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A comparison of methods for measuring the induction time for bubble–particle attachment

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ABSTRACT

Froth flotation is an exceedingly complex physicochemical process. The convenience of distilling much of the complexity of the particle–bubble interactions into a single parameter has led to the continuing popularity of the classical ‘induction time’ to quantify the threshold for particle–bubble attachment to occur. Despite this popularity and the simplicity of the concept, there is no single universal method of evaluating the induction period.

In this paper, we begin with a critical review of the available techniques for estimating the induction period. These are: back-calculation from experimental (micro)flotation tests; pushing a particle toward a stationary bubble (or *vice versa*) using an atomic force microscope (AFM); pushing a bubble toward a stationary bed of particles in the ‘*Induction Timer*’; pushing a bubble toward a stationary solid surface using the ‘integrated thin film drainage apparatus’ (ITFDA); and dropping particles onto a submerged stationary bubble using the ‘*Milli-Timer*’ device. Each one of these methods has advantages and disadvantages, and the best choice depends on the application.

In the experimental section, we present quantitative comparison of the induction periods estimated using two different techniques, namely the *Induction Timer* and the *Milli-Timer*. The same particles were tested in each device, under the same conditions. It was found that by tuning the operation of the particle pick-up device, similar estimates of induction period could be obtained to the estimates made by direct observation with the *Milli-Timer*. In the former device a bubble is driven toward a particle bed at a controlled rate, whereas in the latter a particle’s motion is governed by the hydrodynamics. The potential to match these presents an intriguing prospect for better understanding the bubble–particle interaction, and the possibility to ‘calibrate’ the simpler *Induction Timer* against direct observations.

1. Introduction – quantifying the tendency to attach

For froth flotation to be successful, a sequence of several sub-processes needs to occur. For one thing, the chemistry needs to be such that at least one of the particle classes will favour adherence to the air bubbles introduced into the cell. For another thing, the hydrodynamics should be set so that the particles and bubbles collide frequently and vigorously enough to have opportunity to attach, but not so aggressively that particles simply bounce off the bubbles or that particle–bubble aggregates are quickly ripped asunder after attachment. These sub-processes occurring in the pulp are systematically covered *inter alia* by Nguyen and Schulze (2004). There are also important sub-processes taking place in the froth layer. The froth phase sub-processes are less extensively covered in the literature (for overviews see e.g. Klassen and Mokrousov (1963: 353ff.) and Ata (2012)), but in any case have no direct effect on bubble–particle attachment.

With an understanding of the complexity of the interactions, for the practical task of operating a flotation cell there is a benefit to distilling information from the underlying mechanisms into a single parameter. This is a function served by the induction period (or induction time), τ. The induction period is a measure of the time required to form an attachment between a particle and a bubble (Sven-Nilsson, 1934; Nguyen and Schulze, 2004: 257f.), which may depend on e.g. the surface chemistry, particle shape, particle and bubble sizes, bubble and particle trajectories, and their relative velocities (Albijanic et al., 2010; Verrelli et al., 2011, 2014).

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Nomenclature

v_a	relative approach velocity of particle and bubble toward each other
τ	induction period
AFM	atomic force microscope
IT	Induction Timer
ITFDA	integrated thin film drainage apparatus
MT	Milli-Timer

That induction period is compared against the time available to form an attachment. In the case of a head-on collision between particle and bubble (Nguyen and Schulze, 2004: 257f.), this would be the 'dwell time', during which the two objects are in close proximity, with a narrow, liquid-filled gap between them. Considering the geometries involved, and the swirling nature of flow within the pulp of a real flotation cell, glancing encounters between particles and bubbles are likely to be more common; in this case the particle is seen to 'slide' over the bubble's surface before either attaching or withdrawing (Verrelli et al., 2011). Here the period available for attachment is called the 'sliding time'. For simplicity we will refer to both dwell and sliding times herein as dwell times.

The basic concept is that τ is intrinsic to a given class of particles, while the dwell time is characteristic of a specific operating condition of a flotation cell (or a region within the cell) – or the operation of a given laboratory device. It turns out that the reality is somewhat more complicated than this.

The induction period can be important in determining the eventual flotation grade and recovery in industrial operations. It has also been demonstrated through computational modelling that the ultimate grade and recovery is likely to become most sensitive to induction time for cases involving 'borderline' materials, i.e. particles that are difficult (not impossible) to float (Koh and Verrelli, 2014).

