Al-Nahrain Journal for Engineering Sciences (NJES) Vol.20 No.1, 2017 pp.281 - 291

The Combined Effect of Rib with Single Large Eddy Break Up Devices on Flow and Heat Transfer Characteristic of Turbulent Flow in Rectangular Duct

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Abstract:

An experimental investigation has been performed to study the effect of combined artificially roughened (ribs) with and without single Large Eddy Break-Up Devices, on flow and heat transfer characteristic of fully developed turbulent flow in rectangular duct. The aspect ratio of rectangular duct is 10, hydraulic diameter 72.72 mm, relative roughness pitch (P/e) 10 and relative roughness height (e/D_h) 0.05. The rib was in the form of circular shape with diameter of (4mm) which was mounted on heated wall of duct at spanwise direction. The experiments have been conducted by varying airflow rate in terms of Reynolds number ranging from $3.2x10^4$ to $6.2x10^4$ and constant heat flux of $600W/m^2$. The heat transfer and friction factor of the flow for rib and combined method were compared with those of a smooth duct under similar experimental conditions. It has been found that the combined method (rib with single Large Eddy Break-Up Devices) has significant effect on the friction factor and heat transfer with decreasing in friction factor with percent(1.2) and increasing Nusselt number with (4.1). Correlations for Nusselt number and friction factor in terms of (Reynolds number and Large Eddy Break-Up Devices) parameters are found which reasonably correlate the experimental data.

Keywords: Drag reduction; turbulence manipulation; large-eddy break-up devices.

Introduction:

Different techniques can be used to activate enhancement of heat transfer coefficient over surface. These techniques can be classified into active, passive and combined methods (passive and active or passive and passive). In the active method heat transfer is improved by supplying extra energy to the fluid or the equipment. While the passive methods can be acquired without any external energy. The use of rib is one of the passive heat transfer technique. Several investigations have been conducted to study the effect of rib parameters on heat transfer and friction factor characteristics [1].

Sriharsha and Prabhu [2], Kumar , Saini et al. [3]and Madhukeshwara and Prakash [4] investigated experimentally the effect of artificial relative roughness (p/e) of (10 - 10.2) , relative roughness height (e/D) of (0.015,0.04,0.043,0.065,0.1, 0.2 and 0.25) and wedge angle (30^o,60^o and 90^o) on the friction factor and heat transfer coefficient for different rang of Reynolds number(3000 to 30000) , it was found that increasing in Nusselt number and friction factor about (1.4 to 2.87) times respectively, as compared to the smooth surface. Lee and Rhee [5] and Tanda [6] studied the effect of channel aspect ratio and relative roughness pitch (p/e) (6.66,10,13.3 and 20) on local heat/mass transfer and the friction losses in rectangular channel with two different V-shaped rib configurations, which are continuous V-shaped rib configuration with a 60^o and 45^o attack angle at range of Reynolds number(9000-35500).The maximum enhancement in Nusselt number and friction factor range is about to be (1.2-2.57) and (2.6-4.3) times that of the smooth duct respectively. Aharwal and Gandhi [7] and Baraskar , Aharwal and Lanjewar [8] investigated the effect of artificial roughness in the form of repeated inclined roughness at rectangular duct with and without gap on the heat transfer and friction factor characteristics. Also the effect of gap position and gap width were taken into investigation for the range of flow Reynolds numbers (3000 to 18,000). It was found that maximum enhancement in Nusselt number range (2.57-2.59) and friction factor is observed to be (2.85 and 2.87) times that of the smooth duct. Large Eddy Break up Devices are also passive techniques that used to modify the drag characteristics of the turbulent boundary layer near the outer edge of the boundary layer which decrease boundary layer turbulence so largest effect of this technique is on local skin-friction coefficients. Roth [9] investigated the cell diameter of honeycome Large Eddy Break up Devices and its height on the reduction of mean wall shear stress and the structure of turbulent boundary layer. It was found that the reduction of mean wall shear stress and local skin friction coefficient at least 10%. Hollis[10] investigated the effect of inserted Large Eddy Break up Devices in the inner wall region on the turbulence characteristics for fully developed pipe flow. It was found that the existence of Large Eddy Break up Devices at inner wall region boundary layer have significant effect on the turbulence structure of the flow downstream of the device. Kuzenkov [11] investigated the effect of the Large Eddy Break up Devices geometry (length of plate and height above surface) and the boundary layer Reynolds number on the effectiveness of the reduction local surface friction coefficient in the boundary layer. It was found that the presence of LEBU devices in the turbulent boundary layer leads to a decrease in the frequency of decelerated-fluid ejection from the wall region into the outer region of the boundary layer. The enhancement of heat transfer by using artificial roughness is associated with a substantial increase in friction factor. It is, therefore, desirable to select combined technique such that the heat transfer is maximized while keeping the friction loss at the minimum possible value. Sommer and Petrie [12] investigated combination effects of a tandem set of large eddy breakup (LEBU) devices with water injected into a turbulent boundary layer flow on the diffusion of drag-reducing polymer solution. A passive contaminant was the diffusion rate of water that the diminished by the (LEBU) devices over a distance of only 10 to 15 boundary layer thicknesses before returning to the case of an unmodified flow. Inaoka and Suzuki [13] investigated experimental study performed of a flat plate turbulent boundary layer disturbed by insertion of a Large Eddy Break-Up (LEBU) plate with a vortex generator. The Large Eddy Break up Devices plate , height(H) of the vortex generator (s) and the angle of attack of the vortex generator and both s and α were changed in three steps,(s = 5, 10, 15 mm), ($\alpha = 10^o,20^o,30°$) and the elevation height of vortex was also changed from (7 mm to 24 mm). It was found that the deterioration in heat transfer caused by the insertion of a LEBU plate could be recovered by attaching the vortex generator to it, and was also found that intensification of the near-wall turbulence may play some role on heat transfer enhancement, particularly, in the up wash fluid region. Gudilin [14] studied the combination effects of Large Eddy Breakup Devices (LEBUs) and longitudinal riblets on reduction of turbulent friction at square section of wind tunnel. It was found that using the combination of LEBUs and riblets makes it possible to reduce the total turbulent friction drag of a flat plate 1800 mm long by 16%. The objective of the present work is to investigate the effect of the combined Single Large Eddy break up Devices with artificial roughness in spanwise direction on thermal and flow characteristic in rectangular channel for turbulent flow at range of Reynolds number ($3.2x10^4$ up to $6.2x10^4$) and constant heat flux of ($600 w/m^2$).

