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International Journal of Heat and Fluid Flow 23 (2002) 441–443

International Journal of
HEAT AND
FLUID FLOW

www.elsevier.com/locate/ijhff

Influence of large-scale streamwise vortical EHD flows on wall turbulence

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Received 12 January 2001; accepted 17 November 2001

Abstract

The influence of large-scale electrostatically induced streamwise vortical flows superimposed on turbulent plane channel flow driven by a pressure gradient was analyzed using direct numerical simulation. This study may be relevant for designing a new drag-reduction optimized configuration for electrostatic precipitators. The EHD flows had a spanwise periodicity of 340 wall units. Regardless of intensity, EHD flows induce an initial transient of ~600 shear-based time units with moderate drag decrease (~6–7%), followed by a steady state with slight drag modification. The behavior of shear stress at the wall was examined in connection with the shape of the EHD flows to identify future directions for further drag reduction.

Keywords: Turbulence; Direct numerical simulation; Electrohydrodynamics; Electrostatic precipitators; Drag reduction

1. Introduction

The object of this work is to examine the modification of a turbulent Poiseuille flow due to large-scale, streamwise electrohydrodynamic (EHD) structures which are generated by high-potential, streamwise wires in the middle of the duct of an electrostatic precipitator (ESP). Under common operating conditions, the ions discharged by the high-potential streamwise wires are accelerated toward the grounded wall and generate spanwise plane jets which, in turn, produce streamwise two-dimensional vortices of the size of the wire-to-wall distance. In a previous paper, we have shown that applying increasing voltages to spanwise wires led to a decrease in overall drag, the maximum reduction being about 6% (Soldati and Banerjee, 1998). In this paper, we examine the configuration with streamwise wires, which can be a possible, new configuration for ESPs if large drag reduction could be found (Soldati and Marchioli, 2001). Previous investigations (Soldati, 2000) suggest that this change in the flow direction could scarcely affect particle collection efficiency in an ESP. Furthermore, in the light of recent numerical (Du and Karniadakis, 2000) and experimental results (Roth et al., 2000; Artana et al., 2001), the strategy proposed in this paper could be exploited also in other industrial fields.

2. Methodology

The physical configuration considered here is a pressure-driven flow of air between infinite parallel plates with thin wires placed streamwise in the middle of the channel. The wires are kept at a potential sufficient to discharge ions which are driven toward the grounded parallel plates. This generates two-dimensional jets impinging on the plates with recirculation back toward the center of the channel. Since the mobility of ionic species in gases is typically over 100 m per second, ionic species distribution and the electrostatic field do not depend on the flow field distribution (Beux et al., 2001). The body force acting on the fluid therefore depends only on the configuration of the electrodes and on the applied potential. In the case of no through-flow (zero pressure gradient), these flows are characterized by the streamlines shown in Fig. 1(a).

The problem is described by the balance equation for the fluid and a reduced set of Maxwell equations for the

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0142-727X/02/$ - see front matter
PII: S0142-727X(01)00154-0

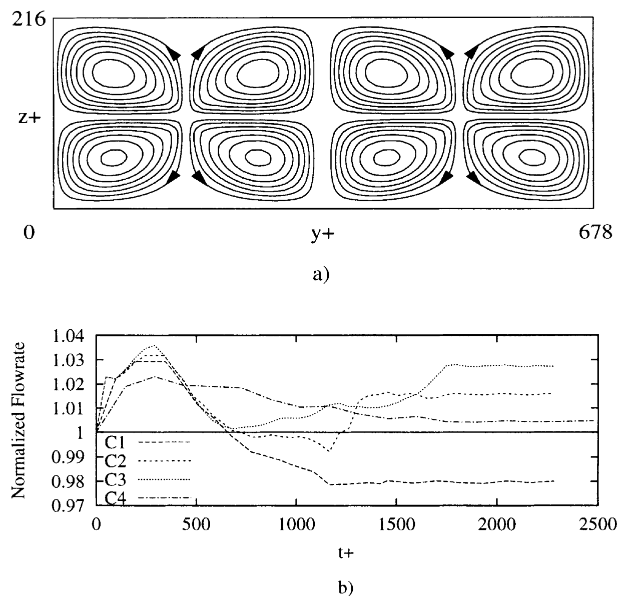

Fig. 1. Shape of forcing flows and time-behavior of overall flowrate in forced cases: (a) Forcing flows streamlines for no through-flow C3 case. Channel flow is through the sheet. Contours go from −35 to 35 with increments of 4 in wall units. (b) Time evolution of forced channel flowrate normalized by unforced channel flowrate.

electrostatic body force distribution (Soldati and Banerjee, 1998). Since this is decoupled from the flow field, it can be calculated once only regardless of how the flow field evolves. We used a two-dimensional finite-difference method to calculate the electrostatic body force field (Soldati and Banerjee, 1998). The fluid is air ($\rho = 1.38$ kg/m^3, and $\nu = 16.6 \times 10^{-6}$ m^2/s) with an imposed pressure gradient corresponding to a shear velocity of $u_\tau = 8.964 \times 10^{-2}$ m/s, and to the shear Reynolds number $Re_\tau = 108$. For the reference case with no EHD effects, the mean velocity is 1.16 m/s and the Reynolds number based on mean velocity and duct width is ~2795. The turbulence field was calculated with a standard pseudo-spectral method with a 64^3 nodes grid (Soldati and Banerjee, 1998).

