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Pressure drop and flow distribution in a group of parallel hydrocyclones: Z-Z-type arrangement

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ABSTRACT

The mini-hydrocyclone has received increasing attention due to its clear advantages of high efficiency, separating precision and relatively low cost. However, its handling capacity decreases as the nominal diameter of a hydrocyclone decreases. Therefore, a group of mini-hydrocyclones are often employed to meet industrial handling capacity which imposes the difficulty of prediction, analysis, and design of such a group of the mini-hydrocyclone system. There is no theoretical model to evaluate design and operation of the system. The objective of this paper is to develop a general theoretical model to evaluate the flow distribution and the pressure drop in parallel mini-hydrocyclone groups with Z-Z-type arrangement. Detailed analytical solutions were obtained so that they can be easily used to predict the pressure drop and flow distribution under the different flow conditions and geometrical parameters. Furthermore, an experimental apparatus with 12 HL/S25-type mini-hydrocyclones parallel in the Z-Z-type arrangement was set up to verify the model under different inlet pressures. It was found that the theoretical pressure drop and flow distribution were in good agreement with the experimental data. Meanwhile, with the combination of the different theoretical calculation cases, the percentage of relative error will be controlled within 1%. The present model also studied the influence of the split ratio on pressure drop and flow distribution since there were two exhaust headers. The uniformity of these distributions increased as the split ratio increased. This paper provided an easy-to-use design guidance to investigate the interactions among structures, operating conditions and manufacturing tolerance, in order to improve the performance of a parallel mini-hydrocyclone separator group.

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1. Introduction

The separation technology has an increasing wide application in industries from the traditional mining engineering to many new fields, such as material disposal, collection of heavy metals (As, Cd, Cu, Hg, Pb, Zn) from pyrite ashes [1], adsorption of organics with nitrogen and sulfur from wastewater [2], treatment of laboratory wastewater mainly containing nitrate [3], remediation of oil-contaminated soil [4], washing of soil contaminated by a variety of heavy metals and radioactive contaminants [5–7], improvement of the irrigation system [8], oil–water separation [9], purifying coke-cooling wastewater [10,11], separation of CHO cells [12], integrity of animal and microbial cells [13], and so on.

It is well known that the smaller the nominal diameter of a hydrocyclone is, the higher the accuracy will be and the smaller the handling capacity as well. A group of parallel mini-hydrocyclone separators is of great interests due to its clear advantages of high and flexible handling capacity, high efficiency, high separating precision and relatively low cost. The research of Tsai et al. [14–16] and Bai et al. [17,18] demonstrated that the miniaturization of a hydrocyclone has great potential to expand separating precision from micron grade to ions, molecular and aggregates, nanometer sub-micron grade. Nowadays, there is still no clear compromise about suitable size range of the parallel mini-hydrocyclone separation. Fig. 1 shows that the separation accuracy and handling capacity of hydrocyclones have an inflection point at nominal diameter 50 mm [19]. Generally speaking, a hydrocyclone is called a mini-hydrocyclone if its nominal diameter is less than 50 mm. However, a single mini-hydrocyclone has small handling capacity. This has restrained use of mini-hydrocyclones in a large scale yet. Connecting mini-hydrocyclones in parallel will overcome the dual constraints of low power consumption and high separation efficiency, under a low pressure about 0.1 MPa. This represents great potential to meet the requirements of the separating precision and the handling capacity as well as the operational stability for a wide range of industrial applications commercialization. Therefore, multiple hydrocyclones have been used extensively

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Nomenclature

A_{1c}	constant in Eq. (19), defined by Eq. (21)
A_{2c}	constant in Eq. (19), defined by Eq. (22)
B_c	constant in Eq. (27), defined by Eq. (28)
B_{1c}	constant in Eq. (20), defined by Eq. (23)
C	constant in Eqs. (31), (36), (41)
$C_f C_v$	coefficients of the turning losses
$d_i d_c d_d$	diameter of the intake, overflow and underflow of a hydrocyclone (m)
D	diameter of the header (m)
f	fanning friction factor
F	cross-section area of headers or hydrocyclones (m^2)
J	constant in Eq. (27)
$l_c l_d$	equivalent length of the overflow and underflow tube in hydrocyclone (m)
L	length of the intake distribution header of a micro-hydrocyclone group (m)
M	constant in Eq. (19), defined by Eq. (25)
n	number of hydrocyclones in parallel-channel configurations
p	dimensionless pressure
P	pressure in the header (Pa)
r	root of the characteristic equation
R	constant in Eq. (26), defined by Eq. (20)
u	dimensionless channel velocity
U	channel velocity (m/s)
V_c	dimensionless volume flow rate in the channels
w	dimensionless velocity in the header
W	velocity in the header (m/s)
x	dimensionless coordinate in the header
X	axial coordinate in the header (m)

