ARTICLE IN PRESS

Renewable and Sustainable Energy Reviews xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Heat transfer augmentation in solar thermal collectors using impinging air jets: A comprehensive review

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ARTICLE INFO

Keywords:
Solar thermal collector
Jet impingement
Heat transfer
Friction factor
Multi criteria decision making

ABSTRACT

Jet impingement has led to considerable augmentation in heat transfer characteristics of solar thermal collectors. The impinging air jets are characterized by different control factors where it becomes essential to study their dependence on performance defining criteria so as to arrive at the optimized impinging jet geometry which create one or combination of following conditions favorable for heat transfer with minimal friction losses inside the collector: (a) breaking laminar sub layer (b) increasing turbulent intensity (c) increasing heat transfer area, and (d) generating vortex or secondary flows. The present article examines the thermodynamic behavior of solar thermal collector, review the experimental investigations reported in the literature to study the dependence of control factors on heat transfer and friction characteristics and review the multi criteria decision making methods towards optimization of control factor combinations for an optimal design of the impinging jet solar thermal collector. This study provides a platform for scientists working in the same research field to design a better heat transfer enhancement contrivance in the form of jet control factors to improve the thermohydraulic performance by maximizing the energy output from the system.

1. Introduction

The future energy demands are increasing both on account of increase in population and standard of living in various parts of globe which has made the human minds to focus the need for alternate energy options available. Clearly, humankind has to set a different course in its need for energy, one that involves less intrusive sources such as solar, wind and geothermal energy. They are the energy sources which do not harm the planet and will never run out. It needs to be again in the crucial areas of energy and the environment in order to assure sustainability for future generations. Solar energy can be used to meet various future energy requirements and is enduring source of energy which is also environmental friendly. The solar thermal collector possesses a significant position amongst solar thermal systems ever since it is extensively used in numerous commercial applications such as to supply hot air to the buildings, industrial and agricultural drying etc. [1]. The solar thermal collectors possess low value of thermal efficiency because of lower convective coefficient of heat transfer between the heated absorber plate surface and the air which increases in the temperature of the system leading to elevated heat losses from the collector and finally lowers its thermal efficiency [2]. The heat from the absorber plate is to be convected efficiently to the air flowing underneath it to augment its overall performance. The lower value of convective coefficient of heat transfer in general is attributed by the existence of viscous sub layer, which has to be wrecked or disturbed so that maximum heat transfer may be achieved by several methods [3]. Also, the performance improvement of solar collectors has been in progress using various other improvements experimentally and analytically [4,5]. Jet impingement over the heated absorber plate marginally improves the convective coefficient of heat transfer because of very thin boundary layer formation compared to parallel air flows [6]. Jet impingement has proved its effectiveness in number of engineering and industrial applications [7–11]. Several authors have studied the heat transfer characteristics of single/multiple jet arrays. Singh et al. [12] performed experimentations to study the flow and heat transfer characteristics of air jet impingement cooling of heated circular cylinder which was maintained at constant heat flux conditions. Luhar et al. [13] performed steady state modeling of non-uniform convective cooling using jet impingement on a microprocessor chip. In their study, the thermal performance in steady and transient conditions were modeled and helped in improving the thermal design and microprocessor optimization. Wang et al. [14] performed an experimental investigation to study the

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http://dx.doi.org/10.1016/j.rser.2017.10.025
Received 29 December 2016; Received in revised form 6 July 2017; Accepted 26 October 2017
1364-0321/

Please cite this article as: Chauhan, R., Renewable and Sustainable Energy Reviews (2017), http://dx.doi.org/10.1016/j.rser.2017.10.025

Nomenclature

A_p	Area of absorber plate, m^2
C_p	Specific heat of air, J/kg K
D_h	Hydraulic diameter of the rectangular duct, m
E_n	Net exergy flow, W
E_s	Exergy inflow associated with solar irradiation collector, W
f	Friction factor
F_R	Collector heat removal factor
F'	Collector efficiency factor
G	Mass velocity of air, kg/m^2 s
H	Height of the rectangular duct, m
I	Solar radiation intensity, W/m^2
L	Length of test section, m
$\dot{m}$	Mass flow rate, kg/s
P_m	Pumping power, W
$(\Delta P)_d$	Pressure difference across the test section, N/m^2
Q_u	Rate of useful energy gain by solar collector, W
T_{fi}	Temperature of inlet fluid, K
T_{fo}	Temperature of outlet fluid, K
T_{pm}	Mean plate temperature, K
T_{fm}	Mean fluid temperature, K
T_{sun}	Temperature of sun, K
T_a	Ambient air temperature, K
U_L	Overall heat loss coefficient
V	Velocity of air in the duct, m/s
W	Width of the rectangular duct, m

