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RESEARCH ARTICLE

EXPERIMENTAL THERMAL PERFORMANCE ANALYSIS OF NANOFLUID ASSISTED SLINKY GROUND HEAT EXCHANGER IN SPACE COOLING APPLICATION

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ABSTRACT

Ground source heat pump has made a severe breakthrough in space conditioning applications due to their high energy efficiency, and expectations for these systems have increased due to using renewable energy. Concerning the increasing expectation, researchers and engineers have increased their research on these systems and focused on cost and efficiency. The efficiency of the ground source heat pump system is directly related to the ground heat exchanger loop, which provides the thermal connection between the heat pump and the ground, and increasing the effectiveness of the ground heat exchanger can be achieved with a nanofluid-based heat transfer fluid. On the other hand, as a ground source heat pump system component, ground heat exchangers have very different design configurations. Among the various configurations, slinky ground heat exchangers are of great interest due to their higher heat transfer efficiency and reduced installation space requirements compared to traditional straight pipe configurations. In this study, the effect of nanofluids on increasing the effectiveness of slinky ground heat exchangers was experimentally investigated and compared with the results obtained using conventional heat transfer fluids. The results obtained from the experimental study determined that using nanofluid at a rate of 0.1% as a heat transfer fluid in slinky ground heat exchangers in cooling applications increased the average effectiveness by about 20%.

Keywords: *Slinky Ground Heat Exchanger, Nanofluid, Effectiveness, Experimental Analysis*

1. INTRODUCTION

The demand for efficient and sustainable space conditioning systems has increased significantly in recent years due to rising energy costs and environmental concerns [1]. Conventional space cooling systems such as air conditioning consume a significant amount of energy and contribute to greenhouse gas emissions. Researchers and engineers have increased their research to develop energy-efficient cooling systems in this context. The use of ground source heat pump (TKIP) in conditioning

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applications is one of the innovative approaches when energy saving and environmental concerns are taken into consideration [2,3].

There are many studies in the literature on different application areas on the subject [4-7]. GSHP systems use the stable thermal properties of the earth with the help of components called soil heat exchanger (GHE). Basically, GHEs are components that effectively exchange heat between the soil and a fluid circulating in buried pipes. Regarding application diversity, GHEs are divided into two as vertical and horizontal [8,9]. Although horizontal GHEs have lower performance compared to verticals, they have a low cost and relatively easy installation [10]. Horizontal GHEs, on the other hand, are classified according to various pave forms. Among these configurations, slinky ground heat exchangers (SGHE) are of great interest due to their higher heat transfer efficiency and reduced installation space requirements compared to traditional straight pipe configurations [11]. Wu et al. [12] reported that the use of SGHE saves up to 30% of installation space.

On the other hand, the performance of GHEs varies depending on many components, such as installation depth, design parameters, and the fluid used in the pipe. The thermal performance improvement of fluids can be achieved with nanofluids (NF), which has recently attracted great interest in the literature. In this context, NAs have the potential to improve the general heat transfer properties of TIDs [7]. NFs are suspensions of nanoparticles dispersed in a base fluid. The addition of nanoparticles changes the thermophysical properties of the base fluid, such as thermal conductivity and convective heat transfer coefficient. Studies conducted on MVCNT [13], Al_2O_3 [14], TiO [15] and SiO [16] reported that suspensions formed with different nanoparticles provide an increase in thermal capacity compared to the base fluid. However, despite extensive theoretical research on NFs, limited experimental data are available regarding their GHE performance, especially in the context of space cooling applications. Including NFs in these systems can reduce energy consumption and the environmental impact associated with space cooling. In summary, it can promote sustainable and efficient cooling technologies.

This study aimed to experimentally investigate the thermal efficiency of NF supported SGHE in space cooling applications and compared with the results obtained using conventional heat transfer fluid (ethylene glycol-water/base fluid) to determine the effect of NF. Investigating the effect of NF under real ambient conditions will shed light on the practical feasibility and potential benefits of incorporating nanofluids into GSHP systems.

