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ON THE ORGANIZED ROUGH ELEMENTS DISTRIBUTIONS AND THE DRAG REDUCTION EFFECTS OF TURBULENT FLOWS IN PIPES

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Abstract: *Predicting the friction force exerted on a surface due to turbulent flow over it, is an important factor in different engineering disciplines such as piping and atmospheric studies. In practical applications and scientific researches, the distribution of rough elements over the surface is usually considered as random. For such a distribution, there are well recognized empirical friction equations such as Colebrook and also established physical theories. However, their applicability on organized roughness distribution, the case the shape and spacing between the rough elements are not random, is under question. In the present work, the effect of the organized roughness distribution on the turbulent friction factor of a Newtonian fluid is investigated. For this purpose, 4 different roughness configurations (smooth, random distribution and two organized ones) are studied in the pipe geometry. It is observed that for specific organized configurations, the well-known plateau of fully rough regime observed for random distribution of rough elements will disappear. As observed for here, int the mentioned configurations the friction factor will decrease by increasing Reynolds number, with same slope as in the inertial range (Blasius range), indicating drag reduction.*
Keywords: *Organized Roughness, Drag Reduction, Turbulent, Pipe Flow*

1. INTRODUCTION

Over past century, there is a huge record of studies on the turbulent flow in the pipes and the factors affecting that, and of course still going on. An important portion of these efforts are directed into the turbulent friction due to roughness and the methods to control and reduce that. The effect of random distribution of roughness elements on the pipe friction factor is classified in pioneering work of the Nikuradse (1950). It is well-known that random roughness will increase the friction factor, and this increment is proportional to the roughness mean size. Also, results into a plateau at higher Reynolds numbers, named as fully rough regime. In this regime, it is assumed that the size of the roughness is much bigger than turbulent length scales, thus the turbulent structures near the wall are affected by roughness, and not the turbulent core.

In contrast to mentioned drag increment, there are many examples in the nature that specific roughness configurations cause drag reduction, allowing more efficient energy consumption. To name few examples, birds and fishes are the most studied ones. Recently several studies have been conducted on this topic. In Walsh and Lindemann (1984) examined several shapes, including triangular, notched-peak, sinusoidal and U-shaped riblets to assess the drag reduction effect. Their study showed maximum drag reductions of 7–8% for riblet spacings of approximately 15 wall units. Consequences of using riblets on the turbulent structure of internal flows are studied by Dubief *et al.* (1997), Lowrey and Harasha (1991) and Rohr *et al.* (1992) (Ladd *et al.*, 1993; Dean and Bhushan, 2012; Viswanath, 2002). More recently complex structures such as fur are examined by Itoh *et al.* (2006) and the maximum drag reduction of 12 percent is documented. To just name the most important reviews in this field, a fairly broad but early review of Walsh (1990), more recent one from Choi (2000) with the emphasize on the work of the ERCOFTAC drag reduction group, Bushnell (2003) overview the drag-reduction techniques for aircrafts, and Jimenez (2004) which covers the flows over rough walls and drag reduction due to riblets must be mentioned.

To classify the current trends in this research field, the method for delaying the boundary layer transition and ones for modifying the turbulence structures in near wall region are the most active ones. The current research deals with the last subject. Here the effects of specific type of roughness elements, elements with regular shape and organized placement are examined. For this purpose, two k-type rough surface is made and mounted inside a pipe. Then the turbulent structures and friction exerted due to this type of unusual roughness is diagnosed and compared with smooth and regular sand-made rough walls. The results reveals strange behavior for the new-type of the roughness studied, specifically the plateau of fully rough regime on the friction versus Reynolds curve seems to disappear and a new (inertial) Blasius type, linear region appears. Also, near wall turbulence intensities change dramatically. Although the cause of this phenomenon is not understood currently, the wake formation behind the rough elements is one of the strong candidates to describe that.

The rest of the paper is organized as explaining the setup of our experiment, the results and finally the discussion of the results and the first tries to explain the phenomenon observed.

