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Energy modeling of photovoltaic thermal systems with corrugated unglazed transpired solar collectors – Part 2: Performance analysis

Siwei Li[a], Panagiota Karava[b,*]

[a] Purdue University, School of Civil Engineering, West Lafayette, IN, USA

[b] Purdue University, School of Civil Engineering and Division of Construction Engineering and Management, West Lafayette, IN, USA

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Abstract

This paper is the second of two companion papers focused on energy modeling and performance analysis of building-integrated photovoltaic thermal (PV/T) systems with corrugated unglazed transpired solar collectors (UTCs). In Part 1, energy models are presented for two configurations: UTC only and UTC with PV panels. The models predict the energy output of the system for different weather and system design conditions and are validated using measured data from an outdoor test facility. In this paper (Part 2), the system performance is evaluated based on data drawn from the literature and simulations with Computational Fluid Dynamics (CFD) and energy models. The analysis includes parameters that are unique for this system, such as the corrugation geometry and the collector orientation. Validated, high resolution CFD simulations are used to study the impact of plate orientation and incident turbulence intensity, based on the comparison of exterior and interior Nusselt (Nu) number and the cavity exit air temperature, as well as the PV surface temperature when UTCs are integrated with PV panels. It is found that for configurations with UTC only, both exterior and interior convective heat transfer is enhanced in the 'vertical' installation, while similar results were obtained for increased incident turbulence intensity levels. However, only minor influences from these two parameters are observed for UTCs with PV panels. The energy model is used to investigate the optimal geometry for both configurations. It is found that parameters such as slope length and corrugation wavelength have the most significant impact on UTC performance while the wavelength and PV panel height have the largest effect for UTCs with PV panels.

Keywords: Energy modeling; Building-integrated photovoltaic-thermal systems; Transpired solar collectors; Corrugated surface

1. Introduction

Building-integrated solar energy technologies, such as solar collectors and photovoltaic panels, coupled with efficient Heating Ventilation and Air Conditioning (HVAC) systems are viewed as means to reduce carbon emissions and dependence on fossil fuels. Solar air collectors are used for many purposes, e.g. preheating ventilation air (Athienitis et al., 2011), hot water heating (Bakker et al., 2005), source for heat pumps to improve their efficiency (Candanedo, 2011), or passive heating in buildings by storing the thermal energy in concrete slabs (Chen et al., 2010). An even more promising building application is the combination of corrugated UTCs with PV panels installed on the façade, which can achieve all the functions of solar air collectors while also generating electricity.

* Corresponding author.
E-mail address: pkarava@purdue.edu (P. Karava).

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Ever since the tests of a prototype UTC installation conducted by Carpenter and Kokko (1991), which proved the feasibility and energy saving potential of UTCs, large-scale systems have been installed and successfully operated for outdoor air heating in Canada and the United States. In parallel efforts, numerical and experimental studies (e.g. Kutscher, 1992; Arulanandam et al., 1999; Van Decker et al., 2001, etc.) attempted to determine the most important parameters that affect the performance of the system and to optimize their selection in order to achieve higher energy efficiency.

Gawlik (1993) investigated sinusoidal-shaped UTCs using numerical simulations and suggested that the flow pattern should be identified (attached or separated flow), before modeling the heat transfer process in corrugated UTCs, since different convective heat transfer correlations are associated with that. When developing the heat transfer correlations through validated CFD simulations in the companion paper (Part 1), both attached and separated flows have been observed. However, no evidence was found to support the notion that it is necessary to distinguish between these flow patterns with different correlations for the convective heat transfer coefficients (CHTC). Gunnewiek et al. (1996, 2002) utilized a two-dimensional CFD model to study the effect of collector height, height-to-depth ratio, incident solar radiation, suction velocity, plate hydraulic impedance and wind flow, including both the wind speed and direction, on the airflow distribution over the collector and made recommendations in order to avoid flow reversal on the plate. Fleck et al. (2002) conducted an experimental study on a flat UTC (plate area of 63 m^2) during the late winter season. Monitoring of the temperature, suction flow rate, solar radiation, wind speed and wind direction, together with the three velocity components near the center of the collector, showed that the efficiency peak occurs at non-zero wind speed for suction velocity between 0.02 and 0.05 m/s. The study also revealed that the thermal efficiency decreases monotonically with increasing incident turbulent intensity (TI). Gawlik et al. (2005) conducted a test for two flat UTC plates with the same properties and geometrical shape, but different thermal conductivity, and concluded that the effect of material conductivity on the thermal performance of UTCs was small. The study by Leon and Kumar (2007) focused on the development of a thermal model to predict the performance of UTCs over a wide range of design and operating conditions and concluded that the solar absorptivity, collector pitch and suction flow rate have the strongest effects on the thermal efficiency. Badache et al. (2012) conducted tests for flat UTCs with two different cavity widths (5 and 15 cm) and found that the heat exchange on the interior side of the collector is weak while the efficiency difference between the two cavity widths was less than 3%.

In summary, the thermal performance of UTCs (mainly flat UTC) depends on various factors that can be divided into the following categories (Shukla et al., 2012):

- Climatic conditions: namely, ambient temperature, incident solar radiation, wind effect, humidity and sky temperature. The wind effect can be identified as wind speed, direction and turbulence intensity while the effect of humidity is usually considered through the dew point temperature, which is used to calculate the sky temperature. The influence from the humidity difference between the ambient environment and cavity exit air on the thermal performance is usually neglected.
- Site constraints: orientation, tilt, and surroundings of the site. Corrugated UTCs are usually mounted on building façades, so the tilt angle is 90° relative to the ground plane. The façade orientation typically determines the incident solar radiation. The surroundings of the site are related to the wind flow field around the system, which includes the effect of wind speed, direction and incident TI and they are already considered in the climatic conditions. Note that, for corrugated UTCs, the plate orientation, i.e. whether the plate is placed horizontally or vertically (as shown in Fig. 1), will affect the thermal performance due to buoyancy.
- Collector configuration: size of collector, cavity dimensions, surface coatings, absorptance, material and porosity. The effects of surface coating can eventually be attributed to the absorptance of the plate and the material mentioned here refers to the thermal conductivity, specific heat and thickness of the plate. For corrugated UTCs, the corrugation dimensions should also be considered, as was introduced in Part 1, namely, the corrugation amplitude and wavelength, crest length and the slope length. When integrated with PV panels, three other geometry dimensions: the width and height of the PV panels and the distance between the PV panels, should also be taken into consideration.
- Geometry of perforations: pitch, dimensions (hole diameter), hole shape and pattern. The perforation shape on corrugated UTCs is different from that used in flat UTCs and the effect of porosity is more often considered, rather than the perforation geometry.
- Building parameters: wall U value and area of wall. In all the previous studies, the back wall of the UTC system is considered, or designed, to be adiabatic. The influence from the area of the wall is more likely due to the surroundings of the site, describing the location of the UTCs inside the airflow field around the buildings, which is included in the climatic conditions.
- Load characteristics: high temperature rise, low temperature rise, process air, recirculation and fan velocity. This can be summarized as the effect of the airflow rate or suction velocity ($m^3/s\,m^2$) in the system.

The above parameters can be re-grouped, based on their influence on corrugated UTCs, as weather (ambient temperature, incident solar radiation, wind speed and direction, incident TI and dew point temperature) and design factors (suction velocity, plate orientation, geometry shape, etc.). Among these, the suction velocity ($m^3/s\,m^2$) and wind