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Performance of a Pavement Solar Energy Collector: Model Development and Validation

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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.

Key Words: Solar Energy, Low Temperature Heat, Heat Transfer, Pavement Solar Collector (PSC), Finite Element Analysis

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Abbreviations:

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

Nomenclatures:

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, deg
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, kWh
R_0	solar constant, W
RH	relative Humidity, %
t	time, s

T	temperature, $^{\circ}C$
V	fluid velocity, $\frac{m}{s}$
W	width of PSC, m
Z	solar zenith angle, deg

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, $Pa\cdot s$
ρ	density, $\frac{kg}{m^3}$
τ	transmissivity,

1. Introduction

Every day road surfaces absorb significant amounts of solar radiation, up to 40 MJ/m² 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 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 used as a pavement de-icing system [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.

This has been implemented by the *Road Energy System* research group, although the energy output of the system remains unpublished [5], [14], [17]. The cold extracted from the pavement during winter can also be stored underground to restore the temperature balance or improve the efficiency when using the stored cold during summer to cover cooling loads of adjacent buildings [14].

2. Model Development

In this study, the geometry of the PSC consists of a number of horizontal pavement layers, one of which contains at least one pipe loop that acts as a heat exchanger. The entire PSC is modeled in 3D using finite element techniques, during which thin wall assumptions or other geometric simplifications are not applied. This approach allows for a comprehensive evaluation of the system since it does not take any geometrical simplifications into account. Accurate models are necessary for the future development of the PSC system.

The pipe is always laid out in a serpentine fashion, which should give us the highest possible outlet temperature and is the most pragmatic to construct. Only the top 300 mm of pavement structure was modeled, as explained in the following section. Each pipe loop is assumed to behave independently within the PSC structure. Hence, the equations are solved for only one loop. Geometrical parameters which characterize the design of the PSC are specified as follows: horizontal distance between two parallel pipe lengths, P_s , inner diameter of the pipe, D_{in} , outer diameter of the pipe, D_{out} , the depth of pipe burial, P_d , which denotes the distance between the pavement surface and the upper level of the pipe, total length of the PSC area, L , thickness of

87 each individual pavement layer, d_i , and properties of materials in the system. The width, W , and
88 total area of the PSC can be calculated as a function of the above parameters. Figure 1 shows the
89 schematic of all geometric parameters involved in this study.

90
91 **Figure 1:** Schematic of involved design parameters in a PSC system.

92 It is assumed that the flow problem is uncoupled from the thermal problem, which is a
93 reasonable assumption in the case of a laminar flow. This allows us to split the problem into two
94 separate problems, and employ two consecutive solvers. The first problem is approached using a
95 laminar flow solver for a stationary case, and the second problem involves solving the transient
96 temperature in the entire PSC system. This approach is computationally economical due to only
97 having to solve for one flow field. The only drawback is the non-variability of the flow rate during
98 system operation. The software used to develop this model was COMSOL Multiphysics.

2.1. Mesh Generation

The middle and majority portion of the PSC geometry is meshed using prismatic elements with a triangular base (Figure 2). Small element sizes were used perpendicular to the fluid flow, where steep temperature gradients are expected. A much larger element size was used parallel to the fluid flow. This strategy becomes possible due to the use of the prismatic elements which are given a small triangular base and a relatively large length. The end parts of the collector geometry, which contain curved parts of the heat exchanger pipe, were meshed with tetrahedral elements. This is necessary due to their complex geometry.

Figure 2: Mesh of FE model, $L = 4$ m, $W = 0.9$ m, total pipe length is 23.6 m, D_{in} is 8 mm.

2.2. Governing equations & corresponding boundary conditions

The governing equations in the system are incompressible Navier-Stokes equations, as follows:

$$V_{i,i} = 0 \quad i = 1, 2, 3 \quad (1)^4$$

$$V_j V_{i,j} = -\frac{1}{\rho} p_{,i} + \frac{\mu}{\rho} (V_{i,jj}) \quad j = 1, 2, 3 \quad (2)$$

With V and p denoting volume and pressure, respectively. μ is working fluid dynamic viscosity, whilst ρ is working fluid density.