Experimental Apparatuses:

An experimental test facility has been designed and fabricated as shown in Fig.(1A, B and C) , it consists of a wind tunnel, setling chamber, centrifugal blower which suck air at room temperature to wind tunnel through bell mouth, travers mechanism to hold probe and heating arrangement. A honeycomb was placed at entry of wind tunnel to provide fairly uniform flow with a minimum turbulence intensity in the wind tunnel. The wind tunnel has a rectangular cross section with dimension width of (400 mm), height of (40 mm) , aspect ratio of 10:1 and hydraulic diameter (72.72 mm). This aspect ratio was considered large enough to ensure the required two-dimensions in the present work. The tunnel consists of an entrance section, a test section and an exit section with length of (2250 mm), (1000 mm) and (1050 mm) respectively. A (7 mm) thick heated Aluminum plate (T-30) was used as a lower surface of channel. A heater with 5 mm thickness was sandwiched between two layers of a 0.1 mm thick Mica covered by two layers of 0.5 mm thick galvanize plate, one of this layer was underneath of heating surface, while the other was insulated with 50 mm thickness of fiber glass and 5 mm thickness of wooden layer to reduce the loses to ambient. The heated wall temperature was measured using (27) thermocouples type-K and (30) thermistors temperature sensor and connected to a digital thermometer type (U3-HV) through extension wire type-K, these sensors were distributed in (z-x) plane, as shown in table (1). A(10 mm) thick Perspex was used as an upper surface of channel, and (25) static pressure taps were located at upper surface to measure pressure drop through channel. (19) of these taps were located at centerline streamwise of the channel, while (6) were in the spanwise direction. These taps were machined by drilling a hole from the inner face of the upper surface with 1 mm to depth 4 mm and then enlarged to 4 mm diameter, each hole has a plastic plug to lock the hole if no measurement taken (Shaw 1960) .Twelve (Y-Z) plane identified by slots with spaced (100 mm) have been selected for the velocity and temperature measurement, the first slot was located at (x/b= 115). For each plane the mesh reading in (Y-Z) plane was (10x4) points. These slots were covered by slides with the same material of upper surface. The measurement slides were drilled with a number of holes, (the hole dimension depends on the device dimension used for measuring). The side walls of channel were constructed from Mica sheet with thickness of (10) mm. All the measuring data in general were recorded along the upper surface for static presser and lower surface for temperature data.

Combined Rib and Large Eddy Break up Devices (Test Section):

The test section of (1000 mm) heated plate consists of (500 mm) smooth surface and (500 mm) of artificially roughened surface, the smooth surface was upstream of rough surface.

This roughness have circular steel ribs with a diameter of (4 mm) and length of (400mm).

These ribs were mounted on heated plate by epoxy in spanwise direction at pitch of (40 mm). The selection of pitch based on optimum value of relative roughness pitch (p/e=10) was reported by Tanda [6]. Single Large Eddy Break up Devices with dimensions of $(40x10)mm^2$,was manufactured from iron sheet (1mm) thickness and mounted in the horizontal plane passing through the symmetry axis of test section through longitudinal slots, one in each side of rough section, its location at 16 mm (0.8δ) from the heated plate [9].

Experimental Procedure:

The test runs to collect data that have been relevant to heat transfer and flow friction under steady state conditions. The steady state is reached when the temperature at a point does not change with time for around (15) minutes. The experimental tests were done for a range of Reynolds number ($3.2x10^4$ – $6.2x10^4$) and constant heat flux ($600W/m^2$). At each Reynolds number , the system was allowed to attain steady state before the data were recorded.

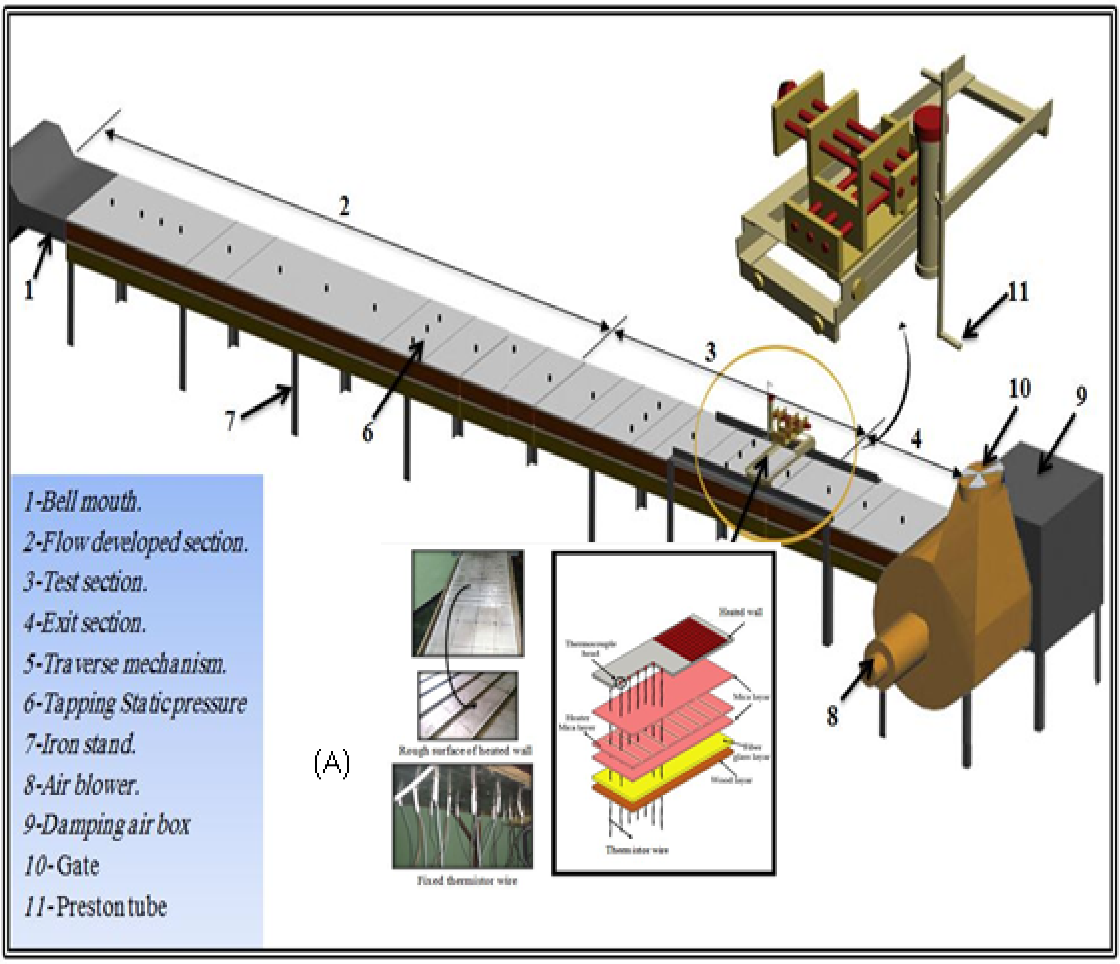
The following parameters were measured:

