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Characterization of liquid entrainment in a counter flowing gas using Phase Doppler Interferometry

B. King[a], T. Cai[b], M. Resetarits[b], K. McCarley[b], R. Whiteley[a], Y. Tamhankar[a], C.P. Aichele[a],*

[a] *School of Chemical Engineering, Oklahoma State University, 420 Engineering North, Stillwater, OK 74078, USA*
[b] *Fractionation Research Incorporated, 424 S. Squire St., Suite 200, Stillwater, OK 74074, USA*

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ABSTRACT

An 8 inch ID spray column was used to characterize the entrainment of water droplets into counter flowing air. The ability of Phase Doppler Interferometry (PDI) to measure the size and velocity distributions of entrained droplets resulting from a single full cone Bete® nozzle was proven, and the total volume of liquid entrained was gravimetrically quantified. The experimental setup consisted of a variable speed pump and air blower which allowed for droplet measurements over a range of gas and liquid rates. This work illustrates the effect of nozzle supply pressure and air rate on the entrainment rates and PDI measured droplet size distributions. The magnitude of the droplet size distribution, as well as the rate of entrainment, increased with the liquid spray rate, but the unimodal distribution peak diameter remained consistent. The same conclusion was true at an increased gas rate, in addition to an overall decrease in entrained droplet Sauter mean diameter and an increase in the total liquid entrained. The use of a theoretical entrainment model with PDI measured droplet diameters was explored. Applying the measured PDI diameters was found to significantly decrease the estimated entrainment from the theoretical entrainment based on a droplet buoyancy concept. This effect was further explored by comparing the sizing of a de-entrainment mesh pad for both cases.

1. Introduction

Spray nozzles are commonly used in the chemical, petrochemical, and refining industries as a reliable method to distribute liquid droplets over a surface or into an open contacting column. In such applications, the existence of entrained liquid droplets can be detrimental to equipment operating performance, downstream equipment, and can result in corrosion or fouling issues.

Entrainment elimination devices, such as Chevron and wire mesh types, are often incorporated into the design of equipment where operating conditions are expected to promote entrainment (Monat et al., 1986; Setekleiv and Svendsen, 2011). To properly design and use an entrainment elimination device, it is common to estimate the rate of entrainment as well as the entrained droplet size and velocity distributions (AMACS, 2017). This potentially leads to the overdesign of entrainment elimination devices and a need for empirical entrainment data. The lack of entrained drop size distribution and relative entrainment rate data are due, in part, to a need for a convenient method to measure entrained droplets without obscuring the measured system. To address this need, utilizing a point source optical measuring device, such as Phase Doppler Interferometry (PDI), provides an ideal method to measure and characterize entrained droplets, since it provides a direct and physically unobscured measurement of a droplets size and velocity.

Entrained droplets from a spray exist as a range or distribution of droplet sizes, and vary with the gas and liquid rates of the system. The goal of the current work is to characterize these effects by using PDI to measure the droplet size and velocity distributions of liquid entrainment from a spray nozzle in the presence of counter flowing air at multiple radial locations within a column. This will allow an entrain-

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* *Corresponding author.*
E-mail address: clint.aichele@okstate.edu (C.P. Aichele).

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ment elimination device to be designed and evaluated in two cases: (1) using estimated/theoretical drop diameter, and (2) using PDI measured drop diameter. Volumetric entrainment rates are also measured by capturing the entrained liquid. This is done in an open contacting column at multiple L/G ratios.

2. Background

Measuring entrainment from a spray without disturbing the experimental system has proven difficult. Lin et al. (1997) studied the entrainment rates from two Bete Fog Nozzle Inc. nozzles and a Koch-Glitsch Inc. nozzle. The results of their work showed that the largest angle nozzle – 120° – produced the largest entrainment rates. Trompiz and Fair (2000) expanded on that work with the same nozzles and developed a model for estimating liquid entrainment in a packed column. Although their model utilizes a drop buoyancy model with reliable estimations and reasonable experimental agreement, it does not account for secondary effects on entrained drop size, and relies on estimated droplet sizes. Utilizing the true entrained droplet size and velocity distribution would inherently include those effects, and the accuracy of such a model could be improved by arriving at simplifying assumptions, as Wicks and Dulker (1960) noted while measuring co-current entrainment for an air–water system. Further, the applicability in a variety of operating conditions and systems could be expanded.

