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Review on Evacuated Glass Tube Based Solar Liquid Heaters

[1]Vaibhav P Shah, [2]Dr N M Bhatt
[1]M.E Thermal Engineering, [2]Director
[1]Department of Mechanical Engineering,
Gandhinagar Institute of Technology, Gandhinagar, Gujarat, India
[1]vaibhav.shah155@gmail.com, [2]nmbhatt19@gmail.com

Abstract **- As the world's population quadruple in the last half-century, the demand for energy also severely increased. In order to meet those global energy demands, engineers and researchers have been developing renewable technologies. Solar energy found to be most promising renewable source. Solar energy can be harvested directly in two forms. The first useful form is electricity, which is obtained by exposing a photovoltaic material to sunlight. This technology is referred to as solar photovoltaic. The second useful form is heat; here heat is transferred from sunlight to a working fluid such as heat transfer oil or water. This technology is generally referred to as solar thermal technology. These technologies are useful at either the industries or residences. Here, in this article typical review has been conducted on solar thermal technology based evacuated tube solar collector for heating liquid fluids.**

Index Terms **- Solar liquid heater, Evacuated tube collector, Heat pipe ETC, Water-in-glass collector, U-tube, Vacuum Tube Collector**

I. INTRODUCTION

We are going through the period of energy crisis. It is due to the prolonged use of coal, gas, diesel like fossil fuels. Use of which affects our environment very badly resulting in global warming, ozone layer depletion, acid rain which is not good for mankind. Rapid increased energy prices and the continuous reduction of the Earth's conventional fuel resources as well as certain environmental problems have been the motivation for the recent growing interest in the search for other alternative methods and techniques to be developed and implemented. In order to meet those global energy demands scientists, engineers and researchers all over the world have been developing and investigating performances of renewable technologies. Solar energy found to be most promising from these sources because solar energy can be converted directly in two forms. The first form is electricity and the second useful form is heat. These solar energy conversion technologies are useful in either the industries or residences.

At the residences, owners can produce their own hot water from the Sun to minimise gas and electric energy costs. Two typical solar collectors exist for generating hot water: flat plate collectors and evacuated tube collectors. Evacuated tube collectors are sometimes more expensive, but are claimed to produce a larger water temperature increase from the ambient. Scheel [1] claimed that ETC collectors were also performed better during cloudy, rainy, windy and sometimes snowy days, depending on the installation. Most resources agree, however, that when designing a solar thermal system that includes space heating, the evacuated tube collector is a better option according to the U.S. Energy Information Administration [2].

II. A REVIEW OF SOLAR EVACUATED TUBE LIQUID HEATING TECHNOLOGIES

Evacuated tube collectors (ETCs) are made of two concentric tubes of borosilicate glass which have absorber coating on its inner glass tube outer to absorb most of solar radiation and the novel thing is that there is vacuum insulation between this two glass tubes which suppresses convective heat losses from glass tube. So evacuated tube collectors found to have better performance than flat plate solar collectors for high temperature operations. Many of methods for heat extraction from all glass evacuated tubes had been developed so far. Here, some of the heat extraction techniques are reviewed in detail.

(a)Water heating Solar collectors

Morrison *et al.* [3] analyzed the water-in-glass evacuated tube collector for water heating. In his research he mentioned that evacuated tube solar collectors performed better than flat plate collectors during high temperature operations. Water-in-glass tube collector seemed to be a better option for domestic utilization because of its simplicity and low cost. Many a times it would be difficult to mount the solar water heaters. In order to avoid all those problems, it was essential to study the performance of the evacuated tube at various angles of inclination to check and confirm that if the performance remains same for all angles of inclination. Runsheng *et al.* [4] studied the thermal performance of water-in-glass evacuated tube solar water heaters with different collector tilt angles. They conducted the experiments at two different angles 22° and 46°. There was no significant variation found in daily thermal efficiencies. But this study did not provide the data for other angles of inclinations, particularly for 0° and 90°.

In recent decade, a number of studies have been conducted on evacuated tube solar water heater systems. Budihardjo *et al.* [5–7] investigated the essentials of system such as collector optical efficiency, collector heat loss, storage tank heat loss, and natural circulation flow rate through collector tubes. Kim *et al.* [8] studied glass evacuated tubes with a co-axial fluid conduit inserted in each tube using a one-dimensional model. Han *et al.* [9] performed a three-dimensional performance analysis using computational fluid dynamics. Kim *et al.* [10] examined four different shapes of absorber tube such as finned tubes, a U-tube welded inside a circular fin, a U-tube welded on a copper plate and a U-tube welded inside a rectangular duct using a numerical method and they found the best absorber tube shape for a solar collector. Ma [11], Liang [12], and Duffie [13] analyzed the thermal performance of a glass evacuated tube solar collector based on the energy balance for a U-tube glass evacuated tube solar collector.