2. NOMENCLATURE

2.1 Symbols

d	Pipe diameter	R	Pipe radius
k_S	Hydraulic roughness	R_e	Reynolds number
L	Distance between high and low pressure taps	$\overline{U}$	Fluid mean velocity

2.2 Greek Symbols

ΔP	Pressure difference across the tube	ν	Fluid kinematic viscosity
λ	Darcy's friction factor	ρ	Fluid density

3. METHODS AND MATERIALS

The hydrodynamic measurements were carried out in flow rig shown in Fig.1. The rig circuit is composed of 4 loops, made of stainless steel pipe, each has 15 meters long and 2 inches of internal diameter (Fig. 2a). The rig is fed by a $1m^3$ tank, using a volumetric pump Netzsch $9.2kW$ which is connected to a frequency inverter WEG (Fig. 2b). Also an electromagnetic flow-meter (InControl) and pressure gauges (Rosemount and Deltabar S) are connected to the circuit for the measurements. All the instruments were calibrated and have been certificated.

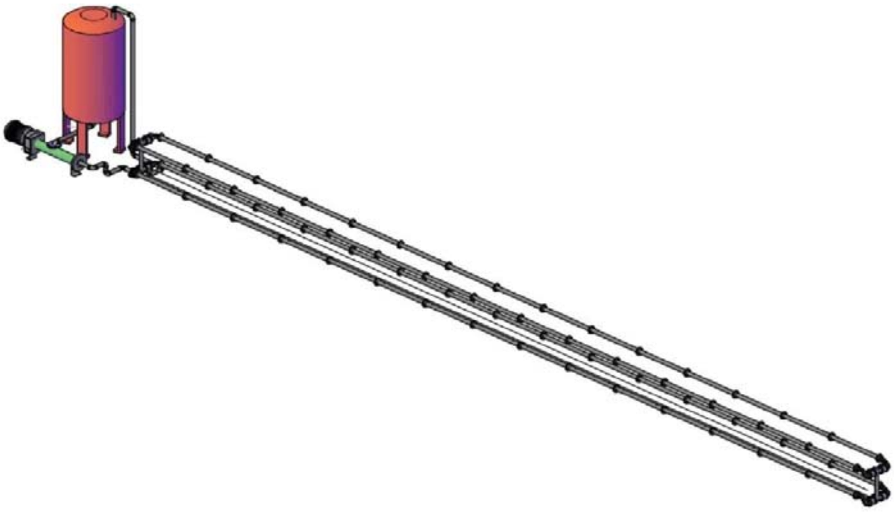


Figure 1: **Schematic drawing of experimental setup.**

Beside this, the instantaneous velocities are are acquired with the Laser-Doppler Anemometry (LDA). The equipment used is for this purpose is Flo Explorer Laser Doppler Anemometer of the Dantec Dynamics.

The data acquisition (for pressure) has been done by using one plate of acquisition system of the National Instruments (16 bytes of resolution) (Fig.3). The pressure gauges are positioned about $70cm$ form each other in the experiments, while just for the sand roughened pipe the distance is $1m$. The fluid considered here is a Newtonian type.

Five different configurations for wall finishing is examined by current experiments. These are shown in 4, consisting smooth surface 4a, usual sand made rough wall 4e, two rough walls with organized-aligned structures shown in Fig. 4b and 4c, and finally a rough wall made using a wire mesh as in Fig. 4d. The topology of the roughness elements placement for the two organized rough walls mentioned above is provided in Fig. 5. As can be seen from this figure, the only major

(a) Experimental Loops.

(b) Reservoir and the Pump.

Figure 2: **Experimental Circuit and Equipment.**

difference between these two rough walls is the the placement of elements, where in the first one is staggered, while the last one uses fully aligned structure. The sand made roughness is made out from the granular silicon carbide with grain size of 100.

