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Fluid Dynamics and Transport Phenomena

# Experimental evaluation and modeling of liquid jet penetration to estimate droplet size in a three-phase riser reactor

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In this work, the effects of injecting an evaporating liquid jet into solid–gas flow are experimentally investigated. A new model (SHED model) and a supplementary model (spray model) have also been proposed to investigate some flow-field characteristics in three-phase fluidized bed with the mean relative error 4.3% between model and measured results. Some experiments were conducted to study the influences of flow-field parameters such as liquid volumetric flow rate, injection velocity, jet angle and gas superficial velocity as well as solid mass flux on the jet penetration depth (JPD). In addition, independent variables were experimentally employed to propose two empirical correlations for JPD by using multiple regression method and spray cone angle (SCA) by using dimensional analysis technique. The mean relative errors between the JPD and SCA correlations *versus* experimental data were 7.5% and 3.9%, respectively. In addition, in order to identify the variable effect, a parametric study was carried out. Applying the proposed model can avoid direct use of expensive devices to measure JPD and to predict droplet size.



## 1. Introduction

High efficiency liquid jet spray has considerable practical applications. Spray hydrodynamics due to injection of an evaporative liquid jet play an important role to the quality of multiphase flows. Sprayed liquid jets are frequently used in various fields comprising evaporative cooling, gasification, internal combustion engines, space rockets, boilers, industrial furnaces and gas turbines in order to increase the rates of heat and mass transfer [1]. Fluid catalytic cracking (FCC) converts heavier petroleum fractions into valuable products such as gasoline and light olefins. The liquid feedstock is injected into a stream of hot catalytic particles, where it vaporizes and cracks into lower molecular weight products [2]. A kinetic model for the FCC reactor was established and model parameters were estimated by plant data [3]. The formation of clusters and accumulation of particles near the wall in dense gas–solid flows are inevitable. Liu and Guo found out that a cluster grows up by capturing the particles in the dilute phase due to its lower vertical velocity [4]. Also, Wang and Guo investigated effects of the cluster porosity, inlet gas velocity and temperature, and coke deposition on cracking reactions of the cluster in FCC riser reactors [5].

In many studies, having a droplet mean diameter such as Sauter mean diameter (SMD) is as important as droplet size distribution [6]. Although, there is a vast literature on this subject, many studies have also been accomplished to understand the nature of sprays and their effective parameters. However, few studies have been reported on experimental estimation of indirect determination of droplet size, using spray pattern visualization, specifically, in a three-phase fluidized bed.

Practical and numerical approaches are used to predict droplet size. Sellens and Brzustowski [7] and Li and Tankin [8] have independently established two models based on maximum entropy method for predicting droplet size distribution. In addition, other researchers applied this method [9–14]. In another work, Aguilar *et al.* theoretically and experimentally investigated SMD and vaporization rate in cryogenic sprays [15]. Sun *et al.* provided a pragmatic guide to determine the influencing factors for achieving an optimized mixing of a jet spray in a confined cross-flow, but along this line, conducting a cold model experiment become necessary [16]. In another study, Li *et al.* assumed the droplet size distribution follow the normal distribution that may be divided even into 11 groups of sizes [17]. Another method was proposed by Sivathanu and Gore [18]. Their method is among discrete probability function, which divides the spray formation process into deterministic and non-deterministic portions. Sovani *et al.* investigated droplet size distribution in Newtonian sprays [19,20]. Li *et al.* proposed a numerical model for water spray injecting through a hollow cone spray nozzle [21] to investigate the effects of droplet size, bed temperature and spray angle.

Several single droplet vaporization analytical and numerical studies have appeared in the literature [11,14,18–20]. Iyer *et al.* have developed a model to study two-fluid Diesel sprays [22]. Bossard and Peck investigated experimentally the droplet size distribution effects on the ethanol spray applying a horizontal flame jet [23]. They held the SMD and fuel–

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air ratio fixed and observed that flame structure, burning rate and gas emissions were strongly affected by droplet size. Hayashi *et al.* investigated the effects of droplet size distribution and SMD of fuel spray on the soot formation [24,25]. They used a phase-Doppler anemometer for experiment and conducted 3D direct numerical simulation (DNS). Dynamics of vaporization has been investigated by Deepu *et al.* in a hot laminar air jet [26].

Yokota and Matsuoka [27] and Hiroyasu and Arai [28] derived two correlations using their experimental data to calculate angles of spreading of spray at various amounts of high pressure ambient air. Ohrn *et al.* used 40 different plain-orifice atomizers to examine the effects of nozzle geometry and flow conditions on spray cone angle [29]. The main result of their study is the spray cone angle variations with injection pressure in various internal geometries of the atomizers [30].

There are approximately 400 FCC units including 1.9 million metric ton per day, constituting more than 17% of the total oil refining capacity [31]. The droplet size and spray penetration length (SPL, the distance from injection nozzle to jet nose) are the most important parameters to calculate vaporization time [32]. Nozzle geometry has a drastic impact on the bed hydrodynamics at the zone close to the atomizer.

The most efficient models to interpret atomization are Taylor analogy breakup (TAB) and the enhanced-TAB (E-TAB). An alternative to TAB model has been developed by Reitz, named the WAVE breakup model, which considers the breakup of the injected liquid due to the relative velocity between the liquid and other phases [33]. The model assumes that the time of breakup and the drop size are related to the Kelvin–Helmholtz instability developed in the jet. In either the long-wave or the short-wave case, drop breakup and alteration of the distinct droplets are assumed to behave according to the Weber analysis. During breakup, the diameter of drops obeys the most probable drop size based on the Rosin–Rammler distribution. In addition, droplet properties have an intrinsic dependence on the Ohnesorge number [34–36].

