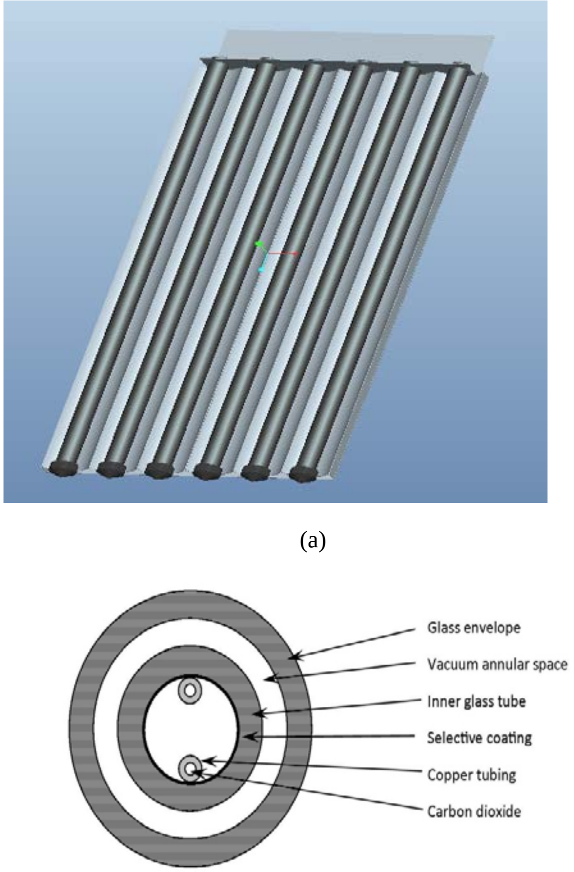


Fig. 2 Evacuated Tube Solar Collector (a) Front-View (b) Cross-Sectional View [27]

To begin with, the supercritical CO_2 fluid (refrigerant) passes into the solar collector where it gets evaporated by the incident solar energy. The vaporized refrigerant passes through the header, and finally the high temperature vapor get through the immersed HX, where it gets condensed. The energy is rejected through the refrigerant to the water, via the heat exchanger immersed in the storage tank. Once the heat is transferred, the CO_2 is again fed back down to the collector system to continue the process over again. Circulation of CO_2 from the collector to the storage tank and vice-versa is affected by buoyancy forces. The design mentioned above serves as a promising potential to supply hot water in solar-adverse regions such as Fargo, North Dakota and can be suitable for a variety of residents, especially for those living in apartment blocks with south-faced outside walls and windows.

Fig. 3 Front View of SWH System

III. RESULTS AND DISCUSSION

The current study aims at using evacuated tube U-pipe solar collector as evaporator and examines the system on various operating parameters such as solar radiation, ambient temperature, storage volume, initial tank temperature etc. Several operating parameters are varied to obtain the optimal performances of the system in terms of heat recovery efficiency, and collector efficiency. The following equations were used to calculate performance parameters [27].

$$Q_u = A_c F' \left[I(\tau_g \alpha_g) - U_L (T_f - T_a) \right] \tag{1}$$

$$F' = \frac{1/U_L}{W\left[\frac{1+U_L/C_b}{U_L\left[d+(W-d)F\right]} + \frac{1}{C_b} + \frac{1}{h_f \pi d} \right]} \tag{2}$$

$$F = \frac{\tanh\left[m(W-d)/2\right]}{m(W-d)/2} \tag{3}$$

$$m = \left[\frac{U_L}{\lambda \delta \left(1 + U_L / C_b\right)} \right]^{1/2} \tag{4}$$

$$Q_w = M_w C_p \left(T_{wo} - T_{wi}\right) \tag{5}$$

$$\eta_{col} = \frac{Q_u}{A_c I_T} \tag{6}$$

$$\eta_{RE} = \frac{Q_w}{Q_u} \tag{7}$$

The experimental set-up was tested in Fargo, North Dakota, and the data collected on May 22, 2013 was used to examine the effect of incident solar radiation on the system. The system was set in operation from 08:00 to 17:00 hours. Fig. 4 clearly shows that during the test day, it was a clear sky day.

