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A numerical study of cutting bubbles with a wire mesh

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HIGHLIGHTS

- A novel combined Volume of Fluid Immersed Boundary method is presented.
- The combined method is used to numerically study bubble cutting by a wire mesh.
- Bubbles with Eotvos > 4 can squeeze through the wire mesh.
- Bubbles with Eotvos > 15 are cut by the wire mesh.

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ABSTRACT

Gas-liquid-solid flows are frequently encountered in chemical, petrochemical and biochemical industries. To overcome the heat and mass transfer limitations in trickle bed reactors and bubble slurry columns, respectively, a micro-structured bubble column (MSBC) can serve as an attractive alternative. In a MSBC, wire meshes are introduced to cut the bubbles in smaller bubbles and enhance the surface renewal (and hence gas-liquid mass transfer) rates, by deformation of the bubbles. Earlier (Jain et al., 2013) modeling efforts using the Euler-Lagrange approach to simulate a micro-structured bubble column employed a bubble cutting closure based on purely geometrical considerations. To improve on this ad hoc procedure in this paper we explore the possibilities of Direct Numerical Simulations to gain more insight in this complex phenomenon with the ultimate aim to develop improved closures.

A combined Volume of Fluid-Immersed Boundary method was applied to simulate the interactions between bubbles and wire meshes. When the bubbles are aligned with the opening of the wire mesh, cutting of the bubbles is not observed in our simulations, while cutting was expected based solely on geometrical considerations. When the Eötvös number, Eo, is larger than 4, the bubbles are highly deformable and squeeze themselves through the opening of the wire mesh. In addition, the bubble gets stuck underneath the mesh when the bubbles are small ($Eo \leqslant 4$) and/or the opening is in the wire mesh is small. Almost all bubbles that hit the intersection of two crossing wires get stuck underneath the mesh, except for large bubbles ($Eo = 15$), which get cut by the mesh. Based on these results, it is concluded that the cutting of bubbles depends on the Eötvös number, the opening of the wire mesh and geometrical considerations. However, the results also seem to indicate that the diameter of the wire mesh will also influence the cutting behavior.

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1. Introduction

Gas-liquid-solid flows are frequently encountered in chemical, petrochemical and biochemical processes. Generally, the solid phase acts as a catalyst to convert the gaseous reactants into liquid products. These processes are mainly performed in trickle bed reactors and bubble slurry columns, which experience heat transfer limitations and mass transfer limitations respectively.

Along the height of bubble (slurry) columns, the specific gas-liquid interfacial area is typically reduced due to coalescence, which limits the mass transfer rate. This will consequently reduce the overall mass transfer rate between gas and the liquid phase. To overcome these limitations, a wire mesh can be inserted into the column to cut the large bubbles. Besides cutting the bubbles, the interaction between the wire mesh and the bubbles will also enhance the interface dynamics resulting in a higher surface renewal rate and consequently higher mass transfer coefficients. The enhancement of surface renewal rate occurs at the desired

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Nomenclature

Roman symbols

d	diameter (m)
F	phase fraction
$\mathbf{F}$	force density (N/m^3)
$\mathbf{g}$	gravity constant (m/s^2)
$\mathbf{n}$	normal
p	pressure (Pa)
t	time (s)
$\mathbf{t}$	tangent
$\mathbf{u}$	liquid, fluid velocity (m/s)
V	volume (m^3)

Greek symbols

μ	viscosity (Pa·s)
ρ	density (kg/m^3)
σ	surface tension coefficient (N/m)
$\boldsymbol{\tau}$	stress tensor
ψ	velocity component (m/s)

Abbreviations and subscripts

b	bubble
c	central
DNS	Direct Numerical Simulations
g	gas phase
IB	Immersed Boundary
l	liquid phase
nb	neighboring
m	marker
Mo	Morton number
Eo	Eötvös number
Re	Reynolds number
s	solid phase
VoF	Volume of Fluid
w	wire
σ	surface tension

position in case the wire mesh is coated with a catalyst (Höller et al., 2001; Prasser et al., 2001; Ito et al., 2011). Höller et al. (2001) showed that by implementing a similar approach a 10 times higher gas-liquid mass transfer coefficient was obtained in comparison to a bubble column without internals. However, the exact mechanism of break-up and the hydrodynamic interaction with the wire mesh is largely unknown.

1.1. Multi-scale modeling

To improve our understanding of Micro Structured Bubble Columns detailed models based on the general micro-balances can be used. In this context, it should be bared in mind that the multiphase flow in bubble columns in general and the Micro Structured Bubble Columns in particular is actually a complex multi-scale phenomenon. Consequently we adapt a multi-scale modeling approach to simulate the transport phenomena at different scales of interest.

For the large scale motion Euler-Euler model are preferred to simulate bench scale bubble columns by representing the gas-liquid system as interpenetrating fluids. Due to this treatment, the Euler-Euler model requires closures for the interactions between the phases. Euler-Lagrange models are able to describe a lab-scale column by treating all the dispersed phases as Lagrangian particles. However, closures are required for all phase interactions, i.e. bubble-bubble, bubble-liquid, wire mesh-bubble and wire mesh-liquid interactions. The smallest scale models are the Direct Numerical Simulations (DNS), which describe the multiphase flows without any rigorous a priori assumptions. Because the grid spacing in DNS simulations needs to be much smaller than the immersed objects and the bubbles, the number of objects that can be accounted for is limited.

In the multi-scale modeling approach, the Euler-Euler and the Euler-Lagrangian models need closures for the interactions between the bubbles and the wire mesh. Jain et al. (2013) proposed a closure purely based on geometrical considerations. In this work, Direct Numerical Simulation (DNS) will be used to study these bubble-wire mesh interaction to gain insight in the very complex process of the bubble-wire interaction, which can be used in the coarser-grained models.

1.2. Objectives

Several researchers already developed three-phase DNS methods by combining and extending available two-phase methods. Li et al. (2001) combined the Euler-Lagrangian and the DNS approach to model three-phase flows. Because this approach models the particles as point particles, closures for the solid-fluid interactions are still required to accurately model the three phase flows. Deen et al. (2009) and Baltussen et al. (2013) combined a Front Tracking method and an Immersed Boundary (IB) method to obtain a DNS method for gas-liquid-solid flows. The advantage of the method is that there is no artificial coalescence in the Front Tracking method, instead coalescence and break-up of bubbles can only be included via a sub-grid model. Moreover the method is not inherently mass conservative. Ge and Fan (2006), Jain et al. (2012) and Baltussen et al. (2017) combined an IB method with a front capturing method. The advantage of this combination is the inherent ability of simulating coalescence and break-up in the model. However, we note that in cases of a too coarse grid the model can predict non-physical (numerical) coalescence and break-up. When the Volume of Fluid (VoF) method is used, another advantage arises because the method is strictly volume conservative (Jain et al., 2012; Baltussen et al., 2017).

Because of the volume conservative nature of the VoF method and the expected complex topological changes, this work combines the Volume of Fluid method with the second order implicit IB method of Deen et al. (2012). The advantage of this Immersed Boundary method is that the method does not require a calibration through an effective diameter of the wire mesh. Moreover, due to the second order nature of the method accurate results can be obtained at relatively low resolution.

In this work, the interactions with a square wire mesh will be studied. We will first discuss the applied numerical method. Subsequently, the interactions between a single bubble and a wire mesh will be studied for two limiting cases: (i) a bubble hitting the center of an opening in the wire mesh, and (ii) a bubble hitting the intersection of two wires in the mesh.

2. Numerical model

The interactions of a single bubble with a wire mesh were studied earlier using a DNS model that has been developed

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