With the rapid development in industries, a higher temperature is needed in a number of applications such as air conditioning, refrigeration, building heating, sea water desalination, and industrial heating etc. Evacuated solar collectors do not only supply domestic hot water or heating (below 60°C), but they can also be operated at higher temperature application fields (above 60°C). The performance of the evacuated tube solar water heater system is affected by its design and operation. Currently; concentrated solar collectors are used widely because of their stable performance. In terms of solar water heater systems, CPC is the best choice because it does not need any tracking system and it can decrease the cost of moving parts if the concentration ratio is low. Rabl [14] and Tchinda *et al.* [15], [16] examined a detailed thermal performance of a CPC with a flat, one-sided absorber and a CPC with straight-through evacuated tube was examined by Hsieh [17]. Evacuated tube solar water heater systems with and without CPC reflectors have various advantages and scope. O'Gallagher [18] and Sharma *et al* [19]. Studied the advantages of the different types of CPC evacuated tube solar collectors. However, the geometrical concentration ratio *C* is almost always greater than one or equal to one. In practical applications, a CPC will always be truncated for economic reasons [14]. Thus a mini CPC offers more economic advantages because it can be easily transported, easily installed and maintained for domestic purposes.

According to Shariah *et al.* [20] the optimum inclination angle for a thermosyphon solar water heater varies 0^0 to 10^0 for maximum solar fraction in northern region and varies 0° to 20° for southern region. Investigation carried out by Adsten *et al.* [21] showed that the performance of the vacuum tube collector was better than flat plate collector. Vacuum tube collector was independent of climatic variations. Tang *et al.* [22] stated that T-type collectors annually collect slightly more radiation than H-type collectors. For the site latitude larger than 30°, T-type collectors should be installed with a tilt-angle about 10° less than the site latitude, whereas for H-type collectors without diffuse flat reflector, the tilt-angle should be about 20° less than the site latitude. Chow *et al.* [23] had shown that two phase closed thermosyphon system performed better than single phase open thermosyphon system. Economically both the systems were never compete the flat plate collector but suitable for the high temperature applications. Hossain *et al.* [24] found the performance of a thermosyphon solar water heater through simulation system. Positive collector angle was used for northern hemisphere and for space heating steep tilt angles were the right choice. Solar water heater with a thermosyphon system found 18% higher characteristics efficiency than the conventional system due to reduce heat loss for the thermosyphon solar water heater. Zambolin and Col. [25] presented an experimental validation of one ended evacuated tube collector with and without reflector. The results revealed that optical efficiency showed better with wide range of incident angle by using reflectors and east-west tube alignment were preferred for balancing the heat production between summer and winter seasons.

R.E. Collins *et al.* [26] performed an experiment on flat plate and evacuated tubular collectors in thermosyphon systems. The results confirmed that efficiency per unit area of evacuated tubular collector was substantially greater than that of good quality flat plate collectors even at low temperatures. This performance differences would be greater at higher temperatures. Three novel manifolds of the water-in-glass type for evacuated all glass single ended tubular collectors were investigated for series connection of tubes. The efficiency of heat extraction had been determined by measurement of temperatures at various locations. Yin Zhiqiang *et al.* [27] made measurements for the range of tube inclination (0° to 80°) for two absorber tube diameters. Results indicated that buoyancy effect alone results in efficient heat transfer to the top of the tubes. Manifold designs described were possible low cost solutions to problem of manifold evacuated collectors for sub 100°C heat extraction for domestic purposes. Snail *et al.* [28] developed solar collector with vacuum insulation, spectrally selective coating and non imaging concentration were tested and detailed optical and thermal models were prepared. The outer glass envelope of conventional evacuated tube converted into the profile of non imaginary CRC type concentrator. The collector was given the name Integrated Stationary Evacuated Concentrator or ISEC Collector. The peak thermal efficiency of the ISEC was comparable to that of commercial tracking parabolic troughs with net gain for temperatures below 200°C. The ISEC provided a simple, easily maintained solar thermal collector for the range 100°-300 °C for most of climates and atmospheres. Heat transfer and flow structures inside all glass evacuated tubular collectors for horizontal tube connected to vertical manifold channel for different conditions were investigated using CFD by Louise Jivan Shah *et al.* [29].They achieved the highest efficiency for collector with shortest tube length . The optimal inlet flow rate was around 0.4-1 kg/min. Flow structures in glass tube were relatively uninfluenced by the inlet flow rate. Schmid *et al.* [30] used particular type of manifold (single ended metal riser system) to extract heat from Dewar type evacuated tubular collectors. The heat extraction concept was similar to liquid-in-glass system which had shown to perform very well. However, the additional thermal resistance between the selective surface and the metal tube carrying the collector fluid resulted in a performance reduction.

