International Research Journal of Engineering and Technology (IRJET) e-ISSN: 2395 -0056
Volume: 03 Issue: 05 | May-2016 www.irjet.net p-ISSN: 2395-0072

Experimental Analysis of Solar Water Heating System Using Supercritical Fluid

Vaibhav Sharadrao Rede[1], A. P. Pathre[2], S. V. Mohitwar[3]

[1]PG Student, Dept. of Mechanical Engineering, GHRCEM, Amravati, Maharashtra, INDIA

[1,2]Assistant Professor, Dept. of Mechanical Engineering, GHRCEM, Amravati, Maharashtra, INDIA

---***---

Abstract - *A solar collector using supercritical CO_2 as working fluid is proposed in this paper in order to understand indirect 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. CO_2 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 the CO_2 based solar collector an experimental set-up was constructed and tested to study the basic collector characteristics, such as CO_2 temperature and pressure in the collector, and collector performances. The solar radiation has influence on the CO_2 states, being liquid, liquid-gas or supercritical state in the test, it affects the CO_2 pressure and temperature. The time averaged collector efficiency (η_{col}) and heat recovery efficiency (η_{RE}) was found to be 45% and 29% respectively. This study shows the potential supercritical CO_2 based solar collector in the field of solar thermal utilization. The results show that the CO_2 temperature, CO_2 pressure and increase with the solar radiation and supercritical pressure maintain even in low solar radiation which is different from those of traditional solar collector using liquid as working fluid.*

***Key Words*: Supercritical CO_2, Solar water heating system, Solar radiation, Collector efficiency, Heat recovery efficiency**

1.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.

1.1 Solar water heater uses in world

Water heating represents about 15% of households energy uses in Europe, 20% in the United States and even 30% in Japan. Switching from electricity and gas to solar water heating could strongly reduce fossil fuel consumption [12].

World solar thermal capacity has increased 4 times since 2000 with two emerging country profiles. On one side countries like Austria, Germany, Turkey etc with a long-term promotion policy have a high share of systems installed per capita and on the other side, a new market for solar water heaters is developing for many countries, in particular in emerging countries, such as China and Brazil. Solar water heating systems have become popular in China, where basic models start at around 1,500 yen (US$235), much cheaper than in Western countries (around 80% cheaper for a given size of collector). It is said that at least 30 million Chinese households now have one and that the popularity is due to the efficient evacuated tubes which allow the heaters to function even under gray skies and at temperatures well below freezing.

China ranks first in terms of installed capacity, with almost 2/3 of the world's capacity. Over the last few years, China has been the leader in solar water heater system additions with 11 million m^2 installed in 2009. In comparison the three countries that had massively invested in capacities during 2009 lagged far behind China with Turkey installed 380 thousand m^2 in 2009, Australia, around 200 thousand m2 and Portugal, 88 thousand m^2. According to preliminary estimates, the solar water heater market is estimated to have risen to about 185 GW in 2010, of which 70% of new capacities were installed in China and 10% in the European Union[18].

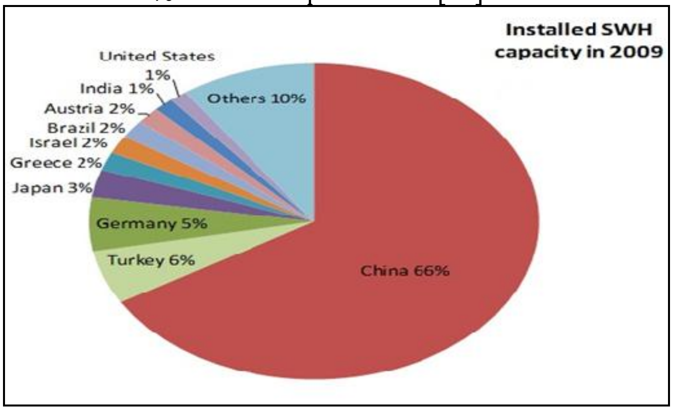

Fig-1: New solar hot water installations during 2009, worldwide[18]

According to preliminary estimates, the solar water heater market is estimated to have risen to about 185 GW in 2010, of which 70% of new capacities were installed in China and 10% in the European Union. The European market for solar water heating contracted again in 2010, by almost 13% after a 10% drop in 2009 due to the global economic crisis in the European Union, the development of solar water heating systems is included in the National Renewable Energy Action Plans by member states and most of European Union countries have set targets for solar heat by 2020[18].

