EXPERIMENTAL INVESTIGATION ON THERMOSYPHON SOLAR WATER HEATER USING CARBON DIOXIDE AS WORKING FLUID

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ABSTRACT

Carbon dioxide (CO_2) is one of the most promising alternative natural refrigerants as it is non-flammable, non-corrosive, and non-toxic to the environment. In comparison to other refrigerants, CO_2 has a minimal effect on the global warming potential (GWP) and ozone depletion potential (ODP); it is a natural refrigerant that does not deplete the ozone. For supercritical carbon dioxide, a small change in temperature or pressure can result in a large change in density, especially close to the critical point. Encouraged by the above idea, simple solar water heater using supercritical carbon dioxide as a working fluid is designed and fabricated. Its performance under solar-adverse conditions such as low ambient temperature and low solar radiation intensity has been investigated and is presented in this paper.

Key Words

Carbon dioxide, solar water heater, refrigerants, insolation

1. INTRODUCTION

Cost effective energy acquisition and consumption would forever be an essential for a nation's economic prosperity and growth. Energy can be obtained from several sources, but in the past, fossil fuels have been the most profitably gathered and consumed source. Over that span, the destructive environmental consequences of fossil fuel consumption were not fully understood or fully addressed. As technology and awareness has grown and evolved, and import-independent, inexhaustible, and clean energy acquisition methods have been developed for the betterment of the humanity [1].

Solar power is inexhaustible, clean, and is one of the best candidates for fossil fuel replacement [2]. 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. One emerging alternative water heating method is solar water heating (SWH). Many studies have been carried out in the field of solar water heating to improve the thermal efficiency of SWH system [3-19], which mainly includes the water-in-glass evacuated tube SWH systems. To develop a reliable and efficient SWH system for winter conditions in solar adverse region such as Fargo, North Dakota, constraints derived from low ambient temperatures and low solar radiation intensity had to be met. The main design considerations include the type of collector chosen, shape of the absorber tube, and the selection of the working fluid.

With regard to the type of collector used, for the desired passive system, evacuated tube collector (ETC) and a flat-plate collector (FPC) are more commonly employed. Evacuated tube collectors differ from flat plate solar collectors by containing a selective coating layer and a vacuum insulation layer around the absorber element, which allows ETC to have high heat extraction efficiency [18]. To further increase the efficiency of the system, heat losses are reduced by the vacuum encompassing the perimeter of the tube. These design differences make ETC's more versatile, and more effective in cold regions. To improve the system performance, an ETC is redesigned to suit the specific system operation characteristics. ETC can attain high temperatures very easily. They are a good fit especially for cold regions as ETC have proven to collect heat even in environments below freezing. Figure 1 depicts the overall configuration of the ETC. The tubes are constructed in multiple layers to produce desirable heat transfer qualities. The selective coating translates the solar energy spectrum into heat generation. This produces greater thermal efficiency under bright sunshine conditions and also attains high efficiency in diffuse sunlight conditions.

The second addressed consideration is the shape of absorber tube [19]. For instance, Perez et al. [20] confirmed that the glass ETC with a semi-cylindrical shaped absorber tube could absorb approximately 16 % more energy than an ETC with a flat-plate shaped absorber tube. Kim and Seo [19] introduced several potential designs of the absorber tube and investigated the performance of the four different shapes of absorber tubes. Results had shown that a "U-tube" placed inside a circular fin assures the best heat transfer performance amongst the four different designs. Therefore, a U-shape absorber tube with two input and output manifold pipes are designed and implemented, in the present work.

The final design task is the selection of a working fluid which plays a very salient role in the development of an efficient, cost effective and environmentally friendly SWH system that can function even when exposed to low ambient conditions. In this study, Carbon dioxide (CO_2) is selected as a working fluid. CO_2 is a non-freezing, non-volatile, non-flammable, non-corrosive, low cost, and non-toxic medium [21]. It does not need to be recovered or reclaimed when repairing or disposing of the equipment but can be exhausted into the atmosphere with negligible impact. Although CO_2 has a minimal effect on the global warming potential, it is a natural refrigerant that has no impact on ozone depletion [22]. Compared to other working fluids, the thermodynamic and transport properties of CO_2 are favorable in terms of heat transfer. Its volumetric refrigeration capacity is 3-10 times higher than CFC (chlorofluorocarbon), HCFC (hydrochlorofluorocarbon) and HFC (hydrofluorocarbon) refrigerants. Leaks in a CO_2 system do not present the safety or environmental hazard of the other refrigerants. As well as being environmentally benign, carbon dioxide's thermophysical properties make it one of the most promising natural refrigerants for water heating and other applications requiring a high temperature increase [Table1]. One property of CO_2 which distinguishes it from other refrigerants is its low critical point i.e. 31.1^{o} C at 73.7 bar (Fig. 2). These properties make CO_2 an ideal working fluid in sub-zero temperatures with low solar insolation. Several experimental studies have been conducted on SWH system using CO_2 as working fluid [23-26]. Based on the above properties and design concepts, a new solar water heater is designed.

