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Effect of Parametric Studieson the Performance of a CO_2 Assisted Solar Water Heating System

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Abstract:-An experimental study was performed to determine the performance of thermosyphon Solar Water Heater(SWH) system under various conditionsusing R744 (CO_2) as the working fluid. The uniqueness of the system was the use of carbon dioxide as a working fluid; which is one of the most promising alternative natural refrigerants. Literature shows that most of the CO_2 utilized SWH systems are active systems. In this study, an attempt has been made to design and fabricate a simple thermosyphon solar water heater using supercritical CO_2 as working fluid to investigate for its feasibility in various operating conditions when exposed to solar adverse regions like those found in North Dakota, USA.The effect of various parameters such as storage volume, inlet tank temperature etc. on the overall performance of a CO_2 assisted SWH systemhas been evaluated.The results indicate that, the measured collector (η_{col}) and heat recovery efficiencies (η_{RE}) were calculated around 65% and 55% respectively.

Keywords:-Solar Water Heating, Thermosyphon, Refrigerant, R744, Evacuated Tube Collector, Heat Recovery Efficiency

I. INTRODUCTION

Cost effective energy acquisition and consumption will continue to be essential factors in determining a nation's economic prosperity and growth [1]. Energy can be obtained through several resources, but in the past, fossil fuel has been the most profitably gathered and consumed source. However, the destructive environmental consequences of fossil fuel consumption were not fully understood or fully addressed [2]. As technology and awareness have grown and evolved, society is now showing keen interest to identify solutions to the problems generated by fossil fuel consumption. The solution steps need to meet constraints in terms of profitability and feasibility such that, an import-independent, inexhaustible, and clean energy acquisition method could be developed.

Among different renewable energy resources, solar power is import-independent, inexhaustible, and clean and is one of the best candidates for fossil fuel replacement. One application of solar power is water heating.

The intended purpose for this experimental study is to raise public awareness of sustainable energy acquisition by demonstrating the promising utilization of solar energy as a heat source for water heating in Fargo. It will also lessen the energy crises threat by providing an energy alternative for basic domestic needs which are currently met by electricity and firewood. The main objectives of the study is to optimize the collector design and identify the key operational parameters to achieve high overall performance of the thermosyphon system in the solar adverse like those found in Fargo, North Dakota, USA region.

II. EXPERIMENTAL INVESTIGATION

An experimental thermosyphon solar water heater has been designed, fabricated and tested in this study. Figures 1(a) and 1(b) shows the front and side view of the solar water heater respectively. The evacuated tube collector, the storage tank, pressure and temperature gauges, valves, and the external insulated line that facilitates the thermosyphon flow can be seen in Fig. 1(a).

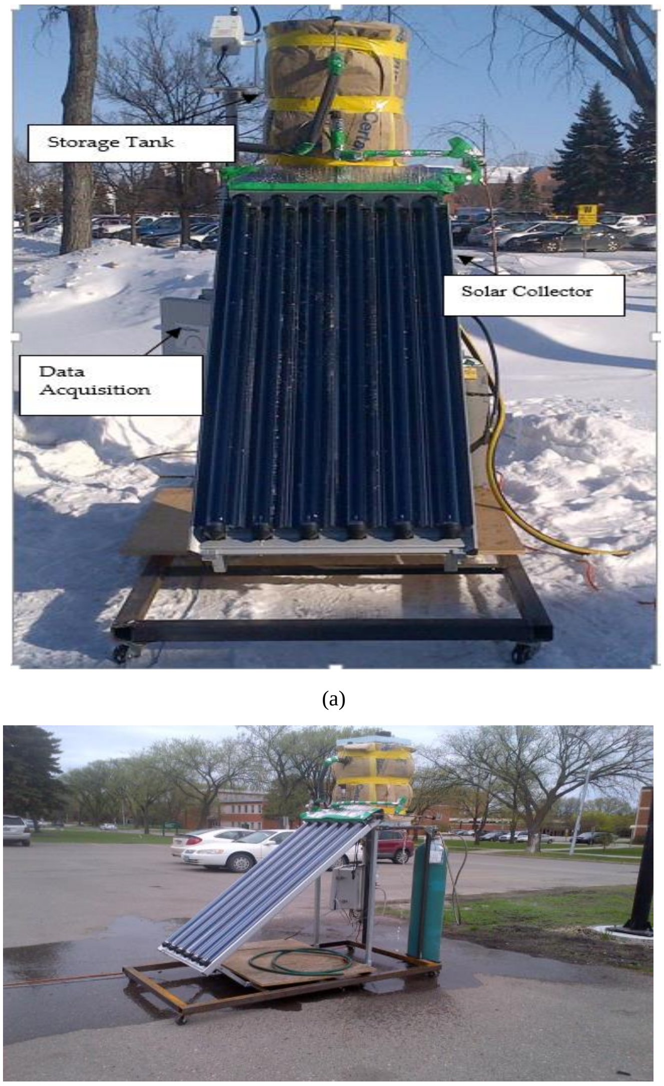
The main design consideration while developing the overall system design in this research is based on the freeze protection strategy. This is because, it is intended to develop a SWH system to suit harsh winter weather conditions experienced in solar adverse regions like Fargo, ND. If proper precautions are not taken, the working fluid would be susceptible to freezing which might cause serious damage to the SWH system [13-16]. Therefore, to develop a reliable and efficient SWH system for winter conditions in solar adverse regions, constraints derived from low ambient temperatures and low solar radiation intensity has to be met.

