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Modeling of droplet–droplet interaction phenomena in gas–liquid systems for natural gas processing

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ABSTRACT

The design of efficient gas liquid separation units for natural gas production lines depends on the accurate estimation of the droplet size distribution. The droplet size can be estimated by considering breakage and coalescence phenomena. In particular, off-shore separation units working at high pressure (100–200 bar) require special consideration of coalescence processes with multiple outcomes. This work discusses the introduction of multiple outcomes in the coalescence process. Numerical experiments are presented in order to highlight the effect of multiple coalescence behavior in the evolution of the droplet size distribution.

1. Introduction

Gas liquid separation units play an important role in natural gas production lines because they may prevent breakdown of expanders, compressors and turbines, hydrate formation, and keep water or hydrocarbon dew point within sales gas or transport specifications, etc. A gas liquid separation unit, as a scrubber, most often consists of a vertical vessel with different internals or separation modules installed in series or in parallel, Fig. 1. The typical internals are the following: An inlet section pipe to distribute the flow uniformly in the scrubbers. Above the inlet arrangement, a removal or coalescing section is often installed consisting of a mesh pad or a vane pack. The mesh pad consists of layers of knitted wires while the vane packs consists of plates that are formed in a zigzag pattern. The final section of the scrubber normally consists of a battery of axial cyclones.

In traditional production processes scrubbers are installed on-shore in safe and stable areas. During the last years an increased interest in sub-sea separation facilities in remote and small off-shore gas fields has been observed (Devegowda, 2003; Austrheim, 2006; Helsør, 2006). A particular aim is to enhance the efficiency of the sub-sea separation process and decrease the amount of water to be transported to the consumers. The estimation of the droplet size distributions development inside the separator plays a major role in designing and optimizing separation units.

The separation process is enhanced by coalescence as the bigger the liquid particle, the easier the separation is. Detailed experimental studies have been reported in the literature enabling the construction of so-called coalescence maps giving the outcome of droplet/droplet collisions. It is important to mention that coalescence is commonly implying the formation of one droplet due to the collision of two or more droplet. However, here the coalescence term is used wider and includes also the possibility of formation of multiple droplets when the new droplet breaks immediately after formation. This complex processes can be described by using the mentioned coalescence maps. These maps are defined in terms of plots of the impact parameter (B) as a function of the Weber number. The Weber number (We) and impact parameter (B) are defined as

$$We = \frac{2R\rho U^2}{\sigma} \tag{1}$$

$$B = \frac{\lambda}{2R} \tag{2}$$

with R being the droplet radius, U the relative velocity, λ the projection of the separation distance between the droplet centers in the direction normal to that of U, and ρ and σ the density and surface tension of the liquid and the gas–liquid interface, respectively. Thus, $B = 0$ designates head-on collisions while $B = 1$ designates grazing collisions. Fig. 2 shows as an example a schematic representation of the various collision regimes of hydrocarbon droplets at 1 atm in

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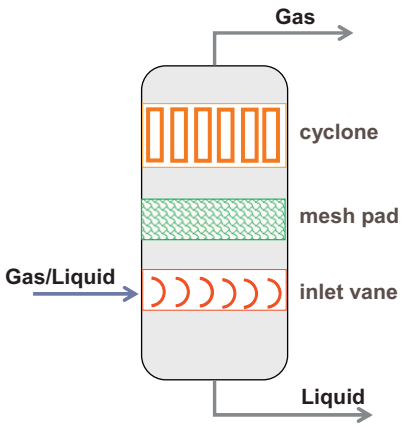

Fig. 1. Sketch of a separation unit.

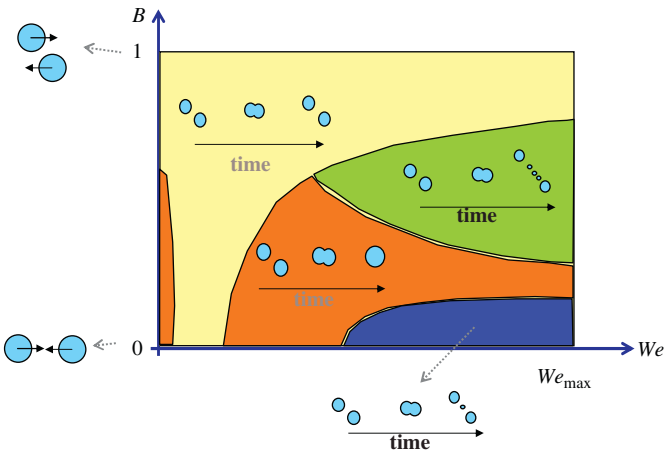

Fig. 2. Schematic of various collision regimes of hydrocarbon droplets in 1 atm air (Qian and Law, 1997).

air (Qian and Law, 1997). As seen, the outcome of binary collisions is not limited to the case of the formation of a single new droplet by coalescence. Instead multiple outcomes can be observed which constitute a severe modeling problem.

