International Communications in Heat and Mass Transfer 50 (2014) 34–43

Contents lists available at ScienceDirect

International Communications in Heat and Mass Transfer

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

Thermal performance of turbulent flow in a solar air heater channel with rib-groove turbulators ☆

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ARTICLE INFO

Available online 14 November 2013

Keywords:
Thermal performance
Solar air heater
Rib
Groove
Channel flow
Turbulator

ABSTRACT

The paper presents an experimental study on turbulent flow and heat transfer characteristics in a solar air heater channel fitted with combined wavy-rib and groove turbulators. The experiments are performed by controlling the airflow rate to obtain Reynolds numbers in the range of 4000 to 21,000. To produce recirculation flow in the tested channel having a constant heat-flux on the upper wall only, the triangular wavy ribs are placed repeatedly on the tested grooved channel walls. Three test cases of different rib-pitch to channel-height ratios (PR = P/H = 0.5, 1 and 2) with a single rib-to-channel height ratio (BR = b/H = 0.25) are introduced in the present work. The wavy ribs are placed with the attack angle of 45° relative to main flow direction. There are three types of rib arrangements, namely, rib-groove on the upper wall only, inline rib-groove, and staggered rib-inline groove on two principal walls. The experimental result reveals that the combined rib-groove on both the upper and lower walls of the test channel provides the highest heat transfer rate and friction factor in comparison with the smooth channel with/without ribs. However, the ribbed-grooved upper wall at PR = 0.5 yields the highest thermal performance. The combined rib-groove turbulator is found to be considerably higher thermal performance than the groove alone.

1. Introduction

Rib/groove is one of the commonly used passive heat transfer enhancement techniques in single-phase internal flows in a channel solar air heater by placing the rib/groove periodically in the absorber plate. For decades, several engineering techniques have been developed for enhancing the convective heat transfer rate from the channel surface. The turbulators used for the cooling/heating channel or channel solar air heater such as ribs [1], fins [2,3], grooves [4,5] or baffles [6,7] are often encountered in order to increase the convective heat transfer coefficients leading to the compact heat exchanger and increasing the efficiency. The reason of this may be that the use of ribs/grooves completely makes the change of the flow field and thus the distribution of the local heat transfer coefficient. The application of rib-groove into the channel is to provide an interruption of boundary layer development, to increase the heat transfer surface area and to cause enhancement of heat transfer by increasing turbulence intensity or fast fluid mixing. Therefore, more compact and economic heat exchanger with lower operation cost can be obtained. In general, the geometry parameters of ribs in the channel are among the most important factor in the design of channel heat exchangers which effects on both local and overall heat transfer coefficients. In particular, the angled rib, rib blockage ratio (BR = b/H), rib pitch ratio (PR) and rib arrangement are all parameters that influence both the heat transfer coefficient and the overall thermal performance.

Several studies have been carried out to investigate the effect of these parameters of ribs on heat transfer and friction loss for two opposite roughened surfaces. Han et al. [8] studied experimentally the heat transfer in a square channel with ribs on two walls for nine different rib configurations for P/b = 10 and b/H = 0.0625. They found that the angled ribs and 'V' ribs yield higher heat transfer enhancement than the continuous ribs and the heat transfer rate and the friction factor were highest for the 60° orientation amongst the angled ribs. For heating either only one of the ribbed walls or both of them, or all four channel walls, Han et al. [9] also reported that the former two conditions resulted in an increase in the heat transfer with respect to the latter one. Han and Zhang [10] studied the heat transfer augmentation in a square channel with various broken ribs of b/H = 0.0625 and P/b = 10 on two channel walls. They found that 60° broken 'V' ribs provide higher heat transfer at about 4.5 times the smooth channel and perform better than the continuous ribs. By using a real time Laser Holographic Interferometry to measure the local as well as average heat transfer coefficient, Liou and Hwang [11,12] investigated experimentally the performance of square, triangular and semi-circular ribs and found that the square ribs give the best heat transfer performance among them. This is contrary to the experimental result of Ahn [13] indicated that the triangular rib performs better than the square one.

☆ Communicated by W.J. Minkowycz

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0735-1933/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.icheatmasstransfer.2013.11.001

Nomenclature

A	convection heat transfer area of channel, m^2
AR	aspect ratio of channel, (W/H)
b	rib height, m
BR	rib blockage ratio, (b/H)
C_p	specific heat capacity of air, J/kgK
D	hydraulic diameter of channel, m
e	groove depth, m
f	friction factor
H	channel height, m
h	average heat transfer coefficient, W/m^2K
I	current, A
k	thermal conductivity of air, W/mK
L	length of test channel, m
$\dot{m}$	mass flow rate of air, kg/s
Nu	Nusselt number, (hD/k)
P	rib pitch spacing (axial length of spacing), m
ΔP	pressure drop, Pa
PR	rib pitch to channel height ratio, (P/H)
Pr	Prandtl number
Re	Reynolds number, (UD/ν)
Q	heat transfer, W
T	temperature, K
TEF	thermal performance enhancement factor
t	thickness of rib, m
U	mean air velocity, m/s
V	voltage, volt
W	width of channel, m
w	width of groove, m