2. MATERIALS AND METHODS

While the overall performance of the GSHP system depends on many external and internal parameters, the performance of GHE generally depends on more specific parameters, such as ground temperature and specific heat capacity of the fluid. In this context, thermal performance tests should be carried out to determine GHE performance. In this context, the heat exchange rate can be calculated by measuring the inlet, outlet temperatures, and flow rate of the fluid passing through the heat exchanger for the cooling mode:

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$$\dot{Q} = mC_p(T_{out} - T_{in}) \tag{1}$$

or

$$\dot{Q} = q\dot{V}C_p(T_{out} - T_{in}) \tag{2}$$

Another important parameter that we encounter in GHEs is GHE effectiveness. The concept of effectiveness here can be defined as the ratio of the actual heat transfer rate to the maximum amount of heat that can be transferred. The effectiveness of the GHE can be calculated using the following equation:

$$\varepsilon = \frac{mC_p\left(T_{GHE,in} - T_{GHE,out}\right)}{mC_p\left(T_{GHE,in} - T_{ground}\right)} \tag{3}$$

or

$$\varepsilon = \frac{\left(T_{GHE,in} - T_{GHE,out}\right)}{\left(T_{GHE,in} - T_{ground}\right)} \tag{4}$$

3. EXPERIMENTAL SETUP

The experimental setup consists of the SGHE buried 2.5 m below the ground surface, a heat pump system, and the cooling area. As mentioned earlier, the SGHE configuration improves the system's overall performance by allowing the heat transfer surface area to increase compared to other GHEs installed in a similar area [17,18].

The space to be conditioned has dimensions of 3 m x 7 m x 2.3 m and the heat load of the area was calculated as 2.2 kW using the HeatCAD package program according to Sivas province. The heat loss value per unit area has been calculated as approximately 104 W/m^2. Estimating the GHE length to meet the heating and cooling demand of the space is an important step in the GSHP system setup. Different methodologies have been proposed in the literature to calculate the GHE length. In this study, a methodology suggested by Chiasson was used [19]. According to the calculated heat load, the required pipe length was calculated as 75 m in total. The SGHE is placed on the ground in 20 spirals with a radius of 0.3 m. The pipe used in SGHE is SDR 11 polyethylene pipe with an outer diameter of 40 mm and a wall thickness of 3 mm. Temperature measurements were carried out with the help of T-type thermocouples from different points, SGHE inlet, outlet and over the pipe. SGHE is integrated into the heat pump with the aid of a 245 L heat exchange tank. NF with 0.1% concentration, prepared by dispersing 8 nm Al_2O_3 nanoparticles in a base fluid (ethylene glycol-water), was used as the heat transfer fluid in the ground loop. The mass flow rate of the fluid circulating in the system was kept at 0,450kg/s with the help of an inverter circulation pump. Heating experiments of the related experimental setup were previously carried out by Kapıcıoğlu [20]. The schematic view of the system is given in Figure 1.

