THE COMBINED EFFECT OF RIB WITH TANDEM LARGE EDDY BREAK UP DEVICES ON FLOW AND HEAT TRANSFER CHARACTERISTIC OF TURBULENT FLOW IN RECTANGULAR DUCT : PART B

Ekhlas Mohammed Fayyedh **Moayed R. Hasan** **Ali Falah Mohammed**
ikhlas60@yahoo.com moayed_hassaan@yahoo.com aalimaster1982@gmail.com
Mech. Eng. Dep ,University of Technology

ABSTRACT :
An experimental investigation was carried out to study the effect of Large Eddy Breakup Devices with of circular ribs on one heated wall of a rectangular duct with fully developed turbulent flow , on heat transfer and flow characteristic. The artificially roughened duct has an aspect ratio (W/H) of 10, hydraulic diameter of 72.72 mm, relative roughness pitch (P/e) of 10 and relative roughness height (e/D_h) of 0.05. The experiments were conducted by varying airflow rate in terms of Reynolds number ranging from $3.2\text{x}10^4$ to $6.2\text{x}10^4$ and constant heat flux of 600 W/m^2.The heat transfer and friction characteristics of the duct were compared with those of a smooth duct under similar experimental conditions. It was found that there was a significant enhancement of Nusselt number for combined high Reynolds number (2.6) and friction factor (3.47).

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

دراسة التاثير المركب للعوائق المستعرضة واجهزة تفكك الدوامة الكبيرة على خصائص انتقال الحرارة للجريان المضطرب داخل مجرى مستطيل

اخلاص محمد فياض مؤيد ارزوقي حسن علي فلاح محمد
الجامعة التكنولوجية/ قسم الهندسة الميكانيكية

الخلاصة :

تم اجراء دراسة عملية للتحقق في تأثير كل من أجهزة تفكك لدوامة الكبيرة للأسطح الساخنة مع عوائق مستعرضة ذات مقطع دائري داخل قناة ذات مقطع مستطيل للجريان المضطرب على خصائص انتقال الحرارة والجريان، المجرى الهوائي ذات نسبة باعيه (W/H =10) قطر هيدروليكي 72.72 ملم ، استخدم انابيب اسطوانية ذات مقطع دائري بقطر 4 ملم و المسافة بينهما 40 ملم ، نسبة الخشونة تمثل (p/e=10)، ارتفاع الخشونة النسبي (e/D_h=0.05). تم إجراء التجارب لمدى من عدد رينولد تتراوح بين ($6.2\text{x}10^4$-$3.2\text{x}10^4$) تمت مقارنة نتائج السطح الخشن بوجود او عدم وجود اجهزة تفكيك الدوامة الكبيرة تحت فيض حراري ثابت في تحسين انتقال الحرارة ومعامل الاحتكاك. لوحظ ان عدد نزلت تزداد بمقدار(2.6) اما معامل الاحتكاك فيتحسن بمقدار (3.47) بوجود اجهزة تفكك الدوامة الكبيرة مع العوائق العرضية .

Received : 10 – 1 - 2016
Accepted : 3 – 2 – 2016

NOMENCLATURE :

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

INTRODUCTION :

A gas turbines , aircraft , solar heater and industrial applications require higher heat transfer, so different technique was used for increasing heat transfer. This technique can be classified into active, passive and combined methods (passive and active, 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. Some examples of the passive methods are rough surface, such as ribs and insertion tabulator devices. 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 the heat transfer and friction factor characteristics .

[Bhagoria and Saini 2002],[Sriharsha and Prabhu 2009] and [Kumar and Mittal 2011] investigated the effect of relative roughness (p/e) for range (10-12.12), relative roughness height (e/D) for different values (0.015,0.033,0.15,0.2 and 0.25) and wedge angle on the friction factor and heat transfer coefficient for a range of Reynolds number (3000 to 30000) , it was found that the increasing in Nusselt number is about (2.4 to 2.57) while the friction factor increased for range (3.72 to 5.3) as compared to the smooth duct.[Lee and Rhee 2009],[Tanda 2011] and [Baraskar and Aharwal 2012] studied the effect of channel aspect ratio and relative roughness pitch (p/e) of (6.66,10,13.3 and 20) on local heat/mass transfer and the friction losses in a 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 was about (1.2-2.57) and (2.6-4.3) times that of the smooth duct, respectively. [Aharwal and Gandhi 2007] 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 considered for Reynolds numbers range of (3000 to 18,000). It was observed that the maximum enhancement in Nusselt number and friction factor is (2.59 and 2.87) times that of the smooth duct, respectively.

