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Technical note

The effect of capillary force on airborne nanoparticle filtration

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ABSTRACT

This paper presents a new model for airborne nanoparticle filtration by considering the effects of capillary force and plastic behavior impaction. This model was also validated using experimental data in literature and that collected by the authors. Results show that the capillary force between particle and the filter surface increases with the relative humidity level, leading to reduced rebound of nanoparticles from a filter media. Therefore, thermal rebound of nanoparticles may only occur at low relative humidity conditions.

1. Introduction

Air filtration is the most effective method for separating nanoparticles from the air. It is widely used in air cleaning, aerosol sampling, and air monitoring devices. Conventional filtration theory states that diffusion dominates the behavior of submicron particles and the filtration efficiency increases inversely with the size of these fine particles. This theory implies that nanoparticles can be effectively captured by properly designed air filters.

However, some researchers have pointed out that nanosized airborne particles (nanoaerosols) may behave like gas molecules upon impaction with the surface of a filter because the kinetic energy is greater than the adhesion energy (Wang & Kasper, 1991). As a result, such small nanoparticles may rebound from filter media upon collision through a mechanism called thermal rebound. By theoretical analysis, Wang and Kasper (1991) predicted that thermal rebound could happen for sub-10 nm particles. Since then, many experimental studies have been conducted to examine the thermal rebound theory (Alonso, Kousaka, Hashimoto, & Hashimoto, 1997; Brochot, Mouret, Michielsen, Chazelet, & Thomas, 2011; Golanski, Guiot, Rouillon, Pocachard, & Tardif, 2009; Heim, Attoui, & Kasper, 2010; Heim, Mullins, Wild, Meyer, & Kasper, 2005; Huang, Chen, Chang, Lai, & Chen, 2007; Ichitsubo, Hashimoto, Alonso, & Kousaka, 1996; Japuntich et al., 2007; Kim, Bao, Okuyama, Shimada, & Niinuma, 2006; Kim, Harrington, & Pui, 2007; Otani, Emi, Cho, & Namiki, 1995; Rengasamy, King, Eimer, & Shaffer, 2008; Scheibel & Porstendörfer, 1984; Shin, Mulholland, Kim, & Pui, 2008; Skaptsov et al., 1996; Steffens & Coury, 2007b; Van Gulijk, Bal, & Schmidt-Ott, 2009; Van Osdell, Liu, Rubow, & Pui, 1990; Wang, Chen, & Pui, 2007; Yamada, Seto, & Otani, 2011). However, very few of them have reported evidences to support the phenomena of thermal rebound in nanoparticle filtration (Ichitsubo et al., 1996; Kim et al., 2006; Otani et al., 1995; Rennecke & Weber, 2013a; Van Gulijk et al., 2009). Van Osdell et al. (1990) showed that no thermal rebound was associated with the removal efficiency of polydisperse silver and monodisperse DOP nanoparticles through fibrous glass and membrane filters. Otani et al. (1995) demonstrated that thermal rebound occurred for circular aluminum tubes for sub-2 nm particles. This experiment was conducted using

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monodisperse silver nanoparticles down to 1 nm and stainless-steel wire screens and a circular aluminum tube. Ichitsubo et al. (1996) measured the penetration of monodisperse NaCl and silver particles up to 7 nm in diameter through a single-stage wire screen; they showed the possibility of thermal rebound for sub-2 nm particles. However, other researchers stated that the results produced by Otani et al. (1995) and Ichitsubo et al. (1996) might be inaccurate due to the mobility shift in the particle size classification devices (Alonso et al., 1997; Heim, Mullins, & Kasper, 2006). Other researchers conducted more experimental investigations using NaCl nanoparticles through fibrous respiratory masks, HEPA filters, Hollingsworth and Vose (H&V) filters, and N95/P100 filters. They did not see the drop in nanoparticle filtration efficiency (Huang et al., 2007; Japuntich et al., 2007; Rengasamy et al., 2008; Steffens & Coury, 2007a; Wang et al., 2007).

