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Numerical Analysis of Solar Pavement Collector for Malaysian Environment

Nurul Aqilah Razeman[1], Zarina Itam[2]*, Salmia Beddu[2], Muhammad Imran Najeeb[2], Nazirul Mubin Zahari[2], Daud Mohammad[2], Mohd Hafiz Zawawi[2], Agusril Syamsir[2] and Norizham Abdul Razak[3]

[1]*College of Graduate School, Universiti Tenaga Nasional, Jalan IKRAM - UNITEN, 43000 Kajang, Selangor, Malaysia*
[2]*Institute of Energy Infrastructure, Universiti Tenaga Nasional, Jalan IKRAM - UNITEN, 43000 Kajang, Selangor, Malaysia*
[3]*School of Aerospace Engineering, Universiti Sains Malaysia, Engineering Campus, 14300 Nibong Tebal, Pulau Pinang, Malaysia*

ABSTRACT

Tapping into solar renewable energy can accelerate Malaysia's energy economy, and one of the ways to achieve this is through solar pavement technology. Solar pavement technology is an emerging field, and Malaysia, through its green policies, welcomes such innovations to promote environmental sustainability. This research investigates the use of conductive pipes for thermal energy harvesting in solar pavement collectors. Design software, Solidworks 2020, and simulation software, Ansys Fluent 19.2, were utilised to optimise the design parameters of the solar pavement collector. These parameters included the pipe materials (copper, stainless steel, and aluminium), pipe depths (30, 40, 50, 60, 70, and 80mm), and pipe spacing (70, 80, 100, 130, and 150mm). Results show that a serpentine configuration with copper piping exhibited the highest heat efficiency, producing an outlet temperature of 54.21°C at a pipe depth of 50 mm and a centre-to-centre spacing of 80 mm. Additionally, the water flow rate of the optimised pipe design reached an acceptable value of 1.562 m/s. Stainless steel, arranged in a serpentine pattern, achieved a maximum temperature of 54.92 ºC, 1.3% higher than copper in the same configuration. However, aluminium in a serpentine pattern showed a 2.9% decrease compared to stainless steel. The generated warm water has potential for household use, reducing reliance on conventional electricity

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E-mail addresses:
aqilahrazeman@gmail.com (Nurul Aqilah Razeman)
iZarina@uniten.edu.my (Zarina Itam)
Salmia@uniten.edu.my (Salmia Beddu)
imran.najeeb@uniten.edu.my (Muhammad Imran Najeeb)
Nazirul@uniten.edu.my (Nazirul Mubin Zahari)
Daud@uniten.edu.my (Daud Mohammad)
Mhafiz@uniten.edu.my (Mohd Hafiz Zawawi)
Agusril@uniten.edu.my (Agusril Syamsir)
norizham@usm.my (Norizham Abdul Razak)
*Corresponding author

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and contributing to a reduction in carbon footprint, given Malaysia's heavy reliance on fossil fuels for electricity generation.

Keywords: Outlet temperature; simulation; solar pavement collector; thermal energy harness

INTRODUCTION

Most countries rely heavily on fossil fuels, accounting for over 50% of their electricity generation. The by-products of this power generation process are greenhouse gases that form a blanket around the Earth's atmosphere, trapping the sun's heat and contributing to global warming. To mitigate dependence on fossil fuels, especially in Malaysia, embracing green renewable energy, such as solar power, emerges as the optimal solution due to its widespread accessibility. Solar energy is easily accessible across most regions in Malaysia, and the heat produced can be harnessed efficiently through innovative technologies like pavement solar collectors. A pavement solar collector extracts heat from the sun's rays and surroundings to generate electricity. The extensive coverage of roads on Earth's surface provides immense potential for embedding such heat-harvesting technologies. This approach aligns seamlessly with various aspects of global research initiatives, exemplified by The World in 2050 (TWI2050) and the United Nations Sustainable Development Goals (Figure 1).

One heat-harvesting technology is the implementation of thermoelectric generators (TEGs). These devices can be seamlessly integrated into road pavements to capture the temperature difference between the surface and subsurface. The heat gradient generated by the sun's rays and ambient heat can be efficiently converted into electricity through TEGs, contributing to sustainable energy generation. Additionally, another viable technology for harnessing heat is the use of phase-change materials (PCMs). These materials leverage latent heat, causing the bitumen in the road pavement to release or harness heat energy. Embedding PCMs in road pavement serves as thermal energy storage during the day. This stored energy can be utilised at night, balancing temperatures and serving as a source for cooling or heating in the surrounding environment. This dual functionality demonstrates the versatility and potential of incorporating innovative technologies like TEGs and PCMs into road pavements for sustainable energy solutions. In addition to harnessing heat, heat harness technology also serves to extend the life of road pavement. Studies have shown that asphalt roads experience permanent damage when temperatures exceed 70°C (Bobes-Jesus et al., 2013).

Furthermore, recent work has focused on enhancing conventional photovoltaic (PV) systems, particularly through the implementation of concentrated photovoltaic thermal (CPVT) technology (Sheikholeslami & Khalili, 2024a). For instance, Sheikholeslami (2023) utilised flat plate mirror concentrators to concentrate sunlight more effectively, augmenting solar energy capture by incorporating multi-walled carbon nanotube (MWCNT) nanoparticles. Moreover, the author has refined the design of PV-thermal (PVT) systems through hybridisation with a thermoelectric generator (TEG). Multiple cooling system designs of PVT-TEG were developed and simulated using the finite volume method to optimise energy conversion efficiency (Sheikholeslami & Khalili, 2024b).

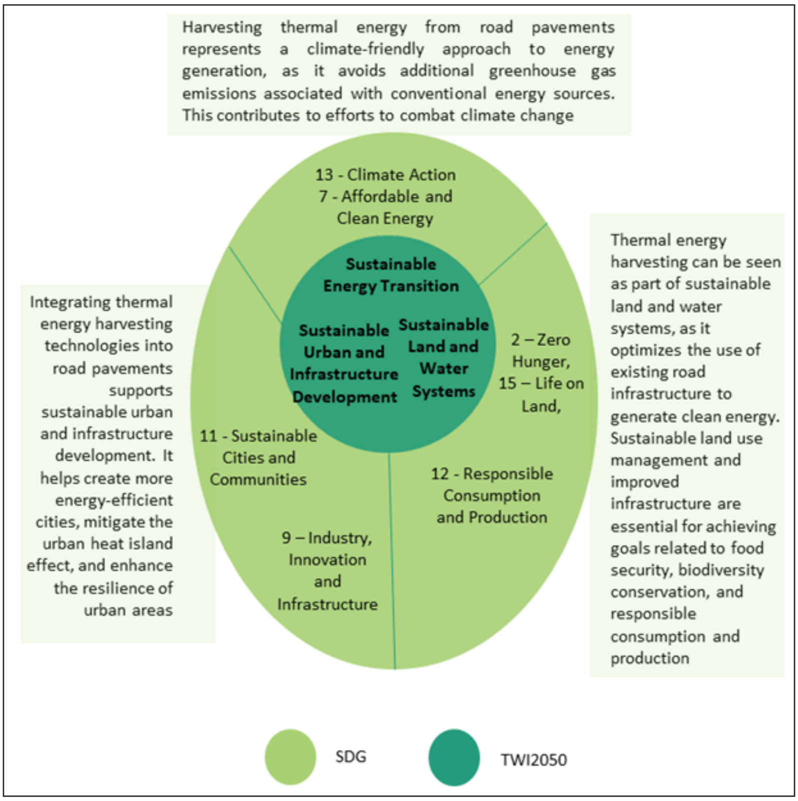

Figure 1. Solar Pavement Collector Align with TWI2050 and SDGs

Pavement solar collectors (PSCs) represent a method of harvesting solar energy and converting it to thermal energy. Zaim et al. (2020) discovered that PSCs consist of a succession of metallic or nonmetallic pipes (such as stainless steel, copper, polyethene, and rubber pipes) embedded in paving slabs, with an active fluid moving and accumulating thermal energy from the hot pavements. The pipes are systematically implanted in asphalt and can extract thermal energy via fluids, such as water. The asphalt transmits heat to compensate for the lower temperature of the fluid. Therefore, cool fluid is introduced while hot fluid is removed from the system.

