Commun. Comput. Phys.
doi: 10.4208/cicp.2009.09.068

Vol. 7, No. 4, pp. 683-717
April 2010

Computer Experiments on Rapidly Rotating Plane Couette Flow

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Received 22 April 2009; Accepted (in revised version) 17 July 2009

Communicated by Jie Shen

Available online 12 October 2009

Abstract. The turbulence in plane Couette flow subjected to system rotation is investigated. The anti-cyclonic rotation rate is well above the range in which roll-cells occur and close to the upper bound, beyond which no stationary turbulent states of motion exist. The mean velocity profile exhibits a linear region over 80% of the cross-section, in which the mean absolute vorticity is driven to zero. Viscous effects still prevail in narrow regions next to the walls, whereas the quasi-homogeneous central core exhibits abnormal anisotropies of the Reynolds stress tensor, the vorticity tensor and the energy dissipation rate tensor. In spite of the distinctly higher turbulence level observed, a 13% drag reduction is found. This paradoxical finding is ascribed to configurational changes in the turbulence field brought about by the system rotation.

AMS subject classifications: 76M12, 76F10, 76F65, 76U05

Key words: Turbulence, plane Couette flow, system rotation, anti-cyclonic rotation, anisotropy tensor, zero absolute mean vorticity.

1 Introduction

Rotation might give rise to remarkable and profound alterations of shear flow turbulence. Ever since the illuminating experimental investigation of a rotating plane channel flow by Johnston *et al.* [20], it has been known that the action of the Coriolis force due to system rotation changes not only the mean velocity distribution but also the turbulent velocity fluctuations. The location of maximum mean velocity is shifted from the channel center towards the so-called '*suction*' side, and the mean velocity profile exhibits a linear region with slope close to twice the imposed rotation rate. The turbulence intensity is reduced

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or sometimes even suppressed near this '*suction*' side, whereas the turbulent agitation is enhanced at the opposite side of the channel, i.e., along '*pressure*' side. These essential observations have later been confirmed and supplemented by more recent experimental studies by Nakabayashi and Kitoh [30, 31] and direct numerical simulations by Kristoffersen and Andersson [22], Lamballais *et al.* [23, 24], Liu and Lu [26] and Grundestam *et al.* [13].

The influence of the Coriolis force due to imposed system rotation depends both on the orientation and the magnitude of the background vorticity $2\mathbf{\Omega}^F$ relative to the mean flow vorticity $\mathbf{\Omega} \equiv \nabla \times \boldsymbol{u}$ in a rotating frame-of-reference. In simple shear flows, like the two-dimensional channel flow, the mean vorticity vector $\mathbf{\Omega}$ is perpendicular to both the mean flow direction, say x, and to the wall-normal direction, say y. If the angular velocity vector $\mathbf{\Omega}^F$ of the rotating frame-of-reference is aligned with $\mathbf{\Omega}$, the local vorticity ratio $S \equiv 2\Omega^F/\Omega$ effectively distinguishes between different flow regimes. In the plane channel flow, for instance, S changes sign where the mean velocity peaks and the rotating channel flow is therefore simultaneously affected by cyclonic ($S>0$) and anti-cyclonic ($S<0$) rotation.

In contrast with the pressure-driven plane channel flow, the shear-driven plane Couette flow exhibits a monotonically increasing mean velocity from one wall to the other with the obvious implication that the entire flow field is either exposed to cyclonic or anti-cyclonic rotation. This fact alone makes the rotating plane Couette flow an attractive prototype for explorations of rotational effects on rotating shear flows. In this context, the notion of '*pressure*' and '*suction*' sides should be discarded. Hart [15] found that the *laminar* plane Couette flow is unstable with respect to inception of counter-rotating roll cells in the parameter range $-1<S<0$ and otherwise stable. In the *turbulent* flow regime, the mean flow vorticity Ω is no longer constant across the flow and S varies with the distance from the wall. Bech and Andersson [6] therefore introduced a rotation number defined in terms of the average mean flow vorticity Ω_{av}, i.e., $Ro \equiv -2\Omega^F/\Omega_{av}$. Here, Ω_{av} also equals the constant vorticity of the corresponding laminar Couette flow. Care should be taken not to mix up the rotation number defined above with the Rossby number routinely used in geophysical fluid dynamics.

In a computational study of turbulent plane Couette flow, Bech and Andersson [6] observed that the roll cell instability was present also in the turbulent case provided that the rotation is anti-cyclonic ($Ro=+0.01$). If the Couette flow, on the other hand, was subjected to weak cyclonic rotation with $Ro=-0.01$, no roll cells appeared and the turbulence was damped as compared with the turbulence level in non-rotating Couette flow. At the same time laboratory investigations by Tillmark and Alfredsson [37] and computer simulations by Komminaho *et al.* [21] showed that cyclonic rotation may completely suppress the turbulence.

While Bech and Andersson [6] were concerned about weak rotation with a rotation number $Ro=\pm 0.01$, the intermediate rotation numbers $Ro=0.10$,0.20 and 0.50 were considered in a subsequent study by Bech and Andersson [7]. The weak but yet distinct roll cells observed already at $Ro=+0.01$ became more regular and energetic at $Ro=+0.10$ and