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Turbulent flow and heat transfer in channels with shark skin surfaces: Entropy generation and its physical significance

Y. Jin, H. Herwig [*]

Institute of Thermo-Fluid Dynamics, Hamburg University of Technology, Hamburg D-21073, Germany

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ABSTRACT

In order to understand the mechanisms by which drag is reduced and heat transfer is affected when a wall is covered by a shark skin like texture the local entropy generation rate was determined and compared to that for a flow over smooth walls. Based on direct numerical simulations (DNSs) details of the turbulence close to the wall could be analyzed and lead to the conclusion that basically certain turbulent structures are lifted off the wall and get rearranged, a mechanism we call *lift off and alignment* (LOA). The distribution of (time mean) entropy generation rates supports this interpretation, showing a reduction next to the wall and an increase further away, however, such that the overall effect leads to a drag reduction. By solving the thermal energy equation it is shown that also heat transfer is reduced thus increasing the thermal body protection.

1. Introduction

Losses in a flow from a thermodynamics point of view are due to irreversible processes in the flow field around bodies or within channels. Major source of these losses are the high shear stresses in the vicinity of the rigid walls due to the non-slip condition on the flow field. With this in mind, it is an obvious question how surface roughness affects the losses in the flow field and whether there might be a reduction in losses compared to the case of smooth walls. Also heat transfer will be affected by a modified velocity field.

In order to better understand the physics of these loss producing mechanisms fluid mechanic considerations might be complemented by some thermodynamic concepts with respect to the irreversible processes involved. Basically these are concepts that assess energy by its value in terms of its convertibility from one form to another.

High valued forms of energy in this context are called *exergy* defined as those energies from which the maximum theoretical work is obtainable in a process that ends at environmental conditions, see Moran et al. [1], for example. The counterpart of this *exergy*, also called available work, is *anergy* so that with this concept energy can generally be regarded as the sum of exergy and anergy.

As a consequence of the second law of thermo-dynamics exergy can get lost but cannot be created. Therefore, in a reversible process *exergy* is preserved whereas irreversibilities (like losses in a flow or temperature field) lead to a loss of *exergy* (in favor of the correspondingly increasing anergy).

Losses in a flow field can thus be determined by their impact on the *exergy*, i.e. by determining the exergy losses. These losses of exergy are thermodynamically linked to the generation of entropy by the so-called Gouy Stodola theorem. It states that the lost exergy corresponds to the product of entropy generation and the environmental temperature, see again Moran et al. [1].

With these concepts we aim at the determination of entropy generation in order to determine the losses in the flow through channels with smooth and rough walls.

When a flow without active heat transfer is considered the entropy generation is almost completely due to the dissipation of mechanical energy, which is an irreversible process. Then one might argue that this dissipation should be examined without referring to entropy and its generation. This, however, would disregard several important aspects, which are:

- Dissipation converts mechanical to internal energy. From this internal energy still work is available when the temperature level is not that of the environment. The internal energy then still has an exergy fraction. This is an important aspect for example for all power plants since their efficiency is determined by the exergy loss in the process. Therefore the exergy loss is the more significant quantity determinable by the entropy generation involved.
- When convective heat transfer is considered, entropy generation is the common quantity that accounts for all losses, i.e. those in the flow field by dissipation and those in the temperature field by an irreversible heat transfer. Again, what counts is the overall loss of exergy, i.e. the generation of entropy.

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[*] Corresponding author. Tel.: +49 (0) 40 42878 3044.
E-mail address: h.herwig@tuhh.de (H. Herwig).