The energy balance of an asphalt solar collector includes the following components and environments: asphalt pavement, pipes, the atmosphere, and fluids moving through the pipe network (Vizzari et al., 2021). Heat exchange systems distribute the energy evenly across the full pavement-atmosphere interaction. Asphalt absorbs heat from the sun, transfers some heat to the surrounding air by convection and emits some of its heat into space. The heat flow causes the road's surface to heat up before its interior, a process known as conduction. Initially, conduction occurs at the asphalt-pipe junction, then convection occurs at the asphalt-fluid contact. Asphalt solar collectors have advanced further than any other road energy collection system, becoming a commonplace technology with a variety of practical uses. For instance, ICAX built a system of pipes to circulate water for heat transfer (Vizzari et al., 2021). A heat storage system is buried beneath the insulated floors of nearby buildings to store thermal energy.

Further studies were conducted by Talib et al. (2016) to investigate piping depths at different burial depths using steel piping. Six physical-model mixtures of asphalt pavement were prepared. Three models were mounted with empty steel pipes, while the others were mounted with steel pipes filled with ethylene glycol to act as heat exchanger fluid. The heat exchanger pipes were placed into the asphalt pavement at different depths. The prototypes were installed outdoors, exposed to sunlight, and connected to a data logger to determine the temperature difference within the asphalt layer. The maximum pavement depth was 150 mm, and the steel pipe was 20 mm in diameter. The findings indicated that ethylene glycol extracted the most heat at a depth of 150 mm, reaching 51.2°C.

Johnsson and Adl-Zarrabi (2020) found that altering the albedo, fluid flow rate, and pipe spacing impacted the pavement solar collectors (PSCs). The authors concluded that efficiency was raised by up to 49% by altering the albedo and flow rate. Placing pipes closely together introduces additional constraints. For instance, the bending radius of pipes cannot be excessively small, as this causes damage to the pipes due to stresses. Additionally, if multiple pipes are placed in the pavement, the load-bearing capability of the pavement could be diminished. In general, a deeper position and closer spacing between pipes result in a greater amount of generated electricity. The measured harvested energy was 245 kWh/m2, with a solar efficiency of 42% (Johnsson & Adl-Zarrabi, 2020).

The thermoelectric generators (TEGs), phase change materials (PCMs), photovoltaic-thermal (PVT), and pavement solar collector (PSC) technologies mentioned possess their respective advantages and disadvantages, yet all offer significant positive aspects. Ultimately, the suitability of adopting these technologies depends largely on the specific location and environmental conditions. By carefully assessing factors such as solar irradiance levels, climate, available space, and local regulations, stakeholders can determine the most appropriate technology for maximising energy generation and addressing local needs effectively.

Based on the literature review, it is evident that the effectiveness of pipe arrangements in heat dynamics and pavement solar collector performance has not been given much consideration. The current work involves conducting experimental and numerical analyses to determine the crucial technical specifications of the built Pavement Solar Collector (PSC) thermal performance based on temperature measurements taken in Malaysia. This work extends the experimental work done by Ahmad et al. (2018), which primarily focused on the materials of pipes using copper and rubber materials. The experimental data were used to validate the numerical modelling presented in this paper. Subsequently, the validated numerical model was employed to optimise the design parameters of the solar pavement collector. These design parameters included the choice of pipe materials (copper, stainless steel, and aluminium), varying pipe depths (ranging from 30 to 80mm) and adjusting the spaces between pipes (ranging from 70 to 150mm).

METHODOLOGY

The software used for the numerical simulation work was Ansys Fluent 19.2 and Solidworks 2020. Two models have been developed: a control sample (no embedded piping) and an asphalt pavement model with various types of piping positioned at varying depths. Figure 2 illustrates the schematic representation of the asphalt pavement model. Both types have identical dimensions of 400mm × 400mm × 100mm, and the pipes possess a diameter of 20mm. Water was employed as the fluid in the pipes, and it remained stationary throughout the simulations.

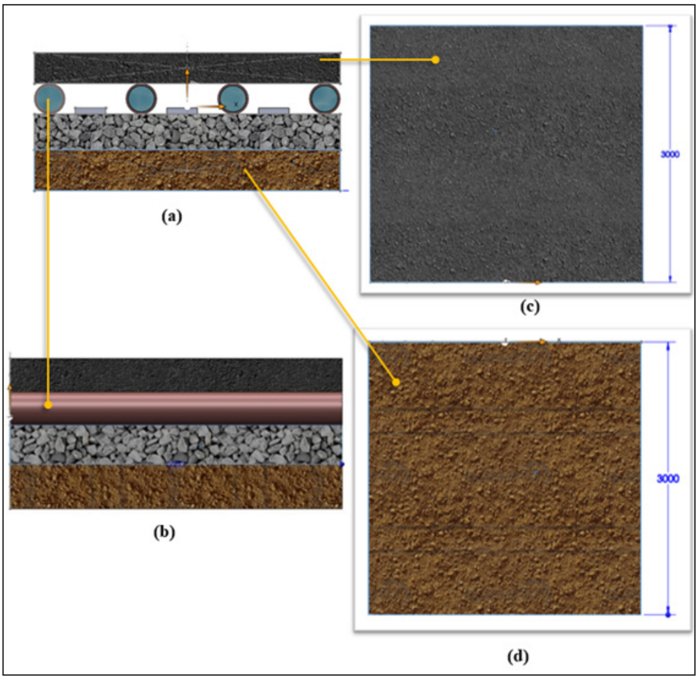

Figure 2. Asphalt pavement layer: (a) Frontal view, (b) Profile view, (c) Top course, (d) Sub-base course

The study employed the model arrangement illustrated in Figure 3. The asphalt pavement layer has been designed to have uniform properties in all directions and evaluated using the finite element method (FEM) to study the effect of temperature distribution on different surfaces of the pavement. The pipe was located at depths varying from 30 mm to 80 mm below the surface of the asphalt pavement. Two contact zones have been created: contact region 1, between the pavement and pipes, and contact region 2, between the pipes and fluid flow. Boundary conditions were established using data on material properties. Figure 3 (a–b) depicts the model with a solitary serpentine pipe, while Figure 3 (c–d) displays the model with several pipes stacked consecutively.

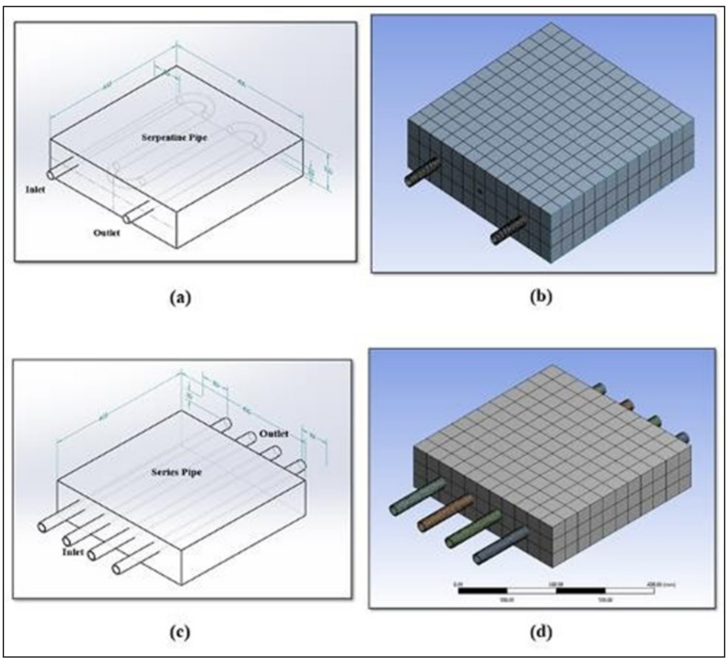

Figure 3. (a) Serpentine pipe configuration (b) Serpentine pipe mesh (c) Series pipe configuration (d) Series pipe mesh

The model was configured to account for energy, materials (fluid and solid), temperature distribution, wall shear stress between the asphalt pavement and fluid, and velocity profiles. Table 1 presents the parameters inputted into Ansys Fluent Workbench 19.2 for running the simulation.

