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Fish hook in classifier efficiency curves: An update

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ABSTRACT

Fish hook in classifier efficiency curves has been receiving attention in the last three decades, more so with the advent of laser diffractometry. In the first part of this paper, we analyse two occurrences of fish hook reported recently in Separation and Purification Technology. It is shown that in both the cases, inaccuracies in measured particle size distributions could be the likely cause of the observed fish hook. In the second part, we re-examine the present state of knowledge on fish hook including the limitations of experimental observations reported so far and the drawbacks of theoretical explanations. Finally, we provide a basis on why it is to be considered nothing more than a scientifically insignificant *placebo*.

1. Introduction

Typically, in any classifier, recovery of particles to underflow, the actual efficiency, can be expected to increase monotonously with size. However, an inflexion in the efficiency curve showing a dip at sub sieve sizes, now commonly referred to as 'fish hook', was reported in early 1980s [1]. Since then, a considerable number of occurrences of fish hook and theories to explain this phenomenon have appeared in literature. In the first part of this paper, we discuss the reliability of two recent occurrences of fish hook [2,3] and show that these could be due to erroneous particle size distributions.

In the second part, we re-examine the present state of state of knowledge on fish hooks and show that experimental observations of the phenomenon reported so far are not based on robust data. We then explain why it cannot be regarded as a scientifically significant physical effect. This is followed by an elucidation of why theoretical explanations proposed so far need considerable improvement. Finally, we show why exclusion of fish hook in simulation models is of little consequence for all practical purposes.

2. Discussion

The precision and accuracy of the efficiency curve in classifiers are dependent on particle size distributions (PSDs) from which they are derived. If the mode of particle size analyses is not specified, the reliability of the PSDs and consequentially the accuracy of the efficiency curve cannot be ascertained. The efficiency curve reported by Lv et al. [2] is subject to this limitation of PSDs of unknown precision and accuracy as they have not disclosed their method of size analysis. However, we can take note that Yang et al. [4] and Yang et al. [5], who are members of the same group and affiliated to the same institution, used Mastersizer 2000. As such, it can be reasonably inferred that Lv et al. too used the same instrument for size analysis.

Noticeably, Lv et al. [2] reported near zero efficiency of ultra fines (near zero sized particles) as shown in Fig. 1. The curve they obtained is remarkably similar to the efficiency curves (Fig. 2) reported by Majumder et al. [6] and Bourgeois and Majumder [7].

In a second report [3] discussed herein, the authors used Microtrac S3500 for determining the PSDs. The efficiency curve reported by them shows a gradual decrease in efficiency with size reaching a minimum, followed by a monotonous increase, a shape most common in fish hook literature.

While Laser diffractometry (LD) is a fast and reliable method for determining PSDs over a broad range of sizes, it could give highly misleading results if the technique is not properly applied. We discuss briefly the problems with LD which could be a source of erroneous PSDs and which significantly influence the results and conclusions of Lv et al. [2] and Vakamalla et al. [3]

2.1. Size analysis by laser diffractometry

ISO 13320:1999 for particle size analysis by Laser diffraction methods recommends application of Mie theory for all <50 μm

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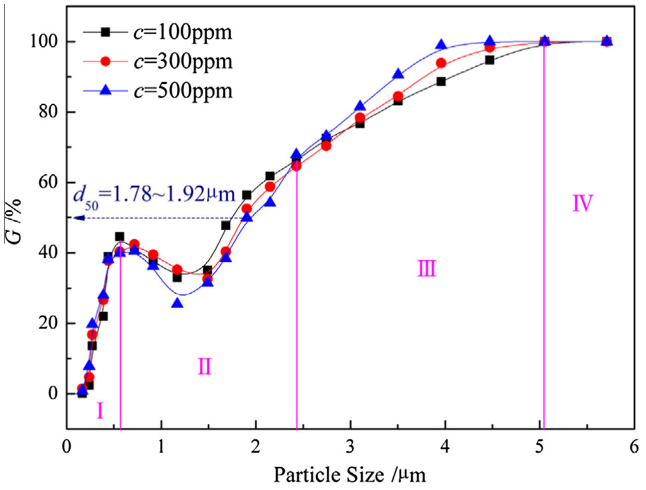

Fig. 1. Actual efficiency curves reported by Lv et al. [2]. Similarity with the curve reported by Majumder et al. [6] (Fig. 2) may be noted. Both report near zero efficiency of near zero sized particles, followed by an increase in efficiency. This is followed by a decrease in efficiency till it reaches a minimum and then a monotonic increase with size.