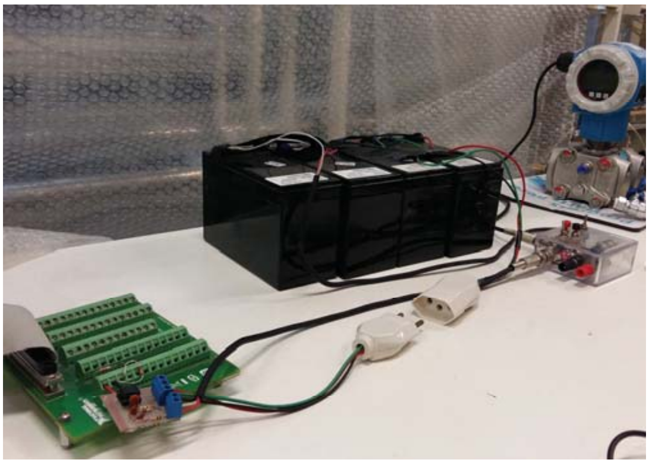
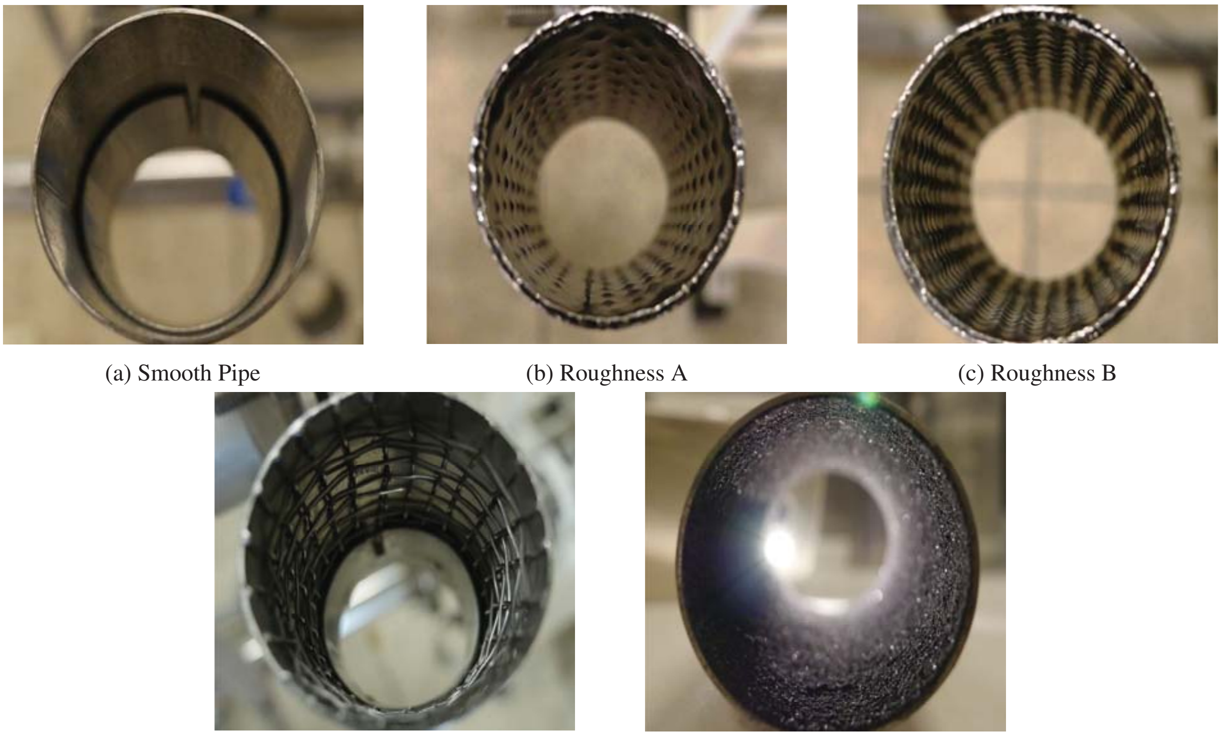


Figure 3: **Eletronic Circuit.**



(a) Smooth Pipe (b) Roughness A (c) Roughness B

(d) Roughness C (e) Roughness D

Figure 4: **Different rough elements geometries.**

The data acquisition is carried out as follows: For a chosen value of the flow rate the pressure along the pipe was measured and analyzed using the LABVIEW program, the pressure loss per unit length is then obtained. The flow friction factor can be calculated using classical Darcy-Weisbach equation (Eq.1).

$$\lambda = \frac{2\Delta P d}{\rho L \overline{U}^2} \quad (1)$$

4. DISCUSSION AND RESULTS

The Figure 6 shows the results of current work. In this figure the friction factor for the five different wall roughness is show and compared together. To verify the experimental process done during these experiments, the results form smooth pipe and sand made roughness ($R/k_S \approx 30$) are compared to well-know Nikuradse experimental data (Nikuradse, 1950) and also Colebrook empirical equation. Both comparison prove the correctness and also the accuracy of the experiments and the measurements.