The flow was computed with the boundary conditions in two consecutive steps. First, a uniform velocity Boundary Condition (BC) ($u_i = -U_0$) and far field pressure ($p = p_\infty$) were prescribed for pipe inlet and outlet, respectively. Then, to achieve a fully developed flow in the system, the outlet velocity profile in step 1 is set for pipe inlet, $u_i = u(x, y)$. The pipe wall had a no-slip velocity BC, $u_{wall} = 0$. In the laminar flow solver, the working fluid is assumed to be pure water at a temperature of 20°C. Therefore, all properties of the working fluid were assumed at 20°C, which is a reasonable assumption for a laminar flow.

The transient heat transfer problem has Eq. 3 as its governing equation, which is the general energy equation. To solve this equation the flow field of the stationary solver is employed during each time step.

$$\frac{\partial T_i}{\partial t} + V_j T_{i,j} = \frac{\lambda}{\rho c_p} T_{i,jj} \quad (3)$$

In Eq. 3, T denotes temperature, t time, λ thermal conductivity, and c_p specific isobaric thermal capacity.

⁴ Equations 1 to 3 are written using indicial notation.

Constant temperature was assumed at fluid inlet ($T_{inlet} = T_0$). The pipe wall also holds a no-slip temperature BC ($T_{wall} = T_{fluid}$). At a depth of 300 mm, the assumption of an adiabatic boundary ($\frac{\partial T}{\partial n} = 0$) is reasonable since the temperature variations that occur in the pavement at this depth are negligible over the time scale that was simulated which never exceeded 24 hours. In the transient heat transfer solver, the properties of the working fluid are assumed to be temperature dependent during the heat transfer simulation, although this does not have a major effect on the results.

2.3. Pavement Materials and Properties

All pavement materials are heterogeneous and exhibit a large number of internal heat transport mechanisms that include: radiation between particles, convection in the pores, phase change processes, vaporization processes, and condensation processes [21]. Because of these complexities, it is necessary to simplify the way the thermal properties are defined. Here, we assume that the pavement materials behave as a homogenous material with isotropic thermal properties. Table 1 contains all the thermal properties that were used in this work. It has been previously shown that asphalt concrete has a thermal conductivity between 0.75 and 2.89 $W/m.K$ [22]. Significant variations in thermal properties of the aggregates cause large differences in the thermal conductivity of the asphalt concrete [11]. However, very often, the reference material tends to report values between 0.8 and 1.5 $W/m.K$ [23]–[26]. The use of aggregates that exhibit a relatively high thermal diffusivity, such as aggregates containing large amounts of quartzite, therefore, ensures an asphalt concrete with a conductivity on the high end of the scale, with values typically around 1.8 $W/m.K$ [11] or higher [23]. Asphalt concrete

typically has a solar absorptivity ranging from 0.85 to 0.93 [26]. The thermal properties of the pipes and pavement materials are assumed to be temperature independent.

Table 1: Thermal properties of used materials.

Material	α	λ [W/m.K]	c_p [J/kg.K]	ρ [kg/m ³]
Reference HMA [23]–[25]	0.9	1.2	950	2350
Crushed gravel [1]	N.A.	1.1	1000	2200
Dry soil [24]	N.A.	1.0	1900	1500
Concrete foundation [1]	N.A.	2.3	1050	2300

2.4. Pavement surface BC

At the surface of the pavement, seven different heat transfer modes and sub-modes take place, including conduction, absorption and reflection of solar radiation, absorption and reflection of longwave radiation, emission of longwave radiation, and convection. Each of these mechanisms were considered in the BC equation for the surface of the pavement structure (see Eq. 4) [12], [22], [27]–[30].

$$-\lambda T_{i,j} = \alpha_{sw} q''_{sw} + \varepsilon \sigma (T_{sky}^4 - T^4) + h(T_a - T) \quad (4)$$

α_{sw} is the shortwave (solar) radiation absorption coefficient, or solar absorptivity, and q''_{sw} is the specific incident solar radiation heat flux. In the longwave radiation part of Eq. 4, more specifically $\varepsilon \sigma (T_{sky}^4 - T^4)$, the Stefan-Boltzmann law ($E_b = \sigma T^4$) was used to calculate the net amount of longwave radiation exchanged between the pavement and its surroundings in combination with the following assumptions (i) emissivity equals the spectral absorptivity, and (ii) grey surface behavior. The latter is the assumption that the spectral absorptivity and emissivity are independent of wavelength [31]. Here, ε denotes the emissivity of the pavement, whilst T_{sky} denotes the hypothetical temperature of the surroundings that is used to estimate

the temperature of the surrounding atmosphere, which absorbs and emits radiation. T_{sky} can be calculated using the Bliss model (Eq. 5) [1], [3], [29]. The convection coefficient, h , will be derived using Eq. 7, which is discussed further. Finally, T_a denotes the dry-bulb air temperature as measured by a standardized weather station.

