International Journal of Engineering & Technology, 7 (3.25) (2018) 333-336

International Journal of Engineering & Technology

Website: www.sciencepubco.com/index.php/IJET

Research paper

Asphalt Collectors – a Solution for the Humid and Hot Climates

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Abstract

The Asphalt Solar Collectors (ASC) technology is well known for his its application in moderate to cold climate; however there is a need to explore a wider scope for this application. This research is an attempt to explore the Asphalt collectors as a solution for the hot and humid climate. The paper explored this by analyzing the performance of the 20m² ASC meeting the demand of the domestic hot water, solar assisted cooling and the atmospheric water generation.

Keywords: *Asphalt solar collectors, hot climate, technology, Saudi Arabia.*

1. Introduction

One of the latest technologies to harvest the solar energy is the use of the asphalt paved surfaces as solar collectors. This technology is still in the nascent stage of development and this technology is known as Asphalt Solar Collectors (ASC). This is one of the trending research topics in the area of solar energy. The main reason for asphalt to capture the interest of the researcher's interest is its thermal properties and its easy availability in the modern cities [1, 2]. This makes ASC relatively easy to integrate with the present infrastructure without any negative impact on the paved road structural performance [3, 4].

An ASC system is actually made up of the asphalt pavement which is normally embedded into the wearing course of pavement. This acts as the heat exchangers, the heat transfer system of the ASC system is shown in the figure 1. In an ASC system the fluid is pumped into the pipe which is embedded in the asphalt paved road which is exposed to the environment. The temperature of the fluid is increased when the heat from the asphalt pavement is transferred to the fluid. In this system the heated fluid is collected in the storage tank so that it can be used for further processing.

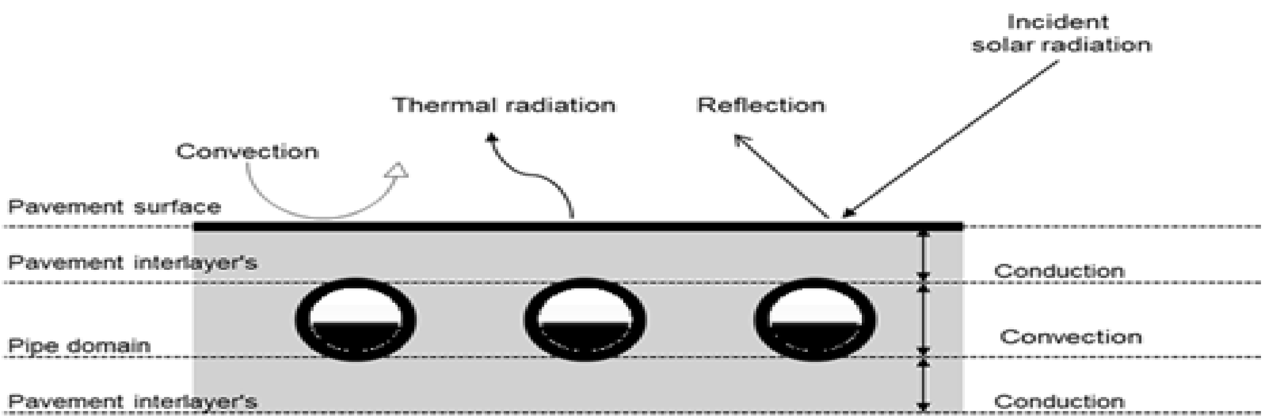

Fig. 1: The mechanism of heat transfer in an ASC system

2. Methodology

The main method used in this research is the simulation using the TRNSYS, which is the numerical software. The weather data from the typical meteorological year (TYR) of the Jeddah city of Saudi Arabia is chosen for this research. One of the main reasons for choosing this data is the climate condition of the city, which typically represents a hot and humid climate. The climate in Saudi Arabia is characterized with very hot summers, mild to warm winters and very less or no rain; furthermore the clouds are clear all through the year in this part of the world. The climate in most part of the northern hemisphere is hot and the temperature along with the high intensity of the solar is at its peak between the month of May and September. The analysis of this research is done using the climatic condition in this period as the ASC performance will be at its peak during this period.

The research simulation boundary conditions included the specific time period, pumping regime, inlet water temperature and the asphalt area. The time period was from 1st April to 30th September with a 1 min time step. The pumping regime followed for this experiment was from sunrise to sunset. The inlet water temperature is the mains water temperature from the TYR weather files. The total asphalt area was $20m^2$.

