Powder Technology 297 (2016) 106–114

Contents lists available at ScienceDirect

Powder Technology

journal homepage: www.elsevier.com/locate/powtec

Modelling of hydrocyclone classifiers: A critique of 'bypass' and corrected efficiency

K. Nageswararao

Taijasa Consultants, 10-116, Visalakshi Nagar, Visakhapatnam 530 043, India

ARTICLE INFO

Article history:
Received 3 February 2016
Received in revised form 29 March 2016
Accepted 9 April 2016
Available online 16 April 2016

Keywords:
Classification
Actual efficiency
Centrifugal efficiency
Reduced efficiency
Normalisation
Empirical models

ABSTRACT

In early 1950s, Kelsall visualised the classification process in which a fraction of feed solids reaches underflow without undergoing classification in a hydrocyclone. We bring to light that this notion of 'bypass' is beyond experimental reach and is purely imaginary. This implies that the corrected efficiency, which is a key performance characteristic in all the successfully used hydrocyclone models and for which bypass is the foundation is also hypothetical.

We discuss the reasons for the continued acceptance of a physical meaning to 'bypass' among the hydrocyclone practitioners. Following a discussion on why the classification process as visualised by Kelsall is purely notional, we bring to light the lack of an experimental basis for 'bypass' and why no physical meaning can be attributed to it. A mathematical interpretation of the method suggested by Kelsall for calculating corrected efficiency is also presented.

A general method for normalising any function $y = f(x)$ where x and y vary between x_{min} to x_{max} and y_{min} to y_{max} respectively into $Y_n(x)$ where the range of Y_n is from 0 to 1, is then proposed. We show that this normalisation can be done in an infinite number of ways by choosing user defined normalising functions and demonstrate our method with a numerical example. Taking into consideration that classifications function is a special case of $y = f(x)$, we show that it too can be normalised in an infinite number of ways. While illustrating our method with examples, we show that the procedure suggested by Kelsall is the simplest method to normalise actual efficiency curves. The similarity between bypass and normalising functions is illustrated with examples; it is shown that both of them are purely notional and have no physical significance.

We bring to light the possibility of development of improved hydrocyclone models using a normalised cut size other than Kelsall cut size. Finally, we propose that the corrected efficiency be denoted as Kelsall efficiency and the corrected classification size as Kelsall cut size, as a tribute to the landmark contribution of Kelsall towards modelling of hydrocyclones.

1. Introduction

A conspicuous feature of the efficiency curve, of a hydrocyclone classifier, that is, the size-recovery relationship of the feed particles to the coarser product, is its non-zero minimum value. To explain this regular observation, Kelsall [1] proposed an innovative and ingenious explanation that a fraction of feed solids 'bypass' to underflow without undergoing cyclone action. Based on his conceptualisation of the classification process, a hypothetical 'centrifugal efficiency', more commonly referred to as the corrected efficiency, $E_c(d)$, could be calculated for which the minimum starts at zero for near zero sized particles. Over the years, the corrected efficiency curve and its derivative, the corrected cut size, d_{50c} have become standard parameters for comparing cyclone performance at different design and operating conditions. They continue to be key parameters in all the hydrocyclone models currently in use [2]. Simultaneously, there is an increased consensus among the mineral processors that bypass is an integral part of the true classification process.

In this paper, we discuss how a perception regarding a physical meaning to bypass evolved and strengthened. We bring to light that the parameters such as tonnage of feed bypassing to underflow, feed subjected to cyclone action and the feed reaching underflow due to cyclone action are only notional and cannot be determined experimentally. We show that as such, bypass can only be notional as it is derived from notional quantities and therefore cannot be part of the classification process actually taking place within the cyclone. This is followed by a mathematical analysis of the method suggested by Kelsall for transforming the actual efficiency to corrected efficiency.

We propose a general method to normalise any function $y = f(x)$ where y varies between y_{min} to y_{max} and x between x_{min} to x_{max} to $Y_n(x)$ such that the range of Y_n is 0 to 1. We demonstrate that this normalisation can be done in an infinite number of ways through user defined normalising functions. It is shown that the technique for

E-mail address: nageswararao.karri@gmail.com.

http://dx.doi.org/10.1016/j.powtec.2016.04.016
0032-5910/

normalisation of actual efficiency to ‘corrected efficiency’ developed earlier [3] is only a special case of the general method.

We illustrate the normalisation procedure of a typical actual efficiency curve by generating different normalised curves from it using different normalising functions. We show that the method suggested by Kelsall is the simplest. The analogy between Kelsall bypass and normalising functions is also illustrated with a numerical example.

Evidently, lack of an experimental basis for bypass is not a constraint for the normalisation of actual efficiency curves and its continued usage in the modelling of hydrocyclones. In fact, it is now possible to choose a normalising function so that the normalised curve is closer the actual efficiency curve than the Kelsall curve. That is, there is a scope for exploring the possibility of using a normalised cut size other than Kelsall cut size and the corresponding reduced efficiency curve for development of improved hydrocyclone models.

