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## Discussion about the thermal rebound of nanoparticles

### Guillaume Mouret<sup>a,b</sup>, Sandrine Chazelet<sup>a,b</sup>, Dominique Thomas<sup>a,\*</sup>, Denis Bemer<sup>b</sup>

<sup>a</sup> Laboratoire Réactions et Génie des Procédés (LRGP), Nancy-Université, CNRS, 1 rue Grandville, BP 20451, F-54001 Nancy, France <sup>b</sup> INRS – Ingénierie des Procédés, Avenue du Morvan, CS 60027, F-54519 Vandoeuvre les Nancy, France

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#### 1. Introduction

For the last few decades, nanoscience and nanotechnologies have developed in such a way that some experts already speak of "the Industrial Revolution of the 21st Century" (Interagency Working Grouping on Nanoscience, Engineering and Technology [1], Keiper [2], Fundación de la Innovación Bankinter [3]). In parallel of this significant development, toxicologists warn us against the potential adverse effects of nanoparticles on both human health and the environment (Kreyling et al. [4], Biswas and Wu [5], Oberdörster et al. [6], Borm et al. [7]). Since 2 million nanotechnology workers are expected by 2015 (National Science Foundation [8], Roco [9]), this raises the problem of risk management.

For a long time, aerosols below 100 nm had been considered to be captured by Brownian diffusion. However, in 1991, a theory has triggered doubts about the filterability of particles smaller than 10 nm. Wang and Kasper [10] indeed developed a filter efficiency model for nanometer-sized particles which incorporates the effect of particle rebound from the fiber surface. It is interesting to note that such a concept of bounce probability is already well known for large particles [11,12] for which filtration efficiency typically decreases above 5  $\mu$ m because of too high inertia. It can also be noted that for nanoparticles, Kops et al. [13] had proposed a first expression of this phenomenon in 1986.

Thus, according to the thermal rebound concept, filtration efficiency E could decrease below 10 nm because of a bounce of particles on the surface of filter medium due to a kinetic energy

\* Corresponding author. *E-mail address:* Dominique.Thomas@ensic.inpl-nancy.fr (D. Thomas).

#### ABSTRACT

In the field of aerosol filtration, the theory of thermal rebound of nanoparticles developed by Wang and Kasper [10] has been subject of discussion for more than two decades since it does not fit the experiment. The main purpose of this theory is that the filtration efficiency of fibrous filters could decrease in the region of 10 nm and below because of an excessive impact velocity of particles. However and despite numerous lab experiments leaded by different teams, the phenomenon has never been clearly observed. We demonstrate in this paper why no thermal rebound effect has ever been measured experimentally. According to our approach, the decrease in filtration efficiency, if any, might only happen below 1 nm, even at high temperatures.

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higher than the adhesion one. The problem is then substantial since the performances of protective equipment such as masks or hood systems are concerned. On the experimental point of view, the studies that have been carried out in the size range 1–20 nm since the early eighties give diverging conclusions. Table 1 provides a review of these research works.  $d_p$  and  $d_f$  are respectively the particle and fiber diameter (m),  $\alpha$  is the packing density of the filtering media, U is the filtration velocity (m s<sup>-1</sup>) and T, the temperature (K). These parameters are given in Table 1 when communicated by their authors.

Nearly no study results in evidence of thermal rebound observations. The few ones which could claim about a particle bounce measurement (Otani et al. [16], Ichitsubo et al. [18]) were shown by Alonso et al. [19] and Heim et al. [22] to be explained by experimental artefacts due to a mobility shift in size-classification devices used. Up to now, only the results of Kim et al. [23], who had no other choice but to work in extreme conditions to select particles as small as 1 nm with their DMA, have never been confirmed or refuted by other authors below 1.3 nm.

After fundamental reminds about the original concept, this paper discusses about the calculations of the thermal rebound effect in order to show that the current inconsistency between the theory and the experiments realized up to now could eventually be justified. The effect of temperature on the particle bounce is also studied in the last part.

#### 2. A sticking problem

In classical filtration theories, the adhesion efficiency  $\varepsilon$  is assumed to be equal to unity, which means that all particles strik-

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Table 1

Literature experimental studies dealing with nanoparticle filtration and thermal rebound evidence.