Several alternative experimental means have been used to estimate τ. Each one has its own unique advantages and disadvantages, which we critically review and summarise in the following. What is also missing in the literature is a quantitative comparison of estimates across different devices. Here for the first time we present measurements on the same sample with the *Induction Timer* and the *Milli-Timer*.

2. Survey of experimental techniques

As mentioned above, there are several experimental techniques available to estimate τ. Before discussing the individual techniques, let us consider the 'ideal' measurement. In this ideal measurement:

- The time period would be unambiguously defined, and directly measured.
- The test procedure would be consistently implemented, it would be fast, and not require expensive instruments or highly-specialised skills to operate.
- The test conditions would replicate the dominant (controlling) sub-mechanisms from a flotation cell, and the results would be relevant to industrial operation.

While this perfect technique does not exist, the available techniques are still useful. There are five main options, as illustrated in Fig. 1, and discussed below.

2.1. Back-calculation from batch flotation tests

As the induction period relates exclusively to particle–bubble attachment, it has been estimated from microflotation tests which eliminate effects from the froth layer and pulp entrainment. These involve passing a slow stream of individual bubbles through a dilute, fluidised bed of particles, as in a Hallimond tube (Hallimond, 1944) – or, more likely, a modified version thereof (Kitchener, 1984). The collection efficiency is then measured.

To estimate τ from the collection efficiency requires some approximation of the governing relation. One formula that has been prominently reported in the literature is the so-called Generalised Sutherland Equation (GSE) (Dai et al., 1998). Regardless of its name, this formulation is derived from a number of assumptions that are strictly not true, such as not fully accounting for the size of the

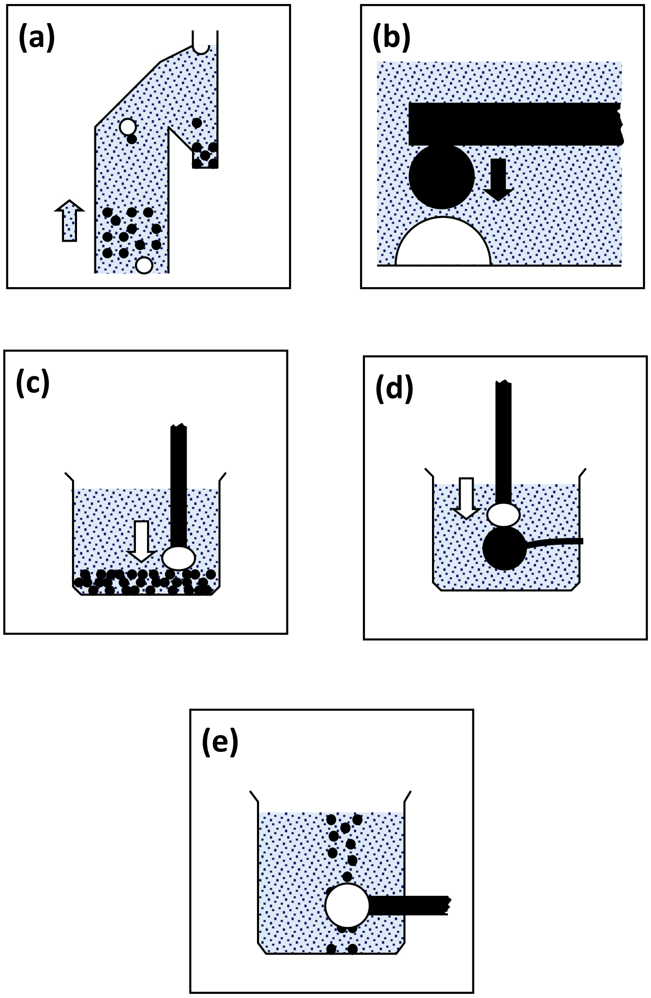

Fig. 1. Schematics illustrating the experimental techniques under discussion – not to scale. (a) Microflotation. (b) Atomic force microscope. (c) *Induction Timer*. (d) Integrated thin film drainage apparatus. (e) *Milli-Timer*. Other embodiments of the techniques are possible. Solid shading represents solids, the patterned areas represent liquid, and unshaded regions represent gas. The arrows indicate externally imposed motion of the respective phase, beyond any buoyancy or sedimentation effects due to gravity.