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Performance of a pavement solar energy collector: Model development and validation

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HIGHLIGHTS

- A novel numerical model is developed that predicts the thermal behavior of a pavement solar collector.
- A parametric study is conducted on the sensitivity of the system to changes in design parameters.
- A new methodology is developed to perform a long-term performance analysis of the system.

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ABSTRACT

Current aims regarding environmental protection, like reduction of fossil fuel consumption and greenhouse gas emissions, require the development of new technologies. These new technologies enable the production of renewable energy, which is both cleaner and more abundant in comparison to using fossil fuels for energy production. This necessity encourages researchers to develop new ways to capture solar energy, and if possible, store it for later use. In this paper, the Pavement Solar Collector (PSC), and its use to extract low temperature thermal energy, is studied. Such a system, which harvests energy by flowing water through a heat exchanger embedded in the pavement structure, could have a significant energy output since pavement materials tend to absorb large amounts of solar radiation. The main objective of this paper is to develop a modeling framework for the PSC system and validate it with a self-instructed experiment. Such a model will allow for a detailed parametric study of the system to optimize the design, as well as an investigation on the effect of aging (e.g. decreasing solar absorptivity) on the performance of the system. A long-term energy output of the system that is currently lacking is calculated based on results of the study on weather parameters. This newly acquired data could be the start of a comprehensive data set on the performance of a PSC, which leads to a comprehensive feasibility study of the system.

1. Introduction

Every day road surfaces absorb significant amounts of solar radiation, up to 40 MJ/m^2 over the course of a day during summer, which causes high temperatures in the pavement structure [1,2]. This thermal energy can be harvested using a heat exchanger system, usually pipes, embedded in the pavement structure. Such a system is often referred to as a Pavement Solar Collector (PSC) [3–6]. The working fluid (air [7] or water) cools down the pavement structure and extracts heat energy which can be used for different purposes, such as production of Domestic Hot Water (DHW), building heating [8,9] or cooling of buildings via adsorption cycles [10].

Pavement Solar Collector (PSC) systems are an appealing candidate in extracting thermal energy from pavements. Recently, there have been some experimental and modeling efforts of these systems by some research groups [3,4,8,9,11,12]. However, these studies are not capable of extracting the total energy output of a large scale PSC system. Hence, it is difficult to determine the feasibility

Abbreviations: BC, Boundary Condition; DHW, Domestic Hot Water; FE, Finite Element; HMA, Hot Mix Asphalt; PSC, Pavement Solar Collector; TMY, Typical Meteorological Year.

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Nomenclature

A	number of hours between solar noon and time of $T_{a,max}$, –
b	temperature decay factor, –
c_p	specific thermal capacity, $\frac{J}{kg\,K}$
d_i	thickness of pavement layer i, mm
D	diameter, mm
f	eccentricity factor, –
FF	wind velocity, $\frac{m}{s}$
h	heat transfer coefficient, $\frac{W}{m^2\,K}$
L	length of PSC, m
Lat	latitude, °
p	working fluid pressure, Pa
P_s	pipe spacing, mm
P_d	pipe depth, mm
q''	heat flux, $\frac{W}{m^2}$
Q	thermal energy, kW h
R_0	solar constant, W
RH	relative Humidity, %
t	time, s
T	temperature, °C
V	fluid velocity, $\frac{m}{s}$
W	width of PSC, m
Z	solar zenith angle, °

Indices:

a	air
atm	atmospheric
avg	average
dp	dew-point
in	inner
max	maximum
min	minimum
out	outer
$rise$	at sunrise
s	pavement surface
set	at sunset
sw	shortwave radiation

Greek letters:

α	surface absorptivity, –
ε	surface emissivity, –
η	efficiency, –
λ	thermal conductivity, $\frac{W}{m\,K}$
μ	dynamic viscosity, Pa s
ρ	density, $\frac{kg}{m^3}$
τ	transmissivity

of the system and its overall performance. Consequently, it is arduous to predict the applicability of the harvested low temperature heat energy.

In this paper, in order to fill this knowledge gap, a modeling framework is developed, and verified experimentally, that can predict the heat energy output of a complete Pavement Solar Collector system with a high degree of accuracy. Such a framework will also be able to help us determine potential design strategies on how to improve such a system. In Section 2 of this paper, the underlying FE model of the PSC is presented. An experiment has been carried out to validate the numerical results, which is discussed in Section 3. A study on the parameters with the highest influence on the performance of the system is conducted and presented in Section 4. A general strategy to perform a long-term evaluation of the PSC system, based on a parametric study on weather parameters, is discussed and validated in Section 4 of this paper. An example of such a long-term evaluation is also presented. The paper is then finalized with a discussion and general conclusions.

W.T. Van Bijsterveld and A.H. De Bondt have previously studied the stresses that arise around the pipe. Their design solution has already been successfully implemented commercially in light traffic roads. This was accomplished by implementing a plastic grid that allows for safe compaction of the asphalt concrete while providing extra strength. Also, asphalt concrete used in the system is modified with polymers and exhibits more flexibility. This allows for easier compaction, or compaction with less force, and ensures that the pavement will not crack as fast as a regular road, and thus, protects the heat exchanger [5,13].

Previous modeling efforts in the literature are mainly limited to small-scale modeling. Loomans et al. [14] presented a model of an entire collector yet uses a 2.5 dimensional approach and the necessary simplifications that accompany such an approach. This model deviates significantly, up to 20%, from the practical experiments discussed in [14]. Carder et al. [15] presented another numerical model, which includes thermal storage of the harvested heat energy.

PSC's have lower energy outputs and lower outlet temperatures compared to classic vacuum tube solar collectors [16], which explains why PSC systems tend to be coupled with a heat pump system [17]. However, PSC's have other unique benefits which are discussed in the next paragraphs of this Section. This paper focusses on PSC systems integrated into asphalt concrete pavement structures, rather than cementitious concrete pavement structures, since the dark color of asphalt concrete causes a high absorptivity of solar radiation. As a consequence, and according to existing literature, an asphalt concrete PSC can harvest more thermal energy compared to cementitious concrete PSC's [3].

It was shown that a PSC can reduce the maximum pavement temperature by about 5 °C, which also leads to a reduction in surface temperature and thus emission of longwave radiation and convective heat transfer [8,9]. A reduction of the maximum pavement temperature will reduce the potential rutting damage and fatigue due to oxidation of the binder in the case of asphalt concrete roads. The life of the pavement can be extended by 5 years when the maximum temperature of the asphalt drops by about 5 °C [8]. Pavement surfaces are widely available and can still be used for other purposes, like a car parking area, which in itself, is another advantage of the PSC.

Although not the focus of this work, the PSC could also be as a pavement de-icing system used [18,19]. Small scale experiments have recently been conducted to study the dynamics of the system and the influence of asphalt concrete thermal properties on such a de-icing system [18]. The SERSO prototype is one of the oldest prototypes of a PSC with the aims of winter maintenance. SERSO was constructed by *PolyDynamics Engineering* underneath the pavement surface of a bridge in Switzerland. This trial has proven the validity of such a system. Maintaining pavement temperatures above 0 °C also reduces the potential of fatigue cracking of asphalt concrete [17,20].

Extracted heat energy can also be stored in an aquifer (or borehole) underground thermal energy system and later be recirculated through the heat exchanger to create a de-icing system.