Prediction of the gas hold-up in a large-diameter bubble column with liquid mixtures and electrolytes

Giorgia De Guido*, Laura Annamaria Pellegrini

Politecnico di Milano, Dipartimento di Chimica, Materiali e Ingegneria Chimica "G. Natta", Piazza Leonardo da Vinci 32, I-20133 Milano, Italy

A R T I C L E   I N F O

A B S T R A C T

Many correlations are available in the literature for computing the gas hold-up in bubble columns, mainly in pure liquids. Contrarily, very few works deal with the gas hold-up in liquid mixtures, giving different opinions about the successful application of Andrew's dynamic surface tension model. This work further investigates this topic using more recent gas hold-up data presented in a previous work for the binary mixture comprising monoethylene glycol and water and measured for a large-diameter bubble column, which differs from the equipment used in the other few works that have pointed out the unusual behavior of the gas hold-up in binary liquid mixtures. The correlation proposed for representing the experimental data on the basis of the dynamic surface tension theory has been applied in the entire range of gas superficial velocities (0.004–0.20 m/s) and it has been also generalized to predict the gas hold-up enhancement due to the presence of electrolytes. The results suggest that the dynamic surface tension model allows to reproduce the experimental gas hold-up data in a qualitative way, but a quantitative agreement is still lacking since the maximum frothing ability has been experimentally observed for a monoethylene glycol concentration lower than that predicted by Andrew's theory.

1.   Introduction

Bubble columns are very adaptable gas–liquid contacting devices in which a gas phase, in the form of bubbles, comes into contact with a liquid phase, which may be a homogeneous solution or contain a suspended solid as in the well-known Fischer–Tropsch synthesis (Schulz, 1999). This type of equipment is frequently applied in industry for various chemical processes as it does not require neither a complex construction nor any mechanically operated part. Shulman and Molstad (1950) have reported that in 1945 bubble columns were used in a pilot plant to chlorinate hydrocarbons, resulting to be extremely effective for this purpose, so that the possibility of extending their use to other gas–liquid contacting problems appeared very promising. As a result, in the following years the use of this type of contacting device, sometimes also referred to as 'sparger column', has been considered to carry out gas–liquid reactions, such as oxidations and hydrogenations (Fair et al., 1962). As reported by Deckwer et al. (1974), bubble columns are frequently employed for the manufacture of important products in the process industry, with some modifications that have been suggested to suit a specific process (Patil et al., 1984). Bubble columns have acquired importance also in the biotechnology field and, in particular, in fermentation and waste water treatment. They have shown certain advantages over fixed bed reactors in the petrochemical application as well (Deckwer et al., 1974).

Despite the simple arrangement and the low energy input requirements, bubble columns are characterized by extremely complex hydrodynamic interactions. This has opened the way to the scientific interest in bubble columns, which has considerably increased in recent years (Zehner and Kraume, 2000). As a result, many empirical correlations and theoretical models have been developed to enable the mathematical simulation of bubble columns.

Nomenclature

Acronyms

AD	Average deviation
AMS	α-Methylstyrene
MEG	Monoethylene glycol
We	Weber number

Symbols

A	Hamaker constant [J]
b_1	Adaptive parameter in Eqs. (10) and (13)
C	Molar density in Eq. (11) [mol/m^3]
c	Force parameter defined in Eq. (14) [N]
c_1	Adaptive parameter in Eqs. (8), (10) and (13)
c_{trans}	Transition concentration of electrolytes [mol/l]
D	Diffusion coefficient [m^2/s]
D^*_H	Dimensionless diameter [–]
d_c	Column diameter [cm]
d_o	Gas sparger holes diameter [mm]
f	Correction factor accounting for the gas hold-up enhancement due to electrolytes
f_{ob}	Objective function in Eq. (5)
g	Gravitational acceleration [m/s^2]
H_c	Column height [m]
H_D	Height of the free surface after aeration [m]
H_0	Height of the free surface before aeration [m]
I	Ionic strength [mol/l]
k	Parameter defined in Eq. (15) [m^{-1}]
$k_L a$	Volumetric mass transfer coefficient [s^{-1}]
n	Adaptive parameter in Eq. (18)
N_{pt}	Number of points used for regression
P	Coalescence probability factor in Eq. (8)
r	Bubble radius [mm]
r_{eq}	Equivalent radius of two coalescing bubbles [mm]
R	Universal gas constant [J/mol/K]
S	Stretching rate in Eq. (11) [s^{-1}]
T	Temperature [K]
u	Superficial velocity [m/s]
U	Bubble velocity [m/s]
V	Molar volume [m^3/mol]
w	Weight fraction
x	Mole fraction

