International Journal of Multiphase Flow 37 (2011) 609–619

Contents lists available at ScienceDirect

International Journal of Multiphase Flow

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

Apparent wall slip velocity measurements in free surface flow of concentrated suspensions

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ARTICLE INFO

Article history:
Received 13 November 2010
Received in revised form 24 February 2011
Accepted 17 March 2011
Available online 23 March 2011

Keywords:
Concentrated suspension
Wall slip
Particle image velocimetry
Free surface flow

ABSTRACT

In this work we have experimentally measured the apparent wall slip velocity in open channel flow of neutrally buoyant suspension of non-colloidal particles. The free surface velocity profile was measured using the tool of particle imaging velocimetry (PIV) for two different channels made of plane and rough walls. The rough walled channel prevents wall slip, whereas the plane wall showed significant wall slip due to formation of slip layer. By comparing the velocity profiles from these two cases we were able to determine the apparent wall slip velocity. This method allows characterization of wall slip in suspension of large sized particles which cannot be performed in conventional rheometers. Experiments were carried out for concentrated suspensions of various particle volume concentrations and for two different sizes of particles. It was observed that wall slip velocity increases with particle size and concentration but decreases with increase in the viscosity of suspending fluid. The apparent wall slip velocity coefficients are in qualitative agreement with the earlier measurements. The effect of wall slip on free surface corrugation was also studied by analyzing the power spectral density (PSD) of the refracted light from the free surface. Our results indicate that free surface corrugation is a bulk flow response and it does not arise from boundary problem such as development of slip layer.

1. Introduction

Suspensions of solid particles in viscous fluids are often encountered in various applications such as paints, polymer, pharmaceuticals products, drilling mud, and food products. Suspensions are also prevalent in a number of natural settings such as debris flow, lava flow, and flood waves carrying extremely high concentration of sediments. At dilute concentrations the suspensions of solid rigid particles in Newtonian fluid are often modeled as effective Newtonian fluid having a concentration dependent viscosity. However, at moderate and high particle concentrations the hydrodynamic interactions significantly alter the flow characteristics and we often observe many interesting phenomena, which are not seen in the flow of a Newtonian homogeneous fluid under similar boundary conditions. Apparent wall slip of particles is one such phenomenon and this has attracted large number of studies (Yoshimura and Prud'homme, 1988; Yilmazer and Kalyon, 1989; Kalyon et al., 1993; Aral and Kalyon, 1994; Jana et al., 1995; Ekere et al., 2001; Kalyon, 2005; Nickerson and Kornfield, 2005; Lam et al., 2007; Ahuja and Singh, 2009). Though, the phenomenon of wall slip is quite old but it still attracts significant attention due to its practical importance. Moreover, the nature of wall slip under various flow conditions is far from understood. The wall slip phenomenon is basically the occurrence of apparent relative velocity between the wall and the fluid at the wall. However, since the fluid is continuum, even in concentrated suspensions there is no 'true slip'. It is in reality an 'apparent slip' created by a region of high velocity gradient close to the wall compared to the bulk. This appears as an apparent slippage of the suspension through a thin liquid-rich layer (slip layer) of thickness δ at the wall (Vand, 1948). The slip layer is depleted of suspended particles compared to the adjacent regions of bulk suspension. As a result, if the Rheological measurements are carried out with smooth geometries, the measured viscosity (also called as apparent viscosity) is much lower than the true viscosity of suspensions. The wall slip effects are generally observed in the flow of highly viscous two-phase materials in rheometers, pipe, or any channel with smooth wall. Near the smooth, solid boundary, the local microstructure is depleted because the suspended particles cannot penetrate the solid walls. This particle deficient layer can also be observed even if there was no flow. This is known as static geometric depletion effect which could result from steric, hydrodynamic, viscoelastic, chemical and gravitational forces acting on the solid particles adjacent to the wall (Barnes, 1995). In some situations, the walls can also repel adjacent particles because of electrostatic forces arising between the particles and the walls. During the bulk flow, the resulting hydrodynamic and entropic forces can move the particles further away from the walls. The presence of large particles as disperse phase, smooth walls, low speeds or flow rates and, wall and parti-

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doi:10.1016/j.ijmultiphaseflow.2011.03.006

cles carrying electrostatic charges are some of the reasons which enhance the slip effects. Shear induced migration (Leighton and Acrivos, 1987b) can also cause depletion of particles near the wall and enhance the wall slip.

It is now well known that to prevent slip at the wall, roughened and serrated wall surfaces can be used (Barnes, 1995). If the slip layer thickness is comparable with the height of surface irregularities, then slip would not develop (Soltani and Yilmazer, 1998). Fig. 1 shows the role played by the surface roughness in the suppression of wall slip effects. Near the plane wall there is a thin liquid-rich layer (slip layer) which is responsible for apparent wall slip. However, in case of rough wall, the particles can move inside the groove of the serrations and hence the whole suspension can be treated as continuum as there is no-slip layer. Therefore, if one carries out velocity profile measurements for the flow geometry with rough wall, both true and apparent velocity profiles will be the same. On the other hand, measurements in smooth wall geometry will show a different apparent velocity profile due to wall slip.

