ARTICLE IN PRESS
Journal of King Saud University – Engineering Sciences (2016) xxx, xxx–xxx

King Saud University
Journal of King Saud University – Engineering Sciences
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ORIGINAL ARTICLES

Exergy based modeling and optimization of solar thermal collector provided with impinging air jets

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Received 12 March 2016; accepted 12 July 2016

KEYWORDS
Solar thermal collector;
Jet impingement;
Exergy;
Heat transfer;
Optimization

Abstract The irreversible absorption of solar energy accompanied by emission for conversion into thermal energy takes place at the cost of exergy losses from the collector and the effectiveness of this conversion is evaluated in terms of exergy efficiency based upon second law of thermodynamics. Presented in this paper is the exergetic efficiency of impinging jet solar thermal collector and its comparison with that of conventional solar collector. The effect of flow Reynolds number, jet diameter, streamwise and spanwise pitch between the jets on exergetic efficiency of impinging jet solar air collector during conversion of solar energy into thermal energy has been studied based upon the correlations developed for heat transfer coefficient and friction factor in the range of investigated flow and geometric parameters. The results reveal that the impinging air jets extract the absorbed exergy from the absorber to the air flowing beneath with higher efficiency than that of the conventional solar air collector. Also, the design plots have been prepared for jet plate parameters with temperature rise parameter in order to obtain an optimum parameter values that would deliver maximum exergetic efficiency for desired value of temperature rise. Design procedure has also been discussed to evaluate the optimum parameters with respect to operating conditions.

1. Introduction

The thermal conversion process of solar energy is based upon the well known phenomenon of heat transfer. Solar energy utilization system is used to trap the available solar energy and convert it into useful forms depending upon the need (Raju and Narayana, 2016; Chauhan et al., 2016; Panchal, 2015; Krishnananth and Murugavel, 2013; Almasoud and Gandayh, 2015; Alaudeen et al., 2014). The efficiency of the solar energy utilization system depends upon the solar insolation; the degree to which the sunlight is concentrated; measures taken to reduce the heat losses from the system and the heat transfer phenomenon through which the heat is transferred to the working fluid. Solar air collector is a simplest form of solar energy conversion system in which the solar radiation

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Peer review under responsibility of King Saud University.

ELSEVIER Production and hosting by Elsevier

http://dx.doi.org/10.1016/j.jksues.2016.07.003
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energy is transformed into thermal energy which is extracted by the air flowing under the absorbing surface.

The commercial viability of solar air collectors mainly depends upon their thermal performance and cost effectiveness with most studies suggesting that the key parameter to enhance the solar collector performance is the rate of heat transfer between the solar energy absorbing surface and the flowing air (Kumar and Rosen, 2011). The information regarding its thermal efficiency is useful for existing and projected future solar energy system design methods. The solar air collectors are generally used for low and moderate temperature requirements such as supplying hot air to buildings, agricultural and industrial drying etc. (Bansal, 1999). Numerous studies have been reported in the literature for heat transfer enhancement in solar air collectors (Shokouhmand et al., 2009; Al-Dabbas, 2015; Chauhan and Thakur, 2014). Impinging air jets helps in increasing the thermal performance of solar collector by increasing the convective heat transfer coefficient from heated absorber surface to the air impinging over it. Impinging air jets released against the heat transferring surface transfer large amount of thermal energy as the impingement boundary layers are much thinner and also the spent fluid after impingement serves to turbulate the surrounding fluid (Zuckerman and Lior, 2006). The other heat transfer applications where jet impingement has proved its superiority are turbine blades (Han, 2004), micro-channel chip cooling (Kandlikar and Bapat, 2007), solar heat absorbers (Roger et al., 2005) etc. Heat transfer using impinging air jets has received considerable research attention in recent years due to high heat transfer rates that occurs in the impingement region and is an active area of research (Meola, 2009).