In the USA, where the market is still underdeveloped, SWH systems benefit from a 30% federal tax credit. The influence of promotion tools on the solar water heater market development is particularly noticeable in Australia where a policy was launched in 2000 that created tradable renewable energy certificates linked to solar water heating system systems.

1.2 Solar water heater uses in India

India is a country with more than 1.2 billion people accounting for more than 17% of world's population. It is the seventh largest country in the world. It faces a formidable challenge in providing adequate energy supplies to users at a reasonable cost. Thus the energy challenge is of fundamental importance. Economic growth, increasing prosperity and urbanization, rise in per capita consumption, and spreads of energy access are the key factors that would be responsible for substantially increasing the total demand of electricity, thus there is an emerging energy supply and demand imbalance. According to the potential for renewable energy in India-2012, the anticipated energy and peaking shortage in the country is estimated to be 10.3 per cent and 12.9 per cent, respectively, in 2011 and 2012 [20].

The total installed collector area increased from 119000 m^2 in 1989 to 525000 m^2 in 2001; and to estimated 3.1 million m^2 by December 2009. The annual average growth in solar water heaters in installations in India during 1995-2008 was 16.8%. Further, this period (1995-2008) can be divided into three phases [19].

- 1995-2000: The average annual growth during this period was 8.2%. A study reported that in 2001, almost 80% of the solar water heaters installations were in the commercial and industrial sectors.
- 2001-2004: The average annual growth rate this period was 20.6%. The market for residential systems became pre-dominant.
- 2004-2008: The average annual growth rate this period was 24.6%.

1.3 Solar water heating with supercritical CO_2 as working fluid

In solar water heating system the solar collector is the heart of the system, in recent years a lot of studies were carried out to improve the collector performances which are mainly by changing the collector size, structure, shape, material, reducing the great loss or by improving the absorptivity of the coating. In solar adverse region we cannot utilize water as working fluid in solar water heating system. This is due to the fact that water based collector are susceptible to freezing. The selection of a working fluid for the solar water heating system plays an important role for the development of an environment friendly, efficient, low cost and can also function in low surrounding temperature. 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.

In past decades, interest in using CO_2 as working fluid increase because of the pressing chlorofluorocarbon (CFC) problem. It is believed that rapid increase in CO_2 into the atmosphere could trigger green house effect. Therefore it is necessary to develop energy systems that halt the green house effect and stabilize or recycle CO_2 as working fluid, which can also gives purpose to a CO_2 capture and storage. The property which make CO_2 as a ideal alternative working fluid to be used in low solar radiation and zero temperature region which is its low critical point. The critical pressure and temperature of CO_2 are 7.38MPa and 31.1°C respectively. The purpose of using supercritical carbon dioxide as working fluid is at close to the critical point small change in pressure and temperature can result in large change in thermo physical properties like density which varies significantly as function of temperature and allows a strong natural convection[3].

Several studies have been initiated utilizing CO_2 as the working fluid, recently Ruchi Shukla have made a detailed study on the collector characteristics with CO_2 as the working fluid in evacuated tube collector. 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. It has been reported that the time averaged collector efficiency (η_{col}) and heat recovery efficiency (η_{RE}) are calculated around 58% and 45% respectively in solar adverse regions, it shows the potential of using CO_2 as the working fluid in solar water heater system [1].
Literature shows that most of the CO_2 utilized solar water heater systems are evacuated tube collector. In this study, an attempt has been made to design and fabricate a simple flat plate collector solar water heater using supercritical CO_2 as the working fluid to investigate for its feasibility and characteristics.