The motivation of the present work comes from the above mentioned studies as well as some recent experiments on surface corrugation in free surface flow of concentrated suspensions (Loimer et al., 2002; Timberlake and Morris, 2005). In a recent experiment Singh et al. (2006) observed that the free surface velocity profile in a gravity driven open channel flow is blunted. The deviation of velocity profile from the Newtonian profile increased as the particle concentration was increased. In the past Karnis et al. (1966) and Sinton and Chow (1991) have also reported velocity blunting but no measurable non-uniformity of particle concentration. Koh et al. (1994) have measured the velocity and concentration profiles in pressure driven flow of concentrated suspension in a rectangular channel. Based on their measurements they speculate that there could be significant 'slip' between the particles and the suspending fluid which increases with increase in particle concentration and size. Blunted velocity profile was also reported in the experiments of Lyon and Leal (1998) when concentration profile showed no inhomogeneities. The motivation of our study on wall slip comes from these observations. It is also our objective to investigate further the work of Singh et al. (2006) and study the effect of apparent wall slip velocity on surface corrugation in the free surface flow of concentrated suspension in open channel. It is well known that non-colloidal concentrated suspensions have non-zero normal stress differences. Many polymeric fluids have large first normal stress difference. Under condition of no-slip, polymeric fluids with negative (extensional) first normal stress difference will behave like a stretched membrane. The non-colloidal suspensions are known to have positive (in the compression sense) first and second normal stress differences. Whether, the presence of wall slip causes the free surface to appear in the form of surface corrugation was the motivation behind studying the effect of wall slip on surface corrugation.

Jana et al. (1995) determined the apparent wall slip coefficient of concentrated suspensions of non-colloidal PMMA particles in a viscous Newtonian fluid in a narrow gap Couette device by measuring the velocity profile across the gap using a laser Doppler anemometer system and then extrapolating the results to the walls. The slip coefficients thereby obtained were found to be insensitive to the magnitude of the applied shear rate. However their measurements could be influenced by lateral migration of particles initiated by the presence of the wall and non-uniform velocity gradients. The wall slip in concentrated suspension can manifest even if there is no shear induced migration. Ahuja and Singh (2009) have studied wall slip in simple shear flow via Stokesian Dynamics simulation and demonstrated that apparent slip is present even in simple shear flow, where the shear induced particle migration is absent. During the flow of suspension the particles cannot cross the wall and physically cannot occupy the space very close to wall as efficiently as they can away from the wall. This wall depletion will always result into a thin layer of fluid called as apparent slip layer. Under the conditions of inhomogeneous shear flow, there can be migration near the wall which can increase the depletion of particles resulting into enhanced slip. However, the method we adapt to measure slip velocity is to compare the velocity profiles from rough wall channel as well as smooth wall channel at the same axial locations. Thus the extent of migration is expected to be same in both the cases. The slip velocity which is difference of the near-wall velocity in these two cases will be the true measure of wall slip.

Loimer et al. (2002) have studied the free surface shape during the simple shear flow of concentrated suspensions of small inertialess particles in a viscous fluid and observed the development of corrugation at the free surface. Subsequent to their findings the flow induced surface corrugation was studied by Timberlake and Morris (2005) and Singh et al. (2006) in the gravity driven flow of concentrated suspensions. The air-suspension interface during the free surface flow of concentrated suspension is found to be highly corrugated even at low Reynolds number and this surface deformation depends on many factors like particle concentration, surface tension and viscosity of the suspending fluid. Our interest was to explore if the wall slip affects the corrugation patterns. By analyzing the power spectral density (PSD) of the refracted light from the free surface, the surface roughness was characterized. Since the relative illumination intensity is associated with the local inclination of the surface, study of temporal and spatial intensity spectra provided valuable information about the wave amplitude and frequency of the surface deformation patterns. By analyzing

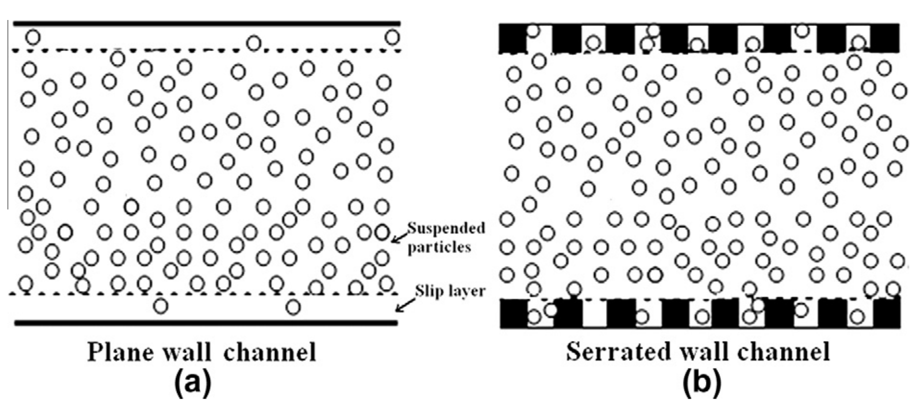

Fig. 1. Schematic diagram showing (a) the formation of slip layer at the plane wall and (b) prevention of slip layer with the rough wall.