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Effectiveness of pavement-solar energy system – An experimental study

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HIGHLIGHTS

- We built a small-scale pilot project of pavement-solar energy utilization.
- Design an automatic monitoring system to record the operating data.
- The average heat absorptivity of pavement-solar energy is 37%.
- The average thermal storage effectiveness of the system is 17%.

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ABSTRACT

A small-scale pilot project was built for the pavement-solar energy utilization in this paper. An automatic data acquisition system was designed to measure the effectiveness of the pavement solar energy system based on the operation data of 24 h a day in both summer and winter. Through 69 days (1656 h) of operation in summer, 2821 kW h of heat energy were stored in soil underground. In the transitional season, 4598 kW h of heat energy were taken out from soil during 104 days (2496 h) of operation in winter. The analysis showed that in summer, solar heat collection of asphalt pavement could effectively reduce 7 °C of its temperature. Under conditions of natural radiation, the average heat absorptivity of pavement was 37% and the average thermal storage effectiveness of the system was 17%. The electrical energy consumed by the system is only 11% of stored heat. During the winter, the asphalt pavement absorbs heat from underground soil which effectively increases its temperature, cutting 32% days of surface temperature below the freezing point. This not only save the energy for ice/snow removal but also mitigate associated safety risks.

1. Introduction

Use of renewable energy has become one of the most important measures to achieve sustainable development. As a result, many countries have released policies to encourage the utilization of renewable energy resources in various sectors [1–3]. As a renewable energy source, solar energy is virtually inexhaustible and its efficient utilization has played a crucial role in dealing with issues associated with use of traditional fossil fuel energy such as environmental pollution and depletion of natural resources [4–6]. At present, the main application modes of solar energy are photothermal conversion and photovoltaic-electricity conversion [7]. Asphalt pavements are featured with a big heat absorbing area and strong heat absorption ability [8]. Especially in suburbs, the pavements are perennially exposed to air. Except for traveling vehicles, there is generally no sun shading. In summer, asphalt pavements subject to solar radiation can reach high temperatures causing not only environmental problems such as the heat island effect on cities but also structural damage due to rutting or hardening as a result of thermal cycles [9]. In winter, there are significant safety risks associated with the snow and ice on pavements due to increased probability of traffic accidents. Most common methods to remove ice or snow on road pavement include manual, mechanical and chemical methods. However, there are limitations associated with these methods of deicing or snow-melting, such as safety risks, erosion of reinforcing steel in pavement, and high cost of maintenance.

As a result, a large number of studies have been undertaken on the pavement solar energy harvesting. Asaeda et al. (1996) studied the heat storage of various pavement materials [10]. Their research indicated that asphalt pavements could absorb more solar radiation than other materials in summer, and could emit more heat into the atmosphere in winter. The average collection efficiency

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Nomenclature

q_{sr}	total solar radiation (W/m^2)
q_L	long-wave radiation of the pavement surface (W/m^2)
q_r	heat convection between the pavement surface and air (W/m^2)
α	thermal radiation absorption rate of the pavement surface
ε	emissivity factor of the pavement surface
h_r	linear radiation parameter (W/m^2)
T_{surf}	pavement surface temperature (K)
T_{sky}	sky temperature (K)
σ	blackbody radiation constant, 5.67×10^{-8}(W/(m^2 K^4))
T_{air}	the ambient temperature (K)
v	wind speed on the pavement surface (m/s)
$q_{\text{CV-FLUID}}$	convective heat flux between the pavement and flowing fluid (W/m^2)
$q_{\text{CD-PAV}}$	heat absorbed and transferred by conduction to deeper layers (W/m^2)
η_1	pavement absorption efficiency from solar
η_2	collection efficiency of system
q_1	heat amount collected from solar (W/m^2)
q_2	heat obtained the system (W/m^2)
m	mass of water (kg/s)
c_p	specific heat capacity of water (kJ/(kg K))
T_{in}	inlet temperature of the system (K)
T_{out}	outlet temperature of the system (K)
A	collecting area (m^2)
Q	heat exchange amount of the heat exchanger (kW)
G	flow rate of the heat exchanger (kg/s)
c	specific heat capacity of fluid (kJ/(kg K))
Δt	inlet and outlet water temperature difference of the heat exchanger (K)
t_1	inlet water temperature of the heat exchanger (K)
t_2	outlet water temperature of the heat exchanger (K)

could reach 36% [11]. Similarly, the pavement solar system could reduce the peak temperature of pavement surfaces by 15–20 °C in summer and effectively increase the average temperature of pavement surfaces by 10 °C in winter [12]. Moreover, a compound system which combines the pavement-solar energy with space heating and cooling was studied [13].

