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Capillary force required to detach micron-sized particles from solid surfaces—Validation with bubbles circulating in water and 2 μm-diameter latex spheres

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ABSTRACT

The adhesion forces holding micron-sized particles to solid surfaces can be studied through the detachment forces developed by the transit of an air–liquid interface in a capillary. Two key variables affect the direction and magnitude of the capillary detachment force: (i) the thickness of the liquid film between the bubble and the capillary walls, and (ii) the effective angle of the triple phase contact between the particles and the interface. Variations in film thickness were calculated using a two-phase flow model. Film thickness was used to determine the time-variation of the capillary force during transit of the bubble. The curve for particle detachment was predicted from the calculated force. This curve proved to be non-linear and gave *in situ* information on the effective contact angle developing at the particle–bubble interface during detachment. This approach allowed an accurate determination of the detachment force. This theoretical approach was validated using latex particles 2 μm in diameter.

1. Introduction

Numerous processes in the chemical and food industries, and in medical applications, involve contact between a fluid flow and a previously contaminated solid surface. On the contaminated surface, microorganisms form biofilms that develop in successive steps: reversible adhesion, anchoring (production of extracellular polysaccharide) and coadhesion of planktonic bacteria to already-attached bacteria. The adhesion forces depend on the development stage and structure of the biofilm [1,2]. Some of the microorganisms in the biofilm may be detached from the surface by the flow, which thus propagates the contamination downstream. The detachment of microorganisms represents a potential health safety risk that needs to be controlled. In addition, research on cleaning methods seeks to optimize the removal of fouling deposits to facilitate the detachment of microorganisms. In both cases, knowledge of the force required to detach microorganisms is a key factor when assessing the risk of contamination or efficiency of cleaning. From a more theoretical point of view, the force of detachment provides indirect knowledge of the force of adhesion between the solid surface and particles, which depends on electrostatic, van der Waals and Lewis acid–base interactions [3,4]. During this study, microorganisms were considered as single micron-sized particles corresponding to the initial stage of microbial contamination or the early stage of biofilm development. Particle detachment forces were developed by the slow transit of an air–liquid interface (a bubble in a flow of water).

The detachment of particles by the transit of an air–water interface involves several complex effects including interface–particle film thinning, variation of adhesion forces, particle movements during detachment, "bumping" of detached particles on still-attached particles, capture of particles by the bubble, etc. In the case of bacteria, detachment can also be affected by initial particle distortion in the near-wall region. These effects are complex and cannot be predicted using a single complete and reliable model in which all the variables are soundly based on theory or literature knowledge. In the present study particles were considered as rigid spheres, and variation of adhesion forces during detachment, particle movements and "bumping" of particles were not taken into account.

The detachment of micron-sized particles by circulating bubbles has been studied experimentally in several studies [5–10]. The

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experimental percentage of detached particles was compared with the average value of the capillary force. The contact angle used for force calculations was deduced from standard macroscopic measurements. Percentage particle detachment and average capillary force are shown to be at their greatest at low bubble velocity, and to decrease linearly with increasing velocity. However, from a physical point of view, the average effect of the capillary force is unlikely to be maintained at its peak value as bubble velocity falls to zero because as the film thickness decreases, capillary forces become oriented towards the wall. Force and particle detachment will decrease when velocity reaches zero. There are no detachment data in the literature for bubble velocities between zero and that corresponding to the highest percentage of detached particles. This lack of data can probably be explained by the experimental difficulty in moving bubbles at very low velocities.

During this study, the entire air–liquid interface was calculated and used to determine the time-variation of the capillary force during transit of the bubble. The contact between particle and air–water interface locally modifies the curvature of the interface, but the surface covered by this interface is much greater than the surface covered by all the particles. Thus the profile of the bubble interface was calculated without taking into account the presence of particles. The particle detachment curve was predicted throughout the bubble velocity range: from near zero velocity to the highest velocity value, at which capillary force vanished. Contact angle value was directly determined from the shape of the experimental detachment curve. The approach was validated using latex particles with a diameter of 2 μm, which corresponds to the mean size of most bacteria (1 μm) and yeasts (5 μm).

