# MASS TRANSFER FROM ENSEMBLES OF NEWTONIAN FLUID SPHERES AT MODERATE REYNOLDS AND PECLET NUMBERS

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**Abstract:** In this work, the rate of mass transfer from an ensemble of mono-size spherical Newtonian droplets (free from surfactants) to a Newtonian continuous phase has been numerically studied at moderate Reynolds and Peclet numbers. A simple spherical cell model (so-called free surface cell model) has been used to account for inter-drop hydrodynamic interactions. Extensive numerical results have been obtained to elucidate the effects of the Reynolds number ($Re_o$), the ratio of internal to external fluid viscosity ($k$), the volume fraction of the dispersed phase ($\varepsilon$) and the Schmidt number ($Sc$) on the local and average Sherwood number ($Sh$) over the ranges of conditions: $1 \leq Re_o \leq 200$, $0.2 \leq \varepsilon \leq 0.6$, $0.1 \leq k \leq 50$ and $1 \leq Sc \leq 10\,000$. It has been observed that the effects of viscosity ratio on the local and average Sherwood number is less significant for small values of the Peclet number ($Pe$) for all values of dispersed phase concentration. As the value of the viscosity ratio increases, the average Sherwood number decreases for all values of the droplet concentration and the Reynolds number. Based on the present numerical results, a simple predictive correlation is proposed which can be used to estimate the rate of inter-phase mass transfer in a liquid–liquid system in a new application. However, it is also appropriate to add here that at higher concentrations, fluid spheres interact significantly, deform and coalesce. All these effects are neglected in this study. Therefore, the present results are valid only for dilute to moderate concentration of the dispersed phase.

**Keywords:** ensemble; fluid sphere; viscosity ratio; mass transfer; Sherwood number.

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## INTRODUCTION

The motion of and mass transfer from drops to viscous liquids is ubiquitous in the chemical, biochemical, and polymer processing industries. In most applications, one encounters clusters of drops, the growth or collapse of which are directly influenced by the rate of mass transfer between the two phases. The rate of mass transfer from a single fluid sphere moving in a continuous fluid medium is greatly influenced by the motion inside the fluid sphere. Experiments have shown that the rate of mass transfer from circulating bubbles and drops is much larger than that from non-circulating bubbles and drops due to the effect of internal circulation on the external flow field. It is readily conceded that one often encounters ensembles of droplets rather than a single drop in most industrial applications. The mass transfer from ensembles of fluid spheres to another immiscible medium is an idealization of many industrially important chemical and processing applications. In most applications, often one fluid is dispersed in the form of droplets moving in another immiscible fluid which leads to enhancement of the rate of mass transfer between the two phases. Some of these applications include, liquid–liquid extraction, distillation, gas absorption, enhanced oil recovery in petroleum industries, production of polymeric alloys and emulsions in paint and detergent industries, fermentation broths, wastewater treatment, and so on (Schramm, 2005). Over the years, extensive literature has been reported on the motion of and mass transfer from single bubbles and drops in Newtonian liquids which has been reviewed thoroughly by Clift *et al.* (1978), Michaelides (2006) and Chhabra (2006). Although, the detailed kinematics of such studies related to single bubbles and drops provides useful information about the basic underlying physical phenomena, often one encounters clusters of bubbles and drops in chemical and processing industries as mentioned above. Therefore, an adequate

understanding of the rate of mass transfer from clusters of drops is a prerequisite to the understanding and rationalizing the overall efficiency of the contacting equipment. This information can be conveniently expressed using dimensionless parameters such as the Sherwood number, Reynolds number, Schmidt number, viscosity ratio and the volume fraction of the dispersed phase. Most of the literature on mass transfer from clusters of drops pertains to the limiting cases of either zero viscosity ratio (bubbles) or infinite viscosity ratio (solid spheres) in the creeping flow or in the potential flow regimes for small and/or large values of Peclet numbers. Indeed, no prior results are available which relate to mass transfer from ensembles of drops at moderate Reynolds and Peclet numbers for intermediate values of the viscosity ratio and the concentration of the dispersed phase.

