EXPERIMENTAL INVESTIGATION ON OVERALL THERMAL PERFORMANCE OF FLUID-FLOW IN A RECTANGULAR CHANNEL WITH DISCRETE V-PATTERN BAFFLE

by

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This work presents the results of an experimental study of thermohydraulic performance of rectangular channel having discrete V-pattern baffle attached on the broad wall. Measurements have been carried out for the aspect channel ratio of 10, Reynolds number from 3000 to 21000, relative baffle height value of 0.50, relative baffle pitch value of 1.5, relative gap width value of 1.0, flow attack angle value of 60°, and relative discrete distance values of 0.26 to 0.83. The heat transfer and friction factor data obtained were compared with the data obtained from a smooth wall channel under similar operating conditions. In comparison to the smooth wall channel the discrete V-pattern baffle channel enhanced the Nusselt number and friction factor by 3.89 and 6.08 times, respectively. The overall thermal performance parameter is found superior for the relative discrete distance of 0.67. Discrete V-pattern baffle roughness shape has also been shown to be overall thermal performance higher in comparison to other continuous (without discrete) V-pattern baffle shape rectangular channel.

Key words: *baffle surfaces, passive enhancement, single phase convection, thermohydraulic performance*

Introduction

Ever increasing demand of useful energy and depletion of conventional energy resources gives rise to highly energy efficient and compact thermal systems. In the last few decades, more attention is being focused towards performance upgradation of energy exchange devices utilized in solar energy collection and storage systems. Rectangular channel is one of the simplest and widely used types of heat exchanger in which heat energy is being exchanged between absorber wall and air flowing through the system. The major drawback of rectangular channel use is low overall thermal performance due to low heat transfer rate between heated wall and air. In order to attain higher thermal performance, it is desirable that the flow of the heat transfer surface should be turbulent [1-3]. The purpose of introducing baffles in the air channel is to create turbulence, so as to raise the heat transfer rate. In order to create turbulence, baffles are placed into the forced flow to make a secondary flow, or swirl/vortex. These are utilized to rise the heat transfer in various engineering applications, including heat exchangers, vortex combustors, and solar air channels [4]. Baffles with different shapes are used, including delta-shaped, winglets, rectangular-shaped winglets, V-shaped, perforated, and multiple baffles that can be attached and bent away from the plate to create turbulence in

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the flow field, which results in enhanced heat transfer [5]. Various investigators have studied the heat transfer enhancement and pressure drop produced by fixing baffle elements of various shapes, sizes, and orientations an artificial roughness on a heated plate [6-16].

Yeh and Chou [6] improved the collector efficiency of an solar air heater (SAH) duct by attaching fins with baffles on the underside of the collector. Park *et al.* [7] experimentally determined the thermal performance of a rectangular air channel with angled shaped baffles to produce roughness on the heated wall of an SAH. Liu *et al.* [8] used angled baffles as roughness shapes and examined the thermal performance with two opposite baffle-roughened walls for Reynolds number, values in the range of 10 000-80 000. Maurer *et al.* [9] investigated the thermal performance of V-shaped and W-shaped ribs provided on one side or both sides of a test channel for Reynolds number range of 80 000-500 000. Sriromreun *et al.* [10] through experimental predictions of the turbulent fluid-flow and heat transfer characteristics for an air channel with Z-shaped baffles. Mousavi and Hooman [11] carried out a systematic experimental and numerical study on the laminar flow, Nusselt number, and friction factor, f, in an air channel fitted with staggered-baffle tabulators. Experimental work was also carried out to validate their numerical results. Sara *et al.* [12] investigated the local heat transfer in a channel having a flat surface with solid and perforated rectangular blocks. The results were compared with those of parallel channels without blocks. Hwang and Liou [13] examined the effects of perforation baffles on the local Nusselt number and local f in a channel. Their study indicated that perforated baffles had the advantages of eliminating the hot spot and providing better thermal performance. Chamoli and Thakur [14] conducted an indoor experimental investigation to study the local Nusselt number and f values of air passing through an air channel that was roughened by V-shaped perforated baffles. Alam *et al.* [15] experimentally investigated the thermohydraulic performance of a rectangular SAH duct equipped with V-shaped rectangular perforated blocks attached to the heated surface.

