

Engineering Applications of Computational Fluid Mechanics

ISSN: 1994-2060 (Print) 1997-003X (Online) Journal homepage: <https://www.tandfonline.com/loi/tcfm20>

Experimental and numerical analysis of a nanofluidic thermosyphon heat exchanger

Mahdi Ramezanizadeh, Mohammad Alhuyi Nazari, Mohammad Hossein Ahmadi & Kwok-wing Chau

To cite this article: Mahdi Ramezanizadeh, Mohammad Alhuyi Nazari, Mohammad Hossein Ahmadi & Kwok-wing Chau (2019) Experimental and numerical analysis of a nanofluidic thermosyphon heat exchanger, *Engineering Applications of Computational Fluid Mechanics*, 13:1, 40-47, DOI: [10.1080/19942060.2018.1518272](https://doi.org/10.1080/19942060.2018.1518272)

To link to this article: <https://doi.org/10.1080/19942060.2018.1518272>



© 2018 The Author(s). Published by Informa UK Limited, trading as Taylor & Francis Group



Published online: 28 Nov 2018.



Submit your article to this journal [↗](#)



Article views: 306



View Crossmark data [↗](#)



Citing articles: 3 View citing articles [↗](#)

Experimental and numerical analysis of a nanofluidic thermosyphon heat exchanger

Mahdi Ramezanizadeh^a, Mohammad Alhuyi Nazari^a, Mohammad Hossein Ahmadi^b and Kwok-wing Chau^c

^aAerospace Engineering Department, Shahid Sattari Aeronautical University of Science and Technology, Tehran, Iran; ^bFaculty of Mechanical Engineering, Shahrood University of Technology, Shahrood, Iran; ^cDepartment of Civil and Environmental Engineering, Hong Kong Polytechnic University, Hong Kong, People's Republic of China

ABSTRACT

Thermosyphons have high effective thermal conductivity and are applicable for different heat transfer purposes including cooling devices and heat exchangers. In the present study, thermal performance of a thermosyphon is experimentally investigated by using Ni/Glycerol–water nanofluid in three concentrations including 0.416, 0.625 and 1.25 g/lit. Experimental results revealed that using the nanofluid with 0.625 g/lit concentration leads to lowest thermal resistances. Afterwards, a thermosyphon-based heat exchanger is designed and numerically investigated to compare its performance with copper heat exchanger. Since the effective thermal conductivity of thermosyphon depends on temperature difference between condenser and evaporator, a novel approach is applied to achieve precise modeling. Effects of mass flow rates of cold and streams and inlet temperature of hot stream on heat transfer rate are evaluated. Results revealed that using thermosyphon instead of copper tubes with the same dimensions results in more than 100% improvement in heat transfer capacity. Moreover, it is concluded that increase in the mass flow rates of the streams and inlet temperature of hot stream lead to increase in heat transfer rate. A 3D graph is represented to evaluate the influences of hot stream temperature and mass flow rate on the heat transfer rate of thermosyphon-based heat exchanger.

ARTICLE HISTORY

Received 26 July 2018
Accepted 28 August 2018

KEYWORDS

Thermosyphon; nanofluid; heat exchanger; thermal conductivity

1. Introduction

Heat pipes are broadly utilized in thermal mediums due to their ability in efficient heat transfer (Alhuyi Nazari, Ahmadi, Ghasempour, & Shafii, 2018; Nazari, Ahmadi, & Ghasempour, 2018). Gravity-assisted heat pipes (thermosyphons) have simple structure and favorable performance. These devices consist of a tube (generally metal tube to have high conductive heat transfer), and partially charged with an operating fluid. The main parts of a thermosyphon are condenser and evaporator sections. The working fluid inside the tube evaporates due to heat transfer with heat sink and moves to condenser since it has lower density in comparison with liquid. Afterwards, by heat dissipation in condenser, the vapor converts into liquid and returns to the evaporator due to gravity. A schematic of a thermosyphon is illustrated in Figure 1.

There are various affecting factors on thermal behavior of thermosyphons (Asirvatham, Wongwises, & Babu, 2016; Jafari, Filippeschi, Franco, & Di Marco, 2017; Sarafraz, Hormozi, & Peyghambarzadeh, 2014). Thermal conductivity of tube is an influential parameter due to its impact on conductive heat transfer mechanism. Filling

ratio is another effective factor. High filling ratios have unfavorable effect on boiling in evaporator section while low filling ratios increase the possibility of dry-out due to lack of liquid in evaporator. The optimum filling ratio obtained based on experimental studies and varies for each case. Inclination angle is another parameter which play key role in heat transfer since it affects fluid circulation inside the thermosyphon. Generally, vertical or near vertical orientations are more appropriate due to assistance of gravity in liquid return from condenser to evaporator. Operating fluid and its thermophysical properties are among the most important factor influence on thermal performance. There are some studies which have focused on modeling the thermal resistance of the heat pipes systems by considering effective factors which give better insight into these parameters (Ahmadi et al., 2018).

