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Modeling and simulation of mixing in water-in-oil emulsion flow through a valve-like element using a population balance model

Jovani L. Favero[a], Luiz Fernando L.R. Silva[b], Paulo L.C. Lage[a,*]

[a] Programa de Engenharia Química, COPPE, Universidade Federal do Rio de Janeiro, PO Box 68502, Rio de Janeiro, RJ 21941-972, Brazil[1]
[b] Escola de Química, Universidade Federal do Rio de Janeiro, Rio de Janeiro, RJ 21941-909, Brazil

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ABSTRACT

Emulsion flows are very common in natural processes as well as in several engineering areas, such as in the process of desalting crude oil that occurs in refineries. This kind of flow is described as a polydispersed multiphase flow. In this work, we evaluated the behavior of water-in-oil emulsion flowing through a duct with an element used to mimic the effect of a globe valve. An Eulerian multi-fluid approach was employed by solving the population balance equation coupled with computational fluid dynamics. Coalescence and breakage models recently developed were extended to this inhomogeneous model. A bivariate population balance problem was also solved to demonstrate the mixing caused by the valve-like element. The simulated results showed good agreement with the available experimental data for the Sauter and DeBroukere mean diameters.

1. Introduction

Crude oil is delivered to a refinery as a water-in-oil emulsion that contains many undesirable impurities, like sand and inorganic salts, which lead to erosion and corrosion in process equipment. Therefore, the first step of crude oil refining is a pretreatment known as desalting (Eow and Ghadiri, 2002). Prior to this process, fresh water is added to the water-in-oil emulsion and the flow is passed by a globe valve for mixing (Cunha, 2008). This valve-like element generates droplet breakage and coalescence in order to promote an adequate mixing of the salty production water and the washing water. This process is a typical example of a polydisperse multiphase flow.

Polydisperse multiphase flows are of great importance not only in the case of emulsion flow, but also in several other equipment found in chemical engineering, as in, extraction columns, cyclones, hydrocyclones, bubble columns and multiphase stirred tank reactors to cite just a few (Ramkrishna, 2000; Marchisio and Fox, 2013). These kind of flows are characterized by one or more phases that are dispersed, as bubbles, droplets or particles, in a continuous one (Drew and Passman, 1998; Ishii and Hibiki, 2006; Crowe et al., 1998).

Despite the large number of works published in the literature over the last decades (for example, Sokolichin and Eigenberger, 1994; Jakobsen et al., 1997; Pfleger et al., 1999; Buwa and Ranade, 2002; Hjertager, 2007, to cite just a few), polydispersed multiphase flows are still subject of intense research and, due to their complexities, its modeling is not too consolidated as that for single-phase flows. In this perspective, the use of computational fluid dynamics (CFD) to solve an Eulerian multi-fluid model coupled with a population balance model (PBM) has shown to be an efficient tool to simulate polydisperse multiphase flow (Chen et al., 2005; Zucca et al., 2006; Silva et al., 2008; Petitti et al., 2010, 2013; Passalacqua et al., 2010; Silva and Lage, 2011; Yan et al., 2011; Buffo et al., 2012, 2013a). Recently, Marchisio and Fox (2013) showed that this formulation can be deduced directly from the so-called generalized population balance equation (GPBE) that is basically the conservation equation for the particle number density including its dependence on all particle and fluid variables that may affect the particulate system behavior.

The development of models to represent the particle–particle interactions, like breakage and coalescence, in polydisperse multiphase flows is a subject of intense research. Several models were proposed in the literature to take into account different multiphase systems as well as to improve the agreement between the simulation results and experimental data. Despite of that, there is still a lack of models that are sufficiently generic and useful to be applied to actual processes found in industry. It is not the scope of this work to discuss in details these models, since there are several reviews in

* Corresponding author. Tel.: +55 21 2562 8346; fax: +55 21 2562 8300.
E-mail address: paulo@peq.coppe.ufrj.br (P.L.C. Lage).
[1] www.peq.coppe.ufrj.br

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Nomenclature

a	aggregation frequency
b	breakage frequency
C	dimensionless mass concentration
Ca	capillary number
C_μ	$k-\epsilon$ model constant
d	droplet diameter
D	droplet dispersion coefficient
f	droplet number distribution function
F	advective moment flux
$\mathbf{F}$	inter-phase momentum exchange
$\mathbf{g}$	gravity acceleration
h	number of internal variables
h_f	critical thickness of the film between coalescing droplets
H	PBE source term
k	turbulent kinetic energy
L_a	channel width
m	mass of one component
m_p	moment power factor
M	moment
n_i	moment order regarding x_i
$\mathbf{n}$	multivariate moment order
$\hat{\mathbf{n}}$	surface normal vector
N	number of dispersed phases and quadrature points
p	pressure
P	conditional daughter particle probability density function in the breakage process
Q	volumetric flow rate
r	phase fraction
r_d	total dispersed phase fraction
Re	Reynolds number
s	number of moments needed to an N-point quadrature in the h-dimensional space
$\mathbf{S}_f$	face area vector
Sc	Schmidt number
St_K	Stokes number based on the Kolmogorov time scale
t	time
$\mathbf{u}$	velocity
$\mathbf{u}_m$	mean mixture velocity, $\mathbf{u}_m = (1-r_d)\mathbf{u}_0 + \sum_{\alpha=1}^{N} r_\alpha \mathbf{u}_\alpha$
v	droplet volume
V_c	effective volume of valve-like element
w	weights
x	abscissas
$\mathbf{x}$	particle properties or internal variables
$\mathbf{y}$	continuous phase variables
$\mathbf{z}$	physical space coordinates or external variables

Greek letters

α, β	phase indexes
δ	Dirac delta function
ϵ	rate of dissipation of turbulent kinetic energy
η	Kolmogorov length scale
θ	collision frequency
ϑ	mean number of droplets formed by a breakage event
λ	coalescence efficiency
μ	dynamic viscosity
ν	kinematic viscosity
ρ	density
σ	surface tension
$\boldsymbol{\tau}$	stress tensor

Subscripts

0	related to the continuous phase
α	related to phase α
crit	critical
d	related to the sum of all dispersed phases
eq	equivalent
I	related to the interface
m	related to the mixture
max	maximum
res	residence

Superscripts

eff	effective
l	laminar
t	turbulent

Abbreviations

CFD	computational fluid dynamics
CQMoM	conditional quadrature method of moments
DQMoM	direct quadrature method of moments
DQMoM-FC	direct quadrature method of moments – fully conservative
LES	Large Eddy Simulation
LU	lower–upper decomposition
MoC	method of classes
MoM	method of moments
OpenFOAM	open source field operation and manipulation
PB	population balance
PBE	population balance equation
PDF	particle distribution function
QBMM	quadrature based moment method
QMoM	quadrature method of moments
RANS	Reynolds-Averaged Navier-Stokes
SVD	singular value decomposition
WRM	weighted residuals method

the literature on this subject (Chesters, 1991; Lasheras et al., 2002; Liao and Lucas, 2009, 2010; Solsvik et al., 2013).

A great query around polydisperse multiphase flow simulation is to choose the method for solving the population balance equation (PBE). There are different numerical approaches, for example, Monte Carlo stochastic methods (Meimaroglou and Kiparissides, 2007; Irizarry, 2008), weighted residuals methods (WRM) (Subramanianand and Ramkrishna, 1971; Hulburt and Akiyama, 1969; Dorao and Jakobsen, 2006; Solsvik and Jakobsen, 2013), methods of classes (MoC) (Lister et al., 1995; Kumar and Ramkrishna, 1996) and methods of moments (MoM) (McGraw, 1997; Marchisio and Fox, 2005; Lage, 2011; Favero and Lage, 2012; Yuan et al., 2012; Petitti et al., 2013). However, there is no method that is accurate, efficient and robust at the same time for the general solution of the PBE.

Due to their easy application, reasonable accuracy and computational cost, the moment methods are preferable to couple the population balance with CFD codes (Wang et al., 2006; Zucca et al., 2006; Silva and Lage, 2011; Yan et al., 2011; Buffo et al., 2012). These methods solve for a selected set of lower order moments of the particle distribution function (PDF). A drawback of the standard moment method is that the obtained system of equations is unclosed (Hulburt and Katz, 1964). This problem was contoured by the quadrature based moment methods (QBMM) which uses an N-point Gaussian quadrature approximation closure whose weight function is the PDF (McGraw, 1997). The so-called Gauss-Christoffel quadrature is calculated from the moments of