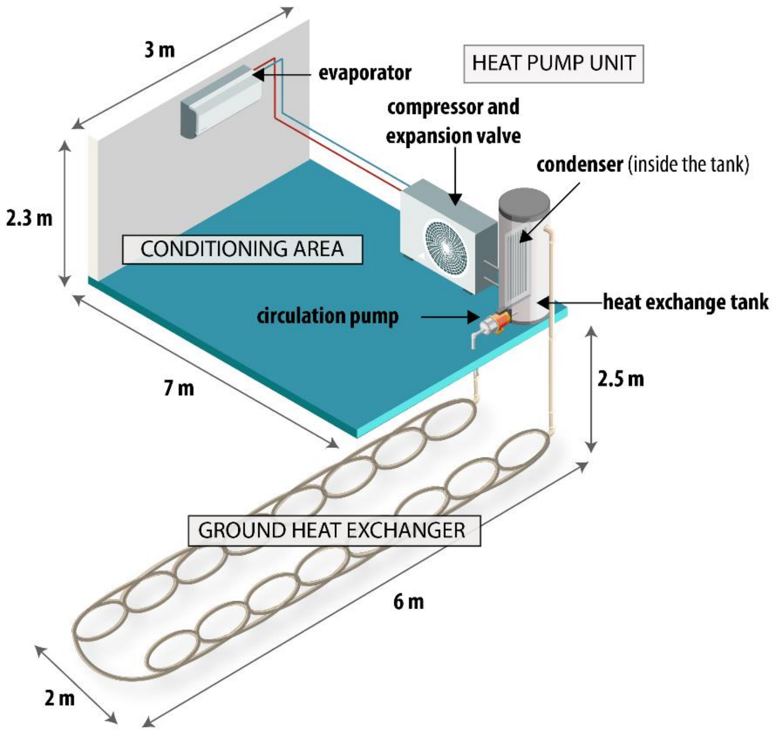

Figure 1. Schematic view of the experimental setup.

The experimental study was carried out in July 2021. In the experimental study, the temperature values for both the base fluid and the NF were monitored during the eight-hour operating period. In order to evaluate the thermal equilibrium in the ground for both fluids, temperatures around the ground were recorded from the beginning of the experiments. The ground temperature change during the experiment period is given in Figure 2.

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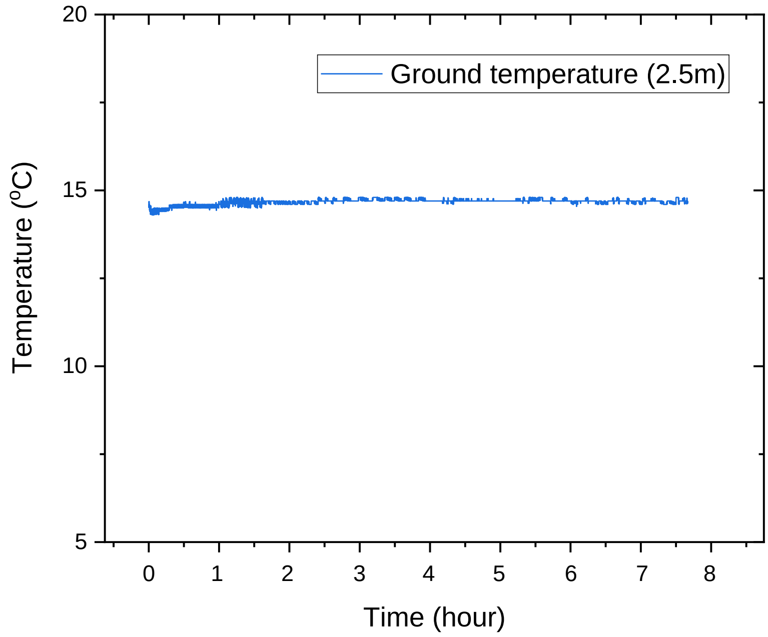

Figure 2. The ground temperature change during the experiment.

Similar working conditions were tried to be achieved in experimental studies and these values were meticulously recorded with the help of a data recorder. During the experimental period, temperature data were taken, one data per second. Some typical data recorded are shown in Table 1.

Table 1. Inlet and outlet temperatures of Al_2O_3 nanofluid with base and 0.1% concentration into SGHE.

Time (min)	Base fluid		Al_2O_3 (%0,1)	
	GHE inlet (°C)	GHE outlet (°C)	GHE inlet (°C)	GHE outlet (°C)
30	20.79	20.49	20.14	19.68
60	23.86	23.10	23.81	23.02
120	26.37	25.43	25.73	24.90
180	28.09	27.08	27.62	26.67
240	29.00	27.99	28.33	27.31
300	30.10	29.17	29.32	28.44
360	29.83	29.08	28.87	28.13
420	29.04	28.45	28.30	27.64

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480	28.37	27.85	27.44	26.86

The experimental uncertainty in this study includes the uncertainties in temperature and flow measurements. Uncertainty analysis was performed using the uncertainty analysis method defined by Kline-McClintock [21]. The overall uncertainty of the measurements is estimated at ±1.46% for mass flow rate and ±0.5 for temperatures.

