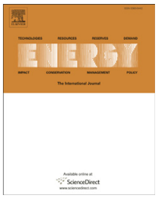
Energy 72 (2014) 731–738

Contents lists available at ScienceDirect

Energy

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



Numerical optimization of solar air heaters having different types of roughness shapes on the heated plate – Technical note

Anil Kumar, Man-Hoe Kim*

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

ARTICLE INFO

Article history:
Received 4 March 2014
Received in revised form
13 May 2014
Accepted 28 May 2014
Available online 25 June 2014

Keywords:
Thermohydraulic optimization
SAH
Heat transfer enhancement
Artificial roughness

ABSTRACT

This paper presents numerical optimization results for the thermal and effective efficiencies of a solar air heater duct as a function of various roughness geometries on the heated plate. A methodology for the prediction of thermal and effective efficiency of the SAH has been developed on the basis of heat transfer and friction factor correlations. Among the roughness geometries considered, the discrete multiple V-shaped rib results in the best thermal and effective efficiencies over the entire range of design conditions. This work also addresses the scope for future research in the area of roughened SAH ducts and will be helpful for researchers investigating new artificial shapes for SAH ducts to enhance the heat transfer.

1. Introduction

SAHs (solar air heaters) typically have a low heat transfer rate between the fluid and the heated plate, which leads to a higher temperature on the heated plate and results in increased heat loss. Use of a turbulence promoter on the heated surface is considered to be an effective technique for enhancing the convective heat transfer coefficient in SAH ducts. Numerous studies have been performed on the wires and ribs of roughened SAH ducts and their *Nu* and *f* characteristics.

Prasad and Saini [1] experimentally studied the thermal performance of an SAH artificially roughened by transverse ribs on the underside of its heated plate. They concluded that transverse ribs result in a greater *Nu* than a smooth surface under similar operating conditions. Maximum performance was observed for $e/D = 0.033$ and $P = 20$. Han and Zhang [2] experimentally studied the effect of truncated V-ribs on the *Nu* and *f* of the heated surface of an SAH duct. They concluded that truncated V-ribs increase thermal performance levels 2.7–4.2 times, whereas the increase in thermal performance without truncated V-ribs is only 2.2–3.5 times. They also concluded that the 60° truncated V-rib results in better thermal performance than the 45° one under similar experimental conditions. Taslim et al. [3] conducted an experimental investigation using LCT to determine the local *Nu* in an air duct with various rib configurations on two opposite surfaces. Their results indicated that the *Nu* was higher for V-ribs pointing downstream.

Gupta et al. [4] investigated the thermal performance of a ribbed air duct with ribs inclined in the main flow direction. Maximum thermal performance was reported for inclined ribs with $e/D = 0.039$, $W/H = 9.8$, $P/e = 10$, $\alpha = 60°$, and $Re = 12{,}000$. Bhagoria et al. [5] investigated the effective efficiency of a wedge-rib-roughened air duct. It was observed that the highest effective efficiency occurs with a wedge angle of 15°. Momin et al. [6] varied the angle of attack of the V-rib roughness and examined its effect on the effective efficiency of an air duct. The highest enhancement in effective efficiency was reported for $P/e = 9$, $e/D = 0.027$, $\alpha = 58°$, and $Re = 13{,}500$.

Wang and Sunden [7] employed LCT and PIV techniques to study the effects of rib angles of attack of 35°, 48°, and 60° on the flow field. They observed the maximum value of effective efficiency at an angle of attack of 60°. Tanda [8] examined the flow and *Nu* of a ribbed surface with various types of heat exchangers and presented the *Nu* and f in an air duct using the LCT method. Karmare and Tikekar [9] investigated the local *Nu* and *f* of an air duct with metal grit ribs.

Kumar and Bhagoria [10] investigated the thermal performance of a W-rib-roughened air duct. Saini and Saini [11] examined the effective efficiency of an SAH duct with a heated plate artificially roughened by arc-shaped ribs. Hans et al. [12] examined the effective efficiency of an air duct with a heated plate artificially roughened using multi V-ribsSingh et al. [13] examined the flow

---

* Corresponding author. Tel.: +82 53 950 5576; fax: +82 53 950 6550.
E-mail addresses: anilkumar@knu.ac.kr (A. Kumar), manhoe.kim@knu.ac.kr, kimmh@asme.org (M.-H. Kim).

