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A systematic study of turbulent heat transfer over rough walls

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ABSTRACT

Direct Numerical Simulations are used to solve turbulent flow and heat transfer over a variety of rough walls in a channel. The wall geometries are exactly resolved in the simulations. The aim is to understand the effect of roughness morphology and its scaling on the augmentation of heat transfer relative to that of skin friction. A number of realistic rough surface maps obtained from the scanning of gas turbine blades and internal combustion engines as well as several artificially generated rough surfaces are examined. In the first part of the paper, effects of statistical surface properties, namely surface slope and roughness density, at constant roughness height are systematically investigated, and it is shown that Reynolds analogy factor (two times Stanton number divided by skin friction coefficient) varies meaningfully but moderately with the surface parameters except for the case with extremely low slope or density where the Reynolds analogy factor grows significantly and tends to that of a smooth wall. In the second part of the paper, the roughness height is varied (independently in both inner and outer units) while the geometrical similarity is maintained. Considering all the simulated cases, it is concluded that Reynolds analogy factor correlates fairly well with the equivalent sand roughness scaled in inner units and asymptotically tends to a plateau.

1. Introduction

Convection heat transfer over rough walls finds applications in several areas of industry. Gas turbine blades are often rough on account of coating or degradation during service [1]. Novel additive manufacturing techniques, which can be used for devices such as heat exchangers, create very rough surfaces [2]. In-cylinder heat transfer in IC-engines [3] and ice accretion on the aircraft [4] are other examples of heat transfer over rough surfaces.

Roughness can significantly alter both skin friction and heat transfer on the wall. A large portion of the published research in this field is devoted to the calculation of equivalent sand roughness k_s for different roughness types and to the understanding of the relation between this quantity and the geometry of roughness. Equivalent sand-grain roughness, first defined by Schlichting in his pioneering work on roughness [5], is the size of sand-grain out of Nikuradse's experiments [6] that produces the same skin friction coefficient as the arbitrary surface of interest[1]. Schlichting was the first who experimentally determined the equivalent sand-grain roughness for several artificially roughened surfaces [5]. Finding a correlation between k_s and surface geometrical properties is particularly difficult for naturally roughened surfaces thanks to their disparate and stochastic nature. Several of the existing correlations are reviewed by Flack and Schultz [7]. Recently, Direct Numerical Simulation (DNS) is also utilized to produce systematic data required for the development of a universal k_s correlation [8,9].

Equivalent sand-grain roughness k_s is predominantly used in the engineering CFD tools to represent the effect of roughness. It is well established that the main effect of roughness on the mean velocity profile is a downward shift in the logarithmic region, which may be parametrized by k_s [10]. In turbulence modeling this can be a basis for the modification of wall functions. It is also widely accepted that, except for a region in the immediate vicinity of the rough wall, the structure of turbulence is unaffected by the roughness [11,12]. In view of the above facts, the equivalent sand-grain roughness approach is expected to function for the flow over rough walls as well as for the flow over smooth walls, as long as the right k_s value is known a priori. For the prediction of heat transfer, however, relying solely on k_s can lead to error as the increase in heat transfer due to roughness is not proportional to that of momentum transfer. In other words, Reynolds analogy does not hold for rough surfaces [13–15].

To address the above-mentioned shortcoming, Aupoix [15] suggests a modified k_s-based approach in the framework of

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[1] In the fully-rough regime.

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Reynolds-averaged Navier Stokes (RANS) modeling, in which a corrected expression for turbulent Prantdl number above rough walls is utilized, thereby heat transfer predictions are meaningfully improved. The likes of the approach suggested by Aupoix, however, require experimental or high fidelity numerical data for calibration and validation. Aupoix [15] uses a Discrete Element Method (DEM) for generating a database, based on which the model coefficients can be tuned. In DEM, roughness is effectively 'modeled' using source terms in the momentum, energy and turbulence transport equations (see [16,17] for examples of DEM in modeling of fully turbulent and transitional flows, respectively). While being computationally less costly, DEM does not provide a level of fidelity comparable to full-geometry resolving DNS (simply referred to as DNS hereinafter). Therefore, as pointed out by Aupoix, further progress in the prediction of heat transfer over rough walls can be achieved by refining the available models through two possible routes: use of available/new experimental databases or creation of a DNS database. The present paper follows the second route.

