International Journal of Multiphase Flow 95 (2017) 54–70

Contents lists available at ScienceDirect

International Journal of Multiphase Flow

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

Numerical investigation of different modes of internal circulation in spherical drops: Fluid dynamics and mass/heat transfer

Christopher A. Edelmann*, Patrick C. Le Clercq, Berthold Noll

DLR Stuttgart, Pfaffenwaldring 38-40, 70569 Stuttgart, Germany

ARTICLE INFO

Article history:
Received 7 December 2016
Revised 2 May 2017
Accepted 19 May 2017
Available online 23 May 2017

Keywords:
Drop
Modes of internal circulation
Drag coefficient
Heat/mass transfer
CFD

ABSTRACT

The results of detailed, three-dimensional numerical simulations of fixed spherical drops in a uniform flow are presented. The fluid dynamics outside and inside of the drops as well as the internal problem of mass (or heat) transfer are studied. Liquid drops in both a liquid and a gaseous ambient phase are considered. Special emphasis is put on the investigation of different modes of internal circulation.

At low Reynolds numbers of the inner fluid, the flow field inside the drop resembles the well known Hill's vortex solution. However, at higher internal Reynolds numbers, stable steady or quasi-steady alternative modes of internal circulation are found. As these modes are not cylindrical symmetric around the streamwise axis, the often applied assumption of a two-dimensional, axisymmetric flow field is not justified in these cases. Thus, major discrepancies to previous numerical studies are obtained. However, it is shown that experimental results support our findings.

For liquid drops surrounded by a liquid, a major influence of the state of internal circulation on the drag is discovered, whereas the drag is nearly unaltered in the case of a liquid drop in gas.

Concerning the internal problem of mass/heat transfer, the various internal flow modes show different characteristics. At low internal Peclet numbers, higher Sherwood numbers are reached for the Hill's vortex-like cases, whereas at higher Peclet numbers, the transfer is faster for the alternative modes. For cases with a Hill's vortex-like solution, asymptotic Sherwood numbers for very high Peclet numbers of around 20 are found, whereas no upper limit for cases with alternative modes can be determined. In the present study a maximum internal Sherwood number of 130 is reached, more than six times the maximum value for a case with a Hill's vortex-like internal solution.

1. Introduction

Drops have been studied for a long time in various areas and a vast amount of literature on this topic exists. An introduction as well as a review of work until 1978 can be found in the book by Clift et al. (1978). Wegener et al. (2014) present a more recent review covering the fluid dynamics and the mass transfer of drops in liquid–liquid systems. Concerning the present study, the literature can be divided into two parts. First, studies of the internal motion and its influence on drag, and second studies of the internal problem of heat/mass transfer. As the early theoretical and experimental work is reviewed in Clift et al. (1978) and the internal droplet motion is hardly accessible by experiments, mainly numerical studies are cited. However, one experimental investigation should be mentioned, which is the work by Thorsen et al. (1968) who studied the terminal velocity of liquid drops falling through water. They found that for some substances a sudden increase of terminal velocity occurs at a certain drop diameter and attributed this phenomena to "different states or levels of internal circulation".

Early numerical works covering the motion inside drops include the investigation by LeClair et al. (1972) who were the first to numerically study a water drop in air, Abdel-Alim and Hamielec (1975) who studied liquid drops in a liquid, and Rivkind and Ryskin (1976) who considered arbitrary ratios of inner to outer viscosity (λ) and outer Reynolds numbers of up to $Re = 200$. Oliver and Chung (1987) verified the early numerical results and studied the fluid mechanics in more detail. Feng and Michaelides (2001) used a method to highly resolve the boundary layer outside of the sphere and simulated cases for viscosity ratios between 0 and ∞ and $Re < 1000$. In all above mentioned studies, two-dimensional, axisymmetric simulations were performed. It was found that the internal motion is rather insensitive to the internal Reynolds number

* Corresponding author.
E-mail address: christopher.edelmann@dlr.de (C.A. Edelmann).

http://dx.doi.org/10.1016/j.ijmultiphaseflow.2017.05.005
0301-9322/

List of symbols

Latin letters

C_D	drag coefficient
C_L	lift coefficient
c	concentration
$\tilde{c}$	volume averaged concentration
d	diameter of the drop (sphere)
D	diffusion coefficient
f	frequency
F_D	drag force
F_L	lift force
$\dot{m}'$	normalized mass (heat) flux
Nu	Nusselt number
p	pressure
Pe	Peclet number
Pr	Prandtl number
Re	outer Reynolds number $Re = \frac{U_o d \rho_o}{\mu_o}$
Re_i	inner Reynolds number $Re_i = \frac{U_i d \rho_i}{\mu_i}$
Sh	Sherwood number
St	Strouhal number $St = \frac{fd}{U_o}$
t	time
t'	nondimensional time (Fourier number) $t' = 4\frac{Dt}{d^2}$
U	absolute velocity of the fluid
U_i	governing inner velocity (maximum absolute velocity inside the drop)
U_o	governing outer velocity (inflow velocity)
$\mathbf{v}$	velocity vector

