TRANSITION DELAY AND DRAG REDUCTION IN PARTICLE-LADEN CHANNEL FLOW

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Summary We perform numerical simulations of particle-laden channel flow and investigate how the presence of a solid phase changes the initial disturbance energy required to trigger subcritical transition. The results indicate that, although linear stability analysis shows hardly any effect on optimal growth, particles do influence secondary instabilities and streak breakdown. At moderate concentrations, particles significantly decrease the amplitude of oblique modes in the flow thus delaying transition initiated by their nonlinear interactions. These effects are related to the reduced drag recently observed in turbulent channel flow laden with heavy particles.

INTRODUCTION

Laminar-turbulent transition in shear flows has been studied extensively in the past but it is still not fully understood. Transition leads to an increase of the drag and is therefore often undesirable. One way to influence the transition and turbulence is by suspending additives in the flow, e.g. polymers [1], rigid fibers [2] or small heavy particles [3], as investigated here. Although many fluid flows of practical interest are seeded with particles, our knowledge about the influence of particles on the flow, in particular on laminar-turbulent transition, is still limited. In shear flows, transition is subcritical and a full nonlinear analysis is therefore needed. The linear lift-up process was identified as a key process in wall-bounded flows: subcritical transition is associated to the presence of streamwise elongated structures, the streaks.

In our previous work [4], the linear stability of flows seeded with either heavy particles was investigated. For a flow with heavy particles only the Stokes drag needs to be taken into account. We have shown that particles do not influence the transient growth of disturbances in plane channel flow. The optimal initial disturbances consist of counter-rotating streamwise vortices forming streamwise-independent streamwise velocity perturbations, as for single phase fluids. The time scale associated to the transient growth of the streaks is larger than the typical particle relaxation time so that heavy particles effectively act just to enhance the suspension density.

However, the numerical simulations in Ref. [3] demonstrate that adding heavy particles reduces the drag of a turbulent channel flow. The latter result indicates that particles have an effect on turbulent structures. Therefore, although particles show no influence in the initial linear stages of transition, they might have an effect on secondary, non-linear, instabilities. The aim of the present paper is therefore to investigate the effect of solid, spherical particles on the evolution of finite-size disturbances leading to turbulent flow. In addition, we will consider drag reduction in a turbulent flow and relate this to the transition delay discussed below.

Numerical method

The numerical code used is a pseudo-spectral solver for the three-dimensional incompressible Navier-Stokes equations with a particle tracking algorithm for the solid phase. The velocity components of the fluid phase are expanded in both x (streamwise) and z (spanwise) direction with Fourier modes and with Chebyshev polynomials in the wall-normal, or y-direction. To advance the momentum equation in time, we use a fourth order Runge-Kutta algorithm.

The particles are evolved by means of a Lagrangian Solver. The fluid velocities are interpolated from the Eulerian grid onto the particle positions using tri-linear interpolation. The time advancement of the particle uses the same Runge-Kutta algorithm as the fluid. The Stokes drag, forcing the momentum equation, can be extrapolated back onto the Eulerian grid using the same tri-linear scheme of the interpolation.

RESULTS

We study a plane Poiseuille flow given as base velocity by imposing a constant mass flux. The streamwise and spanwise dimensions of the domain are $L_x = 2\pi$ and $L_z = 2\pi$, with $L_y = 2$ the channel width. The Reynolds number used in the computations of transition is $R = 2000$. $R = 4200$ ($Re_\tau = 180$) is used for the case of turbulent flow.

In this paper we examine two transition scenarios previously analyzed as representative of subcritical transition, see e.g. Ref. [5]. First we consider transition initiated by streamwise vortices (SV), without any streamwise dependence. Streamwise vortices initiate the largest linear transient growth and are common in many shear flows. The large amplitude steaks induced by the optimal vortices break down to turbulence owing to secondary inflectional instabilities. In the second route to turbulence, we consider at time zero a pair of oblique optimal waves (OW scenario). Each of these waves grows by a non-modal mechanism so that they can nonlinearly interact. From this quadratic interaction, streamwise-independent streamwise vortices are formed that in turn induce streamwise streaks via the lift-up effect. The following breakdown is similar to the SV scenario.

