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OPTIMIZATION AND APPLICATIONS OF REVERSE-FLOW CYCLONES

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Abstract An optimum design approach to reverse-flow cyclones based on the concept of optimizing cyclone dimensions is introduced in this paper. This approach involves optimizing cyclone dimensions by categories, calculating cyclone performance by correlating similitude numbers and optimizing the combination of four cyclone parameters, D, K_A, $\tilde{d}_r$ and v_i, which has been proven to be applicable not only for single-stage cyclone, but also for multistage cyclone separators. Applications of the designed cyclones in FCC units and acrylonitrile reactors are also presented.

Keywords cyclone, optimum design, separation efficiency, pressure drop, FCC unit, acrylonitrile reactor

1. Introduction

Cyclone separator is one of the oldest and most popularly used gas-solid separation devices characterized by low investment and operating costs, and can be used on heavily loaded gases, at high temperature and high pressure. Actually in some processes at high temperature (up to 1000 ^{o}C) and pressure (up to 10 MPa), cyclones are currently the only dedusters available, since these harsh conditions almost exclude the application of other high-efficiency separation devices, such as filters and electric precipitators. Some of the best examples are cyclones employed in Fluidized Catalytic Cracking (FCC), modern coal conversion and combustion processes. Recognizing the above status, many companies, universities and research organizations have, over many years, increased their efforts to optimize cyclone designs to offer true industrial particulate control devices for these extreme operational conditions. These activities cover basic design questions such as maximization of separation efficiency under a given pressure loss or reliable prediction of cyclone performance and fundamental investigations on the gas-solid flow in cyclones. Also, material selection and manufacturing methods are optimized and operational configurations have been developed which ensure highest possible performance and reliability under operational conditions. Over the last two decades, considerable efforts, have been extended into the research and optimization of cyclone design and operational performance at the University of Petroleum, China (Sun et al., 1989; Sun & Shi, 2002; Shi et al., 1993; Shi et al., 1997; Chen & Shi, 2003), and this paper gives an introduction to the design approach of a reverse-flow cyclone with plane top and volute inlet (so-called PV^{TM} cyclone) and applications of PV^{TM} cyclone in FCC units and acrylonitrile reactors.

2. Optimum Design of Cyclone

Publication on cyclone optimization is scarce, probably because, up to the recent past, no single theory could predict, with reasonable accuracy, the behavior of a cyclone of arbitrary geometry and operating under different conditions. Also, it is most unlikely that the optimum design could be found by experimental testing, as too many design parameters are involved. Thus the problem of the optimization of cyclones has been tackled mostly on a trial-and-error basis (Zenz, 2001; Liden & Gudmundsson, 1997). For extreme operating conditions of high temperature and high solids loading, cyclones are required to be manufactured from suitable materials and with proper linings. Consequently, the configuration of lined cyclones should not be too complex for reliable operation. Based on a number of experiments on cyclone performance and the study of gas-solid flow pattern in cyclones, an optimum approach to the design of reverse-flow cyclones has been developed at the University of Petroleum, China. This approach involves optimizing cyclone dimensions by categories, calculating cyclone performance by correlating similitude numbers and optimizing the combination of four cyclone parameters (Shi et al.,1997), thus providing a practical means of designing cyclones for numerous applications.

2.1 Optimization of cyclone dimensions by categories

A cyclone separator with a spiral inlet has many dimensions (Fig. 1). For a long time, the effects of these dimensions on cyclone performance have been analyzed only qualitatively, and methods for quantitative determination of optimum dimensions have not been reported. From detailed studies on the reverse-flow cyclone performance, it was found that the dimensions of a reverse-flow cyclone can be divided into three categories, which can be optimized separately by different methods.

The first category of dimensions has significant influence on efficiency, but almost no influence on pressure drop. These dimensions include the diameter of the dust discharge port d_c, the ratio of the separation space height H_s to the cyclone diameter D, the insert depth of the exit tube

h_r, the height-to-width ratio of the inlet cross section a/b, the configuration of the inlet volute. According to cyclone flow field studies and performance tests for the FCC catalyst-gas system, the optimum values of these dimensions could be found to be d_c/D=0.4~0.5, H_s/D=2.8~3.0, h_r/a=0.8~1.0, and a/b=2.2~2.5.

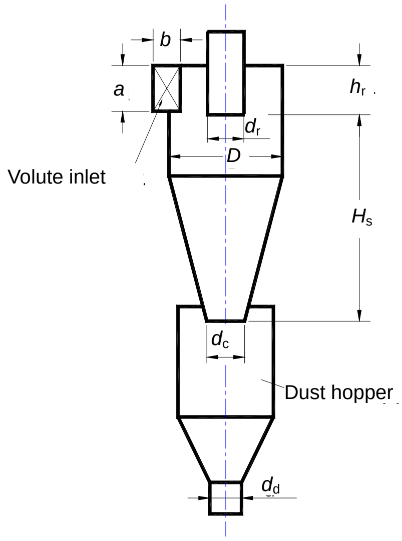

Fig. 1 Principal dimensions of a cyclone.

