Particuology xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Particuology

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

Experimental study and numerical simulation of the characteristics of a percussive gas–solid separator

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ARTICLE INFO

Article history:
Received 11 July 2016
Received in revised form 8 February 2017
Accepted 19 April 2017
Available online xxx

Keywords:
Gas–solid separation
Trajectory imaging
Collision of particles
Numerical simulation
Efficiency of separation

ABSTRACT

The presence of solid particles in the flow of hypersonic wind tunnels damages the appearance of the experiment models in the wind tunnel and influences the accuracy of experimental results. The design of a highly efficient gas–solid separator was therefore undertaken. Particle trajectory imaging methods were used to measure trajectories under different conditions. The flow field and particle movement characteristics for different head angles (HAs) and separation tooth angles (STAs), inlet velocities, and the exhaust gas outlet pressures in the separator, were calculated using simulations based on the discrete phase model. The particle separation efficiency, pressure loss, and flow loss resulting from different structural parameters were also studied. In line with experimental observations, the characteristic angle of particle movements in the separator and the separation efficiency of the separator were found to increase with decreasing HA and with increasing STA. Separation efficiency improves with increasing inlet velocity and with increasing negative pressure of the exhaust gas outlet; however, the corresponding pressure loss and the flow rate of the waste gas also increased.

Introduction

Hypersonic wind tunnels are used for conducting various conventional aerodynamic tests of for example strategic and tactical missiles, as well as spacecraft (Tang, 2004; Tang et al., 2015; Tian, Jing, & Han, 2013; Wu, Luo, & Fan, 2009). To avoid condensation following the dramatic expansion of airflow through the nozzle in the test section, regenerative heaters are used to regulate the temperature of the gas stream. However, various components of the regenerative heaters—insulation materials, regenerator, gas pipeline—will corrode after long term usage and hence there will be small amounts of solid impurities in the wind tunnel flow. The impact between the solid particles in high-speed airflows and the Venturi throat scratches the nozzle surface, shortening its service life and affect the uniformity of flow field. The high-speed particles also have an impact on the test model, damaging its shape and affect the accuracy of test data. Therefore, we must take all possible measures to reduce the presence of solid particles in the airstream.

Many methods have been adopted to improve the airflow quality. The most common method to purify the airflow in hypersonic wind tunnels is the use of a filter, which is typically installed before the nozzle. For example the French ONERA S4-MA wind tunnel uses a 10-μm filtering device (Falempin & Serre, 2011; Serre & Falempin, 2008) and the United States AEDC-VKF (B and C) uses a 5–10 μm filtering device, all before the nozzles (Donaldson & Coulter, 1995; Strike, Donaldson, & Beale, 1981). The hypersonic wind tunnel at the China Aerodynamics Research and Development Centre uses a 10-μm filtering device. This device consists of a multi-layered stainless steel mesh with a total thickness of 7 mm. However, the particles in the stream start to be deposited on the filter, plugging flow pores and reducing the flow area, resulting in pressure loss. The more the wind tunnel run, the more the pressure rises in the chamber behind the filter and the greater the loss of pressure becomes in the flow. This increases gradually up to 60% of the total pressure of the flow. In turn, the flow field instability affects the validity of test data.

Compared with filter-type separators, the impingement separator uses inertia to separate out particles. Its advantages include being difficult to plug and having a low resistance and high separation efficiency (Guo, 2013; Shangguan et al., 1991). Nevertheless, it would be too difficult and costly to perform the research and development required to further improve inertial separators in a hypersonic wind tunnel directly. Studies on particles dynamics with advanced optical measurement tools, i.e., holographic imag-

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http://dx.doi.org/10.1016/j.partic.2017.04.007
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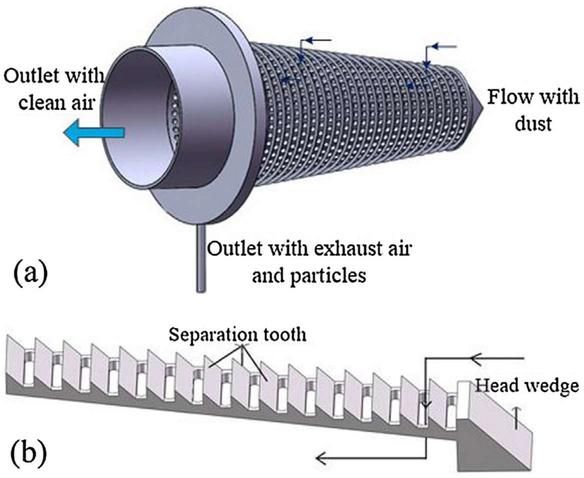

Fig. 1. 3D views of structures of (a) hypersonic gas–solid separator and (b) the simplified separator.