| YearAuthonParticles<br>typeJournal operating conditionsResults1984Schebal and<br>Porstendorfer [14]Silver particles<br>stressesJournal of a (100 nm)<br>a (102 38 mm)<br>a (102 38 mm)<br>a (102 38 mm)<br>a (102 38 mm)Encreases when d,<br>deveates<br>a (102 38 mm)<br>a (102 38 mm)Encreases when d,<br>deveates<br>a (102 30 mm)Encreases when d,<br>deveates<br>a (102 30 mm)1995Otani et al. [16]Silver particles<br>Statiles steel wite<br>statiles steel wit   |              |                        |  |   |                                  |
|--|--------------|------------------------|--|---|----------------------------------|
| 1884Schenbel and<br>PorstudiesSilver particles<br>screens1.5 mm cd_s (130 mm<br>screens) <i>E</i> increases when d_s<br>decreases1890VanOsdell et al.<br>[13]Silver particles<br>Phorytas fibrous<br>mitro $4-30  \text{nm}$<br>$4-20  \text{nm}^{-1}$ <i>E</i> increases when d_s<br>decreases1995Otani et al. [16]Silver particles<br>Statiless steel wite<br>screens $1  \text{nm} < d_s - 10  \text{nm}$<br>$4 - 20  \text{nm}^{-1}$ <i>E</i> increases when d_s<br>decreases1996Skaptsov et al. [17]WO, and MAO,<br>Particles<br>Statiless steel wite<br>screens $1  \text{nm} < d_s - 70  \text{nm}$<br>$4 - 22  \text{nm}^{-1}$ <i>E</i> increases when d_s<br>decreases but<br>methods1996kbitsub et al. [18]Silver particles<br>Statiless steel wite<br>screens $1  \text{nm} < d_s - 70  \text{nm}$<br>$4 - 75  \text{nm}^{-1}$ <i>E</i> increases when d_s<br>decreases but<br>methods1997Alons et al. [19]Silver and NACL<br>particles $1  \text{nm} < d_s - 70  \text{nm}$<br>$4 - 75  \text{nm}$ <i>E</i> increases when d_s<br>decreases but all<br>decreases but all<br>decreases but all<br>screens1997Alons et al. [19]Silver and NACL<br>particles $1  \text{nm} < d_s - 70  \text{nm}$<br>duricles <i>E</i> increases when d_s<br>decreases but all<br>decreases but all<br>decreases but all<br>screens2004Balazy et al. [20]Silver and NACL<br>particles $1  \text{nm} < d_s - 70  \text{m}$<br>duricles <i>E</i> increases when d_s<br>decreases2005Heim et al. [22]NaCL particles<br>respiration $1  \text{nm} < d_s - 20  \text{m}$<br>decreases <i>E</i> increases when d_s<br>decreases2006Kim et al. [24]Silver particles<br>respiration   | Year         | Authors                | Particles and media<br>type              | Operating conditions  | Results                          |
| 1 and<br>Postendiater [14]Satisfies seed wire<br>screens $d = -0.5 \mu m^2$<br>$d = -0.5 \mu m^2$<br>  | 1094         | Scheibel and           | Silver particles                         | 25  nm < d < 120  nm  | Fingrosses when d                |
| 1990National (14)accreans<br>accreans<br>(12) 24 matrix<br>(12) 24 mass)<br>(12)  | 1504         | Porstondörfor [14]     | Staipless steel wire                     | $d_{\rm r} = 50 \mathrm{mm}$  | docrossos                        |
| 1990Van0odel et al.<br>[15]Silver particles<br>Riger particles<br>Sinter stel wire<br>articles $4 - 54 \operatorname{cm}^{-1}$<br>articles<br>stel stel wire<br>articles<br>stel stel wire<br>branc decreasesEncreases when decreases<br>articles<br>stel stel wire<br>articles<br>stel stel wire<br>articles<br>to respect to the stel wire<br>articles<br>to respect to the stel wire<br>to respec   |              | Forstendorier [14]     | Statiliess steel wire                    | $u_{\rm f} = 50 \mu m$  | uccreases                        |
| 1990Unocdail et al.<br>[15]Silver particles<br>filtered<br>science and tubes $L = 4 \times 10^3$<br>$d < 1 \ um < d < d < 1 \ um < d < 1 \ um < d < d < d < d < d < d < d < d < d < $  |              |                        | screens                                  | $\alpha = 0.2798$   |                                  |
| 1990Val kypel et al.Sure particlesAnne de 100mA inne de 100mA inne de 100m1995Quan et al. [16]Silver particles<br>Stainless steel wireInne de 4-00mEincreases when de<br>4-52 µm1995Quan et al. [16]Silver particles<br>screens and tubesInne de 4-00mEincreases when de<br>4-52 µm1996Slaptsov et al. [17]WO, and MoO,<br>particles<br>and tubes1 Inne de 4-10 mmEincreases when de<br>4-52 µm1996Slaptsov et al. [18]Silver and NaCl<br>particlesInne de 4-10 mmEincreases when de<br>4-52 µm1996Ichitsubo et al. [18]Silver and NaCl<br>particlesInne de 4-10 mmEincreases when de<br>4-72 µm1997Alono et al. [19]Silver and NaCl<br>particlesInne de 4-70 mmEincreases when de<br>4-72 µm1997Alono et al. [19]Silver and NaCl<br>particlesInne de 4-70 mmEincreases when de<br>4-72 µm2004Balazy et al. [20]Obel's droppets<br>fibrosis fibresIonme de 4-70 µmEincreases when de<br>4-72 µm2005Heim et al. [21]NaCl and Fibrosis fibres<br>fibres [35 µm]Eincreases when de<br>4-72 µmEincreases when de<br>4-72 µm2006Kim et al. [23]NaCl and Fibrosis fibres<br>fibres [35 µm]Ionme 4-62 µmEincreases when de<br>4-73 µm2007Kim et al. [24]NaCl and Fibrosis fibres<br>fibres [36 µm]Eincreases when de<br>4-74 µmEincreases when de<br>4-74 µm2007Kim et al. [24]NaCl and Fibrosis fibres<br>fibres [36 µm]Ionme 4-64 µmEincreases when de<br>4-74 µm<  | 1000         |                        |  | $U = 2.4 \mathrm{cm  s^{-1}}$   |                                  |
| $\left  15 \right  \\   15 \right  \\   16   16   16   16   16   16   16  $  | 1990         | VanOsdell et al.       | Silver particles                         | $4 \text{ nm} < a_p < 10 \text{ nm}$                                    | E increases when $d_p$           |
| 1995Dani et al. [16]Silver particles<br>Statiles steel wire<br>access and tubes $a = 0.07 - 0.08$<br>$G = 0.4 + 0.0 m M et al. (10 m M et al. (10 m et al.$  |              | [15]                   | Fiberglass fibrous                       | $d_{\rm f}$ < 1 $\mu$ m   | decreases                        |
| 1995Oran et al. [16]Silver particles<br>Stainless stel wire<br>screen and tubesInm $4_0$ + 20 µm<br>$4^{-52}$ µm   |              |                        | filters                                  | $lpha pprox 0.07 {-} 0.08$  |                                  |
| 1955     Okani et al. [16]     Siver particles<br>Stainless stel wire<br>screens and tubes     Imm : d_i < 10 mm   |              |                        |  | $5 \mathrm{cm}\mathrm{s}^{-1} < U < 20 \mathrm{cm}\mathrm{s}^{-1}$      |                                  |
| Since is steel wire<br>screen and tubes $d_{a}$ -52 µm<br>screen and tubes $d_{a}$ -63 µm<br>and tubesdecreases but<br>meretation in tubes<br>increases but on<br>to creases but on<br>to crease but on<br>  | 1995         | Otani et al. [16]      | Silver particles                         | $1 \text{ nm} < d_p < 10 \text{ nm}$                                    | E increases when dp              |
| 1996Skaptsov et al. [17]screens and tubes $a^{-0.31}_{-1}$ penetration in tubes<br>increases below 2 multiply<br>and Moo,<br>r 245,51 stan 337 Kpenetration in tubes<br>increases below 2 multiply<br>et increases when d,<br>decreases below 2 multiply<br>access a multiply<br>access a multiply<br>access a multiply<br>access a multiply access a multiply<br>access access a multiply<br>access access  |              |                        | Stainless steel wire                     | $d_{\rm f} = 52\mu{\rm m}$  | decreases but                    |
