Energy 112 (2016) 588–598

Contents lists available at ScienceDirect

Energy

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

Numerical study on thermal hydraulic performance improvement in solar air heater duct with semi ellipse shaped obstacles

Tabish Alam, Man-Hoe Kim*

School of Mechanical Engineering, Kyungpook National University, Daegu, South Korea

A R T I C L E I N F O

Article history:
Received 11 March 2016
Received in revised form
16 May 2016
Accepted 21 June 2016

Keywords:
Energy
Solar air heater (SAH)
Semi ellipse shaped obstacle
Thermal hydraulic performance

A B S T R A C T

This paper presents numerical study on heat transfer and friction characteristics in rectangular solar air heater duct with semi elliptical shape obstacles. 3-D simulations have been conducted using Renormalization-group k-ε turbulence model. Obstacles are placed on the absorber plate in V-down shape at different angle of attack (α), ranging from 30° to 90°. Two different arrangements of obstacles namely; inline and staggered arrangements have been investigated. Four different values of Reynolds number, ranging from 6000 to 18,000 have been considered to determine the values of Nusselt number and friction factor. Angle of attack (α) and obstacles arrangement significantly affect the Nusselt number and friction factor. In staggered arrangement, maximum enhancement in Nusselt number and friction factor have been observed 2.05 and 6.93, respectively, at an angle of attack (α) of 75° and corresponding enhancement in case of inline arrangement are found as 1.73 and 6.12, respectively. The maximum enhancement in Nusselt number at 75° angle of attack is due to combined effect of high turbulence and lateral movement of air flow. Thermohydraulic performance has also been determined which shows staggered arrangement are more superior than inline arrangement for all values of angle of attack (α) investigated in present study.

1. Introduction

Solar energy is the most spectacular resource of energy which can fulfil energy demand in our society without any adverse effects on the environment. Solar energy can be used to generate electricity, cooking the food, heating the building and some industrial process. Now days, solar air heaters (SAHs) are being used as solar energy collection system due to its simple design, very low cost and maintenance free. Absorber plate transforms insolation into the useful thermal energy of air which is the main component of solar air heater. However, the plain absorber plate has very low thermal performance due to low convective heat transfer between the absorber plate and the flowing air. Due to this low convective heat transfer, higher plate temperature is observed which leads to higher thermal losses to environment. Convective heat transfer can be enhanced by alter the flow pattern using the obstacles in the flow field of air [1]. In order to achieve higher heat transfer coefficient, obstacles develop the following favorable conditions in the flow field; (1) increasing the turbulence intensity near the dead zone, (2) breaking of sub-laminar layer, (3) generating swirl/secondary flow. However, obstacles placed in flow field is also responsible for higher pressure drop and require more pumping power [2].

In order to enhance the heat transfer rate and minimize the pumping power requirement, various obstacles have been investigated and shapes have been optimized. Abene et al. [3] performed experimental study to improve the efficiency-temperature rise couple of the flat plate collector having various obstacles attached to it. The obstacles are waisted ogival lengthways (WOL1), waisted tube (WT), waisted delta lengthways (WDL1), ogival inclined folded (OIF1) and ogival transverse (OT). Collector efficiency and output temperature of an air were improved in the duct equipped with obstacles over smooth duct and highest improvement was reported for WDL1 obstacles. Esen [4] investigated the solar air heater duct provided with obstacles on one side of absorber plate, both side of absorber plate and without obstacles. Inlet temperature, outlet temperature, plate temperature, ambient temperature and mass flow rate were measured. Obstacles on the both sides of absorber plate performed better in comparison to other arrangement. Ozgen et al. [5] investigated the aluminum cans attached on the absorber

* Corresponding author.
E-mail addresses: tabish.iitr@gmail.com (T. Alam), manhoe.kim@knu.ac.kr (M.-H. Kim).