4. RESULT AND DISCUSSION

The temperature of the fluid circulating in a GHE is directly related to parameters such as ground temperature and load amount of the system. Figure 3 shows the inlet and outlet temperatures of the base fluid to the SGHE. From the beginning of the experiments, it is seen that both the inlet and outlet fluid temperatures begin to increase over time. The fluctuation in the initial phase is due to the uneven temperature distribution during the transfer of the fluid in the tank to the ground. This situation ends with the balancing of the ground temperature and the fluid temperature in the first fifteen minutes. In addition, fluctuations were observed during the first ninety minutes due to the amount of heat transfer required by the system during the first operation. The inlet and outlet temperatures of the fluid circulating in the GHE were determined as 27.06 ^{o}C (±3.72 ^{o}C) and 26.42 ^{o}C (±3.77 ^{o}C), respectively.

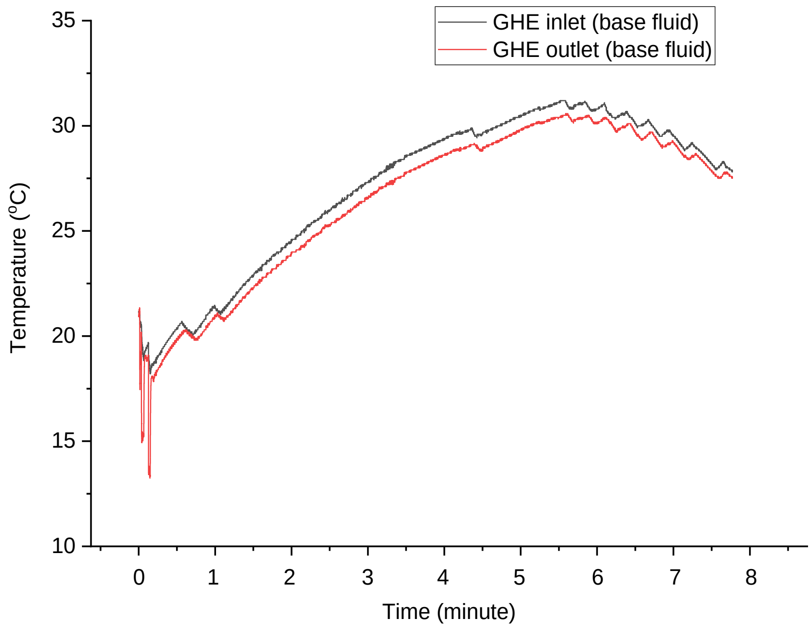

Figure 3. Temperature profile of base fluid in SGHE.

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The experiments for the base fluid were carried out in NF under similar conditions, and the SGHE inlet and outlet temperatures are presented in Figure 4. The temperature value of the fluid in the SGHE shows an increasing trend during the day, similar to the base fluid. The inlet and outlet temperatures of the NF circulating in the SGHE were calculated on average as 26.58 ^{o}C (±3.74 ^{o}C) and 25.87 ^{o}C (±3.67 ^{o}C), respectively. Compared to the base fluid, the average temperature values calculated here are also at lower levels. Also, similar initial conditions were observed for both fluids. Both fluids (base and NF) draw heat from the ground in the first 15 minutes instead of giving it to the ground. This is due to the fact that the fluid in the tank is initially at a lower temperature than the ground. This situation ends with reversing the flow direction of the heat at the end of the fifteen-minute period. However, the fluctuation in NF is lower than in the base fluid. This situation can be associated with the high thermal capacity of NF.

