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Solar Energy 86 (2012) 175–189

SOLAR ENERGY

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Single and two-phase flow modeling and analysis of a coaxial vacuum tube solar collector

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Received 14 April 2011; received in revised form 12 August 2011; accepted 21 September 2011
Available online 20 October 2011

Communicated by: Associate Editor Jayant K. Nayak

Abstract

In this paper, an analytical steady state model is developed to study the thermal performance of an individual vacuum tube solar collector with coaxial piping (direct flow type) incorporating both single and two-phase flows. A system of equations which describe the different heat transfer mechanisms and flow conditions was established, discretised, and solved in an iterative manner. For the case of good vacuum condition (10^{-5} mb) the calculated efficiency curve for single phase flow deviates significantly from the experiments with increasing collector temperature, but agrees well for the case of gas conduction inside the glass envelope at very low pressure ($\ll$1 mb) due to the corresponding increase in overall heat loss coefficient (*U*-value).

For two-phase flow, the occurrence and propagation of flow boiling and condensation inside the collector piping under saturated condition is hypothesized. The modeling results indicate that for all-liquid-single-phase fluid flow, the collector efficiency decreases with decreasing mass flow rate. Once the fluid reaches the boiling point at a certain mass flow rate, no significant reduction in efficiency is observed anymore, which is in accordance with the experimental study.

Keywords: Vacuum tube collector; Single phase flow; Two-phase flow; Boiling and condensation; Collector efficiency

1. Introduction

For certain constant input conditions, as the mass flow rate through an individual direct flow-type vacuum tube collector in a collector panel is reduced the fluid can reach the boiling point at the corresponding pressure, which results in a two-phase fluid flow. This phenomenon is also known as “partial stagnation”. Solar collectors used in high temperature application such as solar cooling, are particularly prone to the occurrence of partial stagnation. Typically vacuum tube collectors are used. So, although there are a large number of research papers regarding the performance of solar collectors including, flat plates, vacuum tubes, heat pipes, concentrating type, etc., but here a selected literature review only related to direct flow type vacuum tube collectors is presented.

Various researchers have analyzed the thermal performance of variety of configurations of vacuum tube solar collectors to estimate the heat extracted and fluid temperature in the collector. Hsieh (1981) developed mathematical formulation to perform a thermal analysis of compound-parabolic concentrator (CPC) having a concentric evacuated double pipe as a heat receiver. Due to the use of selective surface and the vacuum between envelope and receiver, collector shows a very slight drop of efficiency at high operating temperatures. Estrada-Gasca et al. (1992) developed a steady state one-dimensional mathematical model to estimate the theoretical efficiency of an all glass evacuated tube solar collector with an internal or external absorber film deposited on the inner or outer surface of the inner glass cover, respectively. They expressed the variation of

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0038-092X/$ - see front matter
doi:10.1016/j.solener.2011.09.021