A computer simulation of the relative performance of certain truncated symmetrical and asymmetrical fixed reflector design for solar energy collection was performed by Mills *et al.* [31].They concluded that (1) Annual solar fractions of 80% to 95% seems to be feasible with a load matching collector used with energy storage. (2) CPC reflectors always gave the best annual output performance per unit of mirror area and the lowest receiver area for situations of constant annual load. (3) Asymmetrical concentrators were most cost effective for strongly seasonally asymmetrical load patterns. (4) Fixed parabolic systems required much more receiver area than the symmetrical CPC and asymmetrical systems. (5) Using a load matching reflector the amount of storage required to achieve solar fractions of total thermal energy of about 90% in residence appears to be much lower. An evacuated flat plate collector for processed steam production had been investigated by Benz *et al.* [32] for the design of system in operating temperatures between 100°C and 150°C. Losses of the absorber had been drastically reduced using ultra low emissive selective absorber, a low pressure krypton filling in the collector casing. Test facility at outdoor showed very high efficiencies of more than 60% at 100°C steam temperature and of 45% at 150°C steam temperature. The operation behaviour of the prototype was always stable and the steam mass quality showed excellent values of nearly 100%.Morrison *et al.* [33] observed that ETC water-in-glass had better performance than flat plate solar collectors using the International Standard test method ISO 9459-2 for a range of locations. Numerical simulations had shown the existence of inactive region near the sealed end of the tube which influences the performance of collector. ETC had better performance than flat plate solar collectors for high temperature operations.

Many of methods for heat extraction from all glass evacuated tubes had been developed and the water-in-glass concept was found to be the most successful due to its low manufacturing cost. Thermal performance of water-in-glass evacuated tube solar water heaters at nights were experimentally investigated by Runsheng *et al.* [34]. Measurements showed that the water temperature in solar tube was always lower than that in the water tank but higher than the ambient air temperature. This signified that the reverse flow in the system occurs at nights. Results showed that the larger the tilts angle of the collector, the higher the reverse flow rate. The reverse flow in the solar water heater was much higher as compared to that in thermosyphon domestic solar water heaters with flat plate collectors but heat loss from collectors to the air due to the reverse flow in solar water heater was very small and only took about 8 to 10 % of total heat loss of systems.

Kim *et al.* [35] investigated the conventional stationary CPC solar collector which was compared with the single axis tracking CPC solar collector and was investigated for improvement of thermal performance by recording outlet temperature, net heat flux flow onto the absorber and thermal efficiency. They found that thermal efficiency of tracking CPC solar collector is more stable and about 14.9% higher than that of the stationary CPC solar collection. Budihardjo *et al.* [36] experimentally studied optical and heat loss characteristics with simulation model of the thermosyphon circulation of water in single ended tubes and found that performance of typical 30 tubes evacuated tube array was lower than typical 2-panel flat plate array for water heating. Solar collector performance was checked by Michel *et al.* [37] for mainly of two designs heat pipe designs and water-in-glass collector design under local weather conditions at eastern coast of the Mediterranean Sea. They carried out experiments with 20 evacuated tubes, their tank and circulation system in months of November to January. The results indicated that heat pipe collectors were better than water-in-glass designs with higher efficiency of 15 to 20%.