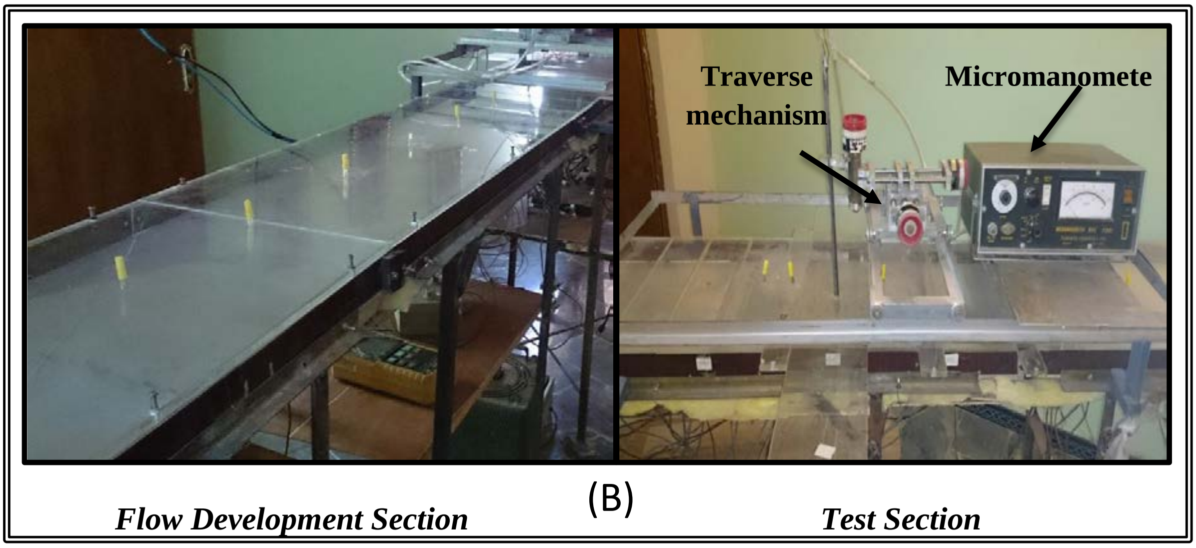
1-Temperature distribution along the lower surface , inlet and outlet temperature of air and traverse temperature through the section.

2- Pressure drop across the test section.

3- Dynamic pressure near the artificial wall using Preston tube.

4- Traverse of dynamic pressure by using Pitot tube.





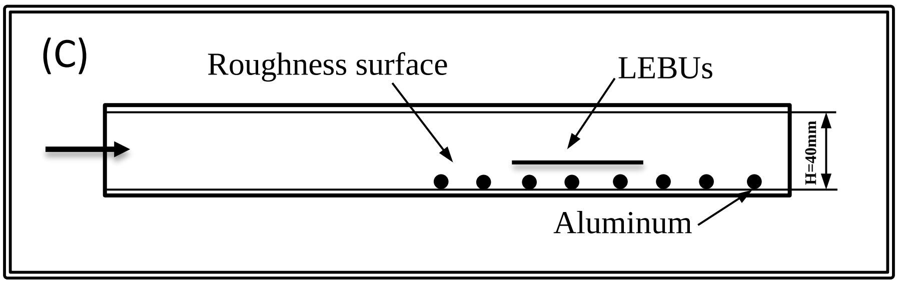


Figure 1: Experimental apparatus
A-Schematic diagram of test rig B- the parts of experimental work C- Test section

Data Reduction:

Steady state values of the heating wall and air temperatures in the duct at various locations were used to determine the values of heat transfer coefficient , Nusselt number , friction factor and thermal performance parameter . The mass flow rate was calculated from the equation:

$$\dot{m} = \rho u_b A_c \quad \dots (1)$$

where u_b is average value of the local stream wise velocity through cross section which can be determined by the measured dynamic pressure using (Pitot-tube).