As per according to literature review, shows that the transverse baffles shape improves the heat transfer by stream separation and generation of vortices on the upstream and downstream of baffles and reattachment of stream in inter-baffles spaces. By angling (inclined) the baffle, the vortices can move along the baffle, with the fluid entering near the leading end of the baffle and coming out near the trailing end, and subsequently joining the main stream, creating span wise rotating secondary flows, which are responsible for the significant span wise variation of the heat transfer coefficient. V-down pattern baffles of extending angled baffles benefits in the formation of two secondary stream cells as compared to one in the case of an angled baffles resultant in a still higher heat transfer rate. Producing discrete in the inclined baffle is found to augment the heat transfer by breaking the secondary stream and producing higher level of turbulence in the fluid downstream of the baffles. It is a possibility that discrete V-pattern baffle will augment heat transfer compared to without discrete V-pattern baffle. To the best of our knowledge, no such type of experimental study has been reported on a rectangular baffle roughened channel with discrete V-pattern baffle.

Experimental details

Details of experimental set-up

To study the effect of discrete in the limbs of V-pattern baffle turbulent promoter on the Nu_b and f_b of air-flow an experimental set-up was designed and fabricated as per the recommendations of ASHRAE standard [16]. A schematic diagram of an experimental set-up and photographic view are shown in fig. 1. The set-up included a rectangular wooden channel associated to a centrifugal blower through a circular galvanized iron pipe. The rectangular channel had a flow cross-sectional width, W, of 300 mm, height, H, of 30 mm, and W/H of 10. It consisted of inlet and exit sections that were interposed by test sections. The upper wall of the test section was heated by an electric heater that provided a consistent heat flux over the entire top surface. Air mass flow rate through the rectangular channel was calculated with a calibrated orifice meter that was linked to a U-tube manometer. Air-flow was regulated with two gate valves that were linked in the lines. The temperature was measured at various locations with calibrated 0.3 mm diameter Cu constantan thermocouples, which were linked to a digital micro voltmeter (DMV) to display the temperature. The pressure drop across the test section was deliberate with a micro-manometer with a least count of 0.001 mm of water. All data were deliberate under steady-state circumstances.

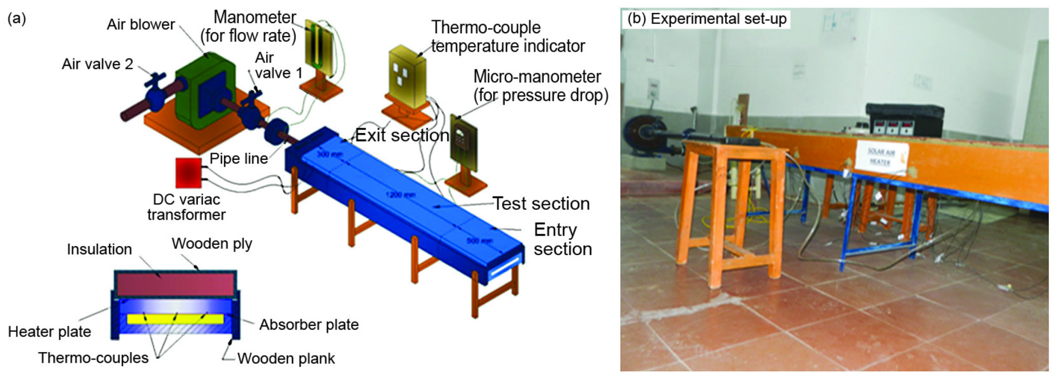

Figure 1. Schematic of experimental set-up; (a) line diagram (b) photographic view

Range of parameters

The rectangular channel has a length of test section L_t = 1200 mm. The height of channel is 30 mm and width is 300 mm, the hydraulic diameter, $D_{hd} = 4A/P = 2H = 54.54$ mm. The 4.0 mm thick wall is made up by aluminium and a constant heat flux equal to 1000 W/m^2 has been applied. The baffle parameters are determined by baffle height, H_b, pitch of baffle, P_b, discrete distance, D_d, gap or discrete width, g_w, length of V-pattern baffle, L_v, angle of attack, α_a, and the shape of the roughness elements. For a specific roughness type, a family of geometrically similar roughness is possible to identify by changing flow angle attack while maintaining constant H_b/H, P_b/H, g_w/H_b, and D_d/L_v. The discrete V-pattern baffle shape is shown in fig. 2, and tab. 1 gives the range of parameters.