Nanofluids are employed in thermal mediums to enhance heat transfer (Fereidoon, Saedodin, Hemmat Esfe, & Noroozi, 2013; Zeinali Heris, Kazemi-Beydokhti, Noie, & Rezvan, 2012). Several studies have experimentally investigated the applications of nanofluids in thermosyphons (Ghaderian et al., 2017; Liu, Yang, & Guo,

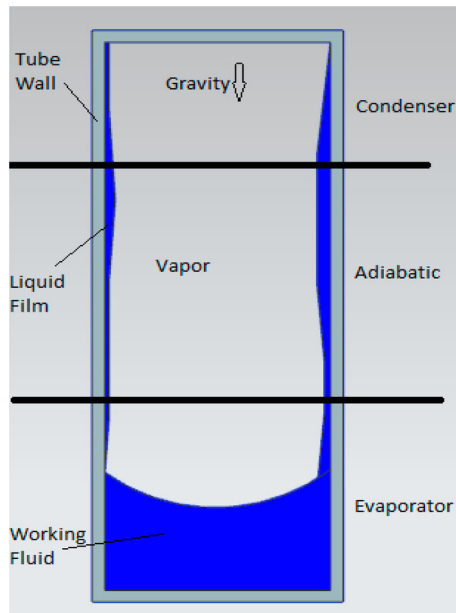


Figure 1. Schematic of a thermosyphon.

2007; Shanbedi, Heris, Baniadam, Amiri, & Maghrebi, 2012). Most of them concluded that using nanofluids can enhance the thermal performance of thermosyphons. Augment in effective thermal conductivity of thermosyphons filled with nanofluids is attributed to enhancement of operating fluid higher thermal conductivity (in comparison with pure fluids) and higher nucleation sites because of sedimentation of nanoparticles.

Computational approaches for solving engineering problems gain importance due to their effectiveness and applicability (Faizollahzadeh Ardabili et al., 2018). Computational Fluid Dynamics (CFD) is a powerful method in modeling various systems (Faizollahzadeh Ardabili et al., 2018). This approach is applicable in various engineering system to obtain their behavior. For instance, Mou et al. (Mou, He, Zhao, & Chau, 2017) used CFD in order to investigate the influence of dimensional changes of buildings on distribution of wind pressure. CFD is applicable in modeling heat transfer with high accuracy (Alizadeh et al., 2018). Due to the mentioned advantages of CFD, it is widely applied to model the thermal devices such as heat exchangers.

In the current research, Ni/Glycerol-water nanofluids in three concentrations are used in a thermosyphons. Afterwards, the thermal characteristics of the thermosyphon filled with the best fluid is used for modeling a heat exchanger. Finally, heat transfer capacity of the heat exchanger in various conditions is compared with a heat exchanger with similar dimensions made of copper. The type of nano particles used in this study is evaluated in thermosyphon for the first time. Moreover, the modeling of nanofluidic thermosyphon heat exchanger is

represented which is another novelty of the present study. The proposed approach for numerical simulation of the heat exchanger is based on a novel method applied in heat pipe modeling in recent studies.

2. Material and methods

The current study contains both experimental and numerical sections. In the first subsection of this part, experimental set-up is explained and the second subsection, numerical approach is described.

2.1. Experimental set-up

In order to evaluate the effect of adding Ni nanoparticles to a base fluid on the thermal performance of a thermosyphon, an experimental set-up was designed. The lengths of evaporator, condenser and adiabatic section of the thermosyphon were equal to 105, 180 and 105 mm, respectively. The outer diameter of the tube was 14 mm and its thickness was 0.75 mm. The material of the tube was copper to achieve the highest heat transfer capacity. A schematic of the tested thermosyphon is shown in Figure 2.

Three K-type thermocouples were used to measure temperatures. Two of them were installed in evaporator section and the other one was located in condenser section. In order to determine thermal resistance of the thermosyphon, average temperature of evaporator is used for calculation. All of the thermocouples were

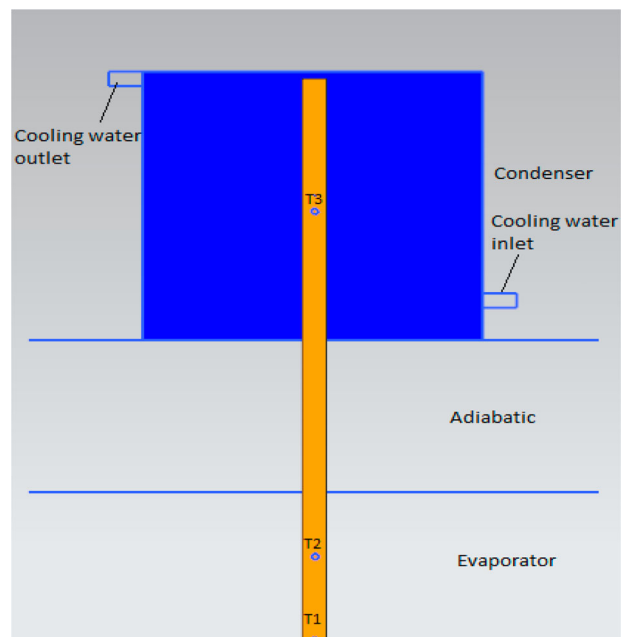


Figure 2. Schematic of the tested thermosyphon.