To enhance the reliability of the stimulated model used in this research, the stimulated model properties are matched with the real site case study. Hence an asphalt pavement is modeled in TRNSYS, which matches with same physical and also the thermal properties of the real case study sample. This is matching is done so that the modeled sample behave similar to the real site situation. The details of the asphalt properties are given in the Figure 2.

Layer	Thickness [m]	Thermal conductivity [W/m*K]	Heat capacity [kJ/kg/K]	Density [kg/m3]
Wearing course	0.05	2.5	1	2300
Base course	0.08	1.8	1.1	2200
Sub-base course	0.25	1.8	0.9	2200
Sub-grade course	30	1.5	0.85	1500

Fig. 2: Asphalt properties in the real site case study by Alawi [5]

This asphalt properties can be considered for the scope of the present research, as the results of this study has shown that it is in general agreement in the thermal behavior of the real sample and the stimulated sample. It also matches with the thermal behavior of the recommendation map of the asphalt grade in Saudi Arabia [6]. The difference between the measured and the stimulated sample is around 5k on an average. The difference in the temperature may be due to different reasons. One of the main reason may be due to the weather data used for the research. The typical metrological year (TYR) weather data is used for this simulation, which will be slightly different from the real time weather data. The details of the temperature difference K and the heat transfer mechanism of ASC are shown in the figure 3.

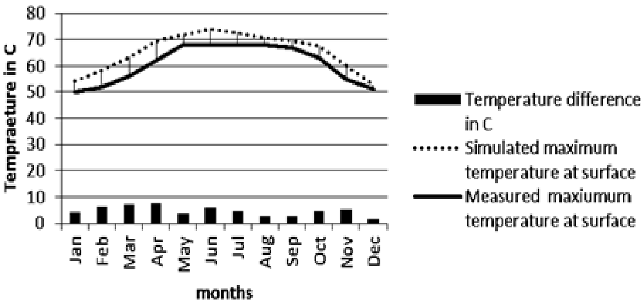

Fig. 3: Temperature difference and the ASC heat transfer mechanism

Once the asphalt thermal properties are set then the next step is the development of the optimized configuration of the different components of the ASC. The system components and the thermal properties are finalized based on the literature review on the previously published articles in this area [7, 8, 9] with the addition of the road rated insulation Styrodur®C 4000 CS, with of conductivity (λ) = 0.032 W/m*K [10]. A sensitivity analysis needs to be done on the asphalt pavement and the heat exchanger to develop an optimized model of the Asphalt Solar Collectors, so that they produce the highest amount of useful energy for the low to medium temperature solar thermal applications. The impact assessment information of each ASC system component on the performance of ASC is used to optimize the ASC. The following criteria are used to measure the performance of the ASC:

- The total measure of the fluid collected between the temp 45 °C and 55 °C at an interval of 2.5 K along the simulation timeframe
- The highest temp. Achieved by the fluid at the outlet point.
- The highest difference in the temperature of the inlet and the outlet point.
- The collected heat by the ASC $q = \frac{V*Cp*\Delta T}{A_{ASC}}$ [W/m²] (1)
- The system efficiency, η = $\frac{\text{heat collected by ASC}}{\text{Solar radtion on ASC}}$ [%] (2)

The details of the investigation variables are given in the two table1 and table 2 below:

Table 1: Heat exchanger properties - ASC system.

Pipe material λ [W/m*K]	Pipe spacing [cm]	Pipe depth [cm]	Pipe diameter [cm]
Copper [401]	10 cm	3 cm	1 cm
PEX [0.47]	15 cm	4 cm	2 cm
PVC [0.19]	20 cm	5 cm	3 cm

Table 2: Thermal properties - ASC system.

Wearing conductivity (λ) [W/m*K]	**Insulation thickens [cm]**	**Insulation depth from surface [cm]**	Wearing heat capacity (C)[kJ/kg/k]
2	**3 cm**	0	**0.9**
2.5	**4 cm**	**5 cm**	**1**
2.88	**5 cm**	**13 cm**	**1.1**

Once the ASC system is set, few of the supporting system are added to this system to assess the overall performance of the complete ASC system in the real time condition. The main support systems added to the ACS system are the water tank, pump and the power source. These support systems are chosen from the commercially available devices so that simulation can match the real life conditions. The vertical insulated water tank was used for the simulation, the tank height is 2m its capacity is 3 m³. The tank heat loss coefficient value is 0.1 [W/m²*K]. The DC water pump with the capacity of 1000 Kg/h was used for this simulation. The DC motor was preferred because of its high efficiency and this could be directly wired to the PV panel without using an additional DC/AC converter. This type of pump is most compatible as this is expected to run with the sun radiations and the backup battery is not necessary. The simulation used the centrifugal pump with 12V, DC power, 13W rated power, with a max. flow rate of 1020l/h and the maximum head 2m [11]. The photovoltaic panel was used as the source of power for the pump. This 12v 30WP pump was most appropriate for this simulation. The panel was installed facing towards the horizontal radiation. This is the most suitable angle for this PV panels for the working hours and in the summer month of the Jeddah [12].The research used the monocrystalline PV, with a peak power of 30WP, 36 cells with efficiency of 16.1% [13].