The critical threshold energy for transition, computed by bisection, is reported as a function of the particle mass fraction f in figure 1 for an a-dimensional particle relaxation time $SR = \tau_p \frac{U}{L} = 5$; the Stokes number defined using the convective

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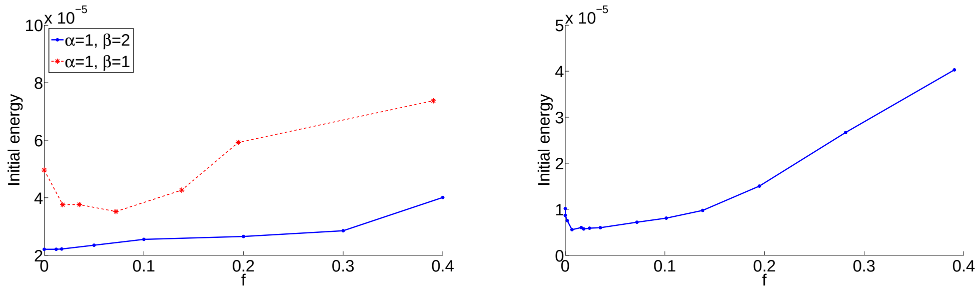

Figure 1. Critical threshold energy for transition as a function of the particle mass fraction f. Left: SV scenario initiated by streaks and two different oblique waves of stream wise and spanwise wavenumber $(\alpha = 1, \beta = 1)$ and $(\alpha = 1, \beta = 2)$. Right: OW scenario initiated by two symmetric oblique waves $(\alpha = 1, \beta = \pm 1)$. $SR = 5$ and $R = 2000$.

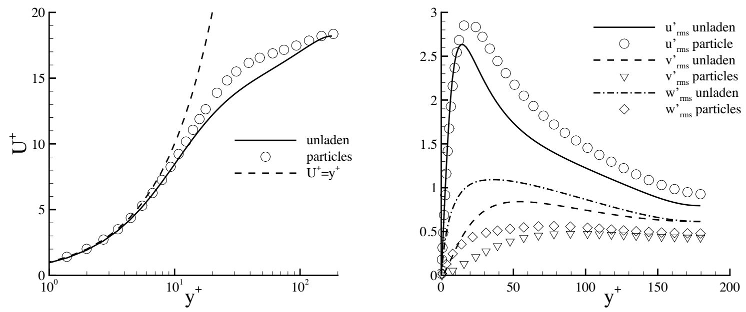

Figure 2. Statistics of turbulent channel flow laden with heavy spherical particles $f = 0.95$, $R = 4200$, $SR = 3.88$, $(SR^+ = 30)$. Left: mean velocity profile. Right: Velocity fluctuations.

time scale of the flow with L the channel half-width and U the laminar centerline velocity. $\tau_p = \frac{2}{9}\frac{r^2}{\nu}\frac{\rho_p}{\rho_f}$, with r the radius of the particle, ρ_p the density of the particle, ρ_f the fluid density and ν the kinematic viscosity.

The data indicate that the energy threshold decreases for low values of the mass fraction f in both scenarios transition. This is due to the fact that the few present particles introduce in the system detrimental disturbances of length scales not initially present. At higher concentrations, conversely, we note an increase of the disturbance energy needed for transition. The threshold energy for the oblique scenario, the lowest of all, shows a more significant increase in the presence of particles, by a factor about 4. Interestingly, for the streamwise-vortex scenario the time at which transition occurs increases significantly with the particle volume fraction when considering disturbances of equal initial energy (not shown here). Our results are explained by considering the reduced amplification of oblique modes in the two-phase flow.

The results presented here can have implications for turbulent flows where drag reduction is observed for relatively large mass fraction. In [6], a regeneration cycle is proposed to underlie wall-bounded turbulent flows. This consists of three steps: i) generation of streaks induced by streamwise vortices, ii) streak breakdown via secondary instabilities, iii) regeneration of elongated vortices by nonlinear interactions between oblique modes originating at the streak breakdown. As shown in [4], the streak generation occurs on a time scale too long for particles to have an effect. However, the present investigation indicates that particles can affect the remaining steps of the cycle. Particles may significantly hinder the last of these three processes, namely the regeneration of streamwise vortices by nonlinear interactions and particles also induce a significant time delay on the streak breakdown (stage ii). To further investigate this point, we performed numerical simulations, see figure 2, to reproduce drag reduction by rigid solid spherical particles [3]. Analysis of these new data will be part of the final contribution.

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