$$T_{sky} = \left(0.8 + \frac{T_{dp}}{250}\right)^{0.25} T_a \quad (5)$$

In Eq. 5, T_{dp} is the dew point temperature. The dew point temperature can be calculated with a high accuracy using the following equation, which is based on dry-bulb air temperature and relative humidity (RH) [32].

$$T_{dp} = \frac{B \left[\log\left(\frac{RH}{100}\right) + \frac{C T_a}{B + T_a} \right]}{C - \log\left(\frac{RH}{100}\right) - \frac{C T_a}{B + T_a}} \quad \text{with } B = 243.04 \text{ and } C = 17.625 \quad (6)$$

The empirical Bentz model was employed to estimate the heat transfer coefficient, h , to characterize the thermal boundary layer just above the pavement's surface regarding heat transfer due to convection [30]. This model only uses the wind velocity (FF) as an input factor, although it does give the best result out of most common empirical models developed for calculating the heat transfer coefficient [1].

$$\begin{aligned} \text{If } FF \leq 5 \text{ m/s} \quad h &= 5.6 + 4.0 FF \\ \text{If } FF > 5 \text{ m/s} \quad h &= 7.2 FF^{0.78} \end{aligned} \quad (7)$$

All values of T_{sky} , T_{dp} , and h are updated using Eqs. 4 to 7 at the beginning of each time step in the simulation. Values of q''_{sw} , T_a , RH , and FF need to be updated based on hourly values provided by given tables from various meteorological databases [33].

2.5. Initial Temperature Field

The PSC seizes its operation during the night due to the lack of incident solar radiation and the subsequent drop in pavement temperatures. This inactivity transforms the thermal state of the PSC overnight towards a state with a one dimensional temperature profile. This temperature profile can be estimated with reasonable accuracy using a simple set of empirical equations (Eqs. 8 and 9) [34] often used for predicting the temperature profile of regular pavement structures containing asphalt concrete. This functions as the initial temperature field for the modeling framework developed here.

$$T_{s,sunrise} \cong T_{s,min} = 0.89 T_{a,min} + 5.2 \quad (8)$$

$$T_{pavement} = T_{s,min} + (0.037 \text{ depth}) - (6.29 \cdot 10^{-5} \text{ depth}^2) \quad (9)$$

Just before sunrise, the daily minimum pavement surface temperature ($T_{s,min}$) tends to be reached, and it can be estimated as a function of the daily minimum dry-bulb air temperature ($T_{a,min}$) (Eq. 8), which tends to occur around the same time. With a similar empirical formula, Eq. 9, the temperature profile of the pavement structure can be further estimated based on the previously calculated minimum surface temperature and as a function of depth. In Eq. 9, $depth$ is the distance, expressed in mm, between the pavement surface and the point of interest perpendicular to the pavement surface [34].

3. Verification & Validation of the Finite Element Model

In order to verify the FE modeling framework, a grid study is performed. This is followed by a validation process by comparing experimental data with the FE modeling output data.

3.1. Grid study

A grid refinement study was performed to ensure that the output of the numerical simulation is independent of the non-uniform grid resolution. Elements for modeling the solid material domain were chosen from sizes ranging from 6 mm at high-end thermal conductivities and solar insolation, and low-end inlet temperatures where the temperature gradient is the steepest, to 75 mm at interior nodes far from the boundaries where flow variables vary only moderately. In the fluid domain, elements with a size of 1.6 mm to 4.6 mm perpendicular to the flow and 70 mm parallel to the flow (length of prism elements) are used. This numerical model converges with the time step of 30 minutes.

3.2. Experimental Set-Up

To validate the model, a similar set of experiments has been carried out. Temperature readings in the model were compared to actual thermocouple measurements in the experiments. The setup existed of a slab of AC with embedded copper pipes. The slab had a total thickness of 4.7'' (119 mm). Two types of Hot Mix Asphalt (HMA) were used to make the slab. The bottom 2.5'' (64 mm) of the slab was prepared with a local mix of AC obtained from a HMA plant (using aggregates identified as greywacke, with quartz and feldspar). In the top layer a quartzite aggregate HMA, prepared in the laboratory, was used. The thermal properties of these asphalt mixes are depicted in Table 2 [11].