This section describes the design processes followed during the experimental set-up.Design processes are performed in two distinct phases: the system design and the component design. The overall system design was finalized based on the following needs/facts: (i) to suit solar adverse regions which experience-low ambient temperatures and low solar insolation conditions, (ii) the system's working principle; that is, it was intended to have the working fluid be circulated in natural convection mode (density driven) in contrast to the conventional forced convection mode using pump and, (iii) to build a residential water heating system to meet the domestic hot water demand. Accordingly, in component design phase, the proper sizing of the individual components such as evacuated tube collector, heat exchanger, and storage tank of the SWH system was carried out.

A. Component Design

With regard to the type of collector, there exists several kinds of solar collectors, among which, evacuated tube collector (ETC) and a flat-plate collector (FPC) are more commonly used for domestic water heating purposes [3]. For the given constraint of low ambient and solar insolation conditions, ETCs are generally employed. ETC has proven to aid inherent maximum operating temperatures and low heat loss at high temperatures relative to the ambient temperature [4][5].

In line with one of the objectives (residential SWH system) of the present study, it was targeted to choose a minimal collector area of 1m^2. Accordingly, six borosilicate glass-in-glass tubes were procured, and assembled together on an aluminum base to form the collector system (Fig. 2). The gross collector area of the ETC is **1.15 m^2**(gross area). To ensure high pressure CO_2 could be safely circulated through the ETC, a copper tube of 15mm thick and 3.7 m long was bent to U-shape (Fig. 3) and was inserted in the inner ETC tube. The U-shaped copper tubes in the ETC were integrated with the headers using multiple stainless steel high pressure compression T-joints [4].



(a)

(b)

Figure 1: Experimental set-up (a) Front view (b) Side view

The storage tank is yet another essential component of the SWH system [6]. It also plays a major role in dictating the system performance [7]. The required volume of the tank was estimated based on the historical weather data of Fargo region and ETC as the heat design. Therefore, a vertical steel storage tank having a volume of 60L with an aspect ratio of around 2 was built. Having decided on the dimensions of the storage tank, the next important design element is the condenser coil. As illustrated earlier, an 'Indirect mode' of heating is adopted in the present study. In the 'Indirect mode,' a heat exchanger (HX) is utilized to transfer absorbed solar heat from the working fluid to the storage tank [8]. An immersed type heat exchanger was fabricated using the same type of copper piping used in fabricating the U-tubes of ETC [9]. One of the main requirements of a heat exchanger is, it must facilitate the complete condensation of vapor thereby maximizing the heat rejection in the storage tank [10].