| $ \begin{array}{ c c c } 12 \mbox{res}^{-1} (J-3 \mbox{support} J-2 \mbox{res}^{-1} (J-3 \mbox{support} J-2 suppo$   |              |                        | screens and tubes                        | $\alpha = 0.31$   | penetration in tubes             |
| 1996Skaptsov et al. [17]<br>particles<br>Stainless steel wire<br>screenes<br>screenes<br>screenes<br>19963.1 mm ed., et 34 mm<br>response but also<br>u - 2.92 cm s - 1E increases when dy<br>decreases but also<br>when 7 decreases<br>decreases but also<br>when 7 decreases<br>decreases but also<br>when 7 decreases<br>decreases but also<br>decreases but also<br>decreases but also<br>when 7 decreases<br>decreases but also<br>decreases but also<br>decreases<br>decreases<br>decreases<br>decreases<br>decreasesI mm ed., et 34 mm<br>decreases<br>decreases<br>decreases<br>decreases<br>decreases<br>decreases1997Alons et al. [19]<br>particles<br>particles<br>[21]<br>all also but al   |              |                        |  | $1.2 \text{ cm s}^{-1} \le U \le 3.6 \text{ cm s}^{-1}$                 | increases below 2 nm             |
| 1996Inducts of all (1)particles<br>straineds steel view<br>screens7-295, 210, sr.1decreases but also<br>were screens1996Ichitsubo et al. [18]Silver and NaCl<br>particles<br>straineds steel view<br>screens $1\mathrm{nm} < d_{q} < 7\mathrm{nm}$<br>$d < r > 22, 200, sr.1Fincreases when d_{p}decreases andstraineds steel viewarc22891997Alonso et al. [19]Silver and NaClparticlesstraineds steel viewarc22891\mathrm{nm} < d_{q} < 7\mathrm{nm}d < r > 22, 200, sr.1Fincreases when d_{p}decreases andstraineds steel viewarc22892004Balazy et al. [20]DEff. Stroletsparticlesscreens and tubesscreens and tubesscreens and tubesfilters1\mathrm{nm} < d_{q} < 27\mathrm{nm}d < r > 22, 200, sr.1F decreases below20042004VanCulijk and Bal[21]NaCl particlesrecens and tubesstainless steel filter andstainless steel filterscreenscreens2.5\mathrm{nm} < d_{q} < 20\mathrm{nm}d < r > 2.5\mathrm{nm} < d_{q} < 20\mathrm{nm}d < r > 2.5\mathrm{nm} < d_{q} < 20\mathrm{nm}d < d < 2.5\mathrm{nm} < d_{q} < 20\mathrm{nm}d < d < 2.5\mathrm{nm} < d_{q} < 20\mathrm{nm}d < d < d < 1.1, 2.1, 2.1, 2.1, 2.1, 2.1, 2.1, 2.1,$   | 1996         | Skaptsov et al [17]    | $WO_2$ and $MoO_2$                       | $31 \text{ nm} < d_{n} < 154 \text{ nm}$                                | $E$ increases when $d_{\rm res}$ |
| 1996Ichitsube et al. [18]Silver and NaCl<br>arriel site lyineImm < d_{7} < 7 and<br>arriel site line site lyineImm < d_{7} < 7 and<br>arriel site line   | 1000         | Shaptsor et an [17]    | narticles                                | T = 295 316 and $337 K$   | decreases but also               |
| $ \frac{1}{12} $   |              |                        | Staipless steel wire                     | I = 2.03; 510 and 557 K   | when T decreases                 |
| 1996Ichitsubo et al. [18]Sitter and NaCl<br>particles<br>stanless stel wire<br>screens $1 \operatorname{nm} < d_{0} < 7 \operatorname{nm}$<br>$d < 2 \operatornamenm}$<br>$d < 2 \operatornamenm}$ Imal d<br>$d < 2 \operatornamenm}$<br>$d < 2 \operatornamenm}$<br>$d < 2 \operatornamenm}$ Imal d<br>$d < 2 \operatornamenm}$<br>$d < 2 \operatornamenm}$<br>$d < 2 \operatornamenm}$ Imal d<br>$d < 2 \operatornamenm}$<br>$d < 2 \operatornamenm}$<br>$d < 2 \operatornamenm}$ Imal d<br>$d < < 2 \operatornamenm}$<br>$d < 2 \operatornamenm}$ Imal d<br>$d < < 2 \operatornamenm}$<br>$d < < 2 \operatornamenm}$ Imal d<br>$d < < 2 \operatornamenm}$ Imal d<br> | 1000         |                        | Statiliess steel wire                    | 0 - 2.92 (11)   | when I decreases                 |
| 1990Interface   |              | Labitation at al. [10] | Scientis                                 | 1   |                                  |
| particles<br>Similes steel wire<br>screens $d=r/s \mu n$<br>$d=r/s \mu n$<br>$d=r/s \mu n$ decreases and<br>$d=r/s \mu n$<br>$d=r/s \mu n$ decreases $d=r/s \mu n$ decreases $d=r/s \mu n$ decreases $d=r/s \mu n$ decrease $d=r/s \mu n$ dec  | 1996         | Ichitsubo et al. [18]  | Silver and NaCl                          | $1 \text{ nm} < a_p < 7 \text{ nm}$                                     | E increases when a <sub>p</sub>  |
| Stanless stel wire<br>screens $a^{-0.28}$ stagmets below 2 nm<br>stagmets below 2 nm<br>( $a^{-75}$ µm<br>( $a^{-75}$ µm<  |              |                        | particles                                | $d_{\rm f} = 75\mu{\rm m}$  | decreases and                    |
| $ \begin{array}{cccccccccccccccccccccccccccccccccccc$  |              |                        | Stainless steel wire                     | $\alpha = 0.289$  | stagnates below 2 nm             |
| 1997Alonso et al. [19]Silver and NaCl<br>apricies<br>Stainless steel wire<br>apricies<br>direct 2004Immedia<br>apricies<br>direct 2004Immedia<br>decreases<br>decreases<br>direct 2004Immedia<br>decreases<br>decreases<br>direct 2004Immedia<br>decreases<br>decreases<br>direct 2004Immedia<br>decreases<br>decreases<br>direct 2004Immedia<br>decreases<br>decreases<br>direct 2004Immedia<br>decreases<br>decreases<br>decreases<br>decreasesImmedia<br>decreases<br>decreases<br>decreases<br>decreasesImmedia<br>decreases<br>decreases<br>decreasesImmedia<br>decreases<br>decreases<br>decreasesImmedia<br>decreases<br>decreasesImmedia<br>decreases<br>decreasesImmedia<br>decreases<br>decreasesImmedia<br>decreasesImmedia<br>decreasesImmedia<br>decreases2004VanCalijk and Bal<br>[21]<br>[21]<br>[21]<br>[21]<br>[21]<br>[21]<br>[21]<br>[21]<br>[21]<br>[21]<br>[21]<br>[21]<br>[21]<br>[21]<br>[21]<br>[21]<br>[21]<br>[21]<br>[21]<br>[21]<br>[21]<br>[21]<br>[21]<br>[21]<br>[21]<br>[21]<br>[22]<br>[22]<br>[22]<br>[22]<br>[22]<br>[22]<br>[22]<br>[22]<br>[22]<br>[22]<br>[22]<br>[23]<br>[23]<br>[23]<br>[23]<br>[23]<br>[23]<br>[23]<br>[23]<br>[23]<br>[23]<br>[23]<br>[23]<br>[23]<br>[23]<br>[23]<br>[23]<br>[23]<br>[23]<br>[23]<br>[23]<br>[23]<br>[23]<br>[23]<br>[23]<br>[23]<br>[23]<br>[23]<br>[23]<br>[23]<br>[23]<br>[23]<br>[23]<br>[23]<br>[23]<br>[23]<br>[23]<br>[23]<br>[23]<br>[24]<br>[24]<br>[25]<br>[25]<br>[24]<br>[25]<br>[25]<br>[25]<br>[26]<br>[26]<br>[26]<br>[26]<br>[26]<br>[26]<br>[26]<br>[26]<br>[26]<br>[26]<br>[26]<br>[26]<br>[26]<br>[26]<br>[26]<br>[26]<br>[26]<br>[26]<br>[26]<br>[26]<br>[26]<br>[26]<br>[26]<br>[26]<br>[26]<br>[26]<br>[26]<br>[26]<br>[26]<br>[26]<br>[26]<br>[  |              |                        | screens                                  |   |                                  |
| particles<br>Stainless steel wire<br>screens and tubesder 73 pm<br>c -0.289<br>creens and tubesdecreases<br>c -0.289<br>cresn -1 U < 100 mm < d_p < 0.05 µm<br>U = 7.05 rm -1E decreases below<br>200 mm<br>200 mm <   | 1997         | Alonso et al. [19]     | Silver and NaCl                          | $1 \text{ nm} < d_p < 7 \text{ nm}$                                     | E increases when dp              |
