LUND UNIVERSITY

Remember the small giants - Occupational exposure and characterization of aerosol particles

Nilsson, Patrik

2016

Link to publication

Citation for published version (APA):
Nilsson, P. (2016). *Remember the small giants - Occupational exposure and characterization of aerosol particles*. [Doctoral Thesis (monograph), Ergonomics and Aerosol Technology].

Total number of authors:
1

General rights
Unless other specific re-use rights are stated the following general rights apply:
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.
• Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
• You may not further distribute the material or use it for any profit-making activity or commercial gain
• You may freely distribute the URL identifying the publication in the public portal

Read more about Creative commons licenses: https://creativecommons.org/licenses/

Take down policy
If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

LUND UNIVERSITY

PO Box 117
221 00 Lund
+46 46-222 00 00

Remember the small giants

Occupational exposure and characterization of aerosol particles

Patrik Nilsson

LUND
UNIVERSITY

DOCTORAL DISSERTATION
by due permission of the Faculty of Engineering, Lund University, Sweden.
To be defended at Stora hörsalen, IKDC. Date: February 29, 2016. Time: 09.00.

Faculty opponent
Dr Christof Asbach
Institute of Energy and Environmental Technology
Duisburg, Germany

Organization	Document name
LUND UNIVERSITY	Doctoral Dissertation
Department of Design Sciences Division of Ergonomics and Aerosol Technology	Date of issue
Author: Patrik Nilsson	Sponsoring organization

Title and subtitle:

Remember the small giants – Occupational exposure and characterization of aerosol particles

BACKGROUND: Exposure to airborne particles in occupational environments can lead to both acute and long-term health effects in humans. To date, particle exposure limits in the air are typically given in terms of mass concentrations. But by only using mass concentration to characterize particles means there is a risk that other relevant characteristics, such as particle size and composition are concealed. This is argued to be the case for exposure to engineered nanoparticles (ENP), which are particles tailored to possess unique properties. The aim of this thesis is to provide knowledge to improve the characterization and risk assessments of particle emissions in selected occupational environments.

METHODS: 1) In a diesel exhaust exposure chamber study, several techniques were combined to determine a wide range of particle characteristics, including particle number, surface, mass, chemistry and morphology. 2) In a hairdresser exposure chamber study, the emissions of particles and persulfate salts during hair bleaching were characterized. 3) In two field studies, the emissions of ENPs in two different production facilities were characterized by filter sampling and by direct reading instruments. A laser vaporization aerosol mass spectrometer (LV-AMS) was used for both selective sampling of emitted particles based on their composition, and for in-situ analysis of ENPs inside the production line.

RESULTS: 1) If diesel exhaust particles are assumed to be spherical, the estimated particle mass concentration from number concentration was overestimated by 261% compared to if their aggregated structures were considered. 2) During the application of hair bleaching, large particles (> 10 µm) were emitted from both bleach powder that was classified as dust-free and powder that was not. 3) Particles emitted during the maintenance of ENP production equipment were predominantly highly agglomerated with nanostructured surfaces, consisting of nanoparticles grown together to larger scales (> 1 µm). With the LV-AMS, emissions were correlated to specific particle types and interferences from background particles could be avoided.

CONCLUSIONS: The ability to compare different diesel exhaust exposure studies will increase if methods are utilized that allow the characterization of particle size, shape, morphology and chemistry and that include different concentration metrics. Exposure assessments of ENP production facilities and hairdresser salons should include methods for coarse particle sampling. LV-AMS is a promising method for selective sampling of emitted particles in occupational environments, and for in-situ analysis of particle production. But the LV-AMS's cost efficiency, practicality, and capability to sample coarse particles need to be extended. Accurate exposure assessments should cover a wide particle size range in order to find the nanoparticles that hide in the form of bigger particles.

Keywords: Agglomerates, engineered nanoparticles, aerosol mass spectrometry, hairdressers, diesel exhaust

Classification system and/or index terms (if any)

Supplementary bibliographical information		Language: English
ISSN and key title 1650-9773 Publication 56		ISBN 978-91-7623-624-6
Recipient's notes	Number of pages	Price
	Security classification	

I, the undersigned, being the copyright owner of the abstract of the above-mentioned dissertation, hereby grant to all reference sources permission to publish and disseminate the abstract of the above-mentioned dissertation.

Signature _____ Date _____

Remember the small giants

Occupational exposure and characterization of aerosol particles

Patrik Nilsson

LUND
UNIVERSITY

Copyright Patrik Nilsson (pp. 1-83)

Faculty of Engineering, Department of Design Sciences
ISBN 978-91-7623-624-6 (print)
ISBN 978-91-7623-625-3 (pdf)
ISSN 1650-9773
Printed in Sweden by Media-Tryck, Lund University
Lund, Sweden, 2016

Abstract

BACKGROUND: Exposure to airborne particles in occupational environments can lead to both acute and long-term health effects in humans. To date, particle exposure limits in the air are typically given in terms of mass concentrations. But by only using mass concentration to characterize particles means there is a risk that other relevant characteristics, such as particle size and composition are concealed. This is argued to be the case for exposure to engineered nanoparticles (ENP), which are particles tailored to possess unique properties. The aim of this thesis is to provide knowledge to improve the characterization and risk assessments of particle emissions in selected occupational environments.

METHODS: 1) In a diesel exhaust exposure chamber study, several techniques were combined to determine a wide range of particle characteristics, including particle number, surface, mass, chemistry and morphology. 2) In a hairdresser exposure chamber study, the emissions of particles and persulfate salts during hair bleaching were characterized. 3) In two field studies, the emissions of ENPs in two different production facilities were characterized by filter sampling and by direct reading instruments. A laser vaporization aerosol mass spectrometer (LV-AMS) was used for both selective sampling of emitted particles based on their composition, and for in-situ analysis of ENPs inside the production line.

RESULTS: 1) If diesel exhaust particles are assumed to be spherical, the estimated particle mass concentration from number concentration was overestimated by 261% compared to if their aggregated structures were considered. 2) During the application of hair bleaching, large particles (> 10 µm) were emitted from both bleach powder that was classified as dust-free and powder that was not. 3) Particles emitted during the maintenance of ENP production equipment were predominantly highly agglomerated with nanostructured surfaces, consisting of nanoparticles grown together to larger scales (> 1 µm). With the LV-AMS, emissions were correlated to specific particle types and interferences from background particles could be avoided.

CONCLUSIONS: The ability to compare different diesel exhaust exposure studies will increase if methods are utilized that allow the characterization of particle size, shape, morphology and chemistry and that include different concentration metrics. Exposure assessments of ENP production facilities and hairdresser salons should include methods for coarse particle sampling. LV-AMS is a promising method for selective sampling of emitted particles in occupational environments, and for in-situ

analysis of particle production. But the LV-AMS's cost efficiency, practicality, and capability to sample coarse particles need to be extended. Accurate exposure assessments should cover a wide particle size range in order to find the nanoparticles that hide in the form of bigger particles.