Ayompe *et al.* [38] monitored year round energy performance of solar water heaters with 4 m^2 flat plate and 3 m^2 heat pipe evacuated tube collectors under same operating conditions. The annual collector efficiency observed were 46.1% and 60.7% for the flat plate collector and evacuated tube collector respectively with system efficiencies of 37.9% and 50.3% for the same systems. Economic analysis showed that both solar water heating systems were not economically viable because of their very low net present worth and their simple payback periods varied between 13 years and 48.5 years of flat plate collector and evacuated pipe collector respectively. Liang *et al.* [39] have carried out study and experiment on the filled type evacuated tube, in which filled layer was used to transfer energy absorbed by the working fluid flowing in the U-tube. The effects of heat loss co-efficient and the thermal conductivity of the filled layer on the thermal performance of the evacuated tube were analyzed and efficiency of evacuated tube was calculated. It was found that filled type evacuated tube with U-tube had favourable thermal performance and efficiency observed was 12% higher than that of the U-tube evacuated tube with a copper fin. Chow *et al.* [40] experimentally and numerically evaluated performance of the two common types of evacuated tube solar water heater single phase open thermosyphon system and two phase closed thermosyphon system. Result showed that daily and annual thermal performances of two phased Thermosyphon system was slightly better than single phase open thermosyphon system but payback periods for two of them were relatively same because of high initial cost so they proved to be less economical then flat plate collector. They may be suitable for the advanced systems with higher temperature demands. Abdul Waheed Badar *et al.* [41] analysed vacuum tube solar collector with co-axial piping (direct flow type) incorporating both single and two phase flows for different heat transfer mechanisms and flow conditions. Results have shown that for all liquid single phase fluid flow, the collector efficiency decreases with decreasing mass flow rate. No significant reduction in efficiency was observed under partial stagnation. Testing of three thermosyphon heat pipe evacuated tube solar water heater for pumped fluid circulation was carried out by David A.G. Redpath [42]. Thermosyphon evacuated tube solar water heaters both with same area of 2 m^2 was monitored. In which one utilized internal heat pipe condensers while other used external ones. The system with internal condensers was found to be 17 % more efficient.

Performance of an evacuated tube heat pipe solar collector was compared by Dan Nchelatebe Nkwetta *et al.* [43] to a concentrated evacuated tube single-sided coated heat pipe absorber. The aperture areas of the solar collectors were 0.107 m^2 and 0.2004 m^2 for the evacuated heat pipe and concentrated evacuated single-sided coated heat pipe absorber respectively. They had conducted experiments for five different transverse angles (0-40°) with a collector tilt angle of 60° to the horizontal. The concentrated evacuated tube heat pipe solar collector showed an improvement of 30% and 25.42% in overall average outlet and inlet fluid temperature differential and total energy collection. Concentrated evacuated tube heat pipe solar collectors made of single sided and double sided absorber have been analysed and compared by Dan Nchelatebe Nkwetta *et al.* [44] under controlled conditions at a tilt angle of 60° to the horizontal. They recorded and compared temperature response, collection efficiency, heat loss efficiency and energy collection rates at the five different transverse angles (0-40°) in increments of 10°.The concentrated double sided absorber evacuated tube heat pipe proved better compared to the concentrated single-sided absorber evacuated tube heat pipe solar collector due to higher outlet temperature with greater temperature differential and improved thermal performance. Solar assisted heat pump with an evacuated tubular collector was designed, constructed and tested for domestic heating system by Ahmet Caglar *et al.* [45]. They investigated the effects of evaporation temperature on heating capacity and performance of system. The maximum value of the coefficient of performance of the solar assisted heat pump was obtained as 6.38 experimentally. Evaporation temperature of solar assisted heat pump changed with source temperature linearly. COP of solar assisted heat pump increased with increasing evaporative temperature. Evaporation temperature influenced COP & collector efficiency oppositely. Investigation of overall performance efficiency and reliability of five types of solar collectors was carried out by A. Sakhrieh *et al.* [46]. Five variations included were blue and black coatings, selective copper, copper and aluminium collectors in addition to evacuated tube collector. Results shown that evacuated tube blue and black coating selective copper collectors were recommended for medium and large scale applications due to their long life, high efficiency and ease of maintenance. Aluminium collectors were recommended for small applications like houses. The maximum water temperature at outlet reached 92°c and evacuated tube collector had the highest efficiency. Heat pipe evacuated pipe collector data were obtained Ayompe et al. [47] from a field trail over a year. The outlet fluid temperature recorded was maximum of 70.30°C. They obtained a collector efficiency of the solar coil 63.2% with system efficiency of 52.0%.

