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Performance of mini-axial hydrocyclones

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ABSTRACT

Axial or uniflow hydrocyclones have been much less studied than the reversed flow hydrocyclones but can be a viable alternative by providing lower pressure drop losses for the same Reynolds number. An experimental and numerical study of a simple mini-axial hydrocyclone with a diameter of 5 mm has shown that the pressure drop characterised by the Euler number, for a given Reynolds number, is lower than for a reverse flow hydrocyclone. The split ratio was found to be dependent on the relative size of the inlet and outlet cross sectional area. Numerical modelling showed that the use of a tangential feed to simplify the hydrocyclone design, rather than using mechanical vanes, led to recirculating vortices and asymmetry in the flow field. The radial velocities were found to be much smaller than the axial or tangential velocities. In contrast, the RMS velocities were found to be of comparable in magnitude in all three axes. The flow field obtained suggests that the shape of the exits, the location of the vortex finder and reducing recirculation can assist in improving the separation efficiency of an axial flow hydrocyclone.

1. Introduction

Cyclones use centrifugal forces to effect the separation of material based on the density and size of the discrete particle or drop from the surrounding continuous fluid phase. There are two main approaches to the flow direction of the feed and product stream. The common method is exemplified by the reverse flow cyclone, where the heavy and lighter product streams exit the cyclone in opposite directions. In the other approach both product streams exit the cyclone in the same direction; and the device is known as the axial flow or uniflow cyclone. The earliest use of axial flow cyclones has been in the separation of particles from a gas stream by incorporating a set of swirlers or vanes at the entrance located within the body of the cylinder prior to the separation section of the cyclone body (Daniels, 1957; Umney, 1948; Jackson, 1963). The simplest design of the exit consists of two concentric tubes where the particles that impact the cyclone wall are discharged and collected from the outer concentric tube while the cleaned gas exits through the central tube. Later a tangential entry for the feed was incorporated and this form of inlet is often used for axial hydrocyclones. Early studies on axial hydrocyclones performance have been carried out for gas dewatering (Swanborn, 1988; Ng et al., 2006), oil-water separation (Dirkzwager, 1996 ; Dickson, 1998; Delfos et al., 2004; Stone, 2007) and paper pulp separation (Ko et al., 2006) but on the whole, the use of axial hydrocyclones in industry is not widespread and the reversed flow hydrocyclone still dominates the cyclone separation scene.

In the coal industry, the Vorsyl cyclone is an example of an axial flow hydrocyclone (Vanangamudi et al., 1992; Rao et al., 1998; Majumdar et al., 2006) where it has been used for dense media separation with claims of improved separation efficiency but little has been published on the mechanism and operation of this device. It differs from other axial hydrocyclones in that the outlet stream is usually connected to another vessel to control the fluid within the piping. The Vorsyl has not been successful in commercial applications but little is known or published on its shortcomings.

Information available on the performance of axial hydrocyclones in the open literature is minimal, particularly for commercially available units. Most of the information on the performance of axial cyclones have been in the area of gas cleaning or particle removal for either air purification (Stenhouse and Trow, 1979; Maynard, 2000; Hsu et al., 2005; Hsiao et al., 2011) or high temperature applications (Gauthier et al., 1990, 1992 Oh et al., 2015). There have been numerous claims of the benefits of an axial cyclone but there has not been any systematic study on the axial cyclone or detailed comparisons with the reverse flow cyclone. Claims include lower pressure drop due to the flow not reversing (Oh et al., 2015), higher performance (Oh et al., 2015), and ease of fabrication (Tan et al., 2009). However the benefits are dependent on the design and the feed stream being separated. Complex designs aimed at improving the flow characteristics, as well as product streams that require elaborate piping to ensure that the outlet pressure drops are minimal, can add to the difficulty in fabrication.

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Nomenclature

a	width of the rectangular feed inlet, m
a_1, a_2, a_3	constants in Eq. (9)
a'	width of the rectangular flow outlet, m
A_x	acceleration term, m^2/s
b	height of the rectangular feed inlet, m
b'	width of the rectangular flow outlet, m
c	diameter of the vortex finder, m
C_D	drag coefficient of particles
C_s	$=0.1$, constant in the Smagorinsky subgrid mixing length
d	distance to the closest wall in LES, m
d_p	particle diameter, m
D	cyclone internal diameter, m
D_H	hydraulic diameter, m
Eu_{in}	Euler number based on the feed inlet conditions, Eq. (6)
$f(t)$	fraction of particles present at time t
F_D	drag force, N
g	gravitational acceleration, m^2/s
L	length of axial hydrocyclone, m
L_s	mixing length scale, m
P	static pressure, N/m^2
Q	volumetric flow rate, m^3/s
r	radial distance from the centre of the hydrocyclone, m
Re_D	Reynolds number based on the hydrocyclone's internal diameter and average velocity
Re_{in}	Reynolds number based on the feed inlet conditions, Eq. (7)
S	deformation tensor, s^{-1}
t	time, s
$\hat{t}$	dimensionless residence time
T	subgrid-stress tensor, m^2/s^2
u	velocity of fluid, m/s
u_p	particle velocity, m/s
v_{in}	feed inlet velocity, m/s
V	grid volume, m^3
x	dimension, m
z	vertical distance from the top of the vortex finder, m

