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A critical analysis of the fish hook effect in hydrocyclone classifiers

K. Nageswararao*
NFTDC, Hyderabad 500 058, India

Abstract

The infrequently reported fish hook in hydrocyclone classifiers has been ignored by many or disputed due to its random and sporadic occurrence. The imprecision of measurement of the actual efficiency and the 'uncertainty principle'/observer effect appear to be main factors in its evolution and partial acceptance. Significantly, fundamental models to date do not predict a fish hook. Current theories to explain it based on size dependent bypass mechanism are mere mathematical transformations. It may be of theoretical/academic interest only as its exclusion in simulation models does not appear to affect cyclone performance prediction. This paper attempts to show that it is still a long way before it could be universally accepted as a scientifically significant physical effect.

Keywords: Efficiency curves; Fish hook effect; Hydrocyclones; Classification; Modelling

1. Introduction

When efficiency is defined as the recovery of particles of size, *d*, to underflow, the efficiency curves of hydrocyclones monotonously increase with size. However, an inflexion in the efficiency curve showing a dip at sub-sieve sizes, called fish hook has been infrequently reported. A typical such actual efficiency curve showing a fish hook is shown in Fig. 1.

The fish hook appears to be a mere placebo effect for all practical applications. It may even be viewed as an excellent example to illustrate the *uncertainty principle*, the influence of the scientist on the outcome of the experiment/theory. Nevertheless, the literature on fish hook phenomenon had contributed immensely to our understanding the operation of cyclones. This paper aims at an in depth analysis of its origin, evolution, passive acceptance, theories to explain it and consequential developments.

2. Origin and current status

The earliest report of the fish hook effect in hydrocyclone practice can be traced to Finch and Matwijenko [1] based on experimental studies at the Sullivan and the Pine Point lead–zinc concentrators. They claim that the inflexion observed in the actual efficiency curves of individual minerals to be real and following the nomenclature of Luckie and Austin [2] christened such a dip as 'fish hook'.

In a later paper, Finch [3] cited a few more instances, which are presumed to show fish hooks (see for example, Refs. [4–6]) and proposed an explanation as well for the existence of such an effect. That such a possibility could occur is endorsed by Kavetsky [7] too, who first reported a mathematical function now referred to as Whiten function, for describing efficiency curves with a dip.

The second phase of the evolution of the concept is attributable to Brookes et al. [8] and Rouse et al. [9]. An important observation by them is its random occurrence. More recently, Williams and colleagues [10–12] have strongly advocated the effect supported by extensive experimental data on small diameter cyclones treating dilute slurries.

Kelly [13] too endorses the existence of the phenomenon. However, he does not add any new experimental evidence of his own. Further, we should mention that Hinde [14,15] also cites occurrences of fish hook and suggested an alternate mathematical function as well to fit the experimental data.

It is also relevant to note that although, experimental work was done with fine feeds, which involved determination of sub-sieve size distributions, it is not reported by other research groups [16–20] etc.

Significantly, JKSimMet incorporates the modified Whiten function [21] to take into account a possible fish hook. However, no research work specifically on this phenomenon is reported by JKMRC, possibly due to their emphasis on industrial application in their programmes (see for example, Ref. [22]). Occasional instances are however, reported periodically [23,24], etc. The current understanding and consensus on this topic is well documented by Heiskanen [25].

* Fax: +91-40-4440592.
E-mail address: nftdchyd@hd1.vsnl.net.in (K. Nageswararao).

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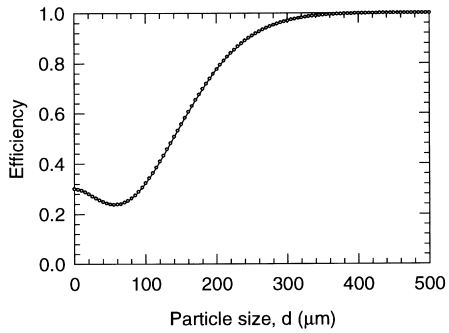

Fig. 1. Typical actual efficiency curve showing a fish hook.

3. Experimental and theoretical basis

Despite strong support for its existence, the fish hook has not yet received widespread acceptance. In order to understand the reasons, it is necessary to review and analyse its origin, experimental basis and the theories proposed to date. These are discussed below.

