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Mathematical modelling and simulation of multiphase flow in a flat plate solar energy collector

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ABSTRACT

Non-conventional collectors where organic fluid or refrigerant experience a phase change have many advantages over conventional collectors which have either air or relatively high temperature boiling liquid. Increase in heat transfer coefficient and system efficiency, corrosion prevention and freeze protection are the main benefits of the first type. In this study, a detailed numerical model of a flat plate collector is developed to investigate the fluid mean temperature, useful heat gain and heat transfer coefficient along the collector tube. The refrigerant HFC-134a was used in the simulation as the working fluid of the collector. The model can both predict the location where the fluid undergoes a phase change in the tube and the state at the exit under given inlet conditions. The effect of boiling on the heat transfer coefficient of the fluid is also investigated. Simulations were performed at three different mass flow rates (0.001, 0.005 and 0.01 kg/s) and three different operating pressures (4, 6 and 8 bar) to be able to see the effect of mass flow rate and pressure on plate temperature, heat loss coefficient, efficiency of the collector and the heat transfer coefficient of the fluid. The simulation results indicate that the heat transfer coefficient of the fluid increases from 153.54 W/m^2 K to 610.27 W/m^2 K in multiphase flow region. In the liquid single phase region, the collector efficiency rises from 60.2% to 68.8% and the heat transfer coefficient of the fluid increases from 39.24 W/m^2 K to 392.31 W/m^2 K with an increased flow rate whereas the collector efficiency decreases from 72.5% to 62.3% as the operating pressure increases from 4 bar to 8 bar. In order to validate the simulation model an experimental test rig was built and the experiments were performed with HFE 7000 as working thermo-fluid. A new simulation model utilizing HFE 7000 has been developed and the outlet temperature of the fluid was compared with the measured outlet temperature. Both measured and simulated results have shown close conformity.

1. Introduction

Utilization of fossil fuels has caused many problems such as the release of CO_2 to the atmosphere and its subsequent effects on our environment. This can be changed if our dependence is decreased on fossil fuels by using alternative renewable energy sources [1]. Due to its lower impacts on environment solar energy can be considered as one of the most favourable option to contribute to the energy demand with extensive applications in industry [2]. There has been an upward trend in various kinds of solar energy harvesting systems. A dynamic model of a solar pond was developed in order to investigate the effect of the sunny area ratios on the efficiency by [3]. Experimental and simulation studies on the thermal performance of a room heated with an attached sunspace were conducted by [4]. The thermal behaviour of volumetric solar receiver with double-layer of porous media and the effects of geometry of each layer on the performance was numerically studied by [5]. Dehghan et al. [6] analysed the effect of radiation heat transfer on forced convective heat transfer mechanism through cellular porous media confined by two parallel plates. The plates subjected to constant heat flux and the Darcy–Brinkman equation was utilized to model the flow through the porous medium [6]. In another study the effects of thermal radiation on the forced convection through cellular porous media considering a combined conductive–convective–radiation heat transfer model were studied by [7].

Solar collectors which convert solar energy into heat produce either hot water or air depending on the working fluid of the collector [8]. Recently, many studies have focused on increasing the efficiency of solar water heaters. An experimental study to investigate the effect of using a mixture of ethylene glycol and copper nanoparticles as a working fluid on the collector efficiency was conducted by [9]. In another study it is reported that using

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Nomenclature

A_p	collector plate area, m^2
Bo	boiling number
C_b	bond conductance
C_p	specific heat of the working fluid, J/kg K
Co	convection number
D	tube diameter, m
D_i	tube inner diameter, m
D_o	tube outer diameter, m
f	friction factor
F	fin efficiency
F_R	collector heat removal factor
Fr	Froude number
G	mass flux, kg/m^2 s
h	heat transfer coefficient, W/m^2 K
H	enthalpy, J/kg
H_{fg}	heat of vaporization, J/kg
k	thermal conductivity, W/m K
L	Length, m
$\dot{m}$	mass flow rate, kg/s
N	dimensionless parameter
N_c	number of glass cover
Nu	Nusselt number
P	pressure, bar
Pr	Prandtl number
Q_{gain}	heat gain of the fluid, W
Q_l	heat loss, W
Q_u	useful heat, W
Q''_u	useful heat rate, W/m^2
Re	Reynolds number
S_{in}	incoming solar radiation, W/m^2
T	temperature, K
U_{back}	heat loss coefficient for the back of the collector, W/m^2 K
U_{edge}	heat loss coefficient for the edge of the collector, W/m^2 K
U_{top}	heat loss coefficient for the top of the collector, W/m^2 K
U_T	total heat loss coefficient of the collector, W/m^2 K
W	tube spacing, m
x	vapour quality

