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Hydrodynamics of gas–solid two-phase mixtures flowing upward through packed beds

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Abstract

The work reported here represents part of an effort to address the challenges related to a newly proposed process for hydrogen production through steam-methane reforming, in which a fine adsorbent carried by the gaseous reactants moves through a packed catalyst bed. Comprehensive experimental work was carried out on the hydrodynamic aspects of gas–solid two-phase mixtures flowing upwards through packed beds. The effects of column diameter, packed particle size, and suspended particle size on the pressure drop and solids hold-ups were investigated. It was observed that the pressure drop of gas–solid two-phase flows depended approximately linearly on the solids flux under the conditions of this work, and the dependence was affected by the suspended particle size, packed particle size, packed column diameter, and gas velocity. However, when the data were reprocessed in terms of the Euler number and the solid-to-gas mass flux ratio, they collapsed into a single line for a given packing condition, and the suspended particle size was found to impose little effect. An analysis was conducted on the pressure drop using a modified version of Metha–Hawley equation by taking into account the effects of suspended particles on the viscosity and density. A reasonably good agreement with experimental data was obtained. The experimental results of the solids hold-ups showed that the particle concentration in packed particle interstices was much higher than that at the entrance to the packed column. Effort was also made to relate the solids hold-ups to the operating parameters. It was found that the dynamic hold-up related fairly well to the solid-to-gas velocity ratio as well as the suspended-to-packed particle size ratio for a given packed column, whereas no clear relationship was obtained for the static solids hold-up. Based on the results of this study, recommendations for future work are given.

Keywords: Gas–solid mixtures; Two-phase flows; Packed bed; Pressure drop; Solids hold-up; Euler number

1. Background

Due to the environmental concerns, world's demand on hydrogen will undoubtedly become greater and greater in the future. Currently, about half of the world's feedstock for hydrogen production is natural gas, which contains mainly methane. The process of hydrogen production using steam-methane reforming (SMR) typically consists in series of a main catalytic reactor (reformer) operated at ~1000 °C, one or two shift reactors (water–gas shift reaction) operated at ~200–450 °C, and a pressure swing adsorber for product separation [1] This process is characterised by high-energy consumption, dependence on the expensive specialised alloys for tubular reactors, sensitivity of downstream shift reactors to the performance of the main reformer, as well as very high capital and operating costs. Furthermore, the technology for current SMR process has been well developed and it is unlikely that any significant improvements are possible. A new process has recently been proposed, which is shown schematically in Fig. 1. The process is based on the combined reaction and separation concept, which uses a stationary catalyst phase and a moving adsorbent for truly in-situ removal of CO_2 (in Column R), and ex-situ regeneration of CO_2 adsorbent (in Column A) thus enabling a continuous operation of the reactor, the use of relatively low capacity adsorbent, introduction of more physical heat to the reactor, and intensification of heat transfer within the reactor. However, some technological *challenges* have to be addressed before the process can be taken up industrially,

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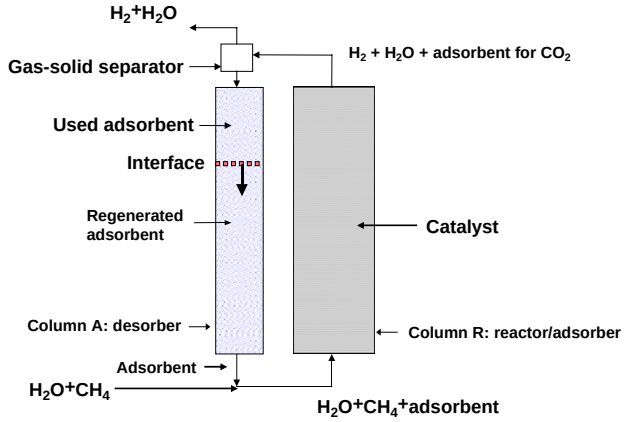

Fig. 1. A newly proposed process for hydrogen production (2 desorbers are needed for a continuous operation).

which include (a) gas–solid two-phase mixtures flowing through the packed bed system in a smooth and controlled manner, (b) attrition of adsorbent particles and erosion of catalyst particles, and (c) heat transfer to and within the reactor. This work aims at addressing Challenge (a), i.e. the hydrodynamic aspects of gas–solid two-phase mixtures flowing through packed beds.