Ahmad et al. (2018) validated the simulation setup using experimental work. According to their research, the highest temperature recorded at the outflow of the serpentine pipe was 53.5°C at a depth of 50 mm. In comparison to the current simulation results, the data shows a temperature of 54.21°C with a minimal error of 1.33%. This validation step confirms that the percentage of errors falls within an acceptable range (Adenan et al., 2023).

Table 1
Properties of pipes and concrete

Item	Parameter	Value
Copper pipe	Inlet Temperature, K (ºC)	314.15 (41.00)
Stainless steel pipe	Inlet Temperature, K (ºC)	317.35 (44.20)
Aluminium pipe	Inlet Temperature, K (ºC)	42.90 (316.05)
	Bulk Density (kg/m3)	2297.17
Asphalt concrete	Thermal Conductivity (W/m.K)	2.19
	Specific Heat Capacity (J/kg/K)	782.04
Normal flow	Velocity (m/s)	0.0205
Peak flow	Velocity (m/s)	0.0409

RESULTS

The investigation into thermal energy harvesting included studying each type of pipe material at various depths (30–80 mm) and pipe spacings (70–150 mm) for both serpentine and series piping configurations.

Numerical Simulation of Thermal Energy Harvesting in Serpentine Piping Systems at Various Depths

Figure 4 illustrates the relationship between the depth of embedded copper pipes, ranging from 30 mm to 80 mm below the surface pavement, and the temperature distribution. Meanwhile, Table 2 presents the different types of piping materials (copper, stainless steel, and aluminium) along with the corresponding outlet temperatures for pipe depths ranging from 30 mm to 80 mm. Figure 4(c) shows that the copper pipe located at a depth of 50 mm has the highest temperature at the outlet pipe, measuring 327.36K (54.21ºC). Conversely, the lowest temperature of 326.23K (53.08ºC) is observed from the pipe at a depth of 80 mm, as depicted in Figure 4(f).

Table 2
Outlet temperature of serpentine pipes at different depths and materials

Pipe material	Inlet Temperature, K (ºC)	Outlet Temperature, K (ºC)					
		30 mm	40 mm	50 mm	60 mm	70 mm	80 mm
Copper	315.15 (41.00)	326.33 (53.18)	326.80 (53.65)	327.36 (54.21)	326.55 (54.21)	326.71 (53.56)	326.23 (53.08)
Stainless steel	317.35 (44.20)	326.72 (53.57)	327.21 (54.06)	328.07 (54.92)	327.57 (54.41)	326.62 (53.47)	326.43 (53.28)
Aluminium	316.05 (42.90)	325.95 (52.80)	326.11 (52.96)	326.35 (53.20)	327.57 (54.41)	326.49 (53.39)	326.44 (53.29)

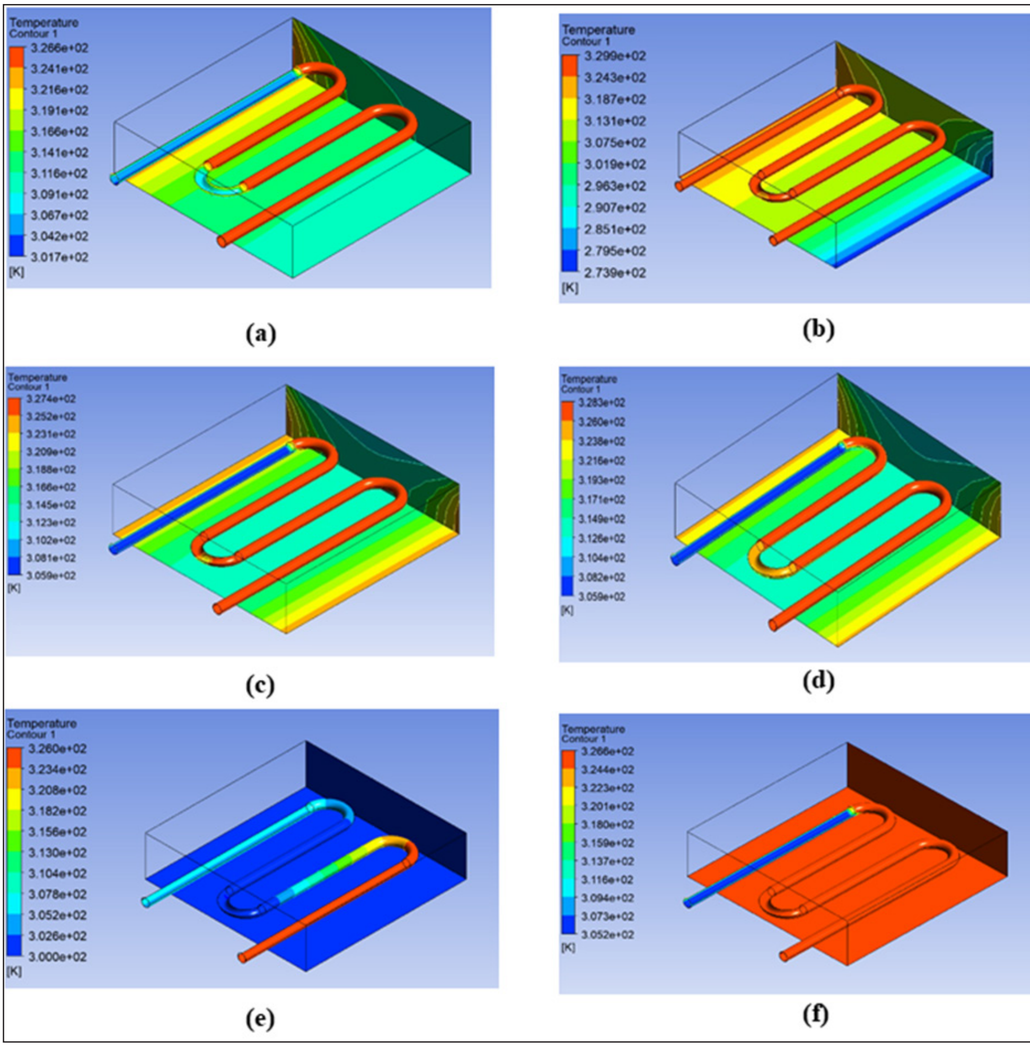

Figure 4. Simulation analysis of serpentine copper pipes at various burial depths: (a) 30 mm, (b) 40 mm, (c) 50 mm, (d) 60 mm, (e) 70 mm, and (f) 80 mm

These findings align with the previous study conducted by Ahmad et al. (2018), which determined that the upper portion of the asphalt pavement collects the most solar energy until the centre depth, while the lower portion collects less. Placing copper pipes in a serpentine arrangement, embedded 50 mm deep in the asphalt pavement, has the potential to reach a maximum temperature of 53.5ºC at the outlet pipe (Ahmad et al., 2018).

Figure 5 illustrates the serpentine configuration of stainless-steel pipes positioned at depths ranging from 30 mm to 80 mm below the top surface of the pavement. Similar to copper piping, the findings indicate that the highest heat extraction from the outlet pipe was 328.07K (54.92°C) at a pipe depth of 50 mm (Figure 5(c)), while the lowest was

326.43K (53.28°C) at a depth of 80 mm, as shown in Figure 5(f). Field monitoring of six asphalt slab samples with stainless steel pipes placed at depths of 50 mm, 100 mm, and 150 mm revealed that the highest heat extraction occurred at 50 mm, reaching a temperature of 53.2°C. Increasing the heat applied to the asphalt surface can significantly raise the temperature. As the asphalt pavement's ability to absorb radiant heat increases, it results in a greater accumulation of heat in the thermal block.