B. Data Acquisition and Processing System

As per the design procedure detailed in the previous section, a thermosyphon water heating system was built and the performance of the SWH system was monitored and controlled by a personal computer-based data acquisition system. The system was installed with the essential instrumentation which was used to measure the key parameters of the system. Collector surface temperatures, storage water tank temperature, as well as temperature of CO_2 at various locations of the system were measured by using J-type thermocouples with an accuracy of ±0.2 °C. The high CO_2 pressures at various locations of the systems were measured, using pressure transmitters with an accuracy of ±0.25%.

With respect to solar radiation, a solarimeter was utilized to measure the intensity of the global solar radiation from sun.The schematic diagram of the system is reproduce here for easy reference (Fig. 4), which details the locations of the instrumentation within the SWH system.

The water temperature in the storage tank and CO_2 temperature at various locations of the system were measured, using J-type thermocouples. Due to possible drift in the thermocouple readings as well as data acquisition errors associated with the reference temperature sensor, the error associated with the thermocouple readings was taken to be ±0.2 °C sheet.

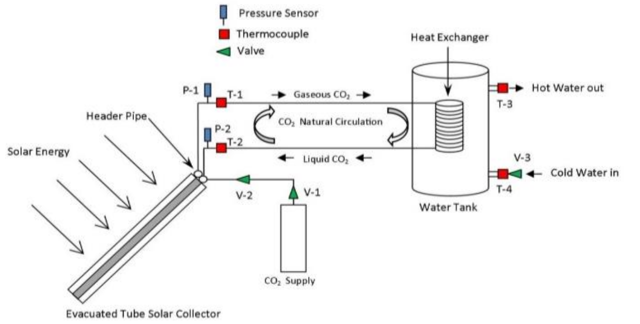


Figure 4: Schematic Diagram of the CO_2-based Thermosyphon SWH

The RSR2 is a rotating shadow band radiometer which was used in this study to measure the global radiation, ambient temperature, wind speed as well its direction, and relative humidity. The data measured was retrieved and processed using RSR CR1000 logger net software from the various sensors. The heart of the monitoring system was a personal compatible computer which was connected through a USB cable to the data acquisition system and was utilized to record the data.

C. Experimental Procedure

Based on the design procedure described in the previous sections, a prototype of a simple thermosyphon SWH system using supercritical CO_2 as the working fluid was designed and installed at the North Dakota State University. The system employs a high performance evacuated tube collector as a heat collecting device, a hot water storage tank (60L) with an immersed heat exchanger (HX) as a condenser ($0.04m^2$), a set of valves, high-accuracy sensors, and a data acquisition system.

A CO_2 cylinder of capacity 7 kg with hand operated valve was used to charge the U- shaped heat removal tubes. The cylinder was connected to main heat removal circuit through high pressure stainless steel valve which could withstand up to 40 MPa. As shown in Fig. 4, Valve 1 (vent valve) helps to relieve the CO_2 pressure, which facilitates the disconnection of the CO_2 reservoir. 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. ZInitially, Valve 1 and Valve 2 were kept open while charging the system, and once the pressure got stabilize to 6 Mpa, the valve of the supply tank, Valve 1 and Valve 2 shut off. However, Valve 1 was immediately released, to vent the excessive CO_2 in the supply line connecting the CO_2 reservoir.

Once the collection system had been charged with CO_2, the system was exposed to sun to gain thermal energy. The collector was located at the North of Dolve hall facing south at a tilt angle of 45° N (optimized for the latitude of Fargo, ND); also it was positioned in such way that it was fully illuminated avoiding any shadows effects.

A typical cycle begins with, R744 (CO_2) set in motion by thermosyphon action. It gets heated in the evacuated tube solar collector. The heating in the solar collector aids a rise in CO_2 temperature, creating a supercritical CO_2 high temperature state [12][13]. This supercritical CO_2 passes through the outlet header pipe to the storage tank. The high temperature and high pressure CO_2 vapor then rejects the heat to the water through the condenser in the storage tank. Once heat is transferred, low temperature CO_2 exits the condenser and move back down to the collector system through the inlet header pipe. One cycle of the operation is thus completed and the system is now ready for the next cycle. Circulation of CO_2 from the collector to the storage tank and vice-versa is affected by buoyancy forces.

