Available online at www.sciencedirect.com

ScienceDirect

Solar Energy 99 (2014) 231–245

SOLAR ENERGY

www.elsevier.com/locate/solener

An evaluation of heat transfer and effectiveness for unglazed transpired solar air heaters

Michael R. Collins *, Hani Abulkhair [1]

Department of Mechanical and Mechatronics Engineering, University of Waterloo, 200 University Ave. West, Waterloo, Ontario N2L 3G1, Canada

Received 8 April 2013; received in revised form 5 November 2013; accepted 14 November 2013
Available online 14 December 2013

Communicated by: Associate Editor Yanjun Dai

Abstract

The use of Unglazed Transpired Solar Collectors (UTSCs) is considered to be one of the most effective methods of reducing HVAC loads in buildings. The operation of the UTSC is relatively simple. A perforated absorber plate is installed in a location where it is exposed to solar radiation. Air is drawn through the perforations, and into the fresh air intake of an HVAC system. This pre-warmed air could make a significant contribution towards decreasing the energy used for heating. Unfortunately, commercially available UTSC products are no longer geometrically similar to the products used to produce correlations used by designers for estimating heat loss and effectiveness. The intent of the current investigation, therefore, is to numerically investigate modern UTSC system performance. Numerical development was successful, and the model was validated by comparison to existing experiments and correlations. An experimental investigation, however, is still required to provide formal validation. Correlations for heat loss and effectiveness have been developed.

Keywords: Solar air heater; Transpired plate; Effectiveness; Numerical model

1. Introduction

In recent years, the environmental impact and availability of energy sources has become increasingly important. It is also recognized that while the development of new energy sources is important, so too is an effort towards energy conservation and smarter energy use. Buildings have long been considered a primary focus for energy efficiency, with the most recent efforts aimed at the concept of a net zero energy buildings.

The amount of energy used to heat buildings in North America is significant. Surveys have shown that space heating in 2010 was the largest energy use in residences in both the US and Canada at approximately 45% and 62%, respectively (D&R International 2006, NRCan, 2013). In the commercial sectors, these percentages are lower at 20% and 45%, respectively, but still significant.

The use of Unglazed Transpired Solar Collectors (UTSCs) is considered to be one of the most effective methods of reducing HVAC loads in buildings (Fig. 1). A UTSC system generally consists of a perforated and blackened absorber plate and a plenum (the area between the back wall and the plate). The operation of the UTSC is relatively simple. The absorber plate is installed in a location where it is exposed to solar radiation; heating the plate and surrounding air. The air is drawn through the perforations, into a plenum, and then into the fresh air intake of an HVAC system. This pre-warmed air could make a significant contribution towards decreasing the energy used for heating. There are two main advantages to this type of solar collector. First, the air is sucked directly through the perforations which make the surface of the absorber operate at a relatively low temperature. Consequently, heat loss will

* Corresponding author. Tel.: +1 519 888 4567x33655.
E-mail address: mike.collins@uwaterloo.ca (M.R. Collins).
[1] Present address: Department of Mechanical Engineering at Concordia University, Montreal, Canada.

0038-092X/$ - see front matter
http://dx.doi.org/10.1016/j.solener.2013.11.012

Nomenclature

α	thermal diffusivity (m^2/s)
A	area (m^2)
A_{abs}	absorber area (m^2)
A_h	hole area (m^2)
C_p	specific heat (J/kg K)
D	perforation diameter (m)
D_h	hydraulic diameter (m)
δ_∞	velocity boundary thickness (asymptotic region) (m)
Δ_∞	thermal boundary thickness (asymptotic region) (m)
ε	effectiveness (dim)
k	plate conductivity (W/m K)
L_e	thermal starting length (m)
L_s	velocity starting length (m)
μ	dynamic viscosity (kg/m s)
$\dot{m}$	mass flow rate (kg/s)
Nu	Nusselt number (dim)
Nu_D	Nusselt number (based on hydraulic diameter) (dim)
Nu_{hl}	Nusselt number for heat loss, dim
p	pressure (kPa)
P	perimeter (m)
Pr	Prandtl number (dim)
q'_{dev}	energy change in developing region (W/m)
$q'_{dev,flat}$	energy change in developing region of a flat plate (W/m)
ρ	density (kg/m^3)
Re_D	Reynolds number (based on hydraulic diameter) (dim)
Re_s	Reynolds number (suction parameter) (dim)
S	perforation spacing (m)
t	plate thickness (m)
T	temperature (K)
T_{abs}	absorber temperature (K)
T_{in}	plenum temperature (K)
T_∞	ambient temperature (K)
u	velocity in x-dir (m/s)
U	thermal transmission (W/m K)
U_∞	free stream velocity (m/s)
v	velocity in y-dir (m/s)
ν	kinematic viscosity (m^2/s)
V_o	suction velocity (m/s)
w	velocity in z-dir (m/s)
x	x-direction
y	y-direction
z	z-direction

be small. Moreover, because there is no need for a glazing cover, the capitol cost and installation of the USTCs are more favorable than other types of solar heaters.

To effectively design UTSC systems, one must have an understanding of the fluid flow, heat transfer, and heat exchanger characteristics of the system. These characteristics need to be understood as a function of ambient wind velocities and suction rates. In this regard, many studies have been made on UTSCs. None, however, were based on a geometry that is currently available to consumers. The aim of the present work is to re-evaluate some of the existing design correlations with consideration of the UTSC geometry currently employed by industry.

2. Background

When considering forced flow over a flat plate (without suction), velocity boundary layer growth can be characterized generally. At the fluid–plate interface, the fluid is assumed to have zero velocity. This fluid layer restricts fluid motion in the adjacent layer through shear stresses. Therefore, the fluid velocity increases as one moves away from the plate to such a point where the plates' influence is negligible, and the free stream velocity is attained. Initially, the boundary flow exhibits laminar behavior and grows with distance from the leading edge of the plate. Transition to turbulence occurs further downstream, depending on the flow velocity and fluid properties, at which point the velocity boundary layer continues to grow.

When homogenous suction occurs, the velocity boundary layer is 'sucked' through the plate. As a result, its thickness is decreased, depending on the ratio of free stream velocity to suction velocity (the average velocity of air flowing through the plate in relation to its entire surface area). If the suction velocity is great enough, the transition to turbulence will not occur and boundary layer growth stops completely (called the asymptotic region). This situation was studied analytically by Schlichting (1979). In that work, it was shown that the minimum suction velocity, V_o, for asymptotic behavior occurred at:

$$V_o = 1.24 \times 10^{-4} U_\infty \tag{1}$$

where U_∞ is the free stream velocity. It is important to note that the suction velocity is based on the absorber surface area. Arpaci and Larson (1984) also analytically examined flow over a perforated plate with suction. By assuming a parabolic velocity profile, they found that the velocity boundary layer thickness in the asymptotic region, δ_∞, was given by:

$$\delta_\infty = \frac{2\nu}{V_o} \tag{2}$$

where ν is the kinematic viscosity. Kutcsher (1992) followed this by analytically determining the starting length