The wall shear stress for smooth surface(τ_w) was calculated for fully developed, two-dimensional channel flow from a momentum balance equation Lien [15]:

$$\tau_w = -\frac{H}{2}\left[\frac{dp}{dx}\right] \quad \dots (2)$$

while for rough surface , friction factor was determined from the measured value of dynamic pressure (by Preston tube) at rough surface using the equation Head and Ram[16] :

$$y^* = 0.5x^* + 0.037 \quad \dots (3)$$

for $y^* < 1.5$, and $u_\tau d/2\upsilon < 5.6$

$$y^* = 0.8287 - 0.1381x^* + 0.1437x^{*2} - 0.006x^{*3} \quad \dots (4)$$

for $1.5 < y^* < 3.5$ and $5.6 < u_\tau d/2\upsilon < 55$

$$x^* = y^* + 2\log_{10}(1.95y^* + 4.1) \quad \dots (5)$$

for $3.5 < y^* < 5.3$ and $55 < u_\tau d/2\upsilon < 800$

where,

$$x^* = \log_{10}\left[\frac{\Delta p d^2}{4\rho\vartheta^2}\right] \quad \dots (6)$$

$$y^* = \log_{10}\left[\frac{\tau_w d^2}{4\rho\vartheta^2}\right] \quad \dots (7)$$

The sicken friction was calculated from the following equation:

$$C_f = \frac{\tau_w}{\frac{1}{2}\rho\, u_b{}^2} \quad \dots (8)$$

The local heat transfer coefficient for the heated element was calculated as:

$$h_i = \frac{Q_{ui}}{A_n(T_{wi} - T_{bi})} \quad \dots (9)$$

where, the rate of heat gain by the air was given by:

$$Q_{ui} = \dot{m} C_p (T_{oi} - T_{ini}) \quad \dots (10)$$

T_b and T_w are the bulk temperature of air and the heating element of heating plate, respectively.

The average heat transfer coefficient was calculated as follows:

$$\bar{h} = \sum_{i=1}^{i=N} h_i / N \quad \dots (11)$$

The heat transfer coefficient was used to determine the Nusselt number such that:

$$Nu = \frac{\bar{h}\, D_h}{k} \quad \dots (12)$$

Where D_h is the hydraulic diameter in (mm) of the rectangular duct, it is calculated:

$$D_h=4WH/2(W+H) \quad …. (13)$$

The Reynolds number based on hydraulic diameter was determined as:

$$Re = \frac{U_b D_h}{\vartheta} \quad … (14)$$

The thermo-hydraulic performance parameter (η) was evaluated Chompookham and Thianpong [17] using the equation:

$$\eta= (Nu/Nus)/(f/fs)^{1/3} \quad … (15)$$

The propagated uncertainty analysis is conducted using the method explained in Coleman and steel [18] and the percent were (4.36% and 0.24%) for heat transfer coefficient and friction factor respectively.

Results and Discussion

Validation of Experimental Data:

The present experimental results for smooth heated wall were utilized to validate the experimental system. Fig. (2) depicts the experimental measured friction factor compared with modified Blasius correlation for fully developed flow and the value of deviation between them is around (9.1%-10.6%) . This figure demonstrates that there is a good agreement with the correlation and the deviation is within the experimental uncertainty. Fig.(3) shows the experimental Nusselt number compared with the prediction from the correlation of Dittus–Boelter correlation [3] and Gnielinski correlation Subramanian [19] , the value of deviation between them is around (27%-29%). It is obvious that the experimental values show a similar trend, where Nusselt number increases with Reynolds number.

Effect of the combined (rib and LEBUD):

Figs.(4and5) give the normalized velocity profiles at upstream and downstream of combined LEBUD with ribs for low and high Reynolds number ($3.2x10^4$ and $6.2x10^4$) respectively. At the downstream of LEBUD, it appeared that velocity deficit for the LEBUD results when compared to the riblet upstream. The velocity deficit gradually diminishes with increasing the streamwise distance. Also, as moving far downstream the streamwise velocity profile near the bottom wall becomes almost the same as in the riblet upstream of LEBUD. At low Reynolds number, upstream of LEBUD (x/b=138) the streamwise velocity profile is shifted away from the wall and the streamwise velocity close to zero near the heated wall, here a separation zone is likely to exist. Also in Fig.(4) immediately downstream of LEBUD (x/b=145.5) , it is observed that the devices cause the flow to accelerate in the near wall region (velocity gradient increase). Then at location (x/b=150) the streamwise velocity profile again have the same tends as in the riblet. At high Reynolds number (as shown in Fig.(5)), upstream of LEBUD (x/b=138)the streamwise velocity profile was more fill than low Reynolds number (larger velocity gradient). Then the flow was accelerated near-wall region due to presence of LEBUD (x/b=145.5) which was extended up to (x/b=150), then returned to the same trend as in riblet case (x/b=152).

The temperature profiles at upstream and downstream LEBUD are presented in Fig.(6) for low and high Reynolds number ($3.2x10^4$ and $6.2x10^4$) respectively. At low Reynolds numbers Fig.(6A), it is observed that the temperature gradient at downstream of LEBUD (x/b=150) is larger than location (x/b=145.5) immediately downstream of LEBUD. (i.e. the effect of device was weak). While at high Reynolds number Fig.(6B) larger temperature gradient is observed at downstream of LEBUD (x/b=148)than upstream. The effect of Reynolds number on the variation of the thermal boundary for upstream and downstream of LEBUD can be seen in Fig.(7). At the upstream of LEBUD (x/b=140), it is clearly that the temperature gradient for high Reynolds number is slightly larger than that in the lower Reynolds number. While at the downstream, larger temperature gradient is observed for high Reynolds number. However greater temperature gradient is found immediately behind LEBUD (x/b=145.5 and 148), i.e. LEBUD is strongly affect at high Reynolds number. This is due to existence of the large negative vortices, which suppressed thermal boundary layer by engulfing the cold fluid from the outer region into the near-wall region. This leads to the thinner thermal boundary layer, hence the large temperature gradient. as reported by Inaoka [13].

The effect of using ribs and combined rib with Large Eddy Break up Devices on average friction factor across the test section factor is present in Fig. (8). In this figure the average friction factor obtained from combined rib with Large Eddy Break up Devices is slightly higher than that from ribs with (1.7%) for low Reynolds number ($3.2x10^4$), while at high Reynolds number ($6.2x10^4$) the friction factor from rib is slightly higher than combined rib with Large Eddy break up Devices with percentage (1.2%) as compared to smooth. The mechanism of reducing surface friction by mounting the Large Eddy Break up Devices plates in a turbulent boundary layer is a decrease in the frequency of decelerated-fluid ejection from the wall region into the outer region of the flow. This leads to an increase in the renewal period of the viscous sublayer and its thickness, which significantly affects the integral characteristics. [10].