Collector surface temperature, storage water tank temperature, and temperature of CO_2 at various locations of the system were measured, using J-type thermocouples. The high CO_2 pressures at various locations of the systems were measured, using pressure transmitters. A solar meter was used to measure the intensity of the global solar radiation incident on the collector surface. The above measuring processes were controlled and monitored by personal computer-based data acquisition software. The data was recorded at 5 min intervals in a data logger, which was used for the data analysis.

Figure 2: Evacuated Tube Collector

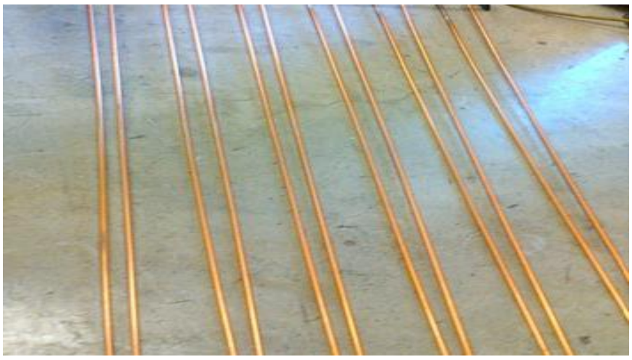


Figure 3: U-tubes Design

A range of tests were performed to determine the performance of the rmosyphon SWH system under various conditions. The experiments were conducted to study the influence of various operating parameters such as storage volume, initial tank temperature etc. on the overall performance of a CO_2 assisted SWH system. A summary of the parametric study has been presented in Table 1

Test Conditions	Initial tank temperature					Storage Tank Volume				
	5˚C	7˚C	10˚C	15˚C		65L	55L	60L	45L	
				x		x				
(a) When storage volume changes and the inlet water temperature remain constant				x			x			
				x				x		
				x					x	
				x						
(b) Volume remain constant but the inlet temperature varies										
	x							x		
		x						x		
			x					x		
				x				x		

Table 1: List of Various Operational Parameters

III. RESULTS AND DISCUSSIONS

Experiments were carried out to study the feasibility and performance of the proposed system using CO_2 as working fluid for Fargo, ND weather conditions. Given the time frame, experiments were performed, for about five months from February up to June 2013. However, the thermosyphon system could not be tested entire day length because both winter and early spring of the year 2013 in North Dakota experienced harsh weather conditions compared to previous years. Most of the days were cloudy and could not get sufficient solar radiation to conduct the test. Even during summer, often the weather was inconsistent due to frequent rain and cloudy conditions. Since it was not practical to carry out experiments for the entire day length, only the operation histories of “1-2” hours during winter, “2-4’ hours (spring), and “6-8” (summer) for typical days are presented for illustration.

Having established a set of typical results on the performance of the system, the effect of varying individual parameters such as storage tank volume, tank inlet temperature etc., was studied subsequently. Several operating parameters are varied to obtain the optimal performances of the system in terms of useful heat gain, heat recovery efficiency, and collector efficiency.

A. *Effect of Storage Tank Volume*

To ensure the reliability of the system design, a proper size of the storage is essential. In order to study the effect of tank volume on the system performance, tank volume of sizes 45L to 65L were chosen to carry out the experiments.

Figures 5-7 illustrates the effect of storage tank volume on the useful heat gain by the collector, collector efficiency and heat recovery efficiency. From Figure 5, it can be clearly seen that, with increase in the tank volume, the energy gain by the collector also increases. 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 (Fig. 6).As the storage tank volume increases from 45L to 65L the time- averaged heat recovery efficiency increases from 40 to 50%.

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. With the increase in the storage volume, the time-averaged collector efficiency increases from 45% to 70% (Fig. 7). However, beyond the storage tank volume above 65 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 60-65 liters m^{-2} turns out to be the optimum size for the proposed design.