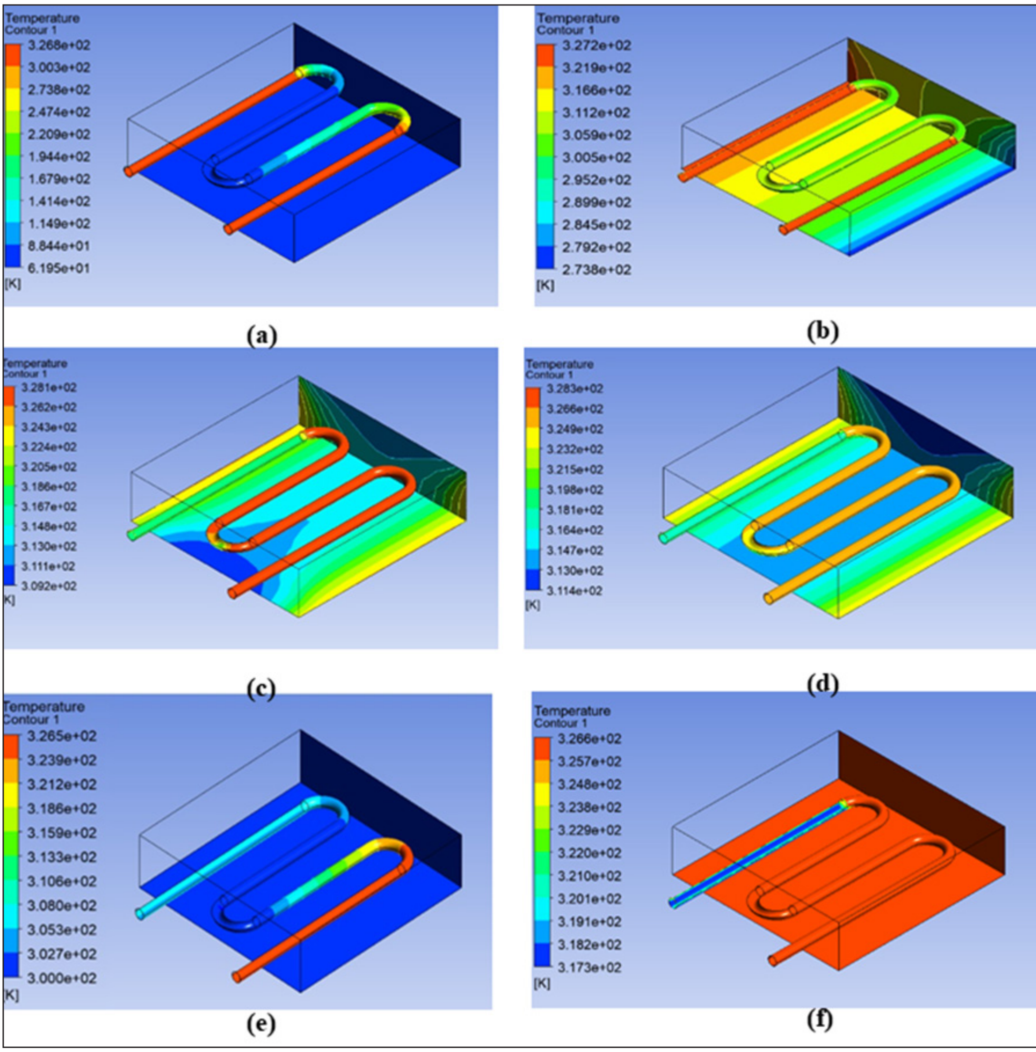

Figure 5. Simulation analysis of serpentine stainless-steel pipes at various burial depths: (a) 30 mm, (b) 40 mm, (c) 50 mm, (d) 60 mm, (e) 70 mm, and (f) 80 mm

Figure 6 presents an analysis of the serpentine configuration of aluminium pipes, with pipe depths comparable to those of copper and stainless steel pipes. Figure 6(e) illustrates that the aluminium pipe achieved the highest heat extraction from the outlet at a depth of 70 mm, with a temperature of 326.54K (53.39°C). Aluminium reached its lowest outlet temperature of 325.95K (52.80°C) at a depth of 30 mm, as depicted in Figure 6(a). The hot air is expelled through the central aluminium pipe in the top channel of the design model. Temperature measurements of incoming and exiting air were conducted using a thermocouple. The highest recorded outlet temperature was 55°C, while the minimum recorded during morning observations was 42°C.

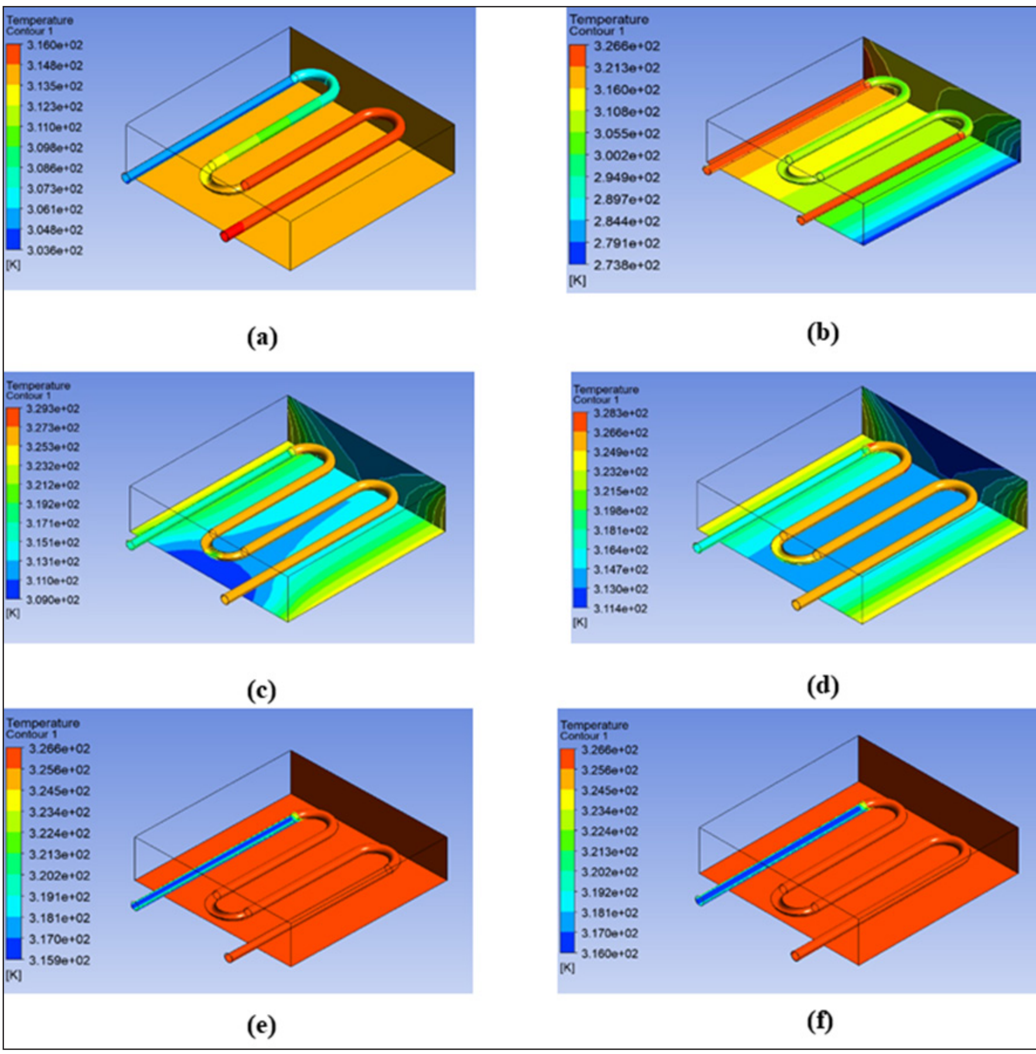

Figure 6. Simulation analysis of serpentine aluminium pipes at various burial depths: (a) 30 mm, (b) 40 mm, (c) 50 mm, (d) 60 mm, (e) 70 mm, and (f) 80 mm

Figure 7 presents tabulated data for the outlet temperature of the serpentine piping system with various materials versus piping depth in graphical form. The graph demonstrates an increasing outlet temperature at intermediate piping depths, followed by a decrease at the deepest piping depths for all materials. As depicted in Figure 7, the aluminium pipe at a depth of 30 mm exhibits the lowest outlet temperature at 325.95K (52.80°C). In comparison, the stainless-steel pipe shows the highest outlet temperature at 328.07K (54.92°C) at a depth of 50 mm. The results indicate that aluminium pipes show the lowest outlet temperature at a depth of 50 mm compared to copper and stainless steel pipes, with temperatures of 327.36K (54.21°C) and 328.07K (54.92°C), respectively.