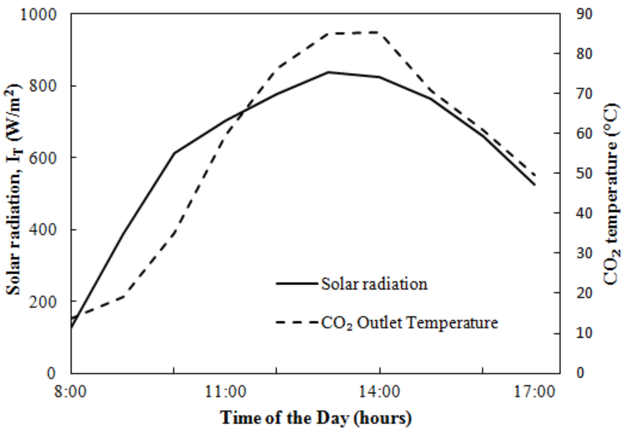


Fig. 4 Variation of Solar Radiation and Ambient Temperature Vs Time of Day

Initially, the system was charged with CO$_2$ until the initial pressure of 5 MPa was achieved, and it was exposed to sunlight. During the initial hours of exposure, a steady rise in CO$_2$ temperature and pressure was noticed. Fig. 5 shows the variations of the measured CO$_2$ temperature and pressure at the outlet and the inlet of the collector. During the test period, the CO$_2$ temperature at the collector outlet varied from 13 °C to 92 °C. From the figure, it can be seen that the CO$_2$ temperature and CO$_2$ pressure in the collector increases with the solar radiation, which is much different from the collector using water as working fluid.

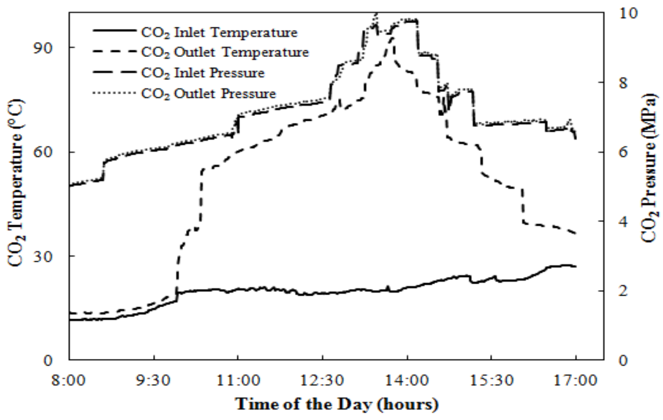
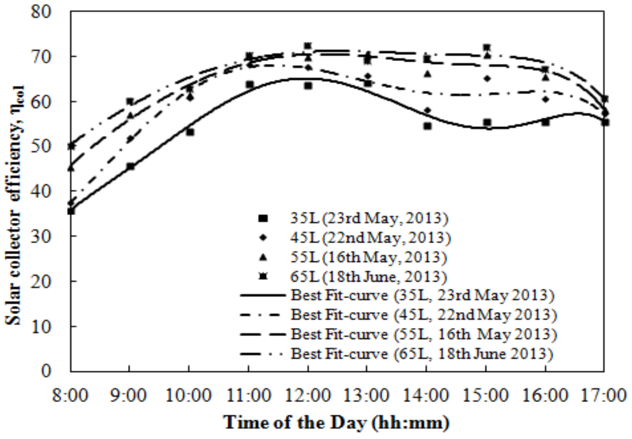
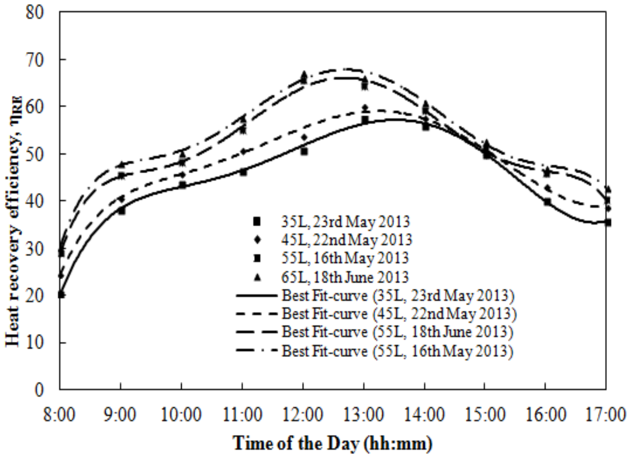


Fig. 5 Variation of CO$_2$ Temperature and Pressure Vs Time of Day

The current study also aims at using evacuated tube U-pipe solar collector as evaporator and examines the system on various operating parameters such as storage volume, initial tank temperature etc. Several operating parameters are varied to obtain the optimal performances of the system in terms of heat recovery efficiency, and collector efficiency. Fig. 6 illustrates the effect of storage tank volume on its performance. It is evident from the trend that, an increase in storage volume affects an increase in both system efficiency and collector efficiency. This is because, for a given collector area, if the storage tank volume increases the condensing temperature decreases which results in marginal decrease in evaporating temperature. Hence, this causes an increase energy gain by the collector, which positively influences the system performance. On the other hand, the lower evaporating temperature of the refrigerant in the solar collector reflects lower heat loss, which results in higher collector efficiencies. However, beyond the storage tank volume above 55 liters the performance parameters (η_{col}) do not vary much. This indicates that, for a given collector area an optimum size of storage tank should be chosen and 55-65 liters m^{-2} turns out to be the optimum size for the proposed design.



