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Numerical study of harvesting solar energy from small-scale asphalt solar collector

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Abstract – This paper studied the heat transfer in an asphalt solar collector with small scale geometry. Solar energy reaches the earth and consequently increases the temperature of the ground, which then leads to the increase of the temperature of the air. Water circulates through a series of pipes embedded in the asphalt pavement for the extraction of solar energy. The radiation in this study was produced from the top asphalt pavement. In this study, the temperature of the asphalt pavement decreased when solar energy was collected from the circulating water. This reduces the heat island effect in the city and decreases the power consumption for air conditioning. The temperature is distributed between the asphalt pavement and the inner pipes. Increase of the flow rate has a great influence on the energy collection by reducing the temperature of the asphalt pavement. The result of this test was obtained using a small-scale asphalt pavement, which showed a high amount of heat collected.

Keywords: Asphalt solar collector, solar energy, energy collection, asphalt pavement

1.0 INTRODUCTION

Recently, the use of sustainable supply of energy is important to reduce the consumption of fuel and emissions from combustion processes for energy generation. The purpose of this study is to demonstrate energy extraction from asphalt pavement, and to make a good use of asphalt pavement. Asphalt pavement can be used for heating and cooling nearby buildings, as well as for the purpose of power generation process. In fact, extracting energy from asphalt pavement contributes to maintaining asphalt pavement from damage due to the high temperature of asphalt pavement in the summer.

On the other hand, the surface temperature of asphalt pavement can be up to more than 70ºC due to solar radiation, where the rise in the temperature of the asphalt pavement is attributed to the high absorbent properties of asphalt [1]. Asphalt solar collector (ASC) can store solar energy even after midnight due to excellent absorbing property, whereas a traditional solar collector cannot store solar energy for a long time. Asphalt pavement is used in a wide range of applications, where it can be used in a lot of areas, and then the energy extracted can be used in other applications [2]. ASC contains a series of pipes embedded in the asphalt pavement. Solar radiation absorbed by the asphalt pavement increases pavement temperature. Water is circulated through the pipes to collect solar energy from the asphalt pavement. The solar energy collected from the asphalt pavement in the summer can be stored in boreholes in the ground and use the energy for snow melting in the winter [3].

ASC is developed as a hydronic system inside the road for capturing solar energy in the summer and snow melting in the winter. The system has been used in Japan by the Organization for Economic Cooperation and Development (OECD) and the International Energy Agency (IEA). The first system used this technique in terms of collection, storage and use of energy to melt snow. It is known as Gaia system [4]. Experimental research was conducted on slab solar collector (SSC) to study the effect of heat transfer on the pipe diameter, pipe spacing and flow rate, where the results showed the efficiency of energy collection ranged between 150-250 w/m^2 in the summer [5]. The Institute of Worcester Polytechnic developed a type of asphalt solar collector called Roadway Power System, in which this system works on the energy extracted from the ASC in the roadway to run a turbine engine to produce electrical energy [6].

2.0 LITERATURE REVIEW

Researchers have been focusing on improving heat transfer in asphalt pavement through several ways, which are by reducing or increasing the flow rate, absorption surface and thermal conductivity of the asphalt pavement. Chen et al. studied the extraction of energy from a small scale asphalt pavement through the influence of flow rate of heat transfer and calculated the time required to reach the steady state temperature, in which the results showed 0.37ºC difference between the incoming and outgoing flow at the study state when the circulating water and the radiation were started simultaneously [5]. On the other hand, the thermal efficiency for asphalt is improved by adding conductive fillers to the asphalt mixture. Actually, conductive fillers have high thermal conductivity and temperature distribution, where the results showed that the effectiveness of thermal conductivity and the asphalt mixture are the key factors to extract the largest amount of energy from asphalt pavement [7,4].

