Chemical Engineering Science 60 (2005) 6235 – 6239

Chemical Engineering Science

www.elsevier.com/locate/ces

The liquid spreading on porous solids: Dual action of pores

R.N. Maiti, R. Arora, R. Khanna, K.D.P. Nigam*

Department of Chemical Engineering, Indian Institute of Technology, Delhi, Hauz Khas, New Delhi, India 110 016

Received 18 November 2004; received in revised form 30 April 2005; accepted 9 May 2005
Available online 21 June 2005

Abstract

Experimental observation of the dual effect of pores in liquid spreading over porous substrates, whereby liquid movement is facilitated as well as restricted is presented based on spreading of micro-liter-sized liquid drops on substrates that have saturated (filled) millimeter-sized pores. The drops were put on porous and nonporous parts of solid substrate. The substrate was then rotated in vertical direction and the resulting motion of drops was recorded by a video camera. The analysis of the recorded images revealed that depending on whether the drop edge is moving toward the pore or away from the pore, the pore acts as accelerator or brake for the drop edge. This dual nature of the saturated pores can be ascribed to the attraction between the liquid in the drop and the liquid inside the pore. Qualitative changes in the morphology of the drop as it slides over saturated pores are also presented to highlight the process. This dual effect of pores is expected to play a major role in processes such as flow through a trickle bed of porous catalyst where it manifests itself in increased wetting efficiencies as well as pronounced hysteresis [Khanna, R., Nigam, K.D.P., 2002. Partial wetting in porous catalyst: wettability and wetting efficiency. Chemical Engineering Science 57, 3401–3405; Maiti et al., 2004. Enhanced liquid spreading due to porosity. Chemical Engineering Science 59, 2817–2820; 2005. Trickle-bed reactors: Porosity induced hysteresis. Industrial and Engineering Chemistry Research, in press.]

Keywords: Liquid spreading on pores; Pinning of contact line; Trickle bed reactor; Wetting efficiency; Hysteresis

1. Introduction

Spreading of liquid over porous solid surfaces is very important in several fundamental and technological scenarios including packed bed adsorbers, trickle bed reactors, coating and printing or painting of porous surfaces. Davis and Hocking (1999, 2000) provided a framework to look at the competition between the imbibation by the pores and spreading to determine the lifetime of drops over porous bases. Recent efforts by Starov et al. (2002a,b,c, 2003) have also provided a valuable insight into the mechanics of the process based on Brinkman's equations for description of flow inside the porous layer and by lubrication and continuum theory for liquid drop flow over it (Starov, 1983; de Gennes, 1985). On another front, the school of Khanna and Nigam (Khanna and Nigam, 2002; Maiti et al., 2004, 2005) have been trying to develop a new framework for studying liquid spreading over porous solids with a view to explaining various wetting efficiency and hysteresis issues in trickle bed reactors. They have predicted several extra features in spreading/retraction of liquid over internally wet porous particles based on *a thought experiment* of tracking the movement of the three-phase (gas–liquid–solid) contact line. They modeled the surface as alternating patches of saturated pore and solid surface. As liquid spreads, the contact line will move over either liquid-filled (saturated) pores or solid-catalyst surface. Whenever the contact line comes across the edge of the liquid-filled pore, it is expected to accelerate and cross the patch to reach to other end. During retraction, the same contact line is expected to be held up by the saturated pore. Maiti et al., 2004 used the above conceptual model to point and explain certain anomalous observations in trickle bed reactor operations such as relatively more liquid spreading on porous but less wettable particles in comparison to non-porous but more wettable particles (Ravindra et al., 1997).

* Corresponding author. Tel.: +91 11 659 1021; fax: +91 11 658 1120.
E-mail address: drkdpn@gmail.com (K.D.P. Nigam).

0009-2509/$ - see front matter © 2005 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ces.2005.05.022

Recently, Maiti et al. (2005) extended the above model to include the concept of participating and nonparticipating particles and explained the difference between the hysteretic behavior of porous and nonporous packings (Ravindra et al., 1997) in trickle bed reactors.

The core input to the conceptual model (Khanna and Nigam, 2002) and subsequent applications (Maiti et al., 2004, 2005) is the dual nature of the saturated pores during the spreading and retracting phenomena. Though, not at all being counter-intuitive, this dual nature has not been proven experimentally. The current work provides this experimental verification and presents the various stages of the motion of drops over saturated pores.

