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A new pressure drop model of gas–liquid cyclone with innovative operation mode

Junwei Yang[a], Chunliu Liu[a], Sheng Li[b], Bing Sun[b], Jiazhi Xiao[a,*], Youhai Jin[a]

[a] State Key Laboratory of Heavy Oil Processing, China University of Petroleum, Qingdao 266580, China
[b] PetroChina Fuel Oil Co., Ltd., QingDao Storage Branch, 266500, China

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ABSTRACT

An innovative operation mode of cyclone, called 'cyclone splitter', was presented to extend the application scope of the conventional cyclones. Three cyclone splitters were tested for their performance on the pressure drop with pure and droplet-laden gases. The influencing mechanisms of the split ratio on the pressure drop of a cyclone splitter were studied by numerical simulation. It was found that the split ratio mainly affects the axial velocity distribution in both cyclone body and outlet tubes. Further studies on the effect of droplet loading on the pressure drop were conducted, with the droplet volume concentration of inlet gas ranging from 0.1 to 1.0%. The experimental results showed that the two-phase Euler numbers decrease with the increasing droplet loading. A new pressure drop model of gas–liquid cyclone was established by introducing a liquid-phase correction coefficient. The two-phase Euler numbers predicted by this model were compared with the measured values, and the mean deviation is less than 10%, which indicates that this pressure drop model is suitable for the cyclone splitters with pure or droplet-laden gases. Furthermore, this model can also be used for the conventional cyclones with the split ratio $F = 100\%$.

1. Introduction

Cyclone separator is one of the most common used devices for the removal of dispersed particles or droplets from carrying gas, because of their simple construction, compactness, and relative ease of maintenance. For most of the cyclones, the conventional operation mode is that all the gas exits the cyclone through a 'vortex finder', which extends downward from the center of the roof. However, an innovative operation mode, which will extend the application scope of cyclones, was presented in this paper. This operation mode can be used for a special situation, e.g. the deep visbreaking process which is a thermal cracking process to upgrade heavy oil in the refinery. As shown in Fig. 1, the high temperature gas-droplets stream flows into a cyclone, only a portion of the gas exits through the overflow, which is different from the conventional operation mode. The remaining gas and droplets exit through the underflow outlet immediately, as this process requires the residence time of droplets in the cyclone should be as short as possible. In this process, the cyclone is not only a separator but also a gas splitter. Thus this operation mode was named 'cyclone splitter', which has two advantages over the conventional mode in this process.

a The ratio of the gas exiting through underflow is adjustable according to the requirements of this process.
b The residence time of droplets in the cyclone splitter is shorter than that in the conventional cyclone, and the liquid backmixing can be decreased.

The ratio of the gas exiting through underflow is controlled by the pressure drop of overflow and underflow in this process. Therefore, the pressure drop is an important performance parameter of cyclone splitter. Many researchers [1–6] have developed different models to estimate the pressure drop of standard cyclones. Most of the pressure drop models can be classified into two categories. One is the purely empirical models, and the other is based on a consideration of the dissipative loss in cyclones. A number of empirical models have been proposed for the cyclone pressure drop, among which, the Shepherd–Lapple model [3] and Casal–Benet model [1] are the most widely used. Common to these empirical models is that they only contain the ratio of the inlet to the overflow outlet areas, thus they are not suitable for the prediction of the pressure drop in cyclone splitter. There are also many models based on the dissipative loss, such as

* Corresponding author. Fax: +86 532 8698 1787.
E-mail address: xiaojiazhi@sina.com (J. Xiao).

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Nomenclature

a Cyclone inlet height (m)
b Cyclone inlet width (m)
C_0 Droplet volume concentration of inlet gas (%)
D Cyclone barrel diameter (m)
D_c Diameter of the core flow (m)
D_e Cyclone outlet tube diameter (m)
D_g Cyclone overflow tube diameter, $D_g = \tilde{d}_g D$ (m)
D_l Cyclone underflow tube diameter, $D_l = \tilde{d}_l D$ (m)
D_m Hydraulic diameter of inlet, $2ab/(a+b)$ (m)
Eu Euler number
F Split ratio (%)
F_s Area of contact surface, $F_s = \tilde{F}_s \pi D^2/4$ (m^2)
f_0 Friction coefficient
f Liquid-phase correction coefficient
K_A Inlet area ratio, $K_A = \pi D^2/4ab$
n Swirl exponent
P_i Static pressure at the cyclone inlet (Pa)
P_u Static pressure at the overflow outlet (Pa)
P_d Static pressure at the underflow outlet (Pa)
Q_i Inlet gas flow rate, m^3/s
Q_u Gas flow rate in overflow tube (m^3/s)
r_c Radius of the core flow, $r_c = \tilde{r}_c R$ (m)
R Radius of cyclone barrel (m)
Re Reynolds number, $Re = \rho_g D V_i / \mu_g K_A \tilde{d}_r$
Re_m Two-phase Reynolds number, $Re_m = D_m V_i \rho_m / \mu_m$
S Insert depth of cyclone outlet (m)
V_i Inlet velocity, m/s
V_θ Gas tangential velocity (m/s)
$\overline{V}_\theta$ Mean tangential velocity in cyclone outlet (m/s)
$V_{\theta w}$ Tangential velocity at radius R, $V_{\theta w} = \tilde{V}_{\theta w} V_i$ (m/s)
V_z Gas axial velocity (m/s)
V_{ze} Axial velocity in outlet annular region (m/s)
ΔP_u Overflow pressure drop (Pa)
ΔP_d Underflow pressure drop (Pa)
ρ_g Gas density (kg/m^3)
ρ_l Liquid density (kg/m^3)
ρ_m Mixture density (kg/m^3)
μ_m Mixture viscosity (Pa s)