Table 1. Range of parameters

S. N .	Parameters	Range
1	Re	3000 to 21000
2	D_d/L_v	0.26-0.83
3	H_b/H	0.50
4	P_b/H	1.5
5	g_w/H_b	1.0
6	α_a	60°

Data reduction

The data collected have been used to compute h_t, Nu, and f. Relevant expressions for the computation of these parameters and some intermediate parameters have been given.

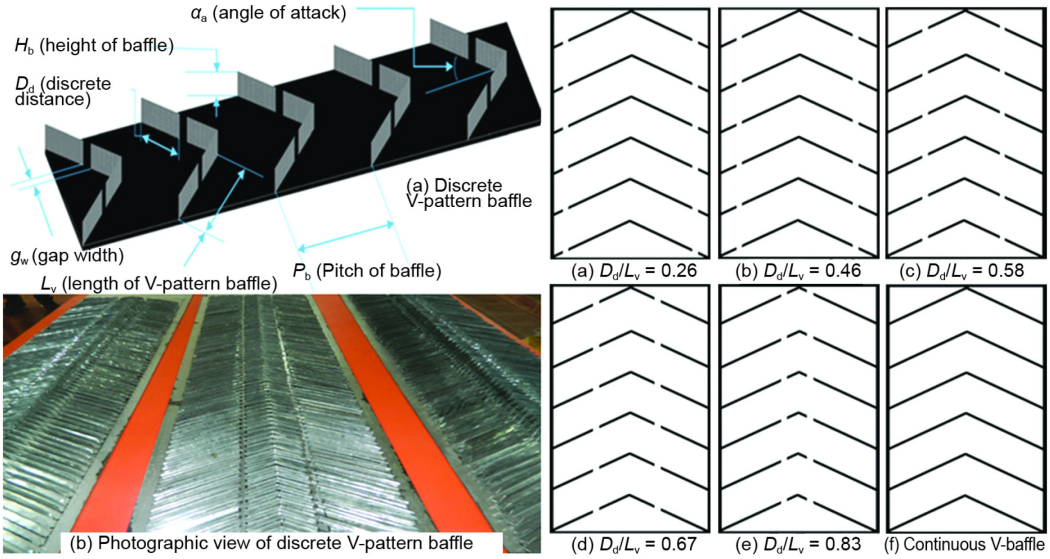

Figure 2. Discussed discrete V-pattern baffle

The mean temperature of the plate is the average of all temperatures of the heated plate:

$$T_p = \frac{\sum T_{pi}}{N} \tag{1}$$

The mean air temperature T_f is a simple arithmetic mean of the measured values at the inlet and the exit temperature of air flowing through the test section:

$$T_f = \frac{T_i + T_o}{2} \tag{2}$$

where $T_o = (T_{A2} + T_{A3} + T_{A4} + T_{A5} + T_{A6})/5$, $T_i = T_{A1}$.

Mass flow rate of air has been determined from the pressure drop measurement across the calibrated orifice meter by using the following formula:

$$m_a = C_{do} A_o \left[\frac{2\rho_a (\Delta p)_0}{1-\beta^4} \right]^{0.5} \tag{3}$$

where $(\Delta p)_0 = 9.81(\Delta p)_0 \rho_a m_a \sin\theta$.

The velocity of air is calculated from the knowledge of mass flow rate and the flow:

$$V = \frac{m_a}{\rho_a WH} \tag{4}$$

The hydraulic diameter is calculated:

$$D_{hd} = \frac{4WH}{2(W+H)} \tag{5}$$

The Reynolds number of air-flow in the duct is calculated from:

$$\mathrm{Re} = \frac{VD_{\mathrm{hd}}}{\nu} \quad]](6)$$

The f is determined from the measured value of $(\Delta p)_{\mathrm{d}}$ across the test section length using the Darcy equation:

$$f = \frac{2(\Delta p)_{\mathrm{d}} D_{\mathrm{hd}}}{4\rho_{\mathrm{a}} L_{\mathrm{t}} V^2} \tag{7}$$

where $(\Delta p)_{\mathrm{d}} = 9.81(\Delta h)_{\mathrm{d}} D_{\mathrm{hd}} \rho_{\mathrm{a}} m_{\mathrm{a}}$.

