Design and Experimental Investigation of Thermosiphoning Heat Transfer through Nanofluids in Compound Parabolic Collectors

DOI : 10.36909/jer.ICEPE.19537

Muhammad Shehryar*, Muzaffar Ali, Furqan Ali, Shaharyar Ahmad, Daniyal Ahmad, Shahzeb Ahmed, Obaid Iftikhar

Department of Mechanical Engineering, University of Engineering and Technology, Taxila, Taxila 47050, Pakistan

* Corresponding Author: m.shehryar@uettaxila.edu.pk

ABSTRACT

The limited availability of fossil fuels, as well as its negative ecological repercussions, has prompted humanity to seek other renewable technologies. One of the obvious options is solar energy, especially for energy deficient and solar rich countries like Pakistan. Flat plate, evacuated tube, and parabolic trough collectors are among the primary solar thermal collectors being employed. However, energy saving can be further enhanced by applying the thermosiphoning concept. Therefore, in the current study, an experimental analysis of a thermosiphoning-based heat transfer mechanism with two different nanofluids (Fe_2O_3 and Al_2O_3) in a compound parabolic trough collector (CPC) is presented. Initially, a numerical analysis is performed through ANSYS to determine fluid flow under free convection at a certain temperature gradient. Afterwards, a laboratory-scale thermosiphoning experimental setup is developed under controlled conditions. Finally, the same phenomena is applied in CPC and analysis is performed under real climate conditions of Taxila, Pakistan. The highest numerical flow rate attained with Fe_2O_3 was 9.3 mL/s, according to the research. In outdoor setup, 10.78 mL/s was the highest flow rate achieved. With some variation, theoretical and analytical results were confirmed with prior studies. As a result, using nanofluids and thermosiphon to lower a pump's mechanical strain can considerably improve the efficiency of the solar thermal system.

Keywords: Thermosiphoning; Nanofluids; Solar Thermal Systems; Compound parabolic collectors (CPCs); Absorber; Thermal conductivity; Boundary conditions; Buoyant pressure; Quasi steady-state.

INTRODUCTION

The high potential of renewable energy resources is enriching Pakistan. It is estimated that the solar capacity is over 100,000 MW. Across the country, direct solar radiation is about 4.5 to 7.0 $kWh/m^2/day$ [1]. Solar thermal systems can balance the energy requirements of the residential, industrial, and commercial sectors. Concentrating collectors such as Compound Parabolic Collectors can be used for medium and industrial process heating (IPH) and energy production are examples of high-temperature implementations. The CPC trough is designed using a combination of two parabola sections facing each other. Any radiation within the acceptance angle finds its way to the absorber tube [2]. The absorber tube transfers the heat to a working fluid. It was discovered most lately in studies that the dispersion of nanoparticles in the working fluid will enhance the heat transfer resulting in a better overall performance of a thermal system. Thermosiphoning is a passive heat exchange phenomenon which circulates fluid without a pump based on density difference created by a temperature gradient. The goal is to experiment and investigate the thermosiphoning heat transfer in CPCs using nanofluids. The methodology involved designing a copper tube on ANSYS, simulating thermosiphoning with nanofluids, creating a mathematical model, designing, and fabricating indoor and outdoor setup, nanofluid preparation and then the calculation of intermittent flow rate and outlet temperatures using experimentations.

The fluid's buoyant pressure is considered the primary driving force, which overrides frictional losses in the pipe [3]. There exists a lot of literature where nanofluids were used to enhance thermal conductivity. Khullar et al. researched about the applications and usage of nanofluids in concentrating parabolic trough collectors [4]. Emmanouil et al investigated thermosiphoning phenomena in a heat exchanger, in a closed loop, as a condenser [5]. Walender used a hypothetical simulation model with several fluids to help explain the thermosiphoning process in the solar system [6]. According to Lu et al., the optimum achievable concentration was 1.20 %, with a 30 % improvement in thermal conductivity [7]. Otanicar et al. investigated the effects of various nanofluids on working fluids in various solar concentrators [8]. Naphon et al. investigated the heat transfer efficiency of a setup employing thermosiphoning [9]. Verma et al. used Al_2O_3 nanofluid to study the effect of mass flow rate and mass fraction [10]. There exists limited literature on thermosiphoning performance analysis of flat plate and parabolic collectors using nanofluids but there is a substantial gap in the research on thermosiphoning in compound parabolic concentrators.

