Separation and Purification Technology 183 (2017) 293–303

Contents lists available at ScienceDirect

Separation and Purification Technology

journal homepage: www.elsevier.com/locate/seppur

Effect of cold air stream injection on cyclone performance at high temperature

An-Ni Huang [a], Norio Maeda [a,b], Satoshi Sunada [a], Tomonori Fukasawa [a], Hideto Yoshida [a], Hsiu-Po Kuo [c,d], Kunihiro Fukui [a,*]

[a] Department of Chemical Engineering, Hiroshima University, 1-4-1, Kagamiyama, Higashi-Hiroshima 739-8527, Japan
[b] TAKUMA Co., Ltd., 2-2-33, Kinrakuji-cho, Amagasaki, Hyogo 660-0806, Japan
[c] Department of Chemical and Materials Engineering, Chang Gung University, Taoyuan 33302, Taiwan
[d] Department of Otolaryngology—Head & Neck Surgery, Linkou Chang Gung Memorial Hospital, Taoyuan 33305, Taiwan

ARTICLE INFO

Article history:
Received 13 January 2017
Received in revised form 6 April 2017
Accepted 6 April 2017
Available online 7 April 2017

Keywords:
Cyclone
High temperature
Particle deposition
CFD

ABSTRACT

A cold air stream was injected into a cyclone operating at a high temperature through slits created in the cylindrical part of the wall. The effects of the cold stream injection on the cyclone performance were investigated by experiment and CFD simulation. The particle deposition on the wall was observed to be closely related to the cyclone wall temperature distribution, with the particles mainly deposited on the high-temperature (>932 K) parts of the wall, and no particle deposition occurring on parts with temperatures lower than 873 K. However, the separation efficiency decreased with increasing flow rate ratio of the cold air stream. This was because the injection of the cold stream caused the bypassing of the hot stream through the vortex finder, thereby decreasing the tangential velocity of the hot gas. Hence, when particle deposition on the wall severely interferes with the operation of a cyclone, the injection of a cold stream can be used to significantly reduce the particle deposition, although this also decreases the separation efficiency and 50% cut size.

1. Introduction

Owing to their construction simplicity and low operation and maintenance costs, cyclones are one of the equipment most widely used for gas-solid separation. The centrifugal force generated by the swirling flow in a cyclone causes the contained particles to move toward the wall and separate from the gas stream. The coarser particles are propelled by stronger centrifugal forces and are collected in the dust box at the bottom of the cyclone. The finer particles remain in the gas stream that exits through the vortex finder at the top of the cyclone. Cyclones can be operated under harsh conditions of extremely high temperature and/or high pressure and are commonly employed in power and incineration plants for removal of solid particles from high-temperature gas streams [1]. Because the temperature of the gas stream significantly affects its physical properties, the flow field and performance characteristics of a cyclone are impacted by the operating temperature. The operation of a cyclone at a high temperature therefore differs from that at ambient temperature. However, only limited studies have evaluated the performance characteristics of cyclones at high temperatures [2–6]. This is largely because of the difficulties of performing high-temperature experiments.

Computational Fluid Dynamics (CFD) is a useful and relatively economic tool that can be used to investigate both the complex flow fields and performance characteristics of a cyclone at high temperatures. The performance of a cyclone is usually evaluated based on the pressure drop and separation efficiency. The pressure drops in a cyclone for different operating temperatures have been previously well predicted by CFD calculations [7,8]. Shi et al. [9] posited that the change in the gas density with the operating temperature affected the pressure drop. The separation efficiency of the finer particles (<10 μm) has also been shown to be significantly affected by the operating temperature [10]. The separation efficiency and cut size of a hot cyclone predicted by CFD calculations also agree well with experimental measurements [8,11].

In the operation of a cyclone, the particle surfaces may become sticky at high temperatures due to local salt melting, resulting in the deposition of some of the particles on the hot cyclone wall. This has some practical implications. For example, the deposition of cokes on a cyclone wall may interfere with the swirling flow and affect the performance of the cyclones [12,13]. Moreover, the

* Corresponding author at: Department of Chemical Engineering, Graduate School of Engineering, Hiroshima University, 1-4-1, Kagamiyama, Higashi-Hiroshima 739-8527, Japan.

E-mail address: kfukui@hiroshima-u.ac.jp (K. Fukui).

http://dx.doi.org/10.1016/j.seppur.2017.04.012
1383-5866/

deposited particles may interact with the cyclone wall and induce corrosion of the wall at high temperatures. A porous conic wall design has been proposed for decreasing particle deposition on the wall through the injection of air from the exterior [14,15].

A number of studies have considered the pressure drop and separation efficiency of cyclones operated at high temperatures. To the best knowledge of the authors, however, there has been no report about how to reduce particle deposition at a high temperature. In the present study, several slits were created in the cylindrical part of the wall of an industrial-scale cyclone operated at a high temperature. A cold air stream was injected into the cyclone through the slits to reduce the wall temperature and particle surface temperature. The resultant solidification of the partially melted and sticky surfaces of the particles was expected to reduce their deposition on the wall. The decreased wall temperature also suppressed particle-wall interaction. The effects of the cold stream injection on the flow pattern, separation efficiency, wall temperature distribution, and particle deposition were investigated by both experiment and CFD simulation.