http://dx.doi.org/10.1016/j.energy.2014.05.100
0360-5442/

Nomenclature

A_p	area of heated plate, m^2
C_p	specific heat of fluid at constant pressure, J/(kg K)
G	mass velocity of fluid through the collector, kg/(m^2 s)
G_d	gap or discrete distance, m
G_p	gap or discrete position, m
Gr	Grashof number
G_P/L_v	relative discrete or gap position
D	hydraulic diameter of duct, m
e	rib height, m
e/D	relative roughness height
f_s	friction factor of smooth duct
f	friction factor of roughened duct
F'	plate efficiency number
F_o	heat removal factor
g	gap or discrete width, m
g/e	relative gap or discrete width
H	depth of duct, m
h	convective heat transfer coefficient, W/(m^2 K)
I	solar intensity, W/m^2
k	thermal conductivity of air, W/(m K)
L	length of test section, m
L_v	length of single v-rib, m
m	mass flow rate, kg/s
Nu	Nusselt number of roughened duct
Nu_s	Nusselt number of smooth duct
P	pitch of the rib, m
P/e	relative roughness pitch
Pr	Prandtl number
Q_u	useful heat gain rate, W
Re	Reynolds number
Ra	Rayleigh number
T_f	average temperature of air, K
T_s	temperature of the sun, K
T_i	initial temperature of air, K
T_o	final temperature of air, K
T_p	average plate temperature, K
U_b	bottom loss coefficient, W/(m^2 K)
U_e	edge loss coefficient, W/(m^2 K)
U_L	overall heat loss coefficient, W/(m^2 K)
U_t	top loss coefficient, W/(m^2 K)
V	velocity of air, m/s
W	width of duct, m
w	width of V-rib, m
W/w	roughness width ratio
ΔT	temperature difference
$\Delta T/I$	performance parameter, K m^2/W
SAH	solar air heater
LCT	liquid crystal thermography
PIV	particle image velocimetry

Greek letter symbols

α	angle of attack, degrees
β	ratio of orifice diameter to pipe diameter
β'	collector tilt angle, degrees
η	thermo-hydraulic performance parameter
ρ	density of air, kg/m^3
ρ_m	density of manometric fluid, kg/m^3
μ	dynamic viscosity of air, N s/m^2
$\tau\alpha$	absorbance-transmittance product
η_{th}	thermal efficiency
η_{eff}	effective efficiency

and local *Nu* characteristics of an air duct with truncated V-rib. Patil et al. [14] examined the effective efficiency of an air duct with a heated plate that was artificially roughened using discrete-V staggered ribs. The roughened heated plate increased the thermal performance by 1.14–2.22 times compared to a smooth surface. Kumar at al [15]. examined the flow and local *Nu* characteristics of an air duct with multiple discrete V-ribs. Compared to a smooth duct, multiple discrete V-rib roughness increased the effective efficiency up to 1.15 times in the range of parameters investigated.

Researchers have used artificial roughness of various shapes and sizes for increasing the *Nu* and thereby improving the performance of SAHs. A number of investigations have been performed to determine and develop relationships and correlations for *Nu* and *f* for a variety of artificial shapes. This paper presents the thermal and effective efficiencies of SAHs with various types and shapes of roughness elements on the heated plate.

2. Comparison of thermal performance of roughened SAH

SAHs with artificially roughened heated plates have a higher *Nu*, which is accompanied by higher *f*. Correlations for *Nu* and *f* have been developed in terms of roughness and flow parameters by several researchers. A comparison between the thermal and effective efficiencies of roughened SAHs with different types of roughness geometry and those of smooth surface SAHs is presented here. These geometries and configurations were chosen because they yield relatively efficient artificial roughness systems.

2.1. System and operating parameters

In order to calculate the thermal and effective efficiencies of a ribbed SAH for a given set of fixed and variable parameters, it is necessary to specify appropriate parameter values or ranges of values. These parameters can be categorized into fixed and variable parameters. Fixed parameters comprise the collector dimensions and components as well as related thermo-physical parameters, ambient temperature, inlet temperature, and wind speeds. A list of fixed parameters is given in Table 1. Variable parameters comprise roughness shapes, i.e., s'/s, p'/p, α, P/e, ϕ, e/D, g/e, d/W, and Gd/Lv, and the design parameters $\Delta T/I$ and I.

2.2. Procedure for performance prediction

The optimum design of the SAH is presented as a function of two basic design parameters:

(i) the performance parameter, $\Delta T/I$
(ii) the solar intensity, I

The calculation procedure for the thermal and effective efficiency is given below.

Step 1. The values of the roughness parameters (e/D), (W/w), (ϕ), (p'/p), (Gd/Lv), (g/e), (r/e), (s'/s), (P/e), and (α) are selected.
Step 2. The values of the design parameters, $\Delta T/I$ and I, are selected.