The effects of ribs and combined ribs with single Large Eddy Brick up Devices on average

Nusselt number are present in Fig.(9).From the figure it is observed that the ribs and combined ribs with Large Eddy Break up Devices yield the considerable heat transfer enhancement with similar trend in comparison with smooth channel and Nusselt number increase with increasing at Reynolds number. The higher Nusselt number is observed for ribs than that of combined of Reynolds number ($3.2x10^4$) with percentage (5.2%) as compared to smooth. This may be due to the fact that the ribs interrupt the development of the thermal boundary layer of fluid flow and create the reverse/re-circulating flow behind the rib. At high Reynolds number range ($3.8x10^4$ up to $6.2x10^4$) the enhancement of Nusselt number for combined higher than rib with percentage of (3.7%-4.1%) respectively as compared to smooth.

Fig. (10) gives comparison of thermal performance parameter (η) for the channel with ribs and combined ribs with (LEBUD) at the same Reynolds number. At low Reynolds number ($3.2x10^4$) highest value of efficiency index can be observed for ribs as compared to combined with the percent (4.8) , while at high Reynolds number ($6.2x10^4$) the combined method gives maximum efficiency index with percent (7.4).

Correlations for Nusselt number and friction factor

It is seen that Nusselt number and friction factor are effective functions of flow with roughness surface , flow Reynolds number (Re) and large eddy break up devices(L_p), The functional relationships for Nusselt number and friction factor can therefore be written as:

Nu= f_1 (Re and L_p/δ).

f= f_2 (Re and L_p/δ).

The final correlation for Nusselt number and friction factor can be written in the following form:

$$Nu= 3.7x10^{-6} (Re)^{1.68} (Lp/ \delta)^{-0.263} \quad \dots (16)$$

$$f = 137 (Re)^{-0.858} (Lp/ \delta)^{0.0208} \quad \dots (17)$$

Fig. (11) and (12) show the comparison of Nusselt number and friction factor between the experimental values and those predicted by the respective correlations (16) and (17). The average absolute percentage deviation of friction factor and Nusselt number between the experimental and predicted values is found to be within 2.9% and 7.7%.

Conclusions:

The experimental work was investigated the effect of artificial roughness(ribs) with and without Large Eddy Break up Devices on flow and heated transfer characteristic at constant heat flux 600W/m2 for the range of Reynolds number ($3.2x10^4$ - $6.2x10^4$) , the following conclusion can be drawn: At low Reynolds number the streamwise velocity profile at location (x/b=138) just downstream of riblet is less full as compared to smooth, while at location (x/b=145.5) where combined effect of Large Eddy Break up devices and rib shows up as sharp spike in the velocity profile which results from the boundary layer that form in the device. The average friction factor from combined slightly higher than ribs with (1.7%) for low Reynolds number, while at high Reynolds number the friction factor from rib is slightly higher than combined rib with Large Eddy break up Devices with percent (1.2) as compared to smooth. The enhancement of Nusselt number for combined higher than rib with percent (3.7-4.1) respectively as compared to smooth for range of Reynolds number ($3.8x10^4$-$6.2x10^4$). Thermal performance parameter (η) for the channel with ribs and combined ribs with (LEBU) Devices fitted is compared at low Reynolds number ($3.2x10^4$) highest value of efficiency index can be observed for ribs to combined with the percent (4.8) , whereas at high Reynolds number ($6.2x10^4$) the combined method gives maximum efficiency index with percent (7.4). Based on the experimental data, correlations are found for Nusselt number and friction factor. These are fairly in agreement with the experimental and predicted values.

Table 1: shown the location of thermocouples on the lower wall surface of duct and location of pressure taps at upper surface

Wall thermocouples location b=20mm					*Static pressure taps b=20mm*				
Na.	**X/b**	**Z/b**			**Na.**	**X/b**	**Z/b**		
1	2.5		10		1	5		10	
2	7.5		10		2	12.5		10	
3	15		10		3	17.5		10	
4	22.5		10		4	22.5		10	
5	30		10		5	35		10	
6	37.5		10		6	47.5		10	
7	45	5	10	15	7	60		10	
8	52.5		10		8	72.5		10	
9	60		10		9	85	5	10	15
10	67.5		10		10	97.5		10	
11	75	5	10	15	11	109		10	
12	82.5		10		12	122.5	5	10	15
13	90		10		13	135		10	
14	97.5		10		14	147.5	5	10	15
15	105	5	10	15	15	160		10	
16	110	5	10	15	16	170		10	
17	115	5	10	15	17	180		10	
18	120	5	10	15	18	190		10	
19	125	5	10	15	19	217.5		10	
20	130	5	10	15					
21	135	5	10	15					
22	140	5	10	15					
23	145	5	10	15					
24	150	5	10	15					
25	155	5	10	15					
26	160	5	10	15					
27	172.5		10						
28	185	5	10	15					
29	197.5		10						