Contents

Abstract 5

Contents 7

Populärvetenskaplig sammanfattning 9

List of papers included in this thesis 11

The author's contributions to the papers 12

Publications not included in this thesis 13

Peer reviewed papers 13

Conference proceedings (selection) 14

Symbols and abbreviations 17

1 Background and aims 21

1.1 Background 21

1.2 Aims 23

2 Introduction 25

2.1 Outdoor aerosols 25

2.2 Indoor aerosols 26

2.3 Occupational aerosols 27

2.4 Inhalation and respiratory deposition of aerosol particles 28

2.4.1 Health effects from inhaled and deposited particles 30

3 Selected occupational environments and associated health risks 33

3.1 Environments with diesel exhaust emissions (Paper I) 33

3.2 Hairdresser salons during hair bleaching (Paper II) 34

3.3 Facilities for production of engineered nanoparticles (Papers III & IV) 34

4 Methods 39

4.1 Instrumentation 40

4.1.1 Laser vaporization aerosol mass spectrometer 40

4.2 Particle emission and exposure characterizations 43

4.2.1 Human exposure to diesel exhaust (Paper I) 43

4.2.2 Hairdresser's exposure during hair bleaching (Paper II) 44

4.2.3 ENP production facilities (Papers III & IV) 45
4.3 Selective and in-situ characterization of ENPs (Papers III & V) 48
5 Results and discussion 51
5.1 Chamber exposure studies 51
5.1.1 Environments with diesel exhaust exposure (Paper I) 51
5.1.2 Hairdresser salons during hair bleaching (Paper II) 54
5.1.3 Diversity of particles 58
5.2 Occupational exposure to ENPs 58
5.2.1 Emissions in ENP production facilities (Papers III & IV) 58
5.2.2 Remember the small giants 64
5.3 Selective and in-situ characterization of ENPs (Papers III & V) 65
6 Summary and conclusions 69
7 Outlook 71
Acknowledgements 73
References 75

Populärvetenskaplig sammanfattning

Partiklar som finns i luften och som vi andas in kan leda till negativa hälsoeffekter bland oss människor. I varje andetag andas vi in tusentals partiklar som tar sig ner i våra luftvägar. Det är normalt. Våra kroppar har försvarsmekanismer som tar hand om och oskadliggör partiklar som vi andas in och som fastnar i våra andningsvägar. Vid för höga halter av partiklar i luften kan vårt försvar dock vara otillräckligt. Extra stora problem har kanske vårt försvar med att ta hand om partiklar som tillverkats av oss människor själva.

Oftast är det de allra minsta partiklarna, de så kallade nanopartiklarna, som får mycket uppmärksamhet. Den här avhandlingen visar att det inte alltid är lämpligt att helt fokusera på de i luften fria nanopartiklarna när man vill studera sambandet mellan luftburna partiklar och hälsoeffekter. Större partiklar kan i till exempel många arbetsmiljöer vara minst lika viktiga att ta hänsyn till.

I en studie av frisörer som bleker hår mätte vi att ett så kallat dammfritt blekmedelspulver ger upphov till partiklar i luften. Dessa partiklar består till stor del av persulfat som kan leda till besvär med andningsvägarna. Ett pulver som är klassat som dammfritt hjälper till att minska partikelhalterna i luften vid omblandning av pulver och väteperoxid, vilket sker innan appliceringen i håret utförs. Men under appliceringen av blekmedlet i håret betyder valet av pulver inte någon större roll. Detta eftersom luftburna partiklar bildas oavsett vilket pulver som används. De partiklar som släpps fria till luften under appliceringen har en storlek som gör att de har en låg sannolikhet att ta sig djupt ner i andningsvägarna, men de kan fastna i de övre luftvägarna varifrån de kan ge upphov till problem.

Vid rengöring av utrustning som används för att tillverka nanopartiklar bestående av metall mättes det att stora partiklar, bestående av tusentals löst sammansatta nanopartiklar frigjordes till luften. Storleken på de större partiklarna var sådan att de har en relativt hög sannolikhet att nå långt ner i luftvägarna, precis som fria nanopartiklar. Om man antar att de stora partiklarna kan brytas upp i de mindre ursprungliga nanopartiklarna efter att de fastnat i lungorna innebär det att en enda inandad stor partikel kan ge upphov till ett hundra till tusenfalt antal nanopartiklar i kroppen. Stora partiklar som innehåller nanopartiklar dominerade även partikelemissionerna på en annan arbetsplats där andra typer av nanopartiklar, så kallade kolnanorör tillverkades och behandlades mekaniskt.

Dieselavgaser är något som de flesta av oss exponeras för, inte bara på arbetsplatser utan även i vår vardagliga miljö. Avgaserna består av både skadliga gaser och skadliga partiklar. I många medicinska studier av dieselavgaser används främst total masskoncentration, det vill säga mikrogram partiklar per kubikmeter luft, som ett mått på exponeringen. I denna avhandling betonas det att detta kan vara missvisande vid jämförelse av resultat från olika medicinska studier. Detta eftersom antalet partiklar i luften och densiteten på partiklarna kan variera i olika exponeringsstudier, även om exponeringen med avseende på masskoncentrationen är densamma. I framtida studier gällande dieselavgaser och hälsoeffekter bland människor är det därför viktigt att beskriva partiklarna i dieselavgaser på fler sätt än endast genom hur mycket de väger.

För många partikeltyper är det idag okänt vid vilka koncentrationer som de kan leda till negativa hälsoeffekter. Det är också ofta okänt vilka mekanismer i kroppen som ligger bakom observerade hälsoeffekter. Att dieselavgaser är skadliga är något som idag är känt men kunskapen om vad det är som gör avgaserna eller partiklarna i avgaserna farliga är inte fullständig. En förhöjd masskoncentration av partiklar i luften har i flera fall visat sig ha en korrelation till ökad förekomst av negativa hälsoeffekter bland människor. Men för vissa partikeltyper, till exempel nanopartiklar, kan tillåtna gränsvärden givna enbart som masskoncentrationer vara otillräckliga. Detta eftersom andra egenskaper, som till exempel antal partiklar, yt-area eller kemisk sammansättning på partiklarna kan vara viktiga för hur de påverkar den mänskliga hälsan. Stora partiklar som består av nanopartiklar kan kanske ge samma eller liknande effekter i kroppen som fria nanopartiklar.

På arbetsplatser kan exponering för kemikalier eller partiklar ske i koncentrationer som man i andra miljöer inte utsätts för. De typer av kemikalier eller partiklar som används på arbetsplatser kan ofta också vara sådana som inte finns i andra miljöer. Ett exempel är kolnanorör. Sådana partiklar används till exempel som tillsats i olika konstruktionsmaterial eftersom de kan ge en ökad materialhållfasthet. Formen på kolnanorör gör att de är snarlika med asbestfiber, vilka är toxiska på grund av sin kemiska sammansättning och fiberform. Huruvida kolnanorör kan klassas som lika skadliga som asbestfiber är dock idag osäkert. De har liknande fiberform, men har till exempel en annan kemisk sammansättning. Osäkerheten kring partiklars hälsoeffekter innebär att riktlinjer och regler för användning och spridning, inte bara av kolnanorör utan av nanopartiklar generellt, ofta är otillräckliga.