2.Experimental setup

The solar collector is a most important component in the solar water heating system. To make sure the system is feasible and further efficient a solar collector with good heating characteristics is required. In proposed project to study the characteristics of CO_2 as a working fluid in a flat plate collector solar water heating system is designed, constructed and tested. The details of the experimental set-up are shown in Fig-2

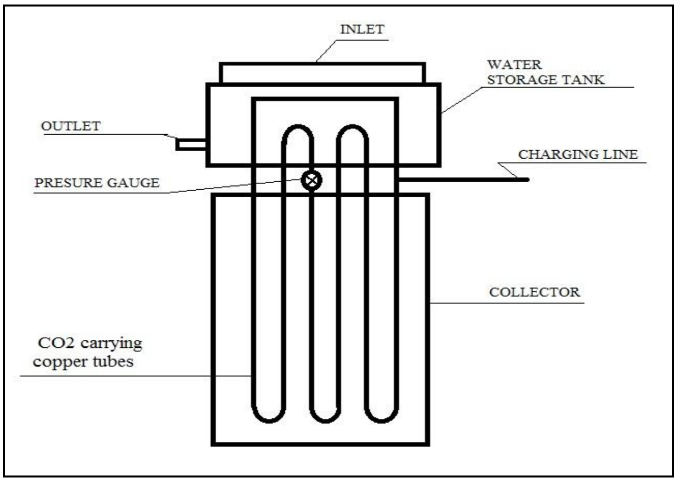

Fig-2: Line diagram of solar water heater

The flat plate solar collector of 0.36 m2 area is used to effectively heat the CO_2 to a high temperature state eventually to a supercritical state. The solar collector consist a copper plate (1 mm thickness) coated with a selective solar absorbing coating. This black colour selective coating with a high solar absorptivity 0.95 and low emissivity 0.193 is applied on the surface of the copper plate. On absorber plate 6 black coated heat pipe with external diameter 10 mm and internal diameter 7 mm is joined in such a way that the heat is absorbed by the copper plate is conducted to the copper tube and transfer heat to the CO_2 with less losses. However, in this study copper was used to effect of higher temperature's when exposed to solar advance conditions due to its high thermal conductivity.
The flat collector rested on a backing insulation layer of 100 mm and all 4 side insulation layer of 50 mm with glass wool. Acrylic sheet (92% transmissivity) was chosen as the upper glazing for the collector. The air gap between the glass cover and the absorber plate was 50 mm, this transparent sheet was secured to the top of the frame by rubber gasket and aluminum angles, which permitted thermal expansion but prevented the entrance of dust and rain. The storage tank design also play's a important role to ensuring the effective of the solar water heating system. In the present study passive mode of heating is adopted for 13 liter capacity of storage tank. The flat plate collector and storage tank were integrated together to form a closed loop. The copper tube's containing high temperature supercritical CO_2 coming from solar collector inserted into a storage tank in a serpentine manner forming a integrated closed loop between collector and storage tank.

The pressure gauge is mounted on the copper tube located in between flat plate collector and storage tank. The refrigerant filling port is also given in between collector and water storage tank to the one copper tube with non return valve shown in fig-2. Collector surface temperature, storage water tank temperature,CO_2 temperature at various locations of the system were measured by using probe temperature gauge with an accuracy of ± 0.1^{0}C.

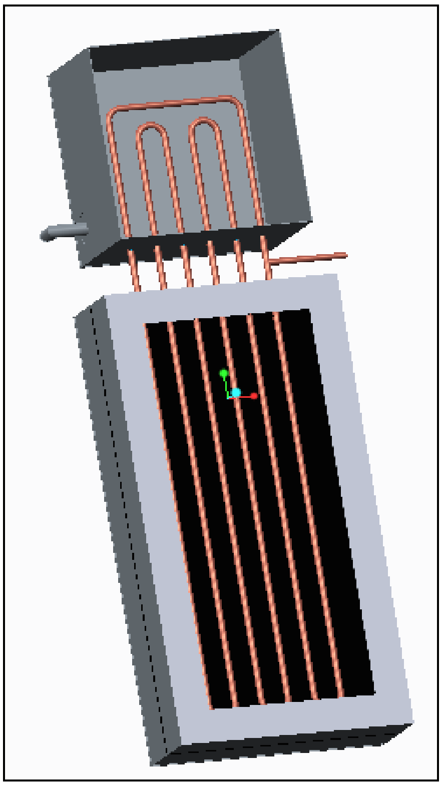

Fig-3: CAD Model

3.Result and discussion

3.1 Flat plate collector performance with supercritical CO2

Flat plate collector with supercritical CO_2 as working fluid is tested to study the changing performance characteristics like CO_2 pressure, CO_2 temperature, useful heat gain and heat recovered by water, storage water temperature, collector efficiency and heat recovery efficiency changes with solar radiation intensity with respective changing time.

