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On the hydrodynamics of a pseudo two-dimensional two-zone gas-solid fluidized bed

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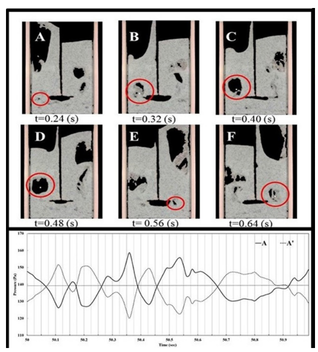
HIGHLIGHTS

- The hydrodynamics of a two-zone gas-solid fluidized bed has been investigated.
- An alternative fluctuating trend was observed for the bed surface height.
- Three different nozzle tip configurations have been studied.
- Both coupled PIV-DIA and CFD techniques have been used in this study.

GRAPHICAL ABSTRACT



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ABSTRACT

The hydrodynamics of a pseudo 2-dimensional two-zone fluidized bed reactor has been studied using both experimental and numerical techniques. In the experimental section a coupled Particle Image Velocimetry (PIV) and Digital Image Analysis (DIA) technique was employed to obtain the averaged particle circulation pattern, bubble dynamics, bed surface fluctuations and the average bubble induced void fraction. To obtain more insight about the hydrodynamics of these fluidized bed types the Eulerian-Eulerian approach was adapted in the numerical section. The results show an alternative reciprocating trend in the bed surface in the left and right sides of the fluidized bed. It was shown that this reciprocating trend originates from two main reasons: the presence of the cavities (small bubbles) below the nozzle tips and the gas hydrodynamics inside the T-shape nozzle. Finally, the average particles circulation patterns, average solid concentration and the granular temperature variation were studied.

1. Introduction

Fluidized bed reactors are widely used in chemical, petrochemical, refinery and other industries because of their excellent heat and mass transfer characteristics. In gas-solid fluidized bed reactors typically the gas stream contains reactants flow up from the bottom section of the bed and solid catalysts are filled inside the reactor [1]. In some processes such as conversion of gaseous hydrocarbons, catalyst particles should be regenerated due to carbon deposition on their surface [2]. In fluid catalytic cracking (FCC) process the catalyst regeneration are accomplished by using of two connected fluidized beds where catalyst particles are regenerated in a secondary fluidized bed with hot gas stream and then are returned to the first fluidized bed reactor [3].

The concept of two zone fluidized bed reactor (TZFBR) was developed to combine both gas reaction and catalyst regeneration steps in a single equipment. TZFBRs are typically used in gas-solid catalytic

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Notations

2D	Two Dimensional
3D	Three Dimensional
CCBM	Counter-Current Back-Mixing
CFD	Computational Fluid Dynamics
DIA	Digital Image Analysis
EPS	Expanded Polystyrene
FBR	Fluidized Bed Reactor
FCC	Fluid Catalytic Cracking
KTGF	Kinetic Theory of Granular Flow
PIV	Particle Image Velocimetry
STD	Standard Deviations
TFM	Two-Fluid Model
TS-TZFBR	Two Section Two Zone Fluidized Bed Reactor
TZFBR	Two Zone Fluidized Bed Reactor
C_D	Drag Coefficient
d_p	Diameter of Particles (mm) or (mesh number)
e_{pp}	Restitution Coefficient of Particles
g	Gravity ($m^3/kg.s^2$)
$g_{0,pp}$	Radial Distribution Function of Particles
h	Height (cm)
I	Unit Tensor (Pa)
k_p	Diffusion Coefficient for Granular Energy
Q	Flow rate (m^3/h) or (L/s)
Re_s	Reynolds Number based on Superficial Velocity
u	Velocity (m/s)
U_g	Gas velocity (m/s)
U_{mf}	Minimum Fluidization Velocity (m/s)
u_p	Particle Velocity (m/s)
u_s	Superficial Velocity (m/s)