3.1. Experimental basis and assumptions

As mentioned earlier, Finch and Matwijenko [1] are to be credited for first reporting this effect. The results of *one test each* on cyclones at Sullivan and the Pine Point lead–zinc concentrators formed the basis for their observation.

They reported collection of *averaged* samples, collected every 15 min over a period of 2 h, around the cyclone in the case of Sullivan concentrator. Although, cyclone feed was collected from two different points (discharge end of the head tank and the pump sump), the sample actually used for all subsequent analysis was that taken at the discharge end of the head tank which feeds a cluster of three cyclones. This feed sample was a composite collected at the beginning, in the middle and at the end of the sampling campaign. At the Pine Point concentrator, the samples were single samples collected at the discharge head, which feeds the cyclones and the product streams.

Although, the feed and product size distribution data were balanced assuming that all size fractions have the same standard error for the Sullivan data, the observed efficiency curves were taken to be exact. For the Pine Point data, the efficiency curves were calculated from the product streams. Interestingly, the data from feed samples appears to have been ignored.

Their results included the individual mineral and overall efficiency curves. The mineralisation was assumed to be galena, pyrrhotite, marmatite and silica for the Sullivan ore; and galena, pyrite sphalerite and calcite/dolomite for the Pine Point ore. Individual mineral classification curves were determined on the assumption that the circulating load could be determined from size–weight assay of the feed and product streams. *The implicit assumption that the minerals are fully liberated at all size fractions should be noted*. It is noteworthy that no corroborating data to support such assumption was provided.

Further, we may note that their data could not have been precise enough to demonstrate fish hook effect as claimed is obvious from the following:

- Although, feed samples were collected at two different points (discharge into the head tank and pump sump), at the Sullivan concentrator, their analysis is based on feed collected at one point only as it gave better correlation with their observations, presumably in tune with their expectations. That experimental errors are significant enough to influence their conclusion is also obvious from the efficiency curves (Fig. 4 of their paper) shown, based on α readjustment technique (α is the weight fraction of feed reporting to underflow according to their notation) and the reconstituted feed technique.
- In the case of Pine Point concentrator, they calculated the efficiency curve based on product streams and did not include the feed sample in their analysis for cross checking, although, feed data were collected.
- They cite Kelsall et al. [26] and note that the minimum efficiency observed for the composite, a, to be the same as a_{m} for individual minerals and equal to water split, R_{f}. Nevertheless, they postulate that $a \neq a_{\mathrm{m}} \neq R_{\mathrm{f}}$ based on their experimental data. They mention however, the known difficulty in reliable R_{f} estimation. However, they hypothesise that the minimum efficiency measured for individual minerals a_{m}, to be the starting point for the curves. This contentious assumption is discussed in detail later.
- It is also worth noting that in any industrial sampling campaign, process fluctuations could occur in the mill-classifier circuit. Thus, their data and conclusions are also subject to the implicit assumption that the circuit behaved the same way throughout the sampling period.

Despite the above limitations, they claim, in all cases, except for the silica in the Sullivan circuit, the Y (actual efficiency according to their notation) value for the finest fraction was greater than the preceding value, thus tending to emphasise Fish hook. The observational theory of Finch is also subject to the interpretative theory namely that average size of the particles as determined is the same 'as what the cyclone senses as the size'.

Although, all the above could be considered as valid objections to accept Finch's contention regarding the fish hook, we could still go by the Popperian methodology [1] [27,28]

[1] According to Popper, scientific theories are an outcome of unjustified (unjustifiable) anticipations, speculations, guesses and tentative solutions to our problems or *conjectures*. It is neither possible nor necessary to justify them inductively. Once a theory is proposed, it is subjected to testing where an attempt is made to refute it. Confirming/corroborating evidence is to be viewed as a serious but unsuccessful attempt to falsify/refute the theory. A theory surviving tests acquires a degree of credibility and could then be considered as tentatively established. However, it can never be proved or disproved either.

and accept the observational theory of Finch. However, it appears that his theory is refutable using his own data.

Roldan-Villasana et al. [11] too acknowledge that errors involved in performing particle size, slurry density and flow rate measurements are substantial and require a careful analysis prior to interpretation of raw results. However, they opine that data reconciliation techniques and sub-sieve sizing with modern instrumental techniques are important factors, which could help in detection of this phenomenon. This is questionable on two counts.

