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Fish hook effect in centrifugal classifiers – a further analysis

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ABSTRACT

Two distinctly different types of fish hooks are reported in literature, of which, the most common shape shows a decrease in efficiency to a minimum followed by a monotonic increase with size. The other shape exhibits an increase in efficiency with size till a critical point is reached; the efficiency then decreases till a minimum is reached, followed by a monotonic increase with size.

Early theories to explain fish hook phenomenon through variable bypass are shown to be simple mathematical transformations. The 'mechanistic model' attributes occurrence of fish hook to a sharp fall in settling velocities in a centrifugal field with change in flow from Stokesian to transient regime. This explanation is shown to be dubious and not in conformity with known principles of physics. Also, the boundary layer model and the entrainment model require considerable refinement as mechanics of fluid flow around irregular particles is not well developed. It is shown that CFD simulations show efficiency curves with or without fish hook effect depending upon the assumptions for simulation.

The method of sizing analyses in detection of fish hook effect is critically discussed. Most of the occurrences of fish hook are reported when sizing analyses are carried out by laser diffractometry using Fraunhofer approximation for data interpretation. When alternate sizing techniques, such as Andreasen pipette, disc centrifuge, Coulter counter, Dynamic Light Scattering etc. are used or when Mie theory is applied in Laser techniques, fish hook is not reported. Fish hook effect appears to be repeatable where it was studied. However, the conditions of reproducibility are to be specified by the proponents, if the phenomenon is to find general acceptance. It is likely that fish hook would continue to be regarded as a placebo. Its exclusion in simulation models does not appear to affect cyclone performance prediction.

1. Introduction

For classifiers, efficiency, defined as the recovery of particles of size, d, to underflow can be expected to monotonously increase with size. However, an inflexion in the efficiency curve showing a dip at sub-sieve sizes has been frequently reported, more so with the advent of laser diffractometry. For hydrocyclones, this dip was first brought to light by Finch and Matwijenko (1977) who christened it as fish hook. A modified Whiten function, which is still in use in JKSimMet, is the first mathematical function to describe an efficiency curve with a fish hook (Kavetsky, 1979).

Although, there are many reports on fish hook phenomenon in the literature, it had not received total acceptance as yet. Its occurrence is reported to be random by Brookes et al. (1984); Rouse et al. (1987) observed it 'at times' and according to Napier-Munn et al. (1996) this effect is seen 'in a significant minority of cases'. Heiskanen (1993) remarks that 'many published Tromp curves show fish hooking'. In fact, Roldan-Villasana et al. (1993) who conducted a systematic investigation of this phenomenon attribute its sporadic and random occurrence for not being accepted unquestionably. More recently, Kilavuz and Gülsoy (2011) and Kraipech et al. (2002) reported fish hooks in all cyclone – material systems studied by them, though it is not prominent in all test conditions. However, Coelho and Medronho (2001) report that no fish hook effect is observed in any of their tests.

In an earlier paper (Nageswararao, 2000), we have critically analysed the origin of fish hook phenomenon, its passive acceptance and theories to explain it. This is a continuation of that paper with the main focus on the more recent theories to explain the fish hook; CFD simulations and a discussion on the techniques of sizing analyses used for detection of this phenomenon. While earlier, we have confined our attention to hydrocyclones only, efficiency curves of all types of centrifugal classifiers including air classifiers, fluidised bed classifiers etc. also are considered in this paper.

2. Shape of the efficiency curve

Since zero sized particles do not exist, the efficiency curve can be thought of as a continuous function defined for all sizes greater than zero only. At an infinitesimally small particle size, say, ϵ, Kelsall (1953)

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conceived it to be equal to water recovery, R_f. A logical extension of this notion is that even when we evaluate the behaviour of individual minerals, the near zero sized particles of all minerals just follow water. That is, even for multi-mineral ores, we can expect that the actual efficiency curves of the ore as well as that of individual minerals start at R_f (Nageswararao, 2000). Del Villar and Finch (1992) actually show such behaviour for coal and a complex sulphide ore.

Laplante and Finch (1984) however differ on this issue. According to them, the starting point of the efficiency curve is dependent on the density of the mineral in conformity with their earlier work (Finch and Matwijenko, 1977). This issue is discussed at length elsewhere (Nageswararao, 2000) and is omitted for brevity.

Conspicuously, the actual efficiency does not start at R_f for near zero sized particles according to most reporting fish hook effect, in tune with Laplante and Finch (for example, Frachon and Cilliers, 1999; Kraipech et al., 2002; Schubert, 2010; Kilavuz and Gülsoy, 2011). However, the shape of the actual efficiency curve reported is typically:

- a gradual decrease from near zero sizes to a minimum
- followed by a monotonic increase with increase in size

as shown in Fig. 1 (Neesse et al., 2004; Schubert, 2004, 2010; Minkov and Dueck, 2012; Dueck et al., 2012a etc.).

The equations which are used to describe efficiency curves with fish hook, (Finch, 1983: Del Villar and Finch, 1992; Roldan-Villasana et al., 1993; Frachon and Cilliers, 1999; Pasquier and Cilliers, 2000; Kraipech et al., 2002; JKTech, 2003) are all for this shape only.

The anomalous shape of the efficiency curve reported by Majumder et al. (2007) and Bourgeois and Majumder (2013) is however distinctly different. It

- starts at zero for near zero sized particles;
- remains constant for some limited size range (Stage 1);
- the efficiency then increases with size till it reaches what they call a critical point (Stage 2);
- a decrease in efficiency follows till it reaches a dip;
- this is followed by a monotonic increase with size.