The experimental results of the following groups of researchers were not openly challenged. Kim et al. (2006) employed monodisperse NaCl nanoparticles down to 1 nm through a fibrous glass filter at 1.22% relative humidity; they showed the possible evidence of drop of nanoparticle filtration efficiency for sub-2 nm particles. Van Gulijk et al. (2009) then tested polydisperse NaCl, $CaCl_2$, $(NH_4)_2SO_2$, and $NiSO_4$ particles passing through a stainless steel grid and a wire screen; they also demonstrated the drop in filtration efficiency of NaCl and $NiSO_4$ particles. Both groups of the researchers claimed that they have successfully observed thermal rebound in nanoparticle filtration. Recently, Rennecke and Weber (2013a) investigated the thermal rebound of nanoparticles under low pressure and demonstrated the possibility of thermal rebound for dense NaCl particles in the range of 20–60 nm.

Despite the large body of literature, uncertainties remain in the theory of airborne nanoparticle filtration. Existing nanoparticle filtration models with the consideration of thermal rebound were built on the Bradley–Hamaker (BH) or Johnson–Kendall–Roberts (JKR) elastic adhesion energy models (Mouret, Chazelet, Thomas, & Bemer, 2011; Wang & Kasper, 1991), and they did not consider the Derjaguin–Muller–Toporov (DMT) elastic adhesion energy model for the calculation of adhesion efficiency, which seems to be more applicable to nanoparticles. Furthermore, all researchers have assumed elastic impact between nanoparticles and the filter media. However, latest advances in molecular dynamic simulation have proven the plastic deformation of nanoparticles upon impact with the surface of the filter media (Awasthi, Hendy, Zoontjens, & Brown, 2006; Awasthi, Hendy, Zoontjens, Brown, & Natali, 2007; Ayesh et al., 2010, Gilabert, Krivtsov, & Castellanos, 2006; Ikeda et al., 1999).

Another factor missing in the theory of airborne nanoparticle filtration is the effect of capillary force between the nanoparticle and the surface of the filter media. Studies have shown the increase of the adhesion energy between a particle and a solid surface at high relative humidity (Bateman, Belassein, & Martin, 2014; Chen, Tsai, Chen, Huang, & Roam, 2011; Stein, Turpin, Cai, Huang, & Mcmurry, 1994; Vasiliou, Sorensen, & McMurry, 1999). It has also been reported that the removal filtration efficiency for micron particles increases with the level of relative humidity (Brown, 1993; Miguel, 2003; Mullins, Agranovski, & Braddock, 2003; Xu, Wu, Lin, & Chen, 2014); however, it is not clear whether this applies to nanosized particles.

The main objective of this work is to develop a new nanoparticle filtration model by considering the effects of thermal rebound and capillary force between nanoparticles and the filter media. This paper presents a new approach using the plastic deformation of nanoparticles upon impaction to determine the particle critical velocity above which thermal rebound occurs. The new model is then validated using our experimental data and those selected from literature. In the experimental phase of this study, the removal filtration efficiency of WO*x* and NaCl nanoparticles through stainless-steel wire screens was evaluated as a function of particle size at air flow rate of 2 liter per minute (lpm).

2. Theoretical analysis

Theoretical analysis prior to this paper have been reviewed in our earlier publication (Givehchi & Tan, 2014) and they are briefly summarized as follows. The penetration efficiency of particles through the filter is (Cheng & Yeh, 1980; Hinds, 1999)

$$P = \exp\left[\frac{-4\alpha\varepsilon EL}{\pi d_f(1-\alpha)}\right] \tag{1}$$

where P is the penetration efficiency, L is the bed thickness, α is the solidity of the filter, d_f is the diameter of the fiber, E is the corresponding single fiber efficiency, and ε is the adhesion efficiency of nanoparticles to the surface of the filter media.

The single-fiber efficiency for nanoparticles depends primarily on the Brownian diffusion mechanism. The diffusional single fiber efficiency of nanoparticles through a wire screen is (Cheng & Yeh, 1981; Kirsch & Fuchs, 1968):

$$E_D = 2.7\,Pe^{-2/3} \tag{2}$$

where Pe is the Peclet number.

It should be noted that the maximum value for single-fiber efficiency is 1. Previous studies (Mouret et al., 2011; Wang & Kasper, 1991) employed diffusion deposition equation (Lee & Liu, 1982) for the calculation of single-fiber efficiency, which led to values of greater than 1 for sub-10 nm particles. Many researchers did not correct the error of the equation, and supper-1 single-fiber efficiency was used for those nanoparticles. The multiplication of these values by an adhesion efficiency with a maximum value of 1 leads to a high filtration efficiency for small nanoparticles.