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Improved heat transfer predictions on rough surfaces

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ABSTRACT

The equivalent sand grain approach is the only approach to account for wall roughness in industrial CFD. As roughness effects are reproduced via a modification of the turbulence model in the wall region, the roughness correction preserves the Reynolds analogy. However, wall roughness increases much more the drag than the wall heat flux, so that the wall heat flux is overestimated with the equivalent sand grain approach. Due to the relative lack of detailed experimental data, the discrete element approach, which accounts for the different dynamical and thermal behaviours of wall roughness, was used to generate a large database to investigate thermal roughness effects. It turns out that, besides the equivalent sand grain height, another parameter has to be introduced to characterize roughness thermal effects. A correction of the turbulent Prandtl number was derived from the database and can be coupled to any roughness correction developed using ONERA's technique. The thermal correction was validated for a wide range of roughness geometries, including academic roughness, in-service turbine blades and vanes and different ice shapes, for reduced equivalent sand grain heights k_s^+ ranging from 10 to 6000, and for flows with pressure gradient. Heat transfer predictions are significantly improved, although heat transfer is generally still slightly overpredicted.

1. Introduction

Although most fluid mechanics research deals with smooth surfaces, wall roughness can be encountered in a wide variety of situations. The very first studies of roughness effects were motivated either by the influence of sea-weeds and shells on a ship hull drag or by the impact of pipe casting on pressure losses Nikuradse (1933, 1937). A large amount of research work is devoted to geophysical flows for which surface roughness naturally occurs, thanks to vegetation canopy on the ground or to rocks and stones in a river. An airplane can be slightly rough, e.g. because of the aging of the paint. In all these cases, the key rôle of roughness is an increase of surface friction.

Surface roughness can moreover lead to an heat transfer increase. This occurs on airplanes, thanks to ice accretion on the leading edge, the change in heat transfer impacting the ice formation rate. On turbine blades, many different processes such as deposit, erosion, pitting or spallation induce roughness which is detrimental to the blade lifetime (Bons et al., 2001). Solid propellant rocket nozzles or reentry nosecaps are designed to stand high heat fluxes thanks to ablation, which makes them rough.

Drag and heat transfer increases due to wall roughness are very different processes. In the fully rough regime, the drag increase is due to pressure forces on the roughness elements. On the other hand, heat transfer increase is mainly due to the combined effects of wetted surface increase and of increased turbulence levels and heat transport within the boundary layer. Consequently, wall roughness increases less the heat transfer than the drag, the Reynolds analogy no longer holds on rough surfaces (Cope, 1945; Dipprey and Sabersky, 1963; Owen and Thomson, 1963; Bons, 2002).

Various approaches can be used to predict flows over rough surfaces. The "highest fidelity" strategy is to compute the flow around the roughness elements. This is presently done at a research level, using Direct Numerical Simulations or Large Eddy Simulations, mainly over simple geometries. A review of such attempts can be found e.g. in Busse and Sandham (2012). Work is usually focused on dynamical aspects of wall roughness, very few works as those of Miyake et al. (2001) accounting for thermal aspects. Flow computations around roughness elements were also performed using a Reynolds Averaged Navier–Stokes (RANS) approach and more realistic geometries such as the Vulcain engine nozzle (Oswald's contribution in Reijasse et al. (1998)) or turbine blades (Bons et al., 2008).

The discrete element approach solves equations for a flow, spatially averaged over the roughness elements, modifying the mean flow equations to account for blockage effects due to the presence of roughness elements as well as drag and heat flux on the

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Nomenclature

Latin alphabet

C	intercept of the logarithmic velocity law
C_θ	intercept of the logarithmic temperature law
C_d	roughness drag coefficient
C_f	skin friction coefficient
C_p	specific heat capacity
d	local roughness diameter
h	roughness height
h_i	stagnation enthalpy
k	turbulent kinetic energy
k_s	equivalent sand grain roughness height
$L,\ L_x,\ L_z$	roughness spacing
Nu_d	roughness Nusselt number
$\mathcal{P}$	Prandtl number
$\mathcal{P}_t$	turbulent Prandtl number
p	pressure
$R\theta$	Reynolds number based upon the momentum thickness
Re_d	roughness local Reynolds number
S	wetted surface ratio
S_{corr}	corrected wetted surface ratio
S_t	Stanton number
s	analogy factor
T	temperature
T_τ	friction temperature
u	longitudinal velocity component
u_τ	friction velocity
v	wall normal velocity component
x	longitudinal coordinate
y	wall normal coordinate