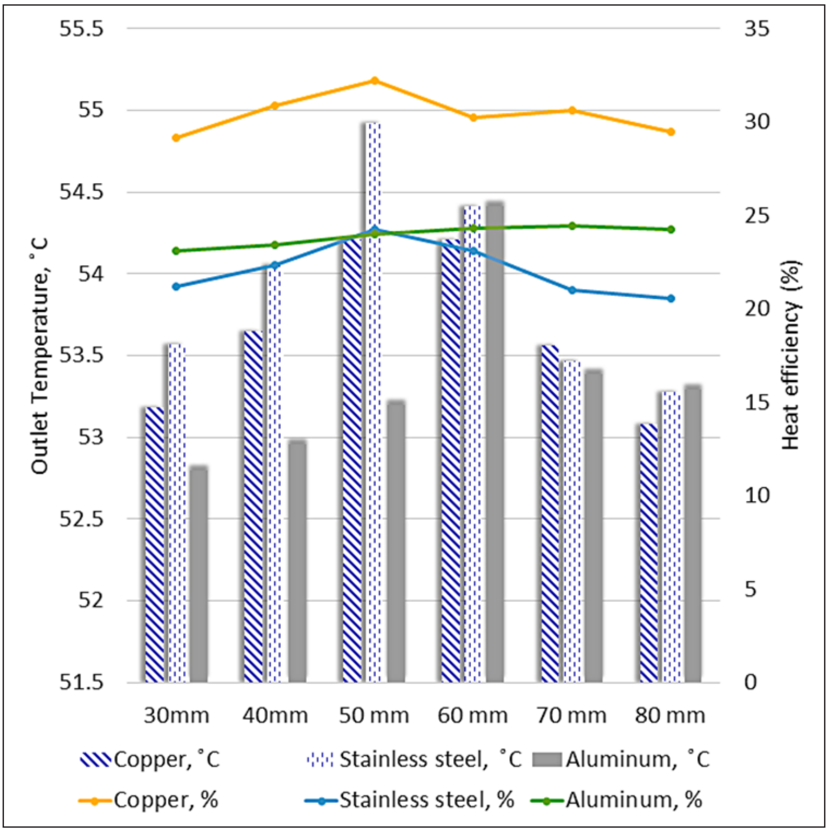

Figure 7. Outlet temperature and heat efficiency of various serpentine pipe materials at different burial depths

Furthermore, Figure 7 illustrates the graphical representation of tabulated data comparing the heat efficiency of serpentine pipes at different depths. Copper pipes achieved the highest heat efficiency of 32.22% at a depth of 50 mm, whereas stainless steel pipes had the lowest heat efficiency of 20.54% at a depth of 80 mm. Notably, the thermal efficiency of even the most optimal heat systems typically ranges around 50% (Vizzari et al., 2021). Therefore, in this study, copper pipes located at a depth of 50 mm were selected as the material for the piping system due to their demonstrated maximum heat efficiency. Additionally, copper pipes possess exceptional thermal conductivity, which ensures efficient heat transfer in both the liquid and gas phases. Their passive operation further contributes to their reliability, making them an integral and dependable component of the thermal management system.

Numerical Simulation of Thermal Energy Harvesting in Series-Arrangement Piping Systems at Various Depths

Figures 8, 9 and 10 illustrate the relationship between the depths of copper, stainless steel, and aluminium pipes buried in the surface pavement, ranging from 30 mm to 80 mm, and

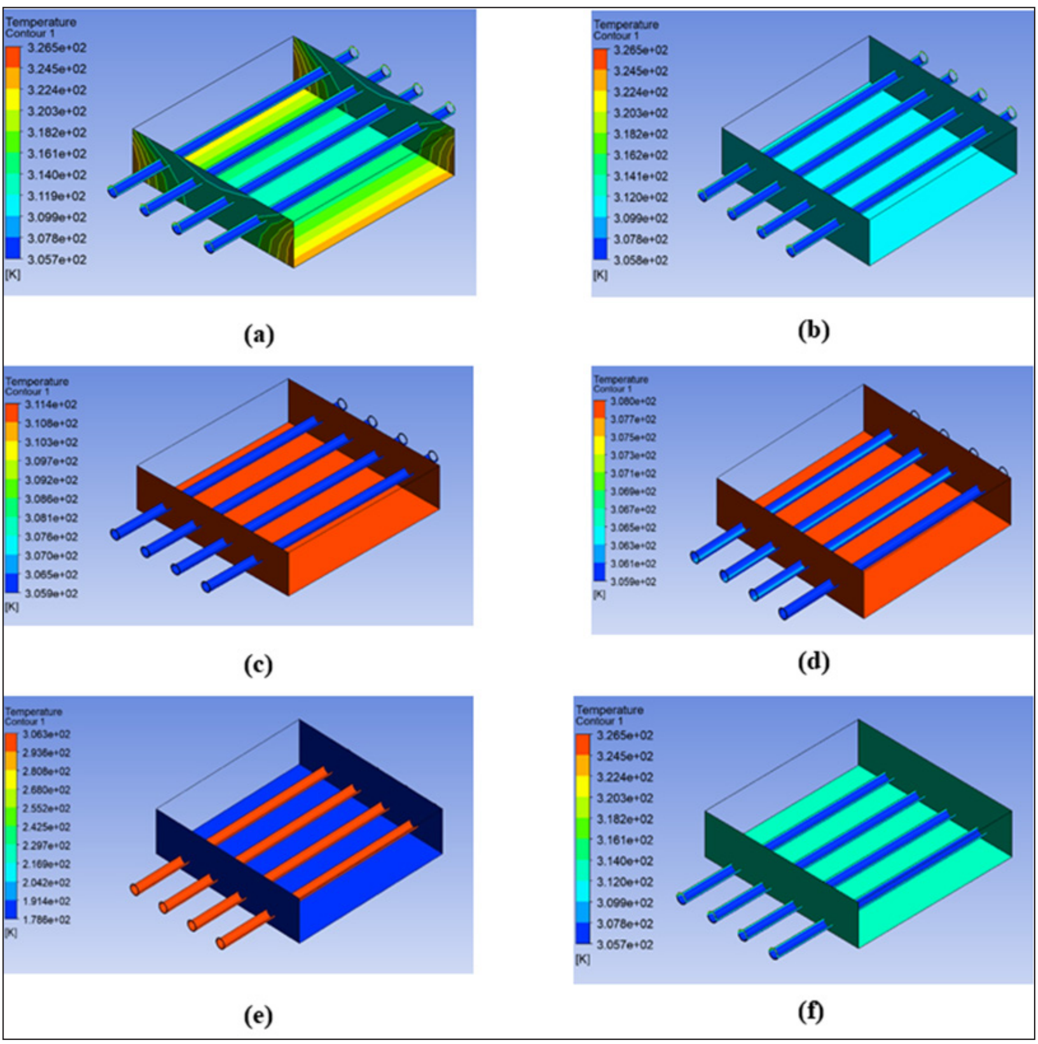

Figure 8. Simulation analysis of series copper pipes at various burial depths: (a) 30 mm, (b) 40 mm, (c) 50 mm, (d) 60 mm, (e) 70 mm, and (f) 80 mm