Firstly, data reconciliation cannot make bad data into good data. Additionally, their observation that the tip of the fish hook sometimes raises well above the normal R_f value contradicts their own assumption for their 'revised mechanistic model'. This raises doubts on the precision of their data.

Secondly, it is common knowledge that the results of reconciliation would be affected depending upon the standard errors assigned for each size fraction. No information on the weights used for each individual size fraction, which would have given an indication regarding the precision of measurement, was provided.

Nevertheless, they conclude that the anomalies observed at the fine end are real based on reconciled data of unknown/unspecified precision. While for getting a general idea about the cyclone performance, such a procedure may be acceptable, for substantiating an otherwise irreproducible and contested (as they themselves record) phenomenon such as the fish hook, their data analysis is perhaps inadequate.

Finally, Roldan-Villasana et al. [11] confirm the significant observation of Brookes et al. [8], namely, the sporadic and random occurrence of fish hook. They opine that this is the main reason why it has not been universally accepted. Interestingly, they provide no indication on the frequency of occurrence (under identical conditions) for their own data.

Kelly [13] too ignores the possible errors in the sampling, analysis and interpretation of Finch's data, while advocating the fish hook effect, despite the earlier reservations expressed by Flintoff et al. [29] on the subject. That he had not supported his contention with additional data is noteworthy.

3.2. Minimum actual efficiency — phenomenological considerations

An important factor in the interpretation of the data by Finch and Matwijenko is the starting point on the efficiency curves, that is the efficiency of zero sized particles. According to them, the minimum efficiency of solids is dependent on the density of the specific mineral.

In this context, we may reiterate that the distribution of zero-sized particles into the products in the same proportion as water is not only logical but also consistent with the known theoretical principles governing the motion of solids in fluid media. That is, the fine particles just follow water. This in fact formed the basis for Kelsall's bypass mechanism [30] that particles of all sizes just follow water in the same proportion as water.

We may also recall the mathematical analysis of Criner [31] and Bloor and Ingham [32], which too corroborate that the minimum actual efficiency would be same as R_f. A logical extension is to assume that even when the feed to cyclone consists of particles of zero-sized particles of different densities, the recovery of these fine particles would be same as that of water irrespective of the density. In other words, it is plausible to assume that the actual efficiency curves of individual minerals as well as the overall curve start at R_f in the case of multi-mineral ores [33].

The experimental results of Bednarski [34] with feed materials of different feed densities, also indicate such conclusion within limits of experimental errors. The data of Kelsall et al. [26] too corroborates such conclusion as noted by Finch and Matwijenko. Furthermore, Laplante and Finch [35] remark, 'The [*actual efficiency*] curves show a smooth decrease with particle size to a value approximately equal to water split' for the individual components in primary cyclones at BMS and MLM concentrators. It is also relevant that for modelling the overall curve as the sum of the component curves, they assume that the short circuit fraction is same for both (light and heavy) the components and equal to water recovery. However, they state that their assumption is contentious and note, ' The shape of the [*efficiency*] curve at the fine end may also be unusual', in conformity with their earlier work (Finch and Matwijenko [1] and Finch [3]).

The anomaly of the assumption that efficiency curves of individual components start at different points, an important foundation for their assertion (of fish hook) may be noted.

Further, one of the assumptions of the revised mechanistic approach proposed by Roldan-Villasana et al. [11] is that '... the hydrocyclone splits the flow causing solids to be divided in at least the same ratio as R_f (considering that the finest particles follow the liquid flow and split in the same ratio as the fluid)'. This can be seen to be in conformity with the theoretical considerations. Yet, elsewhere in the same paper they observe that 'the tip of the fish hook (that is the fine particle end of the curve) *sometimes* [italics ours] raises well above the nominal R_f value', implying that zero sized particles do not follow water — a contradiction with the current belief and understanding.

Furthermore, as rightly pointed out by Frachon and Cilliers [36], the models of both Finch and Del Vilar and Roldan-Villasana et al. predict an efficiency equal to R_f as the particle size approaches zero, inconsistent with their experimental observations.