Large Eddy Break up Devices are also passive techniques that are used to modify the drag characteristics of the turbulent boundary layer near the outer edge of the boundary layer which decrease the boundary layer turbulence, so the largest effect of these techniques showed on local skin-friction coefficients. [Roth 1989] 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 is at least 10%. [Hollis 1992] studied 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 noted that the existence of Large Eddy Break up Devices at the inner wall region boundary layer has a significant effect on the turbulent structure of the flow downstream of the device. [Kuzenkov 1996] 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 accompanied by 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 1992] investigated combination effects of a tandem set of Large Eddy Break up devices(LEBUs) 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 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. [Gudilin 1995] studied the combination effects of Large Eddy Break up Devices (LEBUs) and longitudinal riblets on the reduction of turbulent friction at a 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 tandem Large Eddy Break up Devices with artificial roughness in span wise direction on the thermal and flow characteristic in a 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) , 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 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 two-dimensional flow in present work. The tunnel consist 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 heat loses to ambient. The heated wall temperature was measured using (27) thermocouples type-K and (30) thermistors temperature sensor 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 span wise 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 are 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 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) artificial roughness, the smooth surface was upstream of artificial roughness. This roughness have circular steel ribs with a diameter of (4 mm) and length of (400 mm). These ribs were mounted on heated plate by epoxy at pitch of (40 mm).The selection of pitch based on optimum value of relative roughness pitch (p/e=10) was reported by [Tanda 2011]. Tandem Large Eddy Break up Devices 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 [Hollis 1992] .

EXPERIMENTAL PROCEDURE :

The test runs were relevant to heat transfer and flow friction under steady state conditions. Which is reached after (15) minutes. The experimental tests were done for a range of Reynolds number ($3.2x10^4 – 6.2x10^4$) and constant heat flux ($600W/m^2$).

The following parameters were measured :

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

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:

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

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 2004]:

$$\tau_w = -\frac{H}{2}\left[\frac{dp}{dx}\right] \tag{2}$$

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 1971] :

$y^*=0.5x^*+0.037$ for $y^*< 1.5$, and $u_\tau d/2\upsilon<5.6$ (3)

$y^*=0.8287-0.1381x^*+0.1437x^{*2}-0.006x^{*3}$ for $1.5<y^*<3.5$ and $5.6< u_\tau d/2\upsilon<55$ (4)

$x^*=y^*+2\log_{10}(1.95y^*+4.1)$ for $3.5<y^*<5.3$ and $55< u_\tau d/2\upsilon<800$ (5)

where,

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

and

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

The sicken friction was calculated from the following equation:

$$C_f = \frac{\tau_w}{\frac{1}{2}\rho\, u_b^{\;2}} \tag{8}$$

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

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

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

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

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:

$$\bar{h} = \sum_{i=1}^{i=N} h_i/_N \tag{11}$$

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

$$\mathrm{Nu} = \frac{\bar{h}\,D_h}{k} \tag{12}$$

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

$D_h=4WH/2(W+H)$ (13)

The Reynolds number based on hydraulic diameter was determined as:

$$Re = \frac{U_b D_h}{\vartheta} \tag{14}$$

The thermo-hydraulic performance parameter (η) was evaluated [Chompookham and Thianpong 2010] using the equation:

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

The propagated uncertainty analysis is conducted using the method explained in Coleman and steel (1999) and the percent were (4.36% and 0.24%) for heat transfer coefficient and friction factor respectively .

RESULTS AND DISCUSSION :

1-Validation of Experimental Data:

The present experimental results for smooth heated wall were utilized to validate the experimental system. Figure (2) depicts the experimental measured friction factor compared with 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. Figure(3) shows the experimental Nusselt number compared with the prediction from the correlation of Dittus–Boelter correlation [Kumar and Saini 2013] and Gnielinski correlation [Subramanian 2014] , 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.

2-Effect of the Combined Technique (Rib and LEBD) :

Figure(4) shows the variation of streamwise velocity in the symmetry plane of duct in the fully developed at different locations of streamwise for low and high Reynolds number. At low Reynolds number the streamwise velocity profile at location (x/b=137.5) just downstream of riblet is less full as compared to smooth, therefore the friction factor of riblet is higher than smooth , while at location (x/b=150) where the combined effect of Large Eddy Break up devices and rib shows sharp spike in the velocity profile which results from the boundary layer that form in the device. Also, the fluid near the hot wall has a streamwise velocity close to zero here a separation zone is likely to exit. At downstream of Large Eddy Break up Devices (x/b=165.5), the velocity profile is shifted away from the heated wall. So, the velocity profile of two locations (x/b=150,165.5) lies above the velocity profile of riblet. For downstream of the Large Eddy Break up Devices (x/b=175), the velocity profile is seen relax to the fully developed profile of smooth surface. With increasing the Reynolds number to ($6.2x10^4$) as shown in Figure(5) , the effect of Large Eddy Break up Devices with riblet was clear for disappear a separated zone at locations (x/b=150,165.5), so the velocity profile seems to be more full than velocity profile of riblet. Finally, the velocity profile of two devices lies above the smooth surface.

