International Journal of Heat and Mass Transfer 86 (2015) 113–123

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Transport dissimilarity in turbulent channel flow disturbed by rib protrusion with aspect ratio up to 64

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ARTICLE INFO

Article history:
Received 12 August 2014
Received in revised form 3 February 2015
Accepted 9 February 2015
Available online 14 March 2015

Keywords:
Organized structures
Transport dissimilarity
Turbulent heat transfer
Rib protrusion
Direct numerical simulation

ABSTRACT

Mechanisms for dissimilarities between momentum and heat transport in a disturbed turbulent channel flow of air were studied through direct numerical simulations. A square rib protrusion with an aspect ratio of up to 64 was used to minimize constraints that the side boundary imposed on the wake and the related heat transfer. Channel walls were heated to maintain isothermal conditions. The frictional Reynolds number was set to either 150 or 300. The maximum number of grid points was 96,993,280. A grid convergence test showed that numerical results were independent of grid resolution. The mean pressure obtained from numerical simulation agreed with existing experimental data. Heat transfer characteristics were evaluated using the spatial mean Nusselt number over the ribbed wall and over rib surfaces. This Nusselt number was compared with that for a smooth channel at the same pumping power; the comparison showed that heat transfer increased by as much as 10%. This increase was caused by the simultaneous increase in heat transfer and reduction in skin friction behind the rib over a wall length of 30 times the rib height. Thus, the dissimilarity between local heat and momentum transport involved improving bulk heat transfer and reducing losses to skin friction. Mechanisms leading to the transport dissimilarity were studied via instantaneous structures, turbulence statistics, and spectral analyses. The results suggest that spanwise vortices shed from the rib contributed to the transport dissimilarity. Spanwise vortices entrained fresh fluid into the near-wall region, increasing heat transfer and reducing skin friction simultaneously. This behavior is consistent with reports in the literature obtained by visualization (Yao et al.) and by RANS simulation (Inaoka et al.). The novelty in the present study was that turbulent spanwise vortices and related thermal fields could be reproduced without using a turbulence model. This approach enabled us to know structures of the vortices and the flow three-dimensionality.

1. Introduction

Turbulent transport of heat and mass is utilized in energy conversion and chemical process systems. In such systems, elementary steps are required to maximize heat removal while incurring moderate penalties for pumping losses. To achieve a desirable balance between heat and mass transport, surface roughness or protrusions have been applied. For example, in refrigerators, tubes with internal roughness are used to enhance heat transfer and keep pressure losses at reasonable levels. Compilations are available on academic studies of heat transfer characteristics with wall roughness (for example, see [1]). However, most existing studies do not address any phenomenology that could improve the tradeoff between heat and momentum transport.

Suzuki et al. discussed dissimilarities between heat and momentum transport for turbulent boundary layers disturbed by a cylinder [2]. They found that, in a disturbed flow, improvement in heat transfer and reduction of skin friction occurred locally. They measured turbulence of velocity and temperature to show that outward and wallward interactions contributed to simultaneously increase turbulent heat flux and decrease Reynolds shear stress. Yao et al. visualized channel flow in which a square rod was inserted [3,4]. They considered that the Karman vortex street shed from the rod could develop dissimilar transport of heat and mass. Inaoka et al. performed RANS simulations of the disturbed turbulent boundary layer [5]. Their unsteady two-dimensional analysis showed that the two-dimensional circular motion of Karman vortices entrained fresh fluid to the near-wall region, leading to simultaneous reduction in skin friction and enhancement of heat transfer. However, their approximation for small-scale

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2015.02.018
0017-9310/© 2015 Published by Elsevier Ltd.

Nomenclature

C_f	skin friction coefficient
C_p	specific heat at constant pressure
E_z	spanwise spectral density
f	friction factor
H	height of rib
k_z	spanwise wave number
L_x, L_z	computational domain sizes in x and z directions
N_x, N_y, N_z	grid numbers in x, y, and z directions
Nu	Nusselt number $= 2\overline{q_w}\delta/\{\lambda(\overline{T_w} - T_m)\}$
p	pressure
Pr	Prandtl number
q_w	wall heat flux
Re_m	bulk Reynolds number, $2u_m\delta/\nu$
$Re_{\tau 0}$	friction Reynolds number, $U_{\tau 0}\delta/\nu$
St	Stanton number, $Nu/PrRe_m$
T	temperature
T_w	wall temperature
t	time
u_i	velocity in x_i direction
U_τ	friction velocity, $(\tau_w/\rho)^{1/2}$
u, v, w	velocity in x, y, and z directions
x_i	coordinate in the ith direction; x_1, x_2, and x_3 denote x, y, and z, respectively
x, y, z	streamwise, wall-normal, and spanwise coordinates
δ	channel half width
Δt	time increment
Δx, Δy, Δz	grid spacings in x, y, and z directions
θ	temperature difference, $T_W - T$
λ	thermal conductivity
λ_z	wavelength in z direction
ν	kinematic viscosity
ρ	density
τ_w	wall shear stress