(a)

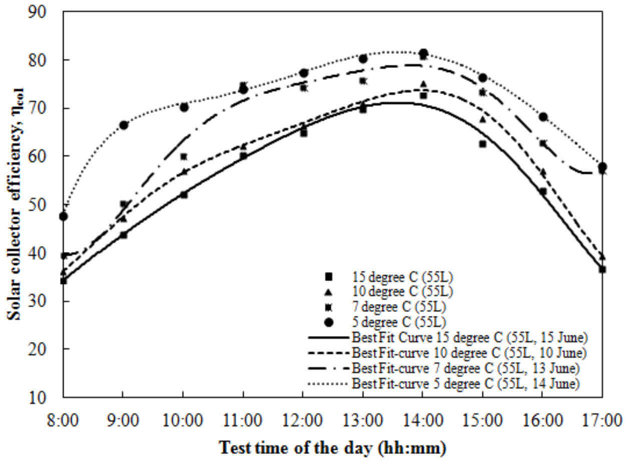


(b)

Fig. 6 Effect of Storage Volume on the System Performance: (a) Solar Collector Efficiency (b) Heat Recovery Efficiency

Fig. 7 shows the effect of inlet tank temperature on the system performance. It is seen that for low initial tank temperatures the performance of the system is higher compared to relatively high initial tank temperature. Hence it is clear from the trend that an increase in initial tank temperatures affects the decrease in system efficiency and marginal decrease in collector efficiency. It is due to the fact that the temperature difference between the condensation and evaporation for the low inlet tank conditions is particularly lower compared to the high initial water temperature in the tank.

Results obtained from the present study are encouraging as it signifies that the environmental benign refrigerant CO_2 (R744), can serve as an efficient working fluid compared to water when exposed to solar adverse conditions. There are several characteristics of CO_2 that contributes to the high efficiency of CO_2-based collector compared to traditional collectors using water as working fluid.



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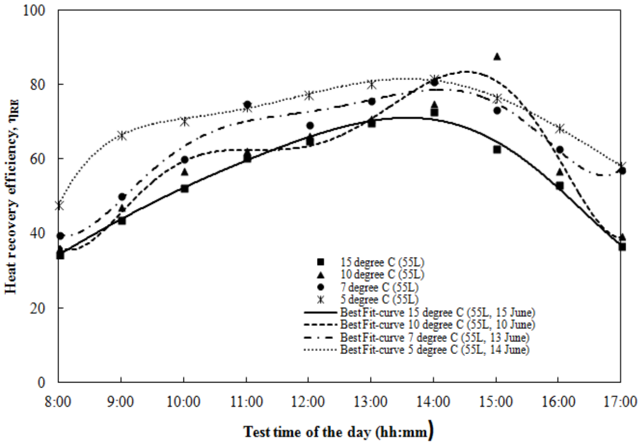

(b)

Fig. 7 Effect of Initial Tank Temperatures on the System Performance: (a) Solar Collector Efficiency (b) Heat Recovery Efficiency

IV. CONCLUSION

A CO_2 assisted water heating system using U-tube evacuated tube collector has been investigated for Fargo, ND, weather conditions. The thermal performance of the system is determined based on the measured collector temperature and water temperature in the storage tank, under different weather conditions. The results indicate that, the time-averaged collector efficiency (η_{col}) and heat recovery efficiency (η_{RE}) are calculated around 59% and 45% respectively. Experiments have shown the potential of using CO_2 as the working fluid in SWH systems when need to be operated in solar adverse regions.

NOMENCLATURE

A_c	the outer surface area of absorber tube, (m^2)
C_b	bond conductance, ($W\ m^{-1}\ K^{-1}$)
d	diameter of the U-tube, (m)
F	fin efficiency of straight fin
F'	collector efficiency factor
h_f	the heat transfer coefficient between the fluid and the U-tube wall, ($Wm^{-1}\ K$)
Q_u	useful energy gain, (W)
Q_w	heat quantity recovered, (W)
T_a	ambient temperature, (K)
T_f	mean temperature of the working fluid, (K)
U_L	overall loss coefficient, ($W\ m^{-2}\ K^{-1}$)
W	the circumferential distance between the U-tubes, (m)
I_T	total solar radiation
M_w	mass of water in storage tank, (kg)
C_p	specific heat of water ($kJ\ kg^{-1}\ K^{-1}$)

GREEK

δ	the thickness of the copper fin, m
η	solar collector efficiency

λ	conductivity of copper fin, W/(m K)
α	Absorptance

SUBSCRIPT

col	collector
RE	heat recovery
w	water
i	inlet
f	fluid
u	useful
o	outlet

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