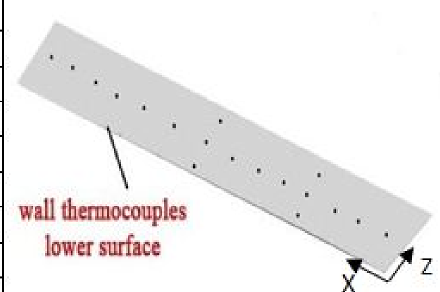
The effect of using ribs and combined rib with Large Eddy Break up Devices on the local and average friction factor across the test section factor is presented in Figure (6) and Figure(7). In Figure(6), it's appeared that the use of ribs and combined ribs with Large Eddy Break up Devices leads to the substantial increase in local friction factor over the smooth surface. The increase in friction factor for both enhancement devices is substantially higher than that for the smooth surface. This can be attributed to flow blockage, higher surface area and the action caused by the reverse flow from enhancement devices. In Figure (7), the average friction factor obtained from combined rib with Large Eddy Break up Devices is slightly higher than that from ribs with (1.3%) for low Reynolds number ($3.2x10^4$) while at high Reynolds number ($6.2x10^4$) the friction factor from rib is slightly higher than the combined rib with Large Eddy break up Devices with percent (1.2%) compared to smooth. The mechanism of reducing surface friction by mounting the Large Eddy Break up Devices plates in a turbulent boundary layer the 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. [Kuzenkov 1996] .The friction factor ratio, shown in Figure(8), increases with increasing Reynolds number. The enhancement of the friction factor for ribs related to smooth surface is between 1.59 to 2.5 , and when combined rib with Large Eddy Break up Devices mounted in channel, the friction factor ratio of combined is enhanced from 1.63 to 2.6 . At high Reynolds number ($6.2x10^4$), the decrease of friction factor for rib is higher than the combined while for low Reynolds number ($3.2x10^4$),it is conversely . Figure(9) shows that local Nusselt number for smooth section is nearly constant while for (rib and combined technique), it was increased along the streamwise direction and relaxed back to smooth far downstream of enhancement devices (x/L=0.095), a higher value of local Nusselt number was at a higher Reynolds number. At low Reynolds number ($3.2x10^4$), the riblet was significant for enhancement heat transfer, while the combined technique was at higher Reynolds number ($6.2x10^4$). The effect of ribs and combined ribs with Large Eddy Brick up Devices on the average Nusselt number is presented in the Figure(10). In this figure, 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 of Reynolds number. The higher Nusselt number is observed for ribs than that of combined case in the range of Reynolds number ($3.2x10^4$ and $3.8x10^4$) with percentage enhancement of (8.2%-6.2%) respectively 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 ($5x10^4$ and $6.2x10^4$), the enhancement of Nusselt number for combined case is higher than rib with percentage (2.5%-2.65%), respectively as compared to smooth . **Thermal** performance parameter (η) for the channel with ribs and combined ribs with (LEBU) Devices fitted is compared at the same Reynolds number in Figure(11).It can be shown at low Reynolds number ($3.2x10^4$), the highest value of efficiency index can be observed for ribs as compared to combined with the value (2.9) while at high Reynolds number ($6.2x10^4$), the combined method gives best efficiency index of (2.4) as compared to rib.

CONCLUSIONS :

On the basic of the experimental investigation of rib and combined (rib with Large Eddy Break up Devices) on heated transfer and flow characteristic at range of Reynolds number ($3.2x10^4$ up to $6.2x10^4$) at constant heat flux, the following conclusions can be drawn: The higher Nusselt number is observed for ribs than that of combined in the range of Reynolds number ($3.2x10^4$ and $3.8x10^4$) with percentage (8.2%-6.2%) respectively as compared to smooth surface. At high Reynolds number range ($5x10^4$ and $6.2x10^4$), the enhancement of Nusselt number for combined is higher than rib with percentage (2.5%-2.65%), respectively as compared to smooth. The average friction factor obtained from combined rib with Large Eddy Break up Devices is slightly higher than that from ribs with (1.3%) for low Reynolds number 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. For thermohydraulic performance at low Reynolds number ($3.2x10^4$), the highest value of efficiency index can be observed for ribs as compared to combined (2.9) while at high Reynolds number ($6.2x10^4$), the combined method gives maximum efficiency index of (2.4) as compared to rib.

Table (1) Location of thermocouples on the lower wall surface of duct and location of pressure taps at the 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						