| Stainless steel wire<br>screens and tubes $0 - 0289$<br>$0 - 0 - 0 - 0 - 1$ $E$ decreases below<br>$2004$ 2004Balazy et al. [20]DEHS droplets<br>ibrous filters<br>Fibres filters<br>filters $1 - 3 - cm \cdot 1^3$<br>$0 - 3 - cm \cdot 1^3$ $E$ depends on the<br>acrosol type2005Heim et al. [22]NaCl and H <sub>2</sub> O particles<br>Fibres filters<br>stainless steel filter and<br>opypropylene wire<br>stainless steel filter and<br>opypropylene wire<br>stainless steel filter and<br>filters $2.5  \mathrm{mr} \cdot d_p < 20  \mathrm{nm}$<br>$4.2 < d_1 < 110  \mathrm{µm}$<br>$0.22 < a < 0.387$ $E$ decreases when $d_p$<br>decreases<br>tube down of the screen,<br>stainless steel filter and<br>polypropylene wire<br>screen $1.3  \mathrm{mm}$<br>$4.2 < (d_1 < 100  \mathrm{µm}$<br>$4.2 < (d_1 < 100  \mathrm{µm}$<br>$4.3 < (d_1 < 100  \mathrm{µm}$<br>$1.3  \mathrm{µm}$ $E$ decreases below<br>$4.3 < (d_1 < 100  \mathrm{µm}$<br>$4.3 < (d_1 < 100  \mathrm{µm}$<br>$4.3 \ \mathrm{µm}$ $E$ decreases below<br>$4.3 \ \mathrm{µm}$<br>$4.3 \ \mathrm{µm}$<br>$4.3 \ \mathrm{µm}$ 2006Kim et al. [23]Silver particles<br>Fibreglass fibrous<br>filters<br>$4.9 \ \mathrm{µm}$<br>$4.9 \ \mathrm{µm}$<br><td></td> <td></td> <td>particles</td> <td><math>d_{\rm f} = 75\mu{\rm m}</math></td> <td>decreases</td>  |              |                        | particles                                | $d_{\rm f} = 75\mu{\rm m}$  | decreases                        |
| 2004Balay et al. [20]Screen and tubes $6crease below10 m c d_r (0.6 µm)E decreases below20 m²2004Balay et al. [20]PIENS on plitters10 m c d_r (0.6 µm)E decreases below20 m²2004VanCulijk and Bal[21]NCI and 1/0 particles1-3 c m s^{-1}20 m²2005Heim et al. [22]MaCl particles2.5 m c d_p < 20 nmE increases when d_pdecreases2006Heim et al. [23]MaCl particles2.5 m s d_p < 20 nmE increases when d_pdecreases2006Kim et al. [23]NaCl particles4.4 cm s^{-1} < U < 6.48 cm s^{-1}2007Kim et al. [24]Silver particlesriberglass fibrousfiltersd_q < 4.0 nmE decreases belowU = 2.5 cm s^{-1}2007Kim et al. [24]Silver particlesriberglass fibrousfilters10 \mu m < d_q < 4.0 nmE increases when d_pU = 2.5 cm s^{-1}2007Kim et al. [25]NaCl particlesriberglass fibrousfilters10 \mu m < d_q < 4.0 nmE increases when d_pU = 2.5 cm s^{-1}2007Kim et al. [25]NaCl particlesriberglass fibrousfilters4.5 m < d_pE increases when d_pd = -0.052007Steffens and Coury[26]NaCl particlesriberglass fibrousfilters4.5 m < d_pE increases when d_pd = -0.052008Sin et al. [27]Silver particlesstainless steel wirescreena = -0.18a = -0.18a = -0.03a = -0.0202008Mouret [28]Cu and C particlesStainless steel wires$   |              |                        | Stainless steel wire                     | $\alpha = 0.289$  |                                  |
| 2004Balazy et al. [20]DENS orplets<br>infrom filters<br>infrom filters<br>infrom filters<br>infrom filters<br>infreq statistics $Unc d_0 < 0.5 \ \mu m$<br>$Un = 0.5^{-1}$ $E$ depends on the<br>aerosol type2004VanCuilijk and Bal<br>[21]NaCl and H <sub>2</sub> O particles<br>infreq statistics $7 \ m < d_q < 25 \ nm < d_q < 20 \ nm$ $E$ depends on the<br>aerosol type2005Heim et al. [22]NaCl and H <sub>2</sub> O particles<br>infreq statistics steel filter and<br>outpyropylene wire<br>statistics steel filter and<br>filters $2.5 \ nm < d_q < 20 \ nm$ $E$ increases when $d_p$<br>decreases2006Kim et al. [23]NaCl particles<br>infreq statistics steel filter and<br>polyropylene wire<br>screen $1 \ m < d_q < 10 \ nm$ $E$ decreases below<br>$4.2 < d_1 < 110 \ \mu m$<br>$4.2 < d_1 < 110 \ m m$<br>$4.2 < d_1 < 110 \ m m$<br>$4.2 < d_1 < 110 \ m m$<br>$4.2 < d_1 < 10 \ nm$<br>$4.2 < d_1 < 4.2 \ nm$<br>$4.2 < d_1 < 10 \ nm$<br><td></td> <td>screens and tubes</td> <td><math>6 \mathrm{cm}\mathrm{s}^{-1} &lt; U &lt; 100 \mathrm{cm}\mathrm{s}^{-1}</math></td> <td></td>  |              |                        | screens and tubes                        | $6 \mathrm{cm}\mathrm{s}^{-1} < U < 100 \mathrm{cm}\mathrm{s}^{-1}$     |                                  |
| 2004VanGuljk and Bal<br>[21]Fibrous filters $U = 7.5  \mathrm{cm}^{-1}$ 20 nm²2004VanGuljk and Bal<br>[21]NaCl and H.Jo particles<br>Fiberglass fibrous<br>  | 2004         | Balazy et al. [20]     | DEHS droplets                            | $10 \text{ nm} < d_p < 0.5 \mu\text{m}$                                 | E decreases below                |
| 2004VanGulijk and Bal<br>[21]NaCl and Hg O particles<br>Fiberglass fibrous<br>filters7 nm < $d_p < 25$ nmE depends on the<br>aerosol type2005Heim et al. [22]NaCl particles<br>stainless steel filter and<br>opolyropylene wire<br>screen.2 5 nm < $d_p < 20$ nm<br>decreasesE increases when $d_p$<br>decreases2006Kim et al. [23]NaCl particles<br>screen1 nm < $d_p < 4100$ nm<br>decreasesE decreases<br>arease2007Kim et al. [24]Silver particles<br>filters1 nm < $d_p < 4100$ nm<br>decreasesE decreases below<br>u = 2.5 cm s^{-1}2007Kim et al. [24]Silver particles<br>filters3 nm < $d_p < 420$ nm<br>decreasesE increases when $d_p$<br>decreases2007Huang et al. [25]NaCl particles<br>filters1 nm < $d_p < 410$ nm<br>decreasesE increases when $d_p$<br>decreases2007Huang et al. [25]NaCl particles<br>respiratory masksS mm < $d_p < 94$ sm<br>decreasesE increases when $d_p$<br>decreases2007Steffens and Coury<br>[26]NaCl particles<br>respiratory masks8.5 nm < $d_p < 94.8$ nm<br>decreasesE increases when $d_p$<br>decreases2008Shin et al. [27]Silver particles<br>stainless steel wire<br>screen3 nm < $d_q < 20$ nm<br>decreasesE increases when $d_p$<br>decreases2008Mouret [28]Cu and C particles<br>stainless steel wire<br>screen3 nm < $d_q < 20$ nm<br>decreasesE increases when $d_p$<br>decreases2008Nou et al. [27]Silver particles<br>Stainless steel wire<br>screen3 nm < $d_q < 20$ nm<br>decreasesE increases when $d_p$<br><td></td> <td>Fibrous filters</td> <td><math>I = 7.5 \text{ cm s}^{-1}</math></td> <td>20 nm<sup>a</sup></td>  |              |                        | Fibrous filters                          | $I = 7.5 \text{ cm s}^{-1}$   | 20 nm <sup>a</sup>               |
| 2004[21]Fiberglas fibrous<br>filters $Largendictor (1) = Left) and (2)marked (2)Largendictor (1) = Left) and (2)marked (2)Largendictor (2)marked (2)2005Heim et al. [22]NaCl particlesmickel wire screen,polypropylene wirescreen2.5  \mathrm{nm} < d_p < 20  \mathrm{nm}4.2 < cd < 110  \mathrm{µm}0.0022 < cd < 0.387polypropylene wirescreen1.44  \mathrm{cm}  \mathrm{s}^{-1} < U < 6.48  \mathrm{cm}  \mathrm{s}^{-1}4.9 \cdot 10  \mathrm{nm}4.9 \cdot 10  \mathrm{nm}E decreasesbelow4.9 \cdot 10  \mathrm{nm}1.3  \mathrm{nm}2006Kim et al. [23]NaCl particlesFiberglass fibrousfilters4.9 \cdot 10  \mathrm{nm}1.3  \mathrm{nm}4.9 \cdot 01  \mathrm{nm}4.9 \cdot 01  \mathrm{nm}E decreases below4.9 \cdot 01  \mathrm{nm}4.9 \cdot 01  \mathrm{nm}2007Kim et al. [24]Silver particlesFiberglass fibrousfilters1.9  \mathrm{nm} < d_r < 4.9  \mathrm{nm}4.9 \cdot 2.5  \mathrm{cm}  \mathrm{s}^{-1} < U < 4.8  \mathrm{cm}  \mathrm{s}^{-1} < U < 4.9  \mathrm{nm}4.9 \cdot 2.0  \mathrm{nm}4.9 \cdot 2.0  \mathrm{nm}E increases when d_pdecreases2007Kim et al. [25]NaCl particlesFibro filters forrespiratory masks2.8  \mathrm{cm}^{-1} < U < 8.8  \mathrm{cm}^{-1} < U < 2.5  \mathrm{cm}^{-1} < U < 8.8  \mathrm{cm}^{-1} < U $  | 2004         | VanCuliik and Bal      | NaCl and HaO particles                   | $7 \text{ nm} \le d \le 25 \text{ nm}$                                  | E depends on the                 |
| 1Intersection typeAction type2005Heim et al. [22]NaCl particles $2.5  \mathrm{cm} < d_p < 20  \mathrm{cm} < d_p < 2$   |              |                        | Fiberglass fibrous                       | / IIII (up (23 IIII   | 2 depends on the                 |