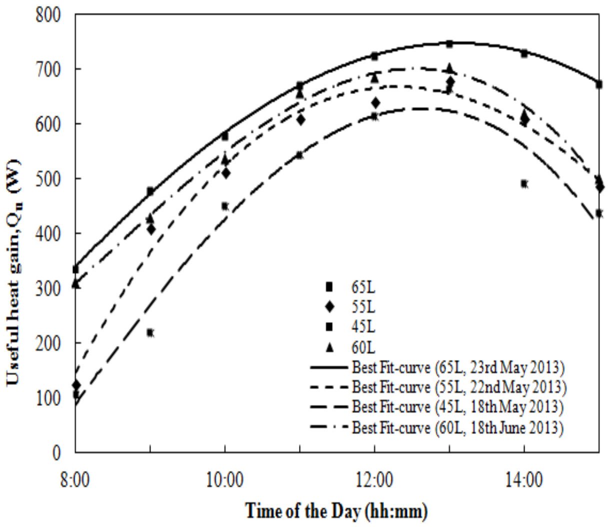


Figure 5: Effect of Storage Volume on the useful Heat Gain

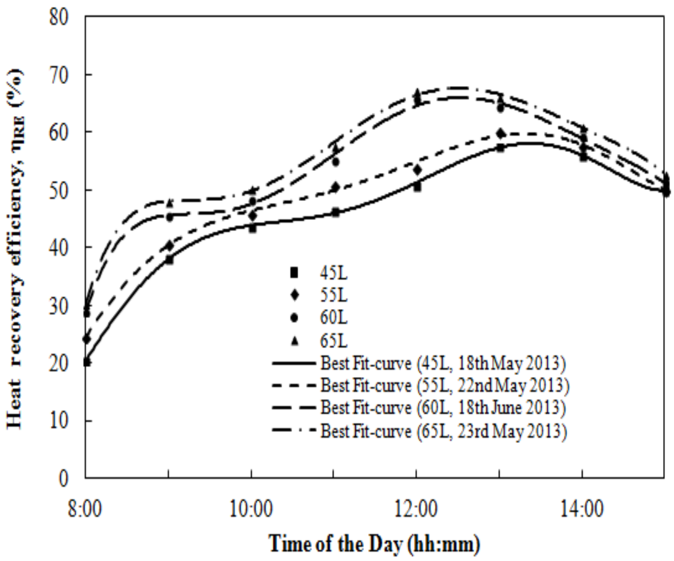


Figure 6: Effect of Storage Tank Volume on Heat recovery Efficiency

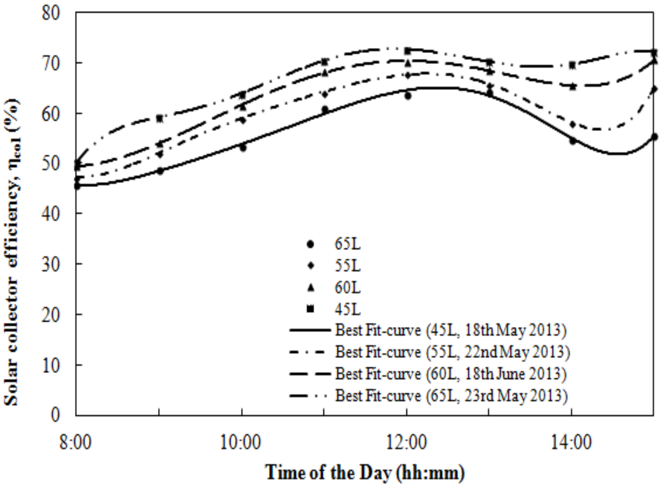


Figure 7: Effect of Storage Volume on Solar Collector Efficiency

B. *Effect of Inlet Tank Temperature*

To determine the effect of inlet tank temperature on the system performance different inlet tank temperature between 5 °C to 15 °C were chosen for comparison. For a given tank volume of 60 L, the effect of different inlet tank temperature on the system performance are shown in Figs. 8-9. From Fig. 8, it should be noted that, lower the initial tank temperature, the rise in storage tank temperature reduces. For an initial tank temperature of 15 °C, the system attained a maximum temperature of about 50 ˚C, against of only 40 °C (for initial tank temperature of 5 °C). This is because, if the initial water temperature in the storage tank is low, the rate of condensing temperature decreases which leads to marginal decrease in evaporating temperature.