A number of experimental reports on turbulent heat transfer over rough surfaces are available in literature. Ligrani et al. [18] report measurements of skin friction coefficient and Stanton number for developing boundary layers over a plate roughened by packed spheres. Stimpson et al. [2] measured pressure drop coefficient and Nusselt number over additively manufactured surfaces in ducts with different hydraulic diameters. Stripf et al. [19] measure heat transfer on a high-pressure turbine vane roughened by distributed truncated cones, and studied the effect of roughness density and upstream turbulence level. In their comprehensive experimental campaign, Bons [14,20] and Bons and McClain [21] examine a number of realistic roughness geometries from gas turbine blades – each geometry representative of a surface degradation mechanism. These authors also systematically study the effects of pressure gradient and upstream turbulence level on both heat transfer and skin friction. Bons [14] uses the Reynolds analogy factor

$$RA = \frac{2St}{C_f}. \tag{1}$$

of a rough wall normalized by that of the corresponding smooth wall RA_0 to quantify the relative augmentation of heat and momentum transfer due to roughness. This concept is used extensively in the present paper.

DNS provides not only accurate results but also absolute access to all flow variables everywhere in the computational domain, making it an ideal choice for generating benchmark data. Only a few DNS reports can be found in the open literature in which heat transfer is taken into account [22–25], which mainly focus on simple 2D geometries. Among the above references, [25] studies one 3D roughness geometry generated by identical cubes. The limited amount of existing DNS data for heat transfer over 3D roughness calls for further work in this area, and the present paper attempts to partially fill this gap.

The present paper provides DNS results for skin friction and heat transfer over several 3D rough surfaces, including both artificial and realistic roughness samples. We systematically study the effect of roughness morphology at fixed roughness height and that of roughness height (in inner and outer scales) at fixed roughness morphology [2]. In total, 25 simulations at friction Reynolds number of 500 are run in a fully-developed channel flow configuration. The results are expected to provide a basis for the calibration and evaluation of the models used by engineers. Apart from that, such a systematic study can shed light on the physics of heat transfer augmentation over rough walls. Two important questions that the present results seek to answer are the following. (1) What are the relevant scales in determining the Reynolds analogy factor over rough walls? (2) Whether and to what extent is this factor affected by merely a change in the surface morphology? The present paper addresses these questions for the statistically homogeneous roughness.

The paper is organized in the following way. Section 2 is devoted to the introduction of the roughness samples – both artificial and realistic. Numerical solution is explained in Section 3. In Section 4, the simulation results are presented. In the present paper, only the integral quantities of direct engineering interest, e.g C_f, St and RA/RA_0 are discussed. Finally, the main findings are summarized in Section 5.

2. Roughness samples

Two types of surface roughness samples are studied in the present paper. (1) Artificial roughness generated by the distribution of roughness elements on a reference smooth plane (bottom plane). (2) Realistic roughness based on scanning of industrial rough surfaces. In the following each type is explained.

2.1. Artificial roughness

Generation of roughness by distributing roughness elements on a smooth surface is common in both experimental and numerical communities. Such roughness geometries are straightforward to parameterize, thus provide the possibility to isolate the effects of different parameters. Study of roughness morphology in this paper is mainly based on the artificial samples.

A full description of our roughness generation approach and the shapes of elements is available in [8]. In what follows, only the aspects important for the present study are discussed for brevity. To form each roughness sample, a certain number of elements – calculated from a prescribed total frontal area – are generated. The height of each roughness element k follows a random function with normal distribution, prescribed mean k_m and standard deviation σ_k. The positions of the roughness elements on the bottom plane are also determined randomly with a uniform distribution. Although such an artificial roughness still lacks the complexity of a realistic roughness, our attempt is to mimic some features of realistic roughness by randomness in size and positioning of elements. Therefore, the presently studied artificial samples can be considered a closer representation of realistic roughness than those generated by same-size regularly distributed elements, widely used in the literature.

Two shapes of roughness elements are used in the present study as shown in Fig. 1. We label the elements on the left and right hand side of this figure A and B, respectively. The roughness elements are axisymmetric. Element A has a less steep side profile and roughly resembles a slightly truncated cone. Element B has a very steep side but is flat on top, hence is more similar to a cylinder

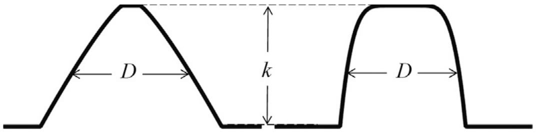

Fig. 1. Side views of two types of roughness elements used in the paper: type A (left) and type B (right). k and D denote height and effective diameter of the element (the diameter of a cylinder with the same frontal area), respectively.

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[2] In the present paper, 'morphology' is an umbrella term referring to the statistical surface properties, which can be changed independent of the characteristic height of roughness (or simply height of roughness elements when the surface is roughened by such elements). "A change of roughness height at fixed morphology" means that the geometrical similarity of roughness is maintained while the characteristic roughness height is scaled up or down in inner/outer units.