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Analysis of flow in rotating packed beds via CFD simulations—Dry pressure drop and gas flow maldistribution

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ABSTRACT

Three-dimensional unsteady-state turbulent rotating single-phase flows were simulated in rotating packed beds (RPB) and were validated using overall dry pressure drop measurements for three RPB designs [Liu, H.-S., Lin, C.-C., Wu, S.-C., Hsu, H.-W., 1996. Characteristics of a rotating packed bed. Industrial and Engineering Chemistry Research 35, 3590–3596; Sandilya, P., Rao, D.P., Sharma, A., Biswas, G., 2001b. Gas-phase mass transfer in a centrifugal contactor. Industrial and Engineering Chemistry Research 40, 384–392; Zheng, C., Guo, K., Feng, Y.D., Yung, C., 2000. Pressure drop of centripetal gas flow through rotating bed. Industrial and Engineering Chemistry Research 39, 829–834]. Analysis of the radial and tangential velocities highlighted the impact of gas feed entrance effects on the peripheral gas maldistribution in the rotating packing module. Recommendations were formulated for an optimum design with the aim to reduce gas flow maldistribution in RPBs. Breakdown of the overall pressure drop in its modular components for the housing, the rotating packing module, the free inner rotational zone, and the gas disengagement showed that the dissipation in the rotating packing could be a minor contributor to the overall pressure drop which may be undesirable in terms of RPB mass transfer and reaction efficiencies. Analysis of the simulated pressure drops allowed development of CFD-based Ergun-type semi-empirical relationships in which the gas-slip and radial acceleration effects, the laminar and inertial drag effects, and the centrifugal effect were aggregated additively to recompose the pressure drops in the rotating packing module.

1. Introduction

Radial flows between two rotating parallel disks represent an important class of basic flows owing to their tremendous industrial applications, e.g., rotating machinery, lubrication, viscosimetry, heat and mass exchangers, biomechanics, etc. (Batchelor, 1951; Stewartson, 1953; Mellor et al., 1968; Bodonyi and Stewartson, 1977; Szeri et al., 1983a,b; Jarre et al., 1996; Sandilya et al., 2001a). In chemical engineering, these devices inspired the rotating packed bed (RPB) in which a radial flow is forced through a rotating porous annular layer placed inside an enclosure, see Fig. 1. RPB also referred to as HiGee for high gravity matured on the basis of pioneering works traced back to the 1960s (Vivian et al., 1965; Jackson and Marchell, 1968; Podbielniak, 1966, 1967; Todd, 1969). When first introduced at Imperial Chemical Industries, RPB was exploited for its induced macro-gravitational field to enhance interfacial mass transfers and to enlarge the loading zone in gas–liquid counter-current flows (Ramshaw and Mallinson, 1981; Ramshaw, 1983).

Compactness of RPBs makes them attractive for intensified reaction/separation purposes and their extension to various areas of separation and materials' synthesis is growing steadily. Numerous environmental applications of high gravity have been demonstrated, such as VOC removal from groundwater (Singh et al., 1992; Chen and Liu, 2002), CO_2 scrubbing (Lin et al., 2008), phenol complexation/extraction from wastewater towards immiscible organic solvents (Yang et al., 2004), biosorption (Das et al., 2008), supercritical CO_2 desorption of toluene from activated carbon (Tan and Lee, 2008), ozone scrubbing (Lin and Su, 2008), bio-oxidation, polymer devolatilization, and hydrogen chloride stripping (Zheng et al., 2000; Cummings et al., 1999; Chen et al., 2004a; Yang et al., 2005), gas exhaust absorption (Lin et al., 2003; He et al., 2003), coal combustion flue gas desulfurization (Pan and Deng, 2002), fly ash filtration in power generation systems (Song et al., 2003), and distillation (Li et al., 2008). Fossil fuel applications of RPB concern seawater deaeration for re-injection into declining offshore oil fields for enhanced oil recovery (Peel et al., 1998), or simultaneous H_2S and H_2O removal from natural gas (Eimer, 2003). SINOPEC at Shengli oilfield used 1.5 m diameter RPB in replacement of gigantic 30-m tall vacuum towers for water deaeration (Zheng et al., 1997). Quite recently, Dow Chemical examined the production of hypochlorous acid using

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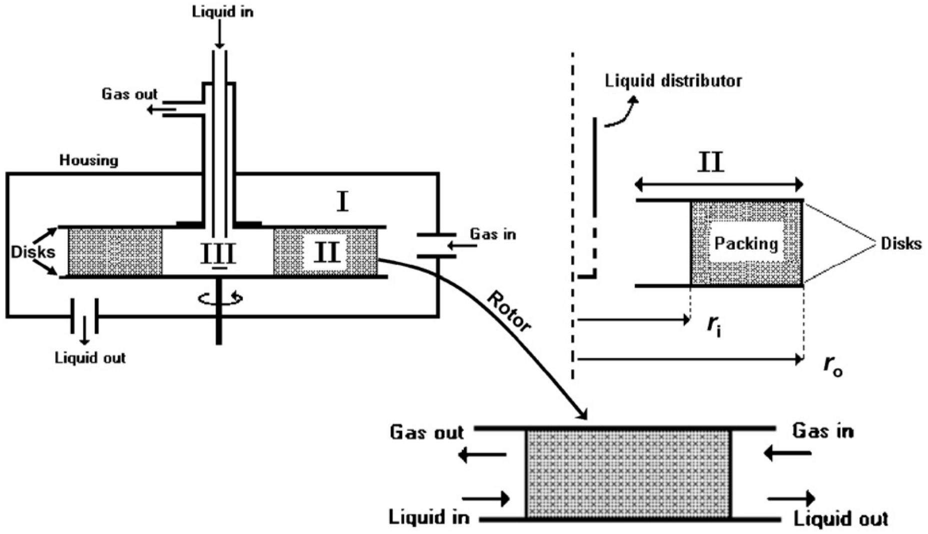