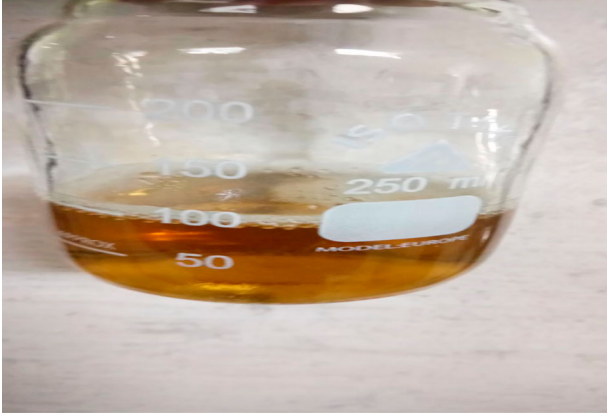


Figure 3. Ni/glycerol-water nanofluid.

connected to LUTRON BTM-4208 SD data logger. The frequency of data acquisition was 0.5 Hz.

Water was utilized in all experiments to cool down the condenser section. The mass flow rate of the water kept constant and its temperature difference between inlet and outlet was lower than 1°C. Since heat input affects boiling, and as a consequence heat transfer, the heat input varied in the range of 30 and 110 W. Ni-Cr heating wire was used in evaporator section as heater. In order to provide heat for the evaporator section, a power supply made by Rayannik Company was used.

The utilized nanofluid was Ni/Glycerol–water as shown in Figure 3. Since Ni nanoparticles were stable in the glycerol, it was used as the based fluid. Water was added to the nanofluid to have working fluid to have fluid with lower density. The volumetric water/glycerol ratio was equal to 3 to 1 in all of the tests. Ni/glycerol nanofluid was prepared by Eastnanotech Company. The average size of nanoparticles was 30 nm. In order to fill the thermosyphon, firstly, a vacuum pump was applied to reduce the amount of non-condensable gases in the tube. Afterwards, the thermosyphon was filled with working fluid. Filling ratio in all tests was equal to 70% of evaporator volume.

2.2. Numerical method

In order to obtain the thermal capacity of the heat exchanger, mass conservation, conservation of momentum and energy equations are utilized. Time-dependent mass conservation equation for fluid flows is represented in Equation (1) (Alizadeh, Ghasempour, Razi Astaraei, & Alhuyi Nazari, 2016).

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = S_m \quad (1)$$

S_m refers to mass sink or source in the domain of flows, ρ is density and \vec{v} is the vector of velocity.

Conservation of momentum for the flow of fluids is shown in Equation (2).

$$\frac{\partial(\rho \vec{v})}{\partial t} + \nabla \cdot (\rho \vec{v} \cdot \vec{v}) = -\nabla p + \nabla \cdot \bar{\bar{\tau}} + \rho \vec{g} + \vec{F}, \quad (2)$$

where p refers to pressure field, g is gravitational acceleration, \vec{F} is the external body force and $\bar{\bar{\tau}}$ indicates the stress tensor as represented in Equation (3).

$$\bar{\bar{\tau}} = \mu [(\nabla \cdot \vec{v} + \nabla \cdot \vec{v}^T) - \frac{2}{3} \nabla \cdot \vec{v} \cdot \bar{\bar{I}}] \quad (3)$$

In this study, k - ϵ turbulent model is applied for turbulence modeling.

$$\begin{aligned} \frac{\partial(\rho k)}{\partial t} + \nabla \cdot (\rho \vec{v} k) &= \nabla \cdot \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \nabla k \right] \\ &+ G_k + G_b - \rho \epsilon \end{aligned} \quad (4)$$

$$\begin{aligned} \frac{\partial(\rho \epsilon)}{\partial t} + \nabla \cdot (\rho \vec{v} \epsilon) &= \nabla \cdot \left[\left(\mu + \frac{\mu_t}{\sigma_\epsilon} \right) \nabla \epsilon \right] \\ &+ C_{1\epsilon} \frac{\epsilon}{k} [G_k + C_{3\epsilon} G_b] - C_{2\epsilon} \rho \frac{\epsilon^2}{k} \end{aligned} \quad (5)$$

In the above equations, k refers to the turbulent kinetic energy, ϵ refers to the dissipation rate, G_k is generation of turbulent energy because of gradients of mean velocity, and G_b represents generation of turbulent energy due to buoyancy. $C_{1\epsilon}$, $C_{2\epsilon}$ and $C_{3\epsilon}$ are the constants of the model. σ_ϵ and σ_k refer to the turbulent Prandtl numbers for ϵ and k respectively. Turbulent viscosity (μ_t) calculated by

$$\mu_t = \rho C_\mu \frac{k^2}{\epsilon} \quad (6)$$

C_μ is a constant. The assumed values for the constants used in Equation (5) are $C_{1\epsilon} = 1.44$, $C_{2\epsilon} = 1.92$, $C_\mu = 0.09$, $\sigma_k = 1$ and $\sigma_\epsilon = 1.3$. More details are explained in ref (ANSYS fluent software package: user's manual, Version 17, n.d.).

