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Separation of nanoparticles: Filtration and scavenging from waste incineration plants

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ABSTRACT

Increased amounts of nanoparticles are applied in products of everyday life and despite material recycling efforts, at the end of their life cycle they are fed into waste incineration plants. This raises the question on the fate of nanoparticles during incineration. In terms of environmental impact the key question is how well airborne nanoparticles are removed by separation processes on their way to the bag house filters and by the existing filtration process based on pulse-jet cleanable fibrous filter media. Therefore, we investigate the scavenging and the filtration of metal nanoparticles under typical conditions in waste incineration plants. The scavenging process is investigated by a population balance model while the nanoparticle filtration experiments are realized in a filter test rig. The results show that depending on the particle sizes, in some cases nearly 80% of the nanoparticles are scavenged by fly ash particles before they reach the bag house filter. For the filtration step dust cakes with a pressure drop of 500 Pa or higher are found to be very effective in preventing nanoparticles from penetrating through the filter. Thus, regeneration of the filter must be undertaken with care in order to guarantee highly efficient collection of particles even in the lower nanometre size regime.

1. Introduction

With rapid advances in technology, the use of engineered nanoparticles has been steadily increasing in the recent past. In spite of the best recycling efforts, these nanoparticles very often end up as inclusions of waste materials which are thermally broken down in waste incineration plants. Waste incineration is also proving to be an attractive alternative as it results in reduction of the waste volume and at the same time providing the possibility of energy recovery (Buonanno and Morawska, 2015). Recent legislations are aiming to reduce waste disposal by landfilling and this has kindled more interest in waste incineration. Volatilization and recombination of the metal inclusions in waste materials, during their incineration often lead to nanoparticle formation. Without proper filtration measures the nanoparticles could end up being released to the atmosphere, which creates environmental and health hazards. The risk of nanoparticle release from the combustion of nanowaste has been addressed by several studies in the last years (Bouillard et al., 2013; Cernuschi et al., 2010; Gottschalk and Nowack, 2011; Kumar et al., 2013; Walser et al., 2012). Bouillard et al. (2013) could show that the combustion of a polymeric compound mixed with carbon nanotubes results in a transfer of carbon nanotubes to the gas phase requiring a proper filtration to prevent release. Cernuschi et al. (2010) investigated the nanoparticle concentration in the exhaust of four differently configured waste incineration plants. Walser et al. (2012) balanced the mass flow of the nanoparticle input to the different waste fractions (slag, quench water, fly ash, clean gas) of a waste incineration plant. Furthermore, they concluded that wet scrubbers and electrostatic precipitators are effective in separating the ultrafine particles. However, the underlying mechanisms of nanoparticle separation and how these processes could be improved by adjusting the operational conditions have not been addressed. Therefore this study focuses on a detailed investigation of the separation processes during the transport of the nanoparticles to the filtration unit as well as the filtration process itself based on pulse-jet cleanable fibrous filter media covered by a filter cake.

In this sense the separation of nanoparticles in waste incineration plants can be described as a twofold process. Nanoparticles formed during waste incineration are carried to the bag house filters by the flue gas along with fly ash particles. These products are cooled down at different stages before reaching the bag house

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filters, and consistently undergo Brownian collisions resulting in adherence to fly ash particles as well as self-aggregation of the nanoparticles. Collisions and subsequent adherence to fly ash particles is termed as scavenging of nanoparticles and results in easier nanoparticle removal at the bag house filters as the fly ash particles have sizes in the micrometre range (Friedlander et al., 1991; Lee and Wu, 2005). However, self-aggregation and diffusion scavenging are competing processes as self-aggregation of the nanoparticles increases the particle size thereby reducing the effectiveness of nanoparticle scavenging. The effectiveness of scavenging depends not only on the size and concentration of the nanoparticles and the fly ash particles but also on the experimental conditions. The extent of scavenging depends on the differences in size of the colliding entities and the mass transfer regime in which collisions are happening (Gopalakrishnan and Hogan, 2011; Gopalakrishnan et al., 2011). An accurate population balance modelling is necessary to study the effectiveness of nanoparticle scavenging for various parameters that are typical for a waste incineration plant.