Table 2: Material properties in experiment.

Material	λ [W/m.K]	c_p [J/kg.K]	ρ [kg/m ³]
HMA Quartzite	1.8	950	2350
HMA Plant Mix	1	1050	2350
Copper	400	385	8700

A grid of copper pipes has been placed on top of the plant mix asphalt concrete. These pipes have an outer diameter of 6/10" (~15 mm) and the distance between the surface of the slab and the top of the tube was 2" (51 mm). A schematic of the embedded copper pipes is shown in Figure 3 (left). However, only the short pipe on the far right is used in the experimental results discussed here.

Figure 3: Left: design schematic of experimental asphalt concrete slab (cross section AA' is depicted schematically in Figure 5), right: overview of asphalt concrete slab.

Thermocouples were installed to measure the temperature of the asphalt concrete along the depth and at multiple points in the slab in both x and y direction, as can be seen in Figure 4 and Figure 5. The temperature of the fluid at the outlet of the pipe was measured using a submersible thermocouple (Thermocouple 14 in Figure 4). Wind velocity and incident solar radiation were measured using a Campbell Scientific, 014A-L anemometer and a Kipp & Zonen/Campbell Scientific, CMP-3 pyranometer, respectively. The wind velocity fluctuated between 0 and 2 m/s according to the anemometer. The incident solar radiation and air temperature reached a maximum of 785 W/m² and 34.3°C, respectively. The air temperature is

measured using a shaded thermocouple. Measurement of these weather parameters facilitates verification of the modeling framework.

Figure 4: schematic cross section, AA', of asphalt concrete slab showing location of TC's.

Figure 5: Close-up of TC wiring and copper pipe.

Initially, the slab was kept under the sun for approximately 4 hours before any water flowed through any of the pipes. Next, a hose connected the water supply to the copper pipe to pump water, with flow rates of 1 to 4 l/min. The sequence of processes is shown in Table 3. The inlet temperature was measured 4 times at equal intervals and varied between 22.1°C and 24.1°C.

The compaction of the set-up is not as perfect as the case in an actual road. In the case of the experimental set-up, a roller was used to compact the asphalt concrete. Early experiments at this scale often have this drawback.

Table 3: List of events during experiment.

	Process	Time (hour)
1.	Start of slab heat-up	8.62
2.	Start of flow rate at 1 l/min	13.35
3.	Change flow rate to 2 l/min	13.39
4.	Change flow rate to 3 l/min	14.52
5.	Change flow rate to 4 l/min	15.12

3.3. Model Verification

A slight modification of the model was needed to account for the variable flow rate. This variability requires the use of a time dependent solver for the computation of the velocity field, instead of the steady state solver. All other modeling aspects can remain the same, including the splitting of the velocity and pressure field, and the temperature field, as described in Section 2.

Thermocouple number 14 (see cross section in Figure 4) registered the outlet temperature in one point of the pipe outlet cross section. Three values, maximum, minimum and average outlet temperatures, were obtained for each time step from the FE model in order to be compared with experimental results, see Figure 6. Due to the small inner pipe diameter and a fully developed flow assumption, it was expected that the outlet temperature would plot in the same range. However, due to the random movement of the thermocouple, the registered point is not exactly fixed over the time and can, therefore, be assumed anywhere over the cross section of the outlet. The experimental data is located in between the maximum and minimum simulated outlet temperature data. As the experimental data is closer to the computed

maximum temperature, which occurs at the inner pipe wall surface, it is reasonable to assume that the thermocouple was located somewhere in the vicinity of the pipe wall. Therefore, it can be observed that there is a good agreement on outlet temperature between the model and the experiment.

Figure 6: Comparison between thermocouple measurements of outlet temperature during experiment and FEA.