Nomenclature

A_{in}	outside surface area of the inner pipe (m^2)
A_{out}	outside surface area of the outer pipe (m^2)
A_{ab}	absorber area (m^2)
A_{ap}	aperture area (m^2)
A_g	glass cover area (m^2)
A_x	flow cross sectional area (m^2)
Bo	boiling number (–)
C_{pf}	specific heat of liquid (J/kg K)
Co	convective number (–)
D_o	outside diameter of outer pipe (mm)
D_i	inside diameter of outer pipe (mm)
d_o	outside diameter of inner pipe (mm)
d_i	inside diameter of inner pipe (mm)
$D_{H,hp}$	hydraulic diameter based on heated perimeter (m)
$D_{H,wp}$	hydraulic diameter based on wetted perimeter (m)
F	fin efficiency factor (–)
F_{p-g}	view factor from absorber to glass (–)
F_c	collector efficiency factor (–)
F_{rf}	Froude number (–)
G	mass velocity (kg/m^2 s)
G_{av}	available solar irradiance (W/m^2)
$h_{r\text{-}t/b\text{-}pg}$	radiative heat transfer coefficient from absorber to glass cover from top or bottom (W/m^2 K)
$h_{r\text{-}t/b\text{-}ga}$	radiative heat transfer coefficient from glass cover to ambient from top or bottom (W/m^2 K)
$h_{c\text{-}t/b\text{-}pg}$	convective heat transfer coefficient from absorber to glass cover from top or bottom (W/m^2 K)
$h_{c\text{-}t/b\text{-}ga}$	convective heat transfer coefficient from glass cover to ambient from top or bottom. (W/m^2 K)
h_{fi}	single phase all-liquid-flow heat transfer coefficient in the inner pipe (W/m^2 K)
h_{fo}	single phase all-liquid-flow heat transfer coefficient at the inner wall of annulus or outer wall of inner pipe (W/m^2 K)
$h_{f,outer}$	single phase all-liquid-flow heat transfer coefficient at the outer wall of annulus (W/m^2 K)
h_{fg}	enthalpy of vaporization (J/kg)
h_f	enthalpy of saturated fluid (J/kg)
h	enthalpy of fluid (J/kg)
h_c	convective heat transfer coefficient (Eq. (31)) (W/m^2 K)
h_f	superficial heat transfer coefficient (W/m^2 K)
h_{NcB}	nucleate boiling heat transfer coefficient (W/m^2 K)
$h_{tp\text{-}boil}$	boiling heat transfer coefficient (W/m^2 K)
$h_{tp\text{-}cond}$	condensation heat transfer coefficient (W/m^2 K)
k	thermal conductivity of copper (W/m K)
k_f	thermal conductivity of fluid (W/m K)
L_{ab}	length of absorber sheet (mm)
$\dot{m}$	mass flow rate of fluid (kg/s)
M	specific mass flow rate (kg/m^2 h)
Nu	Nusselt no.
P_{gas}	gas pressure inside glass envelope (mb)
P_{heated}	heated perimeter (m)
Pr_f	Prandtl no. of liquid (–)
$Q_{f\text{-}outer}$	heat gain of the fluid in the outer pipe (W)
$Q_{f\text{-}inner}$	heat gain of the fluid in the inner pipe (W)
Q_{abs}	heat absorbed on the absorber plate (W)
$Q_{f\text{-}net}$	overall net heat gain of fluid (W)
Re	Reynolds number (–)
Re_e	equivalent Reynolds no. (Eq. (38)) (–)
T_{fi}	temperature of fluid at inlet to collector (K)
T_{fo}	temperature of fluid at outlet of collector (K)
T_{pm}	mean absorber plate temperature (K)
$T_{fm\text{-}outer/inner}$	bulk mean temperature of the fluid in the outer or inner pipe (K)
T_m	arithmetic mean of the fluid temperature at the inlet and outlet of the collector tube (K)
T_a	ambient temperature (K)
$T_{g\text{-}t/b}$	glass cover temperature of the top or bottom portion above or below the absorber (K)
T_{sat}	saturated temperature of fluid (K)
$T_{fi\text{-}outer/inner\text{-}i}$	fluid temperature at the inlet of outer or inner pipe element i ($i = 1, 2, 3, \ldots, n$) (K)
$T_{fo\text{-}outer/inner\text{-}i}$	fluid temperature at the outlet of outer or inner pipe element i ($i = 1, 2, 3, \ldots, n$) (K)
t_{ab}	thickness of absorber sheet (mm)
U	overall heat loss coefficient (W/m^2 K)
U_t	top heat loss coefficient (W/m^2 K)
U_b	bottom heat loss coefficient (W/m^2 K)
U_o	overall heat transfer coefficient (W/m^2 K)
V_{air}	velocity of air (m/s)
W	width of absorber (mm)
x	vapor quality (–)
Y	area correction factor (Eq. (6)) (–)
ΔT_m	mean fluid temperature difference in the outer and inner pipe (K)

Greek symbols

Φ	surface heat flux (W/m^2)
ε_g	emissivity of the glass (–)
ε_p	emissivity of the absorber surface coating (–)
ε_c	emissivity of the copper (polished) (–)
η_c	collector efficiency based on aperture area (–)
$\tau\alpha$	effective transmittance–absorptance product (–)
σ	Stephen Boltzmann constant (W/m^2 K^4)
ρ_f	density of liquid (kg/m^3)
ρ_g	density of vapor (kg/m^3)