Stage 1 above may not be prominent at times (Majumder et al., 2007). Figs. 2a and b show typical efficiency curves as reported by them.

The distinctive difference between the shapes of the efficiency curve as reported by Majumder and co-workers (Majumder et al., 2007; Bourgeois and Majumder, 2013) and all other investigators is noteworthy. No other account of fish hook reports Stages I and 2 of the efficiency curve. Interestingly, in an earlier publication Bourgeois and Majumder (Davailles et al., 2012) reported an efficiency curve with a fish hook similar to the commonly observed shape (Fig. 1).

Significantly, the efficiency of near zero sized particles is zero according to Majumder et al. (2007) and Bourgeois and Majumder (2013); it is equal to R_f according to Kelsall (1953) and Nageswararao (2000) in tune with conventional wisdom that near zero sized particles follow water. Notably, the equations for efficiency curve with fish hook (for example, Kraipech et al., 2002; JKTech, 2003) too give similar results.

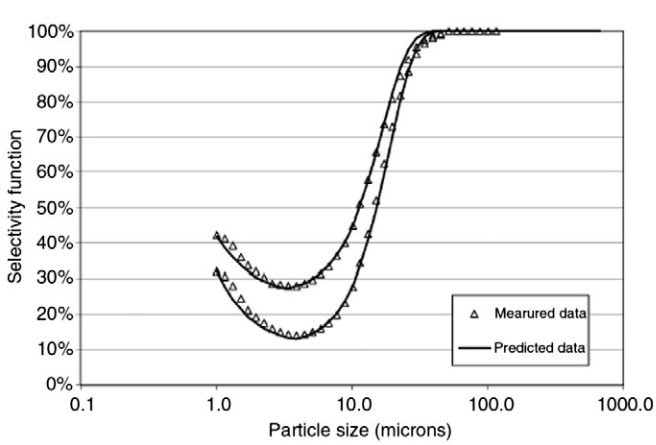

Fig. 1. a. typical efficiency curve showing fish hook (Kraipech et al., 2002).

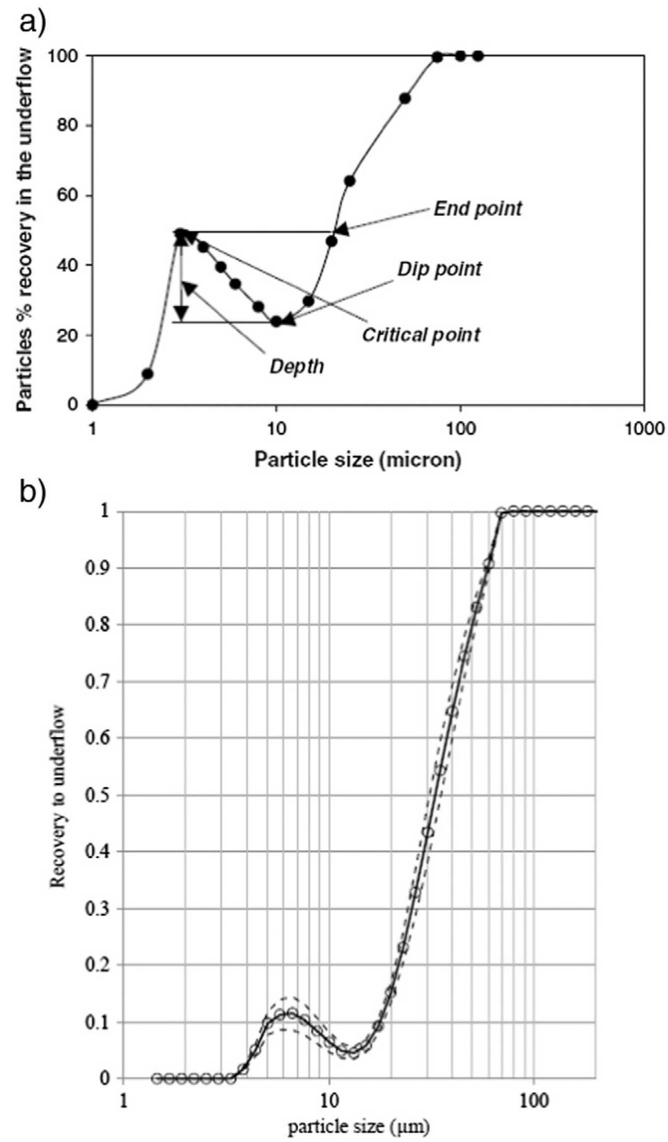

Fig. 2. (a). The shape of the efficiency curve according to Majumder et al. (2007). (b). Experimentally observed efficiency curve showing fish hook in a 100 mm hydrocyclone (Bourgeois and Majumder, 2013).

2.1. Effect of feed size distribution

Zhu et al. (2012a) report that with increasing coarseness of the material the fish hook becomes more prominent. A similar trend is reported by Neesse et al. (2004) and Schubert (2004, 2010).

2.2. Effect of feed solids concentration

Reports on the dependence of fish hook on this important variable are summarised below:

- Schubert (2004, 2010) reports that the dip of the fish hook decreases with increasing solids concentration.
- Neesse et al. (2004) report that the depth increases from 0.01 to 0.04 and reduces as the volumetric fraction of solids, C_v increases to 0.25.