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Heat transfer and friction factor correlations for solar air collectors with hemispherical protrusion artificial roughness on the absorber plate

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Abstract

In order to improve the efficiency of solar air collectors, this paper presents a novel solar air collector with hemispherical protrusion/dimple on the absorber plate, and analyses the performance from the two aspects of optics and thermodynamics. For the purpose of enhancing the absorption rate, the optical path shinning on the dimple and protrusion artificial roughness was simulated by using TRACEPRO software. The optical path of hemispherical and the spherical cap dimple was simulated too. The conclusions show that the hemispherical dimple is the best in term of the optics. Then the heat transfer performance of the hemispherical protrusion (back of the dimple) was investigated by experiments. The investigation has covered Reynolds number (Re) ranging from 3000 to 11,000, relative roughness height (e/D_h) from 0.033 to 0.1and relative pitch (p/e) from 3.5 to 5.5. In order to determine the enhancement in heat transfer and increment in friction factor, values of Nusselt number and friction factor have been compared with those of smooth duct under similar flow conditions. Correlations for Nusselt number and friction factor have been developed for solar air collector with such hemispherical protrusion artificial roughness, which can provide reference for the design of this kind of collector.

Keywords: Hemispherical protrusion and dimple; Heat transfer; Optical path; Solar air collector

1. Introduction

Heat transfer enhancement in a duct/channel is of great interest and importance in many industrial applications such as solar air collectors, heat exchangers, and various cooling devices because higher heat transfer rates increase system efficiency and reduce thermal load. The use of artificial roughness on a surface is an effective technique to enhance heat transfer to fluid flowing in ducts. Artificial roughness can be provided by fixing wires, ribs, wire mesh or expanded metal mesh and by providing roughness in protrusion-shape geometry. Among these enhancement techniques, interest in protrusions has recently increased due to the relatively low pressure penalty compared to other enhancement techniques.

Chukin (1995) studied the effects of channel geometry (converging and diverging channels) on heat transfer for downstream flow over a single hemispherical cavity. Karwa et al. (1999) presented the heat transfer coefficient and friction factor correlations for the transitional flow regime in rib-roughened rectangular ducts. Moon and Lau (2000) investigated effects of the channel height on heat transfer in a rectangular duct with a dimpled surface and found that the dimple indentations enhanced the heat transfer level by about 2.1 times, regardless of the channel

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Nomenclature

e	height of the roughness element (mm)	h	heat transfer coefficient ($W/m^2/K$)
ΔP	pressure drop across the solar air collector	D_h	duct hydraulic diameter (mm)
P	roughness pitch (mm)	f	friction factor
Re	Reynolds number	Nu_0	Nusselt number for smooth duct
ρ_{air}	density of air (kg/m^3)	PF	performance factor
Nu	Nusselt number for solar air collector	f_0	friction factor for smooth duct

height. Ligrani et al. (2001) presented flow characteristics for the channel with the dimple wall having protrusions on the opposite walls using flow visualization and reported the local heat transport distributions. They found that the heat transfer coefficients were enhanced by the protrusions on the top wall and these protrusions caused more mixing and vortices which increased the overall Nusselt number and as well as pressure drop. Moon and Lau (2000), showed that concave and cylindrical dimple configurations enhanced the overall heat transfer rates by 1.7 times. Burgess et al. (2003) conducted an experimental study to investigate the effects of dimple depth on heat transfer enhancement. As a result, they showed that the local and spatially-resolved Nusselt number augmentations increased with the dimple depth. Hwang (2005) introduce heat transfer of internal passage using dimple/protrusion. Sang Dong Hwang et al. (2008) studied the Heat transfer with dimple/protrusion arrays in a rectangular duct with a low Reynolds number range. Saini and Verma (2008) investigate heat transfer and friction factor correlations for a duct having dimple-shape artificial roughness for solar air heaters and developed the correlations for Nusselt number and friction factor for solar air heater duct provided such artificial roughness geometry. Kumar and Bhagoria (2009) reported the heat transfer and friction correlations for artificially roughened solar air heater duct with discrete W-shaped ribs. Bhushan and Singh (2010) presented data on the influence of Reynolds number on heat transfer coefficient distribution on the surface having staggered array of protrusion geometry. Hans et al. (2010) analyzed the heat transfer and friction factor correlations for a solar air heater duct roughened artificially with multiple v-ribs. Giovanni Tanda (2011) investigated the performance of solar air heater ducts with different types of ribs on the absorber plate. And the results show that all the rib-roughened channels performed better than the reference smooth channel in the medium–low range of the investigated Reynolds number values. Brij and Singh (2011) studied Nusselt number and friction factor correlations for solar air heater duct having artificially roughened absorber plate. Agrawal and Tiwari (2011). analyzed the experimental validation of glazed hybrid micro-channel solar cell thermal tile and observed that maximum overall exergy efficiency is 20.28% at 0.000108 kg/s mass flow rate. Singh et al. (2011) studied the heat transfer and friction factor correlations of solar air heater ducts artificially roughened with discrete V-down ribs. García et al. (2012) investigated the influence of artificial roughness shape on heat transfer enhancement: corrugated tubes, dimpled tubes and wire coils. Sethi et al. (2012) studied the correlations for solar air heater duct with dimpled shape roughness elements on absorber plate. Yadav et al. (2013) has been carried out experimental investigation on protrusions arranged in angular fashion as roughness geometry. The maximum enhancement in heat transfer and friction factor is 2.89 and 2.93 times as compared with smooth duct. Agrawal and Tiwari (2013). evaluated enviroeconomic analysis and energy matrices of glazed hybrid photovoltaic thermal module air collector. The effect on annualized uniform cost, EPF and LCCE have been evaluated for the interest rate of 8%, 10% and 12%. Numerous roughness geometries for the study of heat transfer and friction characteristics have been dealt with in the literature such as Karwa et al. (1999).

However, these investigations were carried out only from the heat transfer and the dimples/protrusions are mostly spherical cap. In this study, the heat transfer characteristics and optical properties were investigated for solar air collectors with having hemispherical protrusion artificial roughness on the absorber plate. In order to collect data on heat transfer and fluid flow characteristics, the experiments were set up. The experimental data are presented in the form of Nusselt number and friction factor plots as function of Reynolds number for different roughness parameters, while the optical properties were simulated by software TRACEPRO with having different shapes. Using experimental data collected during extensive experimental study, correlations for Nusselt number and friction factor have also been developed.

2. Experimental apparatus and procedures

2.1. Experimental setup

A schematic diagram of the experimental setup is shown in Fig. 1. The flow system consisted of an entry section, a test section, an exit section, a flow meter and an air blower. The duct was made of aluminum panels having the air channel size as 1950 mm × 950 mm × 50 mm. The diameter of entry and exit section was provided as 100 mm. A 50 mm thick layer of glass wool as an insulating material was provided in order to minimize the heat losses from