2. EXPERIMENTAL MODEL

In this study, the SWH system is designed and constructed to harness solar energy effectively and efficiently for heating applications in solar-adverse regions like Fargo, North Dakota. A schematic diagram of evacuated tube SWH system using CO_2 as working fluid is shown in Fig. 3. In this optimized design, the supercritical CO_2 flow is based on natural convection. The system consists of an evacuated tube collector as a heat collecting source, a hot water storage tank with an immersed heat exchanger (HX), Valves, high-accuracy sensors and data acquisition system.

The heat collecting unit consists of U-pipe ETC (6 tubes) mounted on an aluminum base, with 45° angle inclination. The ETC has high solar absorbance ranging between 0.90-0.92 and possess a low emissivity value of 0.193. The absorbed heat from the ETC is conducted through the inner glass tube wall and removed by the heat removal fluid through copper tubing fabricated into the "U-tube" configuration. Based on pressure rating (12 MPa) and operational temperature range (-15°C to 90°C), the copper tubing having dimension of 12.7 mm OD with 6.35 mm ID are chosen. The copper tubes are inserted in the inner tube with aluminum fins connecting the outer arm of the "U-tube" to the inner wall of the glass tube. According to the authors' best knowledge; there exists no literature reporting about ETC with U-shape copper tubes. ETC with stainless steel "U-tubes" are used generally [25]. In the present experimental set-up, evacuated tube solar collector of 1.15 m^2 (gross area) is used. The heat output from the ETC is delivered to the storage tank through a helical shaped heat exchanger immersed in it

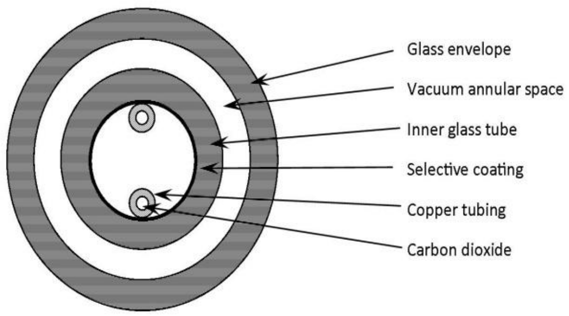

Fig. 1: Cross-sectional view of the evacuated tube solar collector.

As shown in Fig. 3, three valves are utilized in the system. Valve 1 functions as a venting valve, and is installed at the CO_2 filling loop to empty the CO_2 from the system. It relieves the pressure, which facilitates the disconnection of the CO_2 reservoir/supply. Valve 2, is a high pressure needle valve which is installed at the inlet of the solar collector to charge the system from the CO_2 supply (Fig. 3). Valve 3, an automatic valve, is installed at the inlet of the storage tank, to adjust the water flow depending on the water temperature.

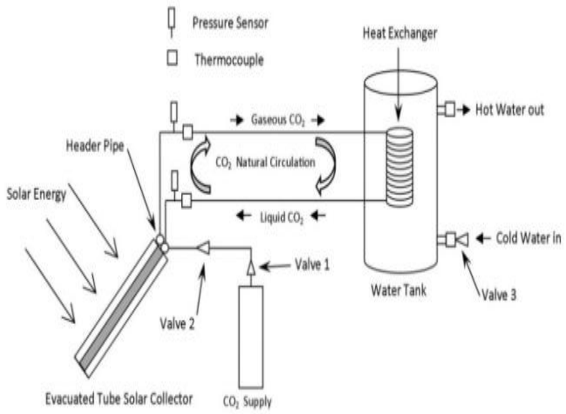

Fig. 3: Schematic diagram of the solar water heater.

Four J-type thermocouples and two pressure transmitters are mounted at various locations in the system to measure CO_2 temperatures and pressures (Fig. 3). A pyranometer is mounted near the collector to measure the instantaneous solar radiation via data acquisition software. To reduce heat losses, fiber glass insulation is used to insulate the storage tank.