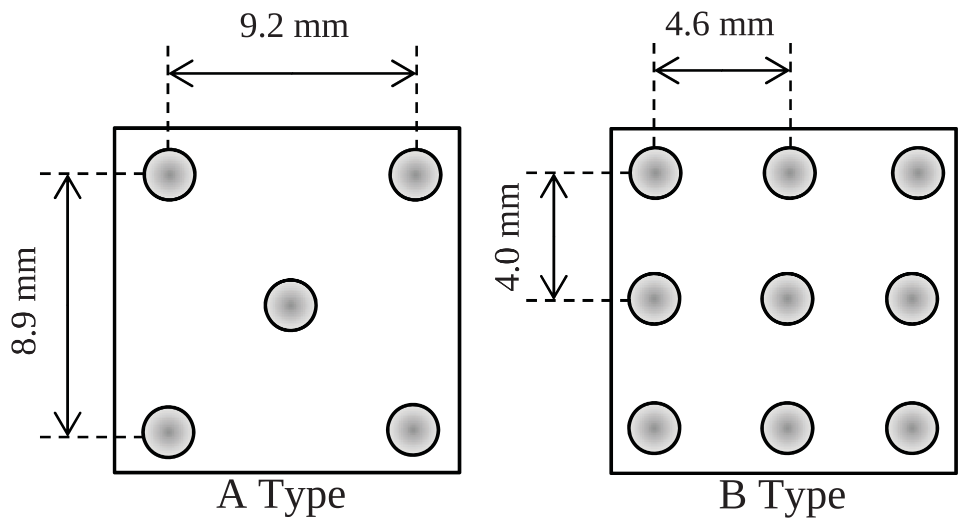


Figure 5: **Rough elements topology.**

For the sand made rough pipe, the fully rough regime is achieved as a plateau at high Reynolds number. This behavior is well-known and is expected for rough pipes at high Reynolds numbers. This phenomenon can be described using the phenomenological turbulent theory of Gioia and Chakraborty (2006). For this regime, the size of rough elements are bigger than the size of the near wall vortices responsible for turbulent momentum transfer. Thus the size of near wall momentum transfer is dictated by rough elements and not the characteristic length of these vortices which is function Reynolds number. Because of this, a region of almost fixed friction factor appears at the high Reynolds, which called fully rough regime.

However, for the two organized roughness of figure 4b and 4c, this plateau just appears (if) at very early Reynolds numbers and replaces rapidly with an exponential decay as can be seen from Fig. 6. As can be seen, the friction show almost same trend in this region as Blasius solution. However, the slope is slightly different and depends on roughness size and configuration.