In addition to the mentioned equations, energy balance was used to obtain temperatures and heat transfer rate. The energy balance for a fluid flow is represented in Equation (7).

$$\frac{\partial}{\partial t}(\rho h) + \nabla \cdot (\vec{v} \rho h) = \nabla \cdot (k \nabla T) + S_h \quad (7)$$

ANSYS CFX 17.0 is used to solve the equations. The equations were discretized by finite volume approach. The structured mesh was used for the domains and the overall number of elements were equal to approximately 945,000. No-slip boundary condition was assumed at the wall of fluid domains. The outlet pressure for both hot

and cold streams assumed to be atmospheric. The inlet velocity of cold stream and mass flow rate of hot streams varied to compare the results. The convergence criterion for the residuals for the equations were set as 10^{-6} . In the simulation process, two heat exchangers, one of them with thermosyphons and another one with copper bars (which have diameter equal to outer diameter of the thermosyphons) were considered.

3. Experimental results

As mentioned in previous section, three nanofluids and a mixture of water/glycerol were used as working fluids. In order to compare thermal performance for each working fluid, the temperatures of condenser and evaporator sections were measured. The thermal resistance of the thermosyphon was calculated by applying Equation (8):

$$R = \frac{\bar{T}_e - \bar{T}_c}{\dot{Q}} \quad (8)$$

where \bar{T}_e and \bar{T}_c are average temperatures of evaporator and condenser sections, respectively. \dot{Q} is thermal energy input which varied between 30 and 110 W.

In Figure 4, thermal resistance of the thermosyphon with various working fluids is represented.

As shown in Figure 4, it can be concluded that there is an optimum concentration for the nanoparticles in the base fluid. Increase in concentration results in nanofluid's higher thermal conductivity (Ahmadi et al., 2018; Ahmadi, Ahmadi, Nazari, Mahian, & Ghasempour, 2018; Ahmadi, Mirlohi, Nazari, & Ghasempour, 2018) which is favorable for heat transfer in the thermosyphon; however, the dynamic viscosity of the fluid will be increased which has adverse effect on thermal performance. Due to this fact, there must be an optimal concentration for solid particles in the base fluid. Moreover, nanoparticles existence can increase nucleation sites which can be another reason for heat transfer

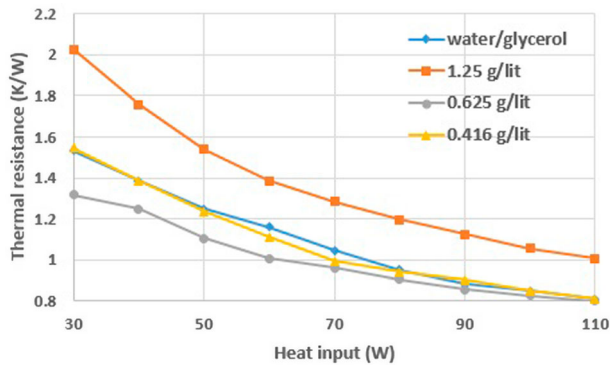


Figure 4. Thermal resistance vs. heat input.

augment (Nazari, Ghasempour, Ahmadi, Heydarian, & Shafii, 2018).

Based on the thermal resistance of the thermosyphon, its effective thermal conductivity was obtained. In order to determine effective thermal conductivity in heat pipes, Equation (9) is applicable (Alizadeh et al., 2016):

$$K_{eff} = \frac{l_{eff}}{R.A} \quad (9)$$

In the above equation R is thermal resistance, A is cross section area of the thermosyphon and l_{eff} is effective length of thermosyphon which can be calculated by using Equation (10).

$$l_{eff} = l_{ad} + \frac{1}{2}(l_e + l_c), \quad (10)$$

where l_{ad} , l_c and l_e refer to lengths of adiabatic, condenser and evaporator sections, respectively.

By using the abovementioned equations, thermosyphon's effective thermal conductivity obtained for various concentrations. Results are represented in Figure 5.

As it was mentioned, the best thermal performance of the thermosyphon was observed in the case of using nanofluid with 0.625 g/lit concentration. Enhancement in thermal performance of the thermosyphon can be attributed to both thermal conductivity and nucleation sites increase. At high concentrations, the dynamic viscosity of the working fluid increases, which has unfavorable impact on heat transfer and fluid circulation. Therefore, there must be an optimum concentration for the solid phase in the base fluid to achieve the highest effective thermal conductivity.

In the next section, the simulation of the heat exchanger is performed based on the data obtained for the thermosyphon filled with nanofluid with 0.625 g/lit concentration.

4. Numerical results

On the basis of experimental data, a numerical simulation was performed to analyze the performance of thermosyphons in heat exchanger. In order to achieve this goal, a heat exchanger was designed with 34 thermosyphons. The structure of thermosyphons in the heat exchanger were rectangular. The distance between thermosyphons centers is equal to 20 mm. The lengths of thermosyphon in hot stream and cold streams are 105 mm. In addition, a distance is considered between the streams which is the adiabatic section of the thermosyphon and its length is 180 mm. A schematic of the designed heat exchanger is shown in Figure 6.