It can also be observed from Figure 7 that the temperature measurements from the thermocouples, embedded within the asphalt concrete of the experimental set-up, follow the same trend as their simulated counterparts. The surface temperature (T17) during the experiment and simulation lie closely together, except for the maximum surface temperature, which was predicted to be slightly higher from the simulation. The thermocouples located between the surface of the asphalt concrete and the copper pipe recorded higher temperatures during the experiment compared to the FE simulation, although with a similar trend. This difference can simply be explained by the empirical nature of Eqs. 8 and 9 which calculate a

rough estimate for the initial temperature of the PSC slab. Uncertainties in the thermal properties of the material and the exact location of the thermocouples are also contributing factors. However, the comparison between the experimental data and the simulation results clearly verifies the modeling framework.

Figure 7: Comparison between thermocouple measurements in experimental asphalt concrete during experiment and FEA, location of the thermocouples can be seen in Figure 4.

4. Results and Discussion

A parametric study on design parameters was conducted using the newly developed model. Through this, it became apparent that the thermal conductivity of the asphalt concrete, the solar absorptivity of the pavement surface and the pipe depth are the most influential design parameters on the performance of the system. These three parameters are discussed in more detail in this section, based on a PSC with a pipe loop length of 70 meters. Other parameters are taken as follows: $P_s = 150$ mm, $P_d = 55$ mm, $T_{inlet} = 15^\circ\text{C}$, $D_{in} = 8$ mm, a flowrate of 50 l/h, as well as weather parameters for an average summer day at a latitude of 35°N (Albuquerque, NM). The simulations performed here are based on a parking lot pavement structure with 90 mm of asphalt concrete with a crushed gravel foundation. The default solar absorptivity of the pavement surface is assumed to be 0.9. The efficiency of the collector (η_{solar}) is defined as the ratio between energy outputs achieved with the PSC (Q_{PSC}) and the thermal energy of the incident solar radiation (Q_{sw}).

A higher thermal conductivity of the asphalt concrete leads to higher and faster thermal gains in the working fluid, which is evident, and has been previously shown through some small scale practical experiments [11]. However, it remained unclear, until now, what the exact influence of the thermal conductivity is on the output of a large-scale system. Figure 8 (left) presents the outlet temperature and solar efficiency of a PSC as a function of the asphalt concrete's thermal conductivity. The efficiency of the collector increases from 17% to almost 20% when the thermal conductivity increases from 1.0 to 2.0 W/m.K. Such an increase is achievable, as discussed in Section 2.3.

The high solar absorptivity value of asphalt concrete is one of the key reasons why the PSC is often preferred in combination with asphalt concrete pavements, rather than cementitious concrete pavement structures. However, when asphalt concrete ages, it becomes lighter in color and will, therefore, reflect more of the incident solar radiation. The results of the numerical modeling in Figure 8 (right) show a linear drop in collector efficiency from about 17% to 15% over the course of a pavements lifetime when the absorptivity drops from 0.95 to 0.65. This is with asphalt concrete with a more common thermal conductivity (1.0 W/m.K).

Figure 8: Peak outlet temperature and solar efficiency as a function of thermal conductivity of the asphalt concrete (left) and pavement surface absorptivity (right).

It is, therefore, important to further investigate how the aging process of the asphalt concrete affects the thermal conductivity and absorptivity. This is necessary to truly optimize the design of the system and to choose the correct materials. A pavement structure with cementitious concrete may, for example, perform just as well in the long term since the solar

absorptivity of cementitious concrete slightly increases over time, whilst asphalt concrete's absorptivity decreases heavily over time.

Figure 9: Peak outlet temperature and solar efficiency as a function of pipe depth (P_d), for different asphalt concrete thermal conductivities.

Pipe depth is the final parameter discussed here. Figure 9 depicts the influence of the pipe depth on the performance of the system. Thermal gains are almost reduced from 21% towards 14% when the pipe moves from a depth of 25 mm to 105 mm. The pipe depths below 75 mm was evaluated with a more realistic tertiary road structure with these pipe depths in mind. This tertiary road contains a total asphalt concrete thickness of 130 mm.

If the average thermal conductivity and solar absorptivity over the PSC's lifetime is 1 W/m.K and 0.75 respectively, the average solar efficiency will be less than 15% with a pipe depth of 55 mm. With a pipe depth of 95 mm, this will be further reduced to 12%. Hence, the long-term system thermal characteristics improvement is paramount, as well as decreasing the pipe depth as much as possible.

