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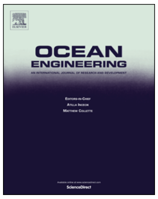

Correlation of frictional drag and roughness length scale for transitionally and fully rough turbulent boundary layers

Uğur Oral Ünal[1]

Istanbul Technical University, Faculty of Naval Architecture and Ocean Engineering, Istanbul, Turkey

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ABSTRACT

This study investigates zero-pressure-gradient turbulent boundary layers for several rough surfaces in the transitionally rough and fully rough flow regimes. The tested surfaces include, but are not limited to marine antifoulings as irregularly rough engineering surfaces. The boundary layer profiles were measured by using a two-dimensional Laser Doppler Velocimetry system. The coatings were applied with different procedures to simulate the effect of different application types. An attempt was made to find a new roughness length scale which provides a good correlation to represent the roughness functions for both transitionally and fully rough flow regimes. Surface roughness measurements with a laser profilometer device were carried out to determine several roughness parameters to be used in the calculation of the roughness length scale. Different roughness calculation methods, with varying low-pass filter window lengths and sampling lengths, were applied to determine their effect on the roughness parameters and hence the roughness function correlations.

The paper presents a new definition for the roughness length scale and covers the details of the measurements, analyses, discussions regarding the differences between the surfaces, the effect of the roughness calculation methods and application type of the antifouling coatings.

1. Introduction

The effect of surface roughness on the turbulent boundary layer flow may be regarded as one of the most studied topics of fluid mechanics research. Alongside the high level of complexity introduced by the physical mechanism of the subject, the fundamental reason of the related extensive research is the wide-range of engineering applications involving fluid flow over rough surfaces. This important application area includes turbomachinery, piping systems, ship, aircraft and automotive industries as well as atmospheric research, etc.

From the engineering point of view, perhaps, the most fundamental question to be answered is about how roughness affects the frictional drag characteristics of the surfaces. The pioneering studies in this area date back more than 150 years, as Darcy (1857) and Nikuradse (1933)'s works on internal flows inside rough pipes being the most striking examples of this extensive research. Colebrook and White (1937) also studied the flow in rough pipes. However the work of Colebrook (1939) with particular attention to the transitionally rough range defined the well-known Colebrook–White law for the correlation of roughness function and the roughness Reynolds number which is also assumed to be valid for engineering surfaces. The widely known Moody diagram (Moody, 1944) also relates the pressure drop in pipes due to relative surface roughness and Reynolds number which was obtained from the results of Colebrook (1939).

In order to get a better understanding of the effect of the roughness on the boundary layer flow, there exist a large number of studies involving particularly regular or geometrically defined roughness types such as spheres, rods, cones, meshes etc. (e.g. Krogstad and Antonia, 1999; Brzek et al., 2010). However, most engineering applications include complex surface roughness structures with random distribution. Antifouling coatings widely-used in the marine environment are good examples for such naturally occurring engineering surfaces. The use of antifouling coatings is of vital importance, particularly for the ship hulls, since the attachment of marine organisms (e.g. algae, slime, barnacles, etc.) to the hull and propeller leads to excessive energy losses and hence higher fuel consumption and carbon emission. Accordingly, an important amount of research studies has been concentrated recently on the irregularly rough walls by the hydrodynamicists, dealing with either marine antifouling coated surfaces or surfaces subject to biofouling (e.g. Schultz and Swain, 1999; Schultz, 2004; Candries and Atlar, 2005, Ünal et al., 2012). The effect of various antifoulings on the boundary

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E-mail address: ounal@itu.edu.tr
URL: http://www.gidb.itu.edu.tr

[1] Tel.: +90 212 2856425; fax: +90 212 2856464.

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layer flow and hence the frictional resistance is clearly presented by these studies. Undoubtedly, these hydrodynamical differences do not only arise from the chemical structure of the coating leading to different roughness characteristics, but they are also directly related to the coating application type, such as spraying and rollering.

The universal validity of the Moody chart is generally acknowledged by the engineering society and it has been frequently used for practical applications. However, as the chart was developed using the equivalent sand grain roughness height, k_s, which cannot be directly assigned without an experimental analysis, its validity can be questioned when a wide range of surface roughness types is considered. The determination of k_s gets more complicated with irregularly rough engineering surfaces, since a significant amount of roughness parameters is involved in the characterisation of the surfaces. These arguments impose several difficulties in the relationship between the roughness of the surface and frictional resistance.