2. Experiment

The cyclone installed after a refuse-derived fuel (RDF) combustion furnace was the object of the present study. The exterior of the cyclone was covered with thermal insulators to avoid heat loss to the surrounding. The finer particles that left the cyclone with the gas were cooled in a cooling tower and captured by bag filters. A schematic of the plant operation units is shown in Fig. 1(a). Fig. 1 (b) shows a schematic diagram of the cyclone; the locations of the slits in the cylindrical part of the wall and the inlet wall are indicated in light gray. The apex cone is shaded dark gray. All the slits are 200 mm high, while those on the inlet wall and cylindrical wall are 5 and 10 mm wide, respectively. The slits on the cylindrical wall are located at three different levels. There are two slits at the top level and three slits at the other two levels. The slits at each level are radially separated by 120°, as shown in Fig. 1(c), with the slits themselves tilted at 45°. Fig. 2 shows the positions of the slits in spread-out view. The relative positions of the thermocouples used for temperature measurement in the experiment are also shown in Fig. 2. The thermocouples were used to measure the wall temperature (T_{Sx}) and the internal temperature of the cyclone (T_{Iy}) at a normal distance of 500 mm from the inside surface of the wall.

Gas-only and particle-laden tests were conducted. The amount of injected cold stream was estimated from the cold stream ratio, which is defined as the ratio of the volumetric flow rate of the cold stream to the volumetric flow rate of the supplied hot stream. In the gas-only tests, the temperature of the hot gas stream supplied to the cyclone was 777 ± 7 K and the volumetric flow rate of the stream was about 570 Nm^3/h, which is equivalent to a velocity of 13.5 m/s. The cold stream was injected through the slits in the cylindrical wall. In the particle-laden tests, the hot gas stream supplied to the cyclone contained fly ashes. The particle-laden tests were conducted on-site in an industrial-scale RDF combustion plant. A schematic of the plant operation units is shown in Fig. 1 (a). Some of the operating conditions of the plant are presented in Table 1. Although the dispersion of the particles and the size distributions of the dispersed particles could affect the experimental results, accurate measurement of the actual particle dispersion in an on-site combustion plant is extremely difficult. Nevertheless, the fly ash concentration in the gas stream to the cyclone was very low (average of 0.25–0.59 g/Nm^3), and it was reasonable to assume that the ashes were well dispersed. The density of the fly ashes ranged between 2500 and 3000 kg/m^3, with a median particle diameter of 16.9 μm (LA-920, Horiba). An apex cone was installed at the top of the dust box and the cold stream was injected through the slits in the cylindrical wall and/or the cyclone inlet. The supplied hot gas stream had a temperature of 976 ± 17 K and volumetric flow rate of 453–640 Nm^3/h, which was equivalent to a velocity of 13.6–18.8 m/s. The experimental conditions are summarized in Table 1.

In the particle-laden tests, the effects of the cold stream injection on the cyclone performance characteristics were investigated in terms of the particle separation efficiency and fly ash deposition on the cyclone wall. The particle separation efficiency (η) was calculated as

$$\eta(\%) = \frac{C_{inlet} - C_{exit}}{C_{inlet}} \times 100\% \quad (1)$$

where C_{inlet} and C_{exit} are the concentrations of the fly ash particles at the cyclone inlet and exit, respectively. The particle concentration C was determined by the JIS Z 8808:2013 method using an isokinetic suction sampling technique. The calculation is based on the mass distribution of the collected particles and the amount of gas absorbed during the sampling.

The fly ash particle deposition on the cyclone wall is defined as

$$\text{Particle deposition } (\%) = \frac{M_{wall}}{M_{wall} + M_{dust\ box} + M_{bag\ filter}} \times 100\% \quad (2)$$

where M_{wall} is the total mass of the particles deposited on the cylindrical and conical parts of the cyclone wall, and $M_{dust\ box}$ and $M_{bag\ filter}$ are the masses of the particles collected in the dust box and bag filter, respectively.

The distributions of the particles deposited on the cylindrical and conical parts of the cyclone wall were recorded by a digital camera. The thickness of the particle deposit was determined by on-site measurement using a thickness gauge. The measurements were then used to develop a particle deposition thickness map.

3. Numerical simulation

The governing equations of the hot and cold gas streams include the transport equations of the fluid mass, momentum, and energy. These partial differential equations were solved using the steady-state finite volume numerical method in the commercial CFD software ANSYS Fluent v17.1. Based on convergence testing of the mesh, the numbers of cells of the cyclone and the cyclone with the extended dust box were set to 1,954,074 and 2,499,923, respectively. The turbulent swirling flow in the cyclone was modeled by the Reynolds stress model (RSM) [16]. The standard wall function was used to model the behavior of the turbulent flow near the wall. The pressure-based coupled algorithm was used for pressure-velocity coupling, while the Presto scheme was used for pressure interpolation. The second-order upwind discretization scheme was applied to the momentum, turbulent kinetic energy, and turbulent dissipation rate. The first-order upwind discretization scheme was applied to the Reynolds stresses.

The one-way Lagrangian-based discrete phase model (DPM) was applied to the motion of the individual particles. Because the particle concentration was relatively low, collision between particles was ignored. The trajectory of the particles was predicted by the discretized force balance equation using the trapezoidal scheme. The effect of the instantaneous fluctuation of the gas phase on the particle motion was modeled by the discrete random model (DRW). The particles were assumed to have been captured by the dust box when they reached the bottom of the box.

Energy balance was used to determine the temperature distribution inside the cyclone after the injection of the cold stream. The gas phase was assumed to have a constant specific heat capacity and to be incompressible. Its density was predicted by the ideal gas law, while the viscosity and thermal conductivity