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Open channel turbulent flow over hemispherical ribs

M. Agelinchaab, M.F. Tachie *

Department of Mechanical and Manufacturing, University of Manitoba, Winnipeg, Manitoba, Canada R3T 5V6

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Abstract

This paper reports an experimental investigation of open channel turbulent flow over hemispherical ribs. A row of ribs consists of hemispheres closely placed to one another in the spanwise direction and cover the entire span of the channel. The pitch-to-height ratio is varied to achieve the so-called *d*-type, intermediate and *k*-type roughness. The Reynolds numbers based on water depth, *h*, and momentum thickness, θ, of the approach flow are respectively, $Re_h = 28{,}100$ and $Re_\theta = 1800$. A particle image velocimetry is used to obtain detailed velocity measurements in and above the cavity. Streamlines, mean velocity and time-averaged turbulent statistics are used to study the effects of pitch-to-height ratio on the flow characteristics and also to document similarities and differences between the present work and prior studies over two-dimensional transverse rods. It was observed that interaction between the outer flow and the shear layers generated by ribs is strongest for *k*-type and least for *d*-type ribs. The results also show that hemispherical ribs are less effective in augmenting flow resistance compared to two-dimensional transverse ribs. The levels of the Reynolds stresses and budget terms increase with increasing pitch-to-height ratio inside the roughness sublayer.

Keywords: Open channel flow; Hemispherical ribs; Wall roughness; Particle image velocimetry

1. Introduction

Turbulent flows over rough surfaces occur in many fluid engineering systems. One effect of surface roughness is to increase momentum transfer and flow resistance. In the area of heat transfer, surfaces are often artificially roughened to augment heat transfer rates. Because of their technological importance, turbulent flow over rough surfaces has been studied quite extensively since the early work of Nikuradse (1933). Different roughness elements such as sand grains, gravels, spheres, wire mesh, and two-dimensional transverse rods attached to surfaces have been used in the past to model surface roughness. The results obtained from prior studies have broadened our knowledge of the structure of rough wall turbulent flow.

Prior research has shown differences between the structure of turbulent flow over smooth and rough surfaces close to the wall or roughness elements. The region over which these differences exist is often referred to as the roughness sublayer, and is defined as the region extending from the wall to about 5 roughness heights (Raupach et al., 1991). Following the terminology of Perry et al. (1969), surface roughness can be classified as *d*-type and *k*-type roughness. If the roughness function depends on Reynolds number based on the roughness height, *k*, and friction velocity, U_τ, (i.e., $k^+ = kU_\tau/\nu$, where ν is the kinematic viscosity), it is termed *k*-type roughness. Research has shown that the *k*-type scaling is not obeyed by grooved surfaces when the cavities are narrow. This type of roughness scales with outer variables (the boundary layer thickness, δ or the pipe diameter, *d*) and is therefore known as *d*-type. For flow over ribs made of repeated two-dimensional transverse rods, roughness classification is based on pitch (*p*) to height (*k*) ratio, p/k. In this case, *d*-type roughness is obtained if $p/k < 4$, $p/k = 4$ is often referred to as intermediate roughness, and $p/k > 4$ corresponds to *k*-type roughness. In *d*-type and intermediate roughness regime, stable

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* Corresponding author. Tel.: +1 204 474 9589; fax: +1 204 275 7507.
E-mail address: tachiemf@cc.umanitoba.ca (M.F. Tachie).

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Nomenclature

C_f	skin friction coefficient
D	diameter of hemisphere
F_u, F_v	flatness factor of streamwise and wall normal fluctuating velocities
h	water depth
H	boundary layer shape parameter
k	rib (hemisphere) height
k_s	sand grain roughness
p	pitch or distance between crests of adjacent ribs (see Fig. 2)
Re_h	Reynolds number based on freestream velocity and water depth
Re_θ	Reynolds number based on freestream velocity and momentum thickness
S_u, S_v	skewness factor of streamwise and wall normal fluctuating velocities
U	streamwise component of mean velocity
U_e	freestream velocity
U_τ	friction velocity
u, v	fluctuating velocity components in streamwise and wall-normal directions
u^2, v^2	Reynolds normal stress in streamwise and wall-normal directions
$-\langle uv\rangle$	Reynolds shear stress
u^3, u^2v, uv^2, v^3	triple correlations
V_k, V_{uv}	transport velocity for turbulent kinetic energy and Reynolds shear stress
x, y, z	streamwise, wall-normal and spanwise coordinates