The standard way of presenting such a relationship is to deal with the roughness function, ΔU^+, and roughness Reynolds number, k^+. The equation associated with these variables can be expressed as $\Delta U^+ = f(k^+)$. This relationship is of critical importance in many aspects. For example, most of the turbulence models used in the computational studies are calibrated to reproduce the correct logarithmic layer displacement to account for the roughness effect in the boundary layer (Patel, 1998; Wilcox, 2006). Once the above relationship is known for a particular kind of surface roughness, it can be reliably used in the turbulence models to predict the additional drag created by that roughness. For example, recently, Demirel et al. (2014) employed the Grigson's roughness function model (Grigson, 1992) in the standard wall function of a commercial software to compute the frictional resistance of antifouling coatings. Moreover, the same relationship allows the determination of frictional drag of scale-up geometries by referring to the similarity analyses in the literature (Granville, 1987; Schultz, 2007). Unfortunately, it is extremely difficult to define the correct roughness length scale which is applicable to any kind of roughness. Whilst the roughness functions strongly depend on the Reynolds number, they are likewise related to the size and structure of the surface roughness. In the fully rough regime, the equivalent sand roughness height k_s, is generally used in lieu of k, as the roughness length scale, based on the Nikuradse's extensive sand grained rough pipe measurements (Schlichting, 1979). Yet, even in the fully rough regime, there is no universal roughness parameter that offers a decent correlation with Nikuradse's roughness functions. That is to say, different types of surface roughness require different conversion equations to specify the correct k_s values, when a single roughness height parameter is used (e.g. Schultz and Flack, 2009). This clearly suggests that a single height parameter is not adequate to provide reliable and universal conversion to k_s for all types of surface roughness.

The picture is even more complicated when the transitionally rough flow regime is also considered besides the fully rough one. As clearly pointed out by Flack and Schultz (2010), the shape of the roughness function in the transitionally rough regime also depends on the roughness type as does the onset of the fully rough regime. For instance, whilst Nikuradse's experiments pointed out an inflectional character in the shape of the roughness functions, the correlations derived from the engineering roughness types, such as the commercial steel pipes, plates, marine coatings, etc., exhibited a monotonically increasing behaviour (Colebrook, 1939; Grigson, 1992). On the other hand, various values of roughness Reynolds number have been stated in the literature for the onset of the fully rough regime (e.g. Jimenez, 2004; Ligrani and Moffat, 1986; Lewkowicz and Musker, 1978).

The problem does not get easier when an engineering roughness is dealt with Colebrook's or Grigson's curve without any conversion to k_s, since the correct roughness length scale to satisfy the correlation function is simply unknown. It is of note that the calculation method of the roughness statistics, e.g. filtering, sampling interval etc., also plays an important role in the roughness function correlations, as it directly affects the parameters used to define the roughness length scale (Medhurst, 1990; Howell and Behrends, 2006). An extensive research has been performed to date, in order to provide a universal roughness length scale which is valid for both transitionally and fully rough flow regimes. Flack and Schultz (2010) provides a detailed review of this active research area. However, none of them was successful to provide a decent correlation for an extended range of roughness type.

This study covers the zero-pressure-gradient turbulent boundary layer experiments of several rough surfaces in the transitionally rough and fully rough flow regimes. Two widely-used commercial marine antifouling systems have been selected as irregularly rough engineering surfaces. The coatings were applied with different procedures to simulate the effect of different application types. In this way, whilst the standard spraying and rollering techniques were adopted (as in e.g. Candries and Atlar, 2003; 2005) for the application of the coatings on the test plates, different roller types were also considered to reveal the importance of the seemingly insignificant application details. To further extend the roughness type and Reynolds number range investigated, a blasted steel and two sand paper coated surfaces were additionally examined. The experiments for a total of nine different surfaces were conducted in the Emerson Cavitation Tunnel (ECT) of Newcastle University, by using a 2D LDV system for the measurement of the boundary layer profiles. An attempt was made to find a new roughness length scale, k, which provides a good correlation to represent the roughness functions for both transitionally and fully rough flow regimes. For this purpose, roughness measurements with a non-contact high precision laser profilometer device were performed and subsequent detailed analyses were carried out to determine the relevant roughness parameters which can be used in the calculation of the roughness length scale, k. The influence of the certain filtering techniques as well as the variation of the sampling lengths and window lengths of the low-pass filter, on the roughness parameters and hence the roughness function correlations, were examined.

The paper does not only present a new definition for the roughness length scale, which results in a decent correlation between the roughness Reynolds number (k^+) and roughness function (ΔU^+), but also covers the details of the measurements, analyses, discussions regarding the differences between the rough and smooth surfaces, the effect of the roughness calculation methods and application type of the antifouling coatings.

2. Experimental set-up and test conditions

600 mm long and 220 mm wide flat plate test specimens were used in the experiments. Two state-of-the-art, well-established antifouling paint systems were selected for the coating of the specimens. One of them was an environment-friendly foul-release (FR) type coating which is coded as AF1 throughout the paper. The other antifouling solution used in the experiments involved the well-known self-polishing copolymer (SPC) technology, which is subsequently referred as AF2. The rollering technique was adopted for the application of both coatings on the test plates. As stated previously, two different roller types, which were recommended and regularly used by coating companies, were considered to reveal the importance of the application in detail. The experimental cases involving the smoother roller are expressed as RS while the cases with the rougher roller were referred as RR. For instance, if the FR type coating is applied with the smoother roller, the case is shown as AF1_RS in this paper. Additionally, the standard spraying technique was used for the application of AF1 and it is coded as AF1_SP. To further extend the roughness type and Reynolds number range investigated, a blasted steel surface (BLA) along with #40 grit (SAND40) and #120 (SAND120) grit fully