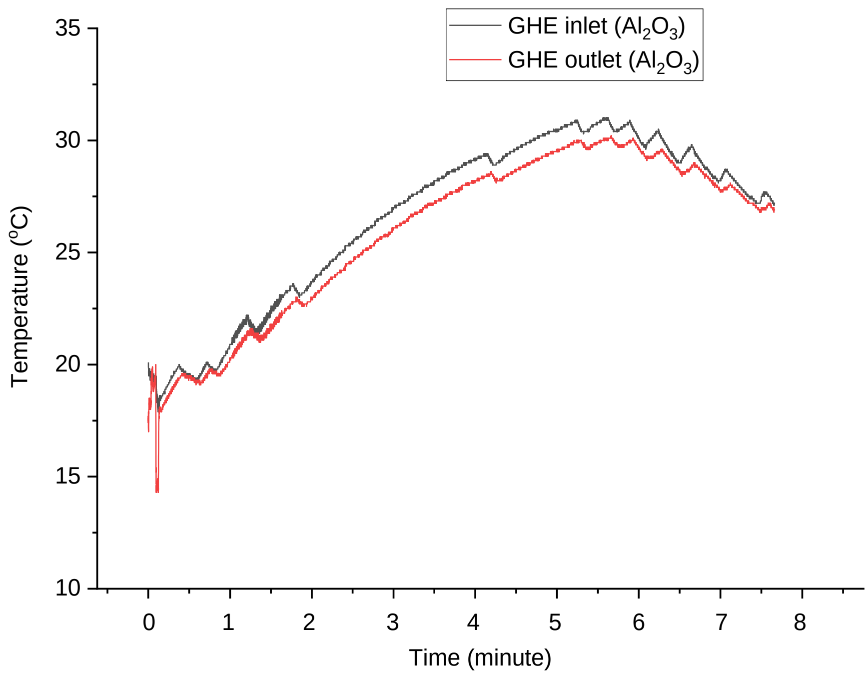

Figure 4. Temperature profile of NF with 0.1% concentration in SGHE.

Figure 5 shows the SGHE effectiveness changes for the use of base fluid and NF as the heat transfer fluid over the eight-hour operating period. The average effectiveness of SGHEs using base fluid and NA is 0.114 (0.061) and 0.137 (0.09), respectively. Due to the heating of the ground due to the increase in the operating time of the system, the performance of the SGHE decreases, so the effectiveness decreases over time. This situation can be explained as follows: the temperature difference between the inlet and outlet fluid temperatures occurs in an almost similar range, so the

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variation in heat transfer is relatively limited. However, the inlet fluid temperature continues to increase with time so that the maximum possible heat transfer increases with time. These two effects cause the effectiveness of GHE to decrease over time. While the difference between base fluid and ground temperature is 11.8 °C on average, this value is around 11.1 °C in NF.

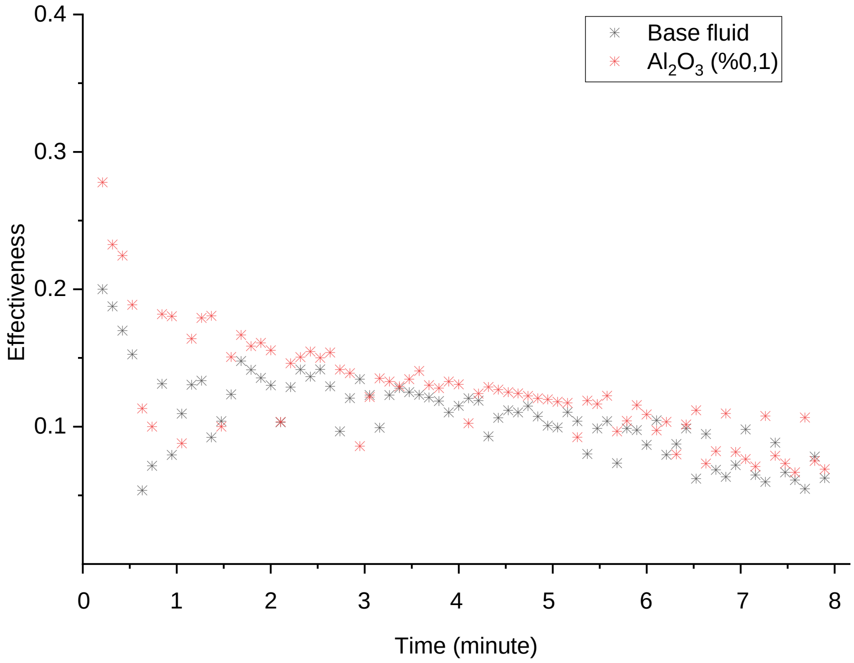

Figure 5. GHE effectiveness of base fluid and nanofluid with 0.1% concentration.