Ny kunskap om exponering på arbetsplatser och eventuella hälsoeffekter är viktigt. Detta för att undvika att inte bara arbetstagare, utan även övriga allmänheten blir exponerade för partiklar som är bevisat skadliga, eller som en dag kan visa sig vara skadliga om de andas in. Den här avhandlingen ger ny kunskap om hur exponeringen av partiklar på olika typer av arbetsplatser kan se ut. Den nya kunskapen kan användas i riskanalyser inom de givna arbetsplatstyperna och för att minska arbetstagares exponering för skadliga, eller eventuellt skadliga partiklar i luften.

List of papers included in this thesis

I) Wierzbicka, A., **Nilsson, P.T.**, Rissler, J., Sallsten, G., Xu, Y.Y., Pagels, J.H., Albin, M., Osterberg, K., Strandberg, B., Eriksson, A, Bohgard M., Bergemalm-Rynell K., Gudmundsson A., **Detailed Diesel Exhaust Characteristics Including Particle Surface Area and Lung Deposited Dose for Better Understanding of Health Effects in Human Chamber Exposure Studies**. *Atmospheric Environment*, 2014, 86, 212-219

II) **Nilsson, P.T.**, Marini, S., Wierzbicka, A., Kåredal, M., Blomgren, E., Nielsen, J., Buonanno, G., Gudmundsson, A., **Characterization of Hairdresser Exposure to Airborne Particles during Hair Bleaching**. *Annals of Occupational Hygiene*, 2015, 60(1).

III) **Nilsson, P.T.**, Isaxon, C., Eriksson, A.C., Messing, M.E., Ludvigsson, L., Rissler, J., Hedmer, M., Tinnerberg, H., Gudmundsson, A., Deppert, K., Bohgard, M., Pagels, J.H., **Nano-objects Emitted during Maintenance of Common Particle Generators: Direct chemical characterization with aerosol mass spectrometry and implications for risk assessments**. *Journal of Nanoparticle Research*, 2013, 15.

IV) Ludvigsson L., Isaxon C., **Nilsson P.T.**, Tinnerberg, H., Messing, M. E., Rissler, J., Skaug, V., Gudmundsson, A., Bohgard, M., Hedmer, M., Pagels. J., **Carbon Nanotube Emissions from Arc Discharge Production: Classification of Particle Types with Electron Microscopy and Comparison with Direct Reading Techniques**. *Annals of Occupational Hygiene*, 2016.

V) **Nilsson, P.T.**, Eriksson, A.C., Ludvigsson, L., Messing, M.E., Nordin, E.Z., Gudmundsson, A., Meuller, B.O., Deppert, K., Fortner, E.C., Onasch, T.B, Pagels, J.H., **In-situ Characterization of Metal Nanoparticles and their Organic Coatings Using Laser Vaporization Aerosol Mass Spectrometry**. *Nano Research*, 2015.

The author's contributions to the papers

I) I designed and constructed the method and system for diesel exhaust generation and dilution. I took part in the planning of the exposures and the methods used for particle characterization. I generated and characterized the aerosol particles. I evaluated parts of the data and wrote parts of the paper.

II) I had a major part in the planning of the hairdresser exposures and the methods for particle characterization. I was in a team that carried out the exposures. I evaluated most of the data and wrote most of the paper.

III) I had a major part in the planning of the emission measurements. I carried out the measurements and evaluated the data. I wrote most of the paper.

IV) I took part in the planning of the emission measurements and had a major part in carrying out the measurements. I participated in the writing of the paper.

V) I had a major part in the planning of the experiments. I carried out the experiments, evaluated the data and wrote most of the paper.

Publications not included in this thesis

Peer reviewed papers

Malik, A., **Nilsson, P.T.**, Pagels, J., Lindskog, M., Rissler, J., Gudmundsson, A., Bohgard, M., Sanati, M., Methodology for Sampling and Characterizing Internally Mixed Soot-Tar Particles Suspended in the Product Gas from Biomass Gasification Processes. *Energy & Fuel*, 2011, 25(4), 1751-1758.

Nilsson, P., Malik, A., Pagels, J., Lindskog, M., Rissler, J., Gudmundsson, A., Sanati, M., Laboratory Evaluation of a Gasifier Particle Sampling System using Model Compounds of Different Morphology. *Biomass Conversion and Biorefinery*, 2011, 1(2), 75-84.

Malik, A., Abdulhamid, H., Pagels, J., Rissler, J., Lindskog, M., **Nilsson, P.**, Bjorklund, R., Jozsa, P., Visser, J., Spetz, A., Sanati, M., A Potential Soot Mass Determination Method from Resistivity Measurement of Thermophoretically Deposited Soot. *Aerosol Science and Technology*, 2011, 45(2), 284-294.

Nordin, E.Z., Eriksson, A.C., Roldin, P., **Nilsson, P.T.**, Carlsson, J.E., Kajos, M.K., Hellen, H., Wittbom, C., Rissler, J., Londahl, J., Swietlicki, E., Svenningsson, B., Bohgard, M., Kulmala, M., Hallquist, M., Pagels, J.H., Secondary Organic Aerosol Formation from Idling Gasoline Passenger Vehicle Emissions Investigated in a Smog Chamber. *Atmospheric Chemistry and Physics*, 2013, 13(12), 6101-6116.

Rissler, J., Messing, M.E., Malik, A.I., **Nilsson, P.T.**, Nordin, E.Z., Bohgard, M., Sanati, M., Pagels, J.H., Effective Density Characterization of Soot Agglomerates from Various Sources and Comparison to Aggregation Theory. *Aerosol Science and Technology*, 2013, 47(7), 792-805.

Hedmer, M., Isaxon, C., **Nilsson, P.T.**, Ludvigsson, L., Messing, M.E., Genberg, J., Skaug, V., Bohgard, M., Tinnerberg, H., Pagels, J.H., Exposure and Emission Measurements During Production, Purification, and Functionalization of Arc-Discharge-Produced Multi-walled Carbon Nanotubes. *Annals of Occupational Hygiene*, 2014, 58(3), 355-379.

Risberg, M., Ohrman, O.G.W., Gebart, B.R., **Nilsson, P.T.**, Gudmundsson, A., Sanati, M., Influence from Fuel Type on the Performance of an Air-blown Cyclone Gasifier. *Fuel*, 2014, 116, 751-759.

Rissler, J., Nordin, E.Z., Eriksson, A.C., **Nilsson, P.T.**, Frosch, M., Sporre, M.K., Wierzbicka, A., Svenningsson, B., Londahl, J., Messing, M.E., Sjogren, S., Hemmingsen, J.G., Loft, S., Pagels, J.H., Swietlicki, E., Effective Density and Mixing State of Aerosol Particles in a Near-Traffic Urban Environment. *Environmental Science and Technology*, 2014, 48(11), 6300-6308.