However, collecting thermal energy from asphalt pavement reduces the temperature of the pavement and reduces the heat island effect on the city. Nevertheless, the results by researchers showed that using a hydronic system to collect energy gives major complications in the temperature distribution in asphalt pavement. Moreover, the base pipes under the asphalt pavement is designed to resist traffic loading, whereas it must pay for the design of the structure of a hydraulic system compared with traditional methods [8]. The efficiency of heat transfer in asphalt pavement is enhanced by increasing the solar energy absorbed. Asphalt is an imperfect black body because it tends towards gray color after each season. Coating the surface of asphalt pavement black increases the absorption property of the pavement surface. The results showed that after the coating process, the amount of solar energy captured is higher than the amount of energy before applying the paint. The results also showed an increase from 8ºC to 12ºC for the temperature difference between the incoming and outgoing flow, as a black surface has a significant effect in enhancing the heat transfer in the pavement. On the other hand, the thermal conductivity of asphalt can be increased by adding quartz stone to asphalt mixture, which contributes to the increase of thermal conductivity of asphalt pavement. Meanwhile, the results showed an increase from 4.5ºC to 10ºC for the temperature difference between the incoming and outgoing flow when quartz stone is added [9].

The energy for air conditioner at home is derived from the energy collected through asphalt pavement stored in the isolated borehole specially made for storing thermal energy. The energy is also used to melt snow in the winter to maintain the safety of asphalt pavement. An interesting result showed a simulation study by producing an ideal design for several variables, such as pipe spacing, flow velocity, and thermal conductivity [10].

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3.0 METHODOLOGY

The geometry was drawn in ANSYS Fluent 14.0. A small-scale pavement consisted a series of pipes circular within the cross section area located at the middle of the pavement is shown in Figures 1a and 1b, and the geometrical parameter was set according to the parameters in Table 1.

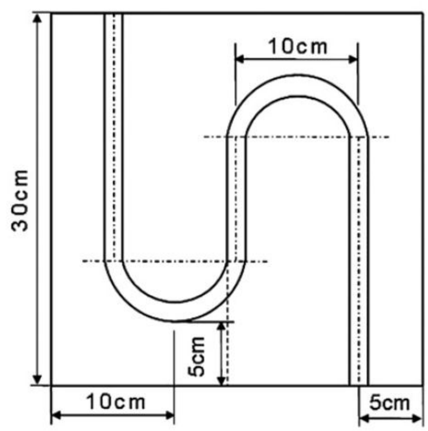

Figure 1a: Schematic diagrams of geometry

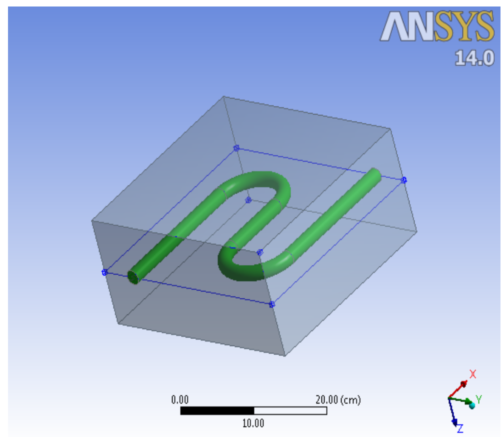

Figure 1b: Drawing geometry in ANSYS Fluent

Table 1: Geometrical parameters

Parameters	Range
Asphalt	
Pavement length	0.3 m
Pavement width	0.3 m
Pavement height	0.15 m
Pipe	
Pipe spacing	0.1 m
Pipe depth	0.075 m
Pipe diameter	0.02 m

3.1 Numerical method

In this work, ANSYS Fluent 14.0 was used for the purpose of computational fluid dynamics, and also used for drawing, meshing, and setting boundary conditions. The governing continuity

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equation, momentum, and energy setting with exact boundary conditions in ANSYS Fluent were solved using finite volume method. The geometry consisted a three-dimensional cube shape, whereas the asphalt pavement consisted a series of pipes with a shape of a snake. Finite volume method using the second order upwind scheme partial differential equation was implemented for the purpose of reaching higher order of accuracy. All questions were solved with a high number of iteration to obtain converged solutions for all the cases of simulation conducted in this study. The solutions were obtained when the residuals were below than 10^{-6}.

