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Optimization of parameters in solar thermal collector provided with impinging air jets based upon preference selection index method

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ABSTRACT

The present study examines the effect of flow and geometric parameters on the performance of solar thermal collector provided with impinging air jets. The investigation has been carried out in terms of performance defining criterions which are pertinent to determine the optimal design of impinging jet solar thermal collector. The experimental investigation indicated that the impinging air jets enhances the thermal performance but at the same time the friction power penalty also increases which depress the overall performance of the system. In view of this the preference selection index (PSI) approach based methodology has been applied using various performance criterions in order to determine the optimal design of the parameters which deliver maximum thermal performance with minimal increase in friction factor inside the collector duct. The optimum configuration of the parameters obtained as a result of proposed method is: streamwise pitch ratio of 0.435; spanwise pitch ratio of 0.869; jet diameter ratio of 0.065 and flow Reynolds number of 16,000.

1. Introduction

Impinging air jets are recognized method of achieving high heat transfer rates and are employed in many engineering applications such as: cooling of electronic equipments [1], cooling of grinding processes [2], solar heat absorbers [3], turbine blade cooling [4], inside of vehicle windscreen [5], solar air heater [6] etc. In all the above investigations the research objectives have been concentrated in studying the heat transfer and fluid flow characteristics related to the specific applications. The impinging air jets have proved its superiority for enhancement of heat transfer from the heated absorber plate to the air flowing beneath in solar collector duct. However, this increase in heat transfer is also accompanied by substantial increase in the pumping power requirements form the blower attached at the other end to maintain the desired mass flow rate of air in the collector duct. Both these factors are affected by the geometric configuration of solar thermal collector and the flow Reynolds number which have to be optimized so as to obtain a set of parameters which will deliver maximum heat transfer with minimum increase in friction factor. The design and development of the system and operating parameters is therefore complicated in which an optimized coalescence of the interdependent parameters has to be sought. Therefore, the selection of system parameters demands uncomplicated, methodical and reasonable method to guide the design engineers to consider a number of performance criterions and their interrelationships.

The multiple criteria decision making (MCDM) methods are quantitative approaches for solving problems involving a large number of alternatives and performance evaluation criterions and have received open acceptance for application in various areas of science, engineering, management etc. [7–13]. It comprises numerous techniques, namely, grey relation analysis, elimination and choice translating reality, preference ranking organization method for enrichment evaluations, compromise ranking method, technique for order preference by similarity to ideal solutions and analytic hierarchy process which have been successfully used to solve many decision-making problems [7–13]. Although, a number of MCDM methods are available in the literature to enable the designers to gather the preeminent alternative, in most of these methods, the alternative rankings is affected by the criterion weight and are quite strenuous to comprehend and obscure to

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Nomenclature

A_o	Area of orifice meter, (m^2)
A_p	Surface area of absorber plate, (m^2)
C_d	Coefficient of discharge
C_p	Specific heat of air (J/kg K)
D_h	Hydraulic diameter of duct (m)
D_j	Diameter of jet (m)
f_c	Friction factor for conventional solar thermal collector
f_{ij}	Friction factor for solar thermal collector with impinging air jets
h	Heat transfer coefficient (W/m^2 K)
I	Radiation intensity (=1000 W/m^2)
k	Thermal conductivity, W/mK
L	Length of the test section (m)
$\dot{m}$	Mass flow rate (kg/s)
Nu_c	Nusselt number for conventional solar thermal collector
Nu_{ij}	Nusselt number for solar thermal collector with impinging air jets
ΔP	Pressure drop across test section (Pa)
ΔP_o	Pressure drop across orifice plate (Pa)
Q_u	Useful heat gain (W)
T_{fi}	Temperature of fluid at inlet (K)
T_{fo}	Temperature of fluid at outlet (K)
T_{pm}	Mean temperature of absorber plate (K)
T_{fm}	Mean temperature of fluid (K)
v	Velocity of air in the duct (m/s)
X	Streamwise pitch (m)
Y	Spanwise pitch (m)

Greek symbols

ρ_{air}	Density of air (kg/m^3)
β	Ratio of orifice diameter to pipe diameter

implement requiring widespread mathematical sophistication. Compared to all other MCDM methods, the preference selection index (PSI) method is more simplistic to comprehend as it does not involve any relative importance between the criterions and the overall preference value is obtained using the concept of statistics. The beauty of PSI method is that it is helpful in evaluation of optimal alternative where there is conflict in deciding the relative importance between the criterions and involves less numerical calculations [14–16].