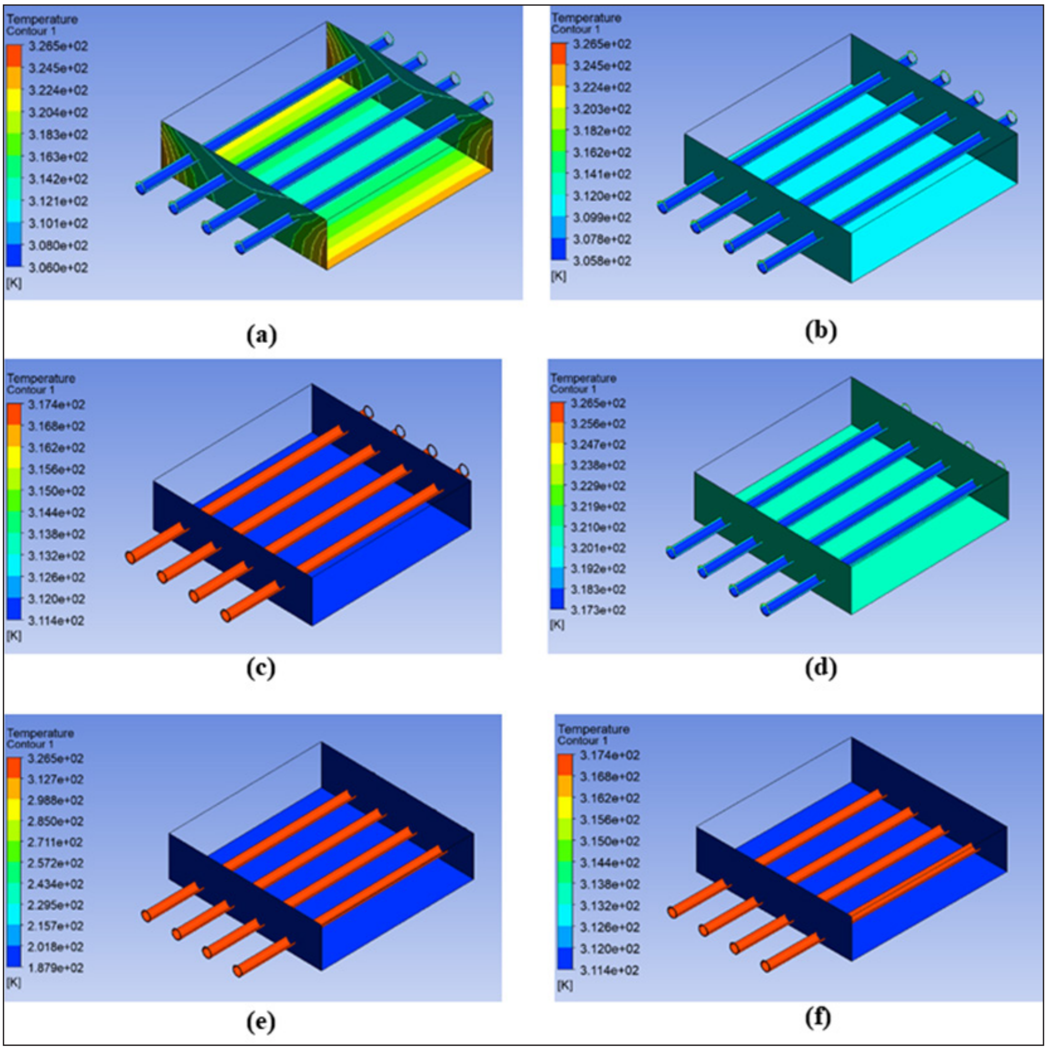

Figure 9. Simulation analysis of a series of stainless-steel pipes at various burial depths: (a) 30 mm, (b) 40 mm, (c) 50 mm, (d) 60 mm, (e) 70 mm, and (f) 80 mm

the temperature distribution. Table 3 provides a concise overview of temperatures at the inlet and outlet points for various depths of piping materials. Stainless steel pipes exhibited the highest heat extraction at the outlet pipe, measuring 317.62K (44.47°C) at a depth of 70 mm. In contrast, copper pipes showed the lowest heat extraction, with the outlet temperature measuring 305.94K (32.79°C) at a depth of 50 mm. The arrangement of pipes has a significant impact on the heat temperature at the outlet of the pavement solar collector.

Table 3
Outlet temperatures for series pipes at varying depths and materials

Pipe material	**Inlet Temperature, K (°C)**	**Outlet Temperature, K (°C)**					
		30 mm	**40 mm**	**50 mm**	**60 mm**	**70 mm**	**80 mm**
Copper	314.15 (41.00)	305.95 (32.80)	305.95 (32.80)	305.94 (32.79)	306.15 (33.00)	306.34 (33.19)	305.95 (32.80)
Stainless steel	317.35 (44.20)	317.35 (44.20)	317.36 (44.21)	317.37 (44.22)	317.43 (44.28)	317.62 (44.47)	317.35 (44.20)
Aluminium	316.05 (42.90)	316.05 (42.90)	316.05 (42.90)	316.06 (42.91)	316.46 (43.31)	316.33 (43.18)	316.05 (42.90)

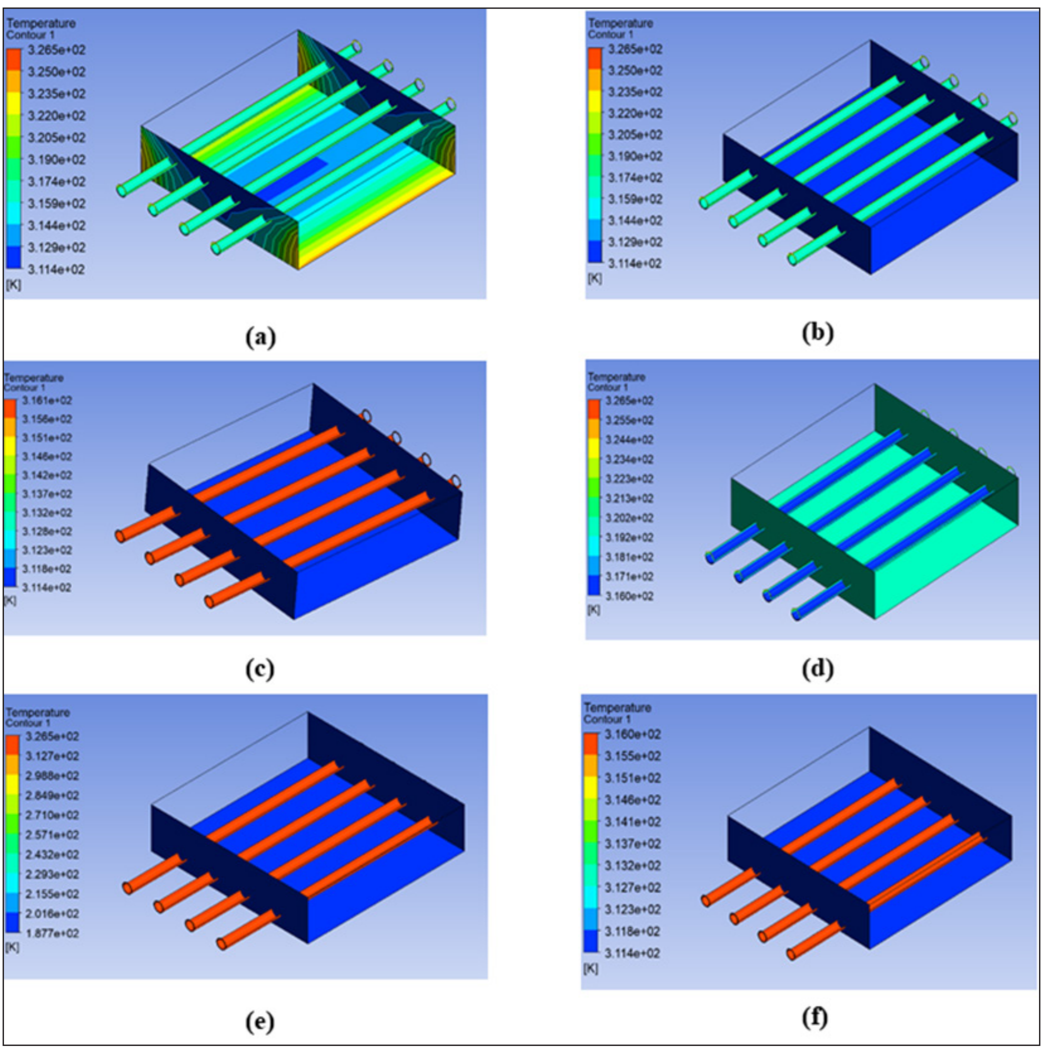

Figure 10. Simulation analysis of a series of aluminium pipes at various burial depths: (a) 30 mm, (b) 40 mm, (c) 50 mm, (d) 60 mm, (e) 70 mm, and (f) 80 mm

