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An Experimental Study of Evacuated Tube Solar Collector by using Supercritical CO2 as Working Fluid

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Abstract: *A solar collector using supercritical CO2 as working fluid is proposed in this paper in order to understand heating of water to increase effective heating of collector for longer duration. The selection of a working fluid plays a very significant role in the development of an efficient, cost effective, and environment friendly solar water heating system.CO2 is one of the most promising alternative natural refrigerants. For supercritical carbon dioxide, a small change in temperature or pressure can result in large change in density, especially in the state close to the critical point, thus natural convective flow of the supercritical carbon dioxide can be easily induced by solar heating. In order to investigate and estimate Co2 based solar collector experimental set-up will be construct and test to study the basic collector characteristics, such as temperature in the collector, and collector performances. The solar radiation has influence on the CO2 states, being liquid, liquid-gas or supercritical state in the test, it affects the CO2 pressure and temperature. The current results indicate that the circulation of supercritical CO2 flow in this solar heater system can be easily induced by natural convection. Without a driving pump, the highest heat recovery efficiency can be up to 56%, which is higher than the efficiencies of other conventional solar water heater systems. It is also found that the natural convection in the system is mainly affected by the intensity, stability, and continuity of solar radiation in a day. Furthermore, the amount of hot water supplied by this system is adequate for an ordinary house-hold usage.*

Keywords: *Solar Evacuated Tube, Supercritical Co2, Solar Radiation, Copper Tubes, Natural Circulation of Co2*

I. Introduction

Increasing population and their demands with economical development in the world results into decreasing conventional resources. In the past few years , it has becomes obvious that fossil fuel resources (coal, oil, gas) will vanish if the present rate of consumption is maintained in the future and fossil fuel era will gradually come towards an end. The combustion of a fossil fuel causes a serious problem, therefore it is necessary to find a solution that will support the increasing energy demands without causing ecological damage. For these purpose solar energy comes to a most promising and an environmentally clean and available in adequate quantities in almost all parts of the world. Due to these abundance availability of solar energy with environment friendly operation and low operating and maintenance cost the use solar water heating system increasing day by day.

The environmental pollution and the energy crisis have brought serious problems to the world environment and sustainable development. The applications of solar energy to electricity generation and heat collection/refrigeration become important, and have received considerable attention. The solar collector is the heart of these solar energy utilization systems. During the last two decades a number of researchers have worked on developing new and more efficient solar collector or improving existing ones. For example, the performance of a water-inglass evacuated tube solar heater is investigated and factors influencing the operation of water-in-glass collector tubes are discussed. The results show the existence of inactive region near the sealed end of the tube which might influence the performance of the collector. However, almost all the previous studies to improve collector performances are based on the methods of changing solar collector structures, improving the absorptivity of the coating or reducing heat loss of the collector. And as far as the authors are aware, few studies on the influence of working fluids on collector performances appear to exist in the open literature. Solar collectors can drive machines only if the working fluid temperature is greatly in excess of the normal boiling point of water. Among the working fluids, water can only be used above 0°C and also water has to be used in a high working pressure. Air thermodynamic cycle efficiency is very low. Ammonia is toxic and silicon oil has high viscosity and difficult to handle. In addition, from the viewpoint of protecting the ozone layer and preventing global warming, there is now strong demand for technology based on ecologically safe ‘natural’ working fluids. Carbon dioxide (R-744) is a non-flammable and non-toxic fluid and friendly to environment.

CO2 has a very low Ozone Depletion Potential (the ratio of the impact on ozone of a chemical compared to the impact of a similar mass of CFC-11) and Global Warming Potential (the ratio of the warming caused by a substance to the warming caused by a similar mass of carbon dioxide). The thermodynamic and transport properties of CO2 seem to be favorable in terms of heat transfer and pressure drop, compared to other typical fluids. The critical pressure and temperature of CO2 are 7.38 MPa and 31.1°C, respectively. This critical temperature is much lower than those of other working fluids.