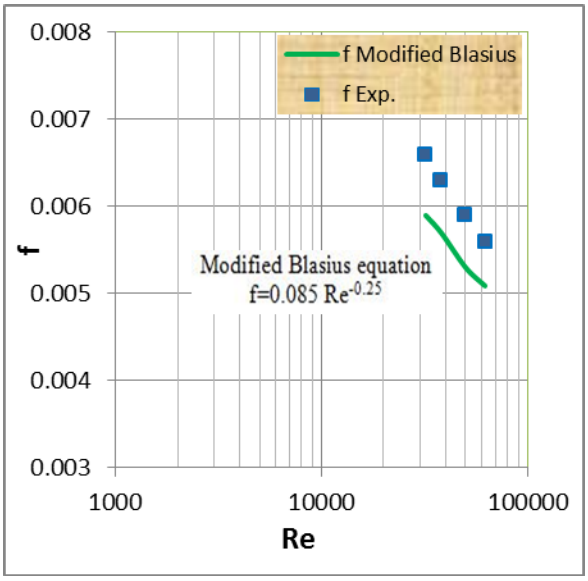


Figure 2: Verification of friction factor for smooth duct

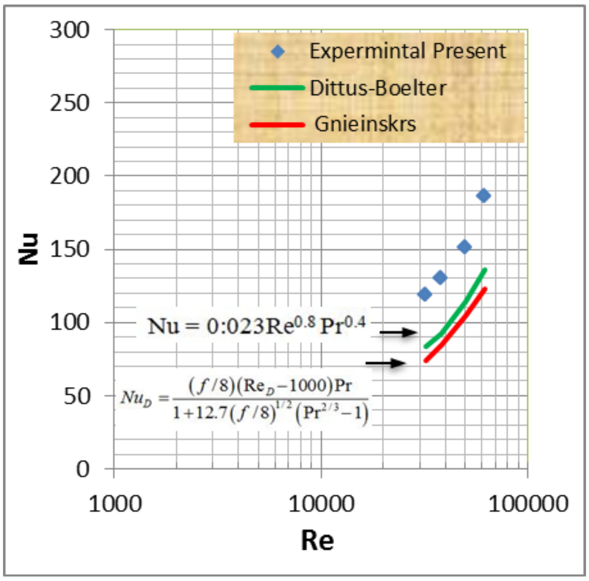
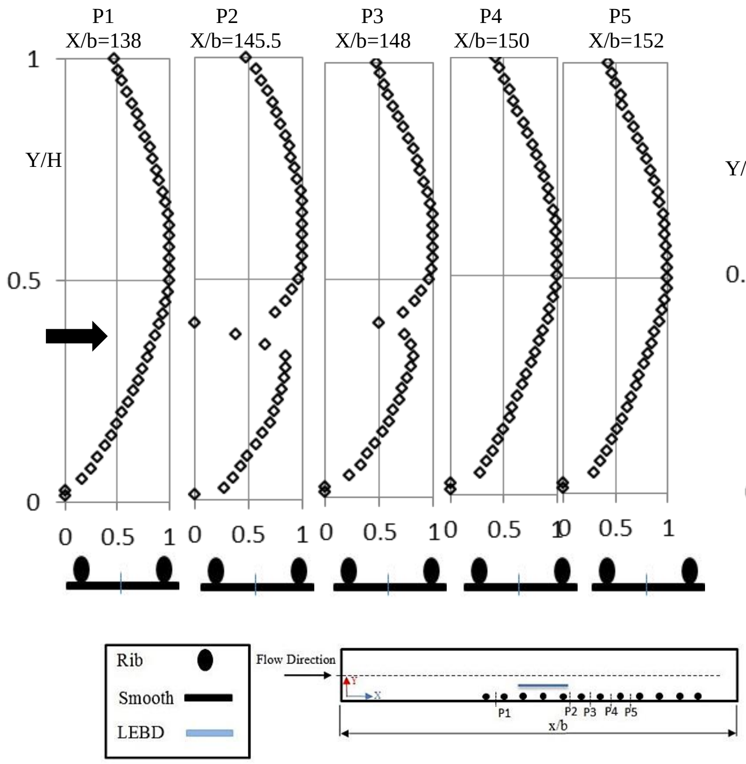
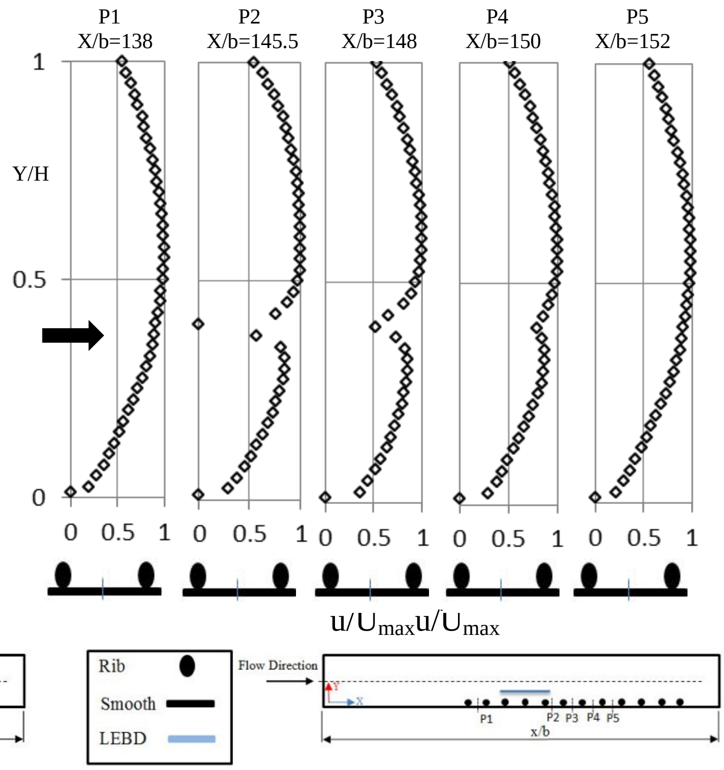


Figure3: Verification of Nusselt number for smooth duct





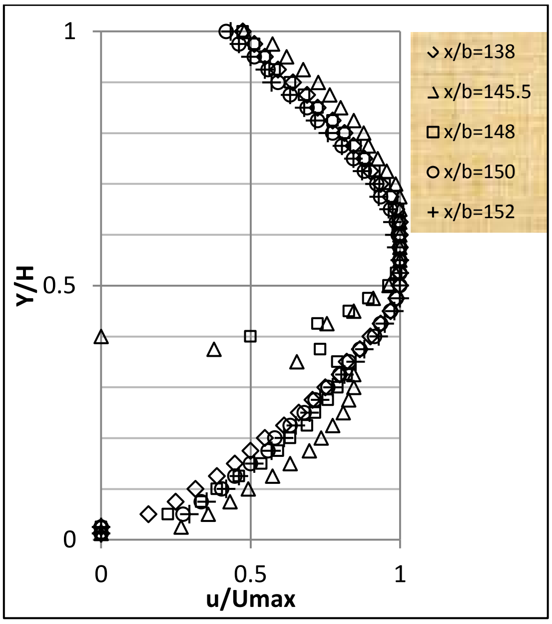


Figure 4: Streamwise velocity profile through the duct at upstream and downstream of LEBUD at Re= 3.2x104