Greek letters

β	Interphase Exchange Coefficient
γ	Collision Energy Dissipation
ε	Volume Fraction
ε_g	Gas Volume Fraction
ε_p	Initial Packing State/Particle Volume Fraction (cm)
η	Dynamic Viscosity of Solid Phase
θ	Granular Temperature m^2/s^2
λ	Bulk Viscosity Pa s
μ	Shear Viscosity Pa s
ρ	Density (kg/m^3)
ρ_g	Gas Density (kg/m^3)
ρ_p	Particle Density (kg/m^3)
τ	Stress Tensor (Pa)
$\upsilon_{p,w}$	Particulate Velocity (Johnson and Jackson)
ψ	Transfer of Kinetic Energy
Φ	Specularity Coefficient

reactions in which the coke deposition and the depletion of the oxygen content of the catalyst lattice cause deactivation of catalyst particles [4]. In this type of reactors one zone of the fluidized bed is used for main reaction and another one is considered for catalyst recovery. This process intensification approach has some benefits such as reducing the capital and operating costs [2]. Fig. 1 shows the schematic of a TZFBR. According to this figure, in TZFBRs commonly the lower part of the bed is used for regeneration of solid catalysts with an oxidizing gas injected through the distributor plate and the upper part (the reaction zone) is equipped with a secondary gas injection pipe which gas reactants are added to the reactor through the nozzles. The products exit from top of the bed.

TZFBRs have been employed in several research works and their performance has been evaluated for a number of processes such as CO combustion [3], alkane dehydrogenation [2,5], steam reforming [6], Hydrogen purification by PROX [7–9], Benzene oxidation to phenol [10–12], and methane aromatization [13]. Recently, Herguido and Menendez reviewed the application of two zone fluidized bed reactors in different chemical processes [14]. They have compared the performance of different chemical reactions in TZFBRs and conventional fluidized bed reactor (FBR). The trends show that for all cases a TZFBR has better performance than a conventional FBR.

The efficiency of TZFBR is influenced by some variables such as position of the gas distributors, particles residence time in each zone, reactor temperature, catalyst activity and selectivity, reactants-to-regeneration gas volumetric ratio, fluidization regime and reactive-to-regenerative bed volume ratio [15]. The steady-state operation can be possible only in equal rates of catalytic reaction and regeneration. Thus, the particle mixing and transport between reaction* and regeneration zones has an important effect on reactor efficiency. The understanding of the reactor hydrodynamics is essential to improve its design [15]. A comparison between a TZFBR and a FBR was done by Talebizadeh et al. and Rischard et al., the results introduced some of the beneficial conditions in use of the TZFBRs [16–18].

To study the hydrodynamics of the fluidized bed reactors, many experimental techniques have been developed, which Particle Image Velocimetry (PIV) technique is known as an important one. In PIV, the velocity vector field can be obtained by adding particles to the fluid stream and their displacement at two instances of time gives the fluid movements [19]. PIV was originally developed to capture the velocity vector field in liquid and gas mediums but recently it was employed to quantify the movement of the solid phase in a bubbling fluidized bed [20,21].

Another visual technique which is typically used in fluidized bed characterization is Digital Image Analysis (DIA). The foundation of this method is based on image acquisition of a pseudo-2D fluidized bed and then a post-processing to segregate the bubbles from the emulsion phase using image contrast [21,22]. Using this technique, some information about the bubble size [23], bubble size distribution, average bubble velocity [21], bubble induced void fraction [23], etc. can be achieved. For example, in a recently DIA work, Julian et al. [24] have derived a new correlation of bubble size evolution for a two-section TZFBR. DIA has been used to evaluate bubble characteristics in the

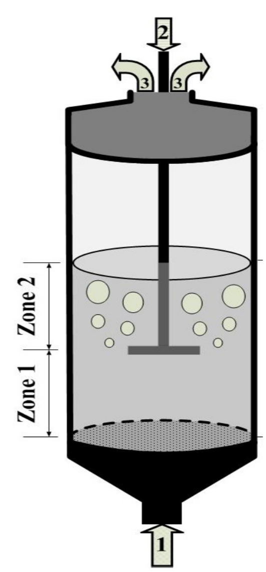

Fig. 1. A schematic diagram of a TZFBR, 1: oxidizing gas stream, 2: reactants stream, 3: products stream.