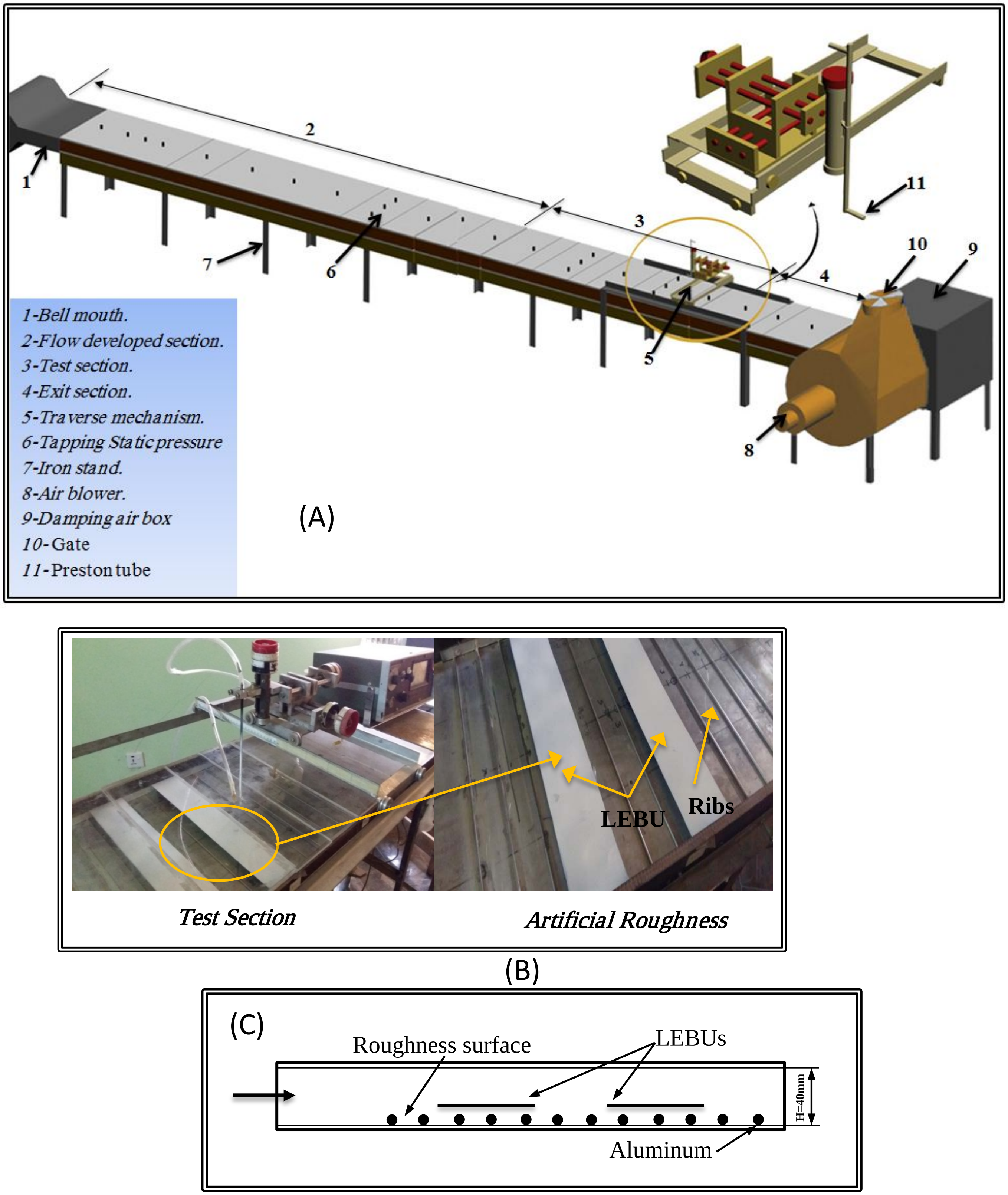


Fig. (1) Experimental apparatus
A-Schematic diagram of test rig B- the parts of experimental work C- Test section