The hot stream of the heat exchanger was water and the cold stream assumed to be air. The thermosyphon's

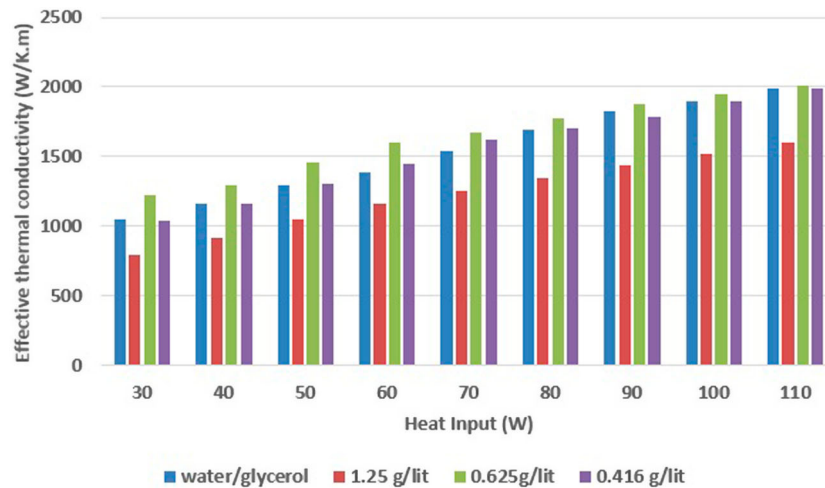


Figure 5. Effective thermal conductivity of thermosyphon.

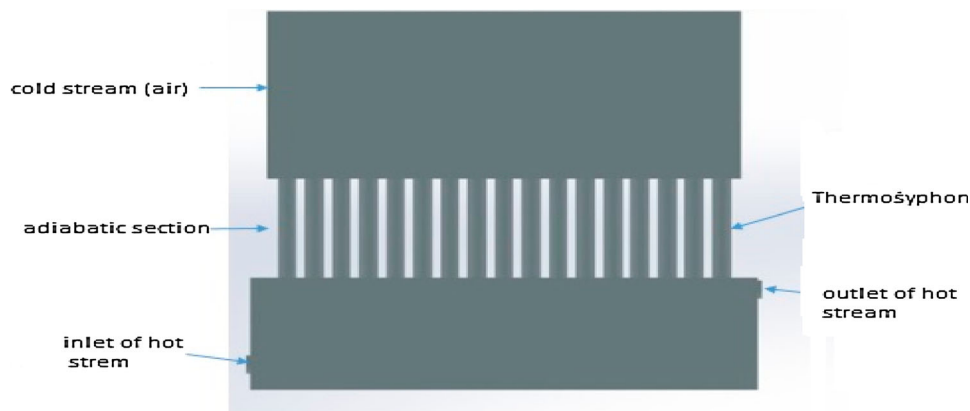


Figure 6. Schematic of heat exchanger.

effective thermal conductivity was assumed as a function of evaporator and condenser temperature difference. This assumption is utilized in heat transfer modeling of other types of heat pipes (Alizadeh et al., 2018). Effective thermal conductivity vs. temperature difference is shown in Figure 7.

In the first step, the influence of water mass flow rate (hot stream) on the thermal capacity of the heat exchanger was investigated. Three mass flow rates including 0.3, 0.5 and 0.7 kg/s were considered in simulation. The inlet temperature of water was 80°C and the velocity and temperature of inlet air (cold stream) were equal to 70 m/s and 20°C. The obtained results under this condition is represented in Figure 8.

According to Figure 8, increase in mass flow rate results in higher heat transfer. Higher mass flow rate of hot water means increase in heat input for the thermosyphons which leads to increase in effective thermal conductivity (as shown in Figure 5); therefore, enhancement in heat transfer rate of thermosyphon heat exchanger is higher than copper heat exchanger.

Another influential parameters on heat transfer rate of heat exchanger is temperature of inlet water. Similar to the previous condition, higher temperatures of hot water increase heat input at the evaporator part of the thermosyphon; therefore, the effective thermal conductivity will increase. In this study, three inlet temperatures including 70, 80 and 90°C were considered in simulation. The air temperature and velocity in this stage were equal to 20°C and 70 m/s, respectively. Mass flow rate of water was 0.5 kg/s. Results are represented in Figure 9.

As shown in Figure 9, increase in water inlet temperature resulted in more enhancement in heat transfer rate of thermosyphon heat exchanger which can be due its two-phase thermal behavior (increase in boiling at higher heat input).

Finally, the effect of inlet air velocity was investigated. It was assumed that the inlet temperature of water is 80°C and its mass flow rate is equal to 0.5 kg/s. The temperature of inlet air is equal to 20°C. The results are shown in Figure 10.

