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A state of art review on methodologies for heat transfer and energy flow characteristics of the active building envelopes

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ABSTRACT

Significant share of total final energy use is accounted by the building sector in most of the countries around the world. One way to reduce building energy consumption is to adopt energy efficiency technologies and strategies. Due to environmental concerns and high cost of energy in recent years there has been a renewed interest in building energy efficiency and integration of renewable energy technologies. Active building envelope technology, i.e. transpired solar collectors (TSCs), provides a cost-efficient way of minimizing energy demand of buildings in accordance with global principle of sustainability, which has also proven reliable for diverse applications such as preheating fresh air delivery into the buildings and supplying domestic hot water in summer etc. The objective of this paper is to review the heat transfer and energy flow characteristics of the active building envelopes, particularly focusing on various types of TSCs. Present work consists of background and concept of TSCs, research literature for thermal performance, theoretical modelling, experimental study and numerical simulation investigation. Diverse mathematical models, including thermal models, air flow models, porosity models, and turbulence models etc., have also been presented and compared. Following that, more than 20 parameters affecting TSC performance have been analyzed and evaluated. The literature has illustrated that the best overall performance of turbulence model is RNG k-ε; the effects of those parameters on TSC efficiency are completely different, depending on local climatic conditions, time and site constraints, and the interaction between different factors.

1. Introduction

Nowadays, the building sector accounts for approximately 40% of the total world final energy consumption and for about one third of CO_2 emissions into the atmosphere, which can result in global warming and climate changes [1,2]. Similarly, in the UK, the domestic sector is responsible for almost 40% of national carbon emissions [3]. The “Climate Change Act 2008” has already set a target of 80% reduction in CO_2 emissions in the UK (relative to 1990 emissions) to be achieved by 2050 [4]. The increasing trend towards building consumption will persist in the coming years due to the extension of built regions and related energy demands [2,5].

The building envelope plays a vital role not only in thermal comfort but also in building energy efficiency. There are significant opportunities for the building envelope to solve the aforementioned problems, which could exploit solar energy through integrating solar thermal technologies into the buildings. Transpired solar collector (TSC) is one of most popular solar thermal technologies, which is also called as active building envelope [6,7] from the perspective of TSC's active generation of solar thermal energy.

Research on TSCs started in the early 1990s [8,9] and was focused on feasibility studies and testing [10,11]. Authors (Shukla et al., 2012) have reviewed the performance of TSCs from the literature before 2012 [12]. In this work, the objective mainly focuses on the heat transfer and energy flow characteristics of TSCs for the recent five years, i.e., from 2012 to 2016, and those literatures were not reviewed by current authors before 2012 [14–43,46,49–54,56–62]. In Section 2, background and concept of active building envelopes will be introduced; in Section 3, the heat transfer and energy flow characteristics of the active building envelopes from the perspective of mathematical modelling,

Abbreviations: BIPV/T, Building-integrated photovoltaic-thermal; BPSC, Back-pass solar collector; CFD, Computational fluid dynamics; CHTC, Convective heat transfer coefficient; D, Diameter; EPSRC, Engineering and Physical Sciences Research Council; GTC, Glazed transpired collector; HEE, Heat exchanger effectiveness; IR, Infrared spectroscopy; P, Pitch; PIV, Particle image velocimetry; PV/T, Photovoltaic/Thermal; RANS, Reynolds-averaged Navier-Stokes; RMSE, Root mean square error; RNG, ReNormalization group methods; RSM, Reynolds Strees Model; SST, Shear Stress Transport; STC, Standard test condition; TI, Turbulence Intensity; TSC, Transpired solar collector; TTC, Transparent transpired collector; UTC, Unglazed transpired collector