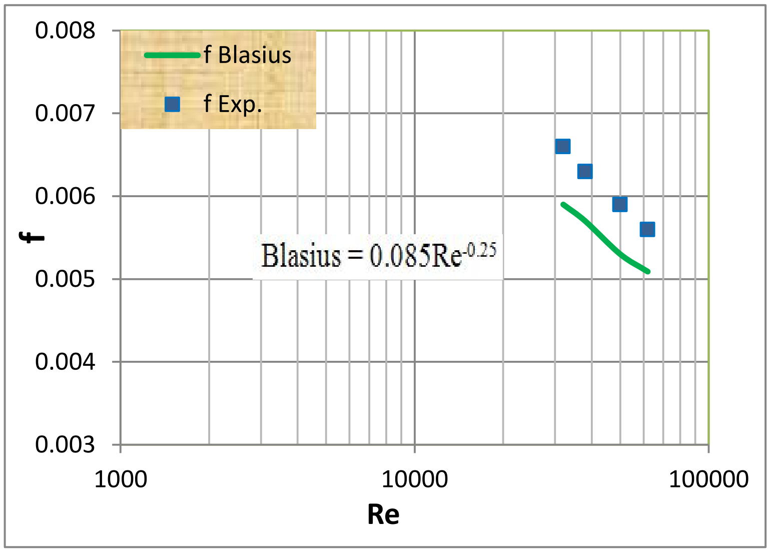


Fig. (2) Verification of friction factor for a smooth duct

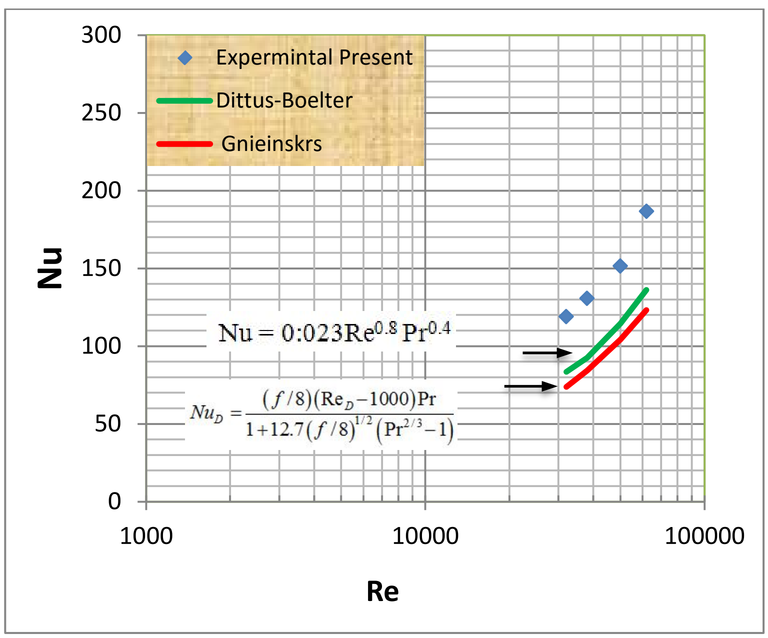


Fig. (3) Verification of Nussult number for a smooth duct

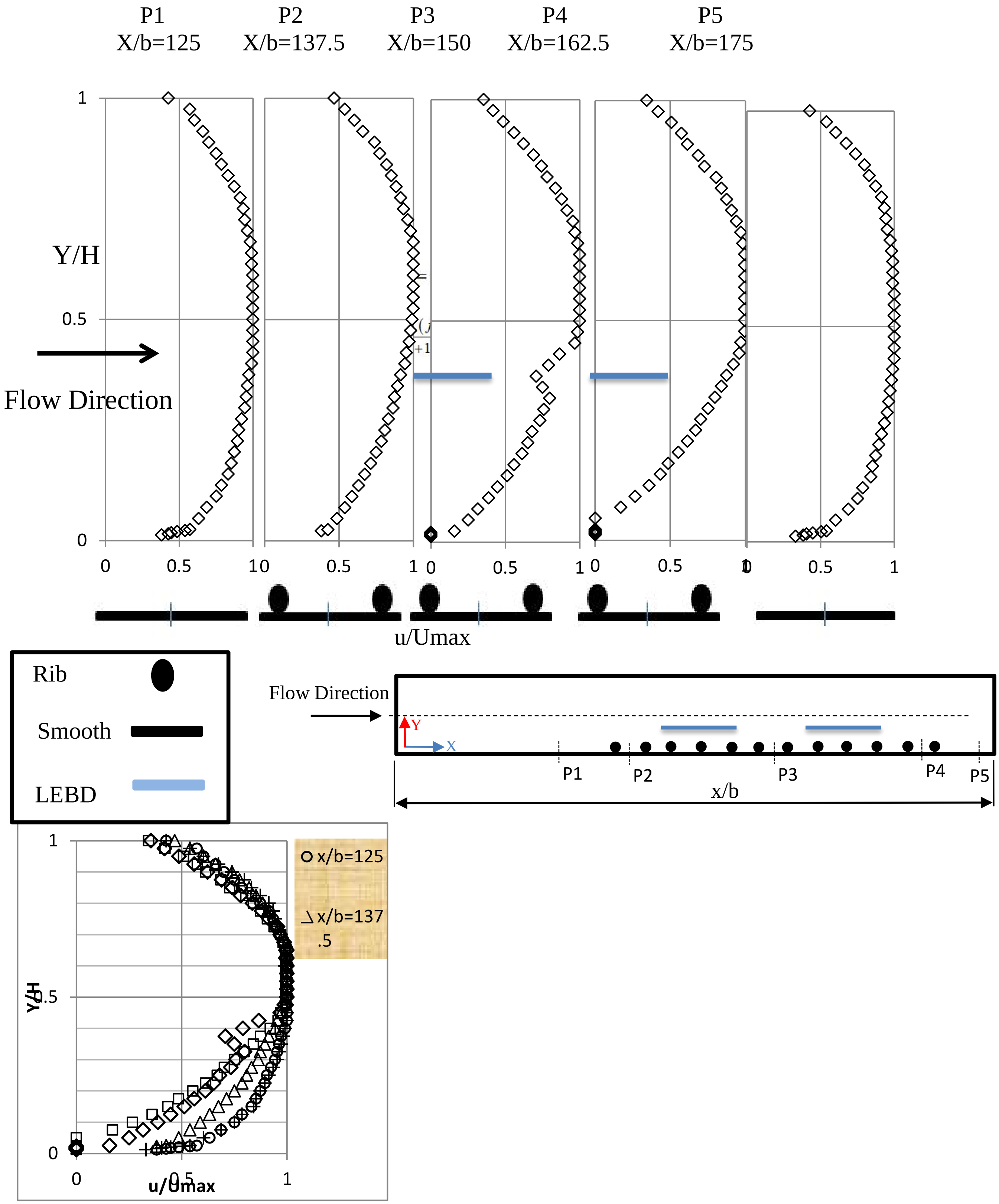


Fig (4) Stream wise velocity profile through the duct for combined plate L=10 cm at Re= $.2x10^4$

