International Communications in Heat and Mass Transfer 41 (2013) 10–16

Contents lists available at SciVerse ScienceDirect

International Communications in Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ichmt

Entropy generation in a transitional boundary layer region under the influence of freestream turbulence using transitional RANS models and DNS☆

E. Ghasemi [a,*], D.M. McEligot [a,b], K.P. Nolan [c], J. Crepeau [d], A. Tokuhiro [a], R.S. Budwig [e]

[a] Dept. Mech. Eng., University of Idaho, 1776 Science Center Dr, Idaho Falls, ID 83402, USA
[b] Aero. Mech. Engr. Dept., Univ. Arizona, Tucson, AZ 85721 USA
[c] Department of Mechanical Engineering, Imperial College London, London SW7 2AZ, UK
[d] Department of Mechanical Engineering, University of Idaho, Moscow, ID 83844, USA
[e] Center for Ecohydraulics Research, University of Idaho, Boise, ID 83702, USA

ARTICLE INFO

Available online 11 December 2012

Keywords:
Entropy generation
Energy dissipation
Transitional boundary layer
Bypass transition
Transitional RANS models

ABSTRACT

In this study, the entropy generation process in the bypass transition scenario is investigated for a flat plate boundary layer. Here transition occurs prematurely due to the presence of strong levels of freestream turbulence. Reynolds-Averaged Navier–Stokes (RANS) models and Direct Numerical Simulations (DNS) are implemented to study the local entropy generation and energy dissipation in pre-transitional and transitional regions comprehensively. Two new transitional RANS models (SST $k-\omega$(4eq) and $k-kl-\omega$) were used for prediction of the onset of transition and the results are compared with DNS ones. Classical laminar theory underpredicts the observed entropy generated. In the pre-transitional boundary layer, the perturbations generated by the streaky structures modify the mean velocity profile and induce a quasi-turbulent contribution to indirect dissipation. In the transition region the pointwise entropy generation rate $(S''')^+$ initially increases near the wall and then decreases corresponding to the distribution predicted for a fully-turbulent boundary layer as the flow moves downstream. All the RANS models predicted transition onset prematurely and, consequently, overpredict the integral entropy generation rate and the skin friction coefficient in the transition region.

1. Introduction

A key to improving efficiency of thermal systems – and thereby to reduce fuel consumption, generation of greenhouse gases and/or waste – is the minimization of entropy generation [1,2]. Therefore, the overall technical aim of the present research is to develop fundamental understanding of the entropy generation process in characteristic wall shear flows. For entropy generation by fluid friction, the rates are reasonably predictable for laminar flows without significant fluctuations and for developed turbulent flows [3–6]. The main concern now lies in prediction for flows undergoing so-called "bypass" transition from laminar to turbulent states (i.e., transition prematurely induced by strong freestream turbulence).

Morkovin [7] described the phenomenon in boundary layers where freestream turbulence of more than 1% leads to rapid transition, bypassing the classic Tollmien–Schlichting scenario, as a "bypass transition". The flow is characterized by the appearance inside the boundary layer of streamwise elongated "streaky" structures of high and low velocities relative to the mean flow, attributed to Klebanoff [8,9]. As the streaks grow downstream, they undergo instabilities [10] which precede the breakdown into patches of localized turbulence known as turbulent spots [11]. The spots grow in size as they are convected downstream and merge until the flow is fully turbulent. In the case where the boundary layer is subjected to significant free stream turbulence, it has been documented that the laminar boundary layer exhibits increased wall shear stress and a significant level of fluctuations or perturbations [12–14]. These variations in laminar flow character are not treated by either the Blasius or Pohlhausen analyses of laminar flows. However, Nolan et al. [15] used the conditionally-sampled data of Volino et al. [16] and showed that the laminar— conditioned data agree well with Pohlhausen.