| 2005Heim et al. [22]NaCi particles<br>NaCi particles<br>Nickel wire screen,<br>screen<br>erren2.5 mm < $d_p < 20  nm$<br>$4.2 < d_r < 110  \mum$<br>$4.2 < d_r < 120  nm$<br>$4 < 120  nm$<br>$4$  |              | [21]                   | fitore                                   |   | acrosoftype                      |
| 2005Heim et al. [22]NaCl particles2.3 mm < $q_p < 2.0$ mm $p_p < 2.0$ mm $p_p < 2.0$ mm $p_p < 2.0$ mm $p_p < 2.0$ mm $q_p < 2.0$ mm $q_p$  | 2005         | Helment at (22)        | litters<br>Na Glassatiales               | 2.5   |                                  |
| Nickel wire screen,<br>stailess steel filter and<br>polypropylene wire<br>screen $4.2 < d_r < 110 \ \mum$<br>  | 2005         | Heim et al. [22]       | Naci particles                           | $2.5 \text{ nm} < a_p < 20 \text{ nm}$                                  | E increases when $a_p$           |
| 2006Kim et al. [23]Nacl particles<br>respiration $1 \operatorname{Arm} s^{-1} < U < 6.48  \mathrm{cm}  \mathrm{s}^{-1}$<br>$a < 0.00  \mathrm{m}$<br>$d_1 = 9.1  \mu \mathrm{m}$<br>$a < 0.00  \mathrm{m}$<br>$d_1 = 9.1  \mu \mathrm{m}$<br>$a < 0.00  \mathrm{m}$<br>$a < 0.00  \mathrm{m}$<br>$d_1 = 9.1  \mu \mathrm{m}$<br>$a < 0.00  \mathrm{m}$<br>$a < 0.00  \mathrm{m}$<br>$d_1 = 9.1  \mu \mathrm{m}$<br>$a < 0.00  \mathrm{m}$<br>$a < 0.00  \mathrm{m}$<br>$d_1 = 9.1  \mu \mathrm{m}$<br>$a < 0.00  \mathrm{m}$<br>$a < 0.00  \mathrm{m}$<br>$d_1 = 9.1  \mu \mathrm{m}$<br>$a < 0.00  \mathrm{m}$<br>$b < 0.00  $  |              |                        | Nickel wire screen,                      | $4.2 < d_{\rm f} < 110 \mu{\rm m}$                                      | decreases                        |
| $ 2006 \qquad Kim et al. [23] \qquad Particles in the second second$   |              |                        | stainless steel filter and               | 0.0022 < α < 0.387  |                                  |
| $ 2006 \qquad \text{Kim et al. [23]} \qquad \text{Screen} \\ \text{Fiber glass fibrous} \\ filters \\ u = 0.06 \\$   |              |                        | polypropylene wire                       | $1.44 \mathrm{cm}\mathrm{s}^{-1} < U < 6.48 \mathrm{cm}\mathrm{s}^{-1}$ |                                  |
| 2006Kim et al. [23]NaCl particles<br>Fiberglass fibrous<br>filters $1 \text{ mr} < d_p < 100 \text{ nm} < f_p < 20 \text{ nm} < f_p < 2007Kim et al. [24]Silver particlesFiberglass fibrousfilters1.9  \mu \text{ m} < d_p < 20 \text{ nm} < f_p < 2007E increases when d_pfilters2007Huang et al. [25]NaCl particlesrespiratory masks4.5  \text{nm} < d_p < 13  \mu \text{ m} \text{ ad}a < 0.035 + 2003 + 2$  |              |                        | screen                                   |   |                                  |
|  | 2006         | Kim et al. [23]        | NaCl particles                           | $1 \text{ nm} < d_p < 100 \text{ nm}$                                   | E decreases below                |
| 2007Kim et al. [24]filters<br>Silver particles<br>Fiberglass fibrous<br>filters $U=2.5  \mathrm{cm}^{-1}$<br>$U=2.5  \mathrm{cm}^{-1}$ $E  \mathrm{increases  when  d_p}$<br>decreases<br>$u=0.118$<br>$u=0.118$<br>$u=0.118$<br>$u=0.118$<br>$u=0.25  \mathrm{cm}^{-1}$ $E  \mathrm{increases  when  d_p}$<br>decreases<br>$u=0.118$<br>$u=0.3105$<br>$u=0.3105$<br>$u=0.3105$<br>$u=0.3105$<br>$u=0.3105$<br>$u=0.3105$<br>$u=0.3105$<br>$u=0.3105$<br>$u=0.3105$<br>$u=0.3105$<br>$u=0.3105$<br>$u=0.3105$<br>$u=0.3105$<br>$u=0.3105$<br>$u=0.3105$<br>$u=0.3105$<br>$u=0.3105$<br>$u=0.3105$<br>$u=0.3105$<br>$u=0.3105$<br>$u=0.3105$<br>$u=0.3105$<br>$u=0.3105$<br>$u=0.3105$<br>$u=0.3105$<br>$u=0.3105$<br>$u=0.3105$<br>$u=0.3105$<br>$u=0.3105$<br>$u=0.3105$<br>$u=0.3105$<br>$u=0.3105$<br>$u=0.3105$<br>$u=0.3105$<br>$u=0.3105$<br>$u=0.3105$<br>$u=0.3105$<br>$u=0.3105$<br>$u=0.3105$<br>$u=0.3105$<br>$u=0.3105$<br>$u=0.3105$<br>$u=0.3105$<br>$u=0.3105$<br>$u=0.3105$<br>$u=0.3105$<br>$u=0.3105$<br>$u=0.3105$<br>$u=0.3105$<br>$u=0.3105$<br>$u=0.3105$<br>$u=0.3105$<br>$u=0.3105$<br>$u=0.3105$<br>$u=0.3105$<br>$u=0.3105$<br>$u=0.3105$<br>$u=0.3105$<br>$u=0.3105$<br>$u=0.3105$<br>$u=0.3105$<br>$u=0.3105$<br>$u=0.3105$<br>$u=0.3105$<br>$u=0.3105$<br>$u=0.3105$<br>   |              |                        | Fiberglass fibrous                       | $d_{\rm f} = 9.1 \mu{\rm m}$  | 1.3 nm                           |
| 2007Kim et al. [24]Silver particles<br>Fiberglass fibrous<br>filters $U=2.5  \mathrm{cm} \mathrm{s}^{-1}$ $E  \mathrm{increases}  \mathrm{when}  d_p$<br>decreases<br>$0.039 < \alpha < 0.05$<br>$5  \mathrm{cm} \mathrm{s}^{-1} < U < 15  \mathrm{cm} \mathrm{s}^{-1}$ 2007Huang et al. [25]NaCl particles<br>Fibrous filters for<br>respiratory masks $4.5  \mathrm{m} < d_p < 4.9  \mu\mathrm{m}$<br>$0.039 < \alpha < 0.05$<br>$5  \mathrm{cm} \mathrm{s}^{-1} < U < 15  \mathrm{cm} \mathrm{s}^{-1}$ $E  \mathrm{increases}  \mathrm{when}  d_p$<br>decreases2007Huang et al. [25]NaCl particles<br>Fibrous filters for<br>respiratory masks $8.5  \mathrm{m} < d_p < 94.8  \mathrm{nm}$ $E  \mathrm{increases}  \mathrm{when}  d_p$<br>decreases2007Steffens and Coury<br>[26]NaCl particles<br>Polyester filter $8.5  \mathrm{nm} < d_p < 94.8  \mathrm{nm}$ $E  \mathrm{increases}  \mathrm{when}  d_p$<br>decreases2008Shin et al. [27]Silver particles<br>Stainless steel wire<br>screen $3  \mathrm{nm} < d_p < 20  \mathrm{nm}$ $E  \mathrm{increases}  \mathrm{when}  d_p$<br>decreases2008Mouret [28]Cu and C particles<br>Stainless steel wire<br>screen $3  \mathrm{nm} < d_p < 20  \mathrm{nm}$ $E  \mathrm{increases}  \mathrm{when}  d_p$<br>decreases2008Mouret [28]Cu and C particles<br>Stainless steel wire<br>screen $4  \mathrm{sm} < d_p < 80  \mathrm{nm}$ $E  \mathrm{increases}  \mathrm{when}  d_p$<br>decreases2009VanGulijk et al.<br>[29]Cu and C particles<br>Fibrous filters $4  \mathrm{sm} < d_p < 20  \mathrm{nm}$ $E  \mathrm{increases}  \mathrm{when}  d_p$<br>decreases<br>decreases2009VanGulijk et al.<br>[29]Cu and C particles<br>Fibrous filters $6  \mathrm{sm} < d_p < 20  \mathrm{nm}$ $E  \mathrm{increases}  \mathrm{when}  d_p < 20  \mathrm{nm}$<br>decreases2009Van   |              |                        | filters                                  | $\alpha = 0.06$   |                                  |
| 2007Kim et al. [24]Silver particles<br>Fiberglass fibrous<br>fiberglass fibrous<br>filters $3 \operatorname{hm} < d_p < 20 \operatorname{nm}$<br>$1.9 \ \mum < d_q < 4.9 \ \mum$<br>$4 < 4.9 \ \mum$<br>$4 < 4.9 \ \mum$<br>$4 < 4.9 \ \mum$<br>decreasesE increases when $d_p$<br>decreases2007Huang et al. [25]NaCl particles<br>Fibrous filters for<br>respiratory masks $4.5 \operatorname{nm} < d_p < 13 \ \mum$ and<br>$\alpha = 0.035$<br>$2.8 \operatorname{cm} s^{-1} < U < 15 \operatorname{cm} s^{-1}$ E increases when $d_p$<br>decreases2007Steffens and Coury<br>[26]NaCl particles<br>Polyester filter $8.5 \operatorname{nm} < d_p < 94.8 \operatorname{nm}$<br>$d = 16 \ \mum$<br>$\alpha = 0.018$ E increases when $d_p$<br>decreases2008Shin et al. [27]Silver particles<br>Stainless steel wire<br>screen $3 \operatorname{nm} < d_p < 20 \operatorname{nm}$<br>$d = 0.3105$ E increases when $d_p$<br>decreases2008Mouret [28]Cu and C particles<br>Stainless steel wire<br>screen $3 \operatorname{nm} < d_p < 20 \operatorname{nm}$<br>$d = 0.3105$ E increases when $d_p$<br>decreases2008Mouret [28]Cu and C particles<br>Stainless steel wire<br>screen $3 \operatorname{nm} < d_q < 20 \ um$<br>$200 \ mm$ E increases when $d_p$<br>decreases2009VanGulijk et al.<br>[29]NaCl particles<br>AnCl CaCl_2 (N(H_2)_5 O4<br>and NiSO4 particles<br>fiberglass $6 \operatorname{nm} < d_p < 20 \ um$<br>$d = 40 \ \mum$ E depends on the<br>aerosol type   |              |                        |  | $U = 2.5 \mathrm{cm}\mathrm{s}^{-1}$                                    |                                  |