The presence of the larger fly ash particles creates a continuously growing dust cake on the fibrous filter medium of the bag house filters thereby increasing the filtration efficiency of the filter system. The dust cake also results in an increase of the pressure drop across the filter making it necessary to periodically remove the dust cake by a pulsed gas jet. The filtration behavior of fibrous filter media has been studied extensively for the separation of coarse fly ash particles (Löffler et al., 1988; Binnig et al., 2009) as well as the separation of nanoparticles (Kim et al., 2007; Wang and Tronville, 2014; Liu et al., 2011; Buha et al., 2013; Wang and Otani, 2013). However, to the best of our knowledge detailed investigations dealing with the effect of a dust cake on a filter medium for the filtration of particles in the lower nanometre regime are not available so far. As suggested before (Buonanno and Morawska, 2015), very few studies on measuring ultrafine emissions from incineration plants are available. Schiller and Schmid (2014) have briefly discussed the filtration efficiency of a precoated filter medium for three precoating thicknesses, but not in the context of waste incineration but for pellet heaters in private households representing a totally different operational scale. This study investigates three of the main operational parameters of dust cake covered filter media namely the filter cake thickness, the face velocity and the flue gas temperature for particles larger than 2 μm. Buonanno et al. (2012) have studied the ultrafine emissions from incineration plants and the role of fiber filters on the filtration efficiencies. However, a detailed analysis on the effect of different operation parameters on the filtration efficiencies and possible emissions from incineration plants has not been done before.

In the first part of the manuscript, we explain the population balance modelling used to study the effectiveness of scavenging of nanoparticles in aiding the filtration process, while the details of the experiments done to mimic the filtration system in a typical waste incineration plant are given subsequently. This study is rather aimed at finding the necessary parameters which would prevent any penetration of the nanoparticles across the filter medium. The product flue gas with nanoparticles as well as coarser fly ash particles, formed in the combustion chamber passes through several economizer ducts before finally reaching the bag house filters. The nanoparticles in the flue gas can grow by Brownian collisions and subsequent coagulation and also get scavenged away by the coarser fly ash particles. We acknowledge that owing to the conditions in the waste incineration plant, especially with the variation in the temperature, condensation may play an important role in removing the nanoparticles. However, as condensation is not considered in our model our results can be considered as a lower limit of separation.

2. Population balance modelling of scavenging

For dilute cases as given here, the rate of collisions (R_{ij}) between two entities i and j is given as:

$$R_{ij} = \beta n_i n_j \tag{1}$$

where β is the collision kernel and n_i and n_j are the respective number concentrations of i and j. Owing to the wide range of particle sizes present in the products of waste incineration, the collision kernel has to consider the different regimes of collision processes (mass transfer regimes) (Gopalakrishnan and Hogan, 2011). Population balance modelling is used to study the evolution of the size distribution of the nanoparticles, as they undergo two different collision processes. The nanoparticles diffuse due to the thermal motion thereby colliding with each other resulting in coalescence leading to larger nanoparticles. They also undergo collisions with coarser fly ash particles, subsequently adhering to the larger particles. This process is referred to as the scavenging of nanoparticles. Self-aggregation of nanoparticles can be represented by a free molecular regime coagulation kernel while transition regime expressions best represent the nanoparticle scavenging by μm-sized fly ash particles. Temperature variations and the accurate expressions for coagulation kernels need to be accounted for in the population balance modelling. Simulation conditions are set using the data obtained from MVA Weisweiler, a waste incineration plant in Germany.

There have been recent advances in the calculation of collision kernels across the entire regimes of mass and momentum transfer (Gopalakrishnan and Hogan, 2011; Gopalakrishnan et al., 2011). In this study we use the expression developed by Hogan and co-workers for modelling the collision modules in the population balance solver. This is more relevant for the interparticle coagulation where the collision kernel for transition regime represents the process better. It is assumed that all collisions result in complete coalescence of the colliding entities resulting in a new and larger spherical particle. A universal non-dimensional collision kernel (H) for spherical entities i and j is a function of only the diffusive Knudsen number (Kn_D) which takes into account the properties of both the colliding entities as well as the operating parameters and is given by:

$$H = \frac{4\pi Kn_D^2 + 25.836 Kn_D^3 + 11.211\sqrt{8\pi} Kn_D^4}{1 + 3.502 Kn_D + 7.211 Kn_D^2 + 11.211 Kn_D^3} \tag{2a}$$

$$Kn_D = \frac{(kTm_{ij})^{1/2}}{f_{ij}(a_i + a_j)} \tag{2b}$$

where m_{ij} and f_{ij} are respectively the reduced mass and friction factors, a_i and a_j are the respective radii of entities i and j, k is the Boltzmann constant and T is the background temperature. The non-dimensional collision kernel (H) is related to the collision kernel β as:

$$H = \frac{\beta_{ij} m_{ij}}{f_{ij}(a_i + a_j)^3} \tag{3}$$

These expressions can be extended to non-spherical particles as well, with suitable description of the particle sizes and geometry (Thajudeen et al., 2012). The friction factors are calculated based on the momentum transfer Knudsen number (Kn) and the Cunningham's correction factor, as given in Eqs. (4a) and (4b). The parameters used in Cunningham's correction factor are obtained from Davies (1945).

$$f_i = \frac{6\pi\mu a_i}{1 + Kn_i(1.257 + 0.4\exp(-1.1/Kn_i))} \tag{4a}$$