The size and velocity distributions of droplets in the presence of a flowing gas is particularly important to entrainment characterization. Early work by Souders and Brown (1934) detailed the quantification of entrainment and plate efficiency in a fractionation column through a theoretical method relating vapor velocity to the quantity of entrainment. Although the equation presented in their work included a droplet diameter parameter, it was considered a constant value rather than an independent variable or a distribution of sizes. Their study also introduced an equation for the suspending velocity of droplets.

A force balance of a suspended spherical droplet relates the resistance of the moving fluid to the force of gravity. The fluid resistance forces and the force of gravity are shown in Eqs. (1) and (2), respectively.

$$F_a = K\mu\frac{\pi^{0.5}}{2}DU_G + C_d\rho_l\frac{\pi D^2}{4}U_g^2 \tag{1}$$

$$F_g = \frac{\pi D^3}{6}(\rho_l - \rho_g)\,g \tag{2}$$

where K and C_d are constants, μ is the vapor viscosity, U_g is the vapor velocity, ρ_l and ρ_g are the liquid and vapor densities, respectively, and D is the theoretical droplet diameter.

Since the viscosity of the vapor is relatively small, Eq. (1) can be reduced to Eq. (3) (Souders and Brown, 1934).

$$F_a = C_d\rho_l\frac{\pi D^2}{4}U_g^2 \tag{3}$$

The force required to suspend a droplet occurs when the sum of all the forces are equal, as shown in Eq. (4). This condition is considered the terminal setting velocity (u_t) of a droplet, when the droplet velocity is zero.

$$F_g = \frac{\pi D^3}{6}(\rho_l - \rho_g)\,g = C_d\rho_l\frac{\pi D^2}{8}U_g^2 = F_a \tag{4}$$

At high Reynold's numbers, Eq. (4) can be rearranged to Eq. (5) during terminal velocity conditions, where $u_l = u_t$.

$$C_D = \frac{4}{3}\frac{gD}{u_r^2}\frac{(\rho_l - \rho_g)}{\rho_g} \tag{5}$$

Since the value of the drag coefficient depends on the drop Reynolds number, a graphical reference may be used to determine this relationship (Bird et al., 1960). As used by Trompiz and Fair (2000), a relationship between the drag coefficient and drop Reynold's number can be derived from Eq. (5) when the entrained droplet diameter is unknown, and the entrained drop velocity matches the gas superficial velocity, $u_r = u_G$, as shown in Eq. (6).

$$\frac{C_D}{Re} = \frac{4}{3}\frac{g\mu_g}{u_r^3}\frac{(\rho_l - \rho_g)}{\rho_g^2} \tag{6}$$

Therefore, using the graphical relationship between drag coefficient and drop Reynold's number, the largest theoretical entrained droplet diameter can be estimated by Eq. (7) for any given gas and liquid system.

$$D = \frac{Re\mu_g}{u_g\rho_g} \tag{7}$$

In the case of droplets generated through a spray nozzle, the largest theoretical droplet diameter has limited practical value due to the number and relative velocities of droplets generated within the spray. Additionally, incorporating this force balance at high Reynold's numbers, as is the case in this work, may contribute to estimation errors since the relationship between drag coefficient and drop Reynold's number is subject to secondary effects such as wall effects, unsteady flow, internal droplet circulation, and the fall of non-spherical droplets (Bird et al., 1960).

Mugele (1960) developed an upper-limit function for determining the maximum stable drop diameter, D_m, also used by Trompiz and Fair (2000), but does not provide explicit details of drop size distribution of entrained liquid. As shown in Eq. (8), the maximum stable droplet diameter in a spray is based on the nozzle orifice diameter, d_0, the physical properties of the gas and liquid, and the relative velocity of the entrained droplets, u_r, in the flowing gas.

$$D_m = 57d_0\left(\frac{d_0\rho_l u_r}{\mu_l}\right)^{-0.48}\left(\frac{\mu_l u_r}{\sigma}\right)^{-0.48} \tag{8}$$

σ is the liquid surface tension. In counter flowing conditions, the relative velocity of gas and entrained droplets is found using Eqs. (9) and (10), where u_l and u_g are the respective gas and liquid velocities, ΔP is the pressure drop through the spray nozzle orifice, and C_0 is the nozzle discharge coefficient. Trompiz and Fair (2000) report using a discharge coefficient of 0.7 for solid cone spray nozzles.

$$U_r = U_L + U_G \tag{9}$$

$$U_L = C_0\left(\frac{2\Delta PU_r}{\mu_L}\right)^{0.5} \tag{10}$$

Trompiz and Fair (2000) then developed an expression to estimate the total entrainment from a spray. Their model is based on the integration of the cumulative volume distribution of entrained liquid and utilizes a bimodal distribution