Stairmand model [5], Barth model [7], Muschelknautz model [8], and core flow model [8]. In addition, a universal model was established by Chen and Shi [9], which is suitable for the cyclones operating with pure or dust-laden gases at normal or high temperatures. There are also numerical simulation studies on the pressure drop of cyclones [10–13]. However, most of the reported models were originally established for the cyclones with all the gas exits through the vortex finder. Up to date, there are no relevant models that could be directly applied to predict the pressure drop of cyclone operated as a cyclone splitter.

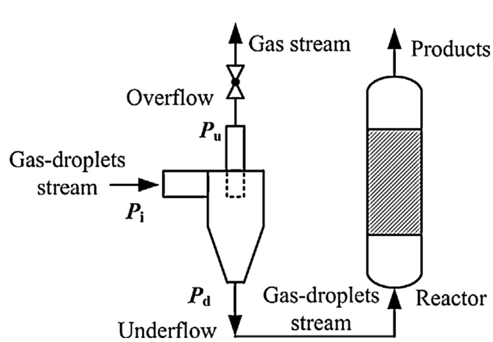

Fig. 1. The sketch of a reverse-flow cyclone operated as a cyclone splitter.

In addition, for the gas-droplets cyclones, once the incoming liquid droplets are centrifuged to the wall of the cyclone, they will form a liquid film. The liquid film on the walls actually exhibits a tremendous hydraulic roughness. However, to the knowledge of the authors, the extent of the effect of liquid on the friction factor has been reported rarely in the cyclone literatures, especially for the droplet volume concentration above 0.1%. Thus, there is little report currently on the pressure drop model of standard reverse-flow cyclone with high droplet loading.

The aim of this work is to study the influencing mechanisms of the split ratio and droplet loading on the pressure drop of cyclone splitters, which is meaningful to enrich the theory systems of the cyclone separation. Three cyclone splitters were tested for their performance on the pressure drop with pure and droplet-laden gases. The numerical simulation was employed to analysis the gas flow pattern in cyclone splitter at various split ratios. Furthermore, a new pressure drop model was established for the cyclone splitters with pure or droplet-laden gases.

2. Experimental

The sketch of the experimental equipment used in this work was shown in Fig. 2(a). Air was drawn into the cyclone using an induced draft fan. The total air flow into the cyclone was controlled through a main valve, and the split ratio was adjusted using two branch valves. The split ratio F was defined as:

$$F = \frac{Q_u}{Q_i} \qquad (1)$$

here Q_i and Q_u refer to the air flow through the inlet and overflow outlet, respectively. The Pitot tube was used to measure the air flow rate, assuming that the velocity at the center of the pipe is equal to the mean flow velocity. Water was injected using an atomizing nozzle, when the feed need to be droplet-laden gas. The nozzle diameter is 25 mm with two swirl vanes in the nozzle chamber, and the jet orifice diameter is 5 mm. The droplet volume concentration of incoming gas ranged from 0.1 to 1.0%. In order to measure the gas flow, the gas-droplets flow in the underflow was separated using a canister-like container.

Generally, the pressure drop over a cyclone was defined as the difference of static pressure between the inlet and the outlet. The static pressure at the inlet cross-section can be easily measured with a pressure tapping in the wall. However, the static pressure is non-uniform over the outlet cross section. Due to the residual swirl in the outlet, a significant dynamic pressure is stored in the swirling motion, which causes the determination of the pressure drop becoming more complicated and difficult. In the past, this problem has been treated in several ways. Stairmand [5] presumably measured the static pressure at the outlet wall immediately downstream of a cyclone, the influence of the swirl was ignored in this measurement. Shepherd and Lapple [3] discharged the gas directly from the cyclone to atmosphere. Meissner and Löffler [14] measured the static pressure after a flow rectifier. Hoffmann [15] observed that the static pressure at the outlet wall is close to the static pressure measured after an ideal rectifier. Therefore, the static pressure at the wall of the outlet tube minus the static pressure at the inlet gives the pressure drop of a cyclone. The pressure drop in this paper was defined as the difference of static pressure between the inlet and the outlet, and taken in a way similar to that of Meissner and Löffler [14]. The static pressures at the outlets were measured after a flow rectifier. The lower end of the pressure tappings were placed before the