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Shear-induced particle migration in three-dimensional bifurcation channel

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ABSTRACT

Flow of concentrated suspension through bifurcation channels are commonly encountered in industrial and biological applications. Shear-induced particle migration in simple and unidirectional geometries like straight channels and tubes have received wide attention but there are very few studies on complex geometries and channels with bifurcations. In this work we report numerical simulation of shear-induced particle migration during low Reynolds number transport of concentrated suspension through Y-shaped three-dimensional bifurcation channel. The effect of bifurcation angle and bulk particle concentration on the velocity, concentration profiles and wall shear stress in the upstream and downstream of bifurcation was studied. It was observed that the velocity profile in the case of concentrated suspension differs significantly from that of Newtonian fluid of same effective viscosity. Near the junction the velocity profile for suspension flow is blunted and the degree of bluntness increases with increase in particle concentration and bifurcation angle. The velocity and concentration profiles in the lateral and span-wise directions of the inlet branch remains symmetric but significant asymmetry was observed in the daughter branches. The locations of the peak velocity and concentration in the inlet and side branch were found to be strongly influenced by the bulk particle concentration and angle of bifurcation. Wall shear stress level was found to be the highest near the bifurcation region.

Introduction

Concentrated suspensions of particles in viscous fluid often find their use in variety of applications in industrial and biological systems. The handling and treatment of concentrated suspension still remains a difficult task in several process industries. During flow of concentrated suspension through channels and tubes the particles interact via hydrodynamic interactions with each other and with the bounding walls. This considerably alters the flow characteristics and we observe several fascinating phenomena like pattern formation and shear-induced particle migration. The phenomenon of shear-induced particle migration has attracted a large number of studies because of its practical applications in material processing operations and biological systems. The observation of decrease in shear viscosity of the concentrated suspension with time during inhomogeneous shearing of concentrated suspension in a Couette device by Gadala-Maria and Acrivos (1980) increased the interests of researchers to this interesting problem. Later, Leighton and Acrivos (1987a,b) explained that the decrease in viscosity was related to the migration of particles from the high shear rate region to the low shear rate region. They also proposed particle flux expressions that give rise to particle migration. Their work was followed by various experimental studies on the migration of particles during flow of concentrated suspensions through various geometries, including pressure driven channel (Koh et al., 1994; Lyon and Leal, 1998) and tube flows (Hampton et al., 1997). These experimental measurements showed that the velocity profile becomes blunted and non-uniform concentration profile develops in tubes and channels. Abbott et al. (1991), Phillips et al. (1992) and Chow et al. (1994) measured concentration profiles in a wide gap Couette device by using Nuclear Magnetic Resonance (NMR) technique. Phan-Thien et al. (1995) carried out experimental and numerical studies on particle migration in concentrated suspensions undergoing flow between rotating eccentric cylinders. van Dinther et al. (2012) have reviewed various experimental methods that can be used to measure the concentration and velocity profiles in microchannels.

Subsequent to the experimental observations of particle migration, theoretical models were developed to explain this phenomenon. There are mainly two classes of continuum models to explain the shear-induced migration in concentrated suspensions. The first phenomenological model called diffusive flux model developed by Phillips et al. (1992) is based on particle flux

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expressions of Leighton and Acrivos (1987b) in which migration is driven by the gradients in shear rate and viscosity. This model was successful in capturing the essential features of migration in Couette and Poiseuille flows but failed to explain migration in curvilinear flows. Krishnan et al. (1996) and later Fang et al. (2002) modified the diffusive flux model for generalized application in curved geometries. Another phenomenological model named as suspension balance model was proposed by Nott and Brady (1994). This model showed that the particle migration is driven by the gradient in the normal stresses. Later, Morris and Boulay (1999) illustrated the importance of anisotropy and normal stress differences in suspension balance model for predictions of migration in curvilinear flows. Their model was employed by Miller and Morris (2006) in the numerical simulations of particle migration of concentrated suspension through rectangular channels. They also introduced the concept of non-local shear rate which is added to the local shear rate to get rid of the unphysical cusp in concentration profile at the center of the channel. Kauzlaric et al. (2011) overcome this problem by incorporating the effective deformation rate tensor in the diffusive flux model which considers the collisions between the particles at the center of the channel where local shear rate is zero. Vollebregt et al. (2010) demonstrated that the driving force for particle migration can be expressed in terms of non-equilibrium osmotic pressure and chemical potential and various shear induced migration models can be generalized as a mixture model. This way they have effectively applied the shear induced migration models to the membrane filtration and further extended it to the separation of bidispersed suspensions. Both the diffusive flux and suspension balance model over predict the wall concentration. Vollebregt et al. (2012) in the mixture model proposed the adjustment of the maximum packing close to the wall, which corrects the depletion of particles near the wall. Recently, van Dinther et al. (2013) have probed the role of shear induced diffusion phenomena in the fractionation of droplets based on their size.

