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Entropy generation analysis on cyclone separators with different exit pipe diameters and inlet dimensions

Lu Duan [a], Xiaolin Wu [a,*], Zhongli Ji [b], Qixian Fang [a]

[a] Department of Chemical Engineering, China University of Petroleum, Beijing 102200, China
[b] Department of Mechanical and Transportation Engineering, China University of Petroleum, Beijing 102200, China

HIGHLIGHTS

- Energy consumption mainly resulted from turbulent dissipation and wall friction.
- Exergy loss increases with V_1 and decreases with $\tilde{d}r$ and K_A.
- Regions near the vortex finder and dust hopper inlet are main energy loss domains.

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ABSTRACT

The method of entropy generation analysis was applied to examine the influences of the exit pipe diameter and the inlet dimensions on the entropy generation in cyclones. The flow fields of the cyclones were simulated using the Reynolds Stress Model (RSM). The simulation results were used to calculate three types of entropy generation caused by direct dissipation, turbulent dissipation and wall friction and then to determine the exergy loss. The results suggested that the exergy loss in cyclones increases with the inlet velocity and that it decreases with the exit pipe diameter and the inlet dimensional parameter K_A. In addition, the energy consumption in the cyclones mainly resulted from the turbulent dissipation and the wall friction. The regions near the vortex finder and the entrance of the dust hopper are the main energy consumption domains in the cyclone. The percentage of the entropy generation around the vortex finder first decreases and then increases with the increase of the exit pipe diameter and K_A, which is the opposite behavior to that around the entrance of the dust hopper.

1. Introduction

The cyclone separator is one of the most important pieces of equipment used in industrial processes. Cyclone separators have been widely used to remove the particles from fluids due to the simple construction, no moving parts and the adaptability to extreme conditions. The pressure drop and separation efficiency are usually two of the most important performance parameters for cyclone separators. Numerous studies have been conducted to reduce the pressure drop, and a number of empirical and semi-empirical models have been established to predict the pressure drop (Ramachandran et al., 1991; Leith and Mehta, 1973; Avci and Karagoz, 2001; Karagoz and Avci, 2005; Zhao, 2004; Chen and Shi, 2007; Wan et al., 2008; Hoffmann et al., 1991). It can be concluded that the low pressure drop can be achieved with large exit pipe diameter, large cone-tip diameter, small inlet dimension parameter, short vortex finder length and high solid loading, etc.

Among these factors, the exit pipe diameter and the inlet dimensions have crucial effects on the cyclone pressure drop (Elsayed and Lacor, 2010). Elsayed and Lacor (2013) studied the effect of the exit pipe diameter on the cyclone performance using the Large Eddy Simulation (LES). The results demonstrated that the maximum velocity and the pressure gradient increase with the decrease of the exit pipe diameter and, thus, improve the separation efficiency and increase the pressure drop. Similar results were also achieved by other experimental and numerical studies (Hesham, 2013; Hoekstra, 2000; Moore and McFarland, 1993). However, Kim and Lee (1990) claimed that an exit pipe with an extremely larger diameter caused little change in the separation efficiency while increasing the pressure drop for a small cyclone. The inlet dimensions also have significant impact on the cyclone performance. Elsayed and Lacor (2011) recommended the optimum ratio of the inlet width to the inlet height based on the simulation results using the RSM and discrete phase model (DPM).

* Corresponding author. Tel.: +86 10 89734336.
E-mail address: wuxl_du@126.com (X. Wu).

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Yang et al. (2013) illustrated that the natural vortex finder shortened with the reduction of K_A. Bernardo et al. (2006) studied the cyclone using the Computational Fluid Dynamic (CFD) method and indicated that the use of a 45° inlet angle effectively increases the separation efficiency and reduces the pressure drop; this result was confirmed by Qian and Wu (2009).

However, the pressure drop only reflects the entire energy consumption in the cyclone and is unable to clarify the mechanism and the location of the energy consumption. The entropy generation analysis method, based on the Second Law of Thermodynamics, provides a new approach to evaluate the energy consumption in the equipment. Bejan (1982, 1996) developed the concept and methodology of minimum entropy generation and deduced the entropy generation rate due to the fluid friction and heat transfer in a fluid element without the chemical reaction and a heat source. Spurk (1997) developed the entropy transport equation. Kock and Herwig (2004, 2005, 2007) ameliorated the model for the entropy generation rate without solving the entropy transport equation. A huge deviation between the results predicted by their model and the Direct Numerical Simulation (DNS) near the wall region was found. Chu and Liu (2009) analyzed the entropy generation rate of the thermal radiation in a high temperature system. The entropy generation analysis is widely used to analyze the flow and heat transfer equipment, such as a centrifugal fan (Behzadmehr and Mercadier, 2009) and heat exchangers with various shapes (Jankowski, 2009; Ben-Mansour and Sahin, 2005; Amani and Nobari, 2011; Biyikoglu, 2009; Kurbas et al., 2007). Duan et al. (2014) first applied the entropy generation analysis method in the research of the energy consumption in the cyclone and built a model for calculating the wall entropy generation. The turbulent dissipation and wall friction were found to be the main factors for exergy loss in a cyclone separator and the regions near the vortex finder and the entrance of the dust hopper were the main energy consumption domains in the cyclone.

