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Replication Studies

Theoretical and experimental analysis on the passive cooling effect of transpired solar collectors

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ABSTRACT

The present study provides results about the experimental performance of the transpired solar collector's passive cooling effect for the first time. In order to see the cooling performance of the transpired solar collector, a slope-adjustable experimental setup was built on the campus of Trakya University, Engineering Faculty, Edirne, Turkey. Solar radiation, ambient temperature, absorber temperature, cavity and back plate temperatures were monitored during summer period for different collector tilts. A physical and a mathematical model have been created to describe the heat transfer processes in the collector. The models were used to evaluate the measured data. It has been found that a natural airflow comes to be through the perforated plate, which acts similarly as in open-end double layer roofs. This airflow discharges the heat from the plenum decoupling the back plate from the exposed perforated plate. The temperature of the back plate, which represents the roof under the transpired collector, is significantly lower compared to that of the exposed roof on a typical sunny day. Similarly, the heat gain of the back plate is remarkably lower than the solar radiation received on the exposed roof. It has been found that the passive cooling effect of the transpired solar collector is increasing with rising intensity of radiation, as the heat transfer coefficient between the plenum and the back plate decreases with increasing solar radiation. Due to the natural character of the airflow in the plenum, wind heat losses are strongly dependent on the airflow's characteristics. Convective losses of the perforated plate have been defined by using two methods energy balance equations and a referenced heat loss correlation.

1. Introduction

The design of buildings and their supply systems targets to provide a required level of indoor comfort and the lowest possible energy consumption at the same time. In order to reach this, both the HVAC system and the building structure have to be intelligently planned and constructed. The current article describes the use of the transpired solar collector – a proven device for solar air heating – for roof ventilation, in order to reduce a building's solar heat gains, which would lead to excessive cooling energy demands in summer. The utilization of the transpired solar collector for the reduction of cooling energy demands is a novel idea, no study has investigated this use yet. This paper presents the theoretical background of the phenomenon, and provides experimental results to reflect on its nature.

The transpired solar collector (TSC) is a perforated metal cladding, installed at 10–30 cm of distance onto the building's façade, which operates as an absorber to heat up the ventilation air for buildings [1]. The air gap is sealed from its sides, so air can enter only through absorber perforations. Air handling units withdraw solar-preheated fresh air from the air gap and therefore need significantly less energy to provide supply air. The air heating process is based on the transpiration of the perforated metal absorber which warms up under solar radiation. Adequate air flow rate and even transpiration must ensure that the absorber heat is continuously taken by the air flow, utilizing it with high efficiency. The main merit of the TSC is that the convective heat losses from the absorber to the ambience can be neglected as the thermal boundary layer is being withdrawn from the external surface through the perforations into the air gap, utilizing the heat before it could be lost. The rate of transpiration is given by the approach velocity [2], which is defined as the flow rate of air over unit surface area of the TSC. In order to give operational boundaries of TSC systems to ensure low losses and thus high efficiency in solar air heating, extensive research has been carried out so far. In 1992 Kutscher [3] laid down

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Nomenclature

Abbreviations

CFD	Computational fluid dynamics
HVAC	Heating ventilation air conditioning
Nu	Nusselt number
Pr	Prandtl number
Re	Reynolds number
TSC	Transpired solar collector

Latin letters

A	Surface [m^2]
c_p	Specific heat capacity [J/(kgK)]
d	Distance [m]
F	View factor [–]
f	Heat transfer coefficient [W/(m^2K)]
H	Collector height [m]
I	Solar radiation incident on the collector [W/m^2]
k	Thermal conductivity [W/(mK)]
$\dot{m}$	Mass flow [kg/s]
$\dot{Q}$	Heat [W]
T	Temperature [°C]
v	Velocity [m/s]

Greek letters

α	Absorptivity [–]
ε	Emissivity [–]
φ	Tilt [°]
μ	Viscosity [kg/(ms)]
ρ	Density [kg/m^3]
σ_{SB}	Stefan-Boltzmann constant