5. CONCLUSIONS

In this study, the effectiveness of using NF in a GHE with a slinky design integrated into a ground source heat pump system in space cooling applications was investigated. NF, which is used as the heat transfer fluid in the system, is prepared from 8 nm Al_2O_3 nanoparticles and has a concentration value of 0.1%. Experimental results showed that the nanofluid supported SGHE exhibited improved thermal performance compared to the base system. The important findings obtained as a result of the study can be listed as follows:

The use of NF in the SGHE system resulted in an improvement of 1.77% in inlet temperatures and 2.08% in outlet temperatures. With these values, the use of NF can be accepted as an indication that it will provide improved cooling performance by improving the SGHE heat transfer properties.

When the GHE effectiveness depending on ground temperature was examined, the average effectiveness of SGHEs using base fluid and NF was 0.114 and 0.137, respectively. With these results, it can be said that the use of NF as a heat transfer fluid increases the effectiveness by nearly 20%.

As a result, it has been observed that NF provides better heat exchange between the ground and the heat transfer fluid, thanks to its enhanced heat transfer properties attributed to the high thermal conductivity of nanoparticles. As a result of this situation, it can be said that it will increase the cooling efficiency by leading to lower fluid outlet temperatures and higher heat transfer rates.

Finally, it should be noted that more research is needed to investigate the economic viability and environmental impacts, as well as the long-term stability and reliability of NFs in GHEs. However, the experimental results provide valuable information for the development and optimization of nanofluid assisted cooling systems.

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REFERENCES

[1] Wang, X., Zhou, C., Ni, L., (2022). Experimental investigation on heat extraction performance of deep borehole heat exchanger for ground source heat pump systems in severe cold region. Geothermics 105, 102539. https://doi.org/10.1016/J.GEOTHERMICS.2022.102539

[2] Kaneko, C., Yoshinaga, M., (2023). Long-term operation analysis of a ground source heat pump with an air source heat pump as an auxiliary heat source in a warm region. Energy Build 289, 113050. https://doi.org/10.1016/J.ENBUILD.2023.113050

[3] Violante, A.C., Donato, F., Guidi, G., Proposito, M., (2013). Experimental evaluation of using various renewable energy sources for heating a greenhouse. Energy Build 65, 340–351. https://doi.org/10.1016/j.enbuild.2013.06.018

[4] Kapıcıoğlu, A., Esen, H., (2022). Economic and environmental assessment of ground source heat pump system: The case of Turkey. Sustainable Energy Technologies and Assessments 53. https://doi.org/10.1016/j.seta.2022.102562

[5] Dehghan B., B., (2017). Experimental and computational investigation of the spiral ground heat exchangers for ground source heat pump applications. Appl Therm Eng 121, 908–921. https://doi.org/10.1016/j.applthermaleng.2017.05.002

[6] Kapıcıoğlu, A., Esen, H., (2019). Experimental investigation on using Al2O3/ethylene glycol-water nano-fluid in different types of horizontal ground heat exchangers. Appl Therm Eng 165, 114559. https://doi.org/10.1016/j.applthermaleng.2019.114559

[7] Esen, H., Inalli, M., (2009). Modelling of a vertical ground coupled heat pump system by using artificial neural networks. Expert Syst Appl 36, 10229–10238. https://doi.org/10.1016/j.eswa.2009.01.055

[8] Coşkun, S., Güler, F., Fazliç, M.A., Ergün, E.H., (2018). Dikey Tip Toprak Kaynaklı Bir Isı Pompasının Simülasyonu. Uludağ University Journal of The Faculty of Engineering 23, 155–168. https://doi.org/10.17482/uumfd.467169

[9] Esen, H., İnallı M., Sengur A., Esen M. (2008). Modelling a ground-coupled heat pump system using adaptive neuro-fuzzy inference systems, International Journal of Refrigeration,31,65-74. https://doi.org/10.1016/j.ijrefrig.2007.06.007