METHODOLOGY

Mathematical Model

The mathematical model of closed loop thermosiphon is difficult to construct and requires some valid assumptions to simplify the model. The main purposes of the model are the determination of the theoretical mass flow rate of the fluid in the heat pipe and flow equations. To simplify the model some assumptions are to be made as follows [3].

- Quasi steady state condition is assumed and 1D flow.
- The temperature distribution inside the receiver tube is linear.
- The flow regime is laminar inside the model.

Buoyant pressure will be the main driving force in the system arising due to difference in densities between the hot and cold fluid. To raise the fluid in the receiver tube the buoyant pressure (P_B) in the system must be greater than the total system pressure losses (ΔP_{L}) due to friction. Establishing heat and mass balance.

$$P_B = g\rho\beta' \, sin(i) \int (T(x) - T) \, dx \tag{1}$$

Where g is gravitational acceleration ($\mathrm{m/s^2}$), ρ is density ($\mathrm{kg/m^3}$), β' is thermal cubic expansion coefficient ($\mathrm{K^{-1}}$), and i is tilt angle of thermosiphon heat pipe (°).

Buoyant pressure in the heat pipe is given by using a relation for buoyant pressure in a solar collector by Beckman and Duffie [11].

$$P_B = g\rho\beta' \, sin(i) \int (T(x) - T)\, dx \tag{2}$$

$$P_B = \frac{g\rho\beta' \, sin(i)\, L}{2}(T_2 - T_1) \tag{3}$$

Here L is the length of the heat pipe.

The pressure drops in the system due to friction and viscous effects are given by Darcy-Weisbach equation.

$$\Delta P_L = f\frac{L}{D}\frac{\rho V^2}{2} \tag{4}$$

Where f is Darcy friction factor, D is diameter of heat pipe, and V is velocity of fluid.

After substitution of friction factor and continuity.

$$\Delta P_L = \frac{32(\rho V L v)}{D^2} + \frac{\sum K(\rho V^2)}{2} \tag{5}$$

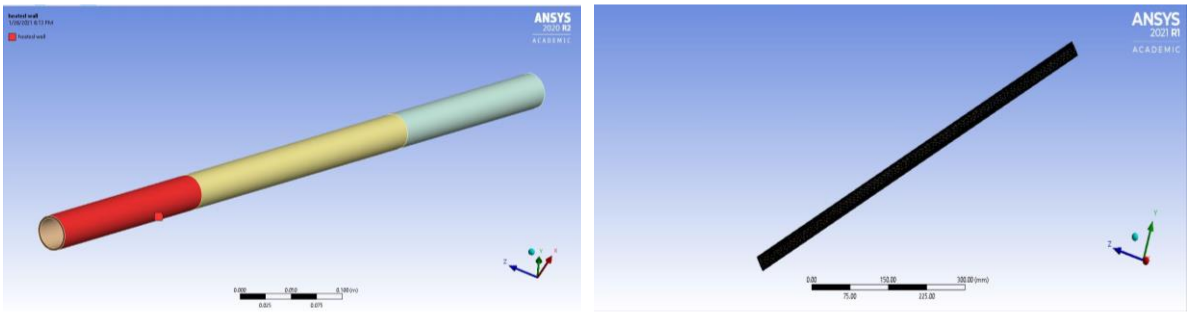
Where v is kinematic viscosity ($\mathrm{m^2/s}$) and K is the loss coefficient.

Substituting (5) and (3) in eq. (1).

$$\frac{g\rho\beta' \, sin(i)\, L}{2}(T_2 - T_1) - \frac{32(\rho V L v)}{D^2} + \frac{\sum K(\rho V^2)}{2} = 0 \tag{6}$$

Numerical Analysis

In the thermosiphon simulation environment, ANSYS software was accustomed to analyzing the receiver tube. This buoyancy-driven issue was solved using the Fluent module and a pressure-based solver. Figure 1 explains the procedure required to construct the receiver tube model: generating geometry, edge scaling, tube sectioning, and meshing.



