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Vertical upward flow of gas–solid two-phase mixtures through monolith channels

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Abstract

This paper reports some recent experimental observations of both gas and gas–solid two-phase flows through small monolith channels. For gas flows, the laminar-to-turbulent transition in monolith channels was observed to occur at a Reynolds number of ~620, much lower than the conventional transition criterion of 2200 for large pipes. Surface roughness of and non-uniform distribution of gas in monolith channels were proposed to be possible reasons. For gas–solid two-phase flows, both pressure drop and solids hold-up were measured. It was found that the pressure drop of gas–solid two-phase flows through monolith channels was significantly lower than that through packed particle beds with even lower surface area per unit bed volume. Reprocessing of the pressure drop data in terms of the dimensionless groups showed that the Euler number depended approximately linearly on the solids-to-gas mass flux ratio for a given superficial gas velocity, and suspended particle size imposed little effect under the conditions of this study. Measurements of the solids hold-up showed that the hold-up in monolith channels increased with a decrease in both the gas velocity and the suspended particle size. The pressure drop results were also compared with semi-theories developed for pneumatic conveying. An overprediction was observed, an indication of the need for more controlled experiments for fundamental understanding of the hydrodynamics in monolith channels.

The work reported here on gas–solid two-phase flows through monolith channels represents the first attempt in this area as no previously studies have been found in the literature.

Keywords: Gas–solid mixture; Two-phase flow; Small channels; Monolith; Pressure drop; Solids hold-up; Friction factor

1. Introduction

In a newly proposed process for low-temperature hydrogen production through steam methane reforming, a stationary packed catalyst bed and a moving circulating adsorbent bed are adopted for in-situ removal of CO_2, and ex-situ regeneration of CO_2 adsorbent thus enabling a continuous operation of the reactor, the use of relatively low capacity adsorbent, and potential intensification of heat transfer within the reactor [1]. One of the technological challenges associated with this process is to maintain the gas-adsorbent two-phase mixture flowing smoothly through the packed bed system in a well-controlled manner. This has been difficult to achieve despite a number of fundamental studies on this topic; see for example Shibata et al. [2], Delebarre et al. [3], Hidaka et al. [4], Panic et al. [5], and more recently, Wang et al. [6]. One of the main reasons for the difficulty is the lack of reliable relationships for predicting pressure drop of gas–solid two-phase mixtures through, and solids hold-ups in, the packed bed. Although promising progress has been made recently in a preliminary study by Wang et al. [6], their work also identifies a disadvantage of the use of packed beds in the intended application, i.e., the static solids hold-up (particles trapped in the interstices of packed particles) is unwanted as it increases pressure drop. This work aims at addressing this issue by using monolith instead of packed beds.

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Monolith consists of an array of small parallel channels, and has found applications in a number of catalytic reaction and separation processes. A substantial amount of effort has been made in the past few decades to investigate the behaviours of fluid flow, heat and mass transfer, as well as reaction performance in monolith reactors; see for example Heiszwoll et al. [7] and Woehl et al. [8]. These studies, however, have been on either single-phase (gas or liquid) flows, or gas–liquid two-phase flows. No report has been found in the literature on gas–solid two-phase mixtures through monolith. This constitutes the specific objective of the present work on the hydrodynamic aspects of the flow. It is noted that the flow behaviour in monolith could be fundamentally similar to that in microchannels, which has emerged as an important area of research in the past two decades due to their potential applications in micropower generation, micro-electro-mechanical systems (MEMS), biomedical use, biotechnology, and computer chips [9,10]. As a consequence, a brief review on the relevant work on micro-channel flows will also be included where appropriate.

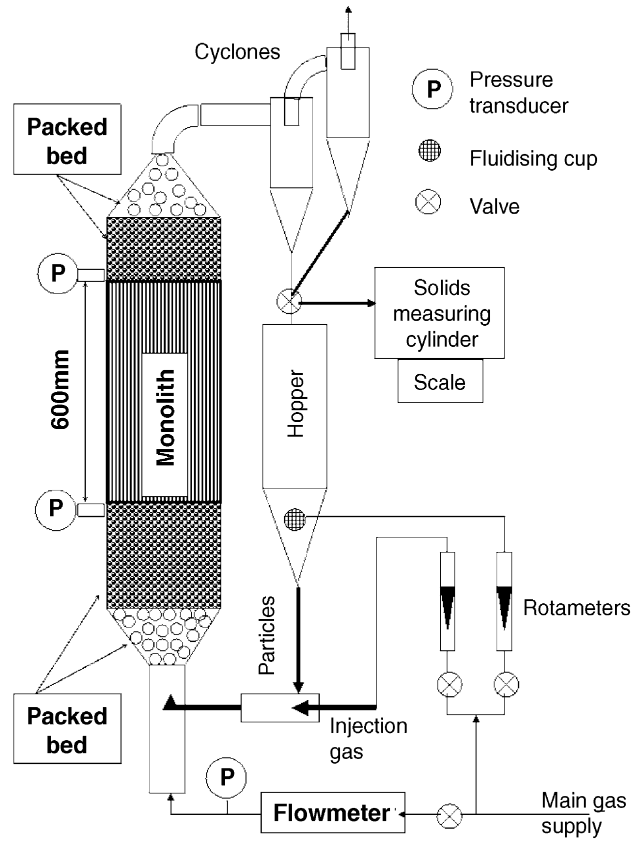

Fig. 1. Experimental system.

2. Experimental techniques

The experimental system used in this work consisted of an acrylic Perspex glass column, two cyclones in series for particle separation, a particle injection unit for introducing suspended particles into the column, a hopper unit 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. 1. There was a bag filter (not shown) installed at the exit of the second cyclone to ensure all particles were captured. The Perspex glass column was 50 mm in inner diameter and 1000 mm long. Two 300-mm long monolith units (Cordierite, Corning) were inserted into the Perspex column in series with the lower end of the lower monolith unit 300 mm above the entrance, and upper end of the upper monolith unit 100 mm below the exit. The parts above and below the monolith units were packed with 10-mm glass balls (Silibeads®). Such an arrangement was intended to make more uniform distribution of suspended particles across the whole cross section. The monolith units had an outer diameter of 50 mm hence a close fit into the column and little gas leaking between the Perspex column and the monolith. Extra care was taken to align the two monolith units to ensure a smooth flow at the connection. The monolith units consisted of 180 straight square channels (3 mm$\times$3 mm) uniformly distributed over the cross-section. Two pressure taps were drilled along the column wall in the test section for measuring pressure drop across the monolith. An expansion funnel and a contraction cone each 150 mm long and packed with glass balls were connected through flanges respectively to the bottom and the top of the packed parts of the 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 particle 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 column. The collected particles were transferred into the hopper by gravity so that solids circulation was realized. The flowrate of the suspended particles was controlled by changing the injection gas flow as well as the main gas flow. There was a by-pass valve (not shown) between the cyclones and the particle hopper for measuring particle flowrate through a measuring cylinder and an electronic scale.

There were three gas streams in the system, namely, the main gas stream, particle injection stream, and fluidizing gas stream. The main gas stream was measured and controlled by a GL turbine type flowmeter (Gx-BSP-1″) linked to a 0126 flow computer (Fluidwell), whereas the other two streams were measured with calibrated rotameters. An RS pressure transducer was used to detect the gas pressure, and pressure drop across the monolith section was measured with a DM2L micro-manometer interfaced to a PC through an RS232 interface. The flowrate of suspended particles was measured by weighing particles collected from the cyclones and the bag filter over time (particles collected in the bag