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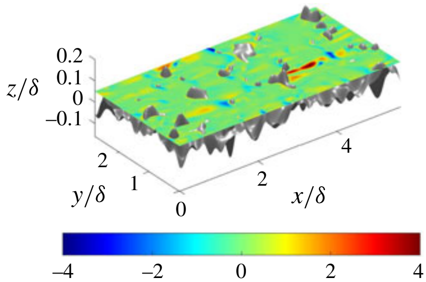
Moving beyond Moody



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Thakkar *et al.* (*J. Fluid Mech.*, vol. 837, 2018, R1) represents a significant advancement in the ability to computationally model rough wall flows. Direct numerical solution (DNS) of turbulent boundary layer flow over an industrial grit blasted surface at relevant roughness Reynolds numbers, from hydraulically smooth to fully rough regimes, is a path forward to parametrically study a wide range of surface roughness. The methodology described in this paper, coupled with validation experiments, ultimately should lead to improved frictional drag predictions.

Key words: turbulent boundary layers

1. Introduction

Engineers do not currently have the ability to accurately predict the drag of a generic rough surface. After decades of detailed measurements and recent computations of boundary layer flow over rough surfaces, the friction drag on a surface is only accurately known for the tested surfaces.

Engineering predictions of surface roughness is generally characterized by k_s, the equivalent sand grain roughness height. This is the size of uniformly packed sand grains tested by Nikuradse (1933) that produces the same frictional drag in the fully rough regime. Therefore, k_s is a hydraulic scale, not a physical scale, and this is what is listed on the Moody diagram (1944) (figure 1) as ϵ, the equivalent roughness height. I suspect that the word equivalent has often been ignored and the words roughness height have been used. If this is the case, then which roughness height? The mean, the peak-to-trough, or the root mean square (r.m.s.) roughness height? Even if you select one of these roughness scales, all are dependent to some extent on the spatial sample size of your measurement region. Therefore, the Moody diagram is only accurate for surfaces with known k_s in the fully rough regime.

The transitionally rough regime poses its own set of challenges. The transitionally rough regime is characterized by contributions from viscous and form drag on the roughness elements. At low Reynolds numbers, viscosity damps out flow disturbances caused by surface roughness. For these conditions, the flow is classified as hydraulically smooth. As Reynolds number increases, the turbulent eddies caused

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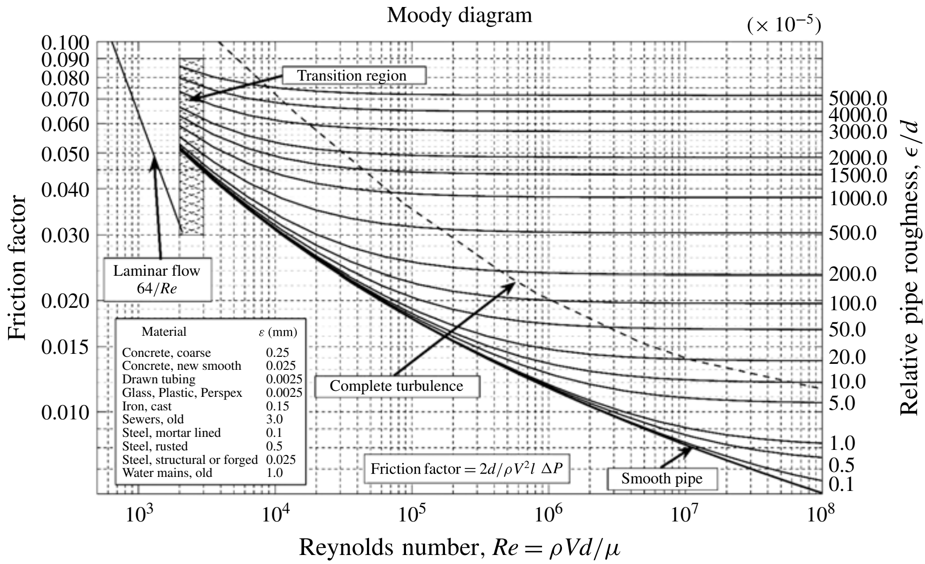

FIGURE 1. Reprinted with permission from L. F. Moody, Friction factors for pipe flow, *Trans. ASME*, vol. 66, 1944, pp. 671–684. Copyright 1944 ASME.

by the roughness elements are not fully damped by viscosity and form drag on the roughness contributes to the overall drag, increasingly with increased Reynolds number. Eventually, form drag is the dominant mechanism, and the flow becomes fully rough. The mechanisms responsible for this transition from hydraulically smooth to fully rough are not fully understood. Do roughness effects occur gradually as the roughness Reynolds number ($k^+ = U_\tau k/\nu$, where k is the roughness height, U_τ is the friction velocity and ν is the kinematic viscosity) increases, as assumed by the Colebrook (1939) roughness function (used in the Moody diagram), or is the onset of roughness effects more abrupt, occurring at a finite k^+ as represented by a Nikuradse (1933) roughness function?