(a) (b)

Figure 1 (a) Tube sectioning. (b) Receiver tube meshing

Aspect ratio and skewness were the primary mesh quality characteristics considered. It was also observed that grid independence exists. Presto Model, Boussinesq Model, and SIMPLE Model were some of the modeling techniques used. The intake velocity was adjusted to 0 m/s, the inlet temperature was adjusted to 300 K, the pipe wall temperature was set to 420 K, and the output pressure (gauge) was set to 0 Pa. After that, simulations were run with several working fluids, including water, water + Al_2O_3, and water + Fe_2O_3.

EXPERIMENTATION

Indoor Setup

Indoor experimentation included thermosiphoning performance analysis on a small-scale setup by using nanofluid ($Fe_2O_3 + H_2O$). In this, 500 mL of nanofluid was prepared in the laboratory. For a concentration ratio of 0.025%, the weight of the nanoparticles found out was 0.64 g. The setup consisted of an electric coil heating source, thermocouple (K-type), beaker, and a set of copper tubes having different size and diameters. The parameters under observation were tube angle, working fluid type, and type of inlet configuration. Indoor setup is shown in Figure 2.

Figure 2 Indoor Setup

Outdoor Setup:

The outdoor setup consists of a Compound Parabolic Collector along with temperature sensors and flow rate meters. It is oriented in North-South direction at a tilt angle of 45. Outdoor setup for thermosiphoning is shown in Figure 3.

Figure 3 Outdoor Setup

The design specifications of CPC geometry are tabulated in Table 1.

Table 1 CPC design specifications

Receiver tube length	1.859 m
Inner tube diameter	0.0109 m
Outer tube diameter	0.0584 m
CPC concentration ratio	2.43
Ideal concentration ratio	2.45

Aperture width	0.4456 m
Aperture length	1.859 m
Aperture height	0.5549 m
Aperture area	0.8283 m^2
Gap between tube and reflector	0.0483 m
Half acceptance angle	12°

The CPC collector received solar radiations from sun and concentrated them to heat the receiver tube. Storage tank 1 was used as inlet tank in which nano fluids or water was placed. The temperature at the system's inlet and outlet was measured using a K-type thermocouple. The flow rate at the output was measured using a flow rate sensor. It was an open cycle circuit. Figure 4 shows the working of outdoor setup for thermosiphoning.