The main criteria to measure the performance of the new ASC is its ability to meet the load demand of the 2kW Absorption solar cooling (AC), an atmospheric water generator (AWG) with a water extraction efficiency of 35%m [14] and a domestic hot water demand (DHW) of 600 Liter /day which represent a consumption of about 10 persons [15] which are the 3 solar thermal applications.

Table 3: Water pump specification

Applica-tion	Minimum driving tem-pera-ture	Maximum driving tem-pera-ture	Load time profile	ΔT supply & return tem-pera-ture
AC	65 ^{0}C	N/a	9 am-6 pm	5K [16]
AWG	60 ^{0}C	N/a	2 - 8 am	5K
DHW	55 ^{0}C	60 ^{0}C	20 - 21 pm	N/a

The highest and the lowest temperature is determined based on the information from the previously published work in this area [14, 17, 18, 19]. The optimum time is between 9am to 6pm for the AC loading as it is the representative typical cooling demand load profile. Similarly, 2am to 8am is chosen for the AWG load as during this time the humidity is highest, this will allow the system to extract highest volume of water from the air. The criteria for evaluation of the ASC system includes the below mentioned targets.

- Working hours
- The volume of water collected above the base driving temperature

- The collected heat by the ASC $q = \frac{V * Cp * \Delta T}{A_{ASC}}$ [W/m²] (1)
- The system efficiency, $\eta = \frac{\text{heat collected by ASC}}{\text{Solar radtion on ASC}}$ [%] (2)
  - The system working fraction,

1. $f = (\frac{\text{working hours}}{\text{load hours}}$ x100) [%] (3)

To simulate the effect of the load of every application on the return water temperature to the storage tank an air to water heat exchange is installed. The main reason for using the heat exchanger is to increase the system stability which is easily controlled and specified which can be easily integrated during field testing in the real conditions. The performance of the heat exchanger is recalculated in every scenario separately with the help of the number of transfer unit effectiveness method (NTU) [16]. The schematic representation of the newly developed ASC is shown in the figure 4.

The sensitivity analysis revealed that the heat insulation and the asphalt heat capacity had the most positive impact on the temperature difference between the fluid inlet and outlet temperatures. Increasing the system depth had, on the other hand the most negative impact on the same criteria, followed by increasing the pipe spacing [20,21,22. The asphalt conductivity and solar absorptivity showed very little influence on the system performance. Increasing the heat insulation thickness made a slight impact on the system performance. Thus the ASC optimized system is developed as specified in (Table 8 and 9)

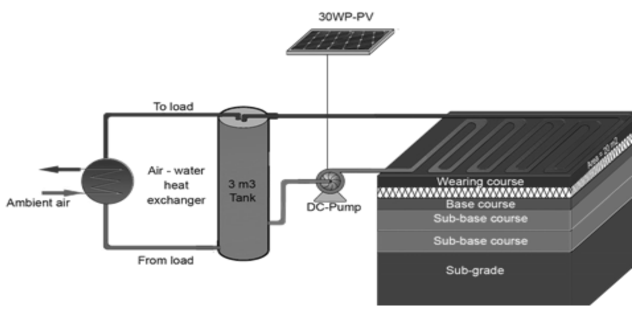

Fig. 4: The newly developed ASC system.

2.1. Specification of the Developed ASC Optimized Systems

After the completion of the sensitivity analysis it was very evident that the asphalt heat capacity and the heat insulation were the two major factors which have a positive impact on the difference in the temperature between the fluid inlet and the outlet. Similarly, there is a negative impact on the temperature difference when there is an increase in the depth of the system and the spacing in the pipe. However, there was negligible influence of asphalt conductivity and solar absorptivity on the system performance. There was a minor impact on the system performance when the thickness of the heat insulation thickness was increased. The ASC optimized system was developed using the asphalt wearing thickness of 0.05 [m] with the thermal property of λ 2.5 [W/m*K], C 0.9 [kJ/kg/k] and ρ 2300 [kg/m3]. The insulation had a thickness of 0.03[m] with the thermal property of λ 0.032 [W/m*K], C 1.47 [kJ/kg/k] and ρ 38 [kg/m3]. The optimizers ASC models heat exchanger had the pipe depth of 0.03[m], the value of λ is 0.47 [W/m*K],flow rate is 875 [kg/h]. The pipe had the spacing of 0.1[m], diameter of 0.02 [m] and the thickness of 0.02[m].