The heat transfer rate, Q_u, to the air is given by:

$$Q_u = m_{\mathrm{a}} c_p (T_{\mathrm{o}} - T_{\mathrm{i}}) \tag{8}$$

The heat transfer coefficient for the heated test section has been calculated from:

$$h_{\mathrm{t}} = \frac{Q_u}{A_p (T_{\mathrm{p}} - T_{\mathrm{f}})} \tag{9}$$

The h_{t} can be used to determine Nusselt number which is defined:

$$\mathrm{Nu} = \frac{h_{\mathrm{t}} D_{\mathrm{hd}}}{K_{\mathrm{a}}} \tag{10}$$

Validation of experimental data

The values of Nusselt number and f determined from experimental data for a smooth channel have been compared with the values obtained from the Dittus-Boelter eq. (11) for Nusselt number, and modified Blasius eq. (12) for the friction factor [17].

The $\mathrm{Nu_s}$ for a smooth channel is given by the Dittus-Boelter equation:

$$\mathrm{Nu_s} = 0.23\mathrm{Re}^{0.8}\mathrm{Pr}^{0.4} \tag{11}$$

The f_{s} for a smooth channel is given by the modified Blasius equation:

$$f_{\mathrm{s}} = 0.085\mathrm{Re}^{-0.25} \tag{12}$$

The comparison of the experimental and estimated values of $\mathrm{Nu_s}$ and f_{s} as a function of Reynolds number are shown in figs. 3(a) and 3(b), respectively.

Results and discussion

A study was conducted to understand the effect on $\mathrm{Nu_b}$ and f_{b} of the flow Reynolds number and discrete distance in V-pattern baffle used to provide roughness for a rectangular channel. The outcomes concerning with discrete V-pattern baffle channel have been compared with those obtained for the continuous V-pattern baffle and smooth wall channel under similar operating conditions in order to find the enhancement in heat transfer and friction.

Heat transfer and fluid-flow

The effect of $D_{\mathrm{d}}/L_{\mathrm{v}}$ in V-pattern baffle on $\mathrm{Nu_b}$ and f_{b} characteristics is determined foe a rectangular channel with one surface artificially roughened and heated. The values of $\mathrm{Nu_b}$ for fixed values of the $g_{\mathrm{w}}/H_{\mathrm{b}}$ of 1.0, and different values of $D_{\mathrm{d}}/L_{\mathrm{v}}$ is presented in fig. 4.

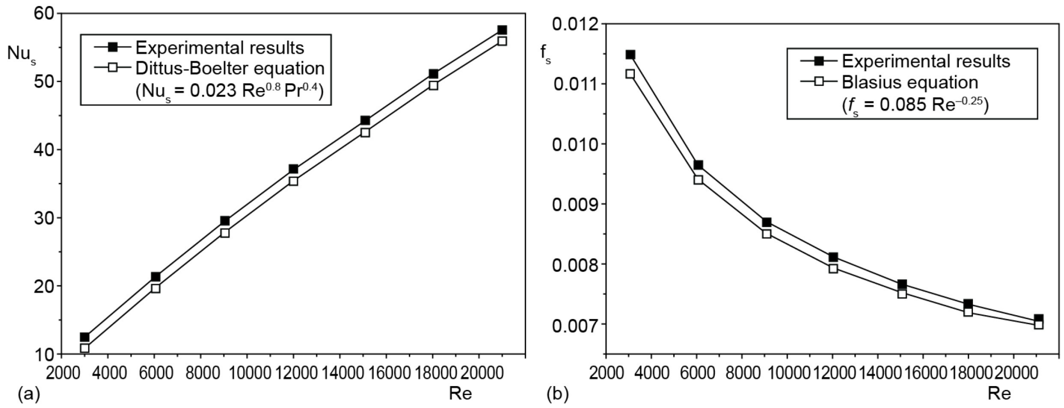

Figure 3. Comparison of experimental and predicted values for smooth wall with Re; (a) $\mathrm{Nu_b}$, (b) f_b