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Nomenclature

A_c	effective area of the collector in m^2
A_h	area of the holes in m^2
A_{PV}	total PV area in m^2
C_f	conversion factor (thermal to mechanical) and given as 0.2
C_p	specific heat capacity of air in J/kgK
D	perforation/hole equivalent diameter in m
F_{pb}	view factor between the UTC plate and the back wall
F_R	heat removal factor
G	incident solar irradiance on the UTC plate per unit area in W/m^2
h	convective heat transfer coefficient in W/m^{2}K
H	total height of UTC-2stage in m
H_u	UTC height in m
i	control volume index
k	air thermal conductivity in W/mK
N_h	holes number
Nu_x	Nusselt number (= hx/k)
P	hole pitch in m, i.e., distance between center of hole and center of next closest hole
ΔP	pressure drop in Pa
P_{PV}	electrical energy generated by PV panels in W/m2
Pr	Prandtl number (=α/υ)
Q	air volume flow rate in m^3/h
Q_{conv}	convective heat flux between difference surfaces (or air) in W/m2
Q_{gain}	thermal heat gain from the collector in W
Q_{rad}	radiative heat flux between different surfaces in W/m2
Q_{solar}	solar radiation absorbed by the plate (or PV module) in W/m2
q_u	heat collected from the collector in W
Re_x	Reynolds number (= vx/υ) where v is relevant velocity scale
T_{amb}	ambient temperature in K or °C
T_c	cavity exit air temperature in K
$T_{collector}$	collector temperature in °C
T_{in}	inlet temperature in K or °C
T_{out}	outlet temperature in K or °C
T_p	UTC plate surface temperature in K
T_{ref}	surface temperature of PV module under STC in K
T_s	air temperature through the perforation in K
T_{sky}	sky temperature in K
T_{sun}	sun temperature in K
U_L	overall heat loss coefficient in W/m2K
V_{suc}	mean surface suction velocity in m/s
V_{win}	air flow free-stream velocity or wind speed in m/s
W_{el}	electrical power in W
W_{fan}	fan power in W
W_{pc}	PV power in W
$W_{thermal}$	thermal power in W
x_n	hole spacing along flow path in mm

Greek symbols

α	air thermal diffusivity in m^2/s
β_{ref}	temperature coefficient of the PV module in %/K.
ε	effectiveness ratio of collector
ε_b	emissivity of the back wall
ε_p	emissivity of the UTC plate (PV panel)
η_c	efficiency of the TSC in %
η_{ci}	instantaneous efficiency of the BPSC in %
η_{ef}	effective efficiency in %
η_{et}	equivalent thermal efficiency in %
η_{fl}	first law efficiency in %
η_{pm}	fan motor efficiency in %.
η_{PV}	electrical efficiency for PV panels in %
$\eta_{PV/T}$	combined thermal and electrical efficiency for BIPV/T systems in %
η_{sl}	second law efficiency in %
η_{Tref}	electrical efficiency of PV module under STC in %
τ_α	effective transmittance-absorptance factor
σ	Stefan-Boltzmann constant (5.67×10^{-8} W/(m^{2}K^4))
σ_p	plate porosity
υ	air kinematic viscosity in m^2/s
ξ	porosity of the TSC plate

experimental study, numerical simulations particularly CFD, and parametric sensitivity analysis including more than 20 parameters affecting TSC performance are indicated in detail, respectively; finally, conclusions and future work are drawn in Section 4.

2. Background and working principle for TSC

Active building envelopes, i.e., TSCs derived from Canada and USA and research on TSCs started in approximately early 1990s. TSCs have been already widely employed in USA and Canada and the technology has been extensively monitored by their government agencies. In addition, Natural Resources Canada has developed a feasibility tool called RETScreen to model the energy savings from TSCs [13]. However, TSCs are relatively new for other regions e.g. Europe and China.

Authors already described the historical development and working principle of TSCs, collector construction and its parameters, diverse types of TSCs in detail [12]. In this work, all those aforementioned contents will be not introduced again. The concept of TSCs is just presented using schematics below (Fig. 1(a)). There have already been some TSCs (active building envelop) applied in the existing buildings below (Fig. 1(b-d)).

Solar energy is employed by TSCs to heat the perforated absorber surface, which could transfer thermal energy to the ambient air for preheating fresh air delivered into buildings/room. Generally, the perforated absorber plate is a metallic sheet e.g. steel or aluminium, which could be integrated to the building façade and PV panels, and could generate solar thermal energy actively. Therefore, TSCs are also called as active building envelopes as mentioned before [6,7].

3. Heat transfer and energy characteristics of TSCs

Investigations on TSCs for the heat and airflow mass transfer, thermal efficiency, heat exchange efficiency, exergy efficiency, energy characteristics have been carried out for lots of researchers in last approximately 30 years, i.e., since 1991. Authors have already reviewed thermal performance of TSCs from the literature before 2012 [12]. In this work, a detailed summary for various models and study in recent 5 years has been presented in chronological order as shown in Table 1.

There are four different investigation methodologies for thermal performance of TSCs as follows:

1) Mathematical modelling study;
2) Physical experimental study including PIV, IR, prototype experiments and monitoring;
3) Numerical simulations including computational fluid dynamics (CFD); and
4) Parametric sensitivity studies.