3. Results

The results of this research show that the performance of the ASC system under the 3 loads gave a very positive result. The results are shown in the output details given in the figure 5, 6 and 7. Overall the system showed that there is good potential in meeting the generation of the atmospheric water and also to supply for the demand of the domestic hot water load. The generation of atmospheric water is very important, especially in the country like Saudi Arabia which has a humid climate conditions. The results showed that the system of 20m^2 ASC system can extract upto 1516 liters of water from the air and also reach an overall average of 25% efficiency in the month of August working under the load of DHW.

Month	Avg.Tank Temp.	System working hours.	System working fraction	water collected above min. driving temp.	Avg.effici-ency	Avg.Heat gain
	[°C]	[h]	270 working hrs/month [%]	[Liter/m^2]	[%]	[kW/m^2]
May	64.71	90.85	33.65%	2491.56	12.13%	110.71
June	64.70	51.58	19.10%	1836.77	9.58%	87.97
July	64.86	82.93	30.72%	2191.88	12.34%	102.31
Aug.	64.84	87.87	32.54%	2341.35	13.39%	100.10
Sep.	64.78	53.17	19.69%	1789.38	10.54%	87.20

Fig. 5: Performance - load of the 2kW Absorption solar cooling (AC)

Month	Avg.Tank Temp.	System working hours.	System working fraction	water collected in above min. driving temp.	Amount of generated water	Avg. system efficiency	Avg. Heat gain
	[°C]	[h]	(180 hrs/ month)[%]	[Liter/m^2]	[Liter/m^2]	[%]	[kW/m^2]
May	62.05	162.98	90.55%	3502.19	57.99	16.15%	148.02
June	61.22	145.90	81.06%	3067.60	54.27	14.86%	136.60
July	61.94	167.27	92.93%	3278.33	64.15	17.03%	140.09
Aug.	62.01	168.27	93.48%	3676.46	75.82	19.42%	144.92
Sep.	61.30	149.07	82.81%	3146.35	66.07	16.75%	139.89

Fig. 6: Performance - load of an atmospheric water generator (AWG) with a water extraction efficiency of 35%

Month	Avg.Tank Temp.	System working hours.	System working fraction	water collected above min. driving temp.	Avg. system efficiency	Avg. Heat gain
	[°C]	[h]	(30 hrs /month)[%]	[Liter/m^2]	[%]	[kW/m^2]
May	60.06	58.00	97%	3028.23	21.97%	198.39
June	59.19	49.93	83%	2945.83	20.07%	183.97
July	59.63	54.47	91%	2879.48	22.25%	181.80
Aug.	59.32	58.03	97%	3162.40	24.62%	191.35
Sep.	59.02	48.90	82%	2923.23	23.66%	193.21

Fig. 7: Performance - load of 600 L/day of domestic hot water (DHW)

4. Conclusion:

This paper has investigated the performance of asphalt solar collectors in hot humid climates by means of simulation with TRNSYS 16. The performance of the simulated asphalt pavement model is provisionally validated against empirical data from the case study city to ensure the reliability of the created TRNSYS model.

The main aim of this research study was to assess the performance of the ASC in the hot humid climate using the technique of simulation with the TRNSYS 16. The performance was validated by comparing it with the empirical data of the case study city. This validation is done to increase the reliability of the model created by TRNSYS.A sensitivity analysis was done using all the commercially available supporting system so that it matches with the real life conditions. The overall result of the sensitivity analysis has shown that heat exchangers parts of the ASC which include the pipes and the fluids, impact very significantly on the performance of the ASC system as compared to the asphalt properties of the system. The fluid heat capacity, fluid flow rate and the depth of the heat exchangers influence significantly in achieving the maximum temperature difference between the inlet and the outlet fluid. The assessment of the performance of the new developed system was analyzed and evaluated in a typical domestic hot water demand, load of an absorption cooling cycle and also an atmospheric water generator. This evaluation was done between the months of May to September. It can be safely concluded that the ASC performance which meets the highlighted solar thermal conditions has a good potential for the use of ASC technology to meet the demand of the domestic hot water and also the generation of atmospheric water. The generation of the atmospheric water is of prime important especially for the climate conditions which is hot humid. This becomes more relevant if we take into consideration the abundant availability of the asphalt paved roads.

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