It has been shown that the onset of roughness effects, the shape of the roughness function in the transitionally rough regime and the Reynolds number where the flow becomes fully rough are highly dependent on roughness geometry (Flack & Schultz 2014). Since there are a myriad of roughness geometries, a way is needed to categorize surface roughness by easy to measure statistical or roughness feature properties. Additionally the measurement region upon which these properties are based should be identified, and potentially scales that do not contribute to the drag need to be removed before determining surface statistics. This filter should also be based on a roughness scale. There are a number of issues that need to be addressed before developing a robust engineering correlation, hence the reason that the contributions by Thakkar, Busse & Sandham (2018) (for example, dispersive sheer stress as shown in the figure by the title) and other recent simulations of rough wall flows are so important. Realistic rough surfaces at relevant Reynolds numbers are being computed and there is hope in making headway towards identifying roughness scales to inform engineering predictions of surface drag.

2. Overview

A number of recent simulations over complex roughness have been performed with the goal of understanding the near wall turbulence and developing predictive correlations for drag. Mathematically generated surfaces with a range of scales allow for parametrically changing surface parameters. Anderson & Meneveau (2011) performed a large eddy simulation (LES) for flow over a multi-scale, fractal-like roughness, similar to the range of scales in natural terrains. Realistic roughness was studied by Yuan & Piomelli (2011) using LES for roughness replicated from hydraulic turbine blades, with surface features parametrically changed to study the influence of roughness slope on the surface drag. Three-dimensional sinusoidal roughness in the transitionally rough regime was investigated using direct numerical solution (DNS) by Chan *et al.* (2015) and MacDonald *et al.* (2016). It was shown in these studies that the roughness function could be accurately determined using the minimal-span channel technique (Chung *et al.* 2015) which allows for low Reynolds number simulations ($Re_\tau = U_\tau h/\nu = 180$, where h is the channel half height). This is encouraging since a large number of parameters can be investigated at a lower computational cost. Forooghi *et al.* (2017) also used DNS at low Re_τ to determine the equivalent sand grain roughness for randomly distributed roughness elements of random size and prescribed shape. Correlations are presented considering roughness heights, slopes, density and moments of the surface elevation p.d.f.

Thakkar *et al.* (2018) are the first to use DNS to study a realistic irregular roughness, similar to the sand grain roughness of Nikuradse (1933), for the entire range of roughness Reynolds numbers from hydraulically smooth to fully rough. This is an extension of their previous work (Thakkar, Busse & Sandham 2017) where they presented roughness results in the upper part of the transitionally rough regime and the fully rough regime for grit blasted and graphite surfaces. DNS with engineering roughness is a true advancement, and they have developed techniques to tile these surfaces within the computational domain. The grit blasted surface is deemed Nikuradse-like because it follows the Nikuradse roughness function with $k_s^+ = 0.87k^+$. The authors expect other sand-grain-like surfaces to have similar behaviour. The interesting question is what makes a surface sand-grain-like: sharp protrusions, close packing, a distinct range of scales, positive or negative skewness?

3. Future

Tremendous progress has been made in the prediction of frictional drag on rough surfaces. The way forward is to study both realistic roughness and mathematically generated surfaces that contain a range of surface features. Recent computations have shown that drag producing roughness scales can be adequately represented at relevant Reynolds numbers. Rough surfaces with a range of scales can be characterized by surface statistics or other mathematical parameters. These parameters can be derived from measured surface scans. Are the important features the r.m.s. height and the skewness of the p.d.f. (Flack & Schultz 2010), effective slope (Napoli, Armenio & De Marchis 2008; Chan *et al.* 2015), distribution of peak roughness heights (Forooghi *et al.* 2017) or others? Surely the roughness density and the sheltering that occurs as the roughness becomes more closely packed (i.e. MacDonald *et al.* 2016) must be important for sparse roughness.

The feature of the Moody diagram that should definitely be reconsidered is the Colebrook function in the transitionally rough regime. This function is a monotonic variation in the skin-friction, asymptotically approaching the limits of hydraulically smooth and fully rough regimes. While Colebrook's experiments (Colebrook 1939) on commercial pipes followed this function, more recent work on industrial pipes (Allen, Shockling & Smits 2005; Langelandsvik, Kunkel & Smits 2008) and Nikuradse sand

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grains (1933) did not display this behaviour. Gioia & Chakraborty (2006) discuss that the shape of the friction factor (or roughness function) is related to the size of eddies shed by the roughness elements. At low Reynolds numbers, dissipation of the small eddies shed from the roughness elements leads to a depressed value of the friction factor. The range of eddies become larger at higher Reynolds number resulting in more vigorous momentum transfer and increased drag. With an abundance of roughness geometries, it is likely that a wide range of friction factor shapes are possible in the transitionally rough regime.

Are we ready to move beyond the Moody diagram and characterizing the roughness by k_s? The equivalent sand grain roughness height is a convenient scale in the fully rough regime but not necessarily useful in the transitionally rough regime. Other scales may better characterize the onset of roughness effects, the shape of the roughness function and the transition to fully rough behaviour. This area of research is still very active and the ability to simulate realistic roughness with a wide range of surface parameters will ultimately lead to improved predictive tools.

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