Greek symbols

Δ	Difference
ε	Hold-up
θ	Function of x and V_i defined by Eq. (12)
μ	Dynamic viscosity [Pa s]
ρ	Density [kg/m^3]
σ	Surface tension [N/m]

Subscripts

bubbly	Referred to the bubbly flow regime
calc	Calculated value
churn	Referred to the churn-turbulent flow regime
exp	Experimental value
G	Gas phase
i	Referred to the i-th component
L	Liquid phase

When dealing with this type of contacting device, the gas hold-up, ε_G, represents an important hydrodynamic parameter, which has a twofold application (Shah et al., 1982). On the one hand, by definition it gives the volume fraction of the phases present in two-phase bubble columns and, thus, their residence time. On the other hand, in conjunction with the volume-to-surface mean bubble diameter, it allows to determine the extent of the specific interfacial area and, thus, to determine the mass transfer rate between the gas and liquid phases. It can also be used to evaluate the volumetric gas–liquid mass transfer coefficient, $k_L a$. The dependence of the $k_L a$ on the gas hold-up becomes evident if the experimental correlation (Eq. (1)) of Akita and Yoshida (1973) is taken into account, which has been reported to apply not only to the liquid-batch operation in a bubble column, but also to the counter-current operation (Seno et al., 1990).

$$\frac{k_L a \cdot d_c^2}{D_L} = 0.6 \left(\frac{\mu_L}{\rho_L D_L} \right)^{0.5} \left(\frac{g d_c^2 \rho_L}{\sigma} \right)^{0.62} \left(\frac{g d_c^3 \rho_L^2}{\mu_L^2} \right)^{0.31} \varepsilon_G^{1.1} \qquad (1)$$

For these reasons, the gas hold-up in bubble columns has been the subject of numerous studies and many correlations have been proposed for its calculation, as a result of the large scatter in the reported data, which is mainly due to the sensitivity the gas hold-up exhibits with respect to several factors, including the physical properties (density, viscosity and surface tension) of the system (Shah et al., 1982).

It is the purpose of this work to investigate the behavior of the gas hold-up in a bubble column filled with the monoethylene glycol (MEG)-water liquid mixture at different MEG concentrations. To accomplish that, the gas hold-up experimental data presented in previous works (Besagni et al., 2017a; De Guido et al., 2016) have been used. To the authors' knowledge, most of the works available in the literature on the gas hold-up in bubble columns have dealt with the behavior of the gas phase in the presence of pure liquids and only a few studies (Bhaga et al., 1971; Shah et al., 1985; Syeda et al., 2002) have presented the gas hold-up as a function of concentration for binary systems. These studies are reported in Table 1, also providing the details on the column geometry (bubble column diameter, d_c, bubble column height, H_c, type of gas sparger), on the gases and liquids used for the experimental campaign and on the operating conditions in terms of the gas superficial velocity, since they should be taken into account when comparing the conclusions drawn in the different works.

Bhaga et al. (1971) have reported some "anomalous observations" for the gas hold-up behavior in binary organic liquid mixtures in a glass bubble column ($d_c = 3.82$ cm, $H_c = 1.14$ m, fritted glass sparger, hydrogen as the gas phase). The liquid systems they have considered are: α-methylstyrene (AMS) + cumene, ethanol + toluene, n-octane + toluene, toluene + AMS, toluene + cumene, toluene + ethylbenzene, acetone + benzene. Results have been reported at 298.15 K and at a gas superficial velocity of 2.13 cm/s. The "anomalous observations" reported by Bhaga et al. (1971) consist in a higher gas hold-up for the organic liquid mixtures than for either pure components. As for the AMS + cumene mixture, the gas hold-up has resulted to be constant for an AMS content between 20 and 80 mol% and to decrease sharply at either end of the concentration range. The increase in the gas hold-up for the ethanol + benzene system has been found to exhibit a maximum sharper than the one observed for the AMS + cumene system and shifted towards lower ethanol concentrations (showing no relation with the composition of the minimum boiling azeotrope, which occurs at 62.5 wt% ethanol). Also for all the other systems (with the only exception of toluene + ethylbenzene and acetone + benzene) an increased hold-up at intermediate concentrations has been shown. The authors have discussed the "anomalous results" in light of the existing theories based on surface tension gradients (Andrew, 1960; Hovestreijdt, 1963; Kitchener and Cooper, 1959; Lowry and Van Winkle, 1969; Marrucci, 1969; Zuiderweg and Harmens, 1958), pointing out that none of them can explain the experimental observations and suggesting the development of an adequate hold-up theory which should consider both the generation of bubbles at the sparger, as well as the coalescence of bubbles in the column.