3.1.1 Solar radiation and air temperature changing with time

Available solar radiation energy effects the performance of solar device, even the diffused radiation and presence of green house gas in particular region has shows significant role on solar based device.

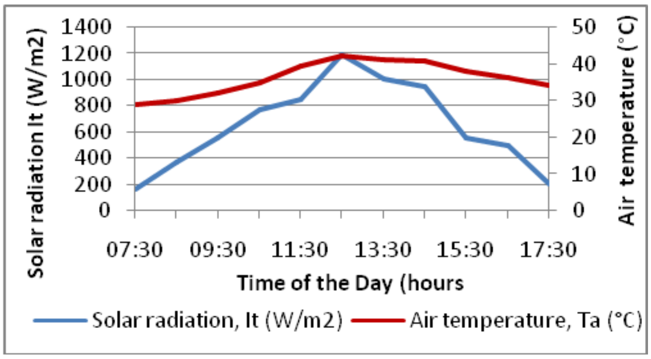

Fig-4: Variation of Solar radiation and Air temperature vs. Time of the day

Thus the solar radiation behavior for particular day is observed and discussed. Fig-4 shows that during the test day from morning to noon the air temperature increases with increasing solar radiation intensity and air temperature decreases from noon to evening with decreasing solar radiation intensity.

During the test day sky is clear and time averaged solar radiation and ambient temperature were 680 W/m^2 and 36 °C respectively.

3.1.2 CO_2 pressure and CO_2 temperature changing with time

The CO_2 pressure is measured by pressure gauge and CO_2 temperature is measured by probe temperature gauge in the experimental test. CO_2 at a pressure of 7 MPa is charged into the system and it was exposed to sunlight. During test hours, it was noticed that not only CO_2 temperature but also CO_2 pressure in the collector, was influenced by solar radiation. This variation of CO_2 pressure and CO_2 temperature values are measured in experimental test. Measured data of CO_2 pressure and CO_2 temperature at collector outlet with the test time are shown in Fig-5.

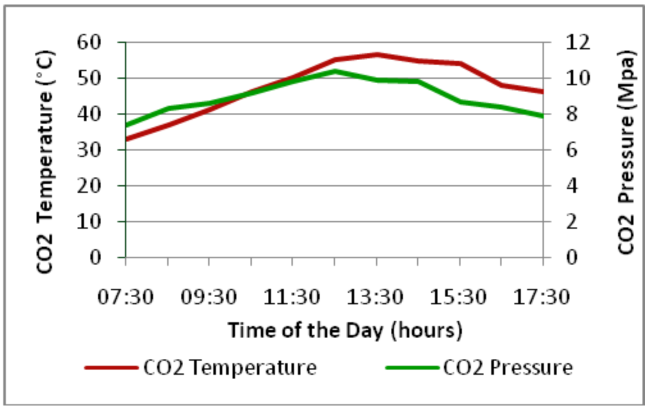

Fig-5: Variation of CO2 Temperature and Pressure vs. Time of the day

During the initial hours of exposure, a steady rise in CO_2 temperature and pressure was noticed. After the supercritical pressure (7.5MPa) slightly increasing in pressure results in large change in pressure is observed. It is due to the fact that, when CO_2 temperature is close to its supercritical state, even a small change in pressure and temperature results in dynamic changes in its thermophysical properties [1]. After 12:30 solar radiation intensity decreases which results in decreasing pressure, even though pressure is decreases the slightly increase in temperature is observed .

3.1.3 Storage tank water temperature

Furthermore, measured data of storage tank water temperature with the test time are shown in Fig-6. The gain in solar radiation intensity results into an increase in CO_2 temperature which reflected in terms of rise in storage tank water temperature.

