Available online at www.sciencedirect.com
ScienceDirect
International Communications in Heat and Mass Transfer 34 (2007) 971 – 978
International Communications in HEAT and MASS TRANSFER
www.elsevier.com/locate/ichmt

Mass transfer from a spherical bubble rising in power-law fluids at intermediate Reynolds numbers ☆

S.D. Dhole [a], R.P. Chhabra [a,*], V. Eswaran [b]

[a] Department of Chemical Engineering, Indian Institute of Technology, Kanpur, 208 016, India
[b] Department of Mechanical Engineering, Indian Institute of Technology, Kanpur, 208 016, India

Available online 7 May 2007

Abstract

The effects of Reynolds number, Schmidt number and power law index (n) on the mass transfer characteristics of a single spherical bubble rising in an incompressible power law fluid have been investigated numerically for the 2-D axisymmetric and steady flow over the ranges of conditions as $5 \le Re_{PL} \le 100$, $1 \le Sc \le 1000$ and $0.7 \le n \le 2$. Based on the present numerical results, a simple mass transfer correlation is developed to estimate the value of Sherwood number in a new application. Furthermore, the variation of the local Sherwood number over the surface of the bubble has also been analyzed to delineate the effects of Reynolds number, Schmidt number and power law index (n) on mass transfer from a bubble, thereby showing the extent of mass transfer from the front and the rear parts of the bubble.

Keywords: Reynolds number; Schmidt number; Power law index; Sherwood number; Bubble

1. Introduction

An understanding of mass transfer characteristics together with the hydrodynamics of single bubbles and bubble swarms is required for efficient operation and design of many process equipments in a diverse range of industrial operations such as bubble columns, three phase fluidized bed reactors, food and agro-product processing applications, degassing of polymeric melts, etc. [1]. While one frequently encounters ensembles of bubbles in the above-mentioned operations, experience has shown that an understanding of transport phenomena from an isolated bubble is germane to the successful modeling of ensembles of bubbles. Consequently, some research efforts have been directed at studying the phenomenon of mass transfer from stationary and freely rising single bubbles in Newtonian and non-Newtonian fluids. Since the present study is concerned with the mass transfer from rising bubbles to power law fluids, the pertinent limited literature is reviewed here.

Owing to the non-linearity of the momentum equations, only approximate results are available on mass transfer from a bubble to power law fluids even in the creeping flow regime. Thus, both Hirose and Moo-Young [2] and Bhavaraju et al. [3] presented perturbation solutions which predicted a slight enhancement in mass transfer in mildly shear-thinning liquids, which are in line with the scant experimental results of Moo-Young et al. [4]. These results are

☆ Communicated by A.R. Balakrishnan and S. Jayanti.

* Corresponding author.
E-mail address: chhabra@iitk.ac.in (R.P. Chhabra).

0735-1933/$ - see front matter
doi:10.1016/j.icheatmasstransfer.2007.03.017

applicable at high Peclet number and in the limit of vanishingly small Reynolds numbers. On the other hand, Barnett et al. [5] reported mass transfer from rising CO_2 bubbles in two CMC solutions (n=0.805, 0.842). Similarly, Calderbank et al. [6] reported experimentally measured values of mass transfer coefficient from rising bubbles in an aqueous solution of polyox (n=0.54). The ranges of conditions covered in both these studies are well beyond the creeping flow regime. While no theoretical/numerical studies are available in the literature on mass transfer from bubbles to power law liquids in the intermediate Reynolds number range, a few attempts have been made to study the mass transfer from drops to power law liquids. In the limit of small values of viscosity ratio ($X_E \sim 0$), these studies can be used for the purpose of qualitative predictions. For example, Wellek and Gurkan [7] studied mass transfer from Newtonian drops falling freely in power law liquids ($0.6 \le n \le 1$) in the intermediate Reynolds number range ($5 \le Re_{PL} \le 25$) by using the stream function values presented by Nakano and Tien [8] and Yamaguchi et al. [9]. The ranges of viscosity ratio (X_E) and Peclet number considered in their study extend from 0.01 to 2 and from 100 to 10^6, respectively. However, the numerical results of Nakano and Tien [8] appear to be rather inaccurate [10].

Recently, Feng and Michaelides [10] solved the equations for heat/mass transfer from a bubble rising in a Newtonian fluid by using a finite difference scheme over the range of Reynolds numbers from 1 to 500 and Peclet number from 1 to 1000. Based on their numerical results, they proposed the following correlation for the Nusselt number or Sherwood number for a bubble moving in a Newtonian fluid.

$$Nu = 0.651 Pe^{1/2}\left[1.032 + \frac{0.61Re}{Re+21}\right] + \left[1.6 - \frac{0.61Re}{Re+21}\right] \tag{1}$$

The other pertinent studies relating to mass transfer from bubbles have also been summarized by Feng and Michaelides [10] and Michaelides [11].

From the foregoing discussion, it is evident that very little is known about mass transfer from a bubble rising in power law fluids in the intermediate Reynolds numbers regime, and no prior studies are available for shear-thickening fluids. Therefore, this work aims to provide extensive numerical results on mass transfer from a spherical bubble rising in power law fluids for Reynolds numbers ranging from 5 to 100, Schmidt numbers ranging from 1 to 1000 and power law index varying from 0.7 to 2. Further insights into the mass transfer phenomena are sought by studying the variation of the local Sherwood number on the surface of the bubble for a range of Reynolds number, Schmidt number and power law indices. Based on the numerical results obtained herein, a simple mass transfer correlation is developed which permits the estimation of the value of the Sherwood number in a new application.

2. Problem statement and mathematical formulation

The 2-D axisymmetric steady flow of an incompressible power law fluid with an uniform velocity U_∞ and solute concentration C_∞ past a spherical gas bubble of diameter D placed in an infinite medium is simulated by considering the flow in an artificial tubular domain with a bubble placed symmetrically on the tube axis with slip boundary conditions prescribed on the tube walls, as described elsewhere [12] and shown in Fig. 1.

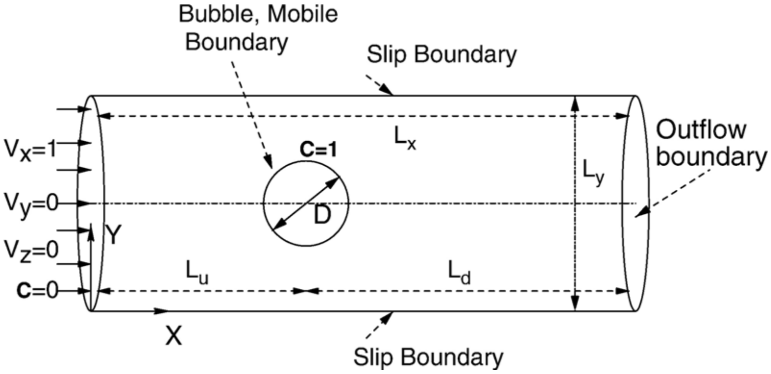

Fig. 1. Schematics of the flow past a spherical bubble.