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A phenomenological model for bubble coalescence in confined highly porous media

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ABSTRACT

In a recent work, Serres et al. (2016) considered the stability of Taylor bubbles entering a confined highly porous medium (open cell solid foam of 96% porosity). This experimental work pointed out that a periodic alternation of gas bubbles and liquid slugs in a millichannel can either keep its regularity, or be destructured at the porous medium entrance. A critical bubble length was proposed as a transition parameter between the two observed regimes. This study presents two key results which complement the previous work and explain the regime transition. (1) The comparison of the Taylor flow upstream the porous medium with the Taylor flow in an empty millichannel demonstrates that the regime transtion is not due to the possible feedback of the foam on the upstream flow. (2) A phenomenological model is proposed, which accounts for the observed bubble coalescence and gas channelling in the porous medium in the range of parameters explored in the experiments.

1. Introduction

Three-phase flows are ubiquitous in a wide range of phenomena, from natural to industrial processes. In the last decades, gas-liquid flows in porous media – either rigid or mobile – have motivated many fundamental and applied studies, with the goal to either understand and predict natural processes such as methane venting (Naudts et al., 2008) and pockmarks (Hovland et al., 2002; Gay et al., 2006) on the oceanic floor or mud volcanoes (Planke et al., 2003; Mastalerz et al., 2007; Mazzini et al., 2007), or to optimize man-made techniques. Among these latters, soil decontamination by air sparging (Semer et al., 1998; Reddy and Adams, 2001), CO_2 sequestration (Kang et al., 2005; Eccles et al., 2009) enhanced oil recovery (Babchin et al., 2008) or catalytic reactors (Losey et al., 2001; Hessel et al., 2005; Marquez et al., 2008) are part of the present societal challenges. Indeed, the strong hydrodynamic coupling between the gas, liquid and – in mobile porous media – solid phase motion, in addition to possible mixing and chemical reactions, make this problem very difficult to tackle.

In the particular context of heterogeneous catalysis, process intensification has led to testing new porous materials and environments. In confined geometries, open cell solid foams are innovative porous media which have a great potential due to their high porosity (up to 96%), leading to low pressure losses, large contact area and possibly enhanced mass and heat transfer (Stemmet et al., 2005; 2006; 2008; Twigg and Richardson, 2007; Tourvielle et al., 2015a; 2015b; Lali et al., 2016; Zapico et al., 2016). However, if the interest of such new material has been undoubtfully highlighted, the hydrodynamics of a confined gas-liquid flow across such medium still has to be characterized.

In a recent work, Serres et al. (2016) have quantified the local hydrodynamics of a periodic gas-liquid flow – Taylor flow – forced into an open cell solid foam in a confined geometry (horizontal square millichannel). They have shown that, in a given range of parameters, the periodic flow in the millichannel disorganizes at the porous medium entrance, leading to a modulation of the upstream Taylor flow frequency. The transition was successfully described in terms of a modified Weber number (see Serres et al. (2016) and Section 3.2 of the present work). A tentative model was proposed in terms of bubble fragmentation at the foam entrance, but without any further quantification.

In the present study, we revisit the work of Serres et al. (2016) based on new experimental evidences. First, we demonstrate that the Taylor frequency upstream can be predicted by a simple model of the periodic gas-liquid flow (Section 3.1). It demonstrates that the existence of the modulated regime is not due to a change in the upstream flow, but rather to the presence of the porous medium. We then propose a phenomenological model (Section 4) based on bubble coalescence and gas channelling – as

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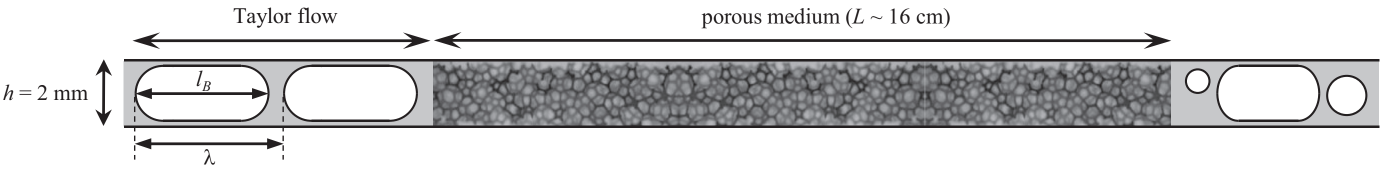

Fig. 1. Sketch of the experimental setup. Periodic gas bubbles and liquid slugs (Taylor flow) are sent at the entrance of a porous medium of length $L \sim 16$ cm in a millichannel of square cross-section $h = 2$ mm. l_B is the typical bubble length and λ the spatial periodicity of the Taylor flow.

evidenced by new experimental measurements. This model successfully describes the transition between the periodic, Taylor-like regime and the modulated regime.

2. Preliminary results

2.1. Experimental setup

The experimental setup is a millichannel of square cross-section $h \times h$ ($h = 2$ mm). The setup is similar to the one presented in Serres et al. (2016), and therefore is only briefly described here. A regular Taylor flow, consisting of a periodic alternance of gas bubbles and liquid slugs (Garstecki et al., 2006; Angeli and Gavriilidis, 2008), is sent at the entrance of a porous medium of length $L \simeq 16$ cm (Fig. 1). This latter consists of a highly porous structure, an open cell solid foam made of vitreous carbon (80 PPI, ERG Aerospace, porosity $\epsilon = 96\%$). The pore size distribution is characterized by X-Ray tomography (GE Phoenix v|tome|x s, RX tube of 160kV with focal point of up to 1 µm) with a spatial resolution of 5 µm. It evidences two pore structures: (1) the cells, corresponding to the void cages of the foam and (2) the windows, which connect two neighboring cells (for more details, see Serres et al., 2016). The typical diameter of the cells and windows are $d_c = 604 \pm 86$ µm and $d_w = 257 \pm 85$ µm, respectively.

