Chemical Engineering Science 158 (2017) 304–313

Contents lists available at ScienceDirect

Chemical Engineering Science

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

A numerical study on efficient recovery of fine-grained minerals with vortex generators in pipe flow unit of a cyclonic-static micro bubble flotation column

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ARTICLE INFO

Keywords:
Cyclonic-static micro bubble flotation column (FCSMC)
Pipe flow unit
Fine-grained mineral
Vortex generators
Streamwise vorticity
Computational fluid dynamics (CFD)

ABSTRACT

In the past decade, intensive research has proved that the cyclonic-static micro bubble flotation column (FCSMC) is an efficient flotation device which can be used to separate fine-grained minerals. The main way to strengthen the recovery of fine-grained minerals is further improvement of the highly-turbulent flow field of the pipe flow unit in the flotation column. With a decrease of fine-grained mineral diameter, the turbulence intensity in the pipe flow should be increased so as to strengthen the recovery of the fine-grained mineral. In this paper, the effect of vortex generators (VGs) on the turbulence kinetic energy and the turbulence dissipation rate in a pipe flow unit are primarily investigated by numerical simulations. The results showed that a staggered arrangement (S=20 mm) exhibited the maximum volume-averaged turbulence kinetic energy and volume-averaged turbulence dissipation rate among different arrangements of VG arrays in the pipe flow unit. Streamwise vorticity was formed behind the VGs along the flow direction. With an increase of VG arrays from 0 to 5, the volume-averaged turbulence kinetic energy increased from 0.015 m^2/s^2 to 0.05 m^2/s^2. Similarly, with an increase of VG arrays from 0 to 5, the volume-averaged turbulence dissipation rate in the pipe flow unit increased from 1.99 m^2/s^3 to 11.8 m^2/s^3. A flotation experiment using coal slime was conducted by using different structures of pipe flow unit (including empty pipe and pipe with different VG arrays). The results showed that cumulative yield and combustible recovery were greatly improved due to the influence of VG arrays. The results of the study are equally beneficial in helping understand the recovery of fine-grained minerals in other separation equipment.

1. Introduction

Froth flotation is a common separation process used to separate fine particles. It is based on the differences in physical and surface chemistry properties of the particles. Flotation columns are widely used as primary flotation equipment to treat fine minerals (Espinosa-Gomez et al., 1988; Han et al., 2014; Martínez-Carrillo and Uribe-Salas, 2008). Among various flotation columns, the cyclonic-static micro-bubble flotation column (FCSMC) (Liu, 2000) shows considerably superior results in its successful application to roughing and scavenging processes in the mineral flotation industry (Zhang et al., 2013). Commercialized in 1994 and patented in 1999 (Liu, 2000, 2002), FCSMC has since been increasingly used (Cao et al., 2009; Li et al., 2012; Yi-jun et al., 2009). A simplified schematic of an FCSMC is shown in Fig. 1. As shown in Fig. 1, an FCSMC consists of a column flotation unit, a cyclone separation unit and a pipe flow unit (Liu, 2002).

The pipe flow unit of an FCSMC is characterized by highly turbulent hydrodynamics environment. The pipe flow unit acts as the main region for bubbles to capture fine refractory minerals (Liu, 2002). It is well known that there are many factors affecting the probability of bubble-particle collision and attachment. Some of these factors include particle size, bubble size and the fluid flow force on a particle during a bubble–particle interaction. Liu and Schwarz (Liu and Schwarz, 2009) developed an integrated CFD-based scheme to predict the effects of both bubble size and particle size on the bubble–particle collision efficiency and they found that the bubble–particle collision efficiency increases with an increase of particle diameter. Nguyen and Evans (Nguyen and Evans, 2002) presented predictions for the bubble–particle interaction forces arising due to the liquid flow in terms of

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http://dx.doi.org/10.1016/j.ces.2016.10.037
Received 31 January 2016; Received in revised form 18 September 2016; Accepted 18 October 2016
Available online 25 October 2016
0009-2509/

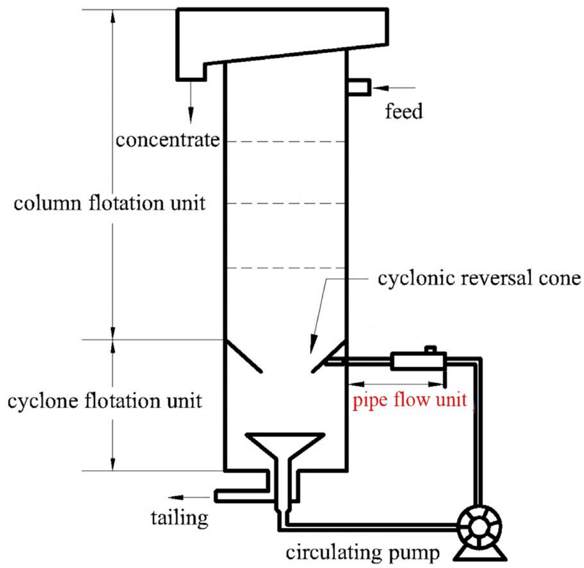

Fig. 1. Schematic of a cyclonic-static micro-bubble flotation column (FCSMC) (Wang et al., 2015).