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 hot header to the HX. The 30 gallon water storage tank used in the experimental set-up is made up of stainless steel, which is placed at the height of the up riser [26]. 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.

Fig. 4: Front view of the solar water heater.

The proposed design (Fig. 4) provides an environmentally-friendly alternative for heating needs and can be easily mounted anywhere on a wall or roof. This design 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. The other components of the system can be combined in a compact way and installed inside a building to avoid the adverse weather related issues.

TABLE 1: Environmental Benefits of CO_2 [27]

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

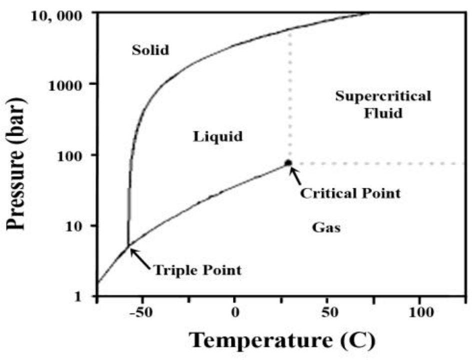

Fig. 2: CO_2 Phase Diagram [21].

3. RESULTS AND DISCUSSION

One of the main objectives of the study is to test the feasibility of the system under adverse winter weather conditions. Two environmental properties that predominately dictate system performance are the solar radiation (I_T) and the ambient temperature (T_a). These two inputs are monitored, and the subsequent heat transfer potential of the CO_2 refrigerant is evaluated based on the outlet and the inlet temperatures of CO_2 in the collector. Based on this data, the system performance factors such as useful heat gain and collector efficiency are calculated [28].

$$Q_u = F'A_c\left[I_T(\alpha\tau) - U_L(T_f - T_a)\right] \tag{1}$$

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

$$m = \left[\frac{U_L}{\lambda\delta(1+U_L/C_B)}\right]^{1/2} \tag{3}$$

$$F = \frac{tanh[m\,(W-d)/2]}{m\,(W-d)/2} \tag{4}$$

$$\eta_{col} = \frac{Q_u}{I_T A_c} \tag{5}$$

The system requires a steady level of solar radiation input to ensure the collector performance is at its best. Test data collected on February 5, 2013 is presented in this paper. Figure 5 shows that the radiation received was good and it had clear sunshine hours from 10:30 am to 2:30 pm. During the test period it was observed that the average ambient temperature and solar radiation values were -12 °C and 380 W/m^2 respectively.

The system was charged with CO_2 until the maximum system pressure of 5.5 MPa was achieved, and then was exposed to sun. It was observed that the temperature of CO_2 was gradually increasing and the variations of the measured CO_2 temperature at the outlet and the inlet of the collector is shown in Fig. 6. During the test hours, the CO_2 temperature varied from 6°C to 12°C at the collector outlet. At 12:00 noon, the CO_2 temperature reached approximately 11°C, despite an ambient temperature was at about -13°C. At such low ambient temperatures and low solar insolation conditions, it is difficult to generate such temperature-gain with conventional solar water heaters. This improved design has successfully generated about 20°C rise in temperature. This is because, when the temperature of CO_2 is close to its supercritical state, even a small change in pressure and temperature results in dynamic changes in its thermo-physical properties.

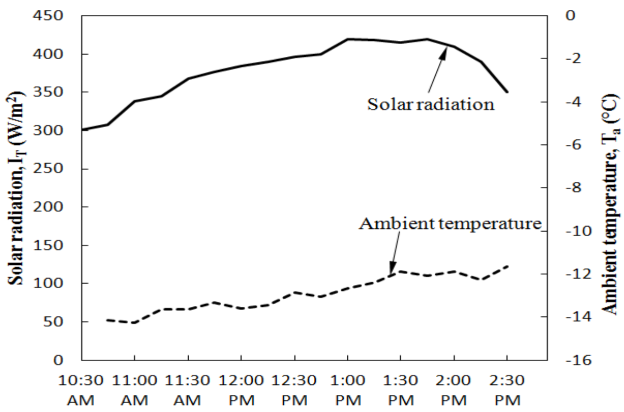

Fig. 5: Solar Radiation and Ambient Temperature Vs Time of Day.