The pavement solar system studies in China are still at its infancy. Vast majority of these studies rely on experiments in laboratory rather than actual cases [14]. Similarly, these experiments focus on the pavement solar energy system running during the daytime. This study fills the gap by investigating an actual case in northern China during both the day and night.

2. Theory of pavement-solar energy utilization

The main forms of heat transfer in the process of pavement-solar energy utilization are heat conducting, heat convection and heat radiation (see Fig. 1). Solar radiation heat collected by the pavement surface is transmitted along the vertical direction in asphalt and subgrade. The net heat absorbed by the pavement surface can be described in the formula (1).

$$q = \alpha q_{sr} - \varepsilon q_L - q_r \tag{1}$$

where ε can be treated as the numerically equivalent of α if the asphalt surface is regarded as diffuse gray surface. The value of α

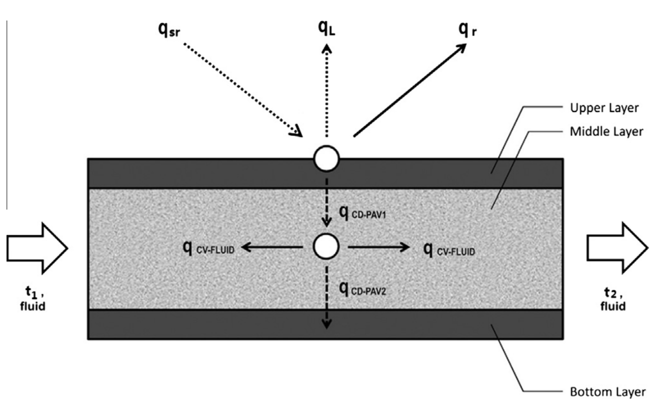

Fig. 1. Heat transfer process of pavement solar energy harvested [19].

(ε) was 0.85 in this study [15]. q_L can be written in an abstract form as shown in the formula (2).

$$q_L = h_r(T_{surf} - T_{sky}) \tag{2}$$

where h_r and T_{sky} can be written in the Bliss empirical formula (see formula (3) and (4)) [16].

$$h_r = 4\varepsilon\sigma\left(\frac{T_{surf}+T_{sky}}{2}\right)^3 \tag{3}$$

$$T_{sky} = 0.0552T_{surf}^{1.5} \tag{4}$$

where σ = 5.67 × 10^{-8} W/(m^2 K^4). q_r can be written in the formula (5).

$$q_r = h(T_{surf} - T_{air}) \tag{5}$$

$$h = 698.24\left[0.00144\left(\frac{T_{surf}+T_{air}}{2}\right)^{0.3}v^{0.7} + 0.00097(T_{surf}-T_{air})^{0.3}\right] \tag{6}$$

where v is the wind speed on the pavement surface, m/s [17,18].

A large proportion of heat collected by the pavement is absorbed by the heat collector while the rest is used to increase the temperature of road surface. $\boldsymbol{\eta_1}$ named as heat absorptivity (see formula (7)), and $\boldsymbol{\eta_2}$ named as thermal storage effectiveness (see formula (8)).

$$\eta_1 = \frac{q}{q_{sr}} \tag{7}$$

$$\eta_2 = \frac{q_1}{q_{sr}} \tag{8}$$

The useable heat obtained by the collector can be calculated in formula (9).

$$q_2 = \frac{mc_p(T_{out} - T_{in})}{A} \tag{9}$$

3. The construction of a pavement-solar energy utilization experiment system

The experiment site was location in Tianjin, which is a coastal metropolitan city of east-central China with 3 months in summer