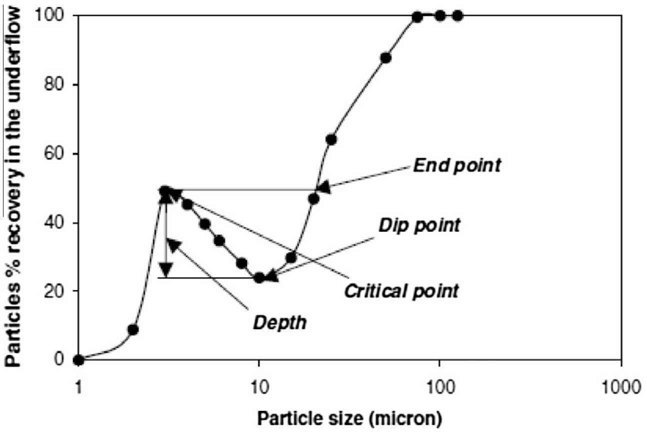

Fig. 2. Efficiency curve showing a fish hook as reported by Majumder et al. [6]. The shape of this curve is distinctly different from all other efficiency curves reporting fish hook. None of them show the initial increase with size till 'critical point'.

particles. Key inputs required for generating theoretical scatter pattern by Mie theory are the refractive index RI, the extinction coefficient (the imaginary refractive index), IRI of the test material and the refractive index of the dispersing medium. During the early years of LD, when computing power was a constraint, Fraunhofer approximation (of Mie theory) was applied for generation of theoretical scatter pattern. This does not require optical properties of test material and as the name implies it generates only an approximate scatter pattern in the sub sieve range. Consequently, whenever Fraunhofer approximation is the optical mode, PSD results are subject to errors in that range.

The software of recent LD instruments includes a database of optical properties of many common materials and dispersants. The data are available as standalone documents as well (for example, [8]). Obviously, where data are "sourced" from these databases, any inaccuracies in the optical parameters become a root cause of errors in the PSDs obtained.

We illustrate this with an example of sourcing RI value for SiO_2 present in the form of crystobalite. From the database issued by Malvern Instruments Ltd [8], we can observe that, for different forms of quartz namely, chalcedony, crystobalite, flint silica, silicon dioxide and tridymite, RI varies from 1.544 to 1.553. Elsewhere, in the same document RI of silica is listed as 1.487 for crystobalite; 1.544 for quartz and 1.468 for tridymite. Clearly, sourcing RI value from this database leads to ambiguity about the true value when SiO_2 is in the form of crystobalite (or tridymite).

Also, it is highly desirable to recheck the data supplied by manufacturers. Rawle [9], reports that for a sample of SiO_2 powder supplied as crystobalite by the manufacturer, the RI was stated as 1.486. The sample actually turned out to be in the form of quartz for which the RI determined experimentally was found to be 1.543.

The imaginary refractive index (IRI) depends on physical properties, such as, colour, surface roughness etc. in addition to chemical composition. Unfortunately, there are no methods by which IRI can be directly measured for use in laser diffractometry. Malvern Instruments Ltd [10] outlines a method for its estimation which relies on the volume concentration (C_v) of particles, a parameter calculated by the instrument. The value of IRI is needed as input for this calculation. The basic principle for this trial and error method involves taking a sample(s) of known C_v and comparing it with the value calculated by the instrument for different assumed values of IRI. That value of IRI for which the agreement between calculated and actual C_v is closest is inferred as the IRI of the test material. It should be noted that to prepare a sample with known C_v, the density of the material needs to be measured.

The influence of optical parameters (RI, IRI) of the test material on the size analysis results from laser techniques has been a subject of thorough investigation. It has been established conclusively [9,11–17] that their influence on the particle size distribution results is significant, more so when the material tested contains <10 μm particles. It is relevant to mention here that one of the objectives of the comprehensive study by Keck and Muller [17] was to clarify whether or not inclusion of optical parameters is necessary as suggested by ISO 13320. Based on a detailed investigation on the influence of RI and IRI on PSDs from LD, they report that depending upon the optical parameters used, the mean size of latex particles 'as measured' varied from:

- 330–905 nm for a tetramodal mixture;
- 284–1005 nm for a trimodal mixture and
- 79–465 nm for a bimodal mixture.

Similarly, for a bimodal mixture, the distributions as obtained from LD were monomodal, bimodal, trimodal, tetramodal and even pentamodal depending upon the RI and IRI values used. Their thorough investigation establishes *conclusively that* ***laser diffractometry for characterisation of sub micron particles gives meaningful results only when correct optical parameters are applied.***

They conclude categorically that any laser diffraction data without information of the optical parameters and also those using guessed parameters must be doubted. They estimate that probably 90% of all published PSD data in sub sieve range obtained from laser diffractometry is false.

It is apparent from the above that by simply selecting the RI and IRI values form databases of the instrument software, or literature or from data provided by material suppliers could cause erroneous inputs for calculation of scatter pattern and hence the resulting size distribution. The only option for getting accurate RI and IRI values of the test materials is to determine them experimentally.

Apart from the necessity to pick up a representative sample [18], for robustness of size analysis results Rawle [9] recommends actual determination of the refractive index (RI) up to two decimal places by Becke line method. Although, PSDs from LD are less sensitive to the value of IRI, determining it experimentally using volume concentration method [10] is recommended. While its value