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Nomenclature

b	geometrical roughness parameter
c_v	specific heat capacity
Ec	$u_m^2/(c_p \Delta T)$, Eckert number
f	friction coefficient
g_i	pressure gradient
h	roughness height
k	thermal conductivity
Nu	Nusselt number
H	half channel height
p	pressure
Pr	Prandtl number
Re	Reynolds number
s	roughness spacing
s_{ij}	strain rate tensor component
$\dot{S}'''_C$	entropy generation rate in the temperature field
$\dot{S}'''_D$	entropy generation rate in the flow field
t	geometrical roughness parameter
T	temperature
u_m	bulk velocity

Greek symbols

α	roughness element alignment parameter
δ	heat transfer parameter
ν	kinematic viscosity
η	$\nu^{3/4}\Phi'''^{-1/4}$, local Kolmogorov length scale
θ	non-dimensional temperature
ρ	density
ω_{ij}	rotation part of the velocity-gradient tensor component
Φ'''	dissipation rate

Subscripts

c	cold
h	hot
R	reference
t	time averaged
s	based on entropy generation

For a discussion of entropy and its generation beyond the above explanations see [2].

1.1. Rough wall geometry

Modifications of the wall surface will be called wall roughness when it extends over large parts of the surface and when the single elements of the surface texture modify the flow and temperature fields as a group with mutual interactions and not as standalone single elements, see Jin & Herwig [3] for that aspect of wall modifications.

Wall roughness can be highly irregular or composed of regular geometrical elements. In the irregular case the geometry of the rough wall can only be described statistically in terms of a mean height of the roughness elements, for example. There may be more than one such parameter, but it always will be a statistically mean description.

In the regular case the exact geometry can be described with only a few parameters with respect to the roughness elements and their position on the wall.

A wide class of such regular wall roughnesses is given by the arrangement of two-dimensional trapezoidal bars shown in Fig. 1. There are six geometrical features of this general case, i.e. five nondimensional geometrical parameters, which are

$$\frac{h}{H}: \text{relative roughness height} \tag{1}$$

$$\frac{h}{s}: \text{relative roughness spacing} \tag{2}$$

$$\frac{h}{b}: \text{aspect parameter} \tag{3}$$

$$\frac{t}{b}: \text{trapezoidal parameter} \tag{4}$$

$$\alpha: \text{roughness element alignment parameter} \tag{5}$$

Special cases of this general arrangement are given in Table 1 including those which represent the shark skin surfaces which are the scope of this study.

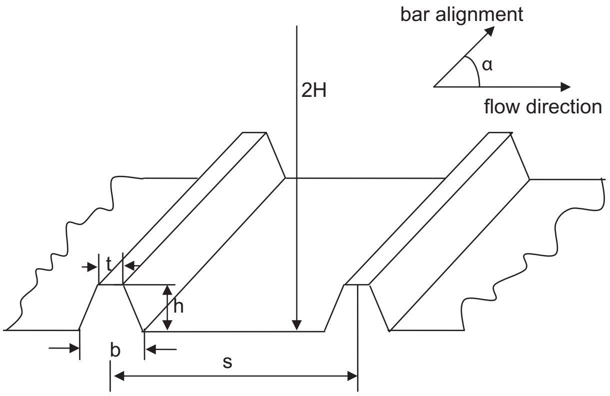

Fig. 1. Geometrical arrangement of a general regular wall roughness. H: half channel height, h: height of the roughness elements, b: bottom width of the roughness elements, t: top width of the roughness elements, s: spacing of the roughness elements, α: inclination angle with respect to the flow direction.

1.2. Shark skin surface texture

With the geometrical arrangement according to Fig. 1 and the special cases shown in Table 1 the alignment parameter α can be identified as the crucial parameter with respect to the "shark skin effect". In the last six cases of Table 1 the alignment angle is $\alpha = 0°$, i.e. the flow direction is along the blades and wedges which here represent the shark skin surface texture. Pictures of real shark skins (see for example Dean & Bhushan [4]) show that this is the geometrical peculiarity, so that surface textures of that kind quite generally are labeled as "shark skin surfaces". In contrast to the bar arrangement with $\alpha = 90°$ the flow direction aligned cases may lead to a reduction in flow resistance (compared to the smooth wall case) or more generally to a reduction in losses of exergy or available work.

1.3. Losses and entropy generation

Losses in the flow field in terms of losses of exergy (available work) are due to entropy generation as explained above. From the field of entropy and its generation detailed information can be extracted in order to understand what happens when shark skin