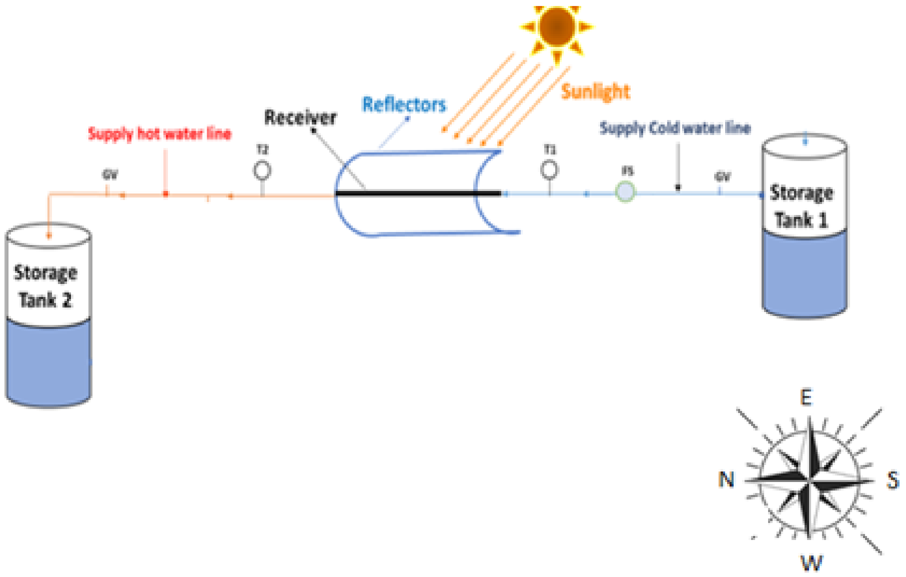


Figure 4 Schematic Diagram for Outdoor Setup

RESULTS AND DISCUSSIONS

ANSYS Fluent solver using transient analysis was used to obtain numerical solutions. The simulations showed that because of heat transfer enhancement, the outlet temperature increased about 29 K, in case of iron oxide nanofluid, from 330 K as compared to water. The temperature gradients are shown in Figure 5. Turbulent eddies and whirling flow were generated in the hot section of tube as the thermosiphoning began and a vortex was created due to possible flow reversal as shown in Figure 5. In comparison to water (0.02776 m/s), the outlet velocity obtained using iron oxide nanofluid was 0.0734 m/s. The intermittent flow rates for water, Al_2O_3 and the Fe_2O_3 nanofluids were 3.50, 4.52 and 9.27 mL/s, respectively. The results reveal that intermittent flowrate and flow velocity increases with rise in fluid temperature in a thermosiphon. Figure 5 shows the simulation graphics.

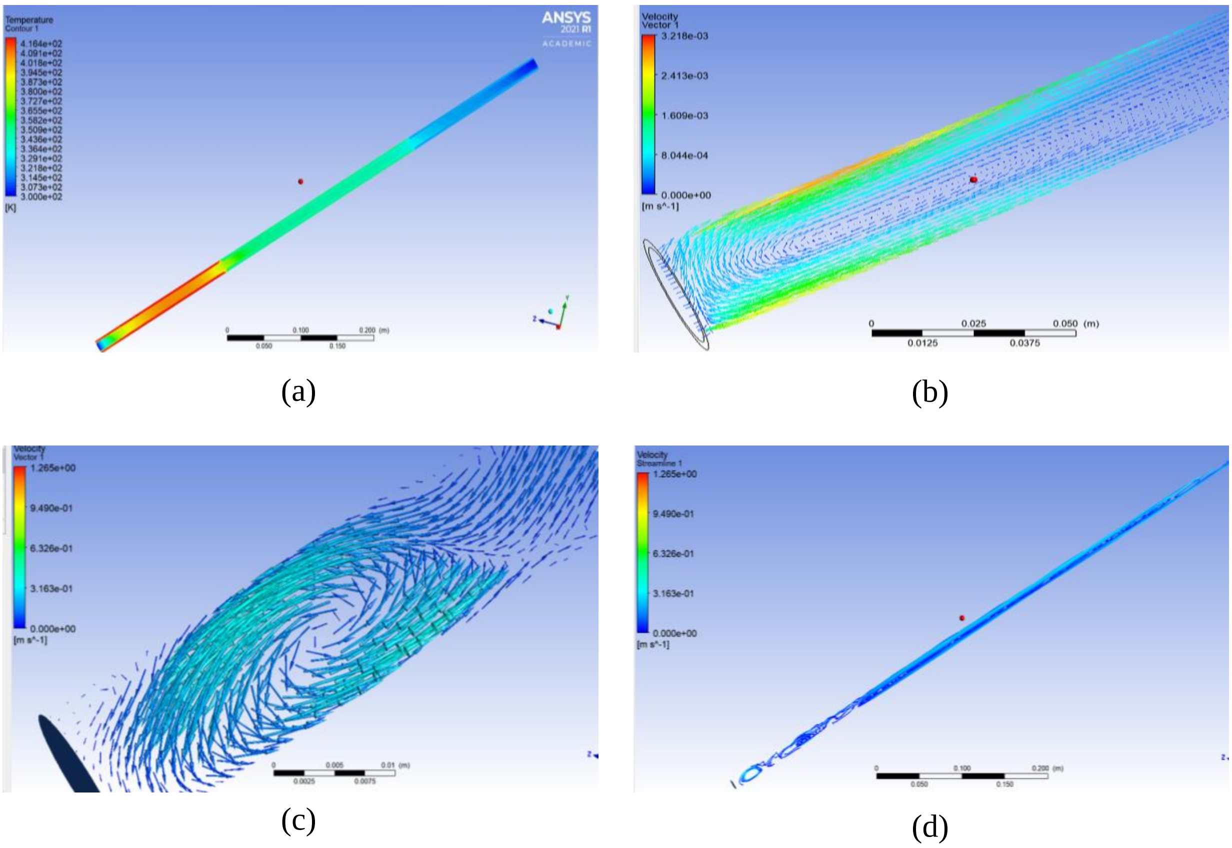


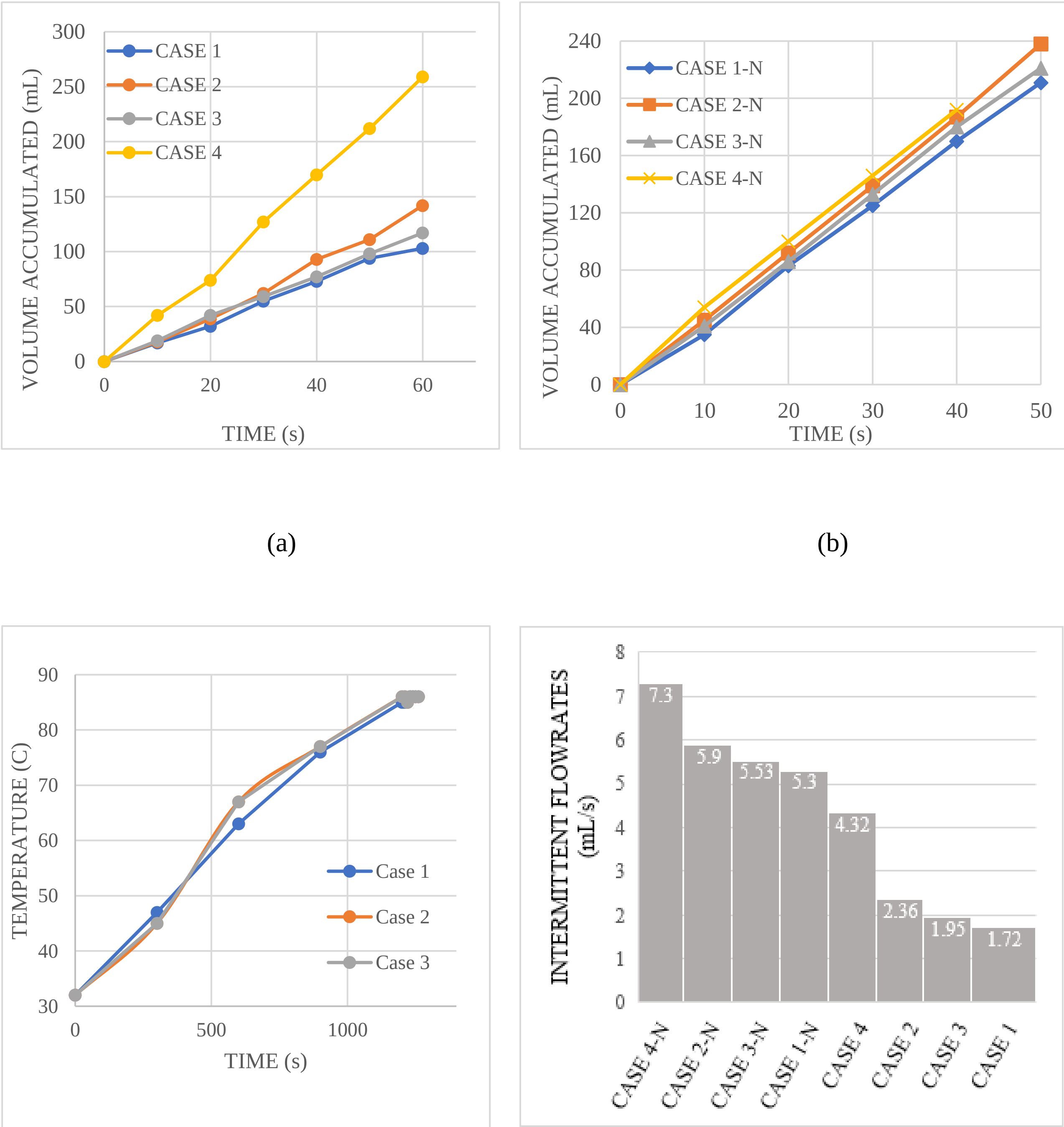
Figure 5 (a) Temperature contours. (b) Velocity vectors. (c) Velocity vectors at heated section. (d) Velocity streamlines.