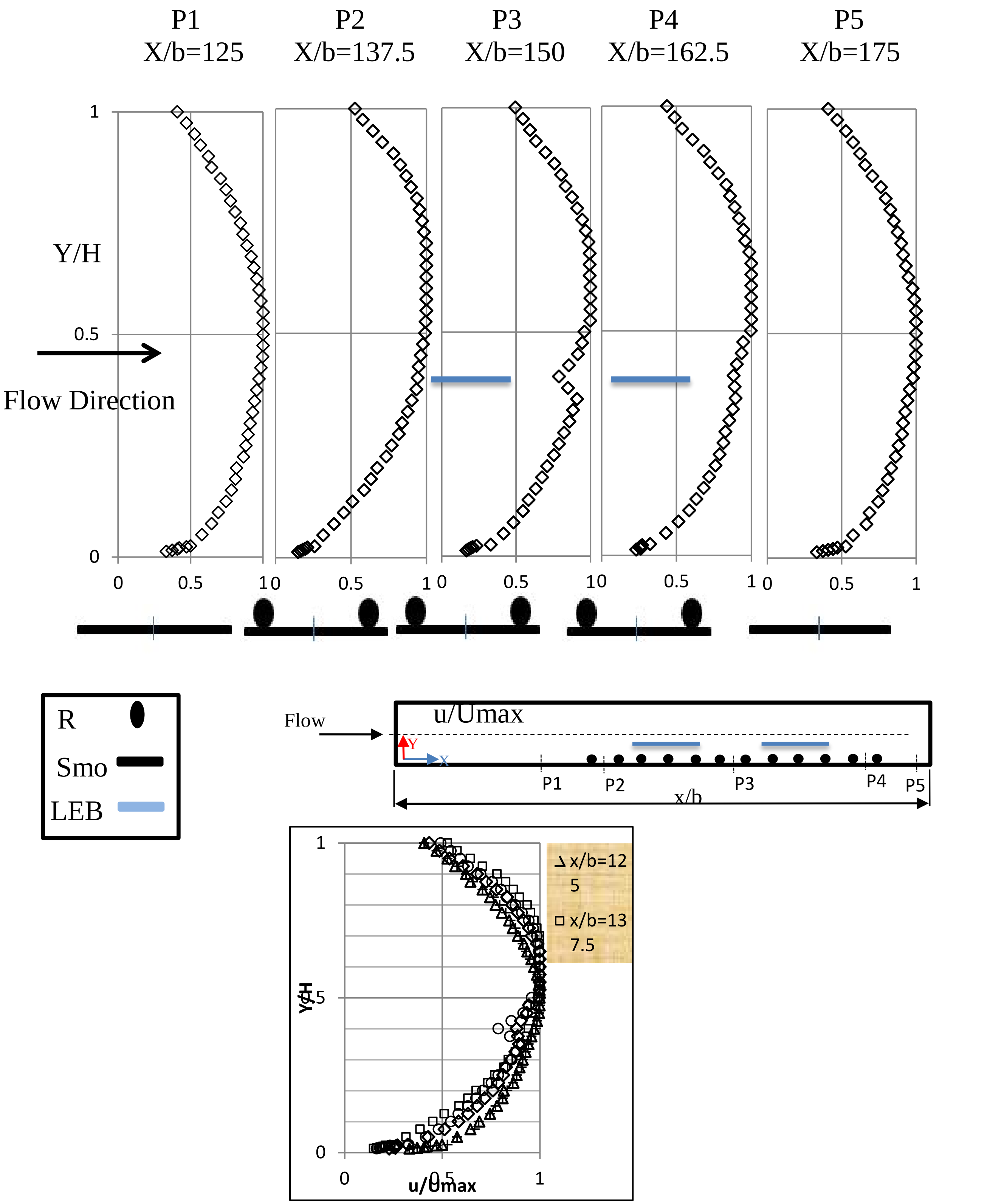


Fig. (5) Stream wise velocity profile through the duct for combined plate L=10 cm at Re= $6.2x10^4$