Greek alphabet

β	blockage parameter
	pressure gradient coefficient
ΔT^+	shift of the logarithmic temperature law due to wall roughness
Δu^+	shift of the logarithmic velocity law due to wall roughness
δ	boundary layer thickness
ε	eccentricity
θ	boundary layer momentum thickness
κ	von Kármán constant
κ_θ	thermal von Kármán constant
λ	thermal conductivity
μ	viscosity
ρ	density
τ_w	wall friction
Φ_w	wall heat flux
ω	specific dissipation rate

Symbols

$^+$	value in wall units
$_e$	value at the outer edge of the boundary layer
$_w$	wall value
$'$	turbulent fluctuation
$\bar{\ }$	ensemble average

roughness elements. The technique was introduced by Robertson (1961) from ideas from Schlichting (1936, 1973). This approach finely accounts for roughness effects but requires to alter the flow equations, which precluded its use in general RANS solvers.

Therefore, the most popular and the only engineering approach is the so-called equivalent sand grain approach. It is made up of two parts. On the one hand, correlations are used to characterize the surface by the sand grain height which, in experiments by Nikuradse (1933, 1937), will give the same drag increase in the fully rough regime. On the other hand, this sand grain roughness height is introduced as a new parameter in the turbulence model to enhance turbulence in the wall region, increase the momentum transport towards the wall and reproduce the drag increase.

The first two approaches deal with the dynamical and thermal problems in different ways and are thus suited to reproduce the difference between drag and heat transfer increases over rough surfaces. On the contrary, the equivalent sand grain approach, which does not reproduce the physics of wall roughness and uses classical turbulence models in such a way that the Reynolds analogy is preserved, overestimates heat flux increase due to wall roughness.

The goal of this article is thus to take advantage of more accurate modelling to improve the heat flux prediction in the framework of the equivalent sand grain approach. The paper is organised as follows. The key characteristic features of flows over rough surfaces, which will be used later, are quickly recalled in Section 2, as well from the dynamical as from the thermal point of view. The discrete element approach, which will be used to derive the thermal correction, is shortly presented in Section 3. Section 4 details the one-dimensional approach and its use to generate a database about dynamical and thermal wall roughness effects. A thermal correction is derived from this database in Section 5 and validated versus a wide panel of experimental data in Section 6. At last, conclusions are drawn and perspectives proposed.

2. Main characteristics of flows over rough surfaces

Only distributed roughness, i.e. for which the roughness size and spacing are small compared to the boundary layer thickness, and of k-type according to Perry et al. (1969) classification, are considered. Let us just recall that k-type roughness, for which roughness effects are linked to the height of the roughness elements, are the most usual ones.

2.1. Velocity shift

Near the wall, the flow is highly perturbed by the presence of the roughness elements so that three to five roughness heights above the surface is needed to recover a flow which is locally homogeneous in planes parallel to a reference surface and no longer depends upon the location w.r.t. individual roughness elements. This region, strongly affected by the exact location of the roughness elements, is called the roughness sublayer. Above it, the main flow characteristics are similar to those over a smooth surface, once scaled by the increased friction level.

Nikuradse pointed out that, above the roughness sublayer, the logarithmic law is preserved but is shifted, as schematically shown in Fig. 1. The logarithmic law thus reads

$$u^+ = \frac{1}{\kappa}\ln y^+ + C - \Delta u^+ \qquad u^+ = \frac{u}{u_\tau} \quad y^+ = \frac{y u_\tau}{\nu} \tag{1}$$

where u_τ is the friction velocity based upon the drag τ_w and the density ρ as $\tau_w = \rho u_\tau^2$, y a wall distance and ν the viscosity.