Also, the current theories to explain the fish hook (Finch [3], Del Villar and Finch [37] and Roldan-Villasana et al. [11]) are all based on the assumption that correction to gross efficiency is due to size dependent bypass compared with constant bypass for all size fractions as suggested by Kelsall [30]. Kelly [13] too suggested that the preliminary proposal of linear size dependence of bypass suggested by Finch [3] is a good approximation to a probable curvilinear relationship.

However, we had shown that no physical/process significance could be attributed to bypass and refuted Kelsall's mechanism (Nageswararao [33]). This is due to the fact that we cannot distinguish by any experimental technique, whether any particle/group of particles reach underflow/overflow due to bypass or centrifugal action. As such, what Kelsall proposed is to be regarded as a mere mathematical transformation. Consequently, the theories proposed to explain the fish hook too could be considered as mathematical transformations.

It is noteworthy that shear induced flocculation of fines during classification but dispersion during size analysis, is suggested as a possible explanation for fish hooks. However, Heiskanen [25] quoting Pekkarinen [38] notes that the shear fields where flocculation can take place are far lower than the shear field obtained in small diameter cyclones. Furthermore, Rouse et al. [8] observed fish hooks even with pure easily dispersed alumina. Moreover, we may note that theoretical/phenomenological models *to date* [for example [31,32,39–44]] do not predict any fish hook effect.

Finally, it is appropriate to remark that for an unusual phenomenon such as fish hook to be accepted by all, observational evidence based on precise measurements or theoretical explanation based on sound fundamental principles is required.

4. Anomalous features

We can identify typical observer dependent features also with the phenomenon of fish hook. These are mainly because the magnitude of the effect is feeble/undetectable. As the precision of measurement of efficiency is poor, the effect becomes ambiguous and detected randomly. These are discussed in detail below.

4.1. Uncertainty principle — the observer effect

As pointed out by Goldstein and Goldstein [45], a useful metaphor to explain anomalous phenomenon or theories thereof is the uncertainty principle. They argue that the scientists are also part of the experiment/theory and their influence on the outcome cannot be ignored. Consequently, their attitude [2] influences the outcome of the experiment (observations) or the theory proposed.Specifically with regard to the theme of this paper, the following are worth noting:

- Austin and Klimpel [5] do not even mention the word fish hook anywhere in their paper. Their primary concern appears to be the minimum actual efficiency of solids. Their important conclusion is that it need not be equal to R_f, under all circumstances. Further, the monotonously increasing smoothed efficiency curve proposed by them implicitly indicates that they attribute the dip to experimental errors rather than possible fish hook.
- Klimpel [6] reports 'The availability of sub–sieve data which was *not* collected in this work, would help clarify the assumption of *a* ('*a*' is the bypass fraction according to his notation) being proportional to the water fraction and the possible existence of a fish hook in the smaller size range'. Of interest is his observation that the reported classifier efficiency is subject to errors. Again, monotonously increasing smoothed actual efficiency curves were presented implicitly ignoring the fish hook.
- Tilyard [4] too does not report any anomaly in the efficiency curve. He specifically states, 'cyclone development has been hindered by the difficulty of sampling around one (modified) cyclone in a cluster'. The mass flows quoted are 454 tonnes/h of mill feed and 3040 tonnes/h of cyclone feed to a cluster of four cyclones.

This author too found sampling to be the most challenging task during his experimental campaign at Bougainville Copper Ltd. [48].

None of the above conducted sub-sieve size analysis. Therefore 'clearly it [*Fish hook*] can not be observed if no experimental data on this fraction are collected', according to Roldan-Villasana et al. Nevertheless, all the above were cited as examples showing fish hook both by them and Finch. Interestingly, the data of Plitt [49], (for example, see Fig. 6 of his paper) is not cited as an example of fish hook, though, the dip is more prominent than any of the above.

It is also relevant to note that Finch's papers [1,3] could have influenced subsequent researchers into giving a serious consideration, if not a total belief in the existence of fish hook effect. Further, unusual efficiency curves with multi-mineral ores (for example, Laplante and Finch [35] and Hinde [14,50], which are plausible and reproducible [15], also could have influenced the belief in fish hook.

It is apt to remark that, for establishing this phenomenon conclusively, it is necessary to quantify the depth of the fish hook in relation to the precision of measurement of the actual efficiency. Until then, it could continue to be ignored or disputed due to the operation of the uncertainty principle.

