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Numerical simulation of the sticking process of glass-microparticles to a flat wall to represent pollutant-particles treatment in a multi-channel cyclone

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ABSTRACT

Ultrafine particles are dangerous to human health and are usually difficult to separate from airflow because of their low inertia, which helps them to stick easily to surfaces because of adhesive forces. This characteristic provides opportunities for adhesive ultrafine particle separation by designing air-cleaning devices that exploit the sticking ability. To understand governing effects in such air-cleaning devices, which can be designed as multi-channel cyclones, the sticking of adhesive spherical glass particles under oblique impact has been investigated numerically by using the discrete element method. An adhesive dissipative contact model was applied by implementing different interaction forces for various-sized ultrafine pollutant particles. Normal loading is represented by the elastic Hertz contact model, whereas viscous damping is described by the modified nonlinear Tsuji model. The influence of deformation-dependent adhesive forces for a range of ultrafine particle sizes is illustrated during the sticking process. Dissipative oscillations during the sticking process were observed because of the influence of viscous damping forces.

Introduction

Air-polluting ultrafine particles can enter the human circulatory system easily through the respiratory tract and cause medical problems. An option to prevent this behaviour, especially for gas streams with a high concentration of ultrafine particles, is to use air-cleaning devices with a desirably high air-cleaning effectiveness. To improve the cleaning efficiency, an assessment of pollutant behaviour is important in the design of devices (see Baltrėnas and Chlebnikovas (2015a) or Hoffmann (2000)). Besides depth and surface-filtration processes that are attributed to high pressure drops (Zhu, Na, & Lu, 2008), or electrostatic precipitators that require the build-up of an electrical field (Parker, 1997), multi-channel cyclones (Baltrėnas & Chlebnikovas, 2015a) provide the possibility for microparticle precipitation as part of a centrifugal force-driven sedimentation process that allow them stick to device partition walls. For details on multi-channel cyclones, see Baltrėnas and Chlebnikovas (2015b).

As the size of the particles decreases, various field forces start contributing to inter-particle and particle-wall behaviour. Therefore, the interaction of ultrafine particles must be assessed properly. Because ultrafine particles are difficult to separate from gases, a detailed knowledge of ultrafine particle behaviour at the microscale is required. Microparticle behaviour deviates from that of larger particles, because their adhesive forces dominate. Because of this characteristic, particles can agglomerate and stick to various surfaces to form dense layers.

An understanding of the fundamentals of particle adhesion with respect to product-quality assessment and process performance is required for air-cleaning devices (Brauet & Varma, 1981). Besides experimental investigations, theoretical studies of microparticle behaviour are required. Some studies have been performed in this field already. A nonlinear model that is applicable to adhesive microparticle interaction was presented by Tomas (2007). Based on the JKR model (Johnson, Kendall, & Roberts, 1971), the sticking process of microparticles to a wall surface was presented by Liu, Li, and Yao (2011). Particle aggregation by adhesive forces was

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investigated by Marshall (2007). The latter studied particle aggregation and capture by walls in a particulate aerosol channel flow. In another investigation, random Brownian diffusion aggregation of suspended nanoparticles was investigated by Peng, Doroodchi, and Evans (2010). Microparticle collision dynamics was modelled by taking into account the van der Waals force and by applying a Monte Carlo (DSMC) method (Wang, Lu, Shen, Liu, & Bouillard, 2007). Modelling of agglomeration in a system of spheres by taking into account a liquid binder and introducing an adhesive force between particles was realized by Simons (1996). Particle stick/rebound criteria during oblique impact were investigated by Konstandopoulos (2006).

Thus far, theoretical investigations (Konstandopoulos, 2006; Liu et al., 2011; Marshall, 2007; Peng et al., 2010; Simons, 1996; Wang et al., 2007) have been limited to stochastic models with insufficient sophisticated particle contact or without consideration of explicit conditions that are encountered in cyclones. We provide a possible contribution to overcome these shortcomings.

First, single-particle behaviour is addressed. This approach is valid as solid concentrations in cyclones are relatively low and particle/particle interactions can be neglected. Additionally, particles do not change the fluid flow significantly (one-way coupling). This paper focuses mainly on theoretical adhesive particle stick models and the effect of adhesion-related energy dissipation during the sticking/capture process. The variation of the sticking behaviour as dependent on particle size has been studied extensively. Numerical investigations include problem identification, numerical simulation, and analysis of the obtained results by applying the discrete element method (DEM) of Cundall and Strack (1979).

Problem formulation

Air-cleaning devices such as multi-channel cyclones (Baltrėnas & Chlebnikovas, 2015b; Jasevičius, Baltreñas, Kačianauskas, & Grubliauskas, 2014) may be able to remove microparticles during centrifugal force-driven sedimentation and filtration; these particles are difficult to separate at less than a few micrometres because their mass is extremely small and thus centrifugal forces acted on them are small compared with other forces. The influence of adhesion on ultrafine particles is significant and is considered in this work.