[10] Florides, G., Kalogirou, S., (2007). Ground heat exchangers-A review of systems, models and applications. Renew Energy. https://doi.org/10.1016/j.renene.2006.12.014

[11] Wu, Y., Gan, G., Verhoef, A., Vidale, P.L., Gonzalez, R.G., (2010). Experimental measurement and numerical simulation of horizontal-coupled slinky ground source heat exchangers. Appl Therm Eng 30, 2574–2583. https://doi.org/10.1016/J.APPLTHERMALENG.2010.07.008

[12] M'hamed, B., Che Sidik, N.A., Akhbar, M.F.A., Mamat, R., Najafi, G., (2016). Experimental study on thermal performance of MWCNT nanocoolant in Perodua Kelisa 1000cc radiator system. International Communications in Heat and Mass Transfer 76, 156–161. https://doi.org/10.1016/j.icheatmasstransfer.2016.05.024

[13] Elias, M.M., Mahbubul, I.M., Saidur, R., Sohel, M.R., Shahrul, I.M., Khaleduzzaman, S.S., Sadeghipour, S., (2014). Experimental investigation on the thermo-physical properties of Al2O3 nanoparticles suspended in car radiator coolant. International Communications in Heat and Mass Transfer 54, 48–53. https://doi.org/10.1016/j.icheatmasstransfer.2014.03.005

[14] Mukherjee, S., Chakrabarty, S., Mishra, P.C., Chaudhuri, P., (2020). Transient heat transfer characteristics and process intensification with Al2O3-water and TiO2-water nanofluids: An experimental investigation. Chemical Engineering and Processing - Process Intensification 150, 107887. https://doi.org/10.1016/j.cep.2020.107887

[15] Hussein, A.M., Bakar, R.A., Kadirgama, K., (2014). Study of forced convection nanofluid heat transfer in the automotive cooling system. Case Studies in Thermal Engineering 2, 50–61. https://doi.org/10.1016/j.csite.2013.12.001

[16] Tadepalli, R., Gadekula, R.K., Reddy, K.V., Goud, S.R., Nayak, S.K., Saini, V., Dondapati, R.S., (2018). Characterization of Thermophysical properties of Al2O3, TiO2, SiO2, SiC and CuO

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Nano Particles at Cryogenic Temperatures. Mater Today Proc 5, 28454–28461. https://doi.org/10.1016/j.matpr.2018.10.132

[17] Fujii, H., Nishi, K., Komaniwa, Y., Chou, N., (2012). Numerical modeling of slinky-coil horizontal ground heat exchangers. Geothermics 41, 55–62. https://doi.org/10.1016/J.GEOTHERMICS.2011.09.002

[18] Sangi, R., Müller, D., (2018). Dynamic modelling and simulation of a slinky-coil horizontal ground heat exchanger using Modelica. Journal of Building Engineering 16, 159–168. https://doi.org/10.1016/J.JOBE.2018.01.005

[19] Chiasson, A.D., (2016). Geothermal heat pump and heat engine systems: Theory and practice. John Wiley & Sons.

[20] Kapıcıoğlu, A., (2022). Energy and exergy analysis of a ground source heat pump system with a slinky ground heat exchanger supported by nanofluid. J Therm Anal Calorim 147, 1455–1468. https://doi.org/10.1007/s10973-020-10498-0

[21] Holman, J.P., (2012). Experimental Methods for Engineers, 8th ed. McGraw-Hill.

NOMENCLATURE

SYMBOLS

GHE	ground heat exchanger
GSHP	ground source heat pump
NF	nanofluid
Q	heat capacity, kW
SGHE	slinky ground heat exchanger
T	temperature, K or ◦C
$\dot{V}$	flow rate (L/s)
Cp	specific heat at constant pressure (kJ kg−1K−1)
Ɛ	effectiveness
ρ	fluid density kg m^{-3}
$\dot{m}$	mass flow rate, kg s-1

SUBSCRIPTS

in	inlet
GHE	ground heat exchanger
out	outlet