Greek symbols

κ	$=0.4187$, von Kármán constant
ν	kinematic viscosity, m^2/s
ν_t	turbulent viscosity, m^2/s
ρ	density, kg/m^3
ρ_p	particle density, kg/m^3
Δ	$=V^{1/3}$, local grid length scale, m

Other symbols

$\bar{\ }$	overbar, indicating filtered values
i, j	subscripts i and j indicating coordinates

1.1. Design variations in axial flow hydrocyclones

The earliest design of axial flow cyclones were vane types, where the vanes or swirlers were incorporated into the cylindrical body preceding the separation section. The feed stream and the product streams flowed in the same direction. A large number of different vane configurations for this design have been documented by Jackson (1963). Common to most of the designs was that the cross sectional area available for flow at the vanes was reduced to provide a central supporting frame for the vanes as well as to ensure that the feed stream was rotated but not mixed. The pressure drop due to the vane fixture can be substantial (Swanborn, 1988; Dirkzwager, 1996; Dickson, 1998; Stone, 2007). Past the vanes, the cross-sectional area is expanded and aerodynamic designs of the expansion section are usually implemented to minimise flow separation. Gauthier et al. (1992) introduced a tangential feed similar to that found in reverse flow cyclones, while Dickson (1998) and Dirkzwager (1996) described a number of tangential feed inlet designs including the scroll inlet, involute, straight and helical. To balance out the flow, opposing entry feed inlets are also used where two feed inlet are located diametrically opposite to one another (Oh et al., 2015) and multiple pilot feed ports have been used (Ko et al., 2006). As both the products exit at the same end of the hydrocyclone, a major design constraint has been the management of the piping layout for the outlet flow.

1.2. Numerical modelling of axial flow hydrocyclones

The flow in axial hydrocyclones is similar to that of swirling flows down a circular pipe. There have been numerous studies focussing on the area of mixing for combustion, and heat transfer enhancement (Gupta, Lilley and Syred, 1984). Early work by Talbot (1954) showed that the flow along the circular pipe showed sinuous oscillations that reduced swirl but maintained laminar flow conditions for $Re_C > 1800$ while for $Re_C > 2500$ the flow started to form periodic eddies that initiated turbulent flow. For low swirl numbers (< 0.25), the tangential velocity profile is predominantly a free vortex while at high swirl numbers (> 1.7) it has a predominantly forced vortex profile (Nissan and Bresan, 1961). Comparing the results of numerical models of axial flow hydrocyclones is difficult as most studies do not have the same design. The first design is that of Gauthier et al., (1990) where the vortex finder occupies most of the cylinder and removes the overflow from the upper section of the axial hydrocyclone. Mokni et al., (2015) showed a Rankine type vortex was present in both the vortex finder and the outer section of the cylinder in the section below the vortex finder mouth. Between the feed inlet and vortex section entry section, the tangential velocity shows a quite substantial free vortex even though the peak tangential velocity was over 40 m/s. The forced vortex formed at the feed inlet was found to focus into and then move down the vortex finder.

The second design is that of Dirkzwager (1996) where a set of vanes is incorporated within the cylindrical body of the hydrocyclone. Kegge (2000) modelled the axial hydrocyclone as an axisymmetric case and did not obtain good agreement indicating that the flow is highly 3-D in nature. Other modelling studies include those of Murphy et al., (2007), Nieuwstadt and Dirkzwager (1995) and Rocha et al., (2009) for $Re_C < 2100$. They all assume that flow would be laminar as with straight flow in a pipe but this criterium is probably not applicable when swirling flow is present. They showed that the swirl number decreased exponentially with distance downstream. The Euler number with axial distance for their cases varied between 12 and 30. Overall the agreement with Dirkzwager's (1996) experimental results was poor for pressure drop and velocities which may be due to their assumption that the flow was laminar.

The third design is the tangential inlet axial hydrocyclone, where the exits are at the opposite end of the cylinder, modelled by Ko et al., (2006) showed that the quadratic (Speziale-Sarkar-Gatski SSG) model outperformed the linear (Launder-Reece-Rodi LRR) models for the Reynolds stress formulation but neither model provided a good match to the experimental data. Modigell and Weng (2000) modelled a similar shaped axial hydrocyclone although the vortex finder was positioned a short distance away from the end. They used the k-ε turbulence model which unfortunately was too dissipative to provide good results.