3.2 Grid optimization

It is important to check the grid optimization of the numerical solution to make sure the present work was done with high range of accuracy. For this purpose, the number of elements for several geometries was implemented as follows: 1= 530,248, 2= 964,286, 3= 1,968,995 and 4= 2,837,992. As shown in Table 2, all cases were tested, and the results of these cases were compared as shown in Figure 2. The differences between these cases with the experimental work were negligible. Therefore, in order to save simulation time, elements for geometry no. 3 (1,968,995) was adopted in the computation. The mesh distribution on the asphalt pavement and the mash around the pipe are shown in Figure 3.

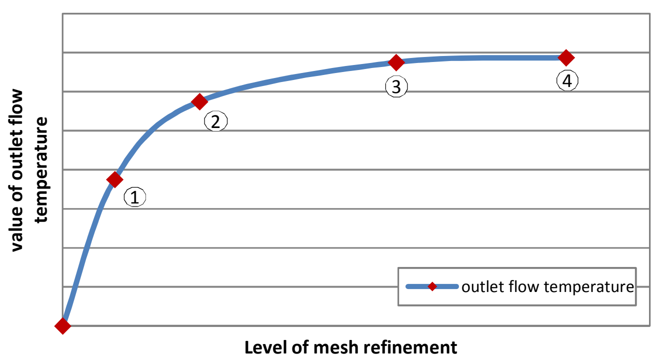

Figure 2: Grid independence of the problem

Table 2: Deviation of mesh

Geometry	Number of Elements	Temperature Out (K)	Deviation
1	530,248	293.25	32.40 %
2	964,286	293.33	8.33 %
3	1,968,995	293.37	2.43 %
4	2,837,992	293.372	1.92 %

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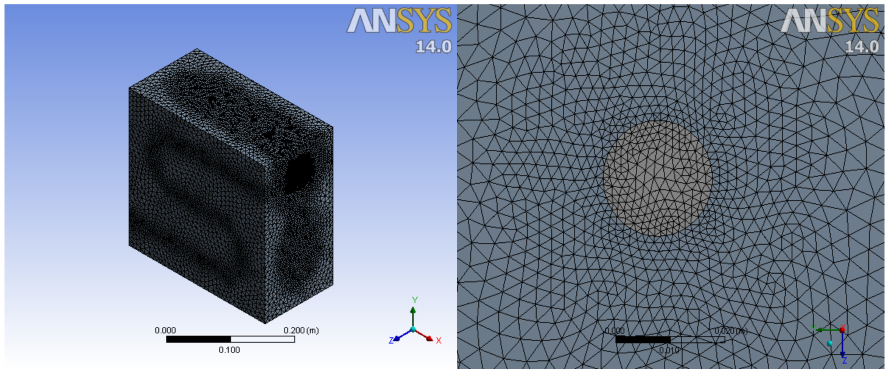

Figure 3: Mesh distribution

3.3 Boundary Conditions

The governing equations are non-linear and coupled partial differential equations, and is the equations are subjected to boundary conditions. The solution of the problem in this study considered unsteady state, three-dimensional pipes inside the asphalt pavement at a winding shape with a circular cross section area, enclosed by all the geometry surfaces of inlet, outlet, upper wall, bottom wall, left side and right side wall boundaries. It was assumed that the incoming flow through the total length was an unsteady laminar flow at ambient temperature (293 K) and pressure (600 kPa). The fluid entered the pipe at the velocity 0.075 m/s, and the upper wall was subjected to radiation at 1200 W/m^2. All sides, except the upper wall, were adiabatic. The thermal conductivity of the asphalt pavement was 1.8 W/m K) [5].

4.0 RESULTS AND DISCUSSION

Laminar flow at low temperature that flows through a series of pipes inside hot pavement reduces the temperature of the pavement to keep the pavement at low temperature, which leads to the extraction of energy from the pavement. In this case, the present work consisted a small-scale pavement kept at constant radiation from the upper wall. Three case validations were done for the capture of solar energy.

4.1 Surface Temperature Variations

There were changes of surface temperature of the ASC slab when the radiation and water circulation were started simultaneously. As the flow velocity was kept constant at 0.075 m/s, the surface temperature of the controlled slab increased continuously with extended radiation. However, the trend in the ASC was different. The rapid increase in the initial phase could be observed, and then followed by a steady state. Finally, the surface temperature came to a constant at the temperature of 36.61°C, as shown in Figure 4 [5].