Recent literature on the topic of entropy generation in wall-bounded flows has been reviewed by Naterer and Camberos [17] and others [3,4,18]. To determine the pointwise entropy generation rate ($S'''\{x,y,z\}$) completely in flows with turbulence or unsteady motion requires evaluation of the instantaneous values of the tensor $(\partial u_i/\partial x_j)$ as given by Kock and Herwig [19]. This quantity is generally not available from RANS code predictions and is difficult to measure directly with accuracy at the wall, where it is most important. Despite extensive studies on laminar, transitional and turbulent boundary layer flows and on effects of freestream turbulence [20–23], few have considered the entropy generation involved [24–29]. Further, the experimental studies have lacked the measurements needed to deduce the entropy generation in

☆ Communicated by W.J. Minkowycz.
* Corresponding author.
E-mail addresses: ghas5622@vandals.uidaho.edu, esmael.ghasemi@yahoo.com (E. Ghasemi).

0735-1933/$ – see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.icheatmasstransfer.2012.11.005

Nomenclature

q^2	Sum of velocity fluctuations squared $(u^2+v^2+w^2)$
S	Entropy
T	Temperature
U, V	Mean velocity components in streamwise and wall-normal directions, respectively
u, v, w	Velocity fluctuations about means in streamwise, wall-normal and spanwise directions, respectively
u_τ	Friction velocity, $(\tau_w/\rho)^{1/2}$
$\bar{u}\,\bar{v}$	Mean fluctuation product in Reynolds shear stress $(-\rho\bar{u}\,\bar{v})$
x, y, z	Coordinates in streamwise, wall-normal and spanwise directions, respectively

Non-dimensional quantities

C_d	Dissipation coefficient, $TS''/\left(\rho U_\infty{}^3\right)$
C_f	Skin friction, $2\tau_w/\left(\rho U_\infty{}^2\right)$
Re	Reynolds number; based on momentum thickness, $U_\infty\theta/\nu$
$(S'')^+$	Entropy generation rate per unit surface area, $TS''/\rho u_\tau^3$
$(S''')^+$	Pointwise volumetric entropy generation rate, $T\nu S'''/\left(\rho u_\tau{}^4\right)$
U^+	Mean velocity, U/u_τ
y^+	Wall-normal coordinate, yu_τ/ν
δ^+	Boundary layer thickness, $\delta u_\tau/\nu$
ε^+	Turbulent dissipation of turbulent kinetic energy, $\nu\varepsilon/u_\tau{}^4$

Greek symbols

δ	Boundary layer thickness; δ*, displacement thickness
ε	Dissipation of turbulence kinetic energy; ε_u, pseudo dissipation for DNS [31]
θ	Momentum thickness
τ	Shear stress; τ_w, wall shear stress

Superscripts

$(-)^+$	Normalization by wall units, ν and τ
$(-)''$	Per unit surface area
$(-)'''$	Per unit volume
$(\overline{\ })$	Time mean value

Subscripts

ap	Approximate
w	Wall
δ	Boundary layer edge
∞	Free stream value

the region near the wall where it is concentrated. Walsh and colleagues have pioneered the prediction and measurement of local entropy generation rate in transitional boundary layers with streamwise pressure gradients [30]. Minkowycz et al. [31] numerically simulated the laminar breakdown and subsequent intermittent and turbulent flow in parallel-plate channels and they investigated the effects of inlet velocity profile and turbulence intensity using the RANS-SST (shear stress transport) turbulence model.

Abraham et al. [32] also used the RANS-SST model to study internal-flow for the low-Reynolds-number range of the laminar-to-turbulent transition regime. The flow considered herein is unheated, incompressible and two-dimensional in the mean sense with zero streamwise pressure gradient. The objective of the present study is to extend the previous works by McEligot, Walsh and coworkers [3,33–35] to obtain better insight of the reliability of transitional RANS models. These models are used in a variety of industrial applications as the computational cost of DNS is high, even at low Reynolds numbers.