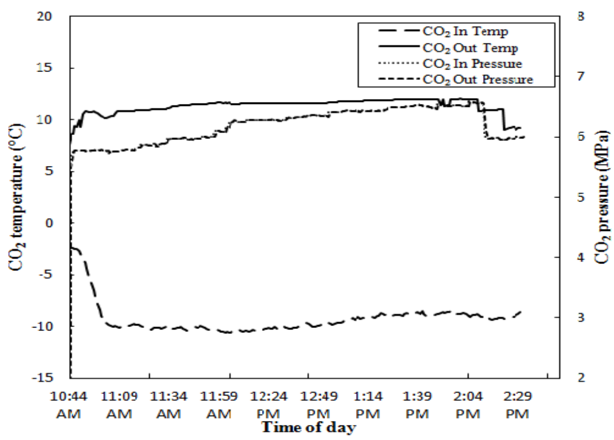

Fig. 6: CO_2 Temperature and Pressure Vs Time of Day.

Figure 6 shows the pressure data of CO_2 both at inlet and outlet conditions of the collector. It could to be seen that at the outlet of the collector the CO_2 pressure ranges from 5.5 MPa to 6.5 MPa at 10:44 am to 2:30 pm, respectively. During test hours, it is noticed that not only CO_2 temperature, but also CO_2 pressure in the collector are influenced by solar radiation. The changes in CO_2 temperature and CO_2 pressure at the collector outlet have similar trends. During the initial hours of exposure, a constant raise in CO_2 temperature and CO_2 pressure is noticed. However, both temperature and pressure was found to decrease drastically because of unexpected cloudy weather conditions.

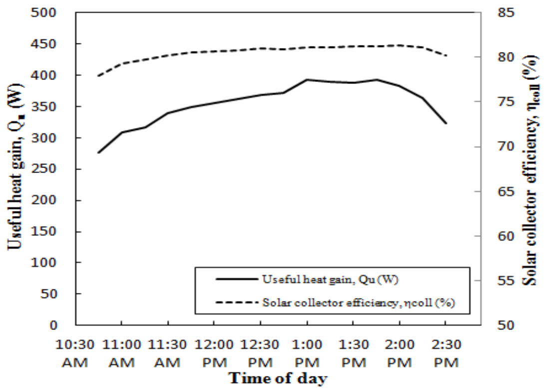

Fig. 7: Useful Heat Gain and Collector Efficiency Vs Time of Day.

The collector useful heat gain (Q_u) and the collector efficiency are plotted in Fig. 7. From the figure, it could be clearly seen that the gain in thermal energy is always stable around 355 W. Based on the data obtained, the time averaged collector efficiency (η_{col}) is calculated around 81%. The results obtained from the present study are encouraging as it signifies that CO_2 can serve as an efficient working fluid compared to water, especially when exposed to low ambient conditions.

4. CONCLUSION

In the present study, an efficient, cost effective, and environmentally friendly SWH system that is functional under low ambient temperatures had been designed and tested. Based on experimental measurements, CO_2 temperature and CO_2 pressure had shown to increase with solar radiation, and the collector efficiency is found to be 81%. This efficiency reflects a net heat gain of 355 W which could meet the domestic water heating purposes. For future studies, modifications need to be made to the present study to monitor overall system efficiency. However, the preliminary testing has confirmed that CO_2 can be a potential candidate for solar water heaters.

5. NOMENCLATURE

A_C the outer surface area of absorber tube, m^2
C_B bond conductance, W/ (m K)
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, W/(m K)
Q_u useful energy gain, W
T_a ambient temperature, K
T_f mean temperature of the working fluid, K
U_L overall loss coefficient, W/ (m^2 K)
W the circumferential distance between the U-tubes, m

Greek

δ the thickness of the copper fin, m
η solar collector efficiency
λ conductivity of copper fin, W/(m K)
α absorptance

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7. REFERENCES

(1) Energy Information Administration, Energy consumption and expenditure tables of the 2005 residential energy consumption survey, EIA, Washington, DC (2005) Accessed January 2001. http:www.cia.gov/emcu/recs/2005/c&e/detailed_tables2005 c&e.html

(2) Ruchi Shukla, K. Sumathy, Phillip Erickson, Jiawei Gong. Recent Advances in the Solar Water Heating Systems: A Review. Renewable and Sustainable Energy Reviews 19 (2013) 173–190

(3) Close DJ. The performance of solar water heaters with natural circulation. Solar Energy. 1962;6:33-40

(4) Ong KS. An improved computer program for the thermal performance of a solar water heater. Solar Energy. 1976;18:183-91

(5) Sodha MS, Tiwari GN. Analysis of natural circulation solar water heating systems. Energy Conversion and Management. 1981;21:283-8

(6) Grossman G, Shitzer A, Zvirin Y. Heat transfer analysis of a flat-plate solar energy collector. Solar Energy. 1977;19:493-502

(7) Huang BJ. Similarity theory of solar water heater with natural circulation. Solar Energy. 1980;25:105-16

(8) B. Norton and S.D. Pobert, Natural circulation solar energy simulated systems for heating water. Appl. Energy 11, 167-173 (1982)

(9) M.F.Young and J.B. Bergguam, Performance charactestics of a thermosyphon solar domestic hot water system. ASME J. Solar Energy Engng 103, 193-199 (1981)

(10) G.L. Morrison and D.B.J.Ranatunga, Thermosyphon circulation in solar collectors. Solar Energy 24, 19-198 (1980)

(11) K. C. Ng, C. Yap, T. H. Khor, Outdoor testing of evacuated-tube heat-pipe solar collectors, Proceedings of the Institution of Mechanical Engineers 2000; 214(part E): 23-30

(12) P.A.Hobson and B.Norton, A design nomogram for direct thermosyphon solar-energy water heaters. Solar Energy 43, 85-95 (1989)

(13) Redpath DAG, Eames PC, Lo SNG, Griffiths PW. Experimental investigation of natural convection heat exchange within a physical model of the manifold chamber of a thermosyphon heat-pipe evacuated tube solar water heater. Solar Energy. 2009;83:988-97

(14) Budihardjo I, Morrison GL. Performance of water-in-glass evacuated tube solar water heaters. Solar Energy. 2009;83:49-56

(15) Huang J, Pu S, Gao W, Que Y. Experimental investigation on thermal performance of thermosyphon flat-plate solar water heater with a mantle heat exchanger. Energy. 2010;35:3563-8

(16) Jaisankar S, Radhakrishnan TK, Sheeba KN. Experimental studies on heat transfer and friction factor characteristics of forced circulation solar water heater system fitted with helical twisted tapes. Solar Energy. 2009;83:1943-52

(17) Jaisankar S, Radhakrishnan TK, Sheeba KN, Suresh S. Experimental investigation of heat transfer and friction factor characteristics of thermosyphon solar water heater system fitted with spacer at the trailing edge of Left–Right twisted tapes. Energy Conversion and Management. 2009;50:2638-49

(18) Redpath D.A.G., S.N.G.Lo and P.C. Eames , Experimental investigation and optimisation study of a direct expansion thermosyphon heat-pipe evacuated tube solar water heater subjected to a northern maritme climate. International Journal of Ambient Energy. 2011 31:2, 91-100

(19) Kim Y, Seo T. Thermal performances coMParisons of the glass evacuated tube solar collectors with shapes of absorber tube. Renewable Energy. 2007;32:772-95

(20) Perez R, Seals R, Anderson J, Menicucci D. Calculating Solar Radiation Received by Tubular Collectors. Journal of Solar Energy Engineering. 1995;117:341-4

(21) Kim, M.H, Pettersen, J, and Bullard, C.W.2004. Fundamental process and system design issues in CO_2 vapor compression systems. Progress in Energy and Combustion Science. Vol 30 pp 119-174

(22) Zhang, X. R., Yamaguchi, H., Fujima, K., Enomoto, M., and Sawada, N., “Theoretical analysis of a thermodynamic cycle for power and heat production using supercritical carbon dioxide”, Energy, Vol.32 (4), pp.591-599, 2007

(23) Riebere R, Naturally circulating probes and collectors for grounded-coupled heat pumps. International Journal of Refrigeration 28:1308-1315, 2005

(24) Ochsner K, Carbon dioxide heat pipe in conjugation with a ground source heat pump (GSHP). Applied Thermal Engineering 28:2077-2082

(25) Zhang XR, Yamaguchi H. An experimental study on evacuated tube solar collector using supercritical CO_2. Applied Thermal Engineering. 2008;28:1225-33

(26) Adnan Shariah, B. Shalabi, Optimal design for thermosyphon solar water heater. Renewable Energy, 1997;11:351-361

(27) Vestergaard, N.P, and Robinson, M.2003.CO_2 in refrigeration Applications. Retrieved October 30, 2009, from Air Conditioning Heating RefrigerationNews:News:www.achrnews.com/Articles/Feature_Article/cc753504ddc5a010VgnVCM100000f932a8c0

(28) Liangdong Ma, Zhen Lu, Jili Zhang, Ruobing Liang, Thermal performance analysis of the glass evacuated tube solar collector with U-tube. Building and Environment 45 (2010) 1959-1967