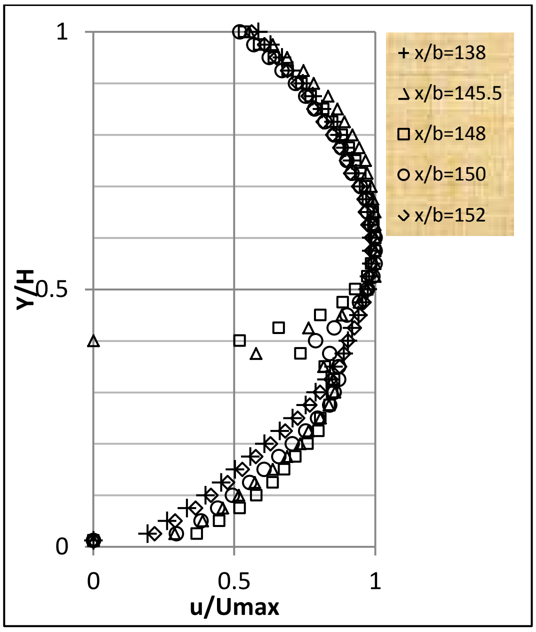


Figure 5: Streamwise velocity profile through the duct at upstream and downstream of LEBUD at Re= 6.2×10^4

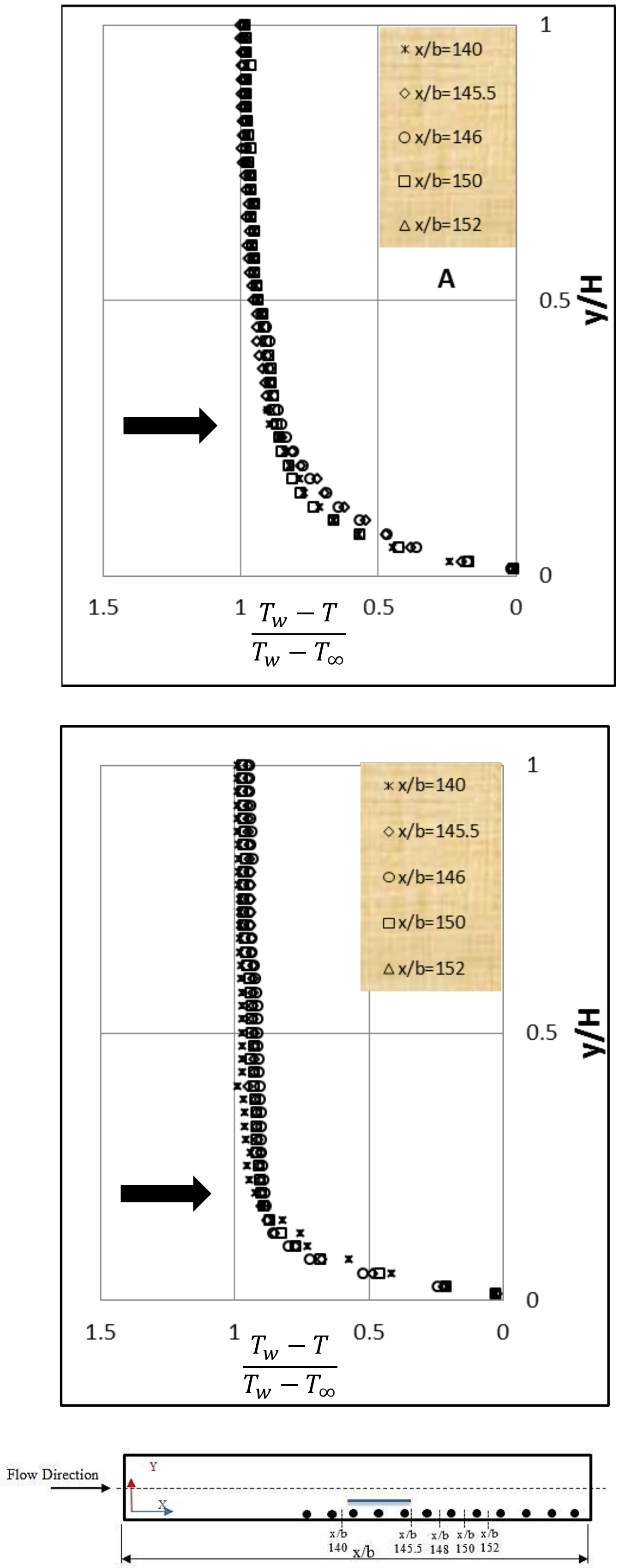


Figure 6: Temperature profile through the duct at upstream and downstream of LEBUD for A-Re =3.2x104 B-Re=6.2x104

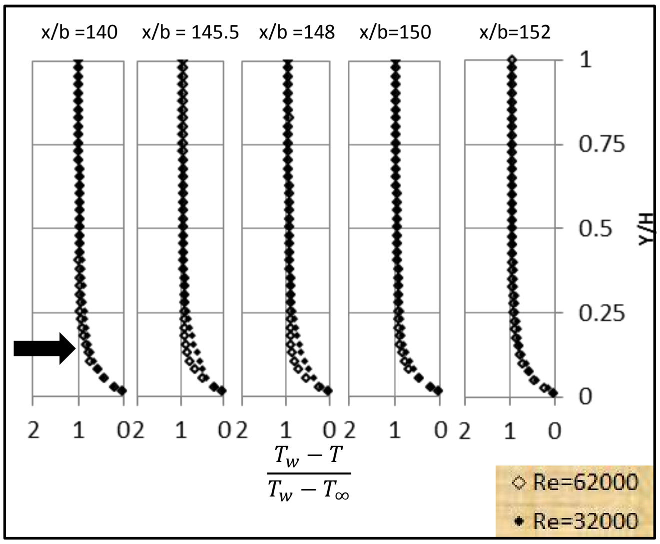


Figure 7: Temperature profile through the duct at streamwise direction for Reynolds number ($3.2x10^4$ and $6.2x10^4$)