http://dx.doi.org/10.1016/j.energy.2016.06.105
0360-5442/

plate in double pass solar air heater duct. Three different absorber plate, namely; (1) Type I (staggered arrangement of cans on both side of the absorber plate), (2) Type II (inline arrangement of cans on both side of the absorber plate), (3) Type III (absorber plate without cans), were investigated. Experiments were performed for air mass flow rate from 0.03 kg/s to 0.05 kg/s. Thermal efficiency was analyzed based on experimental data. Type I absorber plate was found to be better in comparison to Type II and Type III absorber plate. Alam et al. [6] investigated the perforated blocks in the underside of absorber plate. Effects of block height ratio (h/e), pitch ratio (p/e), angle of attack (α), circularity (ψ) and open area ratio (β) on heat transfer and friction characteristics were investigated. Based on the experimental data, Nusselt number and friction factor correlation were developed. Karwa and Maheshwari [7] explored the effect of half (26% open area ratio) and fully (46.8% open area ratio) perforated baffles in the solar air heater duct. An enhancement in Nusselt number for half perforated baffles was reported as 76%–169% in comparison to smooth duct. Promvonge et al. [8] also performed the experiments to study combined effect of delta-winglet (DW) type vortex generators and ribs. Combined DW and rib with pointing upstream (PU-DW) was reported to be better than the DW pointing downstream (PD-DW). PD-DW proved better thermal performance for low angle of attack, however, PU-DW exhibited better heat transfer and friction factor both at 60° angle of attack. Chompookham et al. [9] carried out experimental investigation in order to study the effect of winglet type vortex generator combined with wedge ribs on heat transfer and friction characteristics. Due to combined effects of winglet type vortex generator and wedge ribs, higher values of Nusselt number and friction factor were reported. Effect of the curved trapezoidal winglet had been investigated in the air flow of solar air heat duct by Zhou and Ye [10] and results were compared with rectangular, trapezoidal and delta shaped winglets. It was reported that curved trapezoidal had higher thermohydraulic performance in the fully turbulent flow region. Bekele et al. [11,12] investigated the triangular shaped obstacles in order to enhance the heat transfer rate. They incorporated following parameters; obstacles longitudinal pitch, transverse pitch, height and inclination as obstacles geometry parameters. Using the obstacles on absorber plate significantly improved the performance in comparison to absorber plate without obstacles. The heat transfer coefficient rate and friction factor were found to be strong functions of obstacles geometrical parameters as reported. Sharad and Saini [13] numerically investigated the arc shaped ribs attached on the absorber plate and absorber plate was exposed to constant heat flux of 1000 W/m^2. Parameters were covered as relative roughness height (e/D) from 0.0299 to 0.0426, relative roughness angle (α) from 30° to 60° and Reynolds number (*Re*) from 6000 to 18,000. Maximum enhancement ratio was found to be 1.7, as reported. Singh et al. [14] conducted 3-D CFD analysis using Ansys 15.0. Four different ribs, namely; circular, square, saw tooth and trapezoidal were investigated using RNG k-ε turbulence model. Maximum enhancement in Nusselt number was found for saw tooth ribs.

Results in aforementioned literature show that obstacles shape and size affect the performance of solar air heater because obstacles induce the turbulence in the flow field and reduce the dead zone on the absorber plate. The selection of geometrical parameters of obstacle plays an imperative role in order to get higher turbulence at heated surface. Although different obstacles have been investigated to enhance the heat transfer rate, but these numerical studies are not sufficient due to lack of flow structure understanding around obstacle which effect heat transfer rate. Computational fluid dynamics (CFD) is imperative tool to predict the 3-dimensional flow structure around obstacles and heat transfer characteristics using equations of continuity, energy and Navier-Strokes. In this study, 3D numerical model has been constructed for solar air heater duct, and the heat transfer and friction characteristics of solar air heater equipped with semi ellipse shaped obstacles have been discussed. The effect of two different arrangements of obstacles e.g. staggered and inline on Nusselt Number and friction factor have been investigated. Previous studies [15–17] showed the V-shaping arrangement in case of ribs, baffles and blockages could improve the heat transfer rate. Further, enhancement in Nusselt Number can be expected using the V-shaped arrangement of obstacles, the inclination of the obstacles to flow would induce the secondary flow cells as compared to transverse obstacles which would lead to higher Nusselt Number.

2. Computational details

Present work exploit finite volume based numerical method to analyze 3-dimensional incompressible Nervier-Strokes flow through solar air heater duct having semi ellipse shaped obstacles in V arrangements. Details of computational flow domain, mesh, boundary conditions, solution method, selection of turbulence method and validation of results have been discussed in the following sub sections:

2.1. Descriptions of the computational domain

The length, width and height of the computation domain are 2500 mm, 300 mm and 50 mm, respectively. The whole length consist three sections viz. inlet plenum (800 mm), test section (1200 mm), and outlet plenum (500 mm). The lengths of inlet plenum and outlet plenum are decided on the recommendation of ASHARE Standard [18] which states that minimum length of inlet and outlet plenum should be greater than 5 $\sqrt{}$(WH) and 2.5 $\sqrt{}$(WH), respectively. Three sides of duct are smooth and insulated. Fourth side is the absorber plate on which obstacles are attached. The absorber plate is exposed to uniform flux which has been done to simulate the conventional solar air heater in actual conditions. The height (e) and width (b) of the obstacles are 25 mm and 30 mm, respectively, which are kept constant in all the simulations. Obstacles are placed in an inline and staggered arrangement and four different values of Reynolds number, ranging from 6000 to 18,000 are considered. The values of longitudinal pitch ratio (p_l/e) and transverse pitch ratio (p_t/b) have been considered as 3.5 and 2.33, respectively which are considered in case of triangular shaped obstacles of similar dimensions [11,12]. The arrangement and geometry of the obstacles are shown in Fig. 1 and Table 1 presents the details of the geometry and configurations.

2.2. Computational flow domain and mesh generation

In the present study, 3-D flow domains have been created in Design Modeler of Ansys v 16.0. In order to reduce computational efforts and time, only half width of the flow domain have been considered and symmetry boundary conditions are given at mid-section (z = 0) of the channel. An unstructured mesh have been used to discretize the flow domain in all the cases. In order to resolving the boundary layer in wall bounded flow domain, inflation feature has been used to create the fine prism mesh near the absorber plate and obstacle walls have near wall element spacing less than unity ($y^+ < 1$). Number of elements and nodes have been generated nearly 12.49×10^6 and 3.82×10^6, respectively. A grid independent test has also been conducted for number of elements of 12.49×10^6, 8.59×10^6 and 6.24×10^6 for staggered arrangement of obstacles with angle of attack of 90° at Reynolds number of 6000. The relative variation in Nusselt number has been shown less than 0.3%, for an increment of grid cells from 8.59×10^6 to 12.49×10^6.