Finally we propose that it would be highly appropriate that the corrected efficiency be denoted as Kelsall efficiency and the corresponding cut size as Kelsall cut size, as a tribute to the landmark contribution of Kelsall towards modelling of hydrocyclones,

2. Centrifugal/corrected efficiency

In the development of modelling of hydrocyclone classifiers, ‘corrected efficiency’, the notion conceived by Kelsall [1], is unquestionably a landmark contribution. It paved the way for development of comprehensive mathematical models of hydrocyclone classifiers. In this section, we trace its origin; practical utility and how the concept of ‘bypass’ started gaining acceptance as a true representation of the classification process. We re-examine this notion based on fundamental principles and show that it is only a mathematical transformation. The method for calculation of corrected efficiency proposed by Yoshioka and Hotta [4] is also explained.

2.1. Origin of bypass and corrected efficiency

The classification process as visualised by Kelsall [1] is shown in Fig. 1. Here is an extract: ‘… *A knowledge of cyclone operation leads to the conclusion that if x% is the fraction of the total water which is discharged through the underflow then, independent of any centrifugal forces acting on particles, x% of all particles must leave through the underflow. The additional percentage of particles of a given size which are discharged through the underflow is a measure of the efficiency of elimination of solids due to the cyclone action.…*’

The above conceptualisation on the mechanism of classification is the basis for transforming the actual efficiency curve which varies from R_f to 1 to a hypothetical ‘centrifugal/corrected efficiency’ for which the range is from zero to 1. The more common nomenclature for this performance characteristic is the ‘corrected’ efficiency.

The corrected efficiency curve and the corrected cut size could be used conveniently and effectively to compare the performance of cyclones at different design and operating conditions and accordingly received acceptance without any reservations.

Notably, Yoshioka and Hotta [4] too recognised the necessity for a performance characteristic for comparison of actual efficiency curves and independently proposed a procedure to calculate the corrected efficiency. They are also the first to report the reduced efficiency curve, a plot of the corrected efficiency against dimensionless particle size (d/d_{50c}).

2.2. Physical significance to bypass

Bradley and Pulling [5] are among the earliest who concurred with Kelsall and Yoshioka and Hotta that actual efficiency needs to be corrected for comparative purposes; the notation used by them is centrifugal efficiency. They proposed an equation for the corrected classification size as well. Although, Yoshioka and Hotta [4] are the first to develop a comprehensive hydrocyclone model for which the corrected cut size (d_{50c}) and the reduced efficiency curve are key performance characteristics, an extensive and effective usage of these parameters is attributable to Lynch and colleagues [6–9]. While the Lynch and Rao [6] hydrocyclone model is based on extensive test work on large hydrocyclones (15 cm–50.8 cm units) with concentrated feed slurries, the base data for the model developed by Yoshioka and Hotta is obtained with dilute suspensions and laboratory size units (7.6 cm–15.2 cm units).

Successful application of the Lynch–Rao model [6–11] in the operation and control of grinding circuits in industry marked the beginning of a wide spread use of corrected cut size d_{50c} and the reduced efficiency curve A schematic representation of bypass or short circuit of feed to underflow as presented by them [9] is shown in Fig. 2.

The Lynch-Rao model paved the way for continued usage of the bypass concept and corrected classification size in all hydrocyclone models developed since then [12–23] etc. The continual success of these models in industrial applications for example, [24–27] strengthened the perception that bypass is a true representation of the classification process within the hydrocyclone. A widespread usage of commercial software packages such as JKSimMet and Limn® could be another important reason why a physical significance to bypass and ‘corrected’ efficiency became an integral part of the conventional wisdom in hydrocyclone practice. It is apt to say that the classification process continues to be perceived by the mineral processing community as visualised by Kelsall [1] and Lynch and Rao [9]. In fact, these days a ‘physical’ meaning to ‘bypass’ is so widespread that it is part of standard text books in mineral processing for example [27].

A knowledge of cyclone operation leads to the conclusion that if x% is the fraction of the total water which is discharged through the underflow then, independent of any centrifugal forces acting on particles, x% of all particles must leave through the underflow. The additional percentage of particles of a given size which are discharged through the underflow is a measure of the efficiency of elimination of solids due to the cyclone action.

If y% is the experimentally determined fraction of particles of a given size eliminated via the underflow, then $(y-x)$ % is the fraction eliminated from a total of $(100-x)$ % due to cyclone action. Consequently $\left(\frac{y-x}{100-x}\right) \times 100$ is the corrected percentage of particles of a given size eliminated through the underflow as a result of centrifugal forces within the cyclone.

Fig. 1. The concept of ‘bypass’ and centrifugal efficiency in the words of Kelsall [1].