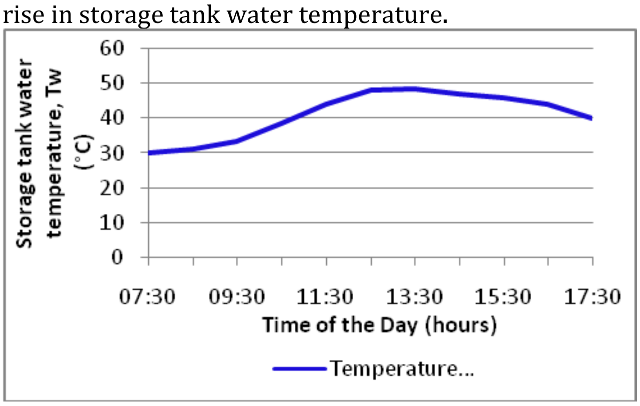

Fig-6: Variation of Storage tank water Temperature vs. Time of the day

In proposed system the water temperature rises with time till 13:30 and after that it get slightly down ,this is due to the decreasing CO_2 temperature with decreasing solar radiation intensity, the insulation, condenser design, wind are the factors responsible for the low water temperature. The water temperature is decreasing from 48.5 °C to 40°C, to maintain it at same temperature choice of insulation and proper heat exchanger design is necessary. In addition to the insulation wind speed is also plays dominant role, During the test day wind speed is recorded as 1.9 m/s at 13:30 and 2.4 m/s at 17:30.

3.1.4 Collector and water storage tank heat gain

Fig-7 shows the collector useful heat gain and recovered heat by water vs. time of the day, it is observed from it collector useful heat and heat recovery by water 197 W and 57 W respectively increases till 12:30 and after that get decreases, this due to increase in CO_2 temperature reflects the heat gain collector and storage tank and looses heat as decrease in CO_2 temperature.

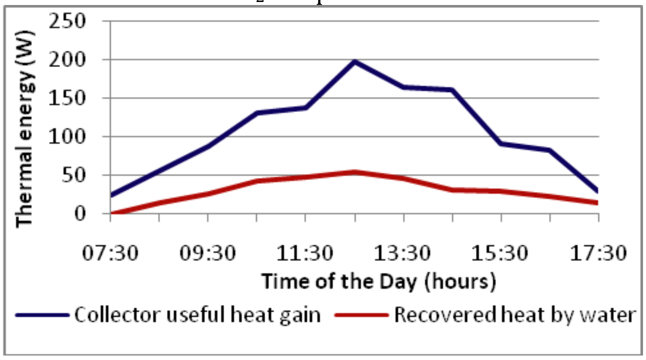

Fig-7: Variation of Collector useful heat gain and Recovered heat by water vs. Time of the day

High temperature range has been observed in collector heat gain as compare to the heat recovered by storage tank water this is due to the design error in heat exchanger while integrating the CO_2 close loop with storage tank. Therefore, to attain higher heat recovery efficiency, storage tank and heat exchanger design must be optimized, in addition to the utilization of an appropriate insulation.

3.1.5 Collector efficiency and heat recovery efficiency

Based on the data obtained which shown in Fig-8, the time averaged collector efficiency (η_{col}) and heat recovery efficiency (η_{RE}) are calculated as 45% and 29% respectively. In Fig-7, blue colour line shows the collector efficiency recorded as 40.8% at 7:30, at the initial test also the proposed flat plate collector recorded a good efficiency. The collector efficiency is depends on solar radiation intensity, area of collector quantity of working fluid circulated and insulation. By considering these factors for proper design of flat plate collector can results into a improving collector efficiency. It is known that heat transfer performance is proportional to the flow rate and velocity and further the Reynolds number [2].

