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Analysis of turbulent flow in channels roughened by two-dimensional ribs and three-dimensional blocks. Part I: Resistance

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Abstract

The characteristics of a turbulent flow in channels with two-dimensional ribs and three-dimensional blocks are investigated in the context of surface roughness effects. Reynolds-averaged Navier–Stokes equations, coupled with the k–ω turbulence model with near-wall treatment, are solved by a finite-volume method. Calculations are carried out for ribs with square, triangular, semicircular and wavy cross-sections over a range of rib spacing (pitch) and Reynolds numbers. The pitch that yields maximum resistance is identified for each roughness. For all cases, the space-averaged velocity profile exhibits a logarithmic region, with a roughness function that varies logarithmically with the roughness Reynolds number. The roughness function depends on the rib shape and pitch ratio but is independent of the absolute rib size. Analysis with three-dimensional blocks reveals similar but more complex behavior. A logarithmic region exists in the velocity profile but with much smaller block heights compared to ribs. The different block arrangements exhibit quite distinct flow characteristics but the differences tend to vanish as the block height decreases. In general, a Reynolds-averaged numerical model successfully describes the principal features of wall roughness that have hitherto fore been the purview of experimental correlations. *Part II* of the paper extends the model to study heat transfer from a rough surface.

Keywords: Distributed roughness; Similarity law; Roughness function; RANS equations; k–ω model

1. Introduction

Turbulent flow over surfaces roughened by simple geometric elements, such as two-dimensional spanwise ribs or discrete three-dimensional protuberances, continue to be of interest in fluids engineering from several perspectives (Schlichting, 1979). Regular roughness elements are routinely used for heat transfer enhancement (Webb et al., 1971; Sparrow and Tao, 1983). They are also used to study surface roughness effects, in general, as they are easily reproduced in the laboratory and modeled in numerical experiments. Measurements on ribbed surfaces, for example, have provided considerable insight into the mechanisms by which surface roughness effects are felt in the interior of the flow. Of particular concern in practical engineering applications is the existence of similarity laws, principal among which is the logarithmic velocity distribution, upon which friction factor and heat transfer correlations are based.

At sufficiently large distance from the roughness elements, the effect of the individual elements vanishes and the net effect on the velocity profile is felt as reduction in the constant B in the logarithmic law. This change in the constant, B, known as the *roughness function*, depends not only on the roughness size but also on its geometry (Schlichting, 1979). In the case of ribs, for example, the roughness function depends on their shape and pitch (spacing between adjacent ribs). Numerous attempts have been

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Nomenclature

b, c	length (streamwise) and width (spanwise) of roughness block, Fig. 10
ΔB	roughness function, downward shift in the logarithmic velocity profile
C_{p}	pressure coefficient $\left(=\frac{p-p_{\mathrm{ref}}}{\frac{1}{2}\rho U_{\mathrm{b}}^2}\right)$
d	spanwise spacing of blocks, Fig. 10
D_{e}	hydraulic diameter, $2H$
f	Darcy friction factor $\left(=\frac{8\tau_x}{\rho \bar{U}^2}\right)$
H	channel height
h	rib height
h^+	roughness Reynolds number $\left(=\frac{hu_\tau}{\nu}\right)$
k	turbulence kinetic energy $(=\overline{u_i u_i}/2)$
p_{ref}	reference pressure, the pressure on top of rib, Eq. (6)
$\hat{p}$	normalized pressure $\left(=\frac{p-p_{\mathrm{ref}}}{\rho U_{\mathrm{b}}^2}\right)$
R^+	roughness correlation, Eq. (9)
$Re_\delta, Re_{D_{\mathrm{e}}}$	Reynolds number $\left(=\frac{\bar{U}\delta}{\nu}\text{ or }\frac{U_{\mathrm{b}}D_{\mathrm{e}}}{\nu}\right)$
$\overline{U}$	average velocity between wall and the point of velocity maximum
U_{b}	bulk velocity
U_l	space-averaged streamwise velocity
u_τ	space-averaged friction velocity $\left(=\sqrt{\tau_x/\rho}\right)$
u^+	non-dimensional velocity $(=U_l/u_\tau)$
w	rib or block pitch, Figs. 1 and 10
x, y, z	streamwise, normal, and spanwise coordinates, Figs. 1 and 10
y^+	non-dimensional normal distance $\left(=\frac{yu_\tau}{\nu}\right)$
y_0	location of zero space-averaged velocity, virtual origin