Greek letters

ρ	density
μ	viscosity
λ	viscosity ratio inner to outer fluid
κ	density ratio inner to outer fluid

Subscripts

cf	creeping flow
f	friction (viscous) component
i	inside the drop
o	outside the drop
p	pressure (form) component

Symbols

$\tilde{}$	averaged quantity
∞	asymptotic value in the limit $t \to \infty$

Re_i and resembles in many cases a Hill's vortex (Hill, 1894). For certain cases, e.g. a water drop in air at $Re = 300$, a secondary circular internal motion emerges in the rear part. Furthermore, Feng and Michaelides (2001) stated that the density ratio (κ) of inner to outer density has nearly no influence on drag. Sugioka and Komori (2007) simulated water drops in air with three-dimensional simulations. At $Re = 300$, they found that even for a uniform air flow, the outer as well as the inner flow field are not axisymmetric. They showed that the secondary internal motion, described by LeClair et al. (1972), is only possible because they assume axisymmetry and is nonexistent if simulated with a full three-dimensional method. Engberg and Kenig (2015) numerically investigated the observation made by Wegener et al. (2010) that in their experiments, in some cases, two different rise velocities were found for the same drop diameter. Even though their main objective was the deformation of the drops, they found a non-axisymmetric solution for nearly spherical drops and drew the conclusion that "the widely-used assumption of axial symmetry has to be carefully checked".

As we are mainly interested in the phenomena inside the drop, only the internal problem of heat/mass transfer will be discussed. The internal problem is of importance if the main transfer resistance is located inside the drop. The heat/mass transfer inside the drop is characterized using the internal Nusselt (heat transfer) or Sherwood (mass transfer) number, denoted by Nu and Sh, respectively. As these numbers are used analogously, only the Sherwood number is used in the following.

For the case of pure diffusion inside the drop, Newman (1931) derived an analytical solution and obtained an asymptotic value for $t \to \infty$: $Sh_\infty(Pe = 0) \approx 6.58$, with Pe denoting the Peclet number. Kronig and Brink (1951) assumed creeping flow and very large Peclet numbers inside the drop and thus obtained a solution for $Re \to 0$ and $Pe \to \infty$, which leads to the result $Sh_\infty(Re \to 0, Pe \to \infty) \approx 17.9$. This result can be interpreted as the fact that the "overall heat and mass transfer rate between the droplet interior and the surface is 2.72 times higher than in the case of the solid sphere" (Abramzon and Sirignano, 1989). This approach is called the "effective conductivity model", and mainly concerns the finding of the factor χ by which the sphere thermal conductivity is increased (see Jin and Borman, 1985; Talley and Yao, 1988), usually ranging from $\chi = 1$ ($Sh = 6.58$) to $\chi = 2.72$ ($Sh = 17.9$). However, only creeping flow is assumed in the aforementioned studies. Handlos and Baron (1957) assumed that the streamlines inside the drop can be approximated using the Hill's vortex solution but superimposed turbulent fluctuations, as they considered very high Reynolds numbers. As a result, they obtained a linear relationship of the Sherwood number as a function of the Peclet number. More recently, Paschedag et al. (2005) studied the influence of changes in material properties and operating conditions on the mass transfer and found only small influence of the Reynolds number on mass transfer. Juncu (2010) studied the influence of very high Peclet and moderately high Reynolds numbers on the transfer and stated that $Sh_\infty(Re_i, Pe \to \infty)$ increases with increasing inner Reynolds number. Their highest result obtained was for a liquid drop with $\lambda = 100$, $\kappa = 1000$, yielding $Sh_\infty(Re_i = 1000, Pe = 100{,}000) = 19.85$[1], and exceeding the results from Kronig and Brink (1951) by only approximately 10%. Colombet et al. (2013) studied spherical gas bubbles at moderate Reynolds numbers. They found that the maximum tangential velocity at the bubble surface is the governing parameter for the description of the transfer and were able to show that all results collapse on a single curve if a appropriately normalized asymptotic Sherwood number is plotted as a function of maximum Peclet number $Pe_{\max}$.

For the present study, three-dimensional numerical simulations of fixed spherical drops were performed with the well validated finite-volume code THETA (see e.g. Knopp et al., 2010). The main purpose of the this paper is to show that for physical relevant parameters, solutions inside spherical liquid drops exist, which do not resemble a Hill's vortex. In particular, it presents in which cases this may occur and how the drag and the internal heat/mass transfer are influenced. The paper is structured as follows. Section 2 covers the used model and the governing equations, whereas Section 3 describes the numerical method. In Section 4, the basic validation and the mesh quality are discussed, followed by the main part (Section 5), covering the results and the discussion. The conclusions can be found in Section 6.

2. Model and governing equations

We consider a fixed spherical drop with diameter d, placed in a uniform flow with inflow velocity U_o. The flow fields inside and outside the drop are governed by the unsteady incompressible

[1] Note that they use a different definition for Re_i with $Re_i = Re \cdot \kappa / \lambda$.