2. Simulation of particle detachment

2.1. Physical processes causing detachment

Experiments on particle detachment were performed in right cuboid flow chambers made of two large parallel plates held apart by two very thin side walls. The problem can be considered as two-dimensional, with a bubble circulating in a flow of liquid between two infinite parallel plates. In this study the bubble spanned the width of the flow chamber, and interception of the particle by the air bubble depended solely on the thickness of the liquid film between the bubble interface and the plates. Friction forces exerted by the slowly moving fluid can be calculated by classical hydrodynamic relations and proved negligible compared with other forces when the distance between the particle and the bubble interface exceeded several microns [11]. For smaller particle–bubble interface distances viscous effects became very marked. They generated a force of repulsion which destabilized and broke the fluid layer between particle and interface. Layer break caused the particles to "jump" in the bubble under the action of capillary forces, and a three-phase contact (TPC) line to form. In this study it was assumed: (i) that contact between particles and bubble interface lasted much longer than the time needed for fluid layer break (induction time), and (ii) that as soon as the particles were detached from the wall they adhered to the bubble interface and were transported away. This second assumption is supported by experimental results obtained by AFM proving that the particle–bubble adhesion force is appreciable for hydrophobic particles with contact angles greater than 20–30° [12–15].

Finally, only the forces favorable to detachment (*i.e.* away from the wall) were taken into account. The approach followed is presented schematically in Fig. 1. Variation of film thickness $e(t)$ was calculated as a function of time t, using a two-phase flow model, the results of which were compared with analytical solutions found in the literature. This film thickness was used to calculate $\phi(t)$ and the magnitude of the capillary force $F_\gamma(t)$ by:

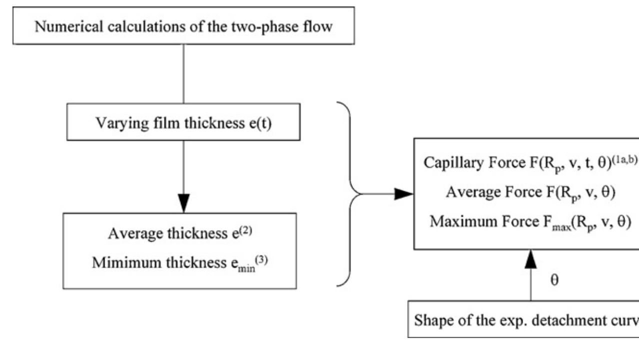

Fig. 1. Schematic diagram of the approach followed to determine the detachment force due to the transit of the bubble.

$$\phi(t) = \frac{a\cos(e(t))}{R_p - 1} \quad (1a)$$

$$F_\gamma(t) = 2\pi R_p \gamma_{lv} \sin(\phi(t))\sin(\theta - \phi(t)) \quad (1b)$$

where R_p is the radius of the particle, γ_{lv} is the surface tension of the liquid (water $\gamma_{lv} = 72.8\,\mathrm{mN\,m^{-1}}$) and ϕ and θ characterize the location of the contact points at the surface of the particle and the three-phase contact angle between the bubble interface and the particle, respectively. This relation can be considered as accurate for spheres with a diameter smaller than 450 μm, but it does not take into account the effects of line tension and curvature, which can be significant for small particles and large values of surface tension of the liquid [16–18].

2.2. Calculations of the film thickness

The motion of bubbles and calculations of the thickness of the liquid film between bubble interface and walls of capillary tubes have been studied by Bretherton [19]. The interface was divided into three main regions: the front and rear menisci and a middle region where the film thickness was constant and equal to:

$$e = e_0 + 1.3375\ \mathrm{Ca}^{2/3} R \quad (2a)$$

$$\mathrm{Ca} = \frac{\mu V}{\sigma} \quad (2b)$$

where Ca is the capillary number, μ is the fluid viscosity, V is the flow velocity, σ is the interfacial tension and R is the radius of the capillary. It was assumed by Bretherton that the liquid film would vanish when the bubble was stationary ($e_0 = 0$). This is, of course, not practically possible because during air injection the bubble cannot enter the capillary if there is no film of fluid between the capillary wall and the bubble [20]. The thickness of this preliminary film depends on the conditions of injection and on the hydrophilic/hydrophobic nature of the surface of the walls. For moving bubbles, Bretherton [19] also described undulation of the air–water interface just upstream of the rear meniscus, leading to a minimum film thickness e_{min} given by:

$$e_{min} = 0.716e \quad (3)$$

More recently, flow patterns and film thickness were calculated numerically by Giavedoni and Saita [21,22]. These calculations were performed using finite element techniques separately on the leading front and rear part of the bubble, which was assumed to be very long. Bretherton's relation was confirmed for capillary numbers between about 10^{-3} and 10^{-2} and a recirculation region was observed in the flow upstream of the bubble [21]. On the rear part of the bubble, the size of the interface undulation increased when the capillary number was small. The detailed shape of this