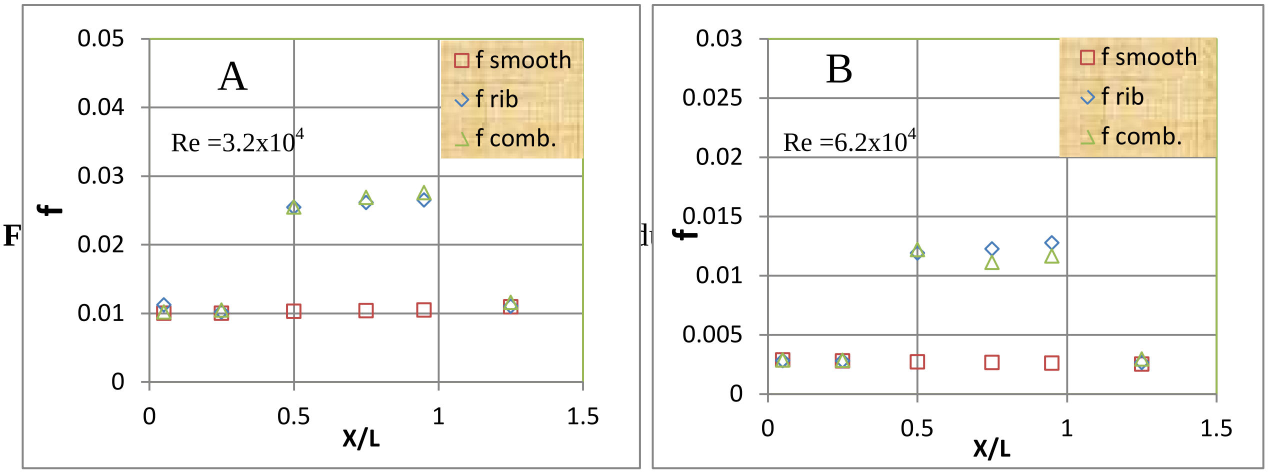


Fig. (6) A,B Distribution of local skin friction for smooth , rib and combined

(rib with tandem LEBUDs=10 cm)

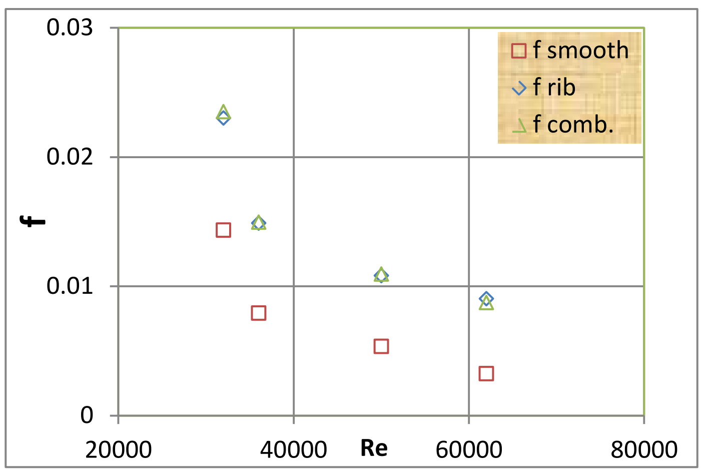


Fig. (7) Effect of Reynolds Number on average friction factor for smooth surface , rib and combined (rib with tandem LEBUDs=10 cm)

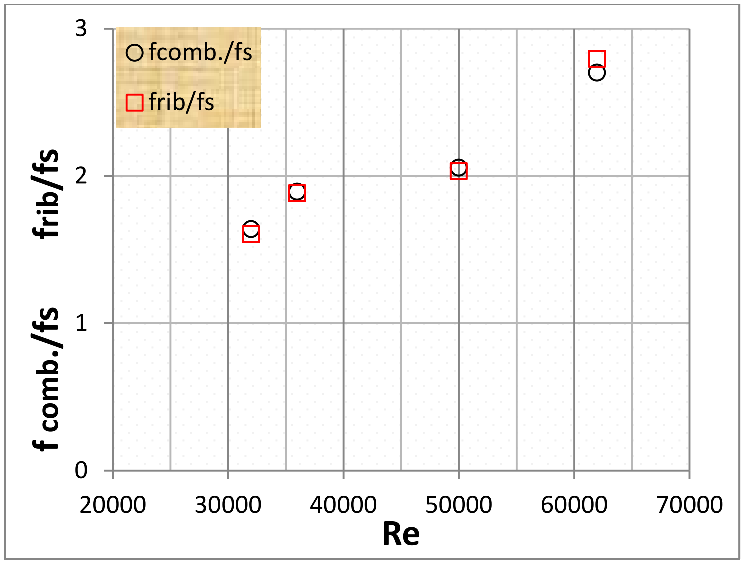


Fig.(8) Variation of average friction factor ratio, (f/fs) over the range of Reynolds number ($3.2x10^4$-$6.2x10^4$)