Indices

air	Air
amb	Ambient
app	Approach
bp	Back plate
cg	Collector-ground
col	Collector
conv	Convection, convective
cs	Collector-sky
gain	Gain
gnd	Ground
in	Internal
loss	Loss
plen	Plenum
rad	Radiation, radiative
sky	Sky
sur	Surroundings
wind	Wind

the heat transfer principles for air flow through low porosity perforated plates. In 2007 Kumar and Leon [2] developed a mathematical model for the thermal performance analysis of unglazed transpired solar collectors. In 2014 Grieg et al. [4] carried out an experimental investigation of the flow structure over a corrugated waveform of a solar air heater. In 2012 Eryener and Akhan [5] carried out a theoretical and experimental investigation on the combination of the TSC with radiant heating panels in order to reheat air when solar radiation is insufficient. In 2014 Gao et al. [6] investigated the application of TSC systems for cold climates when equipped with a layer of glazing. In 2014 Collins and Abulkhair [7] evaluated heat transfer effectiveness of transpired solar collectors. In 2016 Hall and Blower [8] investigated the heat production of transpired solar collectors with low-emissivity coatings.

Parameters for an optimal TSC operation with forced flow have mainly been laid down. However, no research has been made on the summer operation of the TSC when there is no need for air heating and the heat of the absorber is not discharged. One could easily think that the warm metal sheet could enlarge air conditioning demand in summer as it is fixed close to the building's actual envelope. The current study is meant to reflect on the contrary of this assumption: the TSC successfully decouples solar gains from the building by natural convection through perforations. This operation opens up new problems in TSC research as the elaborated heat transfer equations have been laid down for forced flow. Although TSC systems for solar air heating are usually installed on vertical facades, the current article focuses on roof-type TSC systems to see their ability to minimise summer solar loads from large roof areas, which take out a significant amount of a building's air conditioning needs.

The heat from solar radiation, which causes significant daytime cooling demand, can enter a building either directly through windows or indirectly through wall and roof surfaces. Particularly, the roof of a building can heat up to high temperatures, increasing significant cooling load for interior spaces in summer. One of the methods of reducing the effect of solar radiation is to prevent it from reaching building surfaces by employing double layer techniques either on the wall or on the roof. Several studies have examined the energy-saving potential of double roofs, underlining their beneficial effects. In 2004 Shiraishi et al. [9] examined how the indoor cooling load and the indoor thermal environment can be improved by the adaption of a double roofing system with an air passage. It has been found that the thermal shielding performance of the double roof was about 8.6 times of that of an ordinary roof for the analysed conditions. In 2007 Cerne and Medved [10] analysed the 2D heat transfer in a low-sloped roof with forced ventilated cavity made from lightweight building elements. Two cases were distinguished: the air cavity was first configured with a coloured thin metal sheet; and second, with a thin metal sheet with an added layer of thermal insulation and radiant barrier. Results showed that lightweight building elements with ventilated cavity reduce the thermal load of a building compared to the case without cavity. It has been underlined that wind also had a great influence on the building thermal load. By investigating radiation, convection and conduction heat transfer in 2008 Biwole et al. [11] studied double skin roofs formed by adding a metal screen onto an existing sheet metal roof. It has been found that in order to provide the highest efficiency of the open-ended double skin roofs, the surface emissivity of the internal screen, the sheet metal and the external screen has to be as low as possible, the insulation thickness as high as reasonably possible, and the double-skin width over 6 cm and under 10 cm. The following structural features were given to assure near-optimum efficiency: sheet metal of 0.15 emissivity; insulation of 5 cm; an air cavity of 10 cm thickness, and an inclination of over 30° from the horizontal. In the same year Lai et al. [12] used inclined parallel plates, with the upper plate heated by a lighting system to simulate double-skin roofs exposed to solar irradiation. Results have been found for optimal inter-spacing, providing for the most heat gain blocked out for roof inclinations of 30°, 45°and 60°. In 2009 Lee et al. [13] evaluated the effects of cavity ventilation, roof slope, solar radiation intensity, cavity size and shape, and panel profiles on the airflow in a ventilated roof. First, it has been stated that the cooling load can be reduced by a ventilated roof, which is especially useful where the solar heat gain is high. Second, it has been proven that steeper roof slopes result in lower cavity temperatures. In 2011 Ong [14] compared six different roof designs to examine the temperature reduction in the attic. A "roof solar collector", which is a ventilated double-