Subscripts and superscripts

$()_0$	value in smooth channel at same Reynolds number
$()_m$	bulk mean value
$()_r$	value on rough-wall side
$()_s$	value on smooth-wall side
$()'$	fluctuating component
$()^+$	normalized by $U_{\tau 0}$ and ν
$\overline{()}$	ensemble average
$\langle()\rangle$	moving average of 0.8δ in z

vortices is to be verified through a more elaborate treatment. Their argument is expected to be re-examined by a full numerical simulation that will resolve all essential scales of turbulence without use of a turbulence model.

Since Kim et al. [6] and Kasagi et al. [7], high-end computers and high-resolution numerical techniques have been used to directly solve the governing equations. Early simulations were performed for fully developed channel flow under the assumption of longitudinal periodicity. Miyake et al. [8], Nagano et al. [9] and Leonardi et al. [10] solved the periodic flow in a channel with square ribs. Recently, Makino et al. [11], Orellano and Wengle [12] and Yakhot et al. [13] simulated a periodic flow with an isolated protrusion and focused on the fluid dynamics.

In this paper, we report simulations of organized structures that are related to the transport dissimilarity of a disturbed flow between two parallel walls. An isolated rib protrusion having an aspect ratio of 64 was used to explore its wake and the resulting wall heat transfer. Such a wide rib was used to remove artificial constraints imposed on vortices by side boundaries. In the previous works, we simulated ribbed channel flow and examined changes in Reynolds stress [14] and turbulent heat flux [15]. These previous studies used a short rib with an aspect ratio of 15.0. In this paper, we evaluate the balance between heat transfer characteristics and pumping power to understand the usefulness of dissimilar transport in practical applications. Based on a full set of three-dimensional simulation variables, instantaneous structures of the flow and thermal field are examined to determine mechanisms leading to the dissimilarity. Reynolds shear stress and turbulent heat flux are investigated to understand their dissimilarity. Their expansions in wavelength space are also discussed to discover how the dissimilarity appears in the power distribution.

2. Numerical procedure

Fig. 1 shows the computational domain and coordinate system. Fluid with fully developed flow and thermal profiles enters the channel, which has a square rib mounted on a wall surface. The upstream driver part simulates the developed flow and thermal fields. These are used by the ribbed channel part as inlet values for simulating their spatial advancements. In the driver part, periodicity was applied in the streamwise and spanwise directions, but in the ribbed channel, periodicity was applied only in the spanwise direction. All solid walls were treated as nonslip surfaces. Flow rate and temperature were computed at the exit of the ribbed channel by the convective outflow condition [14]. We studied two classes of situations in terms of temperature: (a) constant temperature heating (CT) in which the two walls of the main channel were heated to the same temperature, and (b) constant temperature difference (CTD) in which the two walls were heated to different temperatures.

We used an incompressible Newtonian fluid with constant properties and neglected buoyancy effects. Hence, temperature was treated as a passive scalar. The basic equations that correspond to these assumptions are as follows:

$$\frac{\partial u_j}{\partial x_j} = 0, \quad (1)$$

$$\frac{\partial u_i}{\partial t} + u_j\frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + \nu\frac{\partial^2 u_i}{\partial x_j \partial x_j}, \quad (2)$$

$$\frac{\partial T}{\partial t} + u_j\frac{\partial T}{\partial x_j} = \frac{\lambda}{\rho C_p}\frac{\partial^2 T}{\partial x_j \partial x_j}. \quad (3)$$

In these equations, coordinates are represented by x_i, velocity components by u_i, and temperature by T. We use x, y, and z to designate the streamwise, wall-normal, and spanwise coordinates, respectively. Velocity components are represented by (u, v, w), which correspond to (x, y, z). The present simulation employs the fractional step method [16] and extends it to evaluate the temperature field. The iterative algorithm for velocity evolution by fractional steps is appended with a semi-implicit solver for temperature. Time splitting of the equations was done using the