All simulations with EHD flows started from a channel flow simulation calculated with the same grid for the same shear Reynolds number. The body force is then applied and simulations run until a new steady state is reached. The wires are kept at a potential of 15 000 V for all simulations – a typical potential in ESP applications – while the current flowing through the duct is varied, allowing forcing flows of different intensity.

3. Results and discussion

3.1. Control variable and overall drag modification

We characterized the control flows on the basis of their distribution and intensity for no through-flow

Table 1
Summary of simulations

	Current intensity (A/m^2)	$W_{\text{control}}/W_{\text{channel}}$ (%)
C1	1.00E − 07	2.7
C2	5.00E − 06	8.3
C3	2.00E − 05	25.2
C4	5.00E − 05	58.9

W_{control} is flowrate of unperturbed forcing flows. W_{channel} is flowrate of unperturbed channel flow.

(Schoppa and Hussain, 1998). Current intensity and corresponding flowrates for the four cases investigated are reported in Table 1 for the no through-flow cases. Flowrates are normalized by the flowrate of the channel with no imposed forcing flows: since the pressure drop is the same for all simulations, an increase of channel flowrate indicates drag reduction and a decrease of channel flowrate indicates drag increase. In Fig. 1(b), the time-behavior of the flowrate normalized by the unforced case flowrate is shown for the different cases. In our application – operation of an ESP – we are interested in the steady state. We notice, however, that after induction of EHD flows, there is a transient period lasting about 600 dimensionless time units in which the mean velocity increases for all simulations. The behavior of non-equilibrium three-dimensional boundary layers, such as the one investigated in the present case, is not well understood yet (Coleman et al., 1996), and, at present, we have no sound explanation for this phenomenon. In the steady state, we observe that at very low intensity, drag increases, whereas for higher intensity, drag is reduced. In cases C2 and C3, the mean velocity reaches a steady state with increases of 2% and 3%, respectively. In case C4, the initial peak is lower and the slope toward the steady state is milder. For the present type of forcing flow, maximum drag reduction seems to exist for conditions close to those of case C3.

Corresponding to the little variations of the overall drag at the wall in all cases, we noticed slight modifications of mean flow and turbulence intensity profiles (not shown here).

3.2. Wall stress and impinging EHD jets

Schoppa and Hussain (1997, 1998) suggest that lateral forcing would be appropriate to reduce drag by damping the streak regeneration mechanism. Specifically, they exploit large, frozen vortices with streamwise axis and then analyze the influence these vortices have on wall-shear-stress in the specific way we follow here to extrapolate an ideal best forcing EHD flow. Consider Fig. 2(a), where one single EHD vortex is shown: the EHD jet impinges on the wall at “i”, then the streamlines run parallel to the wall through “c” and return toward the outer flow at “s”. In Fig. 2(b), the behavior

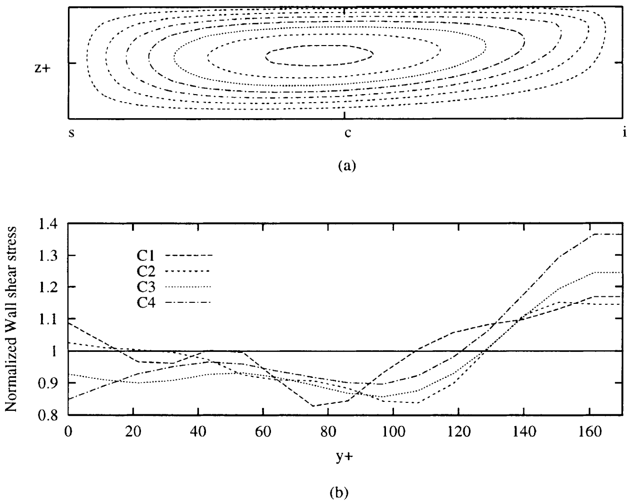

Fig. 2. Unperturbed streamlines of forcing flows (a) and (b) corresponding behavior of time-averaged wall-shear-stress.

of the normalized, time-averaged wall-shear-stress is shown for the different simulations. In all forced cases, the time-averaged wall-shear-stress increases in the impingement region and decreases where the EHD flow streamlines are parallel to the wall. In the lower intensity cases, C1 and C2, the wall-shear-stress increases again close to point s. As in Schoppa and Hussain (1998), we may label the "i–s" region in Fig. 2(a) as vortex forcing and the "c–s" region in Fig. 2(a) as wall-jet forcing. In case C4, the time-averaged wall-shear-stress in the c–s region is about 90% of that in the unforced case. In case C3, which is the most favorable, the time-averaged wall-shear-stress in the c–s region is about 87% of that in the unforced case. Apparently, wall-shear-stress is significantly reduced in the region where the forcing flows are parallel to the wall (as suggested in Schoppa and Hussain, 1997) but it increases considerably in the region where extra drag is generated by the EHD jet impinging on the wall. This increase is, in most cases, sufficient to reduce the beneficial effect of drag reduction to few percent.

Acknowledgements

Computational resources provided by ENEL/CRT, Pisa, Italy on their CRAY T94/164 are gratefully acknowledged. Thanks to Marco Fulgosi, now at ETH, Zurich, for performing some of the simulations.

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