Greeks

ε	dissipation rate of turbulent kinetic energy
δ	boundary layer thickness
κ	von Karman constant
Ω_z	mean spanwise vorticity
ν	kinematic viscosity
θ	boundary layer momentum thickness
ΔU^+	roughness shift

Subscript and superscript

$()^+$	normalization by inner variables U_τ and ν
$()_\mathrm{C}$, $()_\mathrm{L}$, $()_\mathrm{R}$	mean velocity or turbulent quantity obtained at cavity center, crest of left (upstream) rib, crest of right (downstream) rib
$()_\mathrm{S}$	mean velocity or turbulent quantity obtained by averaging over a pitch

vortices are formed in the cavity between ribs and these vortices prevent the outer flow from reattaching on the floor of the cavity. For k-type roughness, on the other hand, the vortices occupy only a fraction of the cavity and the separated flow may re-attach on the floor.

As mentioned earlier, the velocity and thermal fields of turbulent flow over two-dimensional transverse rods and other roughness geometries have been studied extensively using both experimental and numerical methodologies (Akinlade et al., 2004; Furuya et al., 1976; Grass et al., 1993; Krogstad et al., 1992; Ligrani and Moffat, 1986; Liou et al., 1990; Mazouz et al., 1998; Tachie et al., 2003). Reviews of previous works on rough wall turbulent flow are also provided by Raupach et al. (1991), and more recently by Jiménez (2004). Because it is impractical to review all prior studies, only selected and representative experimental and numerical works over two-dimensional rods are summarized. Djenidi et al. (1999) used a laser Doppler anemometry (LDA) to investigate turbulent boundary layer over two-dimensional square rods. The pitch-to-height ratio was $p/k = 2$ giving a d-type roughness. They observed significant variation of the mean and fluctuating velocity inside the cavity and higher turbulence intensities and Reynolds shear stress over the ribs than for a smooth surface. They also performed qualitative flow visualization using a laser-induced fluorescence to elucidate the importance of outflows in producing and sustaining turbulence. Okomato et al. (1993) studied boundary layer flow over square rods over a wide range of pitch-to-height ratios: $2 \leqslant p/k \leqslant 17$. Their flow visualization revealed stable recirculation for $p/k \leqslant 5$. For $p/k = 9$ they observed that the flow reattached to the floor of the cavity. The turbulence intensity in the shear layer increased for $p/k \leqslant 9$ and decreased for $p/k > 9$, and they concluded that interaction between ribs reached a maximum at $p/k = 9$. Sato et al. (1989) conducted LDA measurements in a channel with both top and bottom walls roughened with 10 mm square rods at $p/k = 7$. The top and bottom rods were arranged in symmetric, staggered and unsymmetric configurations. Detailed velocity measurements at various x-positions between the ribs revealed differences among the different configurations.

Because turbulent flow over ribs is remarkably inhomogeneous inside the cavity and the roughness sublayer, the use of single point velocity measurement techniques such as hot-wires and Pitot tubes may miss some of the salient features close to the ribs. Furthermore, Pitot tube and hot-wires are not ideal for measurements inside the cavity where reverse flow and high local turbulence intensities exist. These limitations are overcome with the use of direct numerical simulation (DNS) and large eddy simulation (LES). Though limited to relatively low Reynolds numbers, the quality and scope of information obtained from LES and DNS are unmatchable by experimental methodologies. Some of the prior numerical works are now reviewed. Cui et al. (2003) performed LES in a channel with the bottom wall roughed with square rods arranged to yield three pitch-to-height ratios, $p/k = 1, 4, 9$, corresponding to