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II. Parts of System

Tube (ETC):

This type of collector has a higher efficiency than FPC; this is due to less heat loss issues compared to FPC. However, it is not as competitive as FPC due to its high initial cost. It consists of evacuated tubes to minimize heat losses,copper heat pipes for a fast heat transfer, aluminum casing to support the other components and keep the integrity of the system. ETC systems have a number of important factors that make them more efficient and have less heat losses; one of them is the shape of the absorber tube which can absorb up to 16% more energy than FPC.We studied the various types of solar collectors that can be used and choosed the evacuated solar tube collector

Figure: Solar Evacuated Tubes

Storage Tank

The storage tank is the component that stores hot water to provide it at the required temperature at the required time. It also plays an important role in imposing the performance of the system; they are generally composed of steel, plastic, concrete, fiber glass, or any other material used for water storage. Steel tanks are the most used due to the ease in installing them. Thermal losses are commonly known for the factor that dictates the efficiency of the storage tank. Transferring maximum energy from the bottom of tank where hot water inlet is situated, and cold water inlet canbe in the top, as a result, water mixing is minimized, hence heat losses are also minimized, many types of storage tanks exist in the market (Horizontal, vertical, collector-integrated.)

Working fluid

The working fluid (heat transfer fluid) is responsible for the energy transfer between the collector and the water in the tank loop. The fluid absorbs heat from the absorber and transfers it via a heat exchanger to the water in the storage units. Several fluids are used as heat transfer fluid in solar systems such as air, water, hydro-carbon oils, Glycol/water mixture among others.However, for the choice of the heat transfer fluid, many parameters have to be taken into consideration (boiling point, freezing point, viscosity, thermal capacity), but the commonly used are water and air, because they are non expensive and nature friendly, without mentioning the high thermal capacity of water and noncorrosive properties of air.Many studies were made to increase the efficiency of the heat transfer fluid loop.Several designs were discussed such as refrigerant fluids with a heat pump, among other fluids such as R-11 refrigerant for thermosyphonic effect systems, CFC were commonly used for their inflammability and noncorrosive properties, however since CFC are very harmful to the environment and since the introduction of HCFC, CFC fluids were banned from use.Recent studies have introduced CO2 as a promising HTF. It is inflammable, non-corrosive and non toxic. It can be used in systems with heat pumps. Such system would produce water at 90°C. a study showed that water at 55°C -75°C can be achieved with a heat pump of 4kw with CO2 as HTF. There are many developing opportunities in this field, and several options to be studied; but an economical study has to be made to validate the choice of CO2 as working fluid.We chose CO2 because CO2 can be one of the promising transfer media of heater systems. Besides being non-toxic, non- flammable, and stable at an ordinary temperature and having lower environmental impact, CO2 also easily reaches the critical point (the critical pressure and temperature are 7.38MPa and 31.1C, respectively) and shows a favorable thermodynamic property at its supercritical state.

III. Constructional Details

We filled the CO2 in the copper tube structure. Firstly we constructed the structure of copper tubes by using brazing method. Copper tubes were used to fill the CO2 gas in it.Filled the CO2 gas in the copper tubes by using a non-return valve,into the copper tubes structure.

Figure: CAD model

Figure: Actual Model

IV. Methodology

1.Selecting the physical properties of the super critical CO2 during the process. 2.Constructing the Lab-scale set-up including controlling system.

3.Experimentation – preliminary and as per design of experimentation. 4.Confirmation of the experimental results.

5. Comparing the experimental results with conventional systems.

V. Experimental Calculations

Calculation for normal evacuated solar tube collector

1) To evaluate how well the solar hot water heater performed, we will calculate its efficiency

$$Efficiency = \eta = \frac{Heat\ Energy\ Out}{Heat\ Energy\ In} = \frac{Q_{out}}{Q_{in}}$$

2) So first, we'll need to calculate how much energy was put into to the system by finding the total power, Pin

From above, Pin = 200 Watts

3) Finally, we need to convert heat power (Pin) to heat energy (Qin). Power is an instantaneous measurement (like miles per hour for measuring the speed of a car). To get to energy (like total miles traveled by the car), we take the power and multiply it by the TIME that the system had that power.

