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Construction and configuration of convection-powered asphalt solar collectors for the reduction of urban temperatures

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ABSTRACT

In this paper, an analysis of a convection-powered asphalt solar collector prototype is approached by the means of experimental trials and computational fluid dynamics (CFD) simulations in order to evaluate how to optimise its design for the reduction of high urban pavement temperatures. Since the energy harvesting setup consists of a series of pipes buried in the pavement, their arrangement is here studied and experimentally compared to a possible construction technique consisting of concrete corrugations that aim at replacing the pipes. CFD simulations are employed to optimise the air collection chamber which is placed immediately before the heated air leaves the asphalt solar collector prototype. The data gathered is analysed in terms of energy harvested and exergy.

The results obtained show that for an overall optimal performance, pipes should be installed in a single row under the pavement wearing course. This allowed a surface temperature reduction of up to 5.5 °C in the pavement prototype studied and the highest absorbed energy and exergy measured. In addition, the CFD simulations showed that care has to be put in finding the optimal shape and size for the air collection chamber, as they significantly influence the behaviour of the system.

1. Introduction

High pavement temperatures are known to be responsible for structural damages of pavements such as premature rutting [1,2], reduced comfort for people due to overheating of buildings in an urban environment [3], and an increased energy consumption related to the Urban Heat Island (UHI) effect [1,4–7]. These phenomena are affected by a combination of the paving materials chosen and the weather conditions present in a chosen location, thus, their likelihood is a function of pavement design and location. Due to the fact that location is not an actual variable, it appears clear that appropriate design choices are fundamental to ensure the minimisation of the damages and the discomfort that can arise from high pavement temperatures.

In summer, due to the effect of weather conditions and thermal radiation from buildings, pavement surface temperatures reach peak values, which can get as high as 70 °C [8], therefore, techniques to lower them have been investigated. Research in this field is usually pursued by studying the effect of changes in the materials being used. Examples of the properties modified by researchers include thermal conductivity, specific heat capacity, albedo, and emissivity [9–17]. It is also relevant to mention that asphalt pavements naturally suffer loss of colour over time due to solar radiation. As a consequence, their thermal behaviour changes without the need of any modification and usually implies a slight reduction in the pavement temperature and energy storage capacity [18].

A different approach for the reduction of surface temperatures consists in the circulation of a fluid under the pavement wearing course for the purpose of absorbing energy and, thus, reducing the pavement temperature. This can be done using water [19–23] or by exploiting natural convection, as done by the authors in Refs. [24–26]. The use of natural convection to power energy harvesting requires channels under the wearing course of roads in order to allow the generation of buoyancy-driven air flow, which is able to absorb heat from the upper layers of the pavement. The warmed-up air flowing under the pavement is expelled through a chimney, where the heat may be used for a chosen application. The influence of the chimney height and diameter and the effect of the inlet temperature in the system have been previously discussed [25,26], however, no studies focused on the shape and arrangement of the air channels installed under the pavement or on the role of

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the air collection chamber, i.e., the volume where air is accumulated before exiting the pavement through the chimney, which is here abbreviated to "air box" [26].

In this paper, an asphalt solar collector prototype is experimentally studied with a number of different pipe arrangements and with a novel configuration based on concrete corrugations meant to replace pipes. The results obtained here are intended to demonstrate that a realistic technique to implement convection powered energy harvesting can be developed and that concrete corrugations are a possible candidate for this task. Furthermore, the effect of changes in the size and shape of the air box are here studied by the means of computational fluid dynamics (CFD) simulations to assess their influence on the air speed and temperature at the chimney outlet. The novelty of the present study is in the fact that convection-powered asphalt solar collectors for the purposes of pavement temperature reduction are not studied in the literature, since the operating fluid is usually water.

2. Experimental methods

2.1. Study of pipe arrangements

An asphalt solar collector prototype was built with the same general structure as shown in Refs. [25] and [26]. The system (Fig. 1a) is made of two layers, i.e., an asphalt wearing course (maximum aggregate size of 10 mm, 6% air void content, 50 mm thickness) and an aggregate layer (silica sand, 130 mm thickness).