Two truncated compound parabolic concentrating (CPC) solar collectors which combine the external CPC and the U-shaped evacuated tubes together had been developed by X. Li[a] *et al.* [48]. They carried out study on numerical simulation of optical, thermal and heat transfer fluid behaviours of the CPC collector. This study showed that the tilt angle of the 3×CPC collector is unnecessary to be adjusted in 1 day. Correspondingly, the 6×CPC collector needed to be adjusted five times in a day due to its small half acceptance angle. Tests results indicates that daily thermal efficiency of 3×CPC and 6×CPC collectors can reach 40% and 46% at collector temperature of 200°C respectively. Comparative analysis and evaluation was done of two types of internal concentrator augmented solar collectors evacuated tube heat pipe solar collector array with either an evacuated or non-evacuated direct flow and heat pipe internal concentrator augmented collectors under similar conditions by Dan Nchelatebe Nkwetta *et al.* [49]. They proved that the evacuated and non-evacuated heat pipe augmented concentrators were better options for medium temperature applications due to better temperature response, lower heat loss and higher collection efficiency. Yan Gao *et al.* [50] compared performance of water-in-glass evacuated tube collector and U-pipe collector. It was seen that average thermal efficiency of water-in-glass evacuated tube collector was less than of U-pipe evacuated tube collector. This was due to fluid mass influenced for flow. Chow *et al.* [51] investigated single phase and two phase thermosyphon evacuated tube water heaters in different climate zone of china for system energy performance and economical return. Single phase system was found as an economic option having better cost payback except for locations with extreme cold weather while the thermal efficiency found for two phase design was high and which had a better environmental performance. Water-in-glass evacuated tube was investigated by Xinyu *et al.* [52] according to chinese standards and it was found that the heat loss from the storage tank and capacity of the solar collector affected their thermal performance. Optimum ratio of tank volume to collector area of 57-72 L/m^2. Which had given a system efficiency of 49-57%, meaning that the temperatures of water in tank will be 45°C after one day of heat collection. The recommended polyurethane insulation layer should be required around 50 mm thick with a free forming density of about 35 kg/m^3.Performance evaluation and comparative analysis based on heat extraction of direct flow control evacuated tube solar collectors with and without heat shields was presented by Xinyu *et al.* [53]. They observed that evacuated tube collector with heat shield performed better with collecting efficiency 54.70% at highest temperature of 123.9° c at inlet and which was 31.49% higher than collector without heat shield.

(b)Other liquid heating Solar collectors

Two types of solar evacuated tube collectors had been used by M. Li *et al.* [54] to measure their heating efficiencies and temperature with fluids of water and N_2 respectively. Experiments performed demonstrated that both evacuated tubes presented a good heat transfer with the fluid of water, the heating efficiency was about 70-80%. However, the efficiency of solar concentrating system with evacuated tube for heating N_2 gas was less than 40% when the temperature of N_2 gas researches 320°C-460°C.

Open thermosyphon evacuated tubular solar collector was designed by Lin Lu *et al.* [55] to investigate the thermal performance of device using de-ionized water and water based CuO nanofluids as working fluid. Results showed that the optimal filling ratio to the evaporator is 60% and the performance increases generally with increase of the operating temperature. Substituting water based CuO nanofluids for water as working fluid can significantly enhance the thermal performance of evaporator and evaporating heat transfer coefficients may increase by about 30% compared with those of de-ionized water, the mass concentration was 1.2 % corresponds to the optimal heat transfer enhancement.

Semi-dynamic model of a concentric evacuated tube solar water heater was developed to investigate the effect of working fluid design on technical and economic performance of typical solar water heater by Mobin Arab *et al.* [56]. The effects of using water, ammonia, acetone, methanol and pentane as working fluids of built in heat pipe were compared and found the water as the best working fluid amongst all the other fluids. It was shown that the performance of solar water heater can be significantly enhanced up to 28% economically and 50% from technical point of view.

III. CONCLUSIONS

Various types and developments in solar liquid evacuated tube collector systems have been discussed in detail for future scope of research. Based on these review and discussions, the following could be concluded.

- It was observed that evacuated tube collector had better performance than flat plate solar collector for high temperatures and results confirmed that even at low temperatures the efficiency per unit area of evacuated tubular collector was substantially greater.
- For evacuated tube blue and black coating selective copper collectors were recommended for medium and large scale applications.
- Observations showed that evacuated tube collector with heat shield performed better than collector without heat shield.
- It was clearly indicated that water-in-glass evacuated tube collector had better performance than flat plate collectors but heat pipe collector had 15 to 20 % higher efficiency than water-in-glass collectors which proved to be a better option.
- The thermal efficiency of water-in-glass evacuated tube collector was found less than that of U-pipe.
- Thermal efficiency of tracking CPC collector was more stable and was about 14.9% higher than that of stationary CPC.
- Water was found as the best working fluid for built in heat pipe amongst the all other fluids tested.
- The maximum water temperature at outlet which achieved was 92°C.
- The optimum inclination angle for a thermosyphon solar water heater varies 0^0 to 10^0 for maximum solar fraction in northern region and varies 0° to 20° for southern region.