An overview of the droplet–droplet interaction phenomena can be found in Orme (1997), Simon and Bart (2002). Ashgriz and Poo (1990) presented results of the coalescence process for water drops, Qian and Law (1997) discussed the coalescence process for fuel drops and Gotaas (2007) presented measurements for *n*-decane, monoethyleneglycol (MEG), diethyleneglycol (DEG) and triethyleneglycol (TEG), to mention some examples found in the literate. The coalescence process can also involve two droplets of different liquids (Chen and Chen, 2006; Gao et al., 2005). In general the coalescence maps are related to two droplet of similar size, the difference in the size can be introduced by including an extra dimension representing the droplet size ratio (Post and Abraham, 2002). The coalescence outcomes after the breaking of the new droplet was discussed by Brenn et al. (2001) and Brenn and Kolobaric (2006).

The simulation of dispersed systems and in particular liquid–gas system and sprays is still a challenging area of research (Gouesbet and Berlemont, 1998; Nijdam et al., 2004; Guo et al., 2004). In particular, the high computational cost required for describing the behavior of the dispersed phase can be reduced by using a statistical approach using a Boltzmann-type equation also referred to as a population balance equation (Reyes, 1989; Laurent et al., 2004). Population balance modeling (PBM) is a well established method for describing the evolution of populations of entities such as bubbles, droplets or particles.

The main goal of this work is to discuss the modeling of the coalescence process including multiple outcomes within a population balance framework. Numerical examples are presented showing the effect in the density function by including multiple outcomes in the coalescence operator.

In Section 2, the population balance equation is presented and the introduction of secondary breakage is discussed. Section 3 discusses how to incorporate the information of the coalescence maps in the modeling of the coalescence and droplet formation rate. Section 4 presents a few numerical examples in order to highlight the effects of including multiple collision outcomes. Finally, Section 5 presents the main conclusions drawn from this work.

2. Population balance equation

Based on the population balance approach the dispersed phase is described by a density function for instance $f(\mathbf{r}, \xi, t)$ where $\mathbf{r}$ is the spatial vector position, ξ is the dispersed phase property of interest, and t the time. Thus, the density function $f(\mathbf{r}, \xi, t)\,\mathrm{d}\xi$, can represent the average number of particles per unit volume around the point $\mathbf{r}$ at the instant t with the property between ξ and $\xi + \mathrm{d}\xi$. On the other hand, the density function f can present any property of interest. For example $f(\mathbf{r}, \xi, t)\,\mathrm{d}\xi$ can represent the mass of liquid contained in droplets with the property between ξ and $\xi + \mathrm{d}\xi$ per unit volume around the point $\mathbf{r}$ at the instant t. The evolution of this density function must take into account the different processes that control the density function such as breakage, coalescence, growth and advective transport of the particles. The resulting equation is a non-linear partial integro-differential equation to be solved by a suitable numerical method.

The population balance equation considering one property and time can be written as

$$\mathscr{L} f(\xi, t) = g(\xi, t) \quad \text{in } \Omega \tag{3}$$

$$\mathscr{B}_0 f(\xi, t) = f_0(\xi) \quad \text{on } \Gamma_0 \tag{4}$$

with $\Omega = [\xi_{\min}, \xi_{\max}] \times [0, T]$ where $\xi_{\min}$ and $\xi_{\max}$ are for instance the minimum and maximum particle sizes, and T the final simulation time. The right-hand side (RHS) of Eq. (3) is a source or sink term, representing the external mechanism of adding or removing particles from the system. Eq. (4) contains the initial condition $f_0(\xi)$ of the problem which is applied on $\Gamma_0 = \{(\xi, t) \in \partial\Omega : t = 0\}$ and where $\mathscr{B}_0$ is the identity operator, i.e. $\mathscr{B}_0 f(\xi, t) = f(\xi, t)$.

The operator $\mathscr{L}$ is a non-linear first order partial integro-differential operator defined as

$$\mathscr{L} f(\xi, t) \equiv \frac{\partial f(\xi, t)}{\partial t} + \mathscr{L}_c f(\xi, t) \tag{5}$$

where $\mathscr{L}_c f(\xi, t)$ is the coalescence operator. Normally, the coalescence operator is defined as

$$\mathscr{L}_c f(\xi, t) = f(\xi, t) \int_{\xi_{\min}}^{\xi_{\max} + \xi_{\min} - \xi} c(\xi, s) f(s, t)\,\mathrm{d}s - \int_{\xi_{\min}}^{\xi} c(\xi - s, s) f(\xi - s, t) f(s, t)\,\mathrm{d}s \tag{6}$$

The first term on the RHS of Eq. (6) represents the change in the population due to the loss of droplets by pair interaction processes such as coalescence. Thus, $c(\xi, s)$ is the *coalescence rate* between particles of type ξ and s. It is important to note that the upper limit of the integral is defined such that the coalescence process cannot produce particles exceeding the maximum physical allowable size