Figure 11 presents a visual representation of the temperature outlet of the series piping system at various piping depths. According to the data in Table 3, the analysis reveals that the stainless-steel pipe consistently exhibits the maximum outlet temperature for each depth. In contrast, the copper pipe consistently shows the lowest outlet temperature. Pipes are widely recognised as a cost-effective method for fluid transportation and are commonly used for water, fuel, and other substances. However, in the case of the series pipe arrangement studied here, the temperature at the outlet pipe closely approximated the inlet temperature, except for the copper pipe.

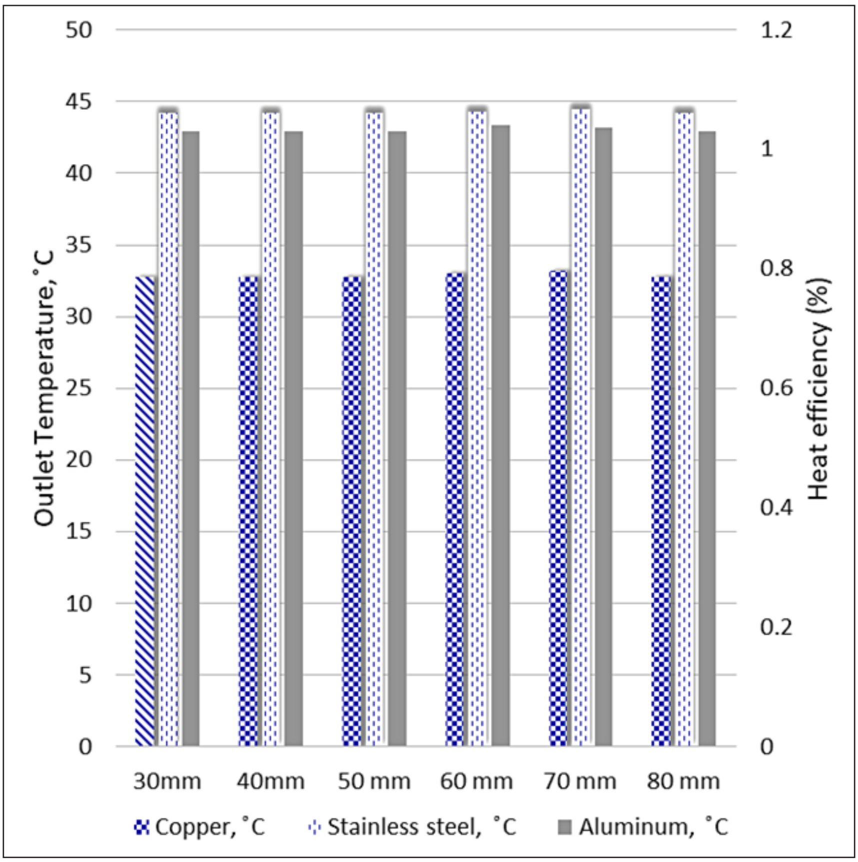

Figure 11. Outlet temperature and heat efficiency of various series pipe materials at different burial depths

A study by Santos-Ruiz et al. (2020) investigates head loss coefficients for local losses, fittings, valves, and friction coefficients for distributed losses along the pipe. The research has indicated the friction caused by the pipe's interior wall (Santos-Ruiz et al., 2020). In contrast to the serpentine pipe, the series pipe did not exhibit a heat efficiency value below 50%, which is typically considered optimal (Pietzonka & Seifert, 2018). Therefore, based on the comparison between the serpentine and series pipes, it can be inferred that the serpentine arrangement is the optimal choice for thermal energy harvesting on pavements. It has achieved the highest temperature outlet, with the copper pipe reaching 54.21°C at a depth of 50 mm and the stainless-steel pipe reaching 44.47°C at a depth of 70 mm.

DISCUSSION

Discussion on Optimising Depth, Spacing, and Pipe Arrangement

Figure 12 compares the outlet temperatures between serpentine and series pipes for three different materials: copper, stainless steel, and aluminium. The results consistently show that the serpentine pipe achieves higher output temperatures compared to the series pipe

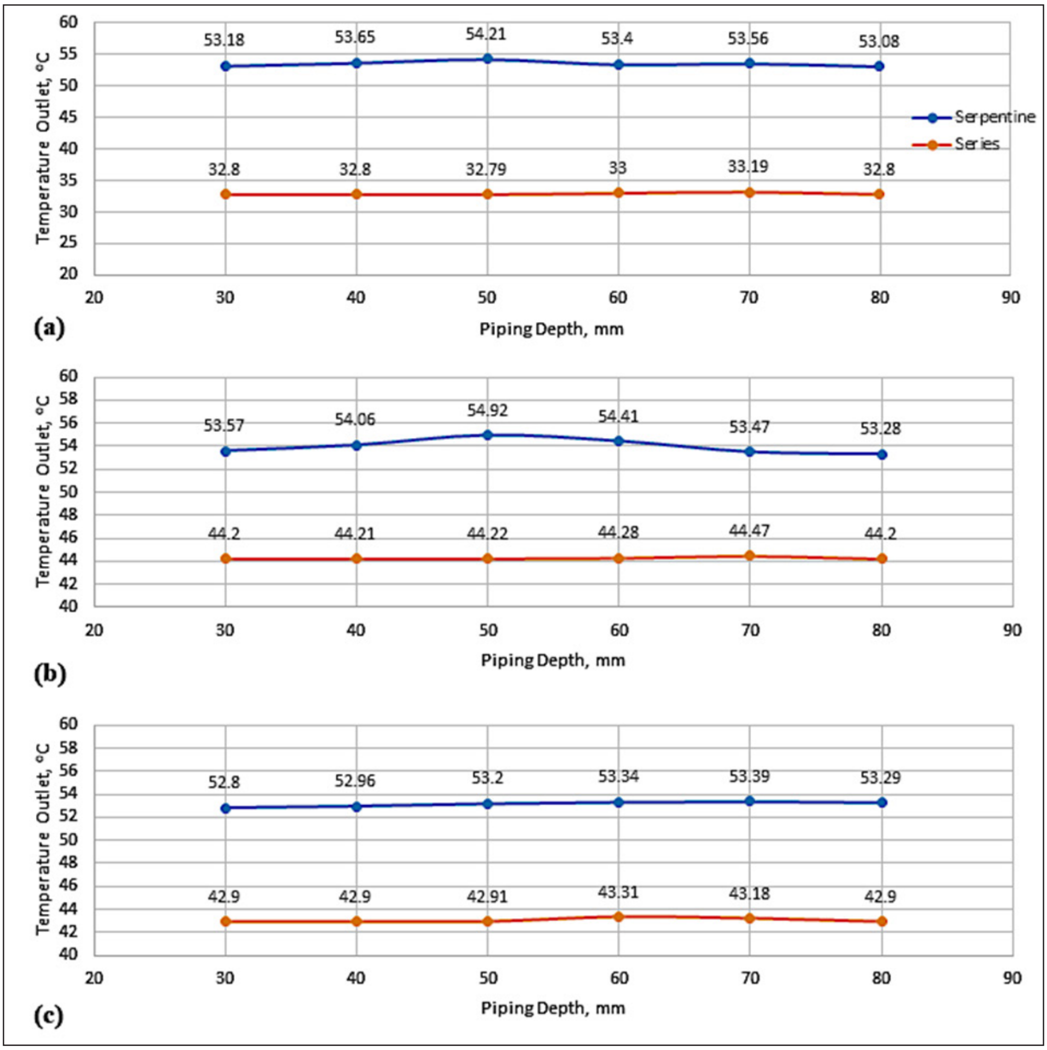

Figure 12. Serpentine and series pipe outlet temperatures for (a) copper pipe, (b) stainless steel pipe, (c) aluminium pipe

for all types of piping materials. While stainless steel pipes exhibit the highest temperatures among the materials tested and are widely used in various industries due to their superior corrosion resistance, formability, and weldability, their use may be limited by factors such as low hardness, poor tribological characteristics, and susceptibility to localised corrosion under certain conditions (Pietzonka & Seifert, 2018).