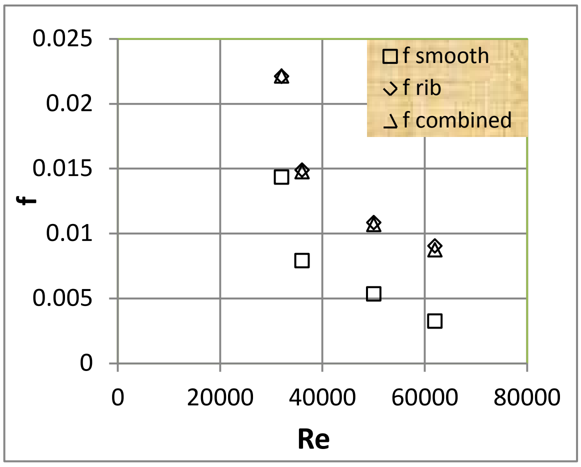


Figure 8: Effect of Reynolds Number on average friction factor for smooth surface , rib and combined (rib with LEBUD)

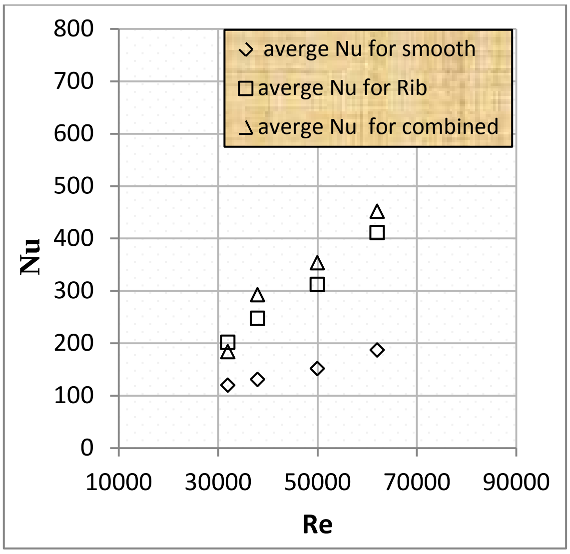


Figure 9: Variation of average Nusselt Number with range of the Reynolds Number ($3.2x10^4$-$6.2x10^4$) for smooth surface , rib and combined (rib with LEBUD)

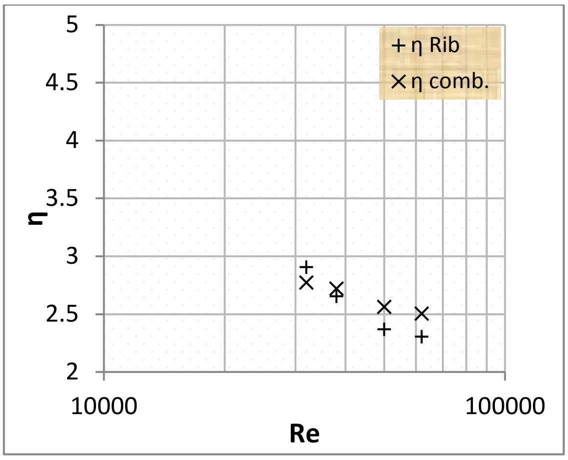


Figure 10: Variation the efficiency index with range of Reynolds number (3.2x104-6.2x104)

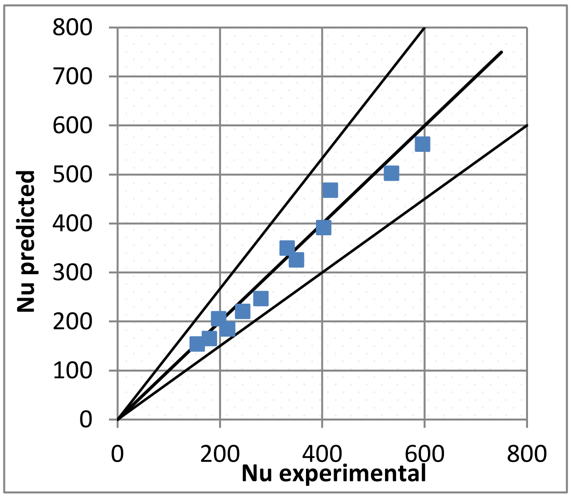


Figure 11: Predicted values vs experimental values of Nusselt number

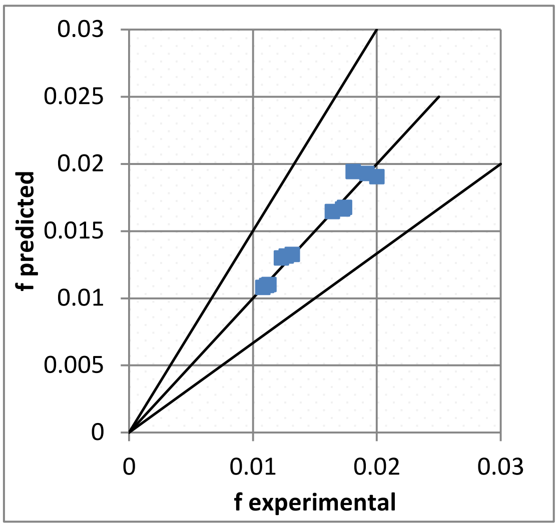


Figure 12: Predicted values Vs experimental value of friction factor

Nomenclature:

AR	Channel aspect ratio, W/H	L	Length of heated surface (mm)
An	Heater area (m^2)	L_p	Length of Large Eddy Break up Devices
D_h	Hydraulic diameter of the rectangular channel, 2 WH/(W+ H) (mm)	LEBD	Large Eddy Break up Devices
e	Rib height (mm)	$\dot{m}$	Air mass flow rate kg/s
e/D_h	Relative roughness height	Nu	Nusselt number
p/e	Relative roughness pitch	P	Rib pitch (mm)
f	Friction factor	qconv	Convective heat flux (W/m^2)
k	Thermal conductivity of air (W/m.K)	Re	Reynolds number
H	Channel height (mm)	T_s	Surface temperature (K)
h	Convective heat transfer coefficient ($W/m^2.K$)	u_b	Bulk velocity (m/s)
δ	Boundary layer thickness	P	Rib pitch (mm)

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