Available online at www.sciencedirect.com

ScienceDirect

Solar Energy 115 (2015) 708–721

SOLAR ENERGY

www.elsevier.com/locate/solener

Thermal modeling of evacuated tube solar air collectors

Pierre-Luc Paradis [a,*], Daniel R. Rousse [a], Stéphane Hallé [b], Louis Lamarche [b], Guillermo Quesada [a]

[a] Industrial Research Chair in Energy Technologies and Energy Efficiency (t3e), École de technologie supérieure, Université du Québec, Montréal, 1100, rue Notre-Dame Ouest, Montréal, Québec H3C 1K3, Canada

[b] École de technologie supérieure, Université du Québec, Montréal, 1100, rue Notre-Dame Ouest, Montréal, Québec H3C 1K3, Canada

Received 29 July 2014; received in revised form 15 February 2015; accepted 20 March 2015
Available online 7 April 2015

Communicated by: Associate Editor Dr. Brian Norton

Abstract

This paper presents a one dimensional thermal model of a solar evacuated tube open at both ends under transient conditions. Variations of fluid mass flow rate, ambient temperature, solar radiation, and wind speed are accounted for. The semi-analytical model relies on the energy conservation equation for small control volumes along the longitudinal axis of the tube. The first order differential equations obtained for each control volume are solved by use of a fully explicit scheme using a fourth order Runge–Kutta algorithm. An experimental setup has been designed, built and calibrated in order to assess the predictions provided by the model. The comparison between simulated and experimentally measured outlet air temperatures showed a good agreement: a root mean square error on the outlet air temperature of about 0.50 K and a mean bias difference of 0.15 K were observed for experiments conducted on a bright sunny day. The validated model applied for steady state heat transfer is then used to conduct an analysis on different parameters. Finally, the influence of the environmental parameters (solar radiation, ambient temperature and wind speed) and the operating condition (airflow) is investigated on different performance indicators like the outlet air temperature, the efficiency, the mean convective heat transfer coefficient and the pressure drop. It appeared that the influence of wind and ambient temperatures is of minor importance although the influence of solar radiation on the outlet air temperature is significant. Moreover, the airflow is the most important parameter acting on the defined performance indicators. Higher is the airflow, better is the efficiency and lower is the outlet air temperature. On the other hand, a low airflow can conduct to as much as 100 K of temperature gain, but the efficiency is then reduced to value as low as 45%.

Keywords: Solar collector; Evacuated tube; Solar thermal; Air

1. Introduction

In Canada, more than 50% of the energy consumption in residential, institutional and commercial sectors is related to space heating and domestic hot water (Ressources naturelles Canada, 2011). Furthermore, in Quebec where most of the electricity is produced by hydro power available at low cost, a large part of this heat (low quality energy) is produced with electricity (high quality energy). Despite that hydro power is a renewable source of energy, use of high grade energy to produce low temperature heat for domestic hot water and space heating is wasteful. Instead, this heat could be produced with solar thermal collectors with a high level of efficiency thus reducing the peak power demand. Several different solar collectors are available on the

* Corresponding author. Tel.: +1 514 396 8800x7503.
E-mail addresses: pierre-luc@t3e.info (P.-L. Paradis), daniel@t3e.info (D.R. Rousse), stephane.halle@etsmtl.ca (S. Hallé), louis.lamarche@etsmtl.ca (L. Lamarche), guillermo@t3e.info (G. Quesada).

http://dx.doi.org/10.1016/j.solener.2015.03.040

Symbols

A	projected surface area of the tube[m^2]
c_p	specific heat [J/kg K]
D	tube outside diameter [m]
d	glass tube thickness [m]
f	friction factor [–]
G	total horizontal solar radiation [W/m^2]
G_r	reflected solar radiation [W/m^2]
G_T	total tilted solar radiation normal to the plane of the collector [W/m^2]
i	time step [–]
j	node along the tube axis [–]
L	tube length [m]
m	mass [kg]
$\dot{m}$	mass airflow rate [kg/s]
n	number of nodes [–]
Nu	Nusselt number [–]
P	pressure [Pa]
Pr	Prandtl number [–]
$\dot{Q}$	thermal power transferred to the fluid [W]
R	thermal resistance [K/W]
Re	Reynolds number [–]
T	temperature [K]
u	air velocity [m/s]
$\dot{V}$	volumetric airflow rate [m^3/s]

Greek symbols

α	absorptivity of the absorber [–]
Δx	length of a node along the tube axis [m]
ε	emissivity [–]
η	efficiency [%]
ρ	density [kg/m^3]
τ	transmissivity of the glass [–]

Subscripts

a	ambient
c	cover tube (outer tube)
conv	convection heat transfer
dyn	dynamic pressure
exp	experimental data
f	fluid (air)
g	glass
in	inner tube/tube inlet
inlet	tube inlet
out	outer tube/tube outlet
outlet	tube outlet
r	receiver tube/absorber tube (inner tube)
ray	radiative heat transfer
sim	simulated data
sky	sky
useful	useful
wind	wind

Abbreviations

CFD	computational fluid dynamics
CFL	Courant–Friedrichs–Lewy condition for stability of the resolution algorithm
c.v.	control volume
HTC	heat transfer coefficient
SRCC	Solar Rating Certification Corporation

market. Most of them use liquid heat transfer fluid to carry the heat from the solar collector to a heat storage tank. However there are few difficulties associated with the installation of solar thermal technology in cold climates such as in Canada. In locations subject to freezing of water in winter, glycol is usually employed to protect piping against bursting for standard technologies such as flat-plate collectors. However, glycol has a lower specific heat than water and a higher viscosity which requires larger volumes of fluid and more pumping power. But the worst drawback is that, in summer, the mixture could boil due to combined long exposures (longer days), low hot water demand, and/or no demand due to holiday in a particular dwelling. Then, the mixture could boil in the collectors and could cause glycol degradation. Since glycol replacement is expensive, this problem prohibitively extends payback periods for a solar thermal system, especially in low temperature areas of the globe where the content of glycol in the fluid is high. A study of the *Energy Technology Laboratory* (*LTE*) of Hydro-Québec carried out on 23 solar domestic water heaters installed in Quebec concluded that the average payback time is above 75 years due in part to the replacement of the glycol that should be done almost every year (Moreau and Laurencelle, 2012).

In order to provide a solution to this problem, air could be used as the heat transfer fluid instead of water. Using air, freezing and overheating problems are avoided. Furthermore, air is free, could be used in an open loop system and presents no risk of contamination in case of leakage of the piping. Of course, the heat capacity of air is low compared to that of liquids but nevertheless it is worth trying to design an air-based collector for specific applications despite this drawback. Moreover, as insulation is closely linked to solar collector performance use of solar evacuated tube then makes sense in cold climates to reduce heat losses in winter when the heating demand is highest.

Hence, a novel solar evacuated tube collector using air as the working fluid is currently developed by Technology of Energy and Energy Efficiency Research Chair (t3e) of École de technologie supérieure (ETS) in Montréal, Canada. The design involves tubes that are open at both ends thus allowing “through flow” of fluid from one end to the other. This type of collector is fairly new according to recent reviews. As a starting point, Solar