4.2. Random occurrence — irreproducibility

A characteristic feature of the fish hook effect is its sporadic and random occurrence. As Roldan-Villasana et al. [11] confirm, 'it is not always observed in all the experimental runs performed under similar conditions'. Brookes et al. [8]

[2] As Lyttleton [46] elaborates, 'if an idea comes to the awareness of a scientist, he will begin to adopt some attitude to it. This will result in some interaction of the idea with all his previous experience, remembered or not, and these will combine of their own accord to determine an attitude'. In this context, the comments of Popper [28] are also relevant. He notes 'observation is always selective. It needs a chosen object, a definite task, an interest, a point of view, and a problem'. The object or point of view 'for the scientist is provided by his theoretical interests, the special problem under investigation, his anticipations, the theories which he accepts as a kind of background, his frame of reference and his horizon of expectations'. Gardner [47] gives an excellent account of the uncertainty principle/observer effect in operation.

too report the effect in only 30% of the total 48 runs. Rouse et al. [9] report fish hook 'at times', while Napier-Munn et al. [21] record that, 'in a significant minority of cases a fish hook is seen'. Heiskanen [25] notes that 'many published Tromp curves show fish hooking'. Significantly, details of the conditions under which the fish hook is *reproducible* are not available.

In this context, the definition for *scientifically significant physical effect* proposed by Popper [27] as that 'which can be regularly reproduced by any one who carries out the appropriate experiment in the way prescribed', is relevant. Although, Popper categorically dismisses such effect for whose reproduction no instructions are given as an 'occult effect', we may keep the issue of fish hook open following the suggestion of Lyttleton [46].

4.3. Placebo effect

We may recall the observations of Roldan-Villasana et al. and Napier-Munn et al. [21] that the effect could be observed only if sub-sieve sizing is done. However, even when sub-sieve sizing was done, it had not been reported by many other research groups. This implies that probably, the depth of the fish hook is not significant compared with the precision of measurement of the actual efficiency. We may therefore infer that excluding it in simulation models causes little difference in the prediction of cyclone performance [15]. No reports to the contrary are available in literature. Therefore, it may be appropriate to treat it as a *placebo effect* at this stage.

4.4. Theory and observation — a paradox

As Lyttleton [46] notes, the observations of phenomenon are first needed to inspire someone to conceive a theory. However, the observations cannot be claimed to be properly understood until a formal theory of them is available. That is, *facts* can be authentic only if explained by hypotheses/theories, whether right or wrong. Yet, *evidence* is required for any theory to be acceptable. This paradox is clearly noticeable for new phenomena for which, there are no theoretical means to assess the relevance of observations.

In the context of the fish hook effect, this paradox at this stage is highly relevant. Clearly, there is a need to establish the engine or cause of the phenomenon.

Finally, any research programme may be called *progressive* if it leads to prediction of new facts [51]. Based on this criterion, we may consider the research programme of Finch to be one of the most progressive. It started as an observational theory. Later, to explain the fish hook, the constant bypass hypothesis of Kelsall is amended to a size dependent bypass. Eventually it provided the basis for the refutation of the bypass hypothesis itself [33]. With hindsight, we could say that the observation of the so-called fish hook by Finch and his subsequent explanation for its existence, as crucial in our understanding of hydrocyclones.

5. Summary

(1) The precision of measurement of the actual efficiency has not been taken into consideration in reporting the occurrence of fish hook effect in hydrocyclone classifiers. In addition, its occurrence is sporadic and random under identical conditions. There is a need to predict the conditions under which it is reproducible. (2) In the light of recent observation by the author that the so-called bypass, suggested by Kelsall is a mere mathematical transformation, the explanatory theories based on size dependent bypass causing the fish hook are refuted automatically. Thus, there is also a need to establish the engine or cause as to why it should occur, if at all. (3) The exclusion of this irreproducible phenomenon in simulation models does not seem to affect cyclone performance predictions. Hence, it appears to be of theoretical/academic interest only. (4) It is desirable that further work be continued in this direction, as this would necessarily involve quantification of the precision of measurement of the efficiency. Irrespective of whether the phenomenon is real or not, the results of such investigations could advance our understanding of the classification phenomenon in general and the accuracy of prediction of simulation models in particular.

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