Weiland, F., **Nilsson, P.T.**, Wiinikka, H., Gebart, R., Gudmundsson, A., Sanati, M., Online Characterization of Syngas Particulates Using Aerosol Mass Spectrometry in Entrained-Flow Biomass Gasification. *Aerosol Science and Technology*, 2014, 48(11), 1145-1155.

Wittbom, C., Eriksson, A.C., Rissler, J., Carlsson, J.E., Roldin, P., Nordin, E.Z., **Nilsson, P.T.**, Swietlicki, E., Pagels, J.H., Svenningsson, B., Cloud Droplet Activity Changes of Soot Aerosol upon Smog Chamber Ageing. *Atmospheric Chemistry and Physics*, 2014, 14(18), 9831-9854.

Hedmer, M., Ludvigsson, L., Isaxon, C., **Nilsson, P.T.**, Skaug, V., Bohgard, M., Pagels, J.H., Messing, M.E., Tinnerberg, H., Detection of Multi-walled Carbon Nanotubes and Carbon Nanodiscs on Workplace Surfaces at a Small-Scale Producer. *Annals of Occupational Hygiene*, 2015, 59(7), 836-852.

Conference proceedings (selection)

Rissler, J., Pagels, J., Abdulhamid, H., **Nilsson, P**., Nordin, E., Sanati, M., Bohgard, M., On-line Particle Density Measurements of Combustion Aerosols: Using the Aerosol Particle Mass Analyzer. *Nordic Society for Aerosol Research* (NOSA), Lund, Sweden, 2009.

Eriksson, A., **Nilsson, P.**, Nordin, E., Swietlicki, E., Hallquist, M., Pagels, J., Ageing Processes of Vehicle Exhaust Aerosols Investigated Through Coupled Aerosol Mass Spectrometer-Thermal Denuder Chamber Measurements. *International Aerosol Conference* (IAC), Helsinki, Finland, 2010.

Wierzbicka, A., Albin, M., Andersson, U., Assarsson, E., Axmon, A., Barregård, L., Berglund, M., Bohgard, M., Broberg, K., Brunskog, J., Gudmundson, A., Gunnskog, A., Hagerman, I., Jönsson, B., Kåredal, M., **Nilsson, P.**, Österberg, K., Pagels, J., Poulsen, T., Rissler, J., Stockfelt, L., Sällsten, G., A Methodology for Assessment of Combined Effects of Particles and Noise on Humans during Controlled Chamber Exposure. *International Aerosol Conference* (IAC), Helsinki, Finland, 2010.

Eriksson, A.C., Nordin, E.Z., **Nilsson, P.T.**, Carlsson, J.E., Wittbom, C., Roldin, P., Kajos, M.K., Rissler, J., Abdisa, F., Hallquist, M., Kulmala, M., Svenningssson, B., Pagels, J., Swietlicki, E., Online Soot Measurement in Smog Chamber Experiments. *European Aerosol Conference* (EAC), Manchester, UK, 2011.

Wierzbicka, A., **Nilsson, P.T.**, Nordin, E., Pagels, J., Dahl, A., Löndahl, J., Gudmundsson, A., Bohgard, M., Can Storage of Cleaning Products be a Source of Ultrafine Particles in a Supermarket? *European Aerosol Conference* (EAC), Manchester, UK, 2011.

Nilsson P., Malik A., Lindskog M., Pagels J., Rissler J., Gudmundsson A, Bohgard M. and Sanati M., Evaluation of a High Temperature Particle Sampling Setup for Separation of Inorganic and Organic Phase Using Laboratory Model Compounds, *European Aerosol Conference* (EAC), Manchester, UK, 2011 (Poster presentation by the author of this thesis).

Nilsson, P.T., Eriksson, A.C., Messing, M.E., Isaxon, C., Hedmer, M., Tinnerberg, H., Meuller, B.O., Svensson, C.R., Deppert, K., Bohgard, M., Pagels, J., Soot Particle-AMS for Time and Composition Resolved Detection of Engineered Metal Particles. *Nordic Society for Aerosol Research* (NOSA), Tampere, Finland, 2011 (Oral presentation by the author of this thesis).

Ludvigsson L., Isaxon, C., **Nilsson, P.T.**, Messing, M.E., Tinnerberg, H., Hedmer, M, Pagels, J., Emissions of Arc Discharge Produced Multi-walled Carbon Nanotubes in an Industrial Environment. *Workplace & Indoor Aerosols*, Lund, Sweden, 2012.

Nilsson, P.T., Eriksson, A.C., Messing, M.E., Isaxon, C., Hedmer, M., Tinnerberg, H., Meuller, B.O., Deppert, K., Bohgard, M., Pagels, J., Laser Vaporization Aerosol Mass Spectrometry for Analysis of Particle Emissions during Maintenance of Aerosol ENP Generators. *Workplace & Indoor Aerosols*, Lund, Sweden, 2012 (Poster presentation by the author of this thesis)

Rissler, J., **Nilsson, P.**, Pagels, J., Eriksson, A., Nordin, E., Swietlicki, E., Svenningsson, B., Frosch, M., Ahlberg, E., Wittbom, C., Löndahl, J., Wierzbicka, A., Hemmingsen, J.G., Loft S., Sjögren, S., Effective Density of Particles in an Urban Environment - Measured with the DMA-APM system for lung dose estimations. *European Aerosol Conference* (EAC), Granada, Spain, 2012

Nilsson, P.T., Eriksson, A.C., Messing, M.E., Isaxon, C., Hedmer, M., Tinnerberg ,H., Meuller, B.O., Svensson, C.R., Deppert, K., Bohgard, M., Pagels, J., Laser Vaporizer-AMS for Exposure Assessment and Detection of Airborne Engineered Metal Nanoparticles. *European Aerosol Conference* (EAC), Granada, Spain, 2012 (Oral presentation by the author of this thesis)

Ludvigsson, L., Isaxon, C., **Nilsson, P.T.**, Hedmer, M., Tinnerberg, H., Messing, M.E., Rissler, J., Skaug, V., Bohgard, M., Pagels, J., Emission Measurements of Multi-walled Carbon Nanotube Release during Production. *Nordic Society for Aerosol Research* (NOSA), Helsingør, Denmark, 2012

Nilsson, P.T., Ludvigsson, L., Rissler, J., Messing, M.E., Isaxon, C., Eriksson, A.C., Hedmer, H., Tinnerberg, H., Deppert, K., Gudmundsson, A., Pagels, J., Contrasting Manufactured Nano Objects Emitted during Maintenance of Common Particle Generators with Originally Synthesized Particles. *European Aerosol Conference*, Prague, Czech Republic, 2013 (Poster presentation by the author of this thesis)