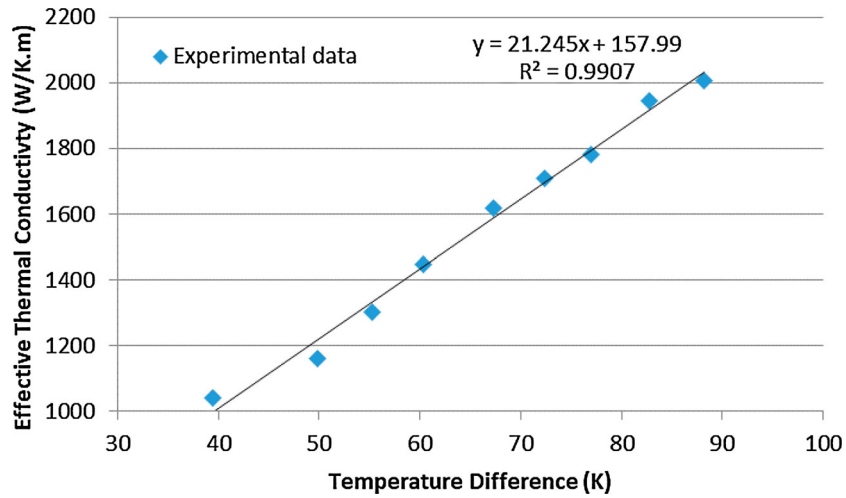


Figure 7. Effective thermal conductivity vs. temperature difference.

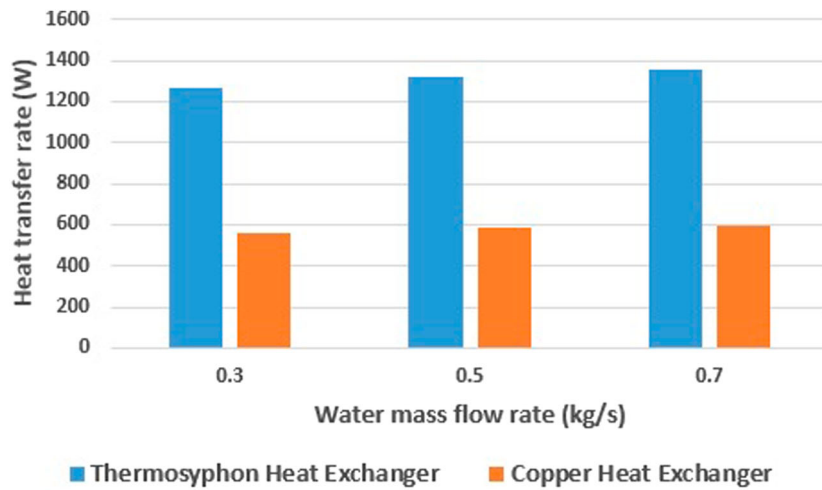


Figure 8. Effect of water mass flow rate on heat transfer rate.

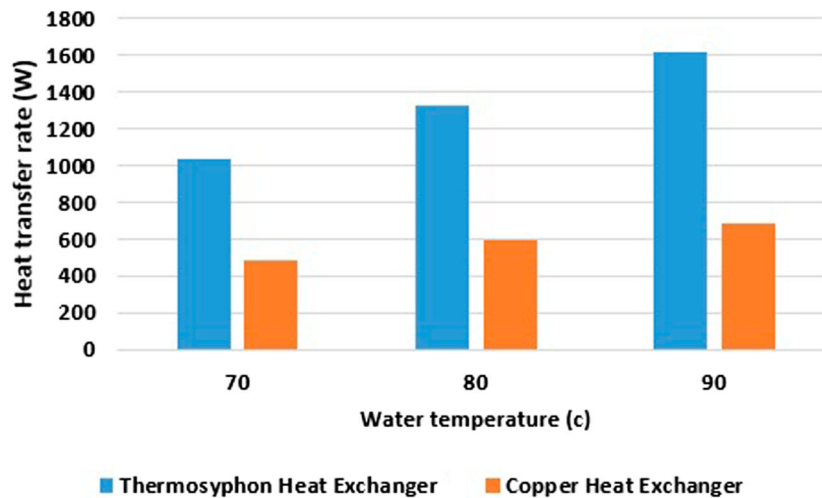


Figure 9. Effect of water inlet temperature on heat transfer rate.

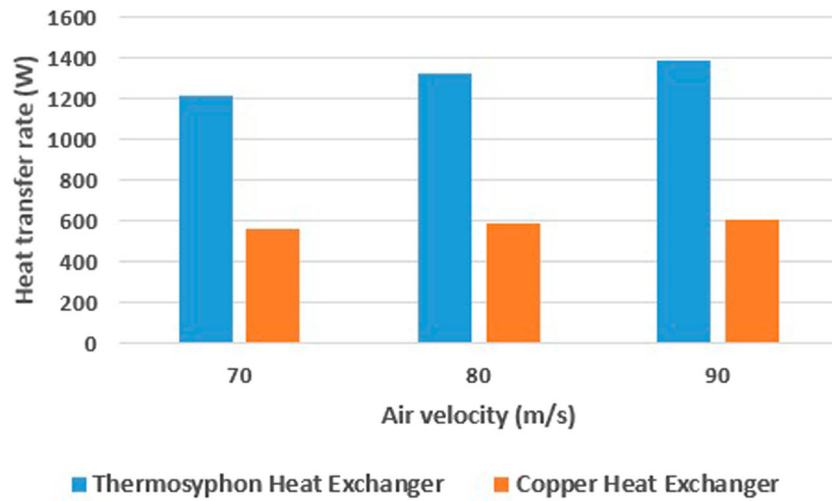


Figure 10. Effect of air velocity of heat transfer rate.

