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Interfacial area measurements and surface area quantification for spray absorption

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ABSTRACT

Sprays are widely used in the chemical industry for absorption operations such as gas conditioning and flue gas desulphurization. Despite the wide usage, spray absorption is poorly understood. For absorption applications, the rate of transfer of solute gas into all of the liquid drops is a strong function of the surface area of drops and hence the dropsize. Experimental measurements of dropsize at multiple locations within the spray plume and robust computation of the cumulative surface area of the drops is required to ascertain the liquid surface area availability. Further, the efficiency of spray contactors can be conveniently expressed in terms of the effective gas–liquid interfacial area measured using the standard chemical technique. The liquid surface area and the effective gas–liquid contact area inside spray columns can differ from each other on account of the large degree of absorption occurring during the process of atomization, and the internal stagnancy of small drops. Further, drop break-up, drop-drop interactions, collision of the spray plume with the column wall, and wall flow affect the liquid surface area availability and the effective gas–liquid contact area to varying degrees. As a result, it is essential to quantify both, the liquid surface area as well as the effective gas–liquid area inside spray columns to gain a fundamental understanding. Present study addresses this gap. Dropsize measurements using a Phase Doppler Interferometer (PDI), robust cumulative drop surface area quantification, and effective interfacial area measurements with the CO_2-0.1 N NaOH system inside a 0.2 m ID laboratory spray column are presented. The effect of L/G ratio and gas–liquid contact height on the effective interfacial area and the cumulative drop surface area are elucidated. The effective interfacial area measurements are compared to results of previous researchers. Further, a methodology to compare the cumulative drop surface area with the effective interfacial area measurements is presented. Results from the study shows that a great degree of mass transfer does occur in the region in the vicinity of the nozzle tip. A large difference is observed in the cumulative drop surface area and the effective interfacial area on account of the large degree of CO_2 absorption taking place during the process of atomization and the large number of internally stagnant drops. This work provides a fundamental insight into spray absorption and will guide in nozzle selection and robust design of spray columns.

1. Introduction

Sprays are widely used in the chemical industry [20]. Flue gas desulphurization, gas conditioning, humidification and particulate removal are prime examples of operations employing sprays [17,20]. A spray can be defined as a series of gas–liquid momentum exchanges in which the liquid is dispersed as drops, while the gas is continuous [14].

For operations such as gas absorption, the rate of transfer of solute gas into all the liquid drops is proportional to the surface area offered by drops [16], and hence the dropsize. Knowledge of dropsize distributions and the cumulative surface area of the drops (liquid phase) is critical in estimating the efficiency of sprays. However, experimental measurements of dropsize distributions are scarcely reported in the literature. Use of correlations to predict dropsize from commercial nozzles can lead to unrealistic quantification of the cumulative drop surface area availability. Vendor dropsize data is frequently extrapolated based on limited experimental measurements [15]. Nearly all of the vendor data available is based on water as the test fluid. Thus, there is a need to measure dropsize distributions for non-water sprays experimentally. Further, these experimental measurements need to be robustly utilized to compute the cumulative drop surface area availability.