Both the diffusive flux and suspension balance models have been used extensively to study the unidirectional and steady flow in simple one and two dimensional geometries, while flow in complex geometries such as bifurcations are not adequately addressed despite the fact that many industrial processes involve flow of suspension through complex 3D geometries. Transport of concentrated suspension through such channels has relevant applications in technological and biological field, like streamline flow of blood through branched arteries and veins. In the biomedical application, the design of artificial valves requires proper understanding of the distribution of particles in bifurcating branches. Krogh (1921) had carried out detailed studies on the physiology of capillaries and observed that in arteries with bifurcations the blood cells do not distribute in the same proportion as the volumetric blood flow. The technique of 'Plasma Skimming' which is used to separate red blood cells from the plasma involves flow of blood through a network of precisely controlled micro fluidic bifurcation channels (Aarts et al., 1988). Ditchfield and Olbricht (1996) and Roberts and Olbricht (2003, 2006) have conducted experiments on the motion of freely suspended particles through multiple bifurcating channels (Y and T shape) and found that there is difference in partitioning of bulk suspension and particles in daughter branches. The magnitude of this difference depends on the bifurcation geometry and the bulk particle volume fraction of the suspension. Schmid-Schonbein et al. (1980), Perkkio and Keskinen (1983) and Barber et al. (2008) have proposed mathematical models to understand the flow and particle partitioning and computed the cell distribution at bifurcations. Balan and Balan (2010) using experiments and numerical simulations have studied the velocity profiles of shear thinning fluids in bifurcating micro channels. Ishikawa et al. (2011) investigated the behavior of red blood cells and cancer cells in symmetric bifurcation channels and Leble et al. (2011) studied the velocity profiles of red blood cells through converging and diverging bifurcations. In a recent review article Kumar and Graham (2012) have discussed the margination of leukocytes, RBCs and platelets and reviewed the shear induced migration models for the segregation behavior in binary suspension of rigid and deformable particles. Most of these studies dealt with dilute concentrations and situations where the size of the particles was almost comparable with the channel width. The flow physics of concentrated suspensions of small particles relative to channel width is less studied numerically and experimentally despite their wide application. Xi and Shapley (2008) have performed NMR experiments on flow of concentrated suspensions through asymmetric T-junction bifurcation channel of rectangular cross-section. They observed that the particles are almost equally partitioned in downstream branches even though the flow partitioning is unequal. Later, Ahmed and Singh (2011) performed numerical simulations based on the diffusive flux model and obtained good agreement with the experimental work of Xi and Shapley (2008). Recently, Reddy and Singh (2014) have carried out numerical simulations of suspension flow through two dimensional oblique bifurcating channels and reported that flow partitioning and particle partitioning do not seem to be the same because of redistribution of particles in the daughter branches. In a significant work Zrehen and Ramachandran (2013) observed the existence of secondary currents in pressure driven low Reynolds number flow of concentrated suspension of non-colloidal particle through a conduit of square cross section. The secondary currents in 3D channel with non-axisymmetric cross-section may influence the particle distribution. The above mentioned studies has motivated us to perform detailed studies on the distribution of particles and its relation to the velocity profile considering utilization of this knowledge in several industrial and biological processes where particle migration is an important issue. To the best of our knowledge there are no experimental and simulation studies on flow of concentrated suspensions in symmetric three dimensional Y shape bifurcation channels that are common in microfluidic devices. In this work, we have studied the flow of concentrated suspension of rigid mono dispersed particles in viscous liquid flowing through 3D symmetric bifurcation channel via Computational Fluid Dynamics (CFD) simulations. The CFD simulations based on continuum models such as diffusive flux and suspension balance has advantage over the computationally intensive particle tracking simulations as they can be generalized for complex geometries. Shapley et al. (2004) have evaluated the performance of diffusive flux and suspension balance model by comparing the simulation results with experimental data obtained from NMR imaging. The diffusive flux model is relatively simple as it couples generalized Newtonian stress/strain relationship with shear-induced migration of particles and effective viscosity depends on the local volume fraction of particles. The modified version of suspension balance model (Morris and Boulay, 1999) considers non-Newtonian rheology of concentrated suspensions (particularly normal stress differences) to incorporate the anisotropy in stresses. Several past studies have confirmed that for rectilinear channel flow, predictions of diffusive flux model and suspension balance model are similar. In bifurcation channel the region where the flow encounters curvature is much smaller compared to the straight section. Since the net migration depends on total strain, the curvature induced flux is not expected to be important. In a previous study on migration in asymmetric T- junction bifurcation channel (Ahmed and Singh, 2011) the predictions from diffusive flux model were found to be in good agreement with the experiments of Xi and Shapley (2008). Thus, for simplicity of implementation, and economy of computations we have chosen diffusive flux model in our present study. The mass, momentum and particle conservation equations of the diffusive flux model were solved