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Investigations on thermo-hydraulic performance of broken arc rib in a rectangular duct of solar air heater

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ABSTRACT

In present paper, solar air heater duct having aspect ratio 12 roughened with broken arc rib has been investigated. The broken arc is formed by creating symmetrical gap in continuous arc with gap width equal to roughness height. It has been planned to investigate the influence of position of gap in arc rib on Nusselt number as well as on friction factor. For this purpose, five broken arc rib roughened plates having relative gap position ranging 0.2–0.8 have been investigated for values of Reynolds number 2000–16000. The remaining roughness parameters like relative roughness height, arc angle, and relative roughness pitch were taken as 0.043, 30° and 8 respectively. The presence of broken arc ribs enhanced the Nusselt number, friction factor and thermo-hydraulic performance up to 2.37, 2.55 and 1.94 respectively, compared to smooth duct. The results of ducts roughened with broken arc rib and continuous arc rib have been compared under similar flow conditions. The effect of gap in continuous arc rib on the flow pattern has also been observed using ANSYS Academic Research CFD 15.0.

1. Introduction

Solar air heaters (SAH) are the most common device which transforms radiant energy to thermal energy by heating air flowing through it. However, because of low convective heat transfer coefficient between air and absorber plate, the conventional SAH have inferior thermal performance. In an attempt to enhance its thermal performance, various investigations have been carried out by modifying its air flow passage by using porous absorber, finned absorber, corrugated absorber, artificially rib roughened absorber, etc. [1]. The use of rib roughness on absorber in conventional SAH has been found economical and effective way of improving the convection heat transfer. The presence of ribs on absorber breaks low heat transfer viscous sub-layer and creates turbulence close to wall because of separation of flow and then reattachment, thereby enhancing the thermal performance of SAH. However, rib roughness increases the pumping energy requirement because of increased friction losses. Numerous studies have been reported on conventional SAHs having rib roughness on absorber plate for enhancement of heat transfer with least pressure loss [2–5].

Literature survey reveals that investigations on rib roughness started with transverse rib [6]. From further investigations, it has been found that continuous inclined rib perform better than transverse rib because of formation of two counter rotating secondary flow cells causing increase in local heat transfer [7]; and the continuous V-shape [7,8] and multi V-shape [9] ribs are still better than inclined rib because of formation of more counter rotating secondary flow cells. Further heat transfer enhancement has been observed when continuous rib is broken with gap equal to rib height due to accelerated flow through gap and redevelopment of secondary flow [10–12]. All these studies [10–12] have also reported that position of gap in broken rib affects the heat transfer.

It is clear from literature review that so far no heat transfer study on arc shaped rib with gap has been done. As mentioned above position of gap affects heat transfer, so it was decided to investigate the 'broken arc rib' i.e. arc shaped rib with gap at different relative gap positions to determine the optimum relative gap position. The gap width was kept same as rib height. The variation in Nusselt number and friction factor due to Reynolds number and relative gap position have been studied under similar boundary conditions to evaluate thermo-hydraulic performance of roughened duct. To find out the advantage of the selected broken arc rib over that of continuous arc rib, a continuous arc rib for same roughness parameters has also been tested under similar boundary conditions. The effect of gap in continuous arc rib on the flow pattern has also been observed using ANSYS Academic Research CFD 15.0. The rib geometry, parameters range, experimental details, results, etc. are presented below:

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Nomenclature

A_o	orifice throat area (m^2)
A_p	absorber plate area (m^2)
C_d	discharge coefficient = 0.617
C_p	constant pressure specific heat (J/kg-K)
D_h	hydraulic diameter (m)
f	roughened duct friction factor
f_s	smooth duct friction factor
h	convective heat transfer coefficient (W/m^2-K)
K_a	thermal conductivity (W/m-K)
L	duct length for pressure drop (m)
$\dot{m}$	mass flow rate (kg/s)
Nu	roughened duct Nusselt number
Nu_s	smooth duct Nusselt number
Q	heat transfer rate to air (W)
Re	Reynolds number
t_{fm}	mean temperature of air (°C)
t_i	inlet temperature of air (°C)
t_o	average exit temperature of air (°C)
t_{pm}	average temperature of plate (°C)
V	velocity of air (m/s)
ΔP_o	pressure drop across orifice meter (N/m^2)
ΔP_d	pressure drop across duct (N/m^2)
η	thermo-hydraulic performance parameter
ρ_a	air density at mean temperature (kg/m^3)
β	orifice throat diameter to pipe diameter ratio

2. Rib roughness geometry and roughness parameters range

SAH rectangular duct was roughened with broken arc rib by pasting aluminium wires on air flow side of the absorber. The general geometry of broken arc rib used for this study is shown in Fig. 1. The broken arc rib roughness can be described by arc angle (α), rib pitch (P), gap width (g), rib height (e), half width of duct (w) and gap position from leading edge of arc (d). These roughness parameters in dimensionless form have been written as relative roughness pitch (P/e), relative arc attack (α/90), relative gap position (d/w), relative gap width (g/e), and relative roughness height (e/D_h). The values of α/90, P/e, g/e and e/D_h for present study were selected as 0.333, 8, 1.0 and 0.043 respectively, based on optimum values of previous investigations [9–11,13]. To determine optimum relative gap position of the present rib roughness, five roughened plates for relative gap position (d/w) values of 0.2, 0.35, 0.5, 0.65, and 0.8 were fabricated. Reynolds number was varied from 2000 to 16,000.

3. Material and methods

To see the effect of relative gap position of broken arc rib on friction in the flow and heat transfer, an indoor test facility has been designed as per guidelines given in ASHRAE standard [14]. It was an open loop system that consisted of a rectangular duct of 2440 mm length with a flow cross-section of 300 mm wide (W) and 25 mm deep (H). The whole length of duct was divided into three sections that is entry, test and exit section. The respective length of these sections was 550 mm, 1000 mm and 890 mm whereas the ASHRAE recommended minimum entry and exit lengths of 433 mm (5 × √(W × H)) and 217 mm (2.5 × √(W × H)) respectively. To create artificial roughness, circular wires in broken arc form were fixed on the air flow side of this absorber plate whereas the remaining three walls of duct were made smooth. The details of the experimental setup, experimental procedure, and equations for computing Nusselt number and friction factor are described comprehensively in previous publication by the authors [5].

For all the rib-roughened plates investigated, the maximum estimated uncertainties in Reynolds number, Nusselt number and friction factor were ± 2.24%, ± 1.96% and ± 5.17%, respectively at *Re* = 2000 and the corresponding values at the *Re* = 16,000 were ± 1.57%, ± 4.28% and ± 3.48% respectively [15].

To investigate the flow pattern due to gap in continuous arc rib, Computational Fluid Dynamics (CFD) analysis of rib roughened duct was carried using software ANSYS Academic Research CFD 15.0. For this purpose, 3D periodic geometries of roughened duct for broken arc rib and continuous arc rib were investigated. The rib parameters were P/e = 8, d/w = 0.65, g/e = 1.0, α/90 = 0.333, and e/D_h = 0.043. For solving the flow field, the turbulence model RNG k-ε with enhanced wall treatment was used. The number of cells were 10,67,856 and 10,90,253 for arc rib with gap and without gap respectively and the convergence limit each for residual of continuity equation, velocity components, k and ε was taken as 10^{-5}.

4. Results and discussion

The effect of relative gap position on Nusselt number and friction factor for Reynolds number ranging from 2000 to 16,000 have been drawn in Fig. 2. It can be viewed that Nusselt number as well as friction factor increases as relative gap position increases from 0.2 to 0.65 and then both decrease with 0.65 to 0.80 increase in relative gap position for all Reynolds numbers. This change in friction factor and Nusselt number may be due to change in flow and heat transfer characteristics of secondary flow at front side of rib. When the relative gap position increases the strength of secondary flow through the gap increases, and on other hand the secondary flow along the rib is gradually heated. The increased strength of secondary flow through gap leads to rise in turbulence in front region of the gap which results in increase in heat transfer, whereas, higher temperature of secondary fluid results in decrease in heat transfer. In the range of relative gap position value of 0.20–0.65, it is anticipated that the increase in heat transfer due to increase in turbulence caused by increased strength of secondary flow dominates over the decrease in the heat transfer caused by increased

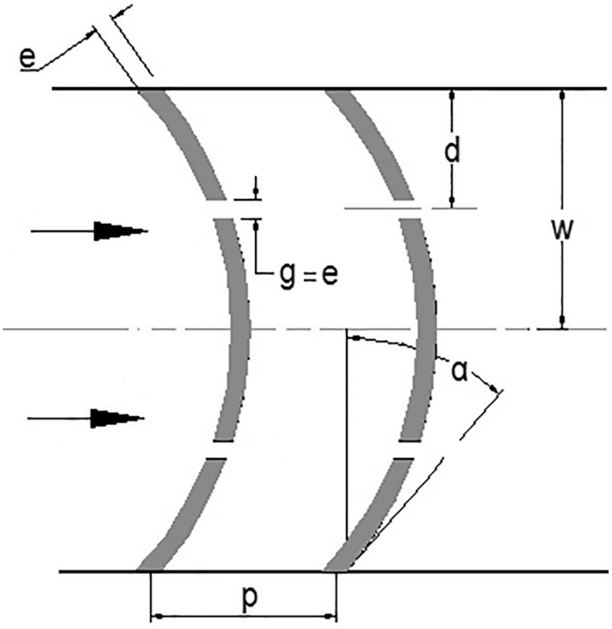

Fig. 1. General arrangement of broken arc-shaped rib.

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