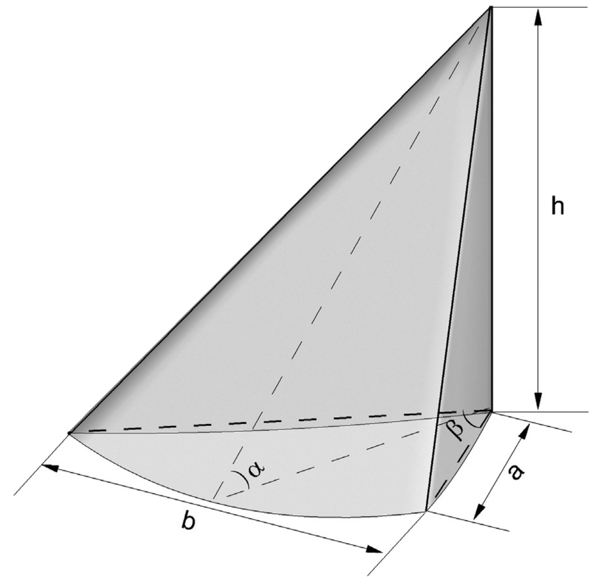

Fig. 2. Geometry of the vortex generator (VG) used in this study.

the separation distances.

In addition, the turbulent flow environment also plays a crucial role in determining the probability of bubble-particle collision and attachment. Koh and Schwarz (2006) reported that the turbulent flow environment plays a crucial role in the probability of bubble-particle collision and attachment. Then, Koh and Schwarz (2003) investigated the distribution of turbulent dissipation rate in the flotation cell using the CFD method, and obtained the result that the probability of collision and attachment increases with an increase in turbulence dissipation rate. Yan et al. (2012) reported that the recovery of fine-grained mineral can be enhanced by increasing the turbulence level in the pipe flow unit in the FCSMC. Accordingly, it is a significant approach to increase the recovery of fine-grained minerals in the FCSMC by increasing the turbulence level in the pipe flow unit. In order to practically achieve this, it is necessary to optimize the inner structure of the pipe flow unit.

With regard to the optimization of the pipe flow unit, several devices can effectively be used to improve the turbulent flow characteristics. One of these devices is the vortex generator (VG). VG was first documented by United and Taylor (1950) and is a device to generate vortices within a fluid's flow. VG has been applied in many fields, such as aeronautics and astronautics, automotive and chemical industry. Research concerning VG has mostly focused on flow separation control (Gao et al., 2015; Lee et al., 2011; Lin, 2002) and heat transfer enhancement (Chokphoemphun et al., 2015; Du et al., 2014; Salviano et al., 2015).

Some previous studies have suggested that VGs can improve the mixing performance. The effects of streamwise vorticity, generated by VGs, on the turbulent mixing have thoroughly been studied by both numerical simulations and laboratory experiments (Mohand Kaci et al., 2009). Gerlinger et al. (2008) performed a numerical investigation of hydrogen/air mixing enhancement by utilizing streamwise vorticity generated by strut geometry (a kind of VG) in supersonic combustion. Ferrouillat et al. (2006) investigated the mixing efficiency in a duct channel with rows of rectangular winglet pairs (RWP) type VGs by a CFD method. The mixing performance, which was enhanced by the streamwise vorticity, was validated and the optimal distance between the VG rows was obtained. Hsiao et al. (2014) studied the enhancement in fluid mixing in a T-shaped micro-channel with winglet pairs (longitudinal VGs) by numerical simulations. Habchi et al. (2010) used CFD simulation and Laser Doppler Anemometry (LDA) to investigate the effects of longitudinal vorticity, generated by table VG, on the turbulent mixing in static mixers.

This paper focuses on the turbulent flow environment in the pipe flow unit of an FCSMC. Several configurations of pipe flow unit with different types of VG arrays were investigated and compared. In order to obtain pivotal flow field information related to the turbulent flow environment in different configurations of the pipe flow unit (such as turbulence kinetic energy and turbulence dissipation rate), a CFD method has been employed. By numerical simulations, the optimal VG arrays arrangement in the pipe flow unit is obtained. Then, serval pipe flow units containing optimal arrangement were manufactured to conduct flotation experiment so as to improve the recovery of fine minerals.

2. Numerical model

2.1. Geometrical model

The VG used in this paper is similar to the one used in a previous study (Panaras and Lu, 2015). The geometry of the VG used in the current study is shown in Fig. 2. The geometric parameters of the VG are as follows: a=b=2.43 mm, h=2.25 mm, α=45°, β=60°. The first row of VGs is mounted on a distance of 20 mm from the inlet of the pipe flow unit.

The pipe flow unit is a circular tube 120 mm in length and 10 mm in inner diameter. The flow direction is the direction of gravity. Three configurations of pipe flow unit, as shown in Fig. 3, were studied in this paper. The details of these configurations are given as follows:

(a) The pipe is equipped with just a single array of VGs. Each array is composed of four VGs rotated at 90° with respect to one another.
(b) The pipe is equipped with dual arrays of VGs in an aligned arrangement. The distance between the two arrays is S=5 mm, 7.5 mm, 10 mm, 12.5 mm, 15 mm, 17.5 mm, 20 mm, 22.5 mm, 25 mm, respectively.
(c) The pipe is equipped with dual arrays of VGs in a staggered arrangement with a stagger angle of 45° relative to the axis. The distance between the two arrays is same as used in the Configuration (b).

2.2. Mesh

2.2.1. Mesh generation

The commercial software ANSYS ICEM CFD 14.5 was employed to