The second category of dimensions significantly affects both efficiency and pressure drop, thus very important for enhancing cyclone performance. The combination of these dimensions should be carefully optimized to achieve the highest efficiency for a given pressure drop. Two parameters belong to this category, the diameter ratio of the exit tube entrance to the cyclone $\tilde{d}_r$, and the area ratio of cyclone cross-section to inlet section K_A. When $\tilde{d}_r$ decreases, the cyclone efficiency increases considerably, while the cyclone pressure drop also increases. Efficiency can be significantly enhanced and pressure drop reduced when a larger K_A value is chosen for a given inlet gas velocity. The optimum values of these two parameters could be determined by a proper optimum method, which will be discussed further along.

The third category of dimensions, such as the dimension of the dust hopper, has no distinct influence on efficiency and pressure drop. The proper values of these dimensions should be chosen by comprehensive consideration of such factors as abrasion, operation duration and operation margin.

2.2 Performance calculation

By analyzing gas and solids motions in a cyclone and considering particle collision, agglomeration and entrainment, the following three categories of dimensionless numbers have been deduced according to the principle of similitude.

The dimensionless numbers for the gas phase are

$$Re = \frac{\rho_g v_i D}{K_A \tilde{d}_r \mu}, \quad Fr = \frac{g H_s K_A^2}{v_i^2}.$$

Those for the solids phase are

$$St = \frac{\rho_p d_p^2 v_i}{18 \mu D}, \quad D_d = \frac{d_p}{d_m}, D_t = \frac{d_m}{D}, \quad \rho_p = \frac{\rho_p}{\rho_g}, \quad C_r = \frac{C_i}{\rho_g}.$$

The dimensionless geometric parameters are

$$K_A = \frac{\pi D^2}{4ab}, \quad \tilde{d}_r = \frac{d_r}{D}.$$

From analysis of several hundred test curves of cyclone grade efficiency, it is found that the separation mechanism differs with particle size. This can be distinguished by the Ψ number. The case of Ψ>0.9 might be considered as "coarse particles" and its separating process depends mainly on the mean gas velocity field in the cyclone. The case of Ψ<0.6 is considered as "fine particles", in which the influence of turbulence field is more significant than that of the mean gas velocity field. The case of 0.6≤ Ψ≤0.9 is considered as "medium particles" and its separation is affected by both the mean velocity field and turbulence field. The grade efficiency of a cyclone separator can be calculated from the following equations (Shi at al., 1997).

$$\begin{aligned} \Psi > 0.9: &\quad \eta_i(d_p) = 1 - \exp(-4.06\psi^{1.29}\tilde{C}_r^x) \\ 0.6 \le \Psi \le 0.9: &\quad \eta_i(d_p) = 1 - \exp(-3.945\psi^{1.05}\tilde{C}_r^x), \\ \Psi < 0.6: &\quad \eta_i(d_p) = 1 - \exp(-11.855\Phi\tilde{C}_r^x) \end{aligned} \tag{1}$$

where

$$\psi = f(St, \mathrm{Re}, Fr, D_d, D_t, \tilde{d}_r),$$

$$\Phi = f(St, \mathrm{Re}, Fr, d_p, D_t, \tilde{d}_r),$$

$$\tilde{C}_r = C_i / C_{i0}, \quad C_{i0} = 10 \ \mathrm{g \cdot m^{-3}}, \quad x = f(C_i).$$

Eq. (1) is valid for the following ranges:

St<2, Re=10^5~2×10^6, Fr=0.1~18, $\tilde{d}_r = 0.2$~0.6, $\tilde{C}_r \le 500$.

The pressure drop can be calculated as follows:

$$\Delta P = (\rho_g + \frac{C_i}{1000})\frac{v_i^2}{2} + \xi_i(\frac{C_{i0}}{C_i})^{0.045}(\frac{\rho_g v_i^2}{2}), \tag{2}$$

where,

$$\xi_i = 8.54 K_A^{-0.833} \tilde{d}_r^{-1.745} \tilde{D}^{0.161} Re_i^{0.036} - 1,$$

$$\tilde{D} = D / 1.0,$$

$$Re_i = \frac{\rho_g v_i D}{\mu}.$$

2.3 Optimum design method

The above analysis has shown that only four parameters, D, K_A, $\tilde{d}_r$ and v_i, need to be properly matched for a cyclone. The goal of optimizing the combination of these four parameters is to achieve maximum efficiency at a given pressure drop. Based on Eqs. (1) and (2), a computer program, called the PV-type cyclone separator optimization design program—PVOD, has been developed. It is suitable not only for a single stage cyclone, but also for multistage cyclone separators in series. To run the program, first input