From a theoretical standpoint, a mathematical description of the inter-drop hydrodynamic interactions is also needed, in addition to the usual conservation equations to model convective transport in these systems. In the literature, two distinct approaches are available to describe inter-drop hydrodynamic interactions. In the first approach, the field equations are solved for specific ordered arrangements (such as square, triangular, simple cubic, body centered cubic, face centered cubic, and so on). While this approach is rigorous, the results naturally depend upon the specific arrangement and extrapolation to even a slightly different configuration is not possible (Chhabra, 2006). These results are frequently expressed in the form of a correction factor to be applied to the case of a single droplet (Stokes' expression), which is a strong function of the type of packing of droplets. For ordered suspensions, this correction is of the order $\varepsilon^{1/3}$, whereas for random suspensions, it is of the order $\varepsilon$. While in the dilute limits, both of these are close to each other, but the two begin to deviate from each other with the increasing values of $\varepsilon$. To date this approach, however, has not only been limited to the zero Reynolds number flow, but has also been used more extensively for solid spheres and bubbles and only scantily for droplets. In the second approach (the so-called cell model), somewhat less rigorous, the inter-drop interactions are approximated by postulating the each fluid sphere to be surrounded by a hypothetical concentric envelope of the continuous phase. The size of the hypothetical envelope is chosen such that the volume fraction of the dispersed phase in each cell is equal to the overall mean volume fraction of the dispersed phase. Thus, the radius of the hypothetical envelope is related to the size of the individual droplet via the mean volume fraction of the system. Qualitatively, this approach is tantamount to imposing an equivalent wall effect, akin to the approach of Di Felice (1996). Thus, this approach converts the difficult many body problem into a conceptually simpler problem involving one droplet confined in a spherical cell. This provided the impetus to the development of the two commonly used cell models, namely, the free surface cell model (Happel, 1958) and the zero vorticity cell model (Kuwabara, 1959). The two models differ only in relation to one of the boundary conditions at the cell boundary. Happel (1958) proposed the cell boundary to be frictionless (zero shear stress) thereby emphasizing the non-interacting nature of cells. On the other hand, Kuwabara (1959) suggested the use of the zero vorticity condition at the cell boundary. While it is virtually impossible to offer a sound theoretical justification for either of these boundary conditions, suffice it to say here that owing to extra dissipation in the zero vorticity cell model, the resulting values of the resistance are larger than those obtained by using the free surface cell model (Chhabra, 2006). The free surface cell model has been used in this work. However, it will be appropriate to start with a short review of the previously available scant literature.

## PREVIOUS LITERATURE

Since the pioneering work on the viscous flow past assemblages of solid spheres at low Reynolds number by Happel (1958) and its subsequent extension to ensembles of bubbles and drops (Gal-Or and Waslo, 1968), the free surface cell model has been extensively used to solve the flow past clusters of bubbles, drops and particles in Newtonian fluids and in a wide variety of non-Newtonian fluids. Owing to the non-linear viscosity equation for non-Newtonian fluids, the velocity and stress variational principles have been combined with the cell models to obtain lower and upper bounds on drag coefficients for swarms of spherical bubbles rising in generalized Newtonian fluids including power-law fluids, Carreau model fluids (Gummalam and Chhabra, 1987; Gummalam *et al.*, 1988; Jarzebski and Malinowski, 1986, 1987a, b; Manjunath and Chhabra, 1992; Manjunath *et al.*, 1994; Zhu and Deng, 1994; Zhu, 1995, 2001; Sun and Zhu, 2004). On the other hand, in the limit of potential flow, Chhabra (1998) extended the work of Marrucci (1965) to bubble swarms rising in power-law liquids using the free surface cell model. Similarly, there are a few studies reported on the flow of Newtonian and other generalized Newtonian fluids in fixed and fluidized bed of spheres (Mohan and Raghuraman, 1976a, b; Kawase and Ulbrecht, 1981a, b; Chhabra and Raman, 1984; Satish and Zhu, 1992; Zhu and Satish, 1992; Jaiswal *et al.*, 1991a, b, 1992, 1993, 1994; Dhole *et al.*, 2004). Gal-Or and Waslo (1968) were the first to use the free surface cell model to study the creeping motion of an ensemble of mono-size spherical drops in an another immiscible incompressible Newtonian liquid with and without the presence of surfactants. This approach has also been shown to yield satisfactory predictions of drag on ensembles of drops moving slowly in power-law and other generalized Newtonian fluids (Jarzebski and Malinowski, 1986, 1987a, b; Tripathi and Chhabra, 1994; Zhu and Deng, 1994; Zhu, 2001). Recently, Kishore *et al.* (2006) have extended this approach to the Newtonian flow past ensembles of mono-size spherical Newtonian droplets at moderate Reynolds numbers up to 500. This model has also been used successfully to capture the sedimentation behaviour of two-fluid spheres (Ferreira *et al.*, 2003) and of composite spheres (Prasad *et al.*, 1990). Most of these studies concerning the hydrodynamics of multi-particle systems have been reviewed recently (Chhabra, 2006).

In contrast, there is only a scant literature on mass and heat transfer from clusters of bubbles, drops and particles, even in the creeping flow regime at intermediate Peclet numbers. Pfeffer (1964) combined the free surface cell model and the thin boundary layer solution to obtain an expression for the average Sherwood number in the limit of large Peclet number and the creeping flow of Newtonian liquids through beds of spherical particles as a function of the fractional void volume. Kawase and Ulbrecht (1981a, b) combined the thin concentration boundary layer approximation with the free surface cell model to elucidate the role of power-law index

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