Hedmer, M., Ludvigsson, L., Isaxon, C., **Nilsson, P.T.**, Skaug, V., Bohgard, M., Pagels, J., Messing, M., Tinnerberg, H., Detection of Carbon Nanotubes and Carbon Nanodiscs on Workplace Surfaces in a Small-scale Produce., *Nanosafe*, Grenoble, France, 2014

Marini, S., **Nilsson, P.T.**, Wierzbicka, A., Kåredal, M., Blomgren, E., Nielsen, J., Buonanno, G., Gudmundsson, A., Airborne Exposure of Hairdressers during Hair Bleaching: A human chamber exposure study. *Indoor Air Conference*, Hongkong, China, 2014

Symbols and abbreviations

AMS	aerosol mass spectrometer
APM	aerosol particle mass analyzer
APS	aerodynamic particle sizer
CE	collection efficiency of the AMS or LV-AMS
C_{in}	inhaled particle concentration
CMD	count median diameter
CNT	carbon nanotube
CPC	condensation particle counter
CPMA	centrifugal particle mass analyzer
C_s	mass concentration of species *s* determined with AMS
d	particle diameter measured by microscopy
d_{ae}	aerodynamic equivalent diameter
DCLA	diffusion limited cluster aggregation
d_m	mobility diameter
DMA	differential mobility analyzer
DMPS	differential mobility partice sizer
d_{pp}	primary particle diameter measured by TEM analysis
DRI	direct reading instrument
d_{va}	vacuum aerodynamic diameter
E_B	particle bounce factor of *CE*
EC	elemental carbon
EDX	energy dispersive X-ray spectroscopy
E_L	inlet and aerodynamic lens transmission factor of *CE*
ENP	engineered nanoparticle

E_S	beam divergence factor of *CE*
E_V	absorption cross section factor of *CE*
GMD	geometric mean diameter
HTF	high temperature furnance
I_s	ion rate of species *s*
LV-AMS	laser vaporization aerosol mass spectrometer (same as SP-AMS)
mIE_s	mass based ionization efficiency of species s
m_p	mass per particle
MPPD	multiple pathway particle dosimetry model
MS	average mass spectrum
MWCNT	multi-walled carbon nanotube
O/C	oxygen to carbon ratio
OC/EC	organic carbon to elemental carbon
PAH	polyaromatic hydrocarbon
PM10	particulate matter smaller than 10 µm (d_{ae})
PM2.5	particulate matter smaller than 2.5 µm (d_{ae})
PToF	particle time of flight
Q	inhaled volumetric flow
Q_{AMS}	AMS sampling flow rate
RIE_s	relative ionization efficiency of species s to nitrate
SEM	scanning electron microscopy
SMPS	scanning mobility particle sizer
SP-AMS	soot particle aerosol mass spectrometer (same as LV-AMS)
SWCNT	single-walled carbon nanotube
t	time of exposure
TDF	total deposited fraction
TEM	transmission electron microscopy
TEOM	tapered element oscillating microbalance
VOC	volatile organic carbon
ρ_0	unity density (1.0 g/cm^3)

$\rho_{eff(I)}$	effective density calculated from m_p and d_m
ρ_p	particle material density

1 Background and aims

1.1 Background

The research presented in this thesis characterizes particle emissions and exposures in selected occupational environments. People in these environments can come in contact with particles that are known to have adverse health effects and/or particles with unknown health effects, the latter of which lack regulatory legislation. It is important to characterize the aerosol particles that are present in occupational environments in order to determine what particles and what particle characteristics are relevant to consider in regards to human health effects.

Vehicles are one of the most common sources of the air pollutants present in the atmosphere, and particulate matter (PM) emitted from combustion engines is associated with adverse health effects (Salvi, 2007). In 2012 the International Agency for Research on Cancer (IARC), which is a part of the World Health Organization (WHO), announced that diesel exhaust was upgraded from Group 2A, "probably carcinogenic to humans", to Group 1, "carcinogenic to humans" (IARC, 2012). The organization concluded that the evidence of the increased risk for developing lung cancer and other diseases from diesel exhaust exposure had grown over the past decades and an upgrade was necessary for future protection of the public health. The negative human health effects from diesel exhaust exposure have thus been declared as certain, but the mechanisms behind the effects are not fully understood. The characterization of diesel exhaust according to its multiple gas and particle characteristics is thus important.

Hairdressers are exposed to a wide variety of products that release chemical substances in both gaseous and particle form into the air. Almost all activities taking place in a hairdresser salon, such as hair cutting, bleaching, dying, spraying and washing, can be considered to be potential hazards as they may induce risks for developing either musculoskeletal disorders, dermal allergic reactions, respiratory symptoms or even cancer (Parra et al., 1992; Harling et al., 2010; Bradshaw et al., 2011). The characterization of emissions and exposures during different activities commonly carried out in hairdresser salons can help understand the mechanisms behind the adverse health effects experienced by hairdressers. Such understanding can eliminate or minimize the exposure.

Environments that have a crucial need for improved particle exposure characterization are those where engineered nanoparticles are produced or handled. Engineered nanoparticles, or engineered nanomaterials, are tailored to possess unique properties. These properties make them highly interesting for many applications in electronics, medicine, cosmetics and composites, for example. The production of such particles or materials is rapidly increasing. But the unique manmade properties may in some cases result in increased toxicity of the particles. Some engineered nanoparticles, like carbon nanotubes, possess shapes that resemble asbestos fibers. But the impact on human health from exposure to carbon nanotubes is uncertain, and there are no governmental regulations that control occupational exposure to these particles. This is mainly because the relevant particle properties for human exposure is a debated topic (Oberdorster et al., 2015).

In 2001 the European Environmental Agency (EEA) published the report *Late Lessons from Early Warnings: The Precautionary Principle 1896-2000*. This report described 12 lessons that can be applied to avoid making similar mistakes as in the past when new technologies are being developed. The questions raised by the 12 lessons in the EEA report are relevant for nanotechnology (Hansen et al., 2008). It is therefore important to develop methods for the characterization of particle emissions and exposures in occupational environments where engineered nanoparticles or nanomaterials are being handled. This needs to be done in order to determine the characteristics of the particles that are considered to be relevant for human health, and to increase the understanding of how human exposure to engineered nanoparticles occurs. Nanotechnology is without a doubt full of potential and is a research field that is important in many applications, both today and in the future. But the precautionary principle should always be applied for engineered nanoparticles and nanomaterials.

An elusive issue when characterizing particle emissions and human exposure to specific particles in occupational environments is the presence of background particles. Background particles can make it hard to identify the particles of interest and new methods for selective detection are needed in the field of occupational exposure assessments. In addition, selective detection that allows the characterization of several particle properties directly inside production lines is needed in the field of nanotechnology, as this can increase the efficiency of production and the understanding of particle formation processes.

1.2 Aims

The overall aim of the research presented in this thesis is to provide knowledge for exposure risk assessments and for toxicological studies of aerosol particles found in occupational environments. This thesis also presents a method for improved characterization of particle emissions and increased understanding and control of aerosol particle production processes.