- It was observed that the reverse flow in the water-in-glass evacuated tube solar water heaters occurs at nights. Results showed that the larger the tilts angle of the collector, the higher the reverse flow rate.

REFERENCES

[1] Scheel, T., "How do you decide between flat plate and evacuated tube collectors when specifying products for a plumbing and heating job? ", Solar Choices, Contractor: The Online Resource for Mechanical Contracting, 2009

[2] U.S. Energy Information Administration, "Solar Thermal Collector Manufacturing Activities 2009", Washington, D.C., 2010

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

[4] Runsheng Tang, Yuqin Yang, Wenfeng Gao, "Comparative studies on thermal performance of water-in-glass evacuated tube solar water heaters with different collector tilt-angles", Solar Energy (2011), Vol.85, pp.1381-1385.

[5] Budihardjo, I., "Evacuated Tubular Solar Water Heaters", Ph.D. Dissertation, the University of New South Wales, Australia, 2005.

[6] Budihardjo, I.; Morrison, G.L.; Behnia, M., "Development of TRNSYS Models for Predicting the Performance of Water-in-glass Evacuated Tube Solar Water Heater Systems in Australia", In Proceedings of the ANZSES Annual Conference, Melbourne, Australia, 27–29 November 2003.Energies, 2012

[7] Budihardjo, I.; Morrison, G.L.; Behnia, M., "A Study of Natural Circulation Flow Rate through Single-ended Evacuated Tube Solar Collectors". In Proceedings of the ISES Solar World Congress, Orlando, FL, USA, 8–12 August 2005.

[8] Kim, J.T.; Ahn, H.T.; Han, H.; Kim, H.T.; Chun, W., "The performance simulation of all glass evacuated tubes with coaxial fluid conduit", International communications in Heat Mass Transfer, 34, 587–597,2007.

[9] Han, H.; Kim, J.T.; Ahn, H.T.; Lee, S.J., "A three-dimensional performance analysis of all-glass evacuated tubes with coaxial fluid conduit", International communications in Heat Mass Transfer, 35, 589–596, 2008.

[10] Kim, Y.; Seo, T., "Thermal performances comparisons of the glass evacuated tube solar collectors with shapes of absorber tube", Renewable Energy, 32, 772–795, 2007.

[11] Ma, L.; Lu, Z.; Zhang, J.; Liang, R. "Thermal performance analysis of the glass evacuated tube solar collector with U-tube", Building Environment, 45, 1959–1967, 2010.

[12] Liang, R.; Ma, L.; Zhang, J.; Zhao, D. "Theoretical and experimental investigation of the filled-type evacuated tube solar collector with U tube", Solar Energy, 85, 1735–1744, 2011.

[13] Duffie, J.A.; Bechman, W.A., "Solar Engineering of Thermal Processes", John Wiley & Sons: New York, NY, USA, 1980.

[14] Rabl, A., "Optical and thermal properties of compound parabolic concentrators", Solar Energy, 18, 497–511, 1976.

[15] Tchinda, R.; Kaptouom, E.; Njomo, D., " Study of the CPC collector thermal behavior ". Energy Conversion, Manag, 39, 1395–1406, 1998.

[16] Tchinda, R.; Ngos, N., "A theoretical evaluation of the thermal performance of CPC with flat one-sided absorber", International Journal of Heat Mass Transfer, 33, 709–718, 2006.

[17] Hsieh, C.K., "Thermal analysis of CPC collectors", Solar Energy, 27, 19–29, 1981.

[18] O'Gallagher, J.J.; Snail, K.; Winston, R.; Peek, C.; Garrison, J.D, " A new evacuated CPC collector tube", Solar Energy , 29, 575–577,1982.

[19] Sharma, N.; Diaz, G. "Performance model of a novel evacuated-tube solar collector based on Minichannels",Solar Energy, 85, 881–890, 2011.

[20] Shariah, A., Al-Akhras, M.A. and Al-Omari, I.A., 2001., "Optimizing the tilt angle of solar collectors",Renewable Energy 26,587–598, 2002.