5. Long Term Evaluation

Using Eqs. 4 to 7, it is now possible to simulate one full day of PSC operation for a given set of weather conditions, as described in the previous Section. This approach allows for an evaluation of all geometrical and material parameters. Here, we also wanted to study the influence of changes in weather parameters on the energy output and solar efficiency of the PSC. Such an analysis provides a physics based estimate of the energy output and solar efficiency of the PSC over time. It should be stressed that the underlying goal of this study is not to be able to predict the energy output of the PSC with a high degree of accuracy continuously over time, but rather to have a good estimate of the total amount of energy harvested over a large period of time, and still have realistic fluctuations in energy output and outlet temperatures. Therefore, a parametric study was carried out on the influence of weather parameters on the PSC system. Data generated during this parametric study can be used to estimate the energy output of the PSC by comparing weather parameter values of TMY data to weather parameter values evaluated in the parametric study, and subsequently interpolating in between energy output data generated in the parametric study. Such a parametric study is, however, not as straightforward as a parametric study on design parameters, since meteorological parameters fluctuate continuously.

The PSC's temperature changes slowly over time, even when large fluctuations occur in weather parameter values. This slow thermal reaction is mainly due to low thermal conductivities of pavement materials [12]. Hence, there is no direct correlation between, for example, incident solar radiation (q''_{sw}) and the power of the PSC for a particular instant. This is because the power of the PSC depends on the entire meteorological cycles that took place

before this point in time. The weather parameters used in the previous section as weather data input (q''_{sw} , T_a , RH , and FF) are, therefore, not chosen as a basis for this parametric study. In order to conduct a meaningful parametric study on weather parameters, it is necessary to choose weather parameters that are able to represent an entire set of diurnal weather parameters. The following daily weather constants meet this requirement and are chosen as a basis for this parametric study: maximum dry-bulb air temperature ($T_{a,max}$), minimum dry-bulb air temperature ($T_{a,min}$), average atmospheric transmissivity ($\tau_{atm,avg}$), average relative humidity (RH_{avg}), and average wind velocity (FF_{avg}). The conversions of these daily constants to realistic diurnal cycles are discussed in the following.

The atmospheric transmissivity (τ_{atm}) factor accounts for the scattering, reflection and absorption processes in the atmosphere that diminish the amount of solar radiation reaching the Earth's surface. According to literature τ_{atm} ranges from 0.2 for a completely overcast sky to 0.81 for a completely cloudless sky [22]. A realistic diurnal solar radiation cycle (q''_{sw}) can be calculated based on the daily average atmospheric transmissivity ($\tau_{atm,avg}$) using Eq. 8 [35].

$$q''_{sw} = R_0 f \tau_{atm}^{sec Z} \cos Z \quad (10)$$

In this equation, R_0 is the solar constant, which is the power caused by shortwave radiation ($0.2\mu m < \lambda < 3\mu m$) impinging on a surface normal to the sun's radiation at the edge of the Earth's atmosphere when the distance between the sun and the Earth is at the average of 1 AU⁵, and is assumed to be 1368 W/m². To modify the values for the actual distance between the sun and Earth, an eccentricity factor (f) is introduced. The eccentricity factor only has a value between 0.97 and 1.03 [2]. The amount of solar insolation at any given time is mainly influenced

⁵ Astronomical Unit

by the zenith angle (Z) and the atmospheric transmission coefficient for a unit of air mass, or simply atmospheric transmissivity (τ_{atm}). The zenith angle is the angle measured from directly overhead to the geometric center of the sun's disc. The Zenith angle and eccentricity factor for any date and time are calculated in the simulation by using astronomical equations reported by Jean Meeus, which require a date, a time and latitude values as input [36].

The diurnal dry-bulb air temperature cycle is calculated based on the daily minimum and maximum dry-bulb air temperatures. A periodic and exponential function (Eqs. 11 and 12) were used to estimate the diurnal air temperature cycle during daytime and nighttime, respectively.

$$\text{If } t_{rise} \leq t \leq t_{set} \quad T_a = (T_{a,max} - T_{a,min}) \sin \left[\frac{\pi(t-t_{rise})}{(t_{set}-t_{rise})+2A} \right] + T_{a,min} \quad (11)$$

$$\text{If } t > t_{set} \quad T_a = (T_{a,set} - T_{a,min}) \exp \left[\frac{-b(t_{set}-t)}{24-t_{set}+t_{rise}} \right] + T_{a,min} \quad (12)$$

A is the number of hours between solar noon and time of $T_{a,max}$ and b is a coefficient which helps to determine the rate of temperature drop (decay factor) after sunset, which can range from 1.8 to 2.3 [37]. In this study, A is assumed to be three hours, and dimensionless b is assumed equal to 2.05, which is the middle of the above mentioned range.