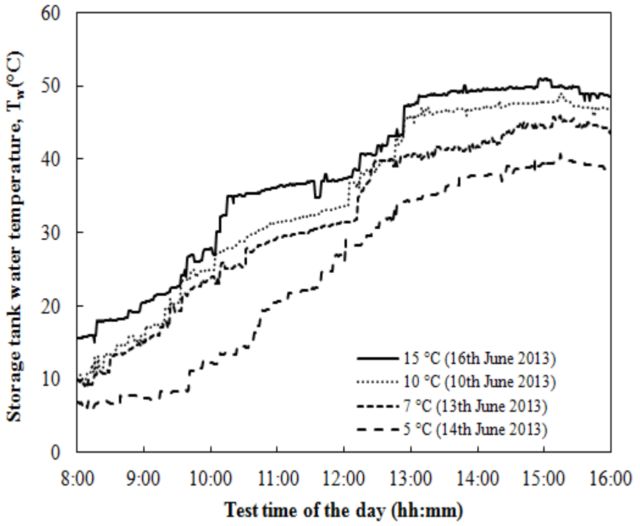
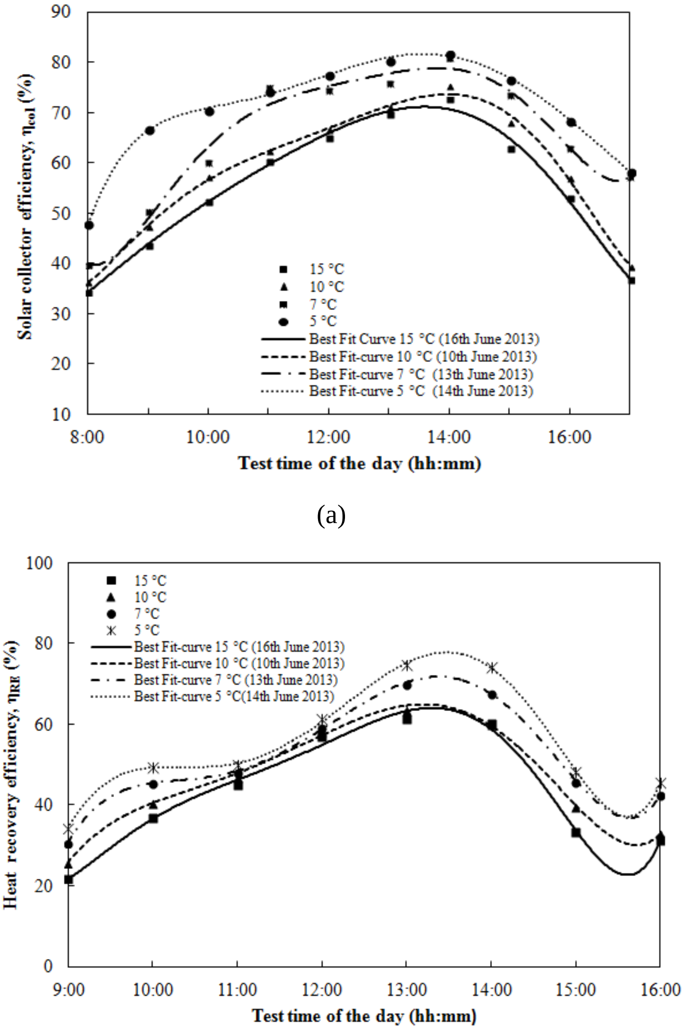


Figure 8: Effect of Initial Tank Temperature on Rise in Tank Water Temperature

Also, it could be apparent from Fig. 9, 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. As the initial tank temperature decreases from 15°C to 5°C, the time-averaged collector efficiencies increases from 55% to 70%. 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.