[21] Adsten, M., Perers, B. and Wackelgard, E., "The influence of climate and location on collector performance", Renewable energy, Vol. 25, pp.499-509, 2002.

[22] Tang, R., Geo, W., Yu, Y. and Chen, H., "Optimal tilt-angles of all-glass evacuated tube solar collectors", Energy, vol.34, pp.1387-1395, 2009.

[23] Chow, T.T., Dong,Z., Chan, L.S., Fong, K.F. and Bai, Y., "Performance evaluation of evacuated tube solar domestic hot water systems in Hong Kong", Energy and Buildings, Vol. 43, pp. 3467–3474,2011.

[24] Hossain, M.S., Saidur, R., Fayaz, H., Rahim, N.A., Islam, M.R., Ahamed, J.U. and Rahman, M.M., "Review on solar water heater collector and thermal performance of circulating pipe", Renewable and Sustainable Energy reviews, Vol. 15, pp. 3801-3812,2011.

[25] Zambolin, E. and Col, D.Del., "An improved procedure for the experimental characterization of optical efficiency in evacuated tube solar collector", Renewable Energy, Vol.43, pp. 37-43, 2012

[26] R.E. Collins, D. Mackey\, G.L. Morrison, "Comparative performance of evacuated tubular collectors and flat plate collectors in thermosyphoning systems", Intersol Eighty Five, Pages 1284-1288, 1986

[27] Yin Zhiqiang, G.L. Harding, "Water-in-glass manifolds for heat extraction from evacuated solar collector tubes", Solar Energy, Volume 32, Issue 2, Pages 223-230, 1984