Greek symbols

δ	distance from wall to the point of velocity maximum
ν, ν_{t}	kinematic viscosity, eddy viscosity
ρ	density
ω	specific dissipation rate
τ_{w}	local wall shear stress $\left(=\mu\frac{\partial u}{\partial y}\Big\|_{\mathrm{w}}\right)$
τ_x	space-averaged wall shear stress, Eq. (6)

made to correlate the effects of different types of roughness with the classical experiments of Nikuradse (1950) on sand-grain roughness.

Dvorak (1969) summarized the previous work on rib roughness and proposed a relation between the rib pitch and the roughness function. Perry et al. (1969) experimentally obtained the roughness function for a boundary layer developing on a surface with distributed ribs. They were the first to make the distinction between the so-called *d*- and *k*-type roughness depending on whether the dominant parameter is the boundary-layer thickness (or pipe diameter, *d*) or the rib height (*k*). Since then a number of experimental studies (Jimenez, 2004) have been conducted to better understand the details of the flow over ribbed surfaces.

More recently, advances in turbulence modeling have led to studies of rib roughness using different numerical methods. For example, Cui et al. (2003a,b) used large-eddy simulations (LES) to compute the flow in a two-dimensional channel with ribs with various pitch to height ratios. They showed that a logarithmic layer exists in the space-averaged velocity distribution some distance above the ribs. They also identified the location of the so-called virtual origin with the position of zero space-averaged velocity. Similar studies are reported by Miyake et al. (2002) and Ikeda and Durbin (2002) using direct numerical simulation (DNS).

The importance of similarity laws in engineering correlations of friction and heat transfer mentioned above, and the success of these recent numerical studies suggest that a more comprehensive numerical investigation would yield useful insights into the effects of discrete roughness elements on these parameters. As neither LES nor DNS are cost effective for such purposes, here we use a numerical model based on the Reynolds-averaged Navier–Stokes (RANS) equations and an established two-equation turbulence model to study the effect of different types of discrete roughness on the velocity profile and related correlations. In particular, the existence of a logarithmic layer is examined and the relevant parameters are identified. Although the RANS approach is not suitable for capturing the flow unsteadiness due to large-eddy motions, it is quite adequate for the present study in which only the mean quantities, both in time and space, are of interest. Calculations are carried out for two-dimensional ribs as well as three-dimensional roughness elements. A brief description of the numerical model is presented as the various components are quite well established, and a simple validation study is performed before describing the principal results.

2. Numerical model and validation

2.1. Governing equations

For steady incompressible turbulent flow, the Reynolds-averaged equations for conservation of mass and momentum may be written as follows:

$$\text{Continuity}: \quad \frac{\partial \mathbf{u}}{\partial \mathbf{x}} = 0 \tag{1}$$

$$\text{Momentum}: \quad \frac{\partial}{\partial \mathbf{x}}\left[\mathbf{u}\mathbf{u} - (\nu+\nu_{\mathrm{t}})\frac{\partial \mathbf{u}}{\partial \mathbf{x}}\right] = -\frac{1}{\rho}\frac{\partial p}{\partial \mathbf{x}} + \frac{\partial}{\partial \mathbf{x}}\left[\nu_{\mathrm{t}}\frac{\partial \mathbf{u}}{\partial \mathbf{x}}\right] \tag{2}$$