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Determination of the bubble-to-emulsion phase mass transfer coefficient in gas-solid fluidized beds using a non-invasive infra-red technique

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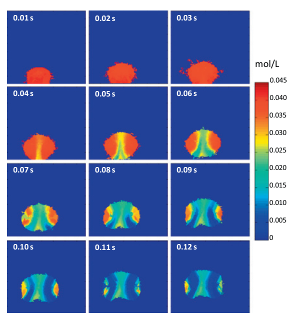
HIGHLIGHTS

- Non-intrusive IR technique used to investigate mass transfer in fluidized beds.
- Whole-field bubble reconstruction to visualize gas tracer concentration profiles.
- Mass transfer in isolated bubbles in good agreement with theoretical descriptions.
- Mass transfer is clearly enhanced in bubbling beds.

GRAPHICAL ABSTRACT



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ABSTRACT

The theoretical approach for the bubble-to-emulsion phase mass exchange in bubbling gas-solid fluidized beds developed by Davidson and Harrison in the early 60's is still widely applied in phenomenological models, mainly because of lack of more detailed experimental data to improve the description. In this study a novel infrared transmission technique that allows the direct and non-invasive measurement of gas concentration profiles inside bubbles with a high temporal resolution has been used for the validation of the theoretical description for the gas exchange. At first, the experimental technique has been further improved concerning the selective removal of particles raining through the bubbles, as well as the reconstruction of tracer gas concentration profiles throughout the gas bubble. The bubble-to-emulsion phase mass transfer coefficients have been measured by injecting tracer gas bubbles into incipiently fluidized beds and beds at freely-bubbling conditions, for beds consisting of glass beads of different particle size and with different injected bubble diameters. The results show that the Davidson and Harrison approach can reasonably well describe the mass exchange for isolated bubbles injected into a bed at minimum fluidization conditions. However, experiments carried out in a freely bubbling bed have shown that the mass exchange rate is considerably enhanced due to the increased gas through-flow through the bubbles. An empirical correlation (with deviations within only 20%) for the volumetric bubble-to-emulsion phase mass transfer coefficient has been developed based on the bubble size and superficial gas velocity, where it is noted that in this work the convective contribution in the mass exchange is dominant.

1. Introduction

For many different applications gas-solid fluidized beds are preferred over other contactors because of their excellent heat and

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Nomenclature

A	absorbance, –
C	gas concentration, mol/L
$C_{t,b}$, $C_{t,e}$	tracer gas concentration as function of time in the bubble and emulsion phases respectively, mol/L
d_b	bubble diameter, m
D_G	gas diffusion coefficient, m^2/s
ε	molar absorbance, $mol^{-1}\ cm^{-2}$
ε_{mf}	bed voidage at incipient fluidization conditions, –
f_w	fraction of the wake phase in a fluidized bed, –
g	gravitational constant, m/s^2
I	IR intensity, –
k_{bc}	gas exchange coefficient between the bubble and cloud phases, s^{-1}
k_{be}	gas exchange coefficient between the bubble and emulsion phases, s^{-1}
k_{ce}	gas exchange coefficient between the cloud and emulsion phases, s^{-1}
ℓ	target length, cm
T	transmittance, –
t	time, s
u_0	superficial gas velocity, m/s
u_b	bubble velocity, m/s
u_{mf}	superficial gas velocity at minimum fluidization conditions, m/s
V_b	bubble volume, m^3

mass transfer characteristics, and efficient particle and thermal mixing inside the reactor [1,2]. Fluidization can be defined as the operation where solid particles are suspended in a fluid rendering the solids phase a fluid-like behavior. When the flow rate of gas fed into the system is just sufficient to suspend the particulate phase (i.e. when the drag force equals the effective gravitational force), the system is at its minimum fluidization conditions, and excess of gas induces the formation of gas voids that rise and coalesce along the bed height. These gas bubbles are responsible of the excellent contacting and mixing of the gas and particles, as they cause macroscale solids circulation inside the reactor. The bubble properties and the movement of the solids are related to the hydrodynamics, while the contact between the gas and solid phases and, in particular, the exchange between the gas inside the bubbles and the gas in the emulsion phase is dictated by mass transfer.