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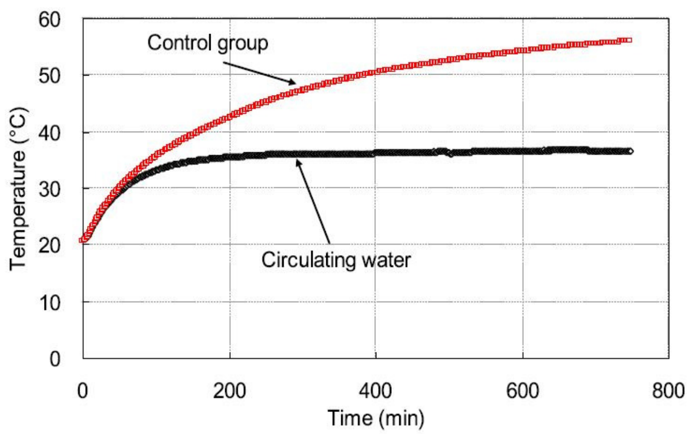

Figure 4: Changes of surface temperature with varying time based on Shaopeng's study [5]

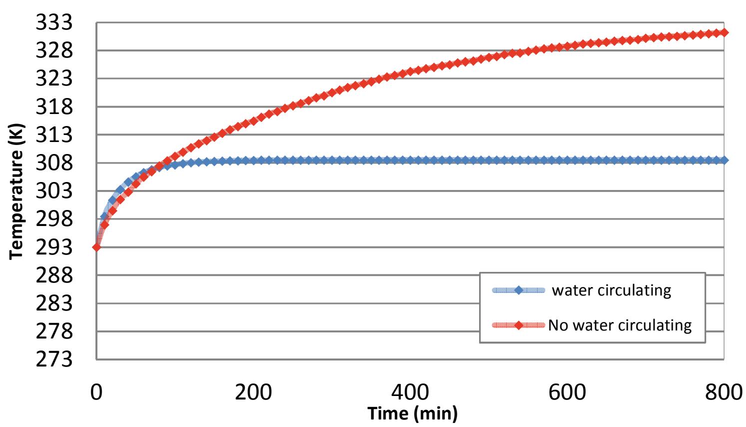

Figure 5: Changes of surface temperature with varying time of the current study for validation purpose

Figure 5 shows the validation in the current study, which had maximum error deviation of 4.3 % compared to the experiment by Shaopeng [5].

Obviously, the pavement temperature varied after water circulated inside the pavement for the purpose of extracting solar energy. The contour view taken after 800 min from the simultaneous start of radiation and water circulation shows that the amount of temperature reduced, as shown in Figure 5.

4.2 Temperature Difference between Inlet and Outlet Water

The temperature of the outlet flow increased as the radiation time increased. The temperature difference between the incoming and outgoing flow was 0.37°C, which was obtained after 500 min.

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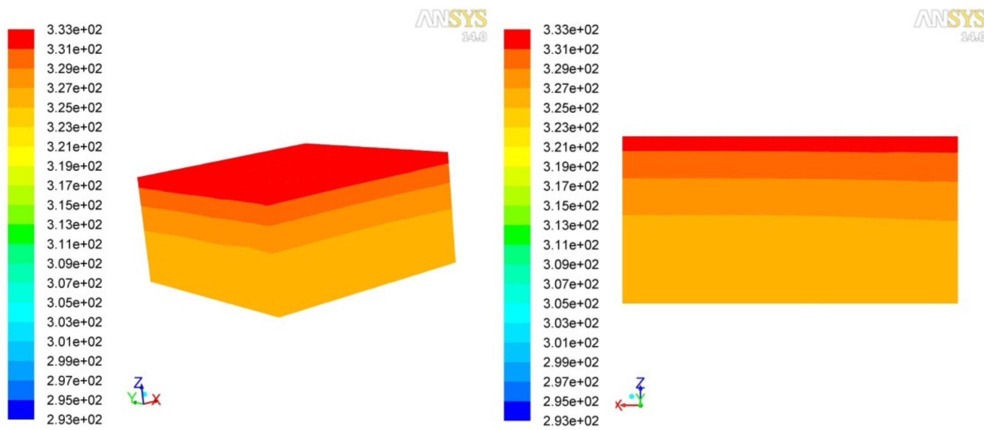