During experimentations on lab scaled model, fluid temperature at outlet section, volume and intermittent flow rate were the main variables involved. The experimentation involved 8 distinct cases using water as working fluid and 4 cases using nanofluid ($\mathrm{water} + Fe_2O_3$). Receiver angles of 30 and 45 degrees are used. Except for case 1, all others employed a tube with a diameter of ½ inches. Cases 1-N and 3-N had a receiver length of 2.5 feet, whereas cases 2N and 4N had a receiver length of 1.5 feet. The nano fluid concentration was 0.025 percent for 1N and 2N, and 0.050 percent for 3N and 4N. The use cases for experimentation are summarized in Table 2.

Table 2 Experimentation Cases Description

Case	Receiver Length (ft)	Diameter (in)	Fluid	Suction Head (cm)
1	2.5	3/4	Water	48
2	2.5	1/2	Water	48
3	2.5	1/2	Water	86
4	1.5	1/2	Water	48
1-N	2.5	1/2	0.025 % Fe_2O_3	48
2-N	1.5	1/2	0.025 % Fe_2O_3	48
3-N	2.5	1/2	0.05 % Fe_2O_3	48
4-N	1.5	1/2	0.05 % Fe_2O_3	48

The results showed that the time to achieve thermosiphoning is greatly reduced using nanofluids. The volume collected increased over time with a substantial increase for cases involving nanofluids. Decrease in tube length in diameter causes the flow rate to increase. The maximum flowrate obtained was 7.3 mL/s for case 4N. There was also a suction from the available head and a continuous flow rate of 55 mL/s was obtained for case 3. Thermosiphoning commenced at about 85 °C with a thermal gradient of about 35 °C between the two ends of tube. For a larger system size, the incident heating should be increased. Thermosiphoning trends are shown in Figure 6.



(c) (d)

Figure 6 (a) Thermosiphoning with water. (b) Thermosiphoning with nanofluid. (c) Variation of temperature. (d) Intermittent flow rates.

Outlet temperature, volume collected, and irregular flow rate are the characteristics for thermosiphoning in an outdoor configuration. Table 3 depicts the evolution of these factors throughout time.

Table 3 Variation in volume and temperature Outdoor Setup

Sr. No	Time (s)	Outlet Temperature (°C)	Accumulated Volume (mL)
1	0	37	0
2	300	45	0
3	600	63	0
4	780	87	0
5	790	88	45
6	800	88.3	136
7	810	88.3	285
8	820	88.3	420
9	830	88.3	539

The intermittent flow rate obtained in this case was 10.78 mL/s. Variation of accumulated volume with time is shown in Figure 7.