The hydrodynamics in fluidized beds have been extensively studied in the literature using many different experimental techniques in 2D (i.e. with small column depth) and 3D reactors [3–13], using intrusive and non-invasive techniques. Among these techniques, the use of optical non-invasive techniques like Particle Image Velocimetry combined with Digital Image Analysis (PIV/DIA) has been widely applied for the development, validation and verification of important correlations and their underlying assumptions reported in the literature, especially because of the relatively inexpensive experimental equipment required for the analysis [14] and the important possibility to obtain combined whole-field instantaneous information on the gas and solids phases simultaneously. On the other hand, mass transfer measurements have also been carried out using different experimental techniques, such as the use of colored gases like N_2O [15], ozone concentration measurements in a pseudo-2D bed [16,17], zirconia oxygen sensors to study nitrogen mixing in bubbles injected into incipiently fluidized beds [18] and gas exchange in 3D fluidized beds using nuclear magnetic resonance [19]. The effect of temperature on the gas exchange has also been measured experimentally by tracer gas measurements using a suction probe connected to a mass spectrometer [20]. Due to the intricate interactions between the hydrodynamics and mass exchange, it is important to obtain detailed information with high temporal and spatial resolution on the hydrodynamics and mass transfer simultaneously to understand how they affect the final performance of a fluidized bed. This is especially important for applications like drying or coating and applications with catalytic and gas-solid reactions, where the efficiency of the gas-solid contact determines the bed performance.

In general, the hydrodynamics of gas-solid fluidized beds have been studied experimentally in great detail, but an accurate numerical description of larger scale fluidized beds is still not straightforward and many underlying and simplifying assumptions (often extrapolated far from the conditions where they were validated) are still required in phenomenological models to describe the bed hydrodynamics [21–24]. Even more difficult is to accurately describe the mass exchange between the bubble and emulsion phase, which is mainly related to limitations in the techniques used until now to measure the mass exchange rates. Often the mass exchange has been measured for injected bubbles into incipiently fluidized beds using gas sampling from inside the bubbles. However, with this technique it is difficult, if not impossible, to measure gas concentration profiles inside the bubbles with high spatial resolution. Therefore, the common assumption for the numerical description of the mass transfer rate is that the gas concentration inside the bubbles is homogeneous.

For the mass transfer in gas-solid fluidized beds, the description given by Davidson and Harrison in 1963 [2] and later corrected by Rowe [15] is still accepted for single injected bubbles. Later, Sit and Grace proposed another similar description of the mass transfer phenomena for non-interacting three dimensional bubbles [16]. These correlations have been summarized in Table 1 and show that the mass exchange occurs as consequence of two different contributions, viz. gas convection through the bubble and gas diffusion from the bubble to the emulsion phase.

In addition, mass transfer in freely bubbling beds has been studied, where in general an increase in the interphase transfer as consequence of the presence of multiple bubbles is observed. Furthermore, it has also been evidenced that higher gas throughflows are expected as compared to isolated bubbles according to the observed flow distribution between the phases [28,29]. To account for this in a heuristic manner, Sit and Grace [16] used the same approach as for isolated bubbles and increased the constant in the convective term. More recently, using detailed two-fluid model simulations it has been confirmed that the gas exchange in freely bubbling beds is greatly enhanced [27].

In the last years, a novel technique based on infrared transmission has been developed and successfully applied for mass transfer measurements in fluidized bed systems [30,31], both for injected bubbles and in the freely bubbling regime. In this technique, an infrared camera is used as detector for the IR absorption by a tracer gas in pseudo 2D beds. The technique allows a much higher spatial resolution as sampling occurs in a projected area of the bed. Furthermore, it also allows a very high temporal resolution as the high-speed IR-camera is able to record images at frame rates up to 100 Hz. This technique can measure the projected instantaneous whole-field concentrations of a tracer gas inside gas voids only.