Greek symbols

ρ_a	Density of air, kg/m^3
η_{eff}	Effective efficiency
η_{exr}	Exergetic efficiency
η_{eff}	Thermal efficiency
η_c	Carnot efficiency
$\tau\alpha$	Transmittance absorptance product

effect of vortex generators on heat transfer placed in the cross flow channel upstream of the jet exit. Bu et al. [15] studied jet impingement heat transfer for aircraft wing anti-icing application using Piccolo tube having aligned jet holes. The parametric effects of impingement heat transfer were revealed in the study and determined optimum tube to surface distance. Hosain et al. [16] studied the heat transfer by turbulent water jets impinging on hot flat steel plates at temperature lower than the boiling point so as to understand the convective heat transfer phenomenon. Aboghrara et al. [17] performed experimental investigation to study the dependence of geometrical parameters on efficiency of jet impingement onto the corrugated heat absorbing surface. They reported 14% more efficiency than conventional design at mass flow rate of 0.01–0.03 kg/s. Huang et al. [18] studied the effect of Reynolds number varied between 800 and 1700 of mixture of air/butane and the distance between nozzle and plate on heating performance of the flame. Craft et al. [19] modeled flow and heat transfer from a row of round jets impinging onto a concave semicircular surface to reproduce important flow features found in internal turbine blade cooling applications. Hasan et al. [20] carried out experimental investigation of jet array impingement using nano-fluids on the photovoltaic thermal collector which resulted in higher electrical and thermal performances. In the entire above research studies the objectives have been concerted in investigating the characteristics of heat transfer and friction behavior related to the particular application. The enhancement in heat transfer is accompanied by generous increase in frictional losses inside the fluid flow channel [21] and both of these factors depend upon the geometric configuration and operating flow Reynolds number.

Several investigations have been carried out by the researchers and scientists using impinging air jets in solar thermal collectors and thus, there is need to review the past and current research so that the further research scopes can be identified and implemented. The present article is thus aimed with following objectives:

(a) To carry out thermodynamic modeling of solar thermal collector based upon effective and exergy efficiency criterion.
(b) To study the augmentation in heat transfer and fluid friction using impinging air jets in solar thermal collector passage.
(c) To study the potency of multi criteria decision making methodologies for successful implementation in solar thermal collectors.
(d) To discuss the scope for further research in solar thermal air collectors using impinging air jets towards maximizing energy efficiency.

In order to achieve the desired objectives, the article is structured batch wise for each objective clearly addressed and explained in their respective context. Firstly, the thermodynamic framework has been performed based upon the first and the second law of thermodynamics, in terms of effective and exergy efficiency respectively. Secondly, the heat transfer distribution and friction behavior of the impinging air jets in a solar thermal fluid flow passage have been reviewed; above and beyond the heat transfer augmentation methods by variation in the control factors of the impinging jets are presented. Thirdly, the multi criteria decision making methods for optimization of control factor combinations have been procedurally explained in detail so as to provide the fellow researchers with all the valuable information at one place. Lastly, the scope for further research has been discussed so as to maximize effective energy delivery while minimizing the friction losses inside the collector channel.

2. Solar thermal collector

Solar thermal collector is a kind of heat exchanger that transforms solar radiation energy into internal energy of the transport medium. The schematic diagram of conventional solar thermal collector is as shown in Fig. 1.

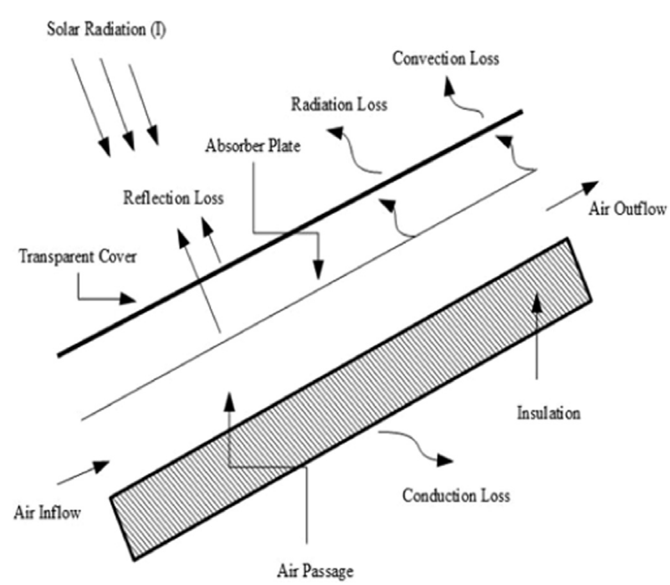

Fig. 1. Schematic diagram of conventional solar thermal collector [22].