The relative humidity and wind velocity are directly evaluated in the model as a constant average value, due to the absence of any clear cyclic pattern for these meteorological phenomena.

Eqs. 10 through 12 filter out much of the natural fluctuations that occur in the meteorological parameters. It is, therefore, necessary to conduct a comparison between output data from simulations based on hourly weather data and output data from a parametric study of

the daily constant weather parameters and subsequent interpolations. Figure 10 contains such a comparison for a period ranging from July 17th through July 23rd.

Figure 10: Comparison between PSC energy output obtained with simulations based on hourly weather data and PSC energy output obtained through a parametric study on weather parameters. For Albuquerque, NM and July 17th through 23rd.

Here, the underlying simulations are all based on TMY3 hourly weather data for Albuquerque, NM. During the parametric study, three different $\tau_{atm,avg}$, each combined with three different pairs of $T_{a,min}/T_{a,max}$ were evaluated in the modelling framework developed here for 6 different dates of the year. Interpolating for a specific date, $\tau_{atm,avg}$, and $T_{a,max}$, leads to a long term prediction of the energy output of the PSC. In Figure 10, a comparison between this long-term prediction strategy and an evaluation using hourly weather data is presented. The outlet temperature profiles of the two evaluations lie closely to each other. The prediction of the work performed by the PSC based data from the parametric study on weather parameters is only

5.1% below a prediction made using hourly weather data contained in the TMY3 database.

Hence, the proposed strategy for long-term evaluation of the PSC is quite accurate.

Figure 11 contains a long term evaluation for Albuquerque, NM with a PSC design embedded in a parking lot and asphalt concrete with a thermal conductivity of 2.0 W/m.K and a solar absorptivity of 0.9. The pipe is located at a depth (P_d) of 45 mm and is spaced at an interval of 100 mm (P_s). The inner diameter (D_{in}) is 8 mm, the flowrate is 50 l/h, and the inlet temperature is 10°C. The PSC's properties are taken as the most optimum conditions.

Figure 11: Long term evaluation of the system for Albuquerque, NM.

The overall solar efficiency of the long-term evaluation presented in Figure 11 is about 26.6%. This number is higher than in the parametric study, mainly due to the much lower inlet temperature. This efficiency comes close to efficiencies computed from previous research [14], with this specific inlet temperature.

6. Conclusion

In this paper, a modeling framework is developed using a finite element method to predict the thermal behavior of a pavement solar collector (PSC). This model results in a realistic energy output of the PSC due to the limited amount of simplifications incorporated in the model. The only simplifications applied to the model are (i) perfect contact between different materials, (ii) homogenous and isotropic pavement materials, (iii) pure water as working fluid, and (iv) no influence of the fluid flow field by the heat exchange in the PSC. An experiment was carried out to validate the model. Experimental data and the modeling framework are in good agreement with respect to fluid outlet temperatures and pavement temperatures. The model can, therefore, be used to evaluate possible benefits of the system on pavement life and to help analyze the use of the generated heat energy.

The modeling framework is used to conduct a parametric study on the influence of weather parameters. This results in computing realistic PSC energy output data over a longer time period, and paves the way for further research regarding the application of this low-temperature heat. A long-term prediction was generated for Albuquerque, NM. The PSC's property values were taken on the 'high-end' of the scale.

The parametric study helps to understand the influence of the most important design parameters on the performance of the system: the thermal conductivity of the asphalt concrete, the pavement surface solar absorptivity, and the pipe depth. The results of this can be used to investigate the feasibility of the system, and of potential improvements that can be made to it. More knowledge on the aging of the system, from a thermal perspective, as well as how to

achieve a shallow pipe depth, will be required in order to investigate the feasibility of the technology in a particular location. Also, other materials may give a better long-term energy harvesting efficiency for the system. This is necessary for future advances in this field.

Finally, modeling of 2D or 3D turbulent flow would be the natural next step in this research. Development of a successful 3D turbulent flow model, even a reduced 2D one, is a novel achievement, which can significantly enhance the modeling of the proposed PSC systems.

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