Fig. 1. Schematic diagram of a rotating packed bed setup and corresponding segmentation (Sections 1–3).

an RPB pilot plant as a reactive stripper by contacting gaseous chlorine with sodium hydroxide solutions (Trent and Tirtowidjojo, 2001, 2002). Other processes under exploration include high-gravity reactive precipitation for nanoparticles production, e.g., calcium carbonate, silica, titania, alumina, zinc sulfide, etc. (Chen and Shao, 2003; Chen et al., 2003, 2004b; Zhu et al., 2003, 2004; Zhang et al., 2004; Li et al., 2003), and for pharmaceuticals such as asthma treating salbutamol, analgesic ibuprofen and other drugs (Ma et al., 2004; Zhou et al., 2003; Chen et al., 2004c).

In spite of RPB superior mass transfer efficiency (Ramshaw, 1993), understanding the partnership between its internals and the distribution of the induced fluid flow is a challenging task (Guo et al., 2000; Sandilya et al., 2001b; Zheng et al., 2000). In spite of a large body of knowledge relating to RPBs, two interrelated issues received partial coverage in the literature. (i) Scarcity of *local* measurements to unfold the details of fluid hydrodynamics and distribution inside the RPB system and (ii) lack of *space resolved* three-dimensional (3D) computational fluid dynamic (CFD) simulations to unveil details about the pressure field and velocity distribution, the gross flow patterns, the maldistribution, etc.

The multizone character of the geometry of RPBs (Fig. 1) in addition to the rotation of the porous bed give rise, unlike radial or axial flows across stationary porous beds, to numerous flow features, e.g., translational, rotational, sudden directional change, bend, swirling, and abrupt contraction/expansion. In an effort to clarify the interactions between fluids and RPB internals in terms of momentum and mass, and energy transfers, knowledge of these features is of great interest from the practical and fundamental viewpoints.

Procurement of local measurements regarding flow pattern, phase holdups, pressure loss, fluid residence time, etc., inside RPBs is somehow difficult. Keyvany and Gardner (1989) studied the fluids residence time distribution but did not reveal much about the internal fluid dynamics. Burns and Ramshaw (1996) in their visual study of liquid distribution across a rotating bed filled with a molded foam packing concluded that the actual liquid flow does not reach uniformity as assumed in several film models. Severe liquid maldistribution is observed at low rotational speed, whereas at higher rotational speed, the flow pattern is shifted from maldistributed rivulet flow to fine droplet flow. Guo et al. (2000) combining residence time distribution and visual studies investigated the liquid flow structure in a rotating bed. They concluded that the inner bed is the region of most intense liquid deformation and mixing, whereas, elsewhere, the liquid flows as a film covering the packing surface. Flooding of RPB occurs at very high gas velocities (Lockett, 1995) producing thin draining films and droplets suggesting that classification into different flow regimes is crucial. Burns et al. (2000) proposed to distinguish between rivulet (pore) flow, droplet flow, film flow, spray flow, mist flow, and flooding. However, these flow regimes still need to be described using consistent models and more elaborate experimentations.

Liquid hold-up is another factor closely related to liquid distribution. Bašić and Duduković (1995) published the first known holdup measurements using an electrical conductivity technique. They were able to assess the degree of anisotropy of liquid distribution as a function of operating variables and questioned the physical justification of using film flow models (i.e., penetration theory, convection–diffusion model) for estimating mass transfer coefficients (Tung and Mah, 1985; Munjal et al., 1989a,b; Xinlin et al., 2000). Pursuing similar objectives, Burns et al. (2000) investigated the behavior of liquid hold-up in high-voidage RPBs. While maintaining that three distinct flow regimes could exist (pore flow, film flow and droplet flow), they concluded that liquid hold-up (i) is inversely proportional to the local packing radius, (ii) is independent of gas flow, (iii) decreases with rotational speed, and (iv) and is weakly affected by liquid viscosity.

Pressure drop analyses in RPBs were reported by Keyvani and Gardner (1989) for air–water flows across high-voidage aluminum foam metal beds. They found that: (i) both dry (gas-phase) and irrigated (gas–liquid) pressure drops are proportional to the squared rotational speed (Ω) and (ii) pressure drop increases with increased gas flow rate (GFR). Liu et al. (1996) also examined the effect of operating variables on pressure drop using lower voidage, rectangular and elliptical, random packings, and found that (i) dry pressure drop and rotor speed are related somewhat linearly, (ii) at high rotor speed, the pressure drop is strongly influenced by GFR and only slightly by liquid flow rate, (iii) at low rotor speed, liquid flow rate (via liquid hold-up) becomes influential on pressure drop, and (iv) high rotor speed and low liquid flow rate can produce lower pressure drop compared to the dry bed pressure drop, in accordance with Keyvani and Gardner (1989), possibly because small amounts of well dispersed liquid acts as a lubricant. Zheng et al. (2000) proposed interesting arguments to explain part of the pressure drop behavior using two-dimensional (2D) mass and momentum conservation equations. They observed that pressure drop is mainly dependent