The gas (G) and liquid (L) are nitrogen and ethanol of density $\rho_G = 1.25$ kg/m^3, $\rho_L = 795$ kg/m^3, viscosity $\mu_G = 1.76 \times 10^{-5}$ Pa s, $\mu_L = 1.15 \times 10^{-3}$ Pa s and $\sigma \simeq 22$ mN/m, the nitrogen-ethanol surface tension at room temperature (Dittmar et al., 2003). The flow-rates are varied as follows, $Q_G = [2 - 35]$ Ncm^3 min^{-1} and $Q_L = [0.5 - 8]$ Ncm^3 min^{-1}, such that their ratio stays in the range $Q_G/Q_L = [0.25 - 35]$, ensuring a regular Taylor flow upstream the porous medium.

One of the experimental cell wall is made of glass, and makes it possible to visualize directly the gas-liquid flow in the millichannel. A fluorescent dye (Rhodamine 6B, 3.2×10^{-5} mol/L) is dissolved inside the liquid phase (ethanol) prior to the injection, ensuring a good contrast between the liquid (bright gray) and the gas (black) phases on the images (Fig. 2a). The experimental data of gas and liquid flow with a porous medium were reanalyzed from Serres et al. (2016), for which images acquisition was performed with a camera Solinocam H2D2 at 113 frames per second mounted on a fluorescence microscope Olympus BX51M. To get a better insight on the gas and liquid flow, additional images acquisition was performed with a fast camera (Optronis CR 600 × 2 at 1000 fps). These experiments made it possible to observe the flow dynamics inside the porous medium (see end of Section 3) and quantify the relevant ingredients for the phenomenological model (Section 4). Finally, similar experiments in an empty channel (without porous medium) were also performed in order to quantify the possible feedback of the porous medium on the upstream Taylor flow.

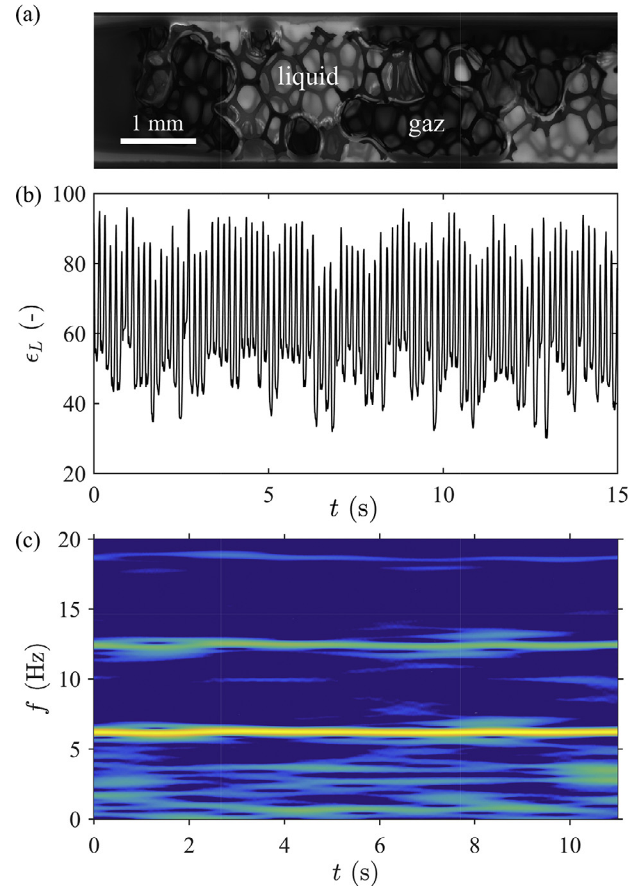

Fig. 2. Data processing [example for $Q_G = 6$ Ncm^3 min^{-1}, $Q_L = 4$ Ncm^3 min^{-1} at the entrance of the porous medium]. (a) Raw image. The gas (dark zones) and liquid (light gray zones) phases are clearly visible, as well as the foam structure. (b) Example of ϵ_L vs. t. (c) Spectrogram associated with (b), computed with a sliding window of width $\Delta t = 4$ s. The main frequency here is $f_0 \simeq 6$ Hz.

2.2. Data processing

After a simple normalization by a reference image and binarization process (Serres et al., 2016), the gas and liquid phases are separated in the raw images (Fig. 2a) and we extract for each image the volume fraction of liquid, ϵ_L. This technique has been previously used in micropacked beds, where it provided a visualization of the flow close to the observed surface (Faridkhou and Larachi, 2012). In open cell solid foams, the high porosity makes it possible to visualize the gas phase over the whole channel depth. It thus provides a good estimation of the local liquid holdup, although the integration over the depth induces an underestimation of the liquid holdup due to the presence of the solid phase. Following Serres et al. (2016), ϵ_L is thus referred to as the *apparent* liquid holdup.

Fig. 2b illustrates an example of apparent liquid holdup variations in time, in which the downward peaks correspond to gas bubbles crossing the image. The frequency content of $\epsilon_L(t)$ is then quantified by means of spatiotemporal diagrams (Fig. 2c) computed with a sliding window of width $\Delta t = 4$ s. The main frequency f_0 is extracted by computing the median value of the frequency corresponding to the maximum peak in the spectrum

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