| Fiberglass fibrous<br>filters $1.9  \mu m \cdot d_1 < 4.9  \mu m$<br>$0.39 < \alpha < 0.05$<br>$5  cm  s^{-1} < U < 15  cm  s^{-1}$ decreases2007Huang et al. [25]NaCl particles<br>Fibrous filters for<br>respiratory masks $4.5  nm < d_p$<br>$2.8  cm  s^{-1} < U < 15  cm  s^{-1}$ $E$ increases when $d_p$<br>decreases2007Steffens and Coury<br>[26]NaCl particles<br>Polyester filter $8.5  nm < d_p < 94.8  nm$<br>$d_r = 16  \mu m$<br>$\alpha = 0.018$ $E$ increases when $d_p$<br>decreases2008Shin et al. [27]Silver particles<br>Stainless steel wire<br>Stainless steel  | 2007<br>2007 | Kim et al. [24]        | Silver particles                         | $3 \text{ nm} < d_{p} < 20 \text{ nm}$                                  | E increases when $d_{\rm p}$     |
| $2007 \qquad Huag et al. [25] \qquad NaCl particles  Fibrous filters 0.039 < \alpha < 0.055 cm s^{-1} < U < 15 cm s^{-1}4.5 nm < d_p E increases when d_pfibrous filters for  respiratory masks \alpha = 0.0352.8 cm s^{-1} < U < 8.6 cm s^{-1}2007 \qquad Steffens and Coury  [26] NaCl particles 8.5 nm < d_p (4e for m decreases\alpha = 0.0352.8 cm s^{-1} < U < 8.6 cm s^{-1}2008 \qquad Shin et al. [27] \qquad Silver particles 3 nm < d_p < 94.8 nm E increases when d_pdecreases and when T is cm < s^{-1} < U < 25 cm s^{-1}3 cm s^{-1} < U < 25 cm s^{-1}2008 \qquad Shin et al. [27] \qquad Silver particles 3 nm < d_p < 20 nm E increases when d_p3 cm s^{-1} < U < 25 cm s^{-1}2008 \qquad Mouret [28] \qquad Cu and C particles 4 nm < d_p < 80 nm E increases when d_p3 cm s^{-1} < U < 7.04 cm s^{-1}2008 \qquad Mouret [28] \qquad Cu and C particles 4 nm < d_p < 80 nm E increases when d_p3 tainless steel wire 1.3 \mu m < d_p < 20 \mu m decreasesa = 0.3105 increases when d_p4 creases and when T2008 \qquad Mouret [28] \qquad Cu and C particles 4 nm < d_p < 80 nm E increases when d_p5 tainless steel wire 1.3 \mu m < d_p < 20 \mu m decreases5 cm s^{-1} < U < 15 cm s^{-1}2009 \qquad VanGulijk et al. MaCl, CaCl_2, (NH_4)_2SO_4 6 nm < d_p < 20 nm E depends on thea erosol type5 tainless steel wire screen and NiSO_4 particles d_f = 40 \mu m a erosol type$  |              |                        | Fiberglass fibrous                       | $19  \mu m < d_{e} < 49  \mu m$   | decreases                        |
| 2007Huang et al. [25]NaCl particles<br>Fibrous filters for<br>respiratory masks $4.5  \mathrm{cm}  \mathrm{s}^{-1}  \mathrm{cU} < 15  \mathrm{cm}  \mathrm{s}^{-1}$<br>$4.0  \mathrm{s15}  \mathrm{m}$ and<br>$a  \mathrm{cercases}$ decreases2007Steffens and Coury<br>[26]NaCl particles<br>Polyester filter $8.5  \mathrm{nm} < d_p < 94.8  \mathrm{nm}$<br>$d_r = 16  \mu\mathrm{m}$<br>$d_r = 10  \mu\mathrm{m}$<br>$d_r = 0.118$<br>$3  \mathrm{cm}  \mathrm{s}^{-1}  \mathrm{s}  \mathrm{s}  \mathrm{c25  cm}  \mathrm{s}^{-1}$ 2008Shin et al. [27]Silver particles<br>Stainless steel wire<br>screen $3  \mathrm{mm} < d_p < 20  \mathrm{nm}$<br>$d_r = 90  \mu\mathrm{m}$<br>$d_r = 90  \mu\mathrm{m}$<br>$d_r = 0.3105$<br>$d_r = 30  \mathrm{nm} < d_p < 80  \mathrm{nm}$ $E  \mathrm{increases}  \mathrm{when}  T_{\mathrm{increases}}$<br>$296  \mathrm{K}  \mathrm{r}  \mathrm{s500  \mu\mathrm{m}}$<br>$200  \mathrm{g}  \mathrm{cu}  \mathrm{ad}  \mathrm{cprease}  \mathrm{stainless}  \mathrm{steel}  \mathrm{wire}$<br>$\mathrm{screen}$ $3  \mathrm{mm}  \mathrm{sd}_p < 80  \mathrm{nm}$<br>$296  \mathrm{K}  \mathrm{r}  \mathrm{s500  \mu\mathrm{m}}$<br>$200  \mathrm{g}  \mathrm{cu}  \mathrm{c28}  \mathrm{screen}^{-1}$ 2008Mouret [28]Cu and C particles<br>$\mathrm{Stainless}  \mathrm{steel}  \mathrm{wire}$<br>$\mathrm{screens}, polyester and\mathrm{bloeg}  \mathrm{scl}  \mathrm{scl}$   |              |                        | filters                                  | $0.039 \le \alpha \le 0.05$   | deereases                        |
| 2007Huang et al. [25]NaCl particles<br>Fibrous filters for<br>respiratory masks4.5 nm < d_p<br>e = 0.035<br>2.8 cm s^{-1} < U < 8.6 cm s^{-1}2007Steffens and Coury<br>[26]NaCl particles<br>Polyester filter8.5 nm < d_p < 94.8 nm  |              |                        | inters                                   | $5 \text{ cm s}^{-1} < U < 15 \text{ cm s}^{-1}$                        |                                  |
| 2007Fidding et al. [25]Nact particles4.5 min ( $a_p$ )E intreases when $a_p$ Fibrous filters for<br>respiratory masksfilter B: $d_r = 13 \mu m$ and<br>$\alpha = 0.035$ decreases2007Steffens and Coury<br>[26]NaCl particles8.5 mc $4q_p$ 94.8 nmE increases when $d_p$ 2008Shin et al. [27]Silver particles $3 \text{ cm s}^{-1} < U < 8.6 \text{ cm s}^{-1}$ 2008Shin et al. [27]Silver particles $3 \text{ rms } d_p < 20 \text{ nm}$ E increases when $d_p$ 2008Mouret [28]Cu and C particles $3 \text{ rms } d_p < 20 \text{ nm}$ E increases when $d_p$ 2008Mouret [28]Cu and C particles $4 \text{ rm} d_p < 200 \text{ rm}$ E increases when $d_p$ 2008Mouret [28]Cu and C particles $4 \text{ rm} d_p < 200 \text{ rm}$ E increases when $d_p$ 2009VanGulijk et al.NaCl, CaCl <sub>2</sub> , (NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub> $6 \text{ rm} < d_p < 20 \text{ nm}$ E increases on the<br>aerosol type2009VanGulijk et al.NaCl, CaCl <sub>2</sub> , (NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub> $6 \text{ rm} < d_p < 20 \text{ nm}$ E depends on the<br>aerosol type2009VanGulijk et al.NaCl, CaCl <sub>2</sub> , (NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub> $6 \text{ rm} < d_p < 20 \text{ nm}$ E depends on the<br>aerosol type   |              | Ulwarm at al. [25]     | NaGlasstialsa                            |   | T in an a construction of        |
| Pibrous filters for<br>respiratory masksInter B: $d_r = 13 \ \mu m$ and<br>$\alpha = 0.035$<br>$2.8 \ cm s^{-1} < U < 8.6 \ cm s^{-1}$ decreases<br>$2.8 \ cm s^{-1} < U < 8.6 \ cm s^{-1}$ 2007Steffens and Coury<br>[26]NaCl particles $8.5 \ nm < d_p < 94.8 \ nm$ $E$ increases when $d_p$<br>decreases<br>$\alpha = 0.118$<br>$3 \ cm s^{-1} < U < 25 \ cm s^{-1}$ 2008Shin et al. [27]Silver particles<br>Stainless steel wire<br>screen $3 \ nm < d_p < 20 \ nm$ $E$ increases when $d_p$<br>decreases and when T<br>increases<br>$206 \ K < 1 < 500 \ K$ 2008Mouret [28]Cu and C particles<br>Stainless steel wire<br>screen $4 \ nm < d_p < 80 \ nm$ $E$ increases when $d_p$<br>decreases<br>$4.17 \ cm s^{-1} < U < 7.04 \ cm s^{-1}$<br>$296 \ K < 1 < 500 \ K$ 2008Mouret [28]Cu and C particles<br>Stainless steel wire<br>screen $4 \ nm < d_p < 80 \ nm$ $E$ increases when $d_p$<br>decreases<br>$4.17 \ cm s^{-1} < U < 7.04 \ cm s^{-1}$<br>$296 \ K < 1 < 500 \ K$ 2008Mouret [28]Cu and C particles<br>Stainless steel wire<br>screens, polyester and<br>fiberglass $0.06 < \alpha < 0.39$<br>$0.06 < \alpha < 0.39$<br>$1.3 \ \mu m < d_p < 200 \ nm$ $E$ increases<br>decreases<br>$E$ 2009VanGulijk et al.<br>[29]NACI, CaCl <sub>2</sub> , (NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub><br>and NiSO <sub>4</sub> particles<br>Stainless steel wire<br>stainless steel wire<br>stainless steel wire<br>stainless steel wire<br>stainless wire<br><td>Huang et al. [25]</td> <td>Naci particles</td> <td>4.5 <math>\lim \alpha_p</math></td> <td>E increases when <math>a_p</math></td>  |              | Huang et al. [25]      | Naci particles                           | 4.5 $\lim \alpha_p$   | E increases when $a_p$           |