The distribution of entropy generation helps identify the regions where energy consumption generates largely in the cyclone, which is of great significance to guide the design of the cyclone. The exit pipe diameter together with the inlet dimensions have large impact on the flow field in the cyclones, and they would even affect the distribution of the entropy generation. Therefore, it is necessary to study the effect of those two geometrical factors on the entropy generation in the cyclone.

In the present study, the flow field of cyclone separators with various exit pipe diameters and inlet dimensions was simulated using the RSM model. A pressure drop experiment was conducted to verify the reliability of the simulation results. An additional study was performed to validate the wall entropy generation model. The exergy loss and the entropy generation were obtained based on the simulated results. Moreover, the effects of exit pipe diameter and inlet dimension on the entropy generation and regional contribution to the energy consumption in the cyclone separator were analyzed.

2. Problem description

The current study considered the Stairmand high efficiency cyclone separator, the dimensions of which are presented in Fig. 1 and Table 1. The non-dimensional exit pipe diameter $\tilde{d}r = De/D$ (the ratio of the exit pipe diameter to the cyclone diameter) and the inlet dimensionless parameter $K_A = (\pi D^2/4ab)$ are presented in Table 1. The ratio of the inlet height to the width a/b is 2.5. Table 1 represents the value of the basic geometrical dimensions of the cyclone separator. Noting that the first five geometrical dimensions are regarded as constant parameters and $\tilde{d}r$ ranges from 0.25 to 0.7, in step of 0.05, while the value set of inlet dimensions is designed to be {5, 10, 12.5, 15, 17.5, and 20}.

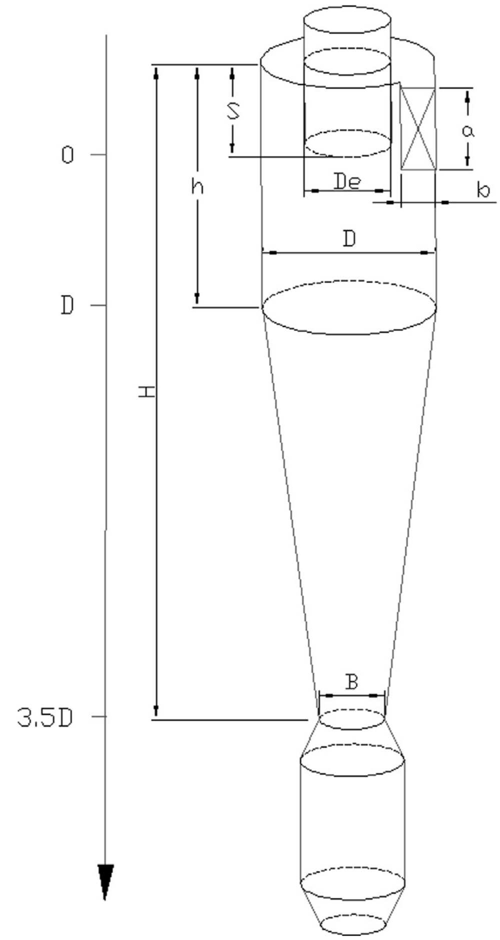

Fig. 1. Schematic diagram for the Stairmand cyclone separator.

Table 1
Geometrical dimensions of the cyclone separator.

Variables	Geometry						
	D/mm	B/mm	h/mm	H/mm	S/mm	$\tilde{d}r$	K_A
Basic	200	75	300	800	100	0.4	7.85

3. Methodology

3.1. Experimental

A set of experiments were performed to measure the pressure drop in the cyclones. The experimental setup is shown in Fig. 2. A blower is applied to draw the air into the cyclone, and the flow rate of the air is controlled by an adjustable valve. Note that pure air at ambient conditions is assumed in the present study. A connection pipe is fitted to change the inlet shape from round to rectangular, providing an orifice for measuring the velocity using the pitot tube. The length of the exhaust gas tube is set to 700 mm to avoid back flow at the exhaust port. One orifice is placed on the inlet tube 300 mm ahead of the cyclone, and the other is placed on the exit tube 100 mm above the roof, through which the static