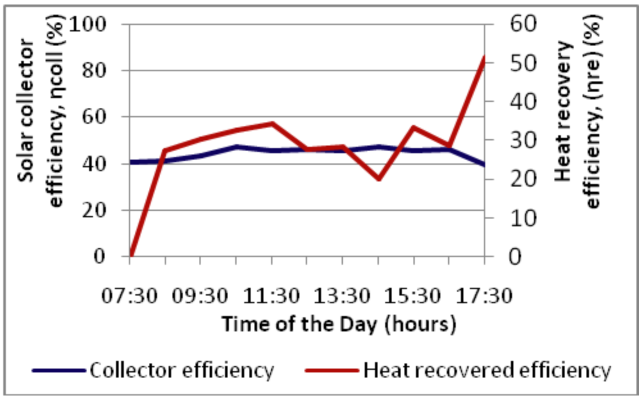

Fig-8: Variation of Collector efficiency and Heat recovered efficiency vs. Time of the day

The heat transfer is found to be enhanced greatly in the case of forced convection case, in proposed methodology the supercritical CO_2 flow is natural convective, so with a forced convection higher collector efficiency is expected .

The heat recovery efficiency range is observed as 51% with day time average efficiency 29% (Fig-8), as mentioned earlier, due to the heat exchanger and condenser design limitation low average efficiency is recorded. Heat recovery efficiency is increases upto 28.33% between 7:30hours to12:30 hours, then it decrease to 19:90% up to 14:30 hours , one interesting parameter come into noticed in terms of heat recovery efficiency which is after 14:30 hours the heat recovery efficiency started increasing, the reason behind it heat recovery efficiency is inversely proportional to the useful heat gain which is decreases with decreasing solar radiation intensity, in addition to that working fluid CO_2 have very low thermal diffusivity which allow it to store heat , at the end of the day when solar radiation is very low results into the less useful heat gain reflects a higher water heat recovery efficiency which can noticed form fig-7, at 17:30 hours the heat recovery efficiency recorded as 51%.

3.1.6 Outlet water temperature comparison with conventional solar water heater

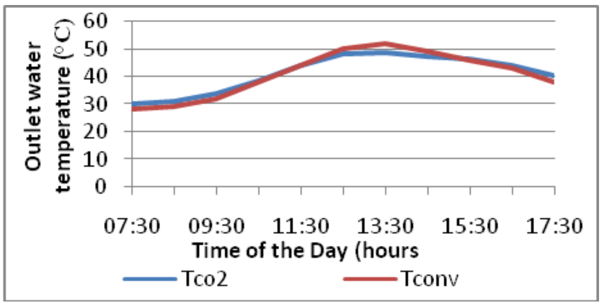

Fig-9 Comparison of outlet water temperature by using CO2 and Conventional water heater vs. Time of the day

Fig-9 shows the variation of outlet water temperature by using CO_2 and conventional water heater. At the initial test, CO_2 using collector maintains a high temperature than conventional water heater, but at the period when highest solar radiation is available conventional heater reach to maximum temperature than proposed method, these variation is occurred due to the different collector are used to compare performance and as stated earlier the error in heat exchanger design of propose method, in addition to that thermo physical properties are also responsible for it.

Fig-10 Prototype Model

4. CONCLUSIONS

In this experiment, solar water heating with supercritical CO_2 as a working fluid is proposed; the basic characteristics of the solar collector have been experimentally studied. Based on the experimental measurements, the following remarks are made. An experimental set-up was constructed and tested. The measured data shows that the CO_2 temperature and pressure increase with increasing solar radiation intensity.

The results indicates that, the time averaged collector efficiency (η_{col}) is recorded around 45% which is more as compare to the conventional flat plate collector and it is cheap in cost as compared to evacuated tube collector. However, the recorded flat collector efficiency is stable throughout the experimental test but it can improve by increasing collector area, number of tubes, tube diameter for increasing quantity of working fluid circulation. The time averaged heat recovery efficiency (η_{RE}) is recorded around 29% it can improve by changing heat exchanger design. Due to passive heating rusting problem can be solved, thus reducing maintenance cost.

This study is made with certain limitation where further investigation can be made to explore more facts on current project.The heat exchanger design can be considered for optimization of maximum heat transfer and may help to recover more heat resulting into better heat recovery efficiency.

REFERENCES

[1] Ruchi Shukla, K. Sumathy, M Raisul Islam, "An experimental study on a density driven water heating system using supercritical CO_2 as working fluid," International journal of environment and resources, vol. 3 (2014) pp 13-21.

[2] X. R. Zhang, H. Yamaguchi, "An experimental study on evacuated tube solar collector using supercritical CO_2 ," Applied Thermal Engineering, vol. 28 (2008) pp 1225-33.

[3] Yamaguchi, N. Sawada, H. Suzuki, H. Ueda, and X. R. Zhang, "Preliminary Study on a solar water heater using supercritical Carbon dioxide as working fluid," Journal of Solar Energy Engineering, vol. 132 (2010) pp132-138.

[4] D. Y. Goswami, F. Xu, "Analysis of a new thermodynamic cycle for combined power and cooling using low and mid temperature solar collectors," Journal of Solar Energy Engineering, vol. 121 (1999) pp 91–97.

[5] Kishan Patel, Mrs. Pragna Patel, Mr. Jatin Patel, "Review of solar water heating system," International Journal of Advanced Engineering Technology, vol.3 (2012) pp 146-149.

[6] S. A. Klein, "A design procedure for solar heating systems," Solar Energy, vol.18 (1975) pp 113-117.A. DUFFLE

[7] D. R. Mills, "Advances in solar thermal electricity technology," Solar Energy, vol. 76 (2004) pp 19–31.

[8] D. Y. Goswami, S. Vijayaraghavan, S. Lu, G. Tamm,

[9] G. L. Morrison, I. Budihardjo, M. Behnia, "Water-in-glass evacuated tube solar water heaters," Solar Energy, vol.76 (2004) pp 135–140.

[10] X. R. Zhang, H. Yamaguchi, K. Fujima, M. Enomoto, N. Sawada, "A feasibility study of CO_2-based Rankine cycle powered by solar energy," JSME International

Journal Fluids Thermal Engineering, vol. 48 (2005) pp 540–547.

[11] Xin-Rong Zhang, Hiroshi Yamaguchi, "Forced convection heat transfer of supercritical CO_2 in a horizontal circular tube," Journal Superscript Fluids vol.41 (2007) pp 412–420.

[12] Soteris A. Kalogirou, "Solar thermal collectors and applications," Progress in Energy and Combustion Science, vol.30 (2004) pp 231–295.

[13] P. Rhushi Prasad, H.V. Byregowda, P.B. Gangavati, "Experiment Analysis of Flat Plate Collector and Comparison of Performance with Tracking Collector," European Journal of Scientific Research, vol.40 (2010) pp 144 -155.

[14] B. Y. H. Liu, R. C. Jordan, "The long-term average performance of flat-plate solar energy collectors," Solar Energy, vol.7 (2003) pp 175-181.

[15] Buchburg, H. Catton, "Natural convection in closed space-a review of application to solar energy collection," Journal of heat transfer, vol.98(1976) pp 98-105.

[16] McAdams, "Heat Transmission," 3rd edition. McGraw-Hill Book, New York, pp 249.

[17] S. P. Sukhatme, J. K. Nayak, "Solar energy-principle of thermal collection and storage" third edition McGraw hill education publication, pp 79-199.

[18] Geraldine Duffour, "Solar water heating in the world: Strong diffusion due to the large impact of incentives, "International Energy Agency (2012).

[19] Narasimhe Gowda, B. Putta Bore Gowda, R. Chandrashekar, " Solar Water Heaters Usage in India – Current Scenario and Vision 2020," International Journal of Recent Development in Engineering and Technology, vol.2(2014) pp16-21.

[20] P. Garg, "Energy Scenario and Vision 2020 in India," Journal of Sustainable Energy and Environment, vol.3(2012) pp7-17.

[21] Chandrasekar, B. Kandpal, "Techno-economic evaluation of domestic solar water heating systems in India," Renewable Energy, vol. 29 (2004) pp 319–332.

[22] P. X. Jiang, Y. J. Xu, J. D. Jackson, "Experimental investigation of convection heat transfer of CO_2 at super-critical pressures in vertical mini-tubes and in porous media," Applied thermal engineering ,vol.24 (2004) pp 1255–1270.

[23] P. Rhushi Prasad, H. V. Byregowda, P. B. Gangavati, "Experiment Analysis of Flat Plate Collector and Comparison of Performance with Tracking Collector," European Journal of Scientific Research, vol.40 (2010) pp 144 -155.