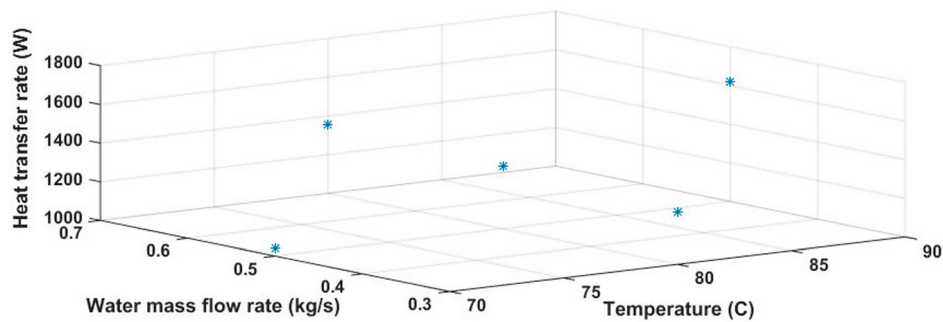


Figure 11. Effect of mass flow rate and temperature of water on heat transfer rate.

Based on the obtained results, increase in air velocity has higher impact on thermosyphon heat exchanger which can be attributed to increase in heat transfer rate in the condenser section of the thermosyphons. Increase in the air velocity which is a cold stream, leads to better cooling condition and lower temperature at the condenser; as a consequence, the temperature difference between condenser and evaporator increase which results in effective thermal conductivity augment as represented in Figure 5.

The effects of water mass flow rate and temperature on heat transfer rate of heat exchanger is illustrated in Figure 11.

Comparing heat transfer rate between thermosyphon heat exchanger and copper heat exchanger reveals that using thermosyphons results in much better thermal performance which is attributed to its higher effective thermal conductivity in comparison with metals. The maximum heat transfer rate for 90°C water inlet temperature and mass flow rates of water equal to 0.5 kg/s and 70 m/s air speed were equal to 1621 and 689 W, for thermosyphon and copper heat exchanger, respectively. Similar to conventional heat exchangers, increase in mass flow rates of the streams leads to higher heat transfer

rate. In addition, it can be concluded that changes in heat transfer rate of thermosyphon heat exchanger is more significant due to its higher heat transfer coefficient.

5. Conclusion

In the current study, thermal performance of a thermosyphon filled with Ni/Water–glycerol was investigated in three concentrations including 0.416, 0.625 and 1.25 g/lit. It was observed that using the nanofluid with 0.625 g/lit concentration led to the best thermal performance. Afterwards, a heat exchange was designed based on the dimensions of the thermosyphon and its heat transfer was compared with another heat exchanger used copper bars with the same dimensions and geometry. Obtained results revealed that using thermosyphon heat exchanger is much more efficient compared with copper heat exchanger. Under a specific condition, it was observed that using thermosyphon heat exchanger led to 135% increase in heat transfer rate in comparison with copper heat exchanger.

Future studies should focus on using more concentrations to obtain the best concentration in order to have

the highest efficiency. In addition, using other base fluids with dispersed Nickel nano particles can lead to better thermal performance which should be considered in future researches.

Disclosure statement

No potential conflict of interest was reported by the authors.

