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Effects of pressure gradients on entropy generation in the viscous layers of turbulent wall flows

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Abstract

By employing results of direct numerical simulations, it is possible to examine entropy generation due to friction in the viscous layers of turbulent flows with significant streamwise pressure gradients, both for boundary layers and channels. About two-thirds or more of the entropy generation per unit surface area S'' occurs there. Increasing the pressure gradient increases direct dissipation and decreases turbulent dissipation (in wall coordinates). The integral of the entropy generation rate per unit surface area to the edge of the viscous layer is relatively insensitive to pressure gradients for channels but decreases moderately for boundary layers.

Keywords: Entropy; Viscous layer; Turbulent; Channel; Boundary layer; CFD

1. Introduction

The local (pointwise) entropy generation rate per unit volume S''' is a key to improving many energy processes and applications [1]. In developing his reciprocal relations for irreversible processes, Onsager [2] extended Lord Rayleigh's "principle of least dissipation of energy" and indicated that the rate of increase of entropy plays the role of a potential. Thus, entropy generation (or "production" [3]) may be used as a parameter to measure a system's departure from reversibility. Bejan [1] has suggested that real systems which owe their thermodynamic imperfections to fluid flow, heat transfer and mass transfer irreversibilities be optimized by minimizing their entropy generation. This approach has been applied to compact heat exchangers, power plants, natural convection, rotating bodies, enhanced heat transfer surfaces, impinging jets, convection in general and other thermal systems.

Kock and Herwig [4] suggest that predicting the efficient use of energy in thermal systems requires accounting for the second law of thermodynamics since the loss of available work [5] is proportional to the amount of entropy produced (e.g., via the Gouy [6]–Stodola [7] theorem cited by Bejan). Therefore, apparatus producing less entropy by irreversibilities. destroys less available work, increasing the efficiency. Neumann et al. [8], Kock and Herwig and others are using computational fluid dynamics (CFD) codes to predict entropy generation for optimization by minimizing it. Since S''' determines the localized contribution to energy losses or reduction in the availability of energy [9,10], insight into the dominant loss sources and their locations can allow reducing them intelligently, thereby improving efficiency. These CFD studies seek to identify the regions of maximum entropy production so they may be attacked and reduced.

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Nomenclature

A_{CS}	flow area
D	diameter
D_{h}	hydraulic diameter, $4A_{\mathrm{CS}}/P_{\mathrm{W}}$
g_{c}	units conversion factor, e.g., 1 kg m /(N s^2), 32.1739 lbm ft/(lbf s^2)
G	mean mass flux, $\dot{m}/A_{\mathrm{CS}}$
$\dot{m}$	mass flow rate
P	perimeter; P_{W}, wetted perimeter
p	pressure
$\dot{Q}$	heat transfer rate
s	specific entropy (i.e., per unit mass)
S	entropy, entropy generation rate
T	temperature
U, V, W	mean velocity components in streamwise, wall-normal and spanwise directions, respectively
V_{b}	bulk or mixed-mean streamwise velocity, G/ρ
u, v, w	velocity fluctuations about means in streamwise, wall-normal and spanwise directions, respectively
u_τ	friction velocity, $(g_{\mathrm{c}}\tau_{\mathrm{w}}/\rho)^{1/2}$
$\overline{uv}$	Reynolds shear stress
x, y, z	coordinates in streamwise, wall-normal and spanwise directions, respectively

Non-dimensional quantities

c_{f}	skin friction coefficient, $2g_{\mathrm{c}}\tau_{\mathrm{w}}/(\rho U_\infty^2)$ or $2g_{\mathrm{c}}\rho\tau_{\mathrm{w}}/G^2$
K_{p}	streamwise pressure gradient, $(\nu/\rho u_\tau^3)\mathrm{d}p/\mathrm{d}x$
K_{v}	acceleration parameter, $(\nu/V_{\mathrm{b}}^2)(\mathrm{d}V_{\mathrm{b}}/\mathrm{d}x)$ or $(\nu/U_\infty^2)\mathrm{d}U_\infty^2/\mathrm{d}x$
Re	Reynolds number, $4\dot{m}/\Pi D\mu$; Re_{Dh}, based on hydraulic diameter, GD_{h}/μ; Re_θ, based on momentum thickness, $U_\infty\theta/\nu$
Re_τ	distance from wall to centerplane, centerline, etc., $y_{\mathrm{c}}u_\tau/\nu$
$(S'')^+$	entropy generation rate per unit surface area, $TS''/(\rho u_\tau^3)$
$(S''')^+$	pointwise volumetric entropy generation rate, $T\nu S'''/(\rho u_\tau^4)$
y^+	distance from wall
ε^+	turbulent dissipation of turbulent kinetic energy, $\nu\varepsilon/u_\tau^4$

Greek symbols

δ	boundary layer thickness
ε	dissipation of turbulence kinetic energy; ε_{u}, pseudo dissipation [21]
Φ	viscous dissipation function
μ	absolute viscosity
ν	kinematic viscosity, μ/ρ
ρ	density
τ	shear stress; τ_{w}, wall shear stress
θ	momentum thickness

Superscripts

$(\_)^+$	normalization by wall units, ν and u_τ
$(\_)'$	per unit length
$(\_)''$	per unit surface area
$(\_)'''$	per unit volume
$(\overline{\ })$	time mean value

Subscripts

b	bulk or mixed-mean quantity (one-dimensional)
c	centerplane, centerline
cs	cross section
cv	control volume
Dh	evaluated with hydraulic diameter D_{h}
gen	generation
in	evaluated at inlet, entry
out	outflow
w	wall
∞	freestream value

In the present study, we primarily examine entropy generation due to shear stresses in idealized "unheated," fully-developed, turbulent channel flows between infinitely-wide flat plates. However, for comparison purposes and to evaluate applicability of the results, we also treat two-dimensional turbulent boundary layers over a classical flat plate with both negligible and favorable pressure gradients in the streamwise direction. Fluid properties are idealized as constant.

We concentrate on the viscous layer because it is typically the region where the largest gradients occur and the production of turbulence is greatest. Following Bradshaw [11], we are here defining the viscous layer as the region where viscous effects are significant, but not necessarily dominant, typically to y^+ about thirty in a classical zero-pressure gradient case (it includes the "laminar" and "buffer" sublayers in some investigators's terminology). The major resistances to momentum, energy and mass transfer occur in this layer – and the pointwise entropy generation rate is greatest here as well.

As will be seen, turbulent channel flows with significant (non-dimensional) streamwise pressure gradients have low Reynolds numbers – and vice versa. Knowledge of such flows has been important in the design of the high temperature engineering test reactor (HTTR) in Japan since its flow rate is "low" to give a high outlet temperature Consequently, the outlet Reynolds number is about 3500 at design operating conditions. For other gas-cooled-reactors