The objective of this article is to explore the applicability of PSI method for performance prediction of solar thermal collector provided with impinging air jets. To meet out with this very objective, an experimental investigation has been carried out to determine the heat transfer and friction values based upon which the performance defining criterions will be evaluated. The proposed methodology is discussed which determines the optimum design parameters so as to achieve maximum performance under desired operating conditions. In an impinging jet solar thermal collector the flow and geometric parameters are characterized as Reynolds number, jet diameter ratio, streamwise pitch ratio and spanwise pitch ratio. The performance evaluation criterions such as thermal enhancement factor, friction enhancement factor, performance index and effective efficiency are apposite to determine the optimal configuration for the system [17–26]. This paper therefore explores the applicability of a novel MCDM method which deals with the decision making problems in the design stage of impinging jet solar thermal collector.

2. Experimental details

The heat transfer and friction characteristics of impinging air jets onto the heated absorber surface have been studied for the set of flow and geometric parameters and the data for Nusselt number and friction factor was recorded. Fig. 1 shows the photographic view of experimental test rig used for investigation and optimization of the respective parameters in a rectangular duct provided with impinging air jets. The experimental test rig has been designed and fabricated in accordance with recommendations of ASHRAE standards [27].

The schematic diagram of experimental test rig is shown in Fig. 2(a) and the cross-sectional view of the impinging jet solar air heater duct is shown in Fig. 2(b). It consists of an entry section (600 mm), test section (1400 mm) and an outlet section (400 mm) followed by the suction blower driven by a 3-phase, 5 KW, 230 V and 2880 rpm motor fixed at another end to propel the air through the collector duct. The mass flow rate of the air flowing through the duct is measured using orifice meter attached with U-tube manometer containing propyl alcohol as a manometric fluid having density of 889 kg/m^3 and to control the air flow rate the control valves are placed before and after the blower exit. The constant wattage of 1000 W/m^2 is provided using an electric heater which is considered to be a standard value for operation and testing the solar thermal systems [28].

The electric heater is fabricated by combining loops of nichrome wire in series and parallel combination of size 140 $\times$ 29 cm located on top wall of the test section with other sides insulated. A variable transformer is connected to maintain a specific voltage and an ammeter to measure the current flowing through the circuit in order to maintain uniform heat flux of 1000 W/m^2. A mica sheet of 0.5 mm thickness is sandwiched between the nichrome wire and the asbestos sheet of 5 mm thickness to prevent back heating from the heater thus preventing top loss. The back side of the heater was insulated with 75 mm glass wool to minimize thermal losses. Also, the glass wool packed in 12 mm ply board box ensures that top heat losses are negligible. The heater was placed 25 mm above absorber plate with help of wooden spacers. The friction losses taking place across the test section are measured using micro-manometer which measures the amount of power required to propel the air into the duct. The calibrated copper-constantan thermocouples are used to measure the temperature of the absorber plate at fifteen locations and were fixed using fast drying thermal adhesive, through 2 mm deep hole of 1.5 mm diameter at the back of the plate. Fig. 3 shows the location of thermocouples on the absorber plate. Three copper constantan thermocouples at exit in transverse direction and one at inlet was provided to measure the temperature of air at inlet and outlet. All the nineteen thermocouples were attached to temperature scanner to display the recorded temperature. The rectangular duct is so carefully designed so that the jet plate is successfully placed at its location. Fig. 4 shows the location of streamwise and spanwise pitch on the jet plate. The variation in the jet plate parameters and the flow Reynolds number for optimization of the parameters is as given in Table 1. These parameters have to be optimized in order to obtain the set of jet plate parameters which suggest the maximum heat transfer with minimum