Greek symbols

α	split ratio of the overflow tube and underflow tube
β	average velocity ratio in the header (W_c/W)
ε	constant in Eq. (20), defined by Eq. (24)
ρ	fluid density (kg/m^3)
τ	wall shear stress (N/m^2)
ζ	average total head loss coefficient for the channel flow
v	kinematic viscosity coefficient (m^2/s)

Subscripts

c	overflow tube
d	underflow tube
i	intake distribution header of a micro-hydrocyclone group
e	overflow exhaust header
u	underflow exhaust header

since 1950s [20–22]. There multiple hydrocyclones were arranged in a cylinder or radially. Thus, the number of hydrocyclones in group was limited due to the configurations or issues of flow distribution.

For large scale applications the number of hydrocycolnes increases quickly and may be over hundreds, for example, in the Methanol to Olefins Project of Shenhua Group Corporation Limited, there are about 300 hydrocyclones. A common arrangement of multiple hydrocyclones is parallel. A typical of parallel mini-hydrocyclone group is a system of mini-hydrocyclones, shown in Fig. 2, compositing parallel single mini-hydrocyclone, in which. The system has an intake header and two exhaust headers. One is for overflow called overflow exhaust header, and other for underflow called underflow exhaust header. The inlet and outlet are opposite sides in all the three headers, coined as a Z-Z-type parallel arrangement (Fig. 2) in which flow directions in the three headers are the

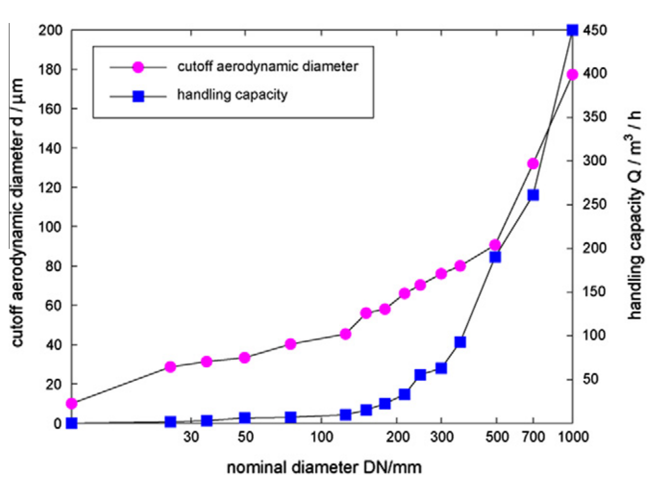

Fig. 1. Influence of hydrocyclone nominal diameter on separating performance.

same. Under the ideal conditions, the handing capacity of a parallel mini-hydrocyclone group is simply the linear sum of unit hydrocyclones under the same separation accuracy as a single mini-hydrocyclone. However, this linear relationship may be difficult to achieve, due to a low pressure, such as 0.1 MPa. Some hydrocyclone separation units may be starved of fluids, while others may have excessive flow, which will reduce the performance of a parallel mini-hydrocyclone group. This situation may be worse due to an uneven flow distribution of the parallel mini-hydrocyclone group. Therefore, the predictions of the flow distribution and the pressure drop are critical to improve separation efficiency and operability in a group of parallel mini-hydrocyclone separators. It is desirable to predict the performance of various parallel mini-hydrocyclone groups under low pressure. Thus, the flow performance can be explored under various geometries of hydrocyclones, resulting in a higher efficiency group and an optimal geometrical structure and cost reduction.

In the past years, many attempts have been made to improve the performance of mini-hydrocyclones using computational fluid dynamics method [19,23], laser Doppler particle analyzer [24,25] and analytical model [26]. However, these researches focused on pressure drop and flow distribution of a single cyclone. In recent years, Wang [27–29] reviewed theoretical models of flow distribution in manifold systems and unified main existing models into a theoretical framework. However, the present system of a mini-hydrocyclone group has an obvious difference from Wang's model. There is a split ratio between two exhaust headers, which represents the flow ratio of the overflow tube and the underflow tube. To the best of our knowledge there is no theoretical model to study the pressure drop and the flow distribution in such a group of parallel mini-hydrocyclones in Z-Z-type arrangement. The new method by Wang's has been extended successfully to the UU-type arrangement [30]. This implied possibility and opens a way to study problems of flow distribution of the Z-Z-type parallel mini-hydrocyclone group.

The objective of this paper is to develop a general mathematical model, based on mass and momentum conservation for prediction

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