$Q_{in} = P_{in} \times \Delta t$Watt-hours $Q_{in}= 200\times 4 = 800$ Watt -hours

4) For this exercise, we'll convert our heat energy (Qin) , from "Watt-hours" to units of "BTU" which stands for British Thermal Units. Just like comparing inches to centimeters, BTUs are the American (IP) units and Watt-hours are the international (SI) units. One Watt-hour = 3.41 BTUs.

$Q_{IN} = Q_{IN}$ (UNITS OF WATT-HOURS) × (3.41BTU/WATT-HOUR)=BTUS

$$Q_{in}= 800 \times 3.41 = 2728 \text{ BTU}$$

5) Next, we need to figure out how much heat energy our solar hot water heaters were able to collect (Q_{out}) and use from the heating lamps (our simulated sun)! The equation we will use to calculate how much heat energy (Q_{out}) we were able to transfer to our wateris:

$Q_{out} = m \times C_p \times \Delta T$

6) Let's start by determining the total mass(m) of the water that we heated.We recorded the total volume(V) of water in gallons.First, we'll convert the total volumefrom gallons to ft^3 (cubic feet), knowing that one gallon is equal to $0.1336ft^3$.

V = (V in gallons) × ($0.1336ft^3$/gallon)=3.038 × 0.1336ft^3

= $0.406ft^3$

7) To convert volume (v) to mass (m), we need to know the densityof water, which is equal to62.42 lbs/ft^3. So,

$$M = (V \text{ IN } FT^3) \times (62.42LBS/FT^3) = LBS \quad M=0.406 \times 62.42 = 25.35 \text{ LBS}$$

Now that we have the mass (m) of the water, the next term we need to help us calculate the heat energy (qout) collected by our water heaters is the specific heat (cp) of the material being heated, thematerial being water in this case. specificheat is a property of a material that describes how much heat energy it takes to warm that material up. every material has its own specific heat. for water, the specific heat, in ip units, is:cp ofwater = 1.0 btu/(lb-°f)

8) finally, we need to figure out the last term in our equation: the temperature difference (dt) of the water. this temperature difference (dt) of the water was achieved by putting heat energy (qout) into the system:

$$\Delta t = t_f - t_i = 127.4 - 86\ °f$$
$$\Delta t = 41.4°f$$

9) now, plug in three values to calculate how much heat energy (q_{out}) our water absorbed from the water heater.

$$Q_{OUT} = M \times C_P \times \Delta T = \underline{25.35} \times \underline{1} \times \underline{41.4}\,BTU$$

$$Q_{OUT} = 1049\ BTU$$

10) now that we've calculated how much heat energy (q_{in}) was put into to the system (our solar water heaters) and how much heat energy (q_{out}) we were able to get out of the system in order to increase the water temperature, we can determine the efficiency our hot water heater:

$$\eta = \frac{Qout}{Qin}$$

$$= \frac{1049}{2728} = 0.385$$

$$= 38.5\ \%$$

Calculation for evacuated tube collector with CO2

1) To evaluate how well the solar hot water heater performed, we will calculate its efficiency

$$Efficiency = \eta = \frac{Heat\ Energy\ Out}{Heat\ Energy\ In} = \frac{Q_{out}}{Q_{in}}$$

2) So first, we'll need to calculate how much energy was put into to the system by finding the total power, Pin

From above, Pin = 200 Watts

3) Finally, we need to convert heat power (Pin) to heat energy (Qin). Power is an instantaneous measurement (like miles per hour for measuring the speed of a car). To get to energy (like total miles traveled by the car), we take the power and multiply it by the time that the system had that power.