The more specific aims are:

- To characterize particle emissions that occur in selected occupational environments according to particle size, shape, surface structure, chemical composition and concentration metrics (number, surface and/or mass) (Papers I, II, III and IV).
- To establish and evaluate new implementations for the laser vaporization aerosol mass spectrometer for:
    - Selective detection of emitted particles in occupational particle emission studies (Paper II).
    - In-situ characterization of engineered nanoparticles and their impurities as they are produced (Paper V).

2 Introduction

An aerosol is defined as a gas and any liquid or solid particles suspended in the gas. The air we breathe is an aerosol and its composition depends on where we are. The air includes gases and particles that originate from natural sources, such as biogenic emissions and sea salt, and anthropogenic components which are gases and particles emitted by human activities.

Aerosol particles are divided into different size ranges (Kulkarni et al., 2011). The smallest ones are the fine particles, which are defined as having a diameter between 0.001 and 2.5 µm. A sub-fraction of the fine particles are defined as ultrafine particles which have a diameter, or at least two out of three dimensions, between 0.001 and 0.1 µm. These ultrafine particles are also referred to as nanoparticles (ASTM International, 2012). A third size range includes coarse particles, which are typically defined as having a diameter between 2.5 and 10 µm. The different size ranges arise due to the different origins and formation mechanisms of particles. Ultrafine and fine particles include, for instance, combustion generated particles like soot, while coarse particles include typically particles that become airborne through mechanical influences. Definitions exist but the dividing points between the different particle size ranges should be considered as adaptive since particles in the air are polydisperse.

Besides being categorized into different size ranges, particles can also be categorized as primary or secondary aerosol particles. Primary aerosol particulate matter includes particles that are emitted from a source in particle phase, while secondary aerosol particulate matter is formed through nucleation and condensation of volatile material in an atmosphere after emission.

2.1 Outdoor aerosols

The composition of the air in the atmosphere is an important parameter for both the climate and human health. Greenhouse gases increases global warming, while most particles (excluding elemental and black carbon) in the air contribute to decreasing global warming and act as coolants in the atmosphere (IPCC, 2013). Particles in the atmosphere do not only have a direct effect on climate, due to their scattering of incoming sunlight, but also an indirect effect as they can serve as sites for water

condensation and are the reason for the formation of clouds and rain. But even though increased levels of particles in the atmosphere may reduce global warming, an increase of particle emissions can lead to severe effects on the global human health. This is because increased levels of particles in the air are associated with increased morbidity and mortality in urban areas (Dockery et al., 1993; Raaschou-Nielsen et al., 2013). Anthropogenic sources, such as combustion processes, are particularly considered with regards to negative human health effects.

Legislation has been passed on the highest permissible particle concentrations in urban environments due to their negative effects on human health. These legislated levels are typically given as PM2.5 or PM10, which are the particulate matter with aerodynamic diameters smaller than 2.5 and 10 µm, respectively. PM2.5, the fine particle fraction, is often divided in urban environments into nucleation and accumulation mode particles. Nucleation mode particles are typically emitted in high number concentrations and coagulate with other particles due to their high diffusion rate (Hinds, 1999). Free nucleation mode particles in the air thus tend to end up on accumulation or coarse mode particles. Accumulation mode particles have a very long lifetime in the air since no particle deposition mechanism is effective in this size range. They accumulate in the air, hence the name. Coarse particles have a short lifetime in the atmosphere due to their large gravitational settling velocity and are predominantly found close to emission sources. PM10 levels measured away from emission sources are therefore typically dominated by the PM2.5 fraction. PM2.5 is also the size fraction that typically includes the highest number of particles.

In the atmosphere, UV sunlight and oxidizers (e.g., OH^- and O_3) may oxidize gaseous compounds into less volatile compounds resulting in the formation of new particulate matter (Robinson et al., 2006). The formation of secondary particulate matter is believed to have a net cooling effect in the atmosphere, but the uncertainty is high regarding the magnitude of the effect (Hallquist et al., 2009). This is also the case regarding the human health effects from secondary particulate matter, since only a limited number of studies exist on the toxicological effects from such aerosols (Nordin et al., 2015).

2.2 Indoor aerosols

Increased levels of PM10 and PM2.5 in outdoor (urban) aerosols are associated with negative human health effects (Pope and Dockery, 2006). However, the majority of the people in the industrialized world spend most of their time indoors, whether at home or at work (Leech et al., 2002; Brasche and Bischof, 2005). Typically, epidemiological studies of particle exposure are based on mass concentrations from the outdoors. But measured levels of outdoor pollutants may be a poor

approximation of personal exposure due to the time people spend in indoor environments (Stroh et al., 2012; Isaxon et al., 2015).

The airborne particles in an indoor environment consist in part of particles that have penetrated into the building from the outdoor environment. Because of the lack of a strong deposition mechanism, the particles penetrating indoors are mainly constituted of fine accumulation mode particles (Nazaroff, 2004), such as soot particles. The main portion of the particles found in indoor environments consists of particles emitted from the activities carried out by the people residing there (Morawska et al., 2013). The most significant sources of particles in households are combustion related, like candle burning, or related to thermal treatments, like cooking (Hussein et al., 2006).

The spatial variation of ultrafine and coarse particles in the air can be very non-uniform due to their relatively short lifetimes in the air as free particles (Wilson et al., 2005). In indoor environments, the proximity between a source of particle emissions and a person is generally closer compared to outdoors proximities. In addition, ventilation in indoor environments results in far less dilution of emitted particles than outdoors. Being able to implement correct techniques and methods for particle characterization in indoor environments is essential in order to capture the complete exposure, which includes particles with short lifetimes in the air.

2.3 Occupational aerosols

Outdoor or indoor environments that can also be classified as occupational environments imply that the risk for being exposed to elevated levels of aerosol particles are higher compared to other environments. Work tasks in occupational environments may give rise to high emissions of particles and types of particles and materials that the general population are not exposed to. Many of the human exposure limits that exist today for specific particles or chemicals are based on findings from occupational environments and toxicological studies, where negative health effects have been associated with specific exposures. It is important to characterize the particle emissions and exposures that occur in occupational environments in order to protect the people who work there. Identifying hazardous material in occupational environments where the products are produced often means that the risks are identified at the early stage of a specific product's lifetime. In this way, knowledge gained from the characterization of occupational exposure can also help to prevent larger populations outside the occupational environment from being exposed to the specific product. Such knowledge can justifiy the adjustment of legislation to control the use of the specific product.

2.4 Inhalation and respiratory deposition of aerosol particles

When particles in the air are inhaled they have a certain probability to be deposited in the respiratory tract. The deposition probability depends on the breathing pattern, lung morphology, state of health, and size and composition of the inhaled particles (Londahl et al., 2014). The pulmonary region of the respiratory tract is often of particular interest when it comes to particle deposition. Here, the defense mechanisms against particles (mainly macrophages) are relatively weak and the air-to-blood barrier is thinnest (Schmid et al., 2009).