ing (Wu, Wu, Yao, Gréhan, & Cen, 2015), has laid the foundation for future research as well as other particle applications (Qi, Niu, Jia, Wang, & Ruan, 2015; Qi, Ruan, Zhang, Wang, & Tan, 2007; Tong, Whitlow, Macrae, Landers, & Harada, 2015; Tong, Chen, Malkawi, Liu, & Freeman, 2016). In this study, the motion and separation of particles in such a separator structure is first tested under normal temperature and pressure conditions. Particle trajectory imaging was used to analyse the trajectories of particles in separators with different characteristic parameters and the change in the direction of motion following the collision between the particles and the separator (Chen, Cui, Wang, Gong, & Yu, 2008; Gao, Zhang, Xia, & Xu, 2007; Xu, 2010; Wu et al., 2011; Wang, 2011). The particle separation efficiency, pressure loss, and waste gas flow rate of the separator were calculated using the discrete phase model (DPM) simulation (Han, 2013; Li, Ma, Du, & Wang, 2011; Luan, 2011; Yuan, Zhu, Geng, & Peng, 2013; Zhao, 2014). The simulation results are in good agreement with the experimental results. The factors which affect the pressure loss, exhaust gas flow rate, and separation efficiency of the separator are identified. This work therefore lays the foundation for the design of a hypersonic gas–solid separator.

Separator structure

The hypersonic gas–solid separator (Fig. 1(a)) basically uses particle inertia to make the particles collide with the outer tube wall of the separator. Exhaust gas is carried out through the high-speed airflow along with the mainstream movement. Gas flows into the wind tunnel through the dentate and porous structure at the front/outlet of the separator. The resultant gas flows have a good degree of circumferential symmetry. For ease of modelling the experiment, the tapered separator is simplified to a cubic structure. This does not change the basic separator structure (Fig. 1(b)) which basically consists of a head wedge and multiple rows of holes and teeth structures. As the dust stream flows through the head wedge, the flow area decreases and its speed increases. Having passed through numerous rows of holes and teeth, a portion of the clean air flows into the wind tunnel through the orifice. As the gas flow diminishes, the corresponding flow area also shrinks.

As the dust stream flows through the separator, the detailed motion of the solid particles has a significant impact on particle separation. During the collision of particles with the separator, the head angle (HA) and separation tooth angle (STA) affect the loss of momentum and the change of direction of the particle (Fig. 2). The flow velocity is different under different wind tunnel conditions, and the velocity of the gas flow determines the velocity of the particles. The pressure of the exhaust gas outlet determines the exhaust gas flow rate, which is important because it ensures that the particles at the exit can be taken away by the exhaust gas. In this paper, the factors affecting the separation of particles, including HA and STA, the flow velocity, and the negative pressure of the exhaust gas outlet, are studied.

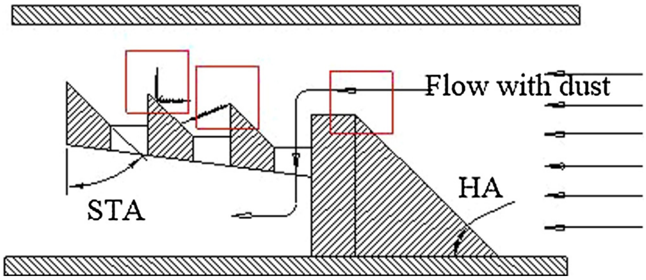

Fig. 2. Major structural parameters of the separator.

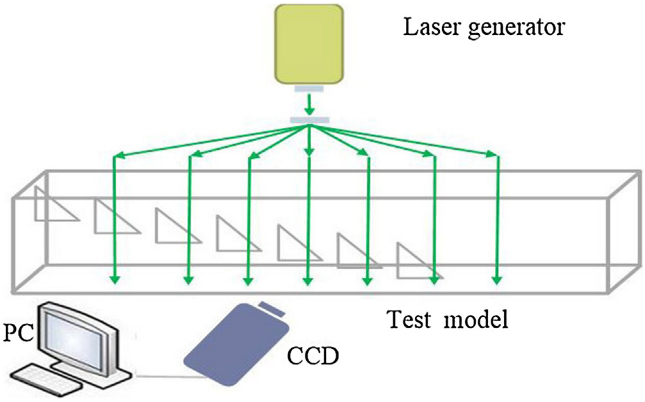

Fig. 3. Schematic diagram of setup.

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Experimental system

Based on the particle trajectory imaging method, an experiment platform (Fig. 3) was erected that basically consists of a laser generator, a CCD camera, a feed system, and a diagnostic section. The laser is a continuous power laser with output power 200 mW and wavelength 532 nm. The CCD camera is an Imager-ProPlus with resolution 2048 × 2048 pixels; the pixel size is 7.4 μm. The particles used are of a uniform size and are introduced to the airflow via a spiral feeder. They are transported to grain imports by compressed air and are carried by the gas flow to the gas–solid separator. The experimental piece is a square channel of cross section 30 mm × 50 mm with an internal fixed particle separator model. Driven by a high-pressure blower, dust in the airflow gets into the separator and the separated particles are carried and discharged along with the exhaust gas. The pump connected to the exhaust gas outlet creates a negative pressure and controls the exhaust gas flow to optimize the discharge of the particles. As the separator is relatively long, the band of laser light cannot illuminate all of the tooth structure of the separator at the one time. Imaging of particle tracks at different positions along the length of the separator is therefore achieved by moving the light source and the CCD camera together; i.e., they scan the length of the experimental set up.

Please cite this article in press as: Wu, X., et al. Experimental study and numerical simulation of the characteristics of a percussive gas–solid separator. *Particuology* (2017), http://dx.doi.org/10.1016/j.partic.2017.04.007