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Review

Hydrodynamics and heat transfer of gas–solid two-phase mixtures flowing through packed beds – a review

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Abstract

Flow of a gas–solid two-phase mixture through a packed bed is relevant to a number of industrial processes such as heat recovery and filtration of dusty flue gases, iron making in shaft reactors, gas purification, and sorption enhanced reaction processes. In spite of the industrial relevance, little work has been reported in the literature. The limited amount of research work has mainly addressed the macroscopic hydrodynamics in terms of pressure drop and solids hold-ups at the ambient temperature. Very little is done, until fairly recent, on solids motion at the single particle level, hydrodynamics at elevated temperatures and heat transfer. This paper reviews the recent development in the field including both the hydrodynamics and heat transfer of gas–solid two-phase mixtures flowing through packed beds, which is believed to represent the state-of-the-art in the field. The review is not aimed to be exhaustive but rather focused on our own work carried out over the past few years in the Institute of Particle Science & Engineering at the University of Leeds. And some of our results are compared with that of other groups.

Keywords: Gas–solid two-phase flow; Hydrodynamics; Heat transfer; PEPT; Euler–Euler multi-fluid model

1. Introduction

Flow of a gas–solid two-phase mixture through a packed bed is relevant to a number of industrial processes such as heat recovery and filtration of dusty flue gases, ironmaking in shaft reactors, gas purification, and sorption enhanced reaction processes. In spite of the industrial relevance, only a limited amount of work has been reported in the literature in the past. These studies can be broadly divided into two categories, co-current flows in which gas flow and particles move on average in the same direction and counter-current flows in which particles move on average in an opposite direction to the gas flow. The co-current flows are more preferred in many cases due to better controllability of particles. The work on the co-current flows of gas–solid two-phase mixtures through packed beds has addressed some aspects of the flow including axial velocity distribution of suspended particles [1–4], solids hold-ups in the bed and pressure drop [4–15], transient accumulation of suspended particles in the initial stage [16], non-uniformity of solids hold-up in the entrance region of the bed [10,11], flow behaviour with a lateral inlet [17], and solids behaviour in a dilute gas–solid two-phase mixture [2,4].

This paper reviews recent development in this field. The focus of the review is on the recent work carried out in the Institute of Particle Science & Engineering at the University of Leeds though comparisons will be made with the results published by other groups. The reason for focusing on our own work is that our approach is much more systematic including experimental work, theoretical analyses and numerical modelling, and covering flow hydrodynamics at both room temperature and elevated temperatures, and solids motion at both the single particle and bulk scales.

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2. Solids circulation technology for non-periodic sorption enhanced reaction processes

Fig. 1 schematically illustrates a solids' circulating technology recently proposed for non-periodic adsorption enhanced chemical reaction processes. The system is for gaseous reactants and products, and consists of a reactor and a desorber. The reactor has a structured packing of catalyst which also serves as an adsorber. Relatively fine adsorbent particles are pneumatically conveyed through the packed structure by gaseous reactants/products for continuous (*in-situ*) removal of a product. Adsorbent regeneration is carried out outside the reactor (*ex-situ*), thus decoupling the reaction and regeneration phases and enabling a steady-state (non-periodic) operation if two desorbers are used. The decoupling of the adsorption and desorption steps is important because many high capacity adsorbents have a slow desorption kinetics [18]. The novel process can be viewed as the adsorptive-reactor equivalent of the fluid catalytic cracking (FCC) process in which adsorbent is the transported medium. Like the FCC process, the benefits of this process are expected to be substantial, with excellent control of adsorbent residence time, the enhanced heat and mass transfer, the continuous supply of feed to a single unit, and an integrated energy supply system.