Figure 6: Contour view of asphalt pavement without water circulation

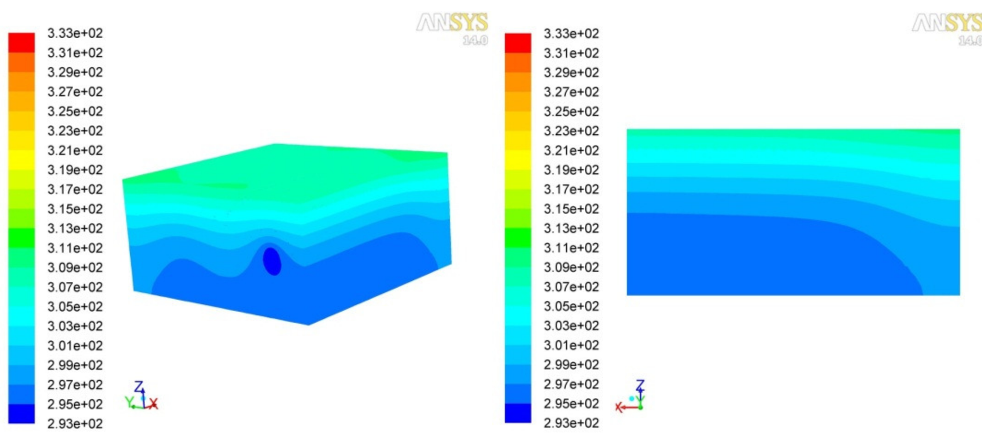

Figure 7: Contour view of asphalt pavement with water circulation

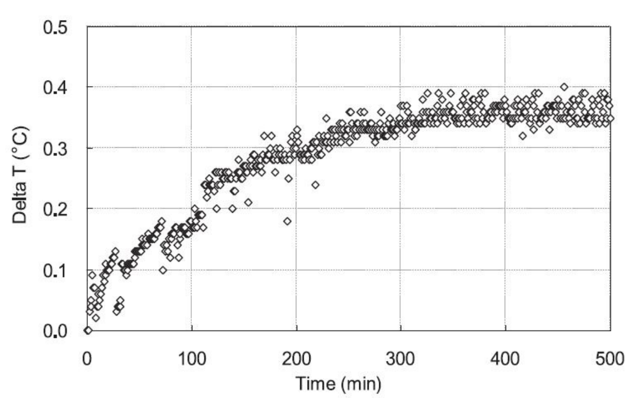

Figure 8: Temperature between inlet and outlet water with varying time based on Shaopeng's study [5]

Figure 9 shows the validation in the current study, which had maximum error deviation of 3.22 % compared to the experiment by Shaopeng [5].

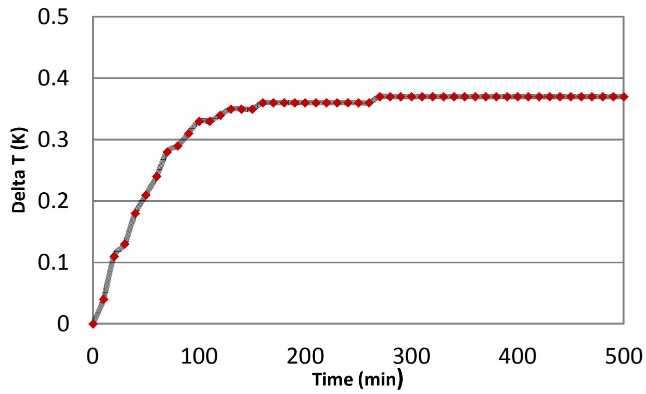

Figure 9: Temperature between inlet and outlet water with varying time of the current study for validation purpose