Greek letters

α	attack angle of rib, degree
ρ	density of air, kg/m^3
ν	kinematics viscosity, m^2/s

Subscripts

b	bulk
0	smooth channel
conv	convection
i	inlet
o	out
pp	pumping power
s	channel surface

Taslim et al. [14] examined the heat transfer behaviors in a ribbed square channel with three b/H ratios ($b/H = 0.083$, 0.125 and 0.167) and a fixed $P/b = 10$ using a liquid crystal technique. They reported that the average Nusselt number was increased with the rise in b/H ratio and the best b/H ratio was found to lie between 0.083 and 0.125. Tanda [15] examined the effect of transverse, angled ribs, discrete, angled discrete ribs, V-shaped, V-shaped broken and parallel broken ribs on heat transfer and friction and reported that 90° transverse ribs provided the lowest thermal performance while the 60° parallel broken ribs or 60° V-shaped broken ribs yielded a higher heat transfer augmentation than the 45° parallel broken ribs or 45° V-shaped broken ribs. Parallel angled discrete ribs were seen to be superior to parallel angled full ribs and its 60° discrete ribs performed the highest heat transfer. Promvonge and Thianpong [16] experimentally studied the thermal performance of wedge ribs pointing upstream and downstream, triangular and rectangular ribs with $b/H = 0.3$ and $P/b = 6.67$ mounted on the two opposite walls of a channel with AR = 15. They found that the in-line wedge rib pointing downstream performed the highest heat transfer but the best thermal performance is the staggered triangular rib. Thianpong et al. [17] again investigated the thermal behaviors of isosceles triangular ribs attached on the two opposite channel walls with AR = 10 and suggested the optimum thermal performance of the staggered ribs could be at about $b/H = 0.1$ and $P/H = 1.0$. Extensive literature reviews over hundred references on various rib turbulators were reported by Varun et al. [18] and Han et al. [19].

Momin et al. [20] experimentally studied on heat transfer and flow characteristics of a solar air heater duct fitted with V-shaped ribs for $b/D = 0.02$–0.034 and the angle of attack (α) = 30° − 90° for a fixed $P/b = 10$. They found that at $\alpha = 60°$, the highest Nusselt number and friction factor values obtained by the ribs are, respectively, 2.30 and 2.83 times above the smooth duct. For using combined/compound turbulators, Chompookham et al. [21] and Promvonge et al. [22] experimentally investigated the effect of using winglet vortex generators in common with several ribs on heat transfer and friction characteristics in an uniform heat flux channel and found that the heat transfer rate increases considerably for using both enhancement devices and is about 50–80% of using a single enhancement device. Promvonge et al. [23] examined numerically the laminar heat transfer enhancement in a square channel with 45° inclined baffle on one wall and reported that a single streamwise vortex flow occurs throughout the channel and helps to induce impingement jets on the upper, lower and side walls. Again, Promvonge et al. [24,25] also investigated numerically the laminar flow structure and thermal behaviors in a square channel with 30° or 45° inline baffles on two opposite walls. They found that two streamwise counter-rotating vortex flows appear along the channel and vortex-induced impinging jets occur on the upper, lower and side walls.

For a system with only one roughened wall and three smooth walls, several investigations [26–30] have been carried out on rib roughened absorber plates of solar air heaters. Correlations for heat transfer coefficient and friction factor have been developed for such a system. However, the increase in heat transfer is accompanied by an increase in the resistance of fluid flow.

From the literature review above, most of the investigations are focused only on the single use of the turbulators or the combined rib/baffle and winglet, providing a similar flow pattern in the channel. A combination of rib/baffle and groove in the channel has rarely been reported. Thus, the main aim of the present work is to extend the experimental data of using the combined rib-groove on the channel walls for three different rib pitch ratios (PR = 0.5, 1 and 2) at a single rib height, BR = 0.25. Also, three types of mounting wavy ribs on the grooved walls, namely, rib-groove on the upper wall only, inline rib-groove and staggered rib-inline groove on two opposite walls on a high aspect ratio (AR = 10) rectangular channel are introduced. The use of the rib-groove turbulators is expected to create vortex flows throughout the tested channel to stronger mixing of flows between the core and the near-wall regimes leading to higher heat transfer rate in the channel. Experimental results using air as the test fluid for the rib-grooves are presented in turbulent flows in a range of Re from 4000 to 21,000.

2. Experimental setup

The experiments were conducted to examine the effect of using combined the wavy-rib and transverse groove on heat transfer and friction characteristics of a channel solar air heater. A schematic diagram of the experimental apparatus is presented in Fig. 1a while the detail of the 45° triangular wavy rib and transverse groove placed on the upper wall only, in-line and staggered rib arrays is displayed in Fig. 1b. Three test cases of different rib-pitch to channel-height ratios (PR = 0.5, 1 and 2) with a single rib-to-channel height ratio (BR = 0.25) are considered in the present work. The form of grooved plates was accomplished by means of wire-EDM (electrical discharge machine) machining with its dimension of 5 mm depth (e), 10 mm width (w) with a single groove