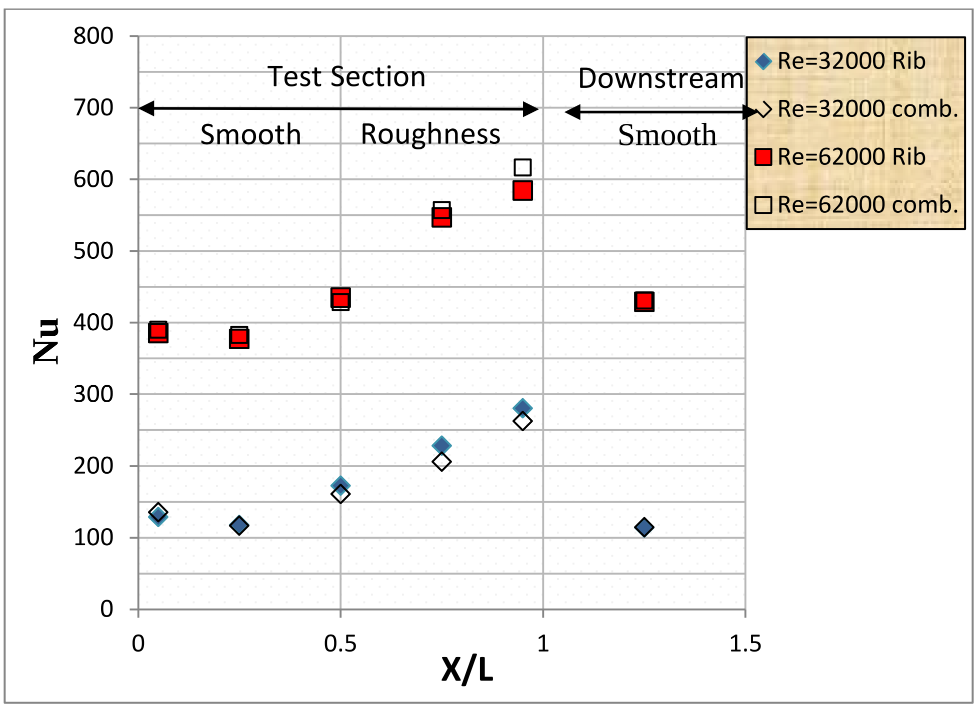


Fig. (9) Effect of rib and combined on the Nusselt Number along streamwise direction over the range of Reynolds Number ($3.2x10^4$-$6.2x10^4$)

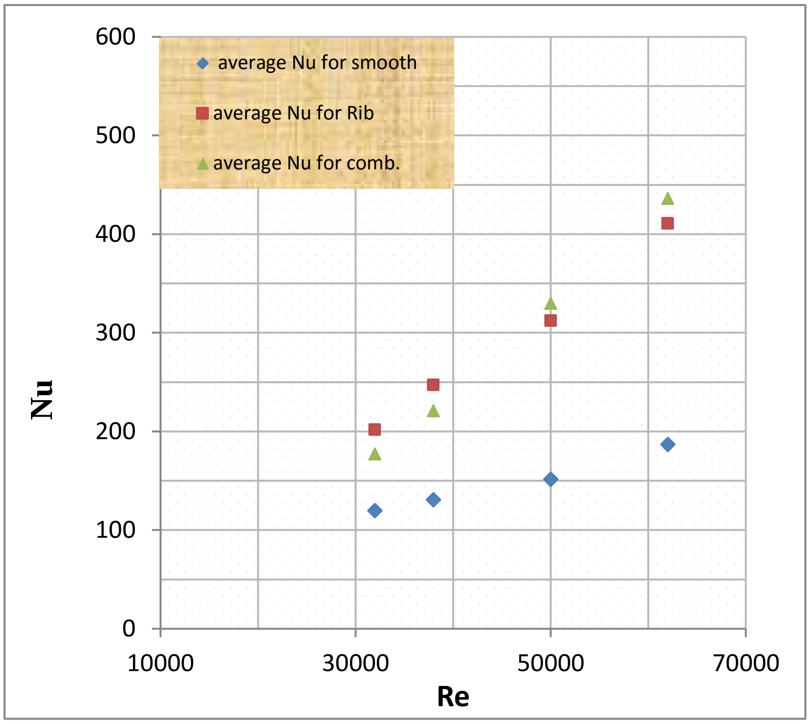


Fig. (10) Variation of average Nusselt Number over the range of the Reynolds Number ($3.2x10^4$-$6.2x10^4$) for (smooth, ribs and combined)

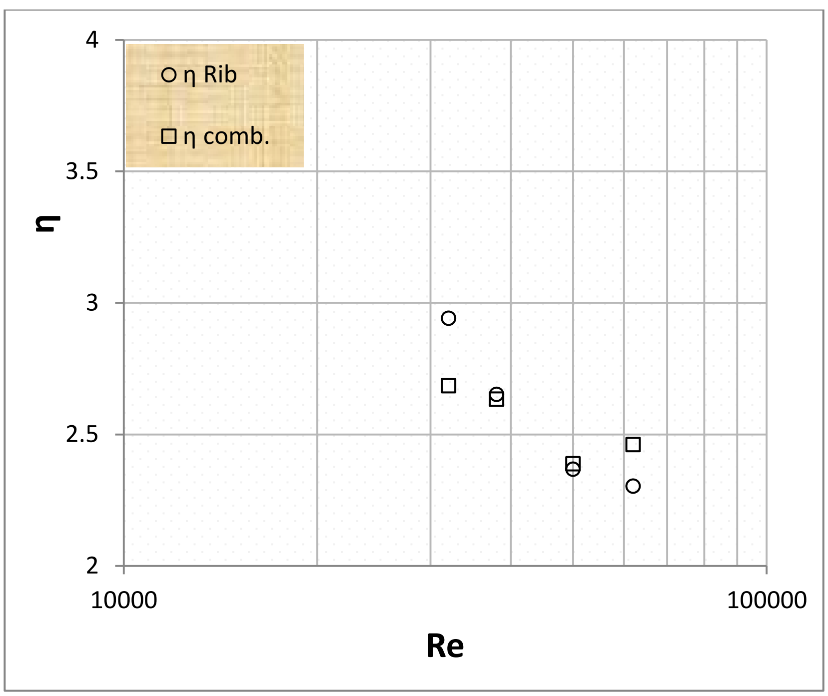


Fig.(11) Variation the efficiency index over the range of Reynolds number ($3.2x10^4$ – $6.2x10^4$)

REFERENCE : **-**

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