Figure 1a shows a total respiratory deposition curve and two pulmonary deposition probability curves according to the multiple pathway particle dosimetry (MPPD) model. One of the pulmonary deposition curves is for light exercise with nasal breathing, and the other is for a sitting (rest) body position with oral breathing. The parameters used in the model (breathing frequency, tidal volume and functional reserve capacity) were chosen according to values given for males in Hinds (1999). Symmetric lung morphology (Yeh and Schum), upright position and unity particle density were used for all three model simulations.

As seen in Figure 1a, the lowest total particle deposition occurs in the interval of 0.1-1 µm. As particles get smaller, their deposition by diffusion increases. In the respiratory tract this means that a peak for the pulmonary deposition probability exists around 0.02 µm (depending on breathing pattern). Smaller particles also have high diffusion rates but they are deposited higher up in the airways and reach the pulmonary region to a lesser degree. The particle equivalent diameter that best describes the deposition of particles when diffusion is governing the deposition is mobility diameter (d_m). A second peak for pulmonary deposition exists above 1 µm. This is because the deposition through sedimentation, impaction and interception increases with increased particle size. These deposition mechanisms are described by the aerodynamic equivalent diameter (d_{ae}). The magnitude and position of the pulmonary deposition peaking above 1 µm is very dependent on the breathing pattern. The two sets of breathing patterns used in Figure 1 (nasal/light exercise and oral/sitting) were chosen as examples to capture a low and high peak for pulmonary deposition probability above 1 µm. Nasal breathing with a sitting position (rest) would, in Figure 1a for instance, have a peak (above 1 µm) in-between the two given examples for pulmonary deposition. The position of the peaks displayed above 1 µm in Figure 1a is also, in contrast to the peaks positioned at lower sizes, dependent on particle density. In Figure 1a, a density lower than unity would shift the upper pulmonary deposition peaks towards a larger particle size while a density higher than unity would shift the peaks towards a smaller size.

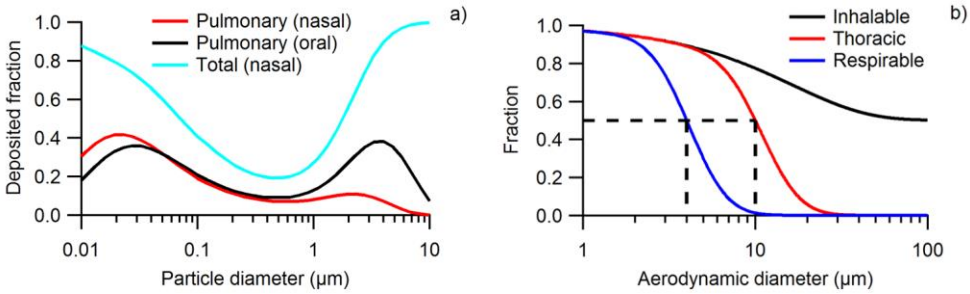

Figure 1. a) Total deposition of particles in the respiratory tract and in the pulmonary region according to the MPPD model. The breathing patterns for pulmonary deposition are nasal breathing during light exercise and oral breathing during rest. These breathing patterns give examples of high and low deposition probabilities for particles > 1 μm. **b)** ACGIH classification of particles according to how deep into the respiratory tract they may reach (Hinds, 1999).

The MPPD model, with the previously mentioned parameters, is used in this thesis to illustrate the deposition probability of particles found in different occupational environments. But it is important to emphasize that the intention with this is only illustrative, because the use of deposition models comes with uncertainties. Particles that are present in the air are typically polydisperse with shapes, densities and compositions that vary with particle size and that can affect deposition probabilities. The chemical composition, or more explicitly the hygroscopicity of the particles, is very important for the deposition probability. Inhalation of hydrophobic 0.1 μm particles can give a deposited dose in the respiratory tract 4 times higher compared to hygroscopic particles (Londahl et al., 2007). This is because hygroscopic ultrafine and fine particles grow by condensation of water in the respiratory tract, which decreases the diffusion rate and deposition. The MPPD model only considers spherical dry hydrophobic particles. Some people are more sensitive to increased particle concentrations in the air, which can be explained by the fact that variations in deposition probability exist between individuals (Heyder et al., 1982; Londahl et al., 2007; Rissler et al., 2012). The MPPD model does not consider any individual differences except age, lung size and breathing patterns.

Based on how deep the particles reach into the respiratory tract, they can be divided into inhalable, thoracic and respirable particles as classified by the American Conference of Governmental Industrial Hygienists (ACGIH, 1997) (Figure 1b). Inhalable particles have a certain probability to at least enter the mouth or the nose. This fraction is defined from experimental studies and consists of averages of measurements obtained with a manikin oriented to a wind of air (< 4 m/s) in different discrete directions (Kennedy and Hinds, 2002). Some experimental studies show that the inhalation efficiency in calm air with very low wind speeds (< 0.2 m/s) may exceed the average achieved at higher wind speeds (Vincent, 2005), which is relevant for many indoor environments with low ventilation rate. A subfraction of the inhalable fraction is made up of thoracic particles. These particles may get

pass the upper airways and reach the thorax (chest). Respirable particles can reach the pulmonary region.

Size selective sampling according to inhalable, thoracic or respirable particle size fractions is typically implemented in occupational environments. To further enhance the protection of workers, the sampling criteria of both thoracic and respirable sampling are shifted towards slightly larger diameters than those obtained from experimental studies (Brown et al., 2013).

2.4.1 Health effects from inhaled and deposited particles

Negative health effects induced by inhalation of particles arise when the dose of deposited particles in an individual's respiratory tract becomes too high for the body's different defense and clearance mechanisms to handle. Some particles (e.g., particles containing cancerogenic material) may induce risks for negative health effects in other regions of the body as well, if they can dissolve or translocate to other organs. To be able to choose adequate sampling methods and sampling criteria, information regarding the characteristics of specific particles and the mechanisms behind health effects are crucial. The dose (amount of deposited material) at which health effects are induced varies heavily depending on the particle type being deposited and how sensitive individuals are to exposure. In principle, even one single deposited particle can be considered as a dose. Several particle characteristics – particle size, number concentration, surface concentration, mass concentration, surface structure, surface reactivity, surface charge, chemical composition, volatile and non-volatile mass fraction and solubility – can all to some extent be related to different observed human health effects (Oberdorster et al., 2005; Giechaskiel et al., 2009; Braakhuis et al., 2014b). The relevant particle concentrations for human exposure can consequently vary depending on the physical, chemical and biological characteristics of inhaled particles.