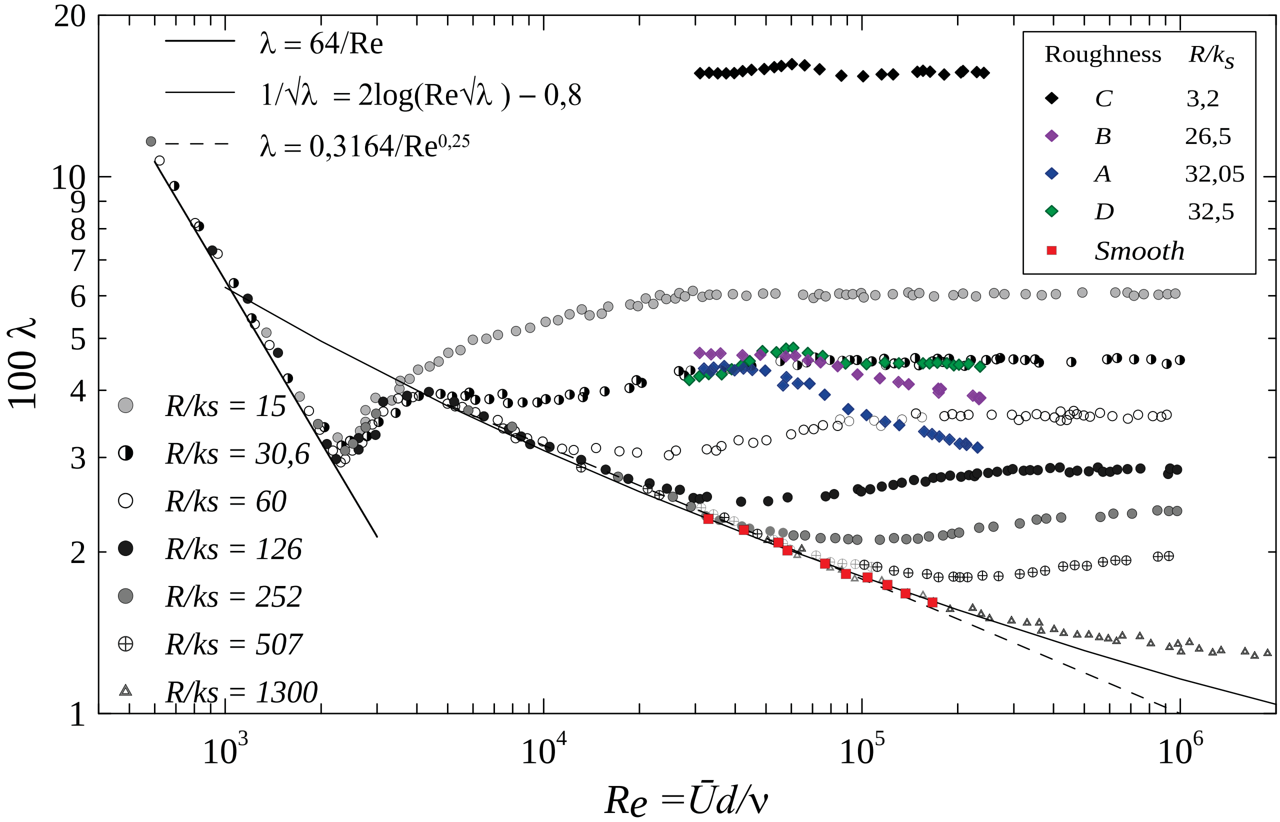


Figure 6: **Comparison of the Obtained Results with Nikuradse Experimental Data.**

There is no clear explanation for this behavior yet. One hypothesis is that due to the organized distribution of the rough

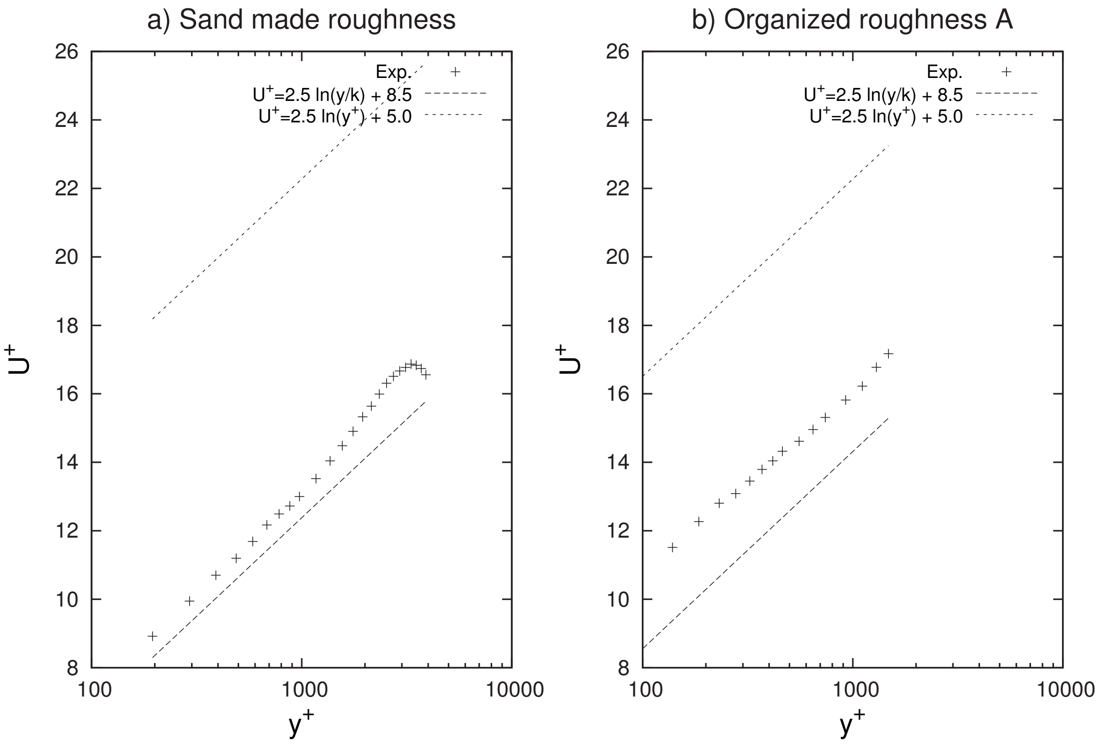


Figure 7: **Mean axial velocity profile.**

elements, some flow structures such as wake flow are formed near the wall, and behind each one of the elements. There is a possibility that rough elements lay inside the wake of the forward elements. If so, the drag force due to the turbulent flow must be vanished enormously. Thus the overall effect would be a considerable drop on the friction factor and the wall shear stress. Another, yet needed to be verified hypothesis is related to Kolmogorov micro-scales. Again, due to phenomenological turbulence theory of Gioia and Chakraborty (2006), the vortices in the size of Kolmogorov micro-scale are responsible for the momentum transfer to the wall and therefore wall shear stress. By increasing Reynolds number these micro-scales become very fine and can fill the gap between the roughness elements again and retain the turbulent flow between the consecutive roughness elements. Thus a semi-smooth behavior would appear again in this gap region and this would result in same behavior seen here. Just to give an estimate, for the current range of experiment, the ratio of Kolmogorov micro-scale to gap distance between two consecutive elements is betwixt 50 to 200.