[28] Keith A. Snail, Joseph J. O'Gallagher, Roland Winston, " A stationary evacuated collector with integrated concentrator", Solar Energy, Volume 33, Issue 5, Pages 441-449, 1984
[29] Louise Jivan Shah, Simon Furbo, "Theoretical flow investigations of an all glass evacuated tubular collector", solar Energy, Volume 81, Issue 6, Pages 822-828, June 2007
[30] R. Schmid, R.E.Collins, B.A. Pailthorpe, "Heat transport in Dewar-type evacuated tubular collectors", Solar Energy, Volume 45, Issue 5, Pages 291-300, 1990
[31] D.R. Mills, A. Monger, G.L. Morrison," "Comparison of fixed asymmetrical and symmetrical reflectors for evacuated tube solar receivers", Solar Energy, Volume 53, Issue 1, Pages 91-104, July 1994
[32] N. BENZ, T. BEIKIRCHER, "High efficiency evacuated flat-plate solar collector for process steam production", Solar Energy, Volume 65, Issue 2, Pages 111-118, 1 February 1999
[33] G.L. Morrison , I. Budihardjo, M. Behnia, " Water-in-glass evacuated tube solar water heaters", Solar Energy, Volume 76, Issues 1–3, Pages 135-140, January–March 2004
[34] Runsheng Tang, Yuqin Yang, "Nocturnal reverse flow in water-in-glass evacuated tube solar water heaters", Energy Conversion and Management, Volume 80, Pages 173-177, April 2014
[35] Yong Kim, GuiYoung Han, Taebeom Seo, "An evaluation on thermal performance of CPC solar collector", International Communications in Heat and Mass Transfer, Volume 35, Issue 4, Pages 446-457, April 2008
[36] I. Budihardjo, G.L. Morrison, " Performance of water-in-glass evacuated tube solar water heaters", Solar Energy, Volume 83, Issue 1, Pages 49-56, January 2009
[37] Michel Hayek, Johnny Assaf, William Lteif, " Experimental Investigation of the Performance of Evacuated-Tube Solar Collectors under Eastern Mediterranean Climatic Conditions", Energy Procedia, Volume 6, Pages 618-626, 2011
[38] Ayompe, L.M., Duffy, A., Mc Keever, M., Conlon, M. and McCormack, S.J., "Comparative field performance study of flat plate and heat pipe evacuated tube collectors (ETCs) for domestic water heating systems in a temperate climate", Energy, Vol.36, pp. 3370-3378,2011.
[39] Ruobing Liang, Liang dong Ma, Jili Zhang Dan Zhao, " Theoretical and experimental investigation of the filled-type evacuated tube solar collector with U tube", Solar Energy, Volume 85, Issue 9, Pages 1735-1744,September 2011
[40] Tin-Tai Chow, Zhaoting Dong,Lok-Shun Chan, Kwong-Fai Fong, Yu Bai, "Performance evaluation of evacuated tube solar domestic hot water systems in Hong Kong", Energy and Buildings, Volume 43, Issue 12, Pages 3467-3474, December 2011
[41] Abdul Waheed Badar, Reiner Buchholz, Felix Ziegler. "Single and two-phase flow modeling and analysis of a coaxial vacuum tube solar collector", Solar Energy, Volume 86, Issue 1, Pages 175-189, January 2012
[42] David A.G. Redpath, "Thermosyphon heat-pipe evacuated tube solar water heaters for northern maritime climates", Solar Energy, Volume 86, Issue 2, Pages 705-715, February 2012
[43] Dan Nchelatebe Nkwetta, Mervyn Smyth, Aggelos Zacharopoulos,Trevor Hyde, "In-door experimental analysis of concentrated and non-concentrated evacuated tube heat pipe collectors for medium temperature applications", Energy and Buildings, Volume 47, Pages 674-681,April 2012
[44] Dan Nchelatebe Nkwetta, Mervyn Smyth, " Performance analysis and comparison of concentrated evacuated tube heat pipe solar collectors", Applied Energy, Volume 98, Pages 22-32, October 2012
[45] Ahmet caglar, Cemil Yamalı, "Performance analysis of a solar-assisted heat pump with an evacuated tubular collector for domestic heating", Energy and Buildings, Volume 54, Pages 22-28, November 2012
[46] A. Sakhrieh, A.Al-Ghandoor, " Experimental investigation of the performance of five types of solar collectors", Energy Conversion and Management, Volume 65, Pages 715-720 January 2013
[47] L.M. Ayompe A. Duffy, "Thermal performance analysis of a solar water heating system with heat pipe evacuated tube collector using data from a field trial", Solar Energy, Volume 90, Pages 17-28, April 2013
[48] X. Li, Y.J. Dai,Y. Li, R.Z. Wang, " Comparative study on two novel intermediate temperature CPC solar collectors with the U-shape evacuated tubular absorber", Solar Energy, Volume 93, Pages 220-234, July 2013
[49] Dan Nchelatebe Nkwetta, Mervyn Smyth, Fariborz Haghighat, Aggelos Zacharopoulos, Trevor Hyde, "Experimental performance evaluation and comparative analyses of heat pipe and direct flow augmented solar collectors", Applied Thermal Engineering, Volume 60, Issues 1–2, Pages 225-233, 2 October 2013
[50] Yan Gao, Qunli Zhang,Rui Fan, Xinxing Lin, Yong Yu, "Effects of thermal mass and flow rate on forced-circulation solar hot-water system: Comparison of water-in-glass and U-pipe evacuated-tube solar collectors", Solar Energy, Volume 98, Part C, Pages 290-301 December 2013
[51] Tin-Tai Chow,Yu Bai, Zhaoting Dong, Kwong-Fai Fong,"Selection between single-phase and two-phase evacuated-tube solar water heaters in different climate zones of China", Solar Energy, Volume 98, Part C, Pages 265-274, December 2013
[52] Xinyu Zhang, Shijun You, Wei Xu,Min Wang, Tao He, Xuejing Zheng, " Experimental investigation of the higher coefficient of thermal performance for water-in-glass evacuated tube solar water heaters in China", Energy Conversion and Management, Volume 78, Pages 386-392, February 2014

[53] Xinyu Zhang, Shijun You, Hongchuan Ge, Yan Gao, Wei Xu, Min Wang, Tao He, Xuejing Zheng, "Thermal performance of direct-flow coaxial evacuated-tube solar collectors with and without a heat shield", Energy Conversion and Management, Volume 84, , Pages 80-87, August 2014

[54] M. Li, L.L.Wang, " Investigation of evacuated tube heated by solar trough concentrating system", Energy Conversion and Management, Volume 47, Issue 20, Pages 3591-3601, December 2006

[55] Lin Lu, Zhen-Hua Liu, Hong-Sheng Xiao, "Thermal performance of an open thermosyphon using nanofluids for high-temperature evacuated tubular solar collectors: Part 1: Indoor experiment", Solar Energy, Volume 85, Issue 2, Pages 379-387, and February 2011

[56] Mobin Arab, Ali Abbas, "Model-based design and analysis of heat pipe working fluid for optimal performance in a concentric evacuated tube solar water heater", Solar Energy, Volume 94, Pages 162-176, August 2013