Subscripts

a	ambient
c	glass cover
col	collector
cb	convective boiling
f	fluid
g	gas
in	inlet
ins	insolation
l	liquid
m	mean
mp	multiphase
nb	nucleate boiling
out	outlet
p	plate
sat	saturation
sp	single phase
w	wind
wf	working fluid

Greek symbols

$\tau\alpha$	transmittance-absorbance product
β	collector tilt angle, °
δ	absorber plate thickness, m
ε	emissivity
ρ	density, kg/m^3
σ	Stefan–Boltzmann constant, W/m^2 K^4
ψ	enhancement factor
μ	dynamic viscosity, kg/m s
Φ	heat flux, W/m^2
η	efficiency, %

Al_2O_3-distilled water nanofluid in the collector increased the thermal efficiency up to 11.7% [10].

Alternatively, collectors using organic fluid or refrigerant provide higher performance than conventional collectors where water or air is used. Because organic fluid or refrigerant undergoes a phase change, this phenomenon increases the heat transfer coefficient of the fluid and leads to an increase in the system performance [11]. Reduced parasitic energy use and freeze protection are the other benefits of such collectors [12].

Collectors using organic fluid or refrigerant can be used for further applications. Evacuated solar collector was used to generate vapour in the solar Rankine system where CO_2 was utilized as the working fluid [13]. Marion et al. [14] conducted both theoretical and experimental studies to indicate the potential mechanical energy generation by using solar thermal collectors which are combined with an organic Rankine cycle (ORC). The system was simulated for three organic fluids R134a, R227ea and R365mfc and the simulation model was validated against experiments using glycol–water mixture [14]. An optimization study of a solar organic Rankine cycle was conducted by [15]. In this study authors considered various models of stationary solar collectors such as a flat-plate collector, compound parabolic collector, and evacuated tube collector. Twelve substances, including dry, wet and isentropic organic fluids were taken into account as working fluids of the system and aperture area of the collector needed per unit of mechanical power output of the cycle was considered as a comparison criteria for different operating conditions of ORC [15]. Wang et al. [16] carried out an experimental study of a low-temperature solar Rankine cycle system where flat plate collectors are used. Pure R245fa, zeotropic mixture of R245fa/R152a (0.9/0.1) and another mixture of R245fa/R152a, (0.7/0.3) were considered in the analyses [16]. An experimental study of a solar thermal system utilizing R245fa was conducted by [17]. Two stationary collectors which are evacuated tube and flat-plate collector were used in the experiments. Results showed that collector efficiencies of evacuated tube and solar collector were found 71.6% and 55.2% respectively [17].

Solar collectors using organic refrigerants also have been utilized in solar assisted heat pump systems. The thermal performance of direct expansion solar assisted heat pump system using two collector configurations which are bare collector and one cover collector were analysed in [18]. Several refrigerants were used to analyse the performance of the system. Authors reported that R-12 gives the highest performance value, followed by R-22 and R-134a [18]. Zhang et al. [19] studied the effects of refrigerant charge, solar collector area and solar collector thickness on the thermal performance of direct-expansion solar assisted heat pump system [19]. Solar assisted heat pump system for low temperature water heating application where solar collector is used as the evaporator of the heat pump was investigated by [20]. A simulation model in order to show the potential use of solar assisted heat pump system for hot water production was conducted by [21]. Authors found that the system can achieve a higher performance than conventional heat pump system [21].