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Nomenclature

A	area of concentric circular zone, m^2
A_c	column cross sectional area, m^2
a_e	effective interfacial area, m^2/m^3
A_{plume}	cross sectional area of spray plume, m^2
a_s	cumulative surface area of drops per unit contactor volume, m^2/m^3
C	correction factor for drop count
C_{CO2}	concentration of CO_2 in the solution, $kmol/m^3$
C_{NaOH}	concentration of hydroxide solution, $kmol/m^3$
d	drop diameter, μm
D_c	diameter of column, m
$D_{CO2,l}$	diffusivity of CO_2 in the liquid solvent, m^2/s
d_o	orifice or nozzle diameter, m
D_{32}	Sauter mean diameter, μm
E	enhancement factor
G	total gas rate, kmol/min
G_I	inert gas rate, kmol/min
h	Barett contributions to Henry's constant calculation, L/mol
$h_{Na^+}, h_{OH^-}, h_{CO2}, h_{CO3^{2-}}$	Barett contributions to Henry's constant calculation, L/mol
H_{CO2}	Henry's constant for CO_2 in solvent, m^3 atm/kmol
$H_{CO2\text{-}PM}$	Henry's constant for CO_2 in solvent as defined by Pohorecki and Moniuk [19], $kmol/m^3$ atm
$H_{CO2,w\text{-}PM}$	Henry's constant for CO_2 in water as defined by Pohorecki and Moniuk [19], $kmol/m^3$ atm
I	ionic strength of solution, mol/L
k_g	local gas side mass transfer coefficient, $kmol/m^2$ min atm
K_G	overall gas side mass transfer coefficient, $kmol/m^2$ min atm
k_g'	local liquid side mass transfer coefficient in gas units, $kmol/m^2$ min atm
$k_g'a_e$	local liquid volumetric mass transfer coefficient in gas units, $kmol/m^3$ min atm
K_Ga_e	overall volumetric mass transfer coefficients, $kmol/m^3$ min atm
k_l^0	physical local liquid side mass transfer coefficient, m/min
k_{OH^-}	second order rate constant, m^3/kmol s
$k_{OH^-}^{\infty}$	second order rate constant at infinite dilution, m^3/kmol s
L	total liquid rate, kmol/min
N_{CO2}	CO_2 flux, kmol/min
n	drop count or number of concentric circular zones
p_{CO2}	partial pressure of CO_2, atm
P_{SA}	planar surface area, m^2
Q_l	specific mass liquid rate, kg/m^2 h
r	radial distance from the column center, m
R	gas constant, m^3 atm/kmol K
S	surface area of all drops in a concentric circular zone, m^2
T	temperature, K
U_g	superficial gas velocity, m/s
U_l	superficial liquid velocity, m/s
V	volume of solvent, m^3
V_{spray}	volume of solvent sprayed, m^3
$Y_{CO2,in}$	CO_2 mole ratio in inlet gas
$Y_{CO2,out}$	CO_2 mole ratio in outlet gas
Z	gas-liquid contact height or column height, m

Subscript

g	gas
i	bin in dropsize measurement or interface in film theory
in	gas inlet
j = 1, 2, 3...	concentric circular zone number
l	liquid
lm	logarithmic
out	gas outlet

Superscript

*	equilibrium

Greek

Δ	difference
ΔV	differential volume of the contactor, m^3

Effective interfacial area measurements between the gas and liquid phases inside spray columns can provide a convenient means to ascertain the efficiency of spray contactors. Further, comparison of spray contactors with other contactors such as packed columns can be conveniently made on an effective interfacial area basis.

The surface area of the liquid phase and the effective interfacial area between gas and liquid phases inside spray columns can differ from each other. The surface area of the liquid phase is merely the cumulative geometric surface area of all drops under the idealized condition of no wall flow, and is a measure of the available area for gas absorption. On the other hand, the effective interfacial area between the gas and liquid phases is the actual gas–liquid contact area utilized for absorption. Drop internal stagnancy, drop breakup, collision of the spray with the column wall, and wall flow can result in differing liquid surface area and the effective gas–liquid interfacial areas inside spray columns. Further, the effective interfacial area measurements also account for the absorption taking place during the process of atomization or drop formation. A great degree of mass transfer has been reported in the region immediately downstream of the nozzle tip where drops are formed [21,30]. Hence, there is a need to ascertain the effective interfacial area as well as the cumulative drop surface area for spray absorption to gain better insight.

The primary objective of this study is to showcase that the cumulative drop surface area and the effective interfacial area for spray absorption can differ from each other. In this study, the cumulative drops surface area and the effective interfacial area measurements are made inside a 0.2 m ID lab-scale spray column by absorption of CO_2 into 0.1 N NaOH (Sodium hydroxide) solution. A novel method, utilized to extract planar drop cumulative surface area from the measured dropsize distributions is presented. The experimental dropsize distribution measurements are made with a state-of-the-art Phase Doppler Interferometry (PDI) system at multiple locations within the spray plume. The effective interfacial area measurements are made with the well-established chemical technique [9,18,27,29]. Effect of L/G ratio on the dropsize measurements, cumulative planar surface area, and the effective interfacial area is presented. The effect of gas–liquid contact height on the effective interfacial area is ascertained. Further, the comparison between the cumulative drop surface area and the effective interfacial is presented.

2. Background

Absorption of CO_2 in a NaOH spray has been widely reported in literature. Mass transfer rates and effective interfacial areas have