References

- Ahmadi, M. H., Ahmadi, M. A., Nazari, M. A., Mahian, O., & Ghasempour, R. (2018). A proposed model to predict thermal conductivity ratio of Al₂O₃/EG nanofluid by applying least squares support vector machine (LSSVM) and genetic algorithm as a connectionist approach. *Journal of Thermal Analysis and Calorimetry*, 1–11. doi:10.1007/s10973-018-7035-z
- Ahmadi, M. H., Alhuyi Nazari, M., Ghasempour, R., Madah, H., Shafii, M. B., & Ahmadi, M. A. (2018). Thermal conductivity ratio prediction of Al₂O₃/water nanofluid by applying connectionist methods. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, 541, 154–164. doi:10.1016/j.colsurfa.2018.01.030
- Ahmadi, M. H., Mirlohi, A., Nazari, M. A., & Ghasempour, R. (2018). A review of thermal conductivity of various nanofluids. *Journal of Molecular Liquids*, doi:10.1016/j.molliq.2018.05.124
- Ahmadi, M. H., Tatar, A., Alhuyi Nazari, M., Ghasempour, R., Chamkha, A. J., & Yan, W.-M. (2018). Applicability of connectionist methods to predict thermal resistance of pulsating heat pipes with ethanol by using neural networks. *International Journal of Heat and Mass Transfer*, 126, 1079–1086. doi:10.1016/j.ijheatmasstransfer.2018.06.085
- Alhuyi Nazari, M., Ahmadi, M. H., Ghasempour, R., & Shafii, M. B. (2018). How to improve the thermal performance of pulsating heat pipes: A review on working fluid. *Renewable and Sustainable Energy Reviews*, 91, 630–638. doi:10.1016/j.rser.2018.04.042
- Alizadeh, H., Ghasempour, R., Razi Astaraei, F., & Alhuyi Nazari, M. (2016). Numerical modeling of PV cooling by using pulsating heat pipe. *The 3rd international conference and exhibition on solar energy ICESE-2016*, Tehran.
- Alizadeh, H., Ghasempour, R., Shafii, M. B., Ahmadi, M. H., Yan, W.-M., & Nazari, M. A. (2018). Numerical simulation of PV cooling by using single turn pulsating heat pipe. *International Journal of Heat and Mass Transfer*, 127, 203–208. doi:10.1016/j.ijheatmasstransfer.2018.06.108
- ANSYS fluent software package: user's manual, Version 17. (n.d.).
- Asirvatham, L. G., Wongwises, S., & Babu, J. (2016). Heat transfer performance of a glass thermosyphon using graphene – acetone nanofluid. *137*(November 2015), 1–9. doi:10.1115/1.4030479
- Faizollahzadeh Ardabili, S., Najafi, B., Shamshirband, S., Minaei Bidgoli, B., Deo, R. C., & Chau, K. (2018). Computational intelligence approach for modeling hydro- gen production: A review. *Engineering Applications of Computational Fluid Mechanics*, 12(1), 438–458. doi:10.1080/19942060.2018.1452296
- Fereidoon, A., Saedodin, S., Hemmat Esfe, M., & Noroozi, M. J. (2013). Evaluation of mixed convection in inclined square Lid-driven cavity filled with AL₂O₃/water nano-fluid. *Engineering Applications of Computational Fluid Mechanics*, 7(1), 55–65. doi:10.1080/19942060.2013.11015453
- Ghaderian, J., Sidik, N. A. C., Kasaiean, A., Ghaderian, S., Okhovat, A., Pakzadeh, A., . . . Yahya, W. J. (2017). Performance of copper oxide/distilled water nanofluid in evacuated tube solar collector (ETSC) water heater with internal coil under thermosyphon system circulations. *Applied Thermal Engineering*, 121, 520–536. doi:10.1016/j.applthermaleng.2017.04.117
- Jafari, D., Filippeschi, S., Franco, A., & Di Marco, P. (2017). Unsteady experimental and numerical analysis of a two-phase closed thermosyphon at different filling ratios. *Experimental Thermal and Fluid Science*, 81, 164–174. doi:10.1016/j.expthermflusci.2016.10.022
- Liu, Z. H., Yang, X. F., & Guo, G. L. (2007). Effect of nanoparticles in nanofluid on thermal performance in a miniature thermosyphon. *Journal of Applied Physics*, 102(1), 013526. doi:10.1063/1.2748348
- Mou, B., He, B.-J., Zhao, D.-X., & Chau, K. (2017). Numerical simulation of the effects of building dimensional variation on wind pressure distribution. *Engineering Applications of Computational Fluid Mechanics*, 11(1), 293–309. doi:10.1080/19942060.2017.1281845
- Nazari, M. A., Ahmadi, M. H., & Ghasempour, R. (2018). A review on pulsating heat pipes: from solar to cryogenic applications. *222*(March), 475–484. doi:10.1016/j.apenergy.2018.04.020
- Nazari, M. A., Ghasempour, R., Ahmadi, M. H., Heydarian, G., & Shafii, M. B. (2018). Experimental investigation of graphene oxide nanofluid on heat transfer enhancement of pulsating heat pipe. *International Communications in Heat and Mass Transfer*, 91, 90–94. doi:10.1016/j.icheatmasstransfer.2017.12.006
- Sarafraz, M. M., Hormozi, F., & Peyghambarzadeh, S. M. (2014). Thermal performance and efficiency of a thermosyphon heat pipe working with a biologically ecofriendly nanofluid. *International Communications in Heat and Mass Transfer*, 57, 297–303. doi:10.1016/j.icheatmasstransfer.2014.08.020
- Shanbedi, M., Heris, S. Z., Baniadam, M., Amiri, A., & Maghrebi, M. (2012). Investigation of heat-transfer characterization of EDA-MWCNT/DI-water nanofluid in a two-phase closed thermosyphon. *Industrial & Engineering Chemistry Research*, 51(3), 1423–1428. doi:10.1021/ie202110g
- Zeinali Heris, S., Kazemi-Beydokhti, A., Noie, S. H., & Rezvan, S. (2012). Numerical study on convective heat transfer of AL₂O₃/water, CuO/water and Cu/water nanofluids through square cross-section duct in laminar flow. *Engineering Applications of Computational Fluid Mechanics*, 6(1), 1–14. doi:10.1080/19942060.2012.11015398