4.3 Maximum Heat Gain

The maximum Delta *T* decreased as the flow rate increased. The relation between the maximum heat that can be extracted and the flow rate is shown in Figure 10. The maximum extracted heat increased slightly as the flow rate increased. The amount of heat can be calculated by using the following formula.

$$q = C_p V \Delta T / A_{pavement} \tag{1}$$

where the q is the heat gained W/m^2, Cp is the specific heat of the flow, **V** is the flow rate, ΔT is the temperature difference between the incoming and outgoing flow, and $A_{pavement}$ is the surface area of the pavement

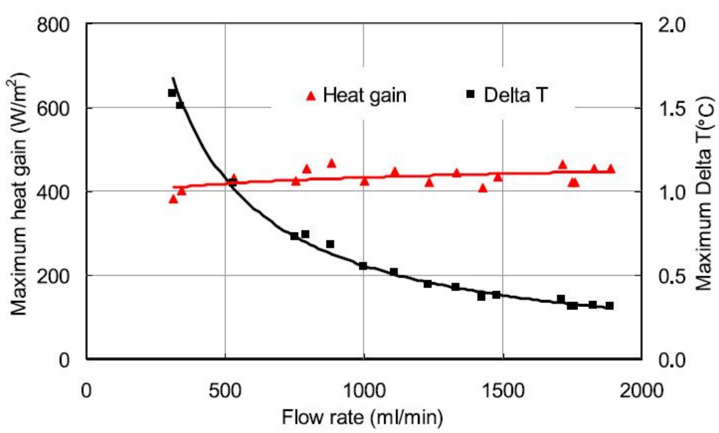

Figure 10: Comparison between the maximum heat gain with different volume flow rates based on Shaopeng’s study [5]

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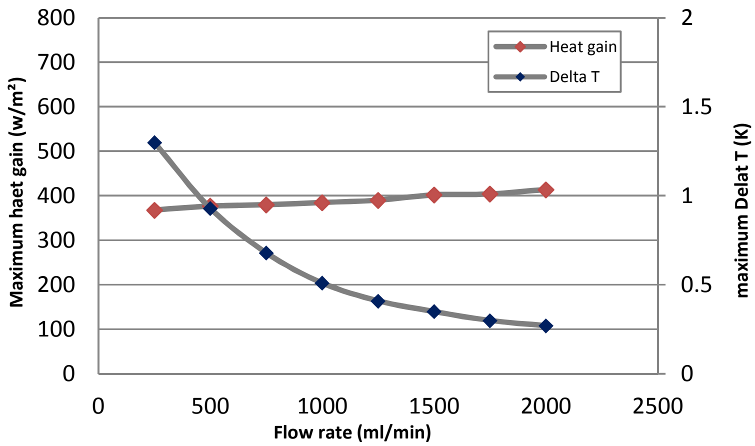

Figure 11: Comparison between the maximum heat gain with different volume flow rates of the current study for validation purpose

Figure 11 shows the validation in the current study, which had maximum error deviation of 7.6 % compared to the experiment by Shaopeng [5]. More heat gain can be extracted from the slab when the flow velocity increased, which enhanced the heat transfer coefficient between the flow inside the pipes.

5.0 CONCLUSION

This study investigated solar energy extracted from asphalt pavement. The amount of the surface temperature cooled down was 22.5°C, which is a good effect to reduce the heat island in the city and protect the asphalt pavement form damage. The heat gain increased as the flow rate increased, which was caused by the enhanced heat transfer coefficient inside the pipes, and subsequently increased the temperature of the outgoing flow. As illustrated in the contour view, there was temperature gradient in the pavement layer from the surface to the pipes, and this gradient was influenced by the thermal properties of the pavement. The heat collected from the pavement reached to a steady state, and it was validated with the result of another experiment to save time and cost. Moreover, to enhance the heat transfer in asphalt solar collector for increasing the thermal energy extracted from the asphalt solar collector in the future work, the recommendation of this study can be summarized as follows:

1- Investigation of the effect of fully developed turbulent flow.
2- Investigation on the other types of working fluids such as nanofluid.

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