2. Entropy equations

For steady, pure laminar two-dimensional flows under boundary layer approximations and without significant fluctuations, the pointwise entropy generation rate (S''') can be expressed as

$$TS'''\{y\} = \mu\phi \approx \mu(\partial U/\partial y)^2 \quad (1)$$

where μ is absolute viscosity and ϕ refers to the viscous dissipation. The non-parallel effects are of the order 1/Re and can be considered small for the DNS results employed herein. For a laminar boundary layer with zero pressure gradient and negligible fluctuations, $(S''')^+ = [f''\{\eta\}/f''\{0\}]^2$ where $(S''')^+$ is $\left(\left(T\nu S'''\right)/\left(\rho u_\tau{}^4\right)\right)$, η is the Blasius parameter $y(U_\infty/(\nu x))^{1/2})$ and $f'\{\eta\}$ is defined as $U\{\eta\}/U_\infty$ where ρ and ν are density and kinematic viscosity, respectively. The function $f''\{\eta\}$ is available from tabulations of the Blasius solution, such as Table 7.1 by Schlichting [36]. In a flow with fluctuations, the time-mean value of dissipation at a point may be expanded to $\mu\phi+\rho\varepsilon$ where the first term represents viscous dissipation of mean-flow kinetic energy (termed "viscous," "direct" or "mean" dissipation) as above and the latter term represents dissipation of turbulent kinetic energy into thermal energy (also referred to as "indirect" or turbulent dissipation) and may be expressed as [36]

$$\rho\varepsilon = 2\mu\left[\overline{\left(\frac{\partial u}{\partial x}\right)^2} + \overline{\left(\frac{\partial v}{\partial y}\right)^2} + \overline{\left(\frac{\partial w}{\partial z}\right)^2}\right] + \mu\left[\overline{\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right)^2} + \overline{\left(\frac{\partial v}{\partial z}+\frac{\partial w}{\partial y}\right)^2} + \overline{\left(\frac{\partial w}{\partial x}+\frac{\partial u}{\partial z}\right)^2}\right]. \quad (2)$$

(This indirect dissipation is not the ε of popular $k-\varepsilon$ turbulence models). We will generally refer to $\mu\phi$ as the viscous contribution or viscous entropy generation rate and to $\rho\varepsilon$ as the turbulent contribution. When expressed in standard wall units, the time-mean pointwise, total entropy generation rate for an unheated two-dimensional flow can be written as

$$\left(S'''\left\{y^+\right\}\right)^+ = \left(\frac{\partial U^+}{\partial y^+}\right)^2 + \left(\frac{\partial V^+}{\partial x^+}\right)^2 + 2\left[\left(\frac{\partial U^+}{\partial x^+}\right)^2 + \left(\frac{\partial V^+}{\partial y^+}\right)^2\right] + \varepsilon^+ \quad (3)$$

where the indirect dissipation ε^+ is $\nu\varepsilon/u_\tau^4$.

By application of boundary layer and other approximations (Eq. 23.8d, Schlichting [36]), Rotta has suggested that total dissipation in a turbulent boundary layer may be evaluated as

$$\mu\phi+\rho\varepsilon \approx [\tau_{visc}+\tau_{turb}](\partial U/\partial y) \approx [\mu(\partial U/\partial y) - \rho\overline{uv}](\partial U/\partial y) \quad (4)$$

so that the approximate volumetric entropy generation rate can be estimated as

$$\left(S'''_{ap}\right)^+ \approx \left[\left(\partial U^+/\partial y^+\right) + \overline{uv}\right]\left(\partial U^+/\partial y^+\right). \quad (5)$$

In the present study we refer to use of this assumption as the approximate technique, as indicated by the subscript. Near the wall, production is negligible whereas turbulent dissipation is significant there — as it also is at the boundary layer edge; thus use of Eq. (5) can be inappropriate but is sometimes the only recourse.

3. Numerical simulations

The results of direct numerical simulation by Nolan and Zaki [37] are employed as benchmarks to assess the possible use of popular turbulence and transition models to predict entropy generation in