2. Experiments

Experiments were carried out with double distilled deionized water on iron in air. A cuboid block of solid of dimensions 35 mm × 35 mm × 10 mm was used as substrate. Several blind holes of 3-mm diameter, which were carefully drilled into half of the substrate, served as pores (Fig. 1). The other half served as nonporous surface. Having both nonporous and porous parts on the same block provided for a better comparison between behavior of liquid drops on pores and nonporous parts of the substrate. The pores were filled with liquid till a visible drop formed outside the pore. The pores were allowed to have as much liquid as they could retain by running off the excess liquid by slowly inclining the substrate. This was done to make sure that the pores are *saturated* with liquid. Liquid drops of equal and known volume were deposited by a micropipette over the pores and nonporous parts of the substrate when it was in horizontal position. This substrate was then rotated in the vertical plane at different angular frequencies by using a rotator, which was specially designed for the experiments. The sliding motion of the drop was observed and recorded in real time by a CCD camera. This rotator could be rotated with a controlled angular frequency ranging between 1° per minute and 20° per minute with a provision to stop at any given inclination and restart from there. This was done to make sure that enough waiting time can be provided at every inclination to let the drops attain equilibrium.

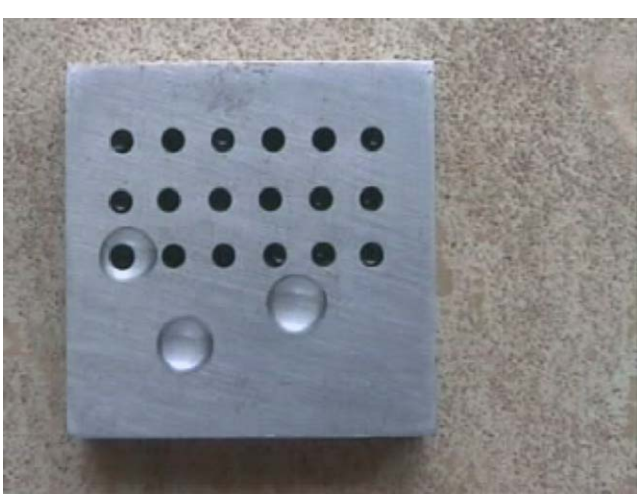

Fig. 1. Top view of the substrate. The pores are of 2-mm diameter. The liquid drops can also be seen resting on the substrate.

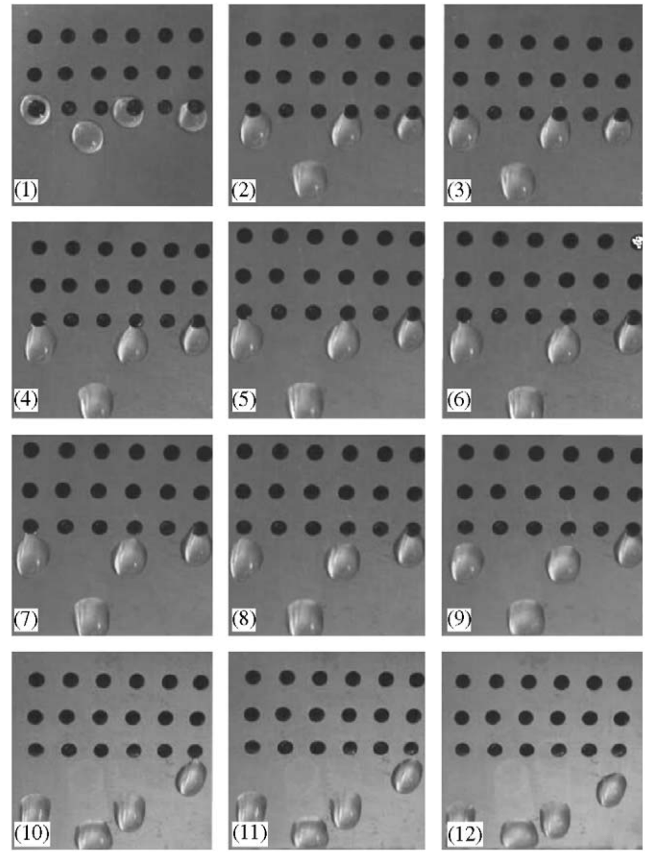

Fig. 2. Top view of one of the experiments of Set 1. The increasing picture numbers denote increasing inclination.

The experiments consisted of three different sets of experiments to firmly establish the dual nature of saturated pores. All these sets involved observing the motion of liquid droplets as inclination is increased gradually. The observations as top views are reported in Figs. 2–5, respectively, as numbered sequences of pictures. Increasing picture number denotes increasing inclination. The sets were different with respect to position of initial placement of the drops on horizontal substrates. The first picture in each of Figs. 2–5 describes the initial placement of the drops. The zoom was adjusted for each set to suit the requirement. The details of various sets are as follows:

- *Set* 1: In the first set, some drops were placed on the pores and some on the nonporous part of the substrate in horizontal position (Picture 1, Fig. 2).