A set of 6, 1 m long, copper pipes were buried in the aggregate layer in 5 different configurations (see Fig. 2). Since in the existing literature there is no guidance on the effect of pipe spacing and arrangement in convection-powered asphalt solar collectors, it was decided to compare the pavement prototype to a shell-and-tube heat exchanger and to test the pipe configurations that are generally used in such a common and widely studied component. As shown in Fig. 2, five configurations were chosen according to the design guidance provided in Ref. [27]. An overview of all the tests performed is available in Tables 1 and 2. The pipes are supported by the front and back panels of the prototype, which also provide a precise control of their position and pitch ratio (center-to-center distance, 37.5 mm). The remaining sides of the prototype were built with timber slabs (18 mm thickness) and thermally insulated with extruded polystyrene foam and bubble foil insulation so as to ensure no external heat loss.

The receptor chamber, into which the air from the pipes flows is called the air box [25,26]. On the top of the air box, a chimney was installed to form the system outlet (see Fig. 1).

In Fig. 1b the components of the prototype are displayed side-by-side in order to allow a clearer understanding of the interrelationship between the two separated timber boxes of which the system is made.

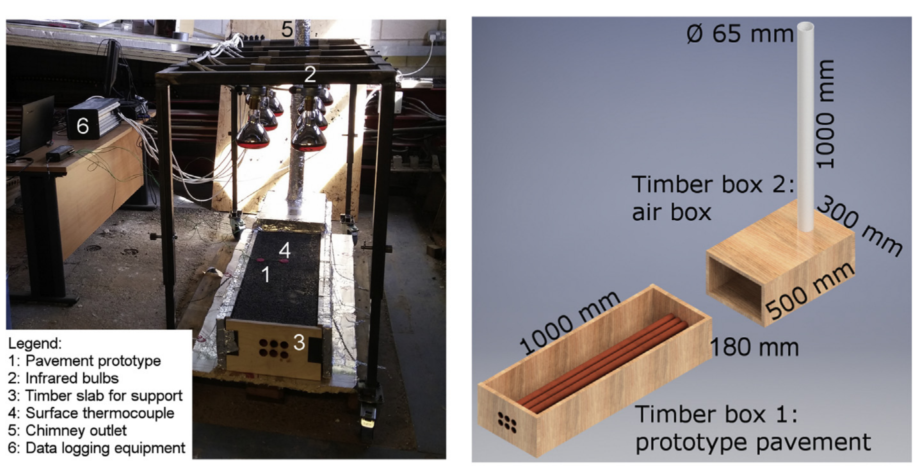
It is important to point out that the experimental method chosen for the analysis of the pipe arrangements was aimed at assessing the effectiveness of the system when the same total volume of pipes is installed in different ways. Therefore, the results obtained evaluate the energy harvesting solar collector based on this parameter and no considerations can be made based on different criteria, e.g., pipes installed per unit width of pavement. This is because to do so it would be highly important to keep into account edge effects and the influence of nearby pipes, which would have a significant influence on such kind of analysis. In this paper, since all the pipes are considered together and they are placed at a high enough distance from the sides of the prototype, edge effects are not expected to have a strong influence on the final results.

2.2. Study of concrete corrugations as a construction technique

In the current literature, construction techniques for the implementation of convection-powered asphalt solar collectors are not studied. For this reason it is necessary to propose a new method for the construction so that this kind of asphalt solar collectors can be considered. In particular, two 40 mm thick concrete slabs were cast in order to replace the pipes considered in the previous literature [24–26] and in subsection 2.1.

The shapes considered for the concrete slabs are triangles and semicircles and their size was chosen to obtain the same total volume as the pipes in order to allow a direct comparison between the two different solutions (see Fig. 7).

The concrete slabs were installed in the prototype just below the asphalt surface, thus, leaving a 90 mm high volume to be filled with silica sand (see Fig. 4a). As shown in Fig. 4, between the concrete slabs and the silica sand a thin geotextile membrane was installed



(a) Photo of the prototype in the laboratory.

(b) Main parts of the prototype disassembled (project phase rendering).

Fig. 1. Asphalt solar collector prototype powered by air convection.