During recent years, phase-Doppler anemometry (PDA) and laser-Doppler anemometry (LDA) were employed for various purposes in practical studies [37]. Bhowmick *et al.* measured differential-pressure fluctuation across a fluidized bed *via* a monitoring technique [38]. Lefebvre and Sridhara carried out the first fundamental survey of penetration of multiple jet configurations [39,40]. This fact that penetration length of multiple jets in a circular duct was lower than single jet was reported by Sridhara [40]. Due to complicated hydrodynamics of the flow in the circulating fluidized bed (CFB), comprehensive reports focused on description of interactions between the phases are insufficient.

The present work establishes several cold experiments and evaluates some variables affecting on hydrodynamics of a three phase fluidized bed due to spray of liquid species. Two models that take into account heterogeneous vaporization of the liquid drop are proposed. This paper presents a method to estimate the jet penetration depth and the size of evaporating droplets flowing through the riser, both numerically and experimentally. The measured values of JPD are considered as a criterion to assess the model predictions. Moreover, drop size is determined when predicted JPD value becomes equal to the measured JPD. Applying the proposed procedure has some tangible benefits and can avoid the need to conduct further expensive measurements. Furthermore, two empirical correlations are derived to calculate both JPD and SCA, respectively.

## 2. Model description

Complicated nature of multiphase flows and the difficulties to solve their mathematical equations prevent to propose a universal model to evaluate the parameters affecting characterizations of multiphase flow in fluidized beds. In this study, hydrodynamic aspects of a three-phase fluidized bed and phase interactions in the riser reactors are evaluated *via* developing a competent model. Here, the liquid species behavior is interpreted based on mutual interactions between gas–solid flow and an evaporating droplet by the proposed model. The evaporating liquid droplet consisting several layers encounters with fluidized phase (air) and hot solid particles, so that a heterogeneous vaporization occurs. Developing the present model that is named SHED (single heterogeneous evaporating droplet) model can be profitable for determining a computational JPD *via* simulation (comparable with the experimental JPD) and consequently, predicting droplet size in any riser height.

As shown in Fig. 1, each layer of a spherical drop is considered to be uniform while mass and heat transfer occur at the outer layer. Temperature gradient in interior layers of liquid species is uniform and the liquid drop outer surface never changes. The net mass transfer between the outer layers and gaseous media is equal to the mass loss due to evaporation.

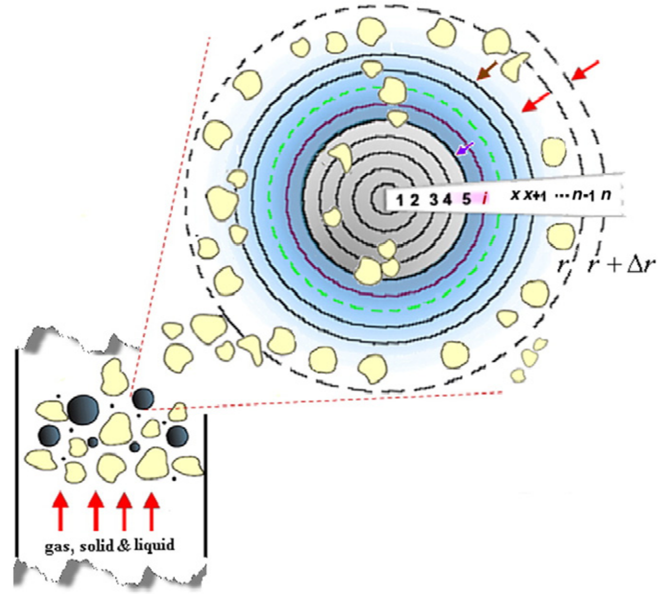


**Fig. 1.** Schematic view of a single heterogeneous evaporating liquid droplet for introducing the SHED model.

Some assumptions in this model are listed:

- Particle-laden flow due to substantial existence of solid particles
- The riser temperature is constant during fluidization
- The drop is covered by the hot solid particles
- Energy is received *via* hot solid particles
- Heterogeneous evaporation due to existence of the solids
- The droplet surface temperature is invariant during evaporating
- Binary diffusion with unity Lewis number in the gas phase.

Spraying the droplets onto a dense environment of catalyst particles does not always provide proper heat transfer. The best way of ensuring fast vaporization of oil droplets in FCC risers is to spray the droplets onto a stream of solid particles phase with a voidage ranging between 70% and 90% [2,39]. The vacuum gas oil (VGO) is dispersed into the riser bottom in the form of drops through a feed nozzle system. The liquid drops contact hot regenerated catalyst particles and are vaporized. The vapor entrains the catalyst particles and catalytic cracking in gaseous phase carried out. In this study, the mean effective diameter of drops (about 200 to 400 μm) is much greater than the solid particle diameter (95 μm) flowing through the riser reactor. Therefore, it is assumed that the drop is surrounded by the solid particles.

Based on this fact, in the flow field, it is considered because of solid particle-laden flow, a great number of particles are located around a vaporizing droplet, so that the droplets are mainly covered by the solid