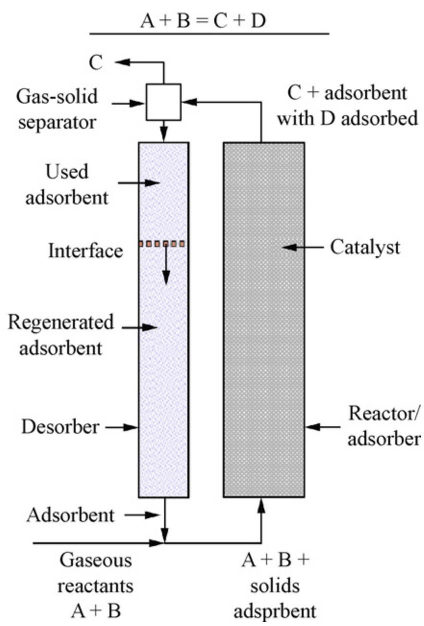

Fig. 1. Non-periodic adsorption enhanced reaction processes: the concept (Interface – refers to fresh-spent adsorbent interface, product D is adsorbed onto adsorbent).

The technological challenges for the proposed system include (a) control of gas–solid mixture flowing through the structured packing and solids circulation, (b) possible attrition/erosion of adsorbent and catalyst particles, (c) heat transfer to and within the reactor and (d) heat supply to the packed bed reactor. The systematic work carried out at Leeds aimed at addressing the above challenges. For doing so, two systems based on the concept shown in Fig. 1 are constructed (Fig. 2). One of the systems is for cold state experimental work studying the hydrodynamic aspects and the solids motion in the system, and the other one for hot state experiments investigating both the hydrodynamics and heat transfer and sorption enhanced chemical reactions using the steam-methane reforming (SMR) for hydrogen production as the model reaction. The details of the experimental systems are briefly described in Section 3.

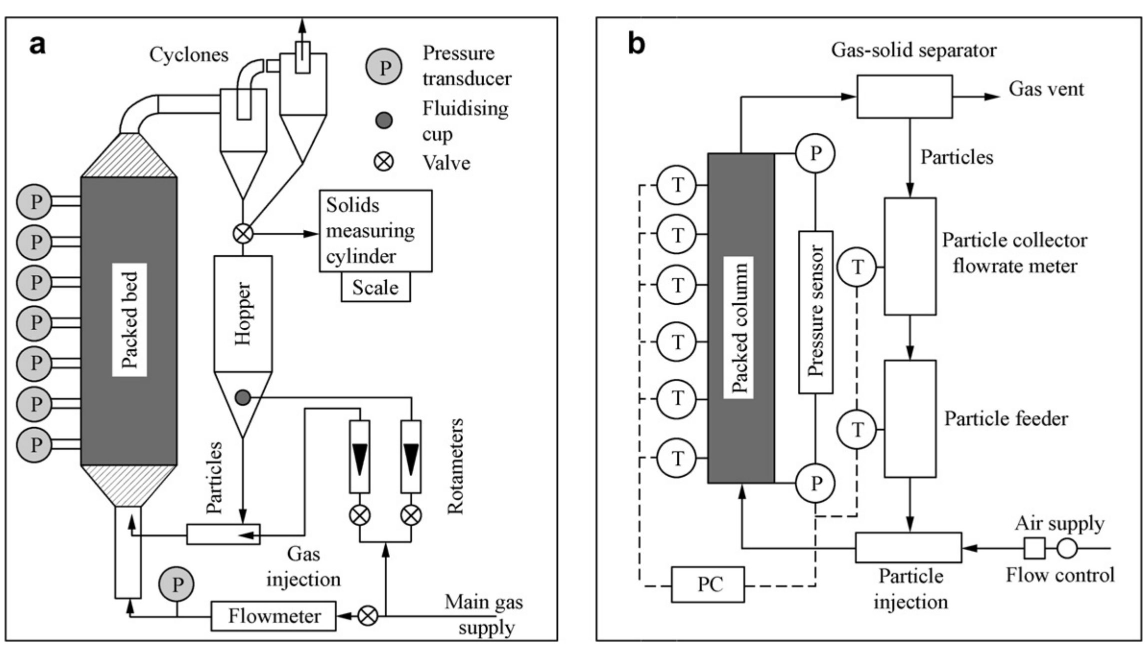

Fig. 2. Experimental systems. (a) System for cold state experiments; (b) system for hot state experiments.