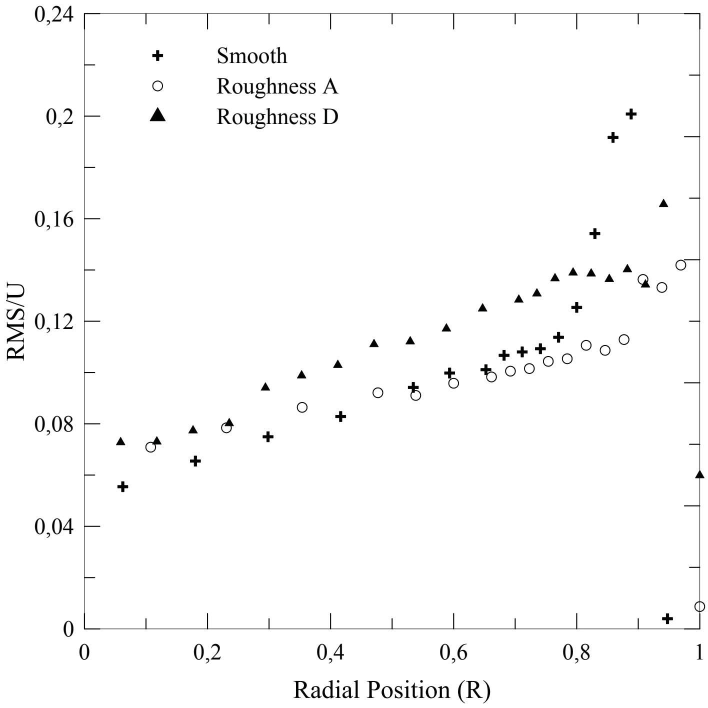


Figure 8: **Turbulence Intensity.**

The results from roughness shown in Fig. 4d, is also showed in Fig. 6. The behavior for this case seems to be related to permeable wall effect, which is not in the scope of current work. A uncertainty analysis was made for all the experimental data. The Reynolds number has an uncertainty of the 10.8% (mostly due to the uncertainties in the Kinematic viscosity) and the friction factor has an uncertainty of 5.7% on the average (mainly due to the uncertainty on the mass flow rate measurements).

Results of the LDA measurements are shown in Fig. 7 and 8. These measurements have been done for the sand made roughness and organized roughness A. For the mean axial velocity profile, as can be seen in Fig. 7, the log law is formed for both type of roughness. Also, as expected this curves are shifted due to the presence of the rough wall. For the sand made case, these profile can be expressed with empirical chart (Eq.2) such as Apsley (2007) with good accuracy.

$$U^+ = \frac{1}{\kappa} ln\left(\frac{y^+}{k^+ + C}\right) + 8.5 \qquad , C = e^{\kappa(8.5-B)} \tag{2}$$

However, for the roughness type A the predictions are far than experiments indicating a modified turbulent structure for this case.

To investigate the turbulent structure deeper, the axial turbulent intensity is plotted in Fig. 8, for smooth, sand made, and type A roughness at almost same Reynolds number. As can be seen, although both roughnesses change the turbulent structure, the type A is more similar to smooth pipe. It seems that the nature of this similarity is same as the reason of the strange behavior in friction plot.

5. CONCLUSION

The influences cause by different roughness elements and also their placement on the turbulent flow of a Newtonian fluid is examined experimentally.

It was observed that for specific arrangements of the rough elements, an strange behavior start to emerge. Specifically, the plateau at the end of friction factor versus Reynolds graph (fully rough regime), will be replaced by an exponential line for high Reynolds. In this case, if the friction factor obtained compared with usual friction due to same size of roughness (randomly distributed), a form of drag reduction can be identified.

This can be seen as a new mean to alter the near wall turbulence structure, and may have applications in drag reduction of liquid transport in pipes. However, the true physics behind this process is unknown and further study is required on that.

6. ACKNOWLEDGEMENTS

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