| 2007Steffens and Coury<br>[26]NaCl particles<br>Polyester filter $a \in 0.335$<br>$2.8 cm s^{-1} < U < 8.6 cm s^{-1}$ 2008Shin et al. [27]Silver particles<br>   |              |                        | Fibrous filters for                      | filter B: $d_f = 13 \mu\text{m}$ and                                    | decreases                        |
| 2007 Steffens and Coury NaCl particles 8.5 cm s <sup>-1</sup> < U < 8.6 cm s <sup>-1</sup><br>[26] Polyester filter $d_r = 16  \mu m$ decreases when $d_p$<br>a = 0.118<br>$3  cm  s^{-1} < U < 25  cm  s^{-1}$<br>2008 Shin et al. [27] Silver particles $3  nm < d_p < 20  nm$ $E$ increases when $d_p$<br>$5  tainless steel wire d_r = 90  \mu m decreases and when Tscreen a = 0.3105 increases4.17  cm  s^{-1} < U < 7.04  cm  s^{-1}2008 Mouret [28] Cu and C particles 4  nm < d_p < 80  nm E increases when d_p5  tainless steel wire 3  \mu m < d_p < 80  nm E increases when d_p4.17  cm  s^{-1} < U < 7.04  cm  s^{-1}296  K < T < 500  K2008 Mouret [28] Cu and C particles 4  nm < d_p < 80  nm E increases when d_p5  tainless steel wire 3  \mu m < d_r < 200  \mu m decreases5  cm  s^{-1} < U < 15  cm  s^{-1}13  \mu m < d_r < 200  \mu m E increases when d_p5  cm  s^{-1} < U < 15  cm  s^{-1}Fibrous filters2009 VanGulijk et al. NaCl, CaCl2, (NH4)2SO4 6  nm < d_p < 20  nm E depends on theaerosol type5  tainless steel wire tm  s^{-1} < U < 15  cm  s^{-1}$  |              |                        | respiratory masks                        | $\alpha = 0.035$  |                                  |
| 2007Steffens and Coury<br>[26]NaCl particles $8.5 \mathrm{nm} < d_p < 94.8 \mathrm{nm}$ $E$ increases when $d_p$ [26]Polyester filter $d_r = 16 \mu\mathrm{m}$<br>$\alpha = 0.118$<br>$3 \mathrm{cm} \mathrm{s}^{-1} < U < 25 \mathrm{cm} \mathrm{s}^{-1}$ decreases2008Shin et al. [27]Silver particles<br>Stainless steel wire<br>screen $3 \mathrm{nm} < d_p < 20 \mathrm{nm}$ $E$ increases when $d_p$ 2008Mouret [28]Cu and C particles<br>Stainless steel wire<br>screen $4.17 \mathrm{cm} \mathrm{s}^{-1} < U < 7.04 \mathrm{cm} \mathrm{s}^{-1}$<br>$296 \mathrm{K} < T < 500 \mathrm{K}$ $E$ increases when $d_p$ 2008Mouret [28]Cu and C particles<br>Stainless steel wire<br>screens, polyester and<br>fiberglass $4 \mathrm{nm} < d_p < 80 \mathrm{nm}$ $E$ increases when $d_p$ 2009VanGulijk et al.NaCl, CaCl <sub>2</sub> , (NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub> $6 \mathrm{nm} < d_p < 20 \mathrm{nm}$ $E$ depends on the<br>aerosol type2009VanGulijk et al.NaCl, CaCl <sub>2</sub> , (NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub> $6 \mathrm{nm} < d_p < 20 \mathrm{nm}$ $E$ depends on the<br>aerosol type  |              |                        |  | $2.8 \text{ cm s}^{-1} < U < 8.6 \text{ cm s}^{-1}$                     |                                  |
| $\begin{bmatrix} [26] & Polyester filter & d_{f} = 16  \mu m & decreases \\ \alpha = 0.118 & 3  cm  s^{-1} < U < 25  cm  s^{-1} \\ 3  cm  s^{-1} < U < 25  cm  s^{-1} \\ 3  cm  s^{-1} < U < 25  cm  s^{-1} \\ 3  cm  s^{-1} < U < 25  cm  s^{-1} \\ 3  cm  s^{-1} < U < 25  cm  s^{-1} \\ 3  cm  s^{-1} < U < 25  cm  s^{-1} \\ 3  cm  s^{-1} < U < 25  cm  s^{-1} \\ 4  r = 90  \mu m & decreases  and  when  T \\ a = 0.3105 & increases \\ 4.17  cm  s^{-1} < U < 7.04  cm  s^{-1} \\ 296  K < T < 500  K \\ 2008 & Mouret [28] & Cu and C particles \\ 5  tainless steel wire & 1.3  \mu m < d_{p} < 80  nm & E  increases  when  d_{p} \\ 5  tainless steel wire & 1.3  \mu m < d_{p} < 80  nm \\ s  creens, polyester and \\ 5  tainless steel wire & 5  cm  s^{-1} < U < 15  cm  s^{-1} \\ Fibrous filters & Fibrous filters \\ 2009 & VanGulijk et al. \\ [29] & AnGULijk et al. \\ [29] & AnGULijk et al. \\ [29] & AnGULige  steel wire \\ Stainless steel $  | 2007         | Steffens and Coury     | NaCl particles                           | 8.5 nm < d <sub>p</sub> < 94.8 nm                                       | E increases when d <sub>p</sub>  |
| $ 2008 \qquad Shin et al. [27] \qquad Silver particles Stainless steel wire screen Stainless steel wire Stain$   |              | [26]                   | Polyester filter                         | $d_{\rm f}$ = 16 $\mu$ m  | decreases                        |
| $\begin{array}{cccccccccccccccccccccccccccccccccccc$   |              |                        |  | $\alpha = 0.118$  |                                  |
| 2008Shin et al. [27]Silver particles<br>Stainless steel wire<br>screen $3 \operatorname{nm} < d_p < 20 \operatorname{nm}$ $E \operatorname{increases} when d_p$<br>decreases and when T<br>increases2008Mouret [28]Cu and C particles<br>Stainless steel wire<br>screen $4 \operatorname{nm} < d_p < 80 \operatorname{nm}$ $E \operatorname{increases} when d_p$ 2008Mouret [28]Cu and C particles<br>Stainless steel wire<br>screens, polyester and<br>fiberglass<br>Fibrous filters $1.3  \mu m < d_p < 80 \operatorname{nm}$ $E \operatorname{increases} when d_p$ 2009VanGulijk et al.<br>[29]NaCl, CaCl_2, (NH_4)_2SO_4<br>and NiSO_4 particles<br>Stainless steel wire<br>screens $6 \operatorname{nm} < d_p < 20 \operatorname{nm}$ $E \operatorname{depends on the}$<br>aerosol type2009VanGulijk et al.<br>(29]NaCl, CaCl_2, (NH_4)_2SO_4<br>stainless steel wire<br>screen screens $6 \operatorname{nm} < d_p < 20 \operatorname{nm}$ $E \operatorname{depends on the}$<br>aerosol type2009VanGulijk et al.<br>(29]NaCl, CaCl_2, (NH_4)_2SO_4<br>screen screen   |              |                        |  | $3 \mathrm{cm}\mathrm{s}^{-1} < U < 25 \mathrm{cm}\mathrm{s}^{-1}$      |                                  |
| LossDimensionDimensionDimensionDimensionDimensionStainlessStainlessSteel wire<br>screen $d_f = 90  \mu$ m<br>$\alpha = 0.3105$<br>$4.17  cm s^{-1} < U < 7.04  cm s^{-1}$<br>$296  K < T < 500  K$ decreases and when T<br>increases2008Mouret [28]Cu and C particles<br>Stainless steel wire<br>screens, polyester and<br>fiberglass<br>Fibrous filters $4  nm < d_p < 80  nm$<br>$6  nm < d_p < 200  \mu$ m<br>decreases when $d_p$ 2009VanGulijk et al.<br>[29]NaCl, CaCl <sub>2</sub> , (NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub><br>and Sinless steel wire<br>Fibrous filters $6  nm < d_p < 20  nm$<br>aerosol type2009VanGulijk et al.<br>[29]NaCl, CaCl <sub>2</sub> , (NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub><br>Stainless steel wire<br>Screen $6  nm < d_p < 20  nm$<br>aerosol type  | 2008         | Shin et al [27]        | Silver particles                         | $3 \text{ nm} < d_p < 20 \text{ nm}$                                    | $E$ increases when $d_{\rm p}$   |