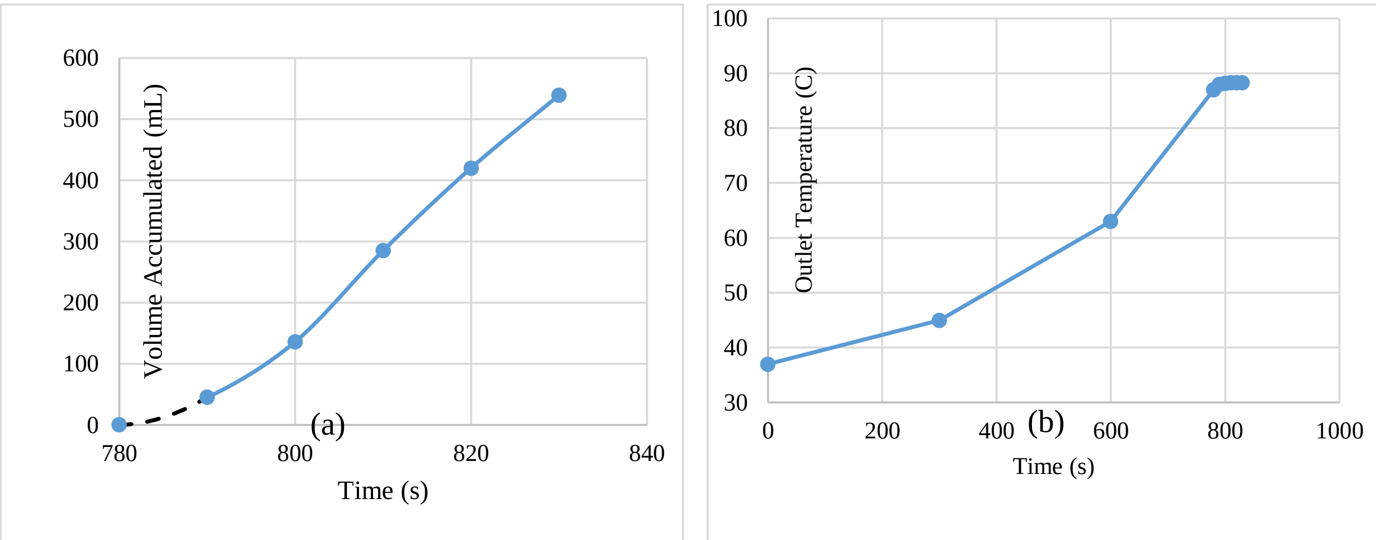


Figure 7 (a) Accumulated Volume Outdoor. (b) Outlet temperature Outdoor Setup

CONCLUSION

The introduction of nanofluids as working fluid and thermosiphon has substantially improved the performance of solar thermal system using CPCs. The system could use selfsustained thermosiphoning partly during its operation. The results revealed that the largest theoretical flow rate using Fe_2O_3 obtained in ANSYS simulations was 9.3 mL/s, 7.3 mL/s in indoor configuration, and 10.78 mL/s in case of outdoor setup. There is a scarcity of literature on compound parabolic collectors using a thermosiphon but comparing numerical results with other research shows a strong correlation between pattern trends and fluid behavior. Solar thermal systems present a great opportunity to meet the heat energy demands of industries, at low operational costs. Pakistan, which is bestowed with extraordinary potential for solar energy, can significantly reduce its reliance on fossil fuels if further research and development is carried out in this domain. Therefore, more research should be done in the future to build a closed loop thermosiphon that can be tested in outdoor conditions.

ACKNOWLEDGMENT

Authors are thankful to Higher Education Commission of Pakistan for providing financial support through NRPU-10483 project.

REFERENCES

[1] B. Widyolar, L. Jiang, J. Ferry and R. Winston, "Non-tracking East-West XCPC solar thermal collector for 200 celsius applications," *Applied Energy,* vol. 216, pp. 521-533, 2018.

[2] S. A. Kalogirou, Solar Energy Engineering (Second Edition), Academic Press, 2013, pp. 125-220.

[3] P. M. E. Koffi, H. Y. Andoh, P. Gbaha, S. Toure and G. Ado, "Theoratical and experimental study of solar water heater with internal exchanger using thermosiphon system," *Energy Conservation & Management,* pp. 2279-2290, 2008.

[4] V. Khullar and H. Tyagi, "Application of nanofluids as the working fluid in concentrating parabolic solar collectors. In Proceedings of the 37th National & 4th International Conference on Fluid Mechanics & Fluid Power.," Chennai, India, 2010.

[5] Emmanouil and Vassilis, "A new heat pipe type solar system.," *Sol. Energy*, pp. 13-20, 2012.

[6] P. Welander, "On the oscillatory instability of a differentially heated fluid loop," *Journal of Fluid Mechanics*, vol. 29, pp. 17-30, 1967.

[7] Z. H. Liu, R. L. Hu, F. Z. L. Lu and H. S. Xiao., "Thermal performance of an open thermosyphon using nanofluid for evacuated tubular high temperature air solar collector.," *Energy Convers. Manag*, vol. 73, pp. 135-143, 2013.

[8] O. TP, Phelan, Prasher, R. G and T. RA., "Nanofluid-based direct absorption solar collector.," *J. Renew. Sustain. Energy*, vol. 2, 2010.

[9] P. Naphon, D. Thongkkum and T. Borirak, "Heat pipe efficiency enhancement with refigerant-nanoparticles mixtures," *Int. Commun Heat Mass Transfer*, vol. 35, pp. 1316-1319, 2008.

[10] V. Verma and K. a. L., "Thermal performance evaluation of a direct absorption flat plate solar collector (DASC) using Al2O3-H2O based nanofluids.," *ISOR J. Mech Civ. Eng*, 2013.

[11] J. A. Duffie and W. A. Beckman, Solar Engineering of Thermal Processes, John Wiley & Sons, Inc., 2020.