(a)

(b)

Figure 9: Effect of Initial Tank Temperatures on the System Performance: (A) Solar Collector Efficiency (B) Heat Recovery Efficiency

C. *Seasonal Performance of the System*

Figure 10 shows the performance of a CO_2 assisted water heating system on typical days with clear sunshine during the sequential months of Feb-June 2013. It can be seen that in late winter (February), although the CO_2 has an increase in temperature, it cannot effectively heat the water in the storage tank. This is because, the fiberglass insulation used for the storage tank could not prevent heat losses when exposed to extremely low ambient temperatures (around-10 ˚C). Preliminary results have indicated that even during extreme winter conditions it is possible to affect CO_2 heating. Thus, the energy gain can be effectively harnessed for water heating purposes through the heat pump technique. However, it is evident from the calculated results that a thermosphoning system is not suitable for solar adverse regions (Fargo, ND) even during late winter and early spring months. However, the CO_2 assisted water system could provide useful heat gain during the late spring as well as summer period. Testing during May and June show a significant increase in storage tank water temperature, compared to the late winter and early spring months of February, March, and April.

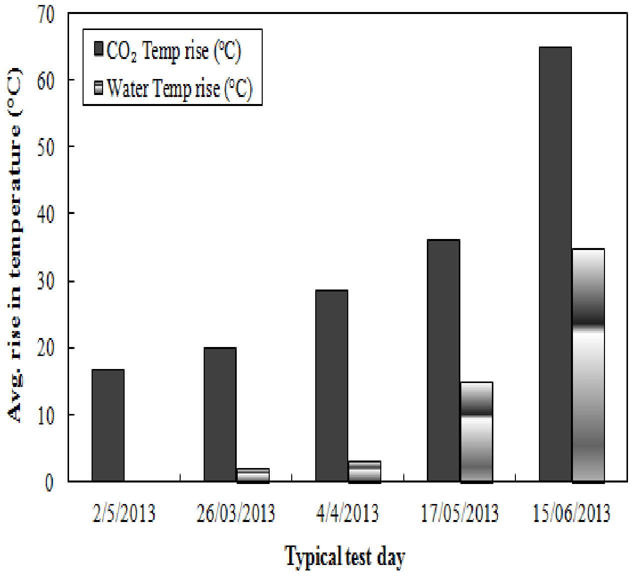


Figure 10: CO_2 Temp and the Correspondence Avg Rise in Tank Temp for Typical Days of Different Month

Furthermore, the variations in the performance factors, such as: the averaged solar collector efficiencies and heat recovery efficiencies on typical days for the period of April to June are shown in Fig. 11.The time-averaged collector efficiencies varies from 40%-65%.

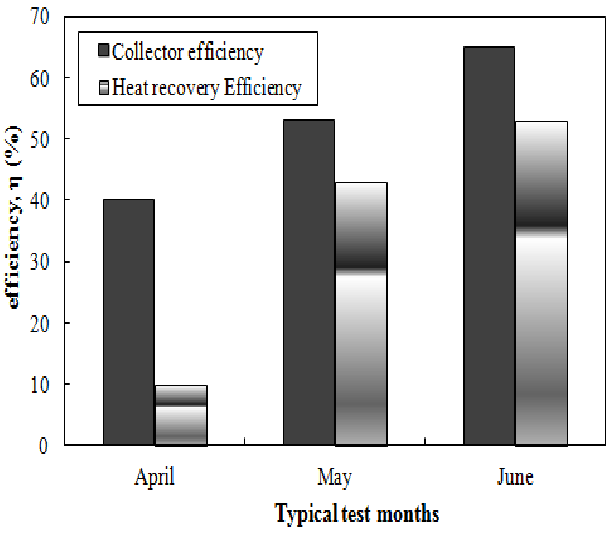


Figure 11: Time-avg Collector and Heat Recovery Efficiencies for Typical Days of Different Month

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 was determined based on the measured collector temperature and water temperature in the storage tank, under different weather conditions. Results showed that: (a) the potential of using CO_2 as the working fluid in SWH systems when need to be operated in solar adverse regions (b) as the storage tank volume increases, the time- averaged heat recovery efficiency increases, (c) an increase in initial tank temperatures affects the decrease in system efficiency and marginal decrease in collector efficiency. However, thermosyphon based SWH system is not recommended for winter conditions. A suggestion for further studies is to investigate the exact economic analysis is required to be done to estimate its market feasibility, especially compared to conventional solar water heater.

Nomenclature

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})
I_T	total solar radiation

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