$Q_{in} = P_{in} \times \Delta t$Watt-hours $Q_{in} = 200 \times 4 = 800$ Watt -hours

4) For this exercise, we'll convert our heat energy (Qin) , from "Watt-hours" to units of "BTU" which stands for British Thermal Units. Just like comparing inches to centimeters, BTUs are the American (IP) units and Watt-hours are the international (SI) units. One Watt-hour = 3.41 BTUs.

$Q_{IN} = Q_{IN}$ (UNITS OF WATT-HOURS) × (3.41BTU/WATT-HOUR)=BTUS

$Q_{in} = 800 \times 3.41 = 2728$ B TU

5) Next, we need to figure out how much heat energy our solar hot water heaters were able to collect (Q_{out}) and use from the heating lamps (our simulated sun)! The equation we will use to calculate how much heat energy (Q_{out}) we were able to transfer to our wateris:

$Q_{OUT} = M \times C_P \times \Delta T$

6) Let's start by determining the total mass(m) of the water that we heated. We recorded the total volume(V) of water in gallons. First, we'll convert the total volumefrom gallons to ft^3 (cubic feet), knowing that one gallon is equal to 0.1336 ft^3.

$V = (V \text{ in gallons}) \times (0.1336 ft^3/gallon) = \underline{3.038} \times \underline{0.1336} ft^3$

$$= 0.406 ft^3$$

7) To convert volume (v) to mass (m), we need to know the densityof water, which is equal to62.42 lbs/ft^3. So,

$$M = (V\ IN\ FT^3) \times (62.42 LBS/FT^3) = LBS\quad M = 0.406 \times 62.42 = 25.35\ LBS$$

Now that we have the mass (m) of the water, the next term we need to help us calculate the heat energy (qout) collected by our water heaters is the specific heat (cp) of the material being heated, the material being water in this case. specific heat is a property of a material that describes how much heat energy it takes to warm that material up. every material has its own specific heat. for water, the specific heat, in ip units, is:cp of water = 1.0 btu/(lb-°f)

8) finally, we need to figure out the last term in our equation: the temperature difference (dt) of the water. this temperature difference (dt) of the water was achieved by putting heat energy (qout) into the system:

$$\Delta t = t_f - t_i = 147.2 - 86\ °f$$

$$\Delta t = 61.2°f$$

9) now, plug in three values to calculate how much heat energy (q_{out}) our water absorbed from the water heater.

$q_{out} = m \times c\ p \times \Delta t = \underline{25.35} \times \underline{1} \times \underline{61.2}$btu

$$Q_{OUT} = 1551.42BTU$$

10) now that we've calculated how much heat energy (q_{in}) was put into to the system (our solar water heaters) and how much heat energy (q_{out}) we were able to get out of the system in order to increase the water temperature, we can determine the efficiency our hot water heater:

$$\eta = \frac{Qout}{Qin}$$

$$= \frac{1551.42}{2728}$$

$$=0.5687$$

$$= 56.87\ \%$$

VI. Conclusion

A solar collector using supercritical CO_2 as working fluid is proposed in the paper. The basic characteristics of the solar collector have been experimentally studied. An experimental set-up was constructed and tested. The measured data show that the CO_2 temperature and pressure increase with the solar radiation. And the CO_2 mass flow rate in the loop also increases with the solar radiation. The variation of the CO_2 pressure and mass flow rate with the solar radiation is much different from the collector using liquid as working fluid, which makes the thermal output control of the CO_2-based collector more complicated and difficult than the traditional collector. During the most time of the tests, the time-weighted average efficiency of collecter using working fluid as water is found at above 38.5% and averaged collector efficiency with using Co_2 as working fluid is measured at 56.87%, which is higher than the collector using water as working fluid. But further investigation is needed in the future to study the nature of the supercritical CO_2 flow and heat transfer in the collector

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