A health risk from inhalation of aerosol particles basically exists if the sequence shown in Figure 2 is fulfilled. First, matter needs to be emitted from a source into the air. Secondly, the emissions have to give rise to an exposure (be inhaled) which in turn leads to a deposited dose in the respiratory tract. In order for effects to be induced, the dose needs to reach a certain level and the particles need to be deposited at a site in the respiratory tract from which health effects can be induced. Measurements of emissions close to a source can rougly be considered as a measure of a worst case exposure. The concentrations of particles are typically at their highest right next to an emission source. Further away from the source, the concentration in the air is reduced. Even though emissions occur, the amount of ventilation, point extraction or kinds of respiratory protection used in a workplace can mean that the degree of exposure is not significant. This thesis research focuses on the characterization of aerosol particle emissions and exposures in selected

occupational environments. The thesis also discusses particle emissions and the implications for risk assessments and dosimetry based on the particle characteristics observed.

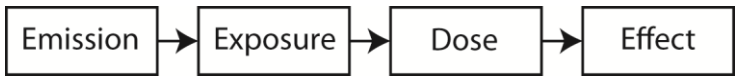

Figure 2. The sequence required for aerosol particles to induce negative human health effects by inhalation. This thesis focuses on the characterization of particle emissions and exposure and relates the particle characteristics to possible fates of the particles in the body.

3 Selected occupational environments and associated health risks

3.1 Environments with diesel exhaust emissions (Paper I)

Significant exposure to elevated levels of diesel exhaust can occur in occupational environments. Examples of occupations with a high probability for exposure to diesel exhaust are miners, caretakers and other operators of diesel powered machines. Exposure may also occur in occupational environments located near streets, including offices.

Epidemiological studies have shown that the risk of dying from lung cancer is significantly higher for miners exposed to diesel exhaust compared to the general population (Silverman et al., 2012). Other negative health effects associated with diesel exhaust exposure are respiratory symptoms, immunologic responses, lung inflammatory and cardiovascular effects (Rudell et al., 1999; Ris, 2007; Barath et al., 2010; Xu et al., 2013). Several of the negative human health effects observed in diesel exhaust exposure and toxicological studies are associated with the particulate matter in the diesel exhaust (Salvi et al., 1999; Hoek et al., 2002). But there is a limited understanding of exactly which particle characteristics and mechanisms that are responsible for the health effects observed.

Comprehensive characterization of diesel exhaust exposure will improve the ability to compare results with other exposure studies, and enhance the possibilities of governments to legislate or adjust hygienic exposure limits for safe environments. By basing diesel particle characterization on the particle properties considered important for human health, and by relating these properties to the observed health effects, can also help to foresee possible health effects from other types of particles (Hesterberg et al., 2010). The comprehensive characterization of diesel exhaust particles in human exposure studies, as presented in Paper I, are thus important.

3.2 Hairdresser salons during hair bleaching (Paper II)

There is a prevalence of different respiratory health effects among hairdressers, such as asthma, rhinitis and nasal congestion. But the mechanisms behind the exposures and health effects are often unknown. Occupational exposures that render rhinitis or asthma, for example, highly affect the well-being of people (Chen et al., 2004; Knoeller et al., 2013) and may result in some having to abandon their profession. In Sweden, only about 40% of the hairdressers are active in the profession eight years after completing their education (Arbetsmiljöverket, 2011b). Whether this is mainly due to health-related issues is not clear, but it can be an important factor. "Health", according to the Constitution of the World Health Organization, is not only a matter of physical well-being but also mental and social well-being (WHO, 2006). It can be argued that having to abandon a job due to health-related issues can affect the mental and social well-being of hairdressers.

Hair bleaching is the activity that gives rise to the most prominent and frequent respiratory symptoms among hairdressers (Leino et al., 1998; Albin et al., 2002; Hollund et al., 2003; Hashemi et al., 2010; Diab et al., 2014). Hair bleaches mainly contain persulfate salts, which can act as allergens and airway irritants. They are therefore considered the constituent responsible for most of the observed respiratory health effects during hair bleaching (Diab et al., 2009).

To minimize hairdressers' exposure to hazardous or irritating compounds, efforts to characterize the exposure are necessary. This is what is done in Paper II in regards to hairdressers' exposure to particles and persulfate during hair bleaching. Bleaching powders less prone to give rise to airborne dust have been developed to minimize the exposure. Paper II compares the particle emissions from two different types of powders, one regular and one labeled as "dust-free".

3.3 Facilities for production of engineered nanoparticles (Papers III & IV)

Nanotechnology is a field of research that develops materials and products with unique properties. At nano-scale, materials often exhibit enhanced properties in terms of for instance mechanical strength, conductivity and reactivity. Nanomaterials therefore possess both technological and economical potentials (Lee et al., 2010). As the demand for nanomaterials and the scale of productions increase, the risk for unintentional release of nanoparticles into the air or environment also increases. Due to the enhanced properties of materials at the nano-scale, it can be argued that metrics other than particle mass concentrations are more relevant for

determining the human health effects (Abbott and Maynard, 2010; Rivera Gil et al., 2010).

The risks from different types of engineered nanoparticles are to date uncertain, but this should not hamper the development of new and novel technologies or materials. Research that covers the possible human health effects, however, has a difficult time keeping up with the development of new nanomaterials. This has resulted in a lack of legislation concerning new nanoparticles. A close collaboration between researchers who develop new nanomaterials, and researchers who work with the safety aspects of nanomaterials, would increase the ability to generate nanomaterials with high benefits and low risks, what is referred to as "safe by design" (Oberdorster et al., 2005; Braakhuis et al., 2014b).

Human exposure to engineered nanoparticles can occur any time during the lifecycle of the particles, or of the material that incorporates them. A life cycle typically starts with the production of the particles or materials and ends at their waste handling or destruction. This thesis considers aerosol particles and the human exposure route by inhalation during the production and maintenance of production equipment. But other exposure routes, such as dermal contact or digestion, are relevant for possible human health effects as well. Engineered nanoparticles can also have environmental effects if released into ecosystems (Nowack and Bucheli, 2007).

Risks for exposure through inhalation of engineered nanoparticles are high during production processes or open handling of nanomaterials (Demou et al., 2009; Koivisto et al., 2012; Brouwer et al., 2013). Building materials or paint coatings that incorporate nanoparticles may release particles during processes such as sanding and sawing (Gomez et al., 2014). Spray products that contain nanoparticles may lead to a high level of exposure during usage (Bekker et al., 2014). Particles consisting of engineered nanoparticles can be emitted into the air through mechanical handling of nanomaterials or during the opening and maintenance of production systems, which typically are enclosed during production (Bello et al., 2009; Peters et al., 2009; Zimmermann et al., 2012). People like technicians and researchers working with the production of nanoparticles make up a group that is thus at risk for being exposed to airborne engineered nanoparticles (Woskie, 2010).

To date, the facilities for the production of nanomaterials and the number of workers at risk for being exposed are typically limited. Exceptions are facilities for TiO_2 and carbon black production that for quite some time now have been producing materials in vast quantities. But the rapid development of nanomaterials production means that production at industrial scales can become a reality in the near future, even for materials that today are produced in quantities of grams per year. It is important to understand how exposures can occur in order to protect the workers not only of today, but also those of tomorrow.

In Paper III, emissