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Heat Transfer and Friction Characteristics of Solar Air Heater Duct Roughened by Broken Arc Shaped Ribs Combined with Staggered Rib Piece

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***Abstract*— In this paper, results of experimental investigation on heat transfer and friction in rectangular ducts roughened with broken arc-rib roughness combined with staggered rib piece has been presented. The rib roughness has relative gap position of 0.65, relative staggered rib position of 0.6, relative staggered rib size of 2.0, relative roughness pitch of 10, arc angle of 30° and relative roughness height of 0.043. The relative gap size was varied from 0.5 to 2.5. The effects of gap size on Nusselt number, friction factor and thermo-hydraulic performance parameter have been discussed and results compared with smooth duct and continuous arc rib roughened duct under similar conditions.**

Keywords*— *Solar air heater, rib roughness, Nusselt number, friction factor, Thermo-hydraulic performance.

I. INTRODUCTION

A solar air heater is a simple device to heat air by utilizing solar energy, which has many applications, such as space heating [1], seasoning of wood [2], crop drying [3]. However, the only drawback of solar heaters is their low thermal efficiency because of low heat transfer coefficient between the absorber plate and air. The low heat transfer coefficient between the absorber plate and air has been found due to formation of viscous sub-layer on the heat-transferring surface of absorber plate. The use of artificial roughness in the form of wires and integral ribs on absorber plate of solar air heaters has been used by many investigators Mulluwork [4], Yadava et al. [5], Sahu et al. [6], Kumar et al. [7], Lanjewar et al. [8], Aharwal [9], Karwa [10], Singh et al. [11], Nagpure et al. [12] to break the viscous sub-layer which results in substantial enhancement in heat-transfer coefficient between the absorber plate and the air.

A large number of experimental studies on heat transfer and flow characteristics have been carried out to investigate the effect of rib roughness on performance of solar air heaters. Prasad and Mullick [13] introduced the application of roughness in the form of small diameter wire attached on the underside of absorber plate to improve the thermal performance of solar air heater for drying purposes. To see the effect of roughness pitch and roughness height on heat transfer and friction, Prasad and Saini [14] investigated the transverse rib roughness in the form of small diameter wires in a solar air heater duct. The study concluded that the roughness pitch and roughness height should be carefully selected in order to have maximum numbers of reattachment points as reattachment of free shear layer between the consecutive ribs enhances the heat transfer rates. Gupta et al. [15] investigated the effect of transverse and inclined wire roughness on fluid flow characteristics of solar air heater duct. It was reported that the inclined rib generates secondary flow cells along inclined rib and these secondary flow cells accelerate main flow which causes higher wall turbulence leading to considerable enhancement in heat transfer. Momin et al. [16] conducted experimental study on V-shaped ribs as artificial roughness attached to the underside of one broad wall of the duct. Study revealed that the flow separations, reattachments, and generation of secondary flows caused by roughness were responsible for higher values of Nusselt number and friction factor as compared to those with smooth absorber plates. It was reported that at Reynolds number of 17034, relative roughness height of 0.034 and for angle of attack of 60o, the V-shaped ribs enhance the values of Nusselt number by 1.14 and 2.30 times over roughened plate with inclined ribs and smooth plate, respectively. An experimental study conducted by Karwa [10] on heat transfer and friction in a high aspect ratio duct with transverse, inclined, V-up continuous, and V-down continuous, V-up discrete, and V-down discrete ribs shows that the enhancement in Stanton number over smooth duct was found to be 65%–90%, 87%–112%, 102%–137%, 110%–147%, 93%–134%, and 102%–142%, respectively and corresponding friction factor ratios for these arrangements were 2.68–2.94, 3.02–3.42, 3.40–3.92, 3.32–3.65, 2.35–2.47, and 2.46–2.58, respectively. Study concluded that the among all the rib arrangements, V-down discrete rib roughness has the highest thermohydraulic performance. Hans et al. [17] reported that use of multiple v-rib roughness on the underside of absober plate improved the thermal as well as thermohydraulic performances of a solar air heater as compared to those of single v-rib roughened solar air heater. Aharwal et al. [9], Singh et al. [11] and Kumar et al. [18]

reported that thermal and thermo-hydraulic performances of solar air heaters further improved by a gap in an inclined rib, V-rib and Multi-V rib, respectively. The results of these studies showed that the creation of a gap at the optimum location in a rib considerably enhances the heat transfer rates compared to continuous inclined rib due to creation of high heat transfer region downstream of gap. In all studies, the gap width equal to rib height was reported to be the optimum gap width. In an attempt to further increase the performance of Solar air heater, Patil et al. [19] studied the effect of broken V-rib roughness combined with staggered ribs on heat transfer and friction in a flow through artificially roughened solar air heater duct. The experimentations were performed to collect the data by varying the Reynolds number (Re) between 3000 and 17,000, relative gap position (s′/s) from 0.2 to 0.8, for the fixed values of relative staggered rib pitch p′/p = 0.6, relative staggered rib size r/e = 1, relative roughness pitch p/e = 10, relative roughness height e/Dh = 0.043, relative gap size g/e = 1, and angle of attack α = 60°. It was reported that V rib roughness with gap combined with staggered rib piece significantly enhanced the heat transfer rates as compared to v-rib with gap. The enhancement in Nusselt number lies between 1.77 and 3.18. The maximum value of Nusselt number and friction factor were observed at relative gap position of 0.6, relative staggered rib position of 0.6, and relative staggered rib size of 2.5.

On the basis of above studies, it can be concluded that V-down ribs perform better than V-up ribs, which in-turn perform better than angled or orthogonal ribs. In addition to this, the studies have shown that ribs having gap perform better than continuous ribs [9, 11, 18, 20] and broken ribs combined with staggered rib pieces outperform ribs having gap [19]. Review of literature revealed that still no study is available on broken arc rib roughness combined with staggered rib piece. Therefore, it appears fruitful to investigate broken arc rib roughness combined with staggered rib piece. In the present investigation, it has planned to explore the effect of gap size on the heat transfer and friction in a solar air heater duct. Extensive experimentations have been conducted in the Reynolds number range of 2000-16000 to generate data pertaining to heat transfer and friction for fully developed turbulent flow through an artificially roughened solar air heater duct. Based on data generated, the variation of Nusselt numbers, friction factors and thermo-hydraulic performance parameter of the roughened ducts as function of relative gap width have been determined to ensure the benefit of roughness geometry selected in this study. Further, the variation of thermo-hydraulic parameter for continuous arc rib has been investigated and compared under similar conditions in order to determine the advantage of duct roughened by broken arc shaped ribs combined with staggered rib piece over continuous arc rib.

II. RIB ROUGHNESS GEOMETRY AND RANGE OF PARAMETERS

The artificial rib roughness was created by fixing aluminium wires of circular cross-section on the underside of absorber plates of solar air heater duct. The general geometry of roughness having broken arc ribs combined with staggered rib piece is shown in Fig. 1. The rib roughness can be described by the values of rib height (e), rib pitch (P), arc angle (α), half width of duct (w), gap position from the side of duct (w’), staggered rib size (r) and staggered rib position (P’) To determine the Nusselt number, friction factor and thermo-hydraulic performance parameter due to change in relative gap size (g/e), the values of flow and roughness parameters considered in this study are given in Table 1. The fixed roughness parameters have been selected on the basis of their optimum values proposed by previous investigators Mulluwork [4], Saini and Saini, [21] , Singh et al. [11], Patil et al. [19].

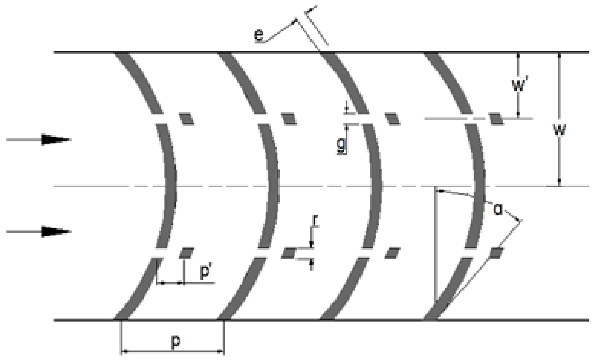

Fig. 1 Roughness geometry

Table 1. Range/values of roughness and flow parameters.

S. No.	Parameter	Range
1.	Reynolds number, Re	2000–16000
2.	Relative gap width, (g/e)	0.5-2.5
3.	Relative gap position, (w’/w)	0.65
4.	Relative staggered rib position, p’/p	0.6
5.	Relative staggered rib size, r/g	2.0
6.	Relative roughness pitch, p/e	10
7.	Arc angle, (α)	30°
8.	Relative roughness height, e/D_h	0.043

III. DESCRIPTION OF EXPERIMENTAL SETUP

An experimental test facility has been designed and fabricated to study the effect of gap width in broken arc ribs combined with staggered rib piece geometry on the heat transfer and fluid flow characteristics of a rectangular duct. A schematic diagram of experimental set up has been shown in Fig. 2. The wooden rectangular duct has an internal size of 2440 mm x 300 mm x 25 mm which consists of entrance section, test section and exit section of lengths of 550 mm, 1000 mm and 890 mm respectively in accordance with the recommendation of ASHARAE standard 93-77 [22]. 1 mm thick galvanized iron sheet having artificial roughness is used as the top broad wall of the rectangular duct. The absorber plate was heated from the top by supplying a constant heat flux by means of an electrical heater. In order to minimize the heat loss from the topside of the heater assembly, the electric heater was fitted over a box made of 12 mm thick plywood, of size 2440 mm×390 mm×100 mm. The hollow inner space of the heater box was filled with glass wool (i.e. 76 mm thick). The complete duct was further insulated with 50 mm thick polystyrene insulation having thermal conductivity of 0.037 W/(m-K) to minimize heat loss to the environment. A calibrated orifice meter connected with a U- tube manometer having kerosene as manometric fluid was used to measure the mass flow rate of air. Calibrated butt-welded copper-constantan thermocouples were used to measure the air and the absorber plate temperatures at different locations. The pressure drop across the test section was measured by digital micro-manometer having a least count of 0.001 Pa.

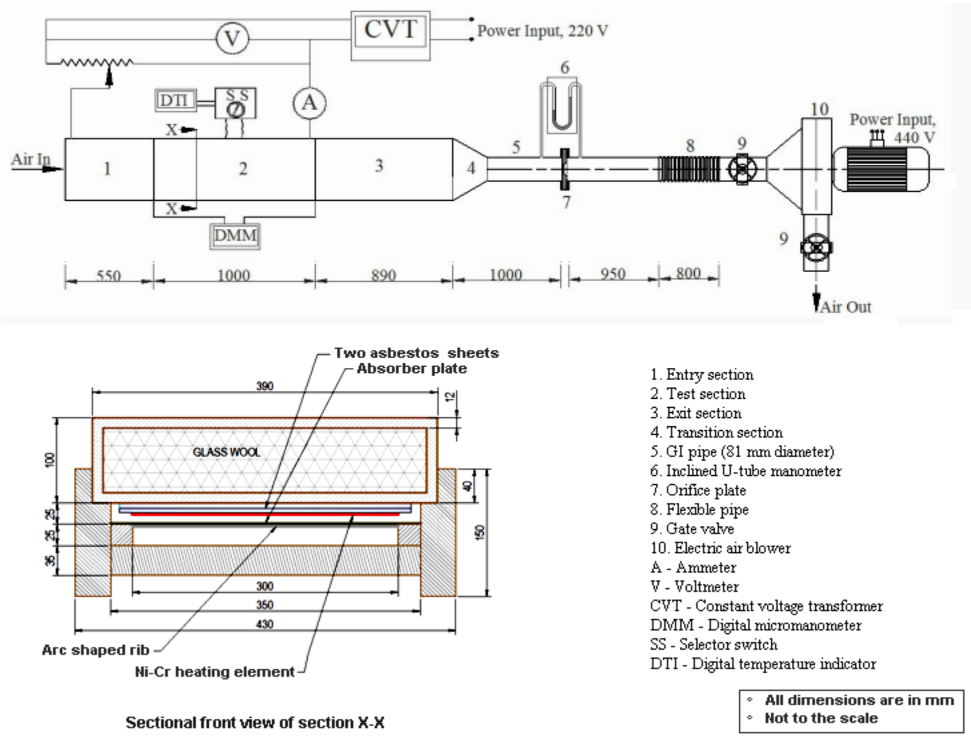

Fig. 2 Schematic of experimental setup

IV. EXPERIMENTATION

The experimental data on rib roughened duct pertaining to heat transfer and flow friction were collected in accordance with recommendation of ASHRAE Standard 93-77 [22]. The roughened plates having broken arc shaped ribs combined with staggered rib piece roughness were tested for different values of relative gap width. In order to compare the results of broken arc shaped ribs combined with staggered rib piece roughened duct with that of smooth duct and continuous arc rib roughened duct, a smooth plate and a continuous arc rib roughened plate were also tested under similar conditions. At the start of each set of experiment, it was ensured that all instruments were working properly and there was no leakage at the joints. All the data were collected under steady state conditions which were assumed to have been reached when the plate and air temperatures do not show any variation for around 10-minutes duration. The steady state for each test run was obtained in about 2-3 hours. The parameters recorded for each set of experiment were inlet air temperature, outlet air temperature at five points in the span-wise direction of the duct, temperature of the heated plate at sixteen locations, pressure drop across the orifice plate and pressure drop across the test section.

Air mass flow rate (m), heat transfer rate to air (Q_u), heat transfer coefficient (h), Nusselt number (Nu) and friction factor (f) have been calculated using the following equations:

$$\dot{m} = C_d\, A_o \left[\frac{2\,\rho_{air}\,(\Delta P)_o}{1-\beta^4}\right]^{0.5} \quad (1)$$

$$Q_u = \dot{m}\, C_p\,(T_o - T_i) \quad (2)$$

$$h = \frac{Q_u}{A_p\left(T_{pm} - T_{fm}\right)} \quad (3)$$

$$Nu = \frac{h\, D_h}{K_{air}} \quad (4)$$

$$f = \frac{2\,(\Delta P)\,\rho_{air}\, D_h}{4\, L_f\, G_{air}^{\,2}} \quad (5)$$

In the above calculations, air properties correspond to mean air temperature.

V. Results and Discussion

A. *Heat transfer characteristics and friction factor characteristics*

The variation of Nusselt number and friction factor with Reynolds number for relative gap width (g/e) of 0.5, 1.0, 1.5, 2.0 and 2.5 has been shown in Figs. 3 and 4 respectively. It can be observed that the Nusselt number increases and friction factor decreases with the increase in as Reynolds number (Re) from 2000 to 16000 for different values of relative gap width. For all Reynolds numbers, the highest value of Nusselt number and friction factor has been observed corresponding to relative gap width of 1.0, and it declines on both side of this value of relative gap width. This variation in Nusselt number and friction factor is due to the variation in turbulence near the staggered rib region caused by mixing of two vortices moving along the staggered rib with the main flow. The variation of turbulence further depends on two factors (i) velocity of air (ii) flow rate of air released from the gap toward the staggered rib piece. Large velocity of air through gap causes more turbulence that results in increase in Nusselt number and friction in flow, whereas smaller flow rate of air through gap causes lesser turbulence that results in decrease in Nusselt number and friction in flow. So the amount of turbulence in the flow is the combined effect of velocity and flow rate of air released through the gap. It is anticipated that for the present study, the combined effect of these two factors is more for relative gap width value of 1.0 which resulted in highest value of average Nusselt number and friction factor at relative gap width value of 1.0. The results are in general agreement with previous study on inclined rib having gap [9], V-rib with gap [11] and multiple V rib with gap [18].

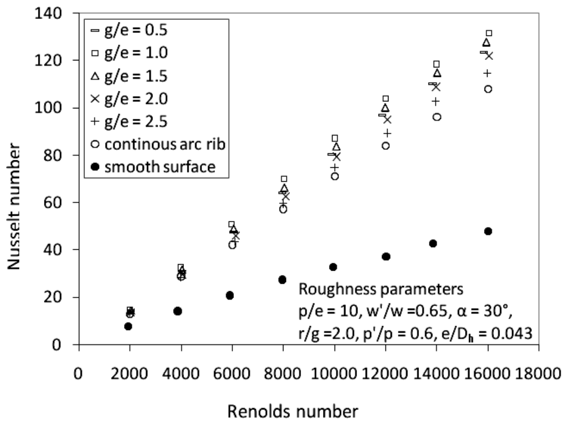

Fig. 3. Variation of Nusselt number with Reynolds number for different values of relative gap width (g/e).

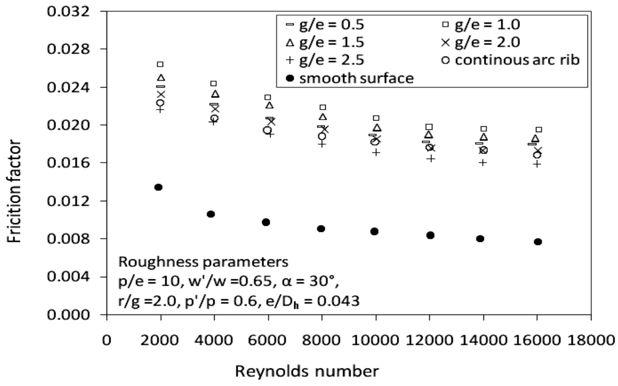

Fig. 4. Variation of friction factor with Reynolds number for different values of relative gap width (g/e).

As the considerable rise has been observed in the value of Nusselt number and friction factor due to the presence of roughness in comparison to the smooth surface for all the values of relative gap width (Figs. 3 and 4) so there is need to quantify the enhancement in Nusselt number and friction factor as a result of roughness over smooth surface. In order to do so the values of the Nusselt number enhancement (Nu/Nus) and friction factor enhancement (f/fs) are presented in Figs. 5 and 6. It is clear from these Figures that gap width considerably affects the Nusselt number enhancement and friction factor enhancement. The maximum enhancement in Nusselt number and friction factor corresponds to relative gap width (g/e) value of 1.0 than at other values of relative gap width. Nusselt number enhancement increases with increase in Reynolds number up to 12000 and then decreases with further increase in Reynolds number. On the other hand, friction factor enhancement goes on increasing with increase in Reynolds number and attained maximum value corresponding to Reynolds number value of 16000. The maximum enhancement in Nusselt number has been found to be 177% at Reynolds number value of 12000 with simultaneous enhancement in friction factor of 137%.

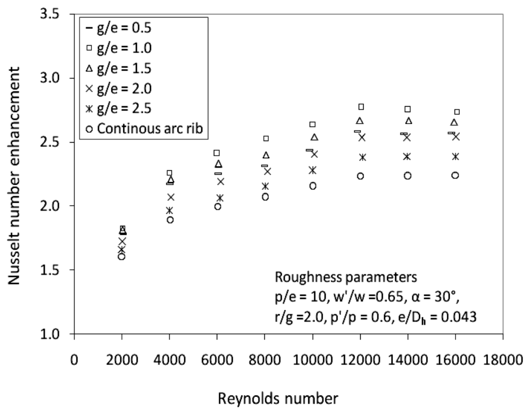

Fig 5 Nusselt number enhancement (Nu/Nus) as a function of Reynolds number for different relative gap width (g/e)

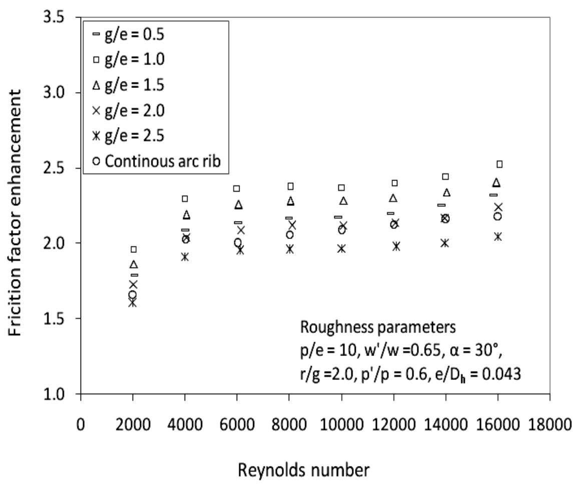

Fig.6. Friction factor enhancement (f/fs) as a function of Reynolds number for different relative gap width (g/e)

B. Thermo-hydraulic performance

It has also been observed from Figures 3 and 4 that the maximum values of Nusselt number and friction factor correspond to relative gap width of 1.0, thereby, meaning that an enhancement in heat transfer is accompanied by friction power penalty due to a corresponding increase in the friction factor. Therefore, it is essential to determine the effectiveness and usefulness of the roughness geometry in context of heat transfer enhancement and accompanied increased pumping losses. In order to achieve this objective, Webb and Eckert [23] proposed a thermo-hydraulic performance parameter 'η', which evaluates the enhancement in heat transfer of a roughened duct compared to that of the smooth duct for the same pumping power requirement and is defined as,

$$\eta = \frac{Nu/Nu_s}{(f/f_s)^{1/3}} \qquad (6)$$

The value of this parameter higher than unity ensures that it is advantageous to use the roughened duct in comparision to smooth duct. The thermo-hydraulic parameter is also used to compare the performance of number of roughness arrangements to decide the best among these. The variation of thermo-hydraulic parameter as a function of Reynolds number for different values of relative gap width (g/e) and for fixed values of other roughness parameters (p/e = 10, w'/w =0.65, α = 30°, r/g =2.0, p'/p = 0.6, e/Dh = 0.043) investigated in this work has been shown in Fig. 7. For all values of relative gap widths, value of performance parameter is more than unity. Hence the performance of solar air heater roughened with broken arc shaped ribs combined with staggered rib piece is better as compared to smooth duct. It is also observed that the value of this parameter is maximum corresponding to relative gap width of 1.0 and it decreases on both sides of this gap width for all values of Reynolds number investigated. This result indicates that it is advatageous to use broken arc rib combined with staggered rib piece having gap width equale to 1.0 as compared to other values of relative gap widths. The highest value of thermo-hydraulic performance parameter obtained is 2.08 at Reynolds numbet of 12000.

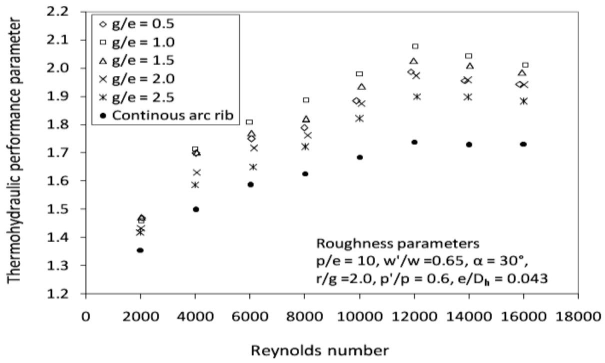

Fig.7.Thermo-hydraulic performance parameter as a function of Reynolds number for different relative gap width (g/e)

Further, in order to determine the advantage of duct roughened by broken arc shaped ribs combined with staggered rib piece over continuous arc rib, the variation of thermo-hydraulic parameter 'η' for continuous arc rib, having relative roughness pitch of 10, arc angle of 30° and relative roughness height of 0.043, has also been ploted in Fig. 9 under similar conditions. It can be seen that the value of thermo-hydraulic parameter parameter is higher for broken arc shaped ribs combined with staggered rib piece as compared to that for a continuous arc rib. Therefore the roughness geometry, broken arc shaped ribs combined with staggered rib piece is thermo-hydraulically better.

VI. CONCLUSIONS

The experimental investigations were conducted on solar air heater duct roughened with broken arc shaped ribs combined with staggered rib piece. The staggered rib piece was fixed at a distance of 0.6 of the main arc rib pitch on the downstream side of gap. The following conclusions are drawn from the present study:

(I) Relative gap width has strong influence on Nusselt number and friction factor of solar air heater duct roughened with broken arc shaped ribs combined with staggered rib piece.

(II) Nusselt number and friction factor are highest at relative gap width equal to rib height and decrease on both sides of this gap width.

(III) Relative gap width equal to rib height yields maximum enhancement in Nusselt number as compared to that of smooth duct for the range of Reynolds number investigated. The highest enhancement in Nusselt number is 177% at Reynolds number of 12000 with corresponding enhancement in friction factor of 137%.

(IV) The highest thermo-hydraulic parameter obtained is 2.08 corresponding to relative gap width value of 1.0 at Reynolds numbet of 12000.Further, in order to determine the advantage of duct roughened by broken arc shaped ribs combined with staggered rib piece over

NOMENCLATURE

A_o	orifice area (m^2)
A_p	absorber plate area (m^2)
AR	Aspect ratio
C_d	discharge coefficient = 0.617 (determined through calibration)
C_p	constant pressure specific heat (J/kg K)
D_h	hydraulic diameter (m)
e/D_h	relative roughness height
e	rib height (m)
f	roughened duct friction factor
f_s	smooth duct friction factor
G_{air}	mass velocity (kg/s m^2)
H	duct depth (m)
h	convective heat transfer coefficient (W/m^2K)
K_{air}	thermal conductivity (W/m K)
L_f	duct length for pressure drop (m)
	mass flow rate (kg/s)
Nu	roughened duct Nusselt number
Nu_s	smooth duct Nusselt number
P	rib pitch (m)
P/e	relative roughness pitch
Pr	Prandtl number
Qu	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)
W	duct width (m)
α	Arc angle (°)
ΔP_o	pressure drop across orifice plate (N/m^2)
ΔP	pressure drop across length Lf (N/m^2)
η	thermo-hydraulic performance parameter
ρ_{air}	air density at mean temperature (kg/m^3)
β	orifice diameter to pipe diameter ratio

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