Flow of a gas–solid two-phase mixture through a fixed bed also occurs in many other processes such as high temperature shaft reactors [2,3], catalytic oxidation–dehydrogenation of butene to butadiene [4], as well as heat recovery and filtration of dusty flue gases [5]. The behaviour of such a flow is complex due to interactions between suspended and packed particles, suspended particles and column wall, gas and packed particles, gas and suspended particles, and gas and column wall. The relative importance of these interactions depends on the physical and mechanical properties of both the suspended and packed particles, the operating conditions, the ratios of the suspended and packed particle sizes to the column diameter, and configuration of the flow system. Despite both industrial and academic importance, the flow behaviour of gas–solid two-phase mixtures through fixed beds has not been extensively explored, and only a small number of publications can be found in the open literature.

The published studies on the flow of gas–solid mixtures through fixed beds can be broadly divided into two categories, co-current flows where gas and particles move on average in the same direction [6,2,3,7–10], and counter-current flows where particles move on average in an opposite direction to the gas flow [11–13]. This work is concerned with the co-current flows, a brief review of the work on this type of configuration is therefore given in the following.

There are only a small number of publications on the co-current flows of a gas–solid two-phase mixture through a fixed bed. These studies have addressed some aspects of the flow including (a) axial velocity distribution of suspended particles [6]; (b) solids hold-ups in the bed and pressure drop [2,3,7–10]; (c) transient accumulation of suspended particles in the initial stage [14]; (d) non-uniformity of solids hold-up in the entrance region of the bed [15]; and (e) flow behaviour with a lateral inlet [16]. However, these studies have not led to a relationship for pressure drop, nor for solids hold-ups within packed beds, which are required for engineering design. In a preliminary study, Wang et al. [17] proposed a relationship for the pressure drop based on a modified version of the Ergun equation, and a correlation for the solids hold-up through intuitive arguments. The relationships, however, were based on the results obtained by using one sized column (100 mm) packed with one particle size (10 mm), and only one sized suspended glass beads were tested in the work. Both relations showed reasonable agreement with the published data in the literature. The specific objectives of this work are therefore to verify and/or improve the relationships by carrying out comprehensive experiments, and to investigate the effects of suspended particle size, packed particle size, as well as the diameter of the packed column.

This paper is organized in the following manner. Experimental techniques are described in Section 2. Experimental results are presented and discussed in Section 3. Finally, a summary of the main conclusions and an outlook into future work are given Section 4.

2. Experimental techniques

The experimental system used in this work is similar to that used by Wang et al. [17]. It consisted of an acrylic Perspex glass column, two cyclones in series for particle separation, a particle injection unit for introducing suspended particles into the packed bed, a hopper for collecting particles from the cyclones and for dispensing the particles to the particle injection unit, and various flow measurement and control devices; see Fig. 2. There was a bag filter (not shown) installed at the exit of the second cyclone to ensure all particles were captured. The column was either 50 mm or 100 mm in inner diameter and 1000 mm long and was packed with either 5-mm or 10-mm glass balls (Silibeads®). Seven pressure taps were drilled along the column wall in the test section for measuring pressure profile in the axial direction of the flow. These taps were equally spaced with an interval of 100 mm. An expansion funnel and a contraction cone each 150 mm long and packed with glass balls of the same size as that in the column were connected through flanges respectively to the bottom and the top of the packed column for smoothly introducing and retrieving the gas–solid mixture. Suspended particles were initially stored in the hopper in which a fluidizing cup was installed in the lower part. This assisted particles flowing down to the injection unit where they were injected by a gas stream through a Venturi nozzle mechanism. Suspended particles were separated by the cyclones after leaving the packed column. The collected particles were transferred into the hopper by gravity so that solids circulation was realized. The flowrate