We analysed a single-level eight-channel cyclone. A single level describes a cyclone with a separation chamber with one level. The flow of polluted air moves tangentially through the inlet to the first and second channels of the cyclone, where air cleaning occurs in parallel. Flow approaches the first channel of the cyclone as limited by a peripheral partition wall and the first quarter-ring. When moving in the radial direction, flow is cleaned from the pollutant particles because of the action of the centrifugal force. When it passes to other channels and meets the quarter-ring wall, the flow splits into a peripheral and a transitional part. Part of the peripheral-flow particles fall in the cyclone, whereas transitional flow is continued to the next channel and to the cyclone outlet. Thus, the air stream is distributed in various curved channels and filtered through spaces between the quarter-rings. Each closed circuit in the separation chamber of the cyclone forms a channel of the cyclone. A vortex flow exerts centrifugal forces, and therefore, sedimentation effects occur in the flow-distribution zone. These forces affect solid-particle sedimentation at the bottom of the multi-channel cyclone, and particles enter the conical hopper. Clean air that passes through all channels of the cyclone escapes through the air outlet. Dusty air is filtered in the active zone of the channel-opening slots and because of the interaction between coagulating solid particles. A parametric numerical study on the scale of a full cyclone is not performed here. An investigation of multi-channel cyclones is not motivated by classical cyclones, where airflow is cleaned of pollutant particles by the action of a centrifugal force. Adhesive forces could be used to demonstrate the cleaning action for the smallest ultrafine particles that are difficult to separate using classical cyclones. Numerical experiments for single-particle behaviour are needed in the first step. To understand microparticle behaviour, investigations were limited to a numerical analysis of the interaction between a microparticle and an internal surface of the cyclone as represented by a flat wall. Experimental results of cyclone efficiency in multi-channel cyclones are addressed to obtain initial data for the numerical investigations. It is not possible to obtain cleaning efficiencies at the single-particle level. To obtain cleaning efficiencies numerically would be possible by multi-particle or statistical analysis at the single-particle level, which could be an additional investigation step. Fig. 1 shows a cross-sectional view of the air-cleaning device, whereas the area between the dashed lines in Fig. 1 represents a zone where pollutant particles may stick.

To increase the separation effectiveness, particle-laden polluted airflow in the boundary layer near partition walls is directed at a small angle towards the wall to cause sticking/agglomeration of pollutant particles. The attractive forces between the particle and the background were considered to be van der Waals forces. Theoretically, the sticking/agglomeration will occur if the particle normal velocity is less than a critical value. This value is a crucial factor to determine particle sticking to the partition wall. In this work, we investigate the sticking process of micro particles (1.2–10 μm) by introducing a model for the sticking process of the particles. The subsequent removal of sticking particles that is necessary in a technical apparatus is not addressed here. A model of the oblique impact of pollutant particles on a flat surface is presented with reference to previously indicated initial conditions. The pollutant particles are considered to be spherical and dry. Because of the small size of the contact surface area between the interacting particle and the partition wall in a multi-channel cyclone (Fig. 1), the partition wall is presented as a flat surface in the numerical simulations.

To represent the impact of particles, two different types of energy-dissipation mechanisms are taken into account, and these cause force–displacement hysteresis. Energy dissipation occurs because of adhesion described by a mechanism, in which the amount of dissipated energy is independent of the initial particle velocity. This phenomenon leads to a velocity threshold, below which adhesion can occur (Jasevičius et al., 2014). Energy dissipation because of viscous damping depends on the initial particle velocity that is described by a mechanism that is based on the known viscous-elastic (Tsuji, Tanaka, & Ishida, 1992) model. Concurrent attractive–dissipative behaviour of an oblique contact with a flat surface has been achieved by modifying both models in terms of normal and tangential directions and applying them as part of the DEM.

Particles with various surface roughness has various influences of adhesive forces, this phenomena is known and observed in physical experiments (Tomas, 2008). Moreover, during particle contact deformation, contact-zone is flattening. Due to the change of contact-zone, here surface asperities and influence of adhesive force are also changing. As a result, it gives dissipation effect for a particle (Jasevičius, Tomas, & Kačianauskas, 2011). Resulting energy dissipation because of adhesion, or the so-called adhesion hysteresis, is a phenomenon where the amount of energy required to separate two surfaces after deformation is greater than the amount of energy gained by bringing the surfaces together. This amount of dissipated energy is taken into account during the theoretical calculation; a description of this phenomenon can be found in Jasevičius et al. (2011). We present a numerical investigation of dust-particle impact on a surface based on known physical experiments, as was done by Poppe, Blum, and Henning (2000). Results