Furthermore, Figure 12 compares the highest temperature readings at the outlets for both piping systems. The serpentine pipe layout consistently shows higher outlet temperatures for all piping materials compared to the series pipe arrangement (aluminium at 23.27%, stainless steel at 23.5%, and copper at 64.27%). The maximum temperature of 54.92 ºC is achieved by stainless steel in a serpentine pattern, 1.3% higher than copper's second-highest temperature of 54.21 ºC in the same arrangement. In contrast, aluminium in a serpentine pattern exhibits a 2.9% decrease compared to stainless steel.

Using a serpentine copper pipe at a depth of 50 mm results in the highest heat extraction value from the outlet pipe. Figure 13 presents the data and graphical trends of pipe spacing versus outlet temperature for copper pipes arranged in a serpentine pattern at a depth of 50 mm. The results highlight that serpentine copper pipes positioned 50 mm below the

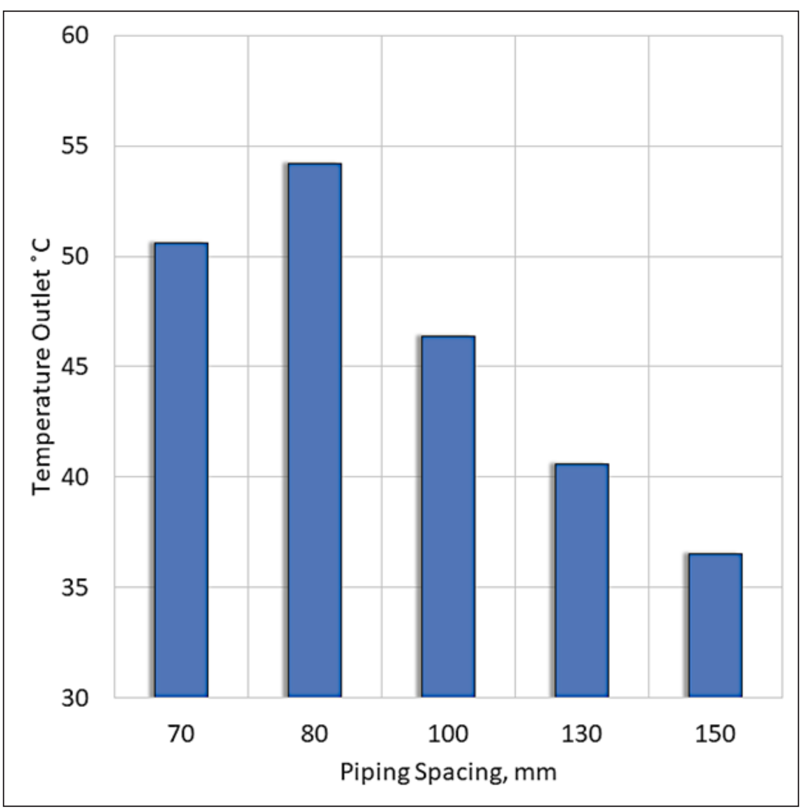

Figure 13. Relationship between outlet temperature and pipe spacing

surface show excellent thermal harvesting potential by achieving the highest heat efficiency. Additionally, it was determined that the optimal pipe spacing is 80 mm, resulting in an outlet temperature of 327.36K (54.21ºC). The investigation of the new multi-control heating system emphasised the crucial role of pipe spacing in determining heat loss and transfer efficiency between pipes (Xu et al., 2021).

Further examination of the optimal pipe configuration presented in this study is essential to verifying the water flow rate inside the pipe, as depicted in Figure 14. The velocity at the inlet pipe was adjusted to 0.0409 m/s, following established guidelines for domestic usage. The velocity at the outlet pipe was measured at 1.562 m/s, with the outlet temperature recorded at 327.36K (54.21 ºC). This velocity range falls within the acceptable guideline range of 1 to 2 m/s for pipe flow rates (Michael Smith Engineers, 2024).

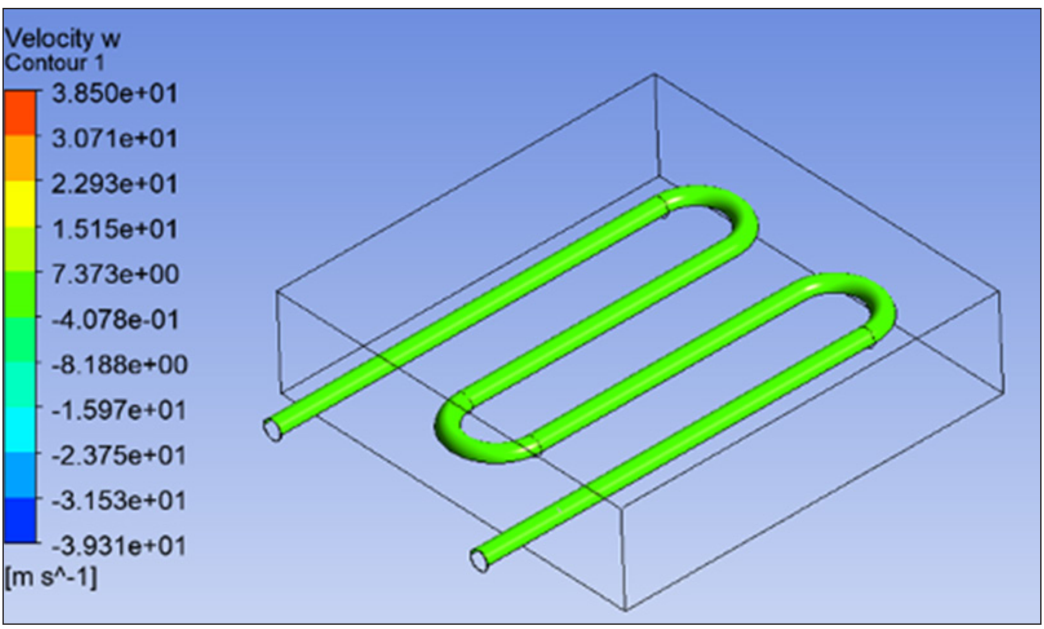

Figure 14. Uniform flow rate in an optimised serpentine pipe

CONCLUSION

The study examined thermal performance using different pipe materials (copper, stainless steel, and aluminium) embedded at various depths (30 mm to 80 mm) beneath the surface pavement. Different pipe spacings (70 mm to 150 mm centre-to-centre) were also analysed. Results show copper piping in a serpentine pattern as the optimal choice for thermal energy harvesting in pavement, achieving the highest heat efficiency (32.22%) and outlet temperature (327.35K or 54.21°C). This arrangement's superior performance is attributed to its larger surface area, which enables greater heat absorption compared to other configurations. For optimal performance, pipes should be placed 50 mm below the pavement surface and spaced 80 mm apart. The achieved flow rate of 1.562 m/s for water circulation meets household demands, with the inlet pipe's flow rate set at 0.0409 m/s. These findings underscore the potential for reducing reliance on fossil fuels, emphasising environmental and economic benefits. Implementing pavement solar collectors can significantly enhance sustainability and economic viability in Malaysia, promoting innovation for a greener future.

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