| 2008 Mouret [28] Cu and C particles steel wire $a_p = 0.3105$ increases $4.17 \text{ cm s}^{-1} < U < 7.04 \text{ cm s}^{-1} < 296 \text{ K} < T < 500 \text{ K}$<br>2008 Mouret [28] Cu and C particles $4 \text{ nm} < d_p < 80 \text{ nm}$ E increases when $d_p$<br>Stainless steel wire $1.3 \ \mu\text{m} < d_p < 80 \text{ nm}$ decreases<br>screens, polyester and $0.06 < \alpha < 0.39$<br>fiberglass $5 \text{ cm s}^{-1} < U < 15 \text{ cm s}^{-1}$<br>Fibrous filters<br>2009 VanGulijk et al. NaCl, CaCl <sub>2</sub> , (NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub> $6 \text{ nm} < d_p < 20 \text{ nm}$ E depends on the<br>and NiSO <sub>4</sub> particles $d_f = 40 \ \mu\text{m}$ aerosol type<br>Stainless steel wire<br>Screen Screen   |              |                        | Stainless steel wire                     | $d_s = 90  \mathrm{\mu m}$  | decreases and when T             |
| 2008 Mouret [28] Cu and C particles $4.17 \text{ cm s}^{-1} < U < 7.04 \text{ cm s}^{-1}$<br>$4.17 \text{ cm s}^{-1} < U < 7.04 \text{ cm s}^{-1}$<br>296  K < T < 500  K<br>500  K = 1.3  |              |                        | screen                                   | $\alpha = 0.3105$   | increases                        |
| 2008 Mouret [28] Cu and C particles $4 \operatorname{nr} < 4_0 < 30 \operatorname{nm}$<br>Stainless steel wire $1.3  \mu m < d_f < 200  \mu m$ decreases<br>screens, polyester and $0.06 < \alpha < 0.39$<br>fiberglass $5 \operatorname{cm} \operatorname{s}^{-1} < U < 15 \operatorname{cm} \operatorname{s}^{-1}$<br>Fibrous filters<br>2009 VanGulijk et al. NaCl, CaCl <sub>2</sub> , (NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub> $6 \operatorname{nm} < d_p < 20 \operatorname{nm}$ <i>E</i> depends on the<br>[29] and NiSO <sub>4</sub> particles $d_f = 40  \mu m$ aerosol type<br>Stainless steel wire<br>screen   |              |                        | sereen                                   | $4.17 \mathrm{cm}\mathrm{s}^{-1} < U < 7.04 \mathrm{cm}\mathrm{s}^{-1}$ | increases                        |
| 2008 Mouret [28] Cu and C particles $4 \operatorname{nm} < d_p < 80 \operatorname{nm} E$ increases when $d_p$<br>Stainless steel wire $1.3 \ \mu m < d_f < 200 \ \mu m$ decreases<br>screens, polyester and $0.06 < \alpha < 0.39$<br>fiberglass $5 \operatorname{cm} s^{-1} < U < 15 \operatorname{cm} s^{-1}$<br>Fibrous filters<br>2009 VanGulijk et al. NaCl, CaCl <sub>2</sub> , (NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub> $6 \operatorname{nm} < d_p < 20 \operatorname{nm} E$ depends on the<br>[29] and NiSO <sub>4</sub> particles $d_f = 40 \ \mu m$ aerosol type<br>Stainless steel wire<br>screen  |              |                        |  | 4.17 CIIIS NUN 7.04 CIIIS   |                                  |
| 2008 Mouret [28] Cu and C particles $4 \operatorname{nm} < d_p < 80 \operatorname{nm}$ E increases when $d_p$<br>Stainless steel wire $1.3  \mu \operatorname{m} < d_p < 80 \operatorname{nm}$ decreases<br>screens, polyester and $0.06 < \alpha < 0.39$<br>fiberglass fiberglass $5 \operatorname{cm} \operatorname{s}^{-1} < U < 15 \operatorname{cm} \operatorname{s}^{-1}$<br>Fibrous filters<br>2009 VanGulijk et al. NaCl, CaCl <sub>2</sub> , (NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub> $6 \operatorname{nm} < d_p < 20 \operatorname{nm}$ E depends on the<br>[29] and NiSO <sub>4</sub> particles $d_f = 40  \mu \operatorname{m}$ aerosol type<br>Stainless steel wire screen   | 2000         | . (22)                 |  | 290 K < I < 500 K   |                                  |
| Stainless steel wire $1.3 \mu\text{m} < d_f < 200 \mu\text{m}$ decreases<br>screens, polyester and $0.06 < \alpha < 0.39$<br>fiberglass $5 \text{cm} \text{s}^{-1} < U < 15 \text{cm} \text{s}^{-1}$<br>2009 VanGulijk et al. NaCl, CaCl <sub>2</sub> , (NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub> $6 \text{nm} < d_p < 20 \text{nm}$ <i>E</i> depends on the<br>[29] and NiSO <sub>4</sub> particles $d_f = 40 \mu\text{m}$ aerosol type<br>Stainless steel wire<br>screen   | 2008         | Mouret [28]            | Cu and C particles                       | $4 \text{ nm} < a_p < 80 \text{ nm}$                                    | $E$ increases when $d_p$         |
| $\begin{array}{cccccccccccccccccccccccccccccccccccc$   |              |                        | Stainless steel wire                     | 1.3 μm < d <sub>f</sub> < 200 μm  | decreases                        |
| $ \begin{array}{c} \mbox{fiberglass} & 5{\rm cm}{\rm s}^{-1}{\rm < U}{\rm < 15cm}{\rm s}^{-1} \\ \mbox{Fibrous filters} \\ \mbox{2009} & VanGulijk et al. & NaCl, CaCl_2, (NH_4)_2SO_4 & 6{\rm nm}{\rm < d}_p{\rm < 20nm} & E{\rm depends on the} \\ \mbox{[29]} & and NSO_4  {\rm particles} & d_f{\rm = 40\mu m} & aerosol  type \\ \mbox{Stainless steel wire} \\ \mbox{screen} \\ \mbox{screen} \end{array} $  |              |                        | screens, polyester and                   | 0.06 < α < 0.39   |                                  |
| Fibrous filters<br>2009 VanGulijk et al. NaCl, CaCl <sub>2</sub> , (NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub> $6 \text{ nm} < d_p < 20 \text{ nm}$ <i>E</i> depends on the<br>[29] and NiSO <sub>4</sub> particles $d_f = 40 \text{ µm}$ aerosol type<br>Stainless steel wire<br>screen   |              |                        | fiberglass                               | $5 \mathrm{cm}\mathrm{s}^{-1}$ < U < 15 cm s <sup>-1</sup>              |                                  |
| 2009 VanGulijk et al. NaCl, CaCl <sub>2</sub> , (NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub> $6 \text{ nm} < d_p < 20 \text{ nm}$ $E$ depends on the<br>[29] and NiSO <sub>4</sub> particles $d_f = 40 \text{ µm}$ aerosol type<br>Stainless steel wire<br>screen   |              |                        | Fibrous filters                          |   |                                  |
| [29] and NiSO <sub>4</sub> particles $d_f = 40 \mu\text{m}$ aerosol type<br>Stainless steel wire<br>screen   | 2009         | VanGulijk et al.       | NaCl, CaCl <sub>2</sub> , $(NH_4)_2SO_4$ | $6 \mathrm{nm} < d_{\mathrm{p}} < 20 \mathrm{nm}$                       | E depends on the                 |
| Stainless steel wire<br>screen   |              | [29]                   | and NiSO <sub>4</sub> particles          | $d_{\rm f} = 40 \mu {\rm m}$  | aerosol type                     |
| screen   |              |                        | Stainless steel wire                     | • •   |                                  |
|  |              |                        | screen                                   |   |                                  |

\*In an electronic communication to D.A. Japuntich referred in a 3M<sup>®</sup> technical data bulletin [30], Albert Podgórski, as a co-author of the Balazy's paper, has indicated that: "Unfortunately, those results were erroneous due to the aerosol spectrometer malfunction (WPS, made by MSP Corp.). Now, the instrument is upgraded by the manufacturer and we have also worked out a new experimental procedure; as a consequence, such a decrease of the filtration efficiency is no longer observed."

ing one fiber of the collecting media are collected. The thermal rebound model of Wang and Kasper is built introducing values of  $\varepsilon$  smaller than one, as the consequence of particle bounce on the fibrous surface. In other words, any contact between particle and

fiber no longer systematically leads to collection. Mathematically, if the approach velocity of the particle is higher than the critical velocity  $V_{cr}$ , defined as the velocity above which rebound is to occur, the particle will not be trapped. Download English Version:

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