However, the literature is found deficient with exergetic optimization studies related to solar air collector provided with impinging air jets. Since, it is desirable that high rates of heat transfer achieved using jet impingement should employ minimum power requirement for propelling the air through the collector duct, therefore the exergy based optimization has been employed for this purpose in order to evaluate by what means is impinging jet solar air collector cost effective than the conventional air collector. The method of exergy analysis is regarded as an essential tool for predicting the solar collector performance as it measures the maximum work potential a system can deliver with minimum energy input. This study therefore presents second law optimization in terms of exergetic efficiency of impinging jet solar air collector which takes into account the pumping power required to maintain the desired flow rate through the collector duct with simultaneous consideration over the useful heat energy extracted by convection mechanism. The effect of different jet plate parameters viz. jet diameter, streamwise and spanwise pitch each normalized by the hydraulic diameter of the duct on exergetic efficiency has been carried out along with conventional solar collector. Based upon the results, design plots for each jet plate parameter have been plotted and also design procedure has been discussed in order to arrive at optimum value of jet parameters for desired value of temperature rise.

2. Exergy analysis

The first law efficiency is a common measure of energy use efficiency concerned with quantity of energy and disregards the form in which energy exists. The second law provides a means of assigning a quality index to energy. Exergy analysis is an assessment technique for systems and processes based upon the second law of thermodynamics and defined as the maximum work potential which can be obtained from a form of energy (Bejan, 1988). The irreversibilities such as friction, heat transfer through a finite temperature difference, mixing, non-quasi-equilibrium compression or expansion always generate entropy and anything that generates entropy always destroys exergy. The exergy destroyed represents the lost work potential and is also called the irreversibility or lost work (Cengel and Boles, 2008). Exergy analysis yields useful results as it deals with irreversibility minimization or maximum exergy delivery, thereby ensuring the most efficient possible conversion of energy for the required task (Lior and Zhang, 2007). Exergy analysis has proved to be a powerful tool in the thermodynamic analysis of energy systems.

The exergy flow diagram of solar air collector is as shown in Fig. 1. The measure of quality of energy involved in a solar collector can be accounted by incorporating the quality of useful energy output and frictional losses along with the other losses occurring inside the solar collector duct. Altfeld et al. (1988) proposed a method based upon second law of thermodynamics for establishing the equivalence of useful energy output and frictional losses in solar air collector. The exergetic efficiency can be expressed as:

$$\eta_{exr} = E_n/E_s \tag{1}$$

In the above equation, the net exergy flow is the increase of exergy flow of air while flowing through the collector and is to be maximized for optimization. The exergy flow is defined as:

$$E_n = IA_p\eta_{th}\eta_c - P_m(1-\eta_{ct}) \tag{2}$$

The first term on the right side of Eq. (2) represents the exergy of absorbed solar energy which is transferred to the flowing air and the second term represents the exergy losses due to friction. The exergy losses due to absorption of irradiation are high enough and also the losses due to heat transfer to fluid, heat transfer to environment and losses due to friction impacts the exergy transfer to the working fluid. The exergy inflow associated with solar irradiation on the surface of the solar collector is given by:

$$E_s = I \times A_p(1 - T_a/T_{sun}) \tag{3}$$

Substituting the values of (E_n) and (E_s) from Eq. (2) and Eq. (3) in Eq. (1), the exergetic efficiency can be computed. As in the Eq. (1) the term in the denominator is constant, thus the exergetic efficiency of the system can be maximized by maximizing the numerator term (E_n) which can be done by minimizing the exergy losses taking place in solar air collector.

3. Mathematical approach

The mathematical model used for computation of the performance of impinging jet solar thermal collector has been discussed to study the variation of flow and geometrical parameters on exergetic efficiency. The important assumptions considered are: steady state condition; negligible heat conduction in the flow direction; negligible edge effects. The range of parameters has been selected based upon the experimental investigation (Chauhan and Thakur, 2013). The performance

Please cite this article in press as: Chauhan, R. et al., Exergy based modeling and optimization of solar thermal collector provided with impinging air jets. Journal of King Saud University – Engineering Sciences (2016), http://dx.doi.org/10.1016/j.jksues.2016.07.003