Figure 4(a) shows the variation of $\mathrm{Nu_b}$ with Re at different values of D_d/L_v for a fixed g_w/H_b of 1.0. It can be seen that $\mathrm{Nu_b}$ rise with an rise in D_d/L_v from 0.58 to 0.67, attains a maxima at D_d/L_v of 0.67 and thereafter it decreases with an rise in D_d/L_v. Producing discrete near the leading edge (say at D_d/L_v = 0.26), the force of the secondary stream may not be enough to energize the main stream passing through the discrete and this discrete distance does not lead to major rise in local heat transfer. A rise in values of D_d/L_v (say at D_d/L_v = 0.58) signifies changing of the discrete toward trailing edge. This raises the force of the secondary stream and heat transfer rises with rise in D_d/L_v up to 0.67. Figure 4(b) shows the values of $\mathrm{Nu_b}$ as a function of D_d/L_v for different Reynolds number. It is observed that at any D_d/L_v the values of $\mathrm{Nu_b}$ is the highest for D_d/L_v of 0.67 for all values of Re. Introduction of a discrete in the V-pattern baffle allows discharge of the secondary stream and mix with main stream through the discrete as shown in fig. 5. This results in its acceleration, which energizes the retarded boundary-layer stream along the surface resultant in the rise of the heat transfer through the discrete width area behind the baffles.

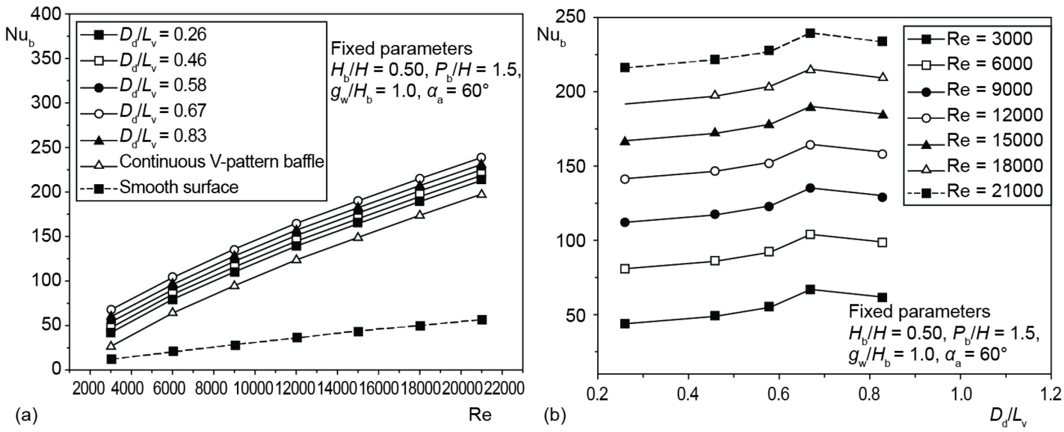

Figure 4. (a) Effect of Reynolds number on $\mathrm{Nu_b}$, (b) effect of D_d/L_v distance on $\mathrm{Nu_b}$

Invariable, use of baffle roughness substantially raise heat transfer from heated wall of rectangular channels. However, there occurs a corresponding rise in frictional losses. The variation of f_b with Reynolds number for different values of D_d/L_v and fixed values of other rib parameters has been shown in fig. 6(a). It is seen that the value of f_b decreases with rise of Reynolds number and towards a constant value as expected. The f_b rises with increase in D_d/L_v of up to 0.67 and reduces with further rise in D_d/L_v. Figure 6(b) clearly shows that the maximum and minimum values of f_b for discrete V-pattern baffle air channel occur for D_d/L_v of 0.67 and 0.26, respectively.

