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Temporal stability of a particle-laden jet

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Abstract

The temporal instability of a particle-laden jet was investigated numerically which took into consideration the parametric effects of jet parameter, B, jet Reynolds number, Re_j, particle mass loading, Z and Stokes number, St. The linear stability theory was used to derive the instability equations of a viscous particle-laden jet flow. The single-phase instability of a top-hat jet was then calculated and compared with the available analytical theories. The numerical results agree well with the analytical results for both the axisymmetric ($n = 0$) and first azimuthal ($n = 1$) modes. The results show that the first azimuthal mode disturbance is usually more unstable than that of the axisymmetric mode. But the axisymmetric mode disturbance can be more unstable when Z is high enough (i.e., $Z \geqslant 0.1$). The higher B and Re_j are, the more unstable the particle-laden jet will be. The existence of particles enhances the flow stability. With the increasing of Z, the jet flow will grow more stable. The inviscid single-phase jet is the most unstable. The wave amplification, c_i first decreases with the increasing of St and then increases afterwards. There exist certain values of St, at which the jet is the most stable.

Keywords: Particle-laden jet flow; Temporal instability; Stokes number; Particle mass loading

1. Introduction

Numerous engineering applications and processes of a two-phase turbulent jet for transporting particles can be identified (i.e., air cleaner systems, ejector scrubbers, air-spray systems, vehicular exhaust jet particle distributions and combustion exhaust systems, etc.). In many of these processes, the distribution of the dispersed particle is a controlling factor in the efficiency and the stability of the processes (Chan et al., 2005a,b, 2006; Lin et al., 2007). Since the stability of particle-laden jet flow is different from that of the single

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phase jet flow (Saffman, 1962; Batchelor and Gill, 1962), it plays a key role in the numerous engineering applications and processes.

Indeed, Batchelor and Gill (1962) derived the coupled ordinary differential equations for the disturbance motion of a single-phase jet and proved the existence of amplified disturbance for any value of the azimuthal wavenumber for a top-hat velocity profile. Lessen and Singh (1973) studied both temporal and spatial instability of axisymmetric free shear layers and concluded that the first azimuthal mode is the most unstable. Mollendorf and Gebhart (1973) solved numerically the fully viscous hydrodynamic stability equations for a laminar vertical round jet for both symmetric and asymmetric disturbances using the proper boundary-layer base-flow velocity profile. Michalke (1984) reviewed the theoretical results on the instability of axisymmetric jets due to the effects of shear layer thickness, Mach number, temperature ratio and external flow velocity. Lin and Lian (1989) studied the effect of the ambient gas density on the onset of absolute instability in a viscous liquid jet. They found that the critical Weber number can be determined as a function of Reynolds number and the density ratio of gas to liquid. Shen and Li (1996) carried out a linear analysis for the temporal instability of an annular viscous liquid jet moving in an inviscid gas medium. They found that the curvature effects in general increase the disturbance growth rate and an ambient gas medium always enhances the annular jet instability. Recently, Cramer et al. (2002) have studied experimentally the breakup of a Newtonian liquid jet into droplets injected horizontally into another flowing immiscible Newtonian fluid under creeping flow conditions. They have found that different breakup mechanisms take place in different flow regions. Funada et al. (2004) have analyzed the temporal and convective/absolute instability of a liquid jet into a gas or another liquid medium using viscous potential flow. Their findings have showed that there are wavenumbers for which the liquid jet is temporally unstable for their studied parameters. Chauhan et al. (2006) have examined the emergence of the absolute instability from the convectively unstable states of an inviscid compound jet. They have found that in addition to being convectively unstable at all Weber numbers, the inviscid compound jet is also absolutely unstable when below its critical velocity.

On the other hand, the instability studies of a particle-laden jet have also been developed. Neglecting the gas viscosity and the fluctuation of suspension velocity, Yang et al. (1990) studied the spatial stability of gas-particle two-phase mixing layer. They found that the existence of small particles enhances the flow stability. Sykes and Lyell (1994) investigated the spatial stability of an inviscid two-phase circular jet and also found that the particles have a stabilizing effect. The spatial growth rate was found to decrease for both the axisymmetric and first azimuthal modes. Parthasarathy (1995) studied both the spatial and temporal stabilities of a circular particle-laden jet. The temporal stability analysis of a particle-laden top-hat jet showed that the presence of particles decreases the wave amplification but increases the wave velocity. However, the increasing of particle mass loading decreases both wave amplification and velocity. The spatial stability analysis showed that the presence of particles decreases the wave amplification rate at all frequencies. However, only top-hat jet profile was investigated in the temporal instability. Recently, Lin and Zhou (2000) have investigated the stability of a moving jet containing dense suspended solid particles and found that the particles affect the instability of the flow field significantly. DeSpirito and Wang (2001) have studied the temporal stability of a particle-laden jet using the direct numerical simulation approach. They have demonstrated that the addition of particles can destabilize the flow at a small particle Stokes number, while the stabilizing effect prevails for an intermediate to a large particle Stokes number. The addition of particles increases the wave velocity at high wavenumber but decreases the wave velocity at low wavenumber. For a given particle mass loading and wavenumber, there is an intermediate particle Stokes number that corresponds to a maximum stability of jet flow. They have showed that this Stokes number is on the order of 1 and depends weakly on the wavenumber. But they have only considered the axisymmetric azimuthal mode disturbance. In fact, the first azimuthal mode disturbance is more unstable. Lakehal and Narayanan (2003) have studied the initial temporal evolution of mixing layers for different Stokes numbers. Their results could also apply for the instability of jet flow.

However, there is no detailed investigation on different azimuthal modes in the instability of a particle-laden jet which takes into consideration the different parametric effects available in the literature. In the present study, it is intended to investigate the parametric effects of jet parameter, B, jet Reynolds number, Re_{j}, particle mass loading, Z, particle Stokes number, St, disturbance wavenumber, β and azimuthal mode, n on the temporal stability of a particle-laden jet.