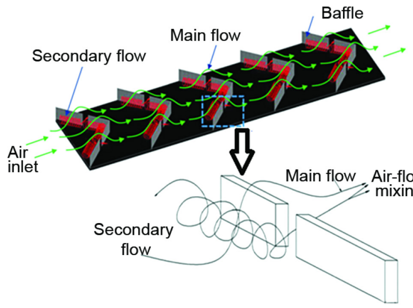

Figure 5. Secondary flow pattern in discrete V-pattern baffle

Thermohydraulic performance

The experimental outcomes predicted an increase in Nu_b with rises D_d/L_v, however, f_b also rises. The rectangular channel efficiency, therefore, depended on these two parameters. The rectangular channel performance enhancement owing to the baffle roughness is normally evaluated on the base of the overall performance parameter, which includes both the thermal and hydraulic concerns. The overall performance parameter was defined as the overall enhancement ratio and expressed [8-15]:

$$\eta = \frac{\dfrac{Nu_b}{Nu_s}}{\left(\dfrac{f_b}{f_s}\right)^{0.33}} \tag{13}$$

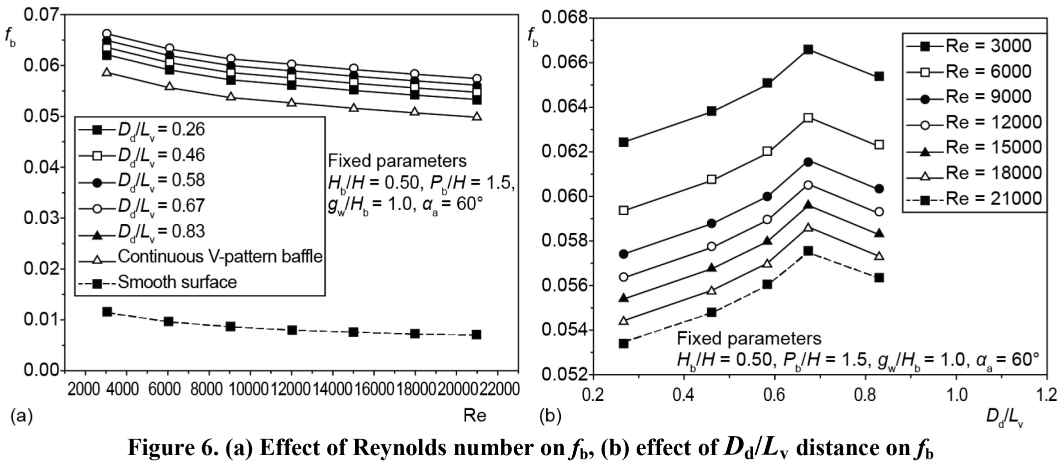

Figure 6. (a) Effect of Reynolds number on f_b, (b) effect of D_d/L_v distance on f_b

It is apparent that only a heated surface roughness that yields a performance parameter value greater than unity is useful. The higher the value of this parameter the better the air channel performance. Figure 7(a) shows the $\eta = (Nu_b / Nu_s)/(f_b/f_s)^{0.33}$ for the rectangular channel with various values of D_d/L_v for Reynolds number range from 3000 to 21 000. It rise with rises in D_d/L_v up to about 60° and then decreased with further rises in D_d/L_v at all Reynolds number values. Therefore, attained a maximum at a flow attack angle of about 60°. Figure 7(b) shows the values of the η as a function of D_d/L_v for different Reynolds number. It is observed that at any D_d/L_v, the values of $\eta = (Nu_b / Nu_s)/(f_b/f_s)^{0.33}$ is the highest for the D_d/L_v of 0.67 for all values of Reynolds number.

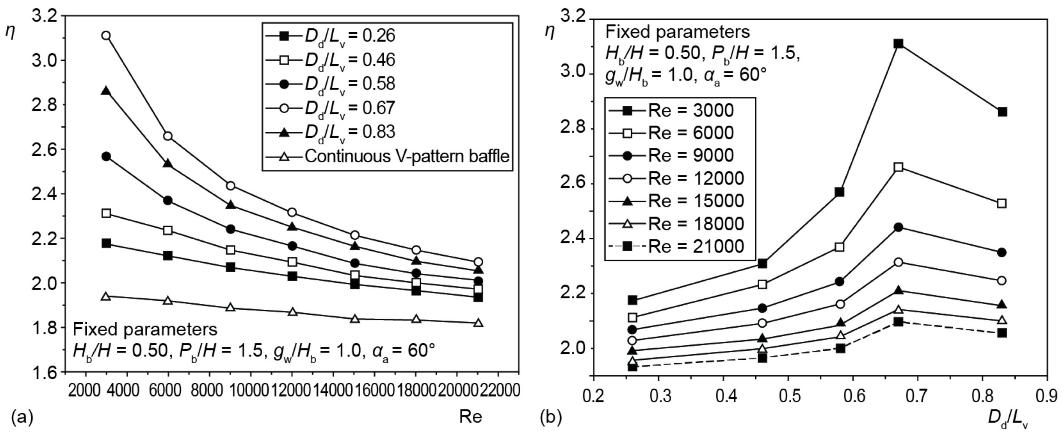

Figure 7. (a) Effect of Reynolds number on η, (b) effect of D_d/L_v on η

Conclusions

On the basis of experimental investigation of Nu_b, f_b, and $\eta = (Nu_b/Nu_s)/(f_b/f_s)^{0.33}$, of rectangular channel fitted with discrete V-pattern baffle shape on the underside of the heated wall, the following conclusions can be drawn from the current work.

- Discrete V-pattern baffle rectangular channel roughness raised heat transfer significantly, and the heat transfer enhancement is a strong function of discrete distance. This reflects that the high-velocity secondary stream jet approaches the V-pattern baffle and creates supplementary turbulence as outcomes of flow separation and reattachment.
- The Nu_b and f_b rise with rise in D_d/L_v attains a maximum value corresponding to D_d/L_v value of 0.67 and with further rise in the value of D_d/L_v, the Nu_b and f_b are found to decrease. The value of Nu_b and f_b is highest for $D_d/L_v = 0.67$ and lowest for $D_d/L_v = 0.26$.
- The optimum value of $\eta = (Nu_b / Nu_s)/(f_b/f_s)^{0.33}$ has been found corresponding to $D_d/L_v = 0.67$. Also, the maximum value in the $\eta = (Nu_b / Nu_s)/(f_b/f_s)^{0.33}$ has been found to be 3.1 corresponding to $D_d/L_v = 0.67$ at Re = 3000 in the range of parameters investigated.
- Discrete V-pattern baffle shape rectangular channel has been found to be better overall thermal performance as comparison to without discrete V-pattern baffle shape rectangular channel.

Nomenclature

A	– area of the channel cross-section, [m^2]
A_p	– surface area of heated plate, [m^2]
A_o	– area of orifice, [m^2]
C_{do}	– coefficient of discharge
c_p	– specific heat of air, [Jkg^{-1}K^{-1}]
D_d	– gap or discrete distance, [m]
D_{hd}	– hydraulic diameter of channel, [m]
D_d/L_v	– relative discrete distance
f	– friction factor
f_b	– friction factor of roughened baffle
f_s	– friction factor without baffle channel
g_w	– gap or discrete width, [m]
g_w/H_b	– relative gap width
h_t	– convective heat transfer coefficient, [Wm^{-2}K^{-1}]
H	– height of channel, [m]
H_b	– height of baffle, [m]
H_b/H	– relative baffle height
K_a	– conductivity of air, [Wm^{-1}K^{-1}]
L_t	– length of test section, [m]
L_v	– length of V-pattern baffle, [m]
m_a	– mass flow rate of air, [kgs^{-1}]
Nu	– Nusselt number
Nu_b	– Nusselt number of baffle
Nu_s	– Nusselt number of channel without baffle
P	– perimeter of the channel cross-section, [m]

P_b – pitch of baffle channel, [m]
P_b/H – relative pitch ratio
Pr – Prandtl number
$(\Delta p)_d$ – pressure drop across test section, [Pa]
$(\Delta p)_0$ – pressure drop across orifice plate, [Pa]
Q_u – useful heat gain, [W]
Re – Reynolds number
T_f – average temperature of air, [K]
T_i – inlet temperature of air, [K]
T_o – outlet temperature of air, [K]
T_p – plate temperature of air, [K]
V – velocity of air, [ms^{-1}]
W – width of channel, [m]

Greek symbols

α_a – angle of attack, [°]
β – ratio of orifice meter to pipe diameter
η – thermohydraulic performance
ν – kinematic viscosity of air, [m^{2}s^{-1}]
ρ_a – density of air, [kgm^{-3}]

References

[1] Kumar, A., Kim, M. H., Thermo-Hydraulic Performance of Rectangular Ducts with Different Multiple V-Rib Roughness Shapes: A Comprehensive Review and Comparative Study, *Renewable and Sustainable Energy Reviews, 54* (2016), Feb., pp. 635-652
[2] Kumar, R., *et al.*, Experimental Investigation of Effect of Flow Attack Angle on Thermohydraulic Performance of Air Flow in a Rectangular Channel with Discrete V-Pattern Baffle on the Heated Plate, *Advances in Mechanical Engineering*, *8* (2016), 5, pp. 1-12
[3] Kumar, A., Kim, M. H., Convective Heat Transfer Enhancement in Solar Air Channels, *Applied Thermal Engineering, 89* (2015), Oct., pp. 239-261
[4] Sethi, M., *et al.*, Correlations For Solar Air Heater Duct with Dimpled Shape Roughness Elements on Absorber Plate, *Solar Energy, 86* (2012), 9, pp. 2852-2861
[5] Kumar, A., *et al.*, Experimental Investigation on Heat Transfer and Fluid Flow Characteristics of Air Flow in a Rectangular Duct with Multi V-Shaped Rib with Gap Roughness on the Heated Plate, *Solar Energy, 86* (2012), 6, pp. 1733-1749
[6] Yeh, H. M., Chou, W., Efficiency of Solar Air Heaters with Baffles, *Energy, 16* (1991), 7, pp. 983-987
[7] Park, J. S., *et al.*, Heat Transfer Performance Comparisons of Five Different Rectangular Channels with Parallel Angled Ribs, *International Journal of Heat and Mass Transfer, 35* (1992), 11, pp. 2891-2903
[8] Liu, J., *et al.*, Heat Transfer Characteristics in Steam-Cooled Rectangular Channels with Two Opposite Rib-Roughened Walls, *Applied Thermal Engineering, 50* (2013), 1, pp. 104-111
[9] Maurer, M., *et al.*, An Experimental and Numerical Study of Heat Transfer and Pressure Losses of V and W Shaped Ribs at High Reynolds Number, *Proceedings, ASME Turbo Expo, 4* (2007), May, pp. 219-228
[10] Sriromreun, P., *et al.*, Experimental and Numerical Study on Heat Transfer Enhancement in a Channel with Z-Shaped Baffles, *International Communication of Heat and Mass Transfer, 39* (2012), 7, pp. 945-952
[11] Mousavi, S. S., Hooman, K., Heat and Fluid Flow in Entrance Region of a Channel with Staggered Baffles, *Energy Conversion and Management, 47* (2006), 15-16, pp. 2011-2019
[12] Sara, O. N., *et al.,* Thermal Performance Analysis for Solid and Perforated Blocks on a Flat Surface in a Duct Flow, *Energy Conversion and Management, 41* (2000), 10, pp. 1019-1028
[13] Hwang, J. J., Liou, T. M., Heat Transfer in a Rectangular Channel with Perforated Turbulence Promoters using Holographic Interferometry Measurement, *International Journal of Heat and Mass Transfer, 38* (1995), 17, pp. 3197-3207
[14] Chamoli, S., Thakur, N. S., Correlations for Solar Air Heater Duct with V-Shaped Perforated Baffles as Roughness Elements on Absorber Plate, *International Journal of Sustainable Energy, 85* (2013), Nov., pp. 73- 81
[15] Alam, T., *et al.*, Experimental Investigation of Thermo Hydraulic Performance of a Rectangular Solar Air Heater Duct Equipped with V-Shaped Perforated Blocks, *Advanced in Mechanical Engineering, 94* (2014), Jan., pp. 83-13
[16] *** ASHRAE Standard 93, Method of Testing to Determine the Thermal Performance of Solar Collectors. American Society of Heating, Refrigeration and Air Conditioning Engineers, Atlanta, Geo, USA, 2003
[17] Taslim, M. E., *et al.,* Experimental Heat Transfer and Friction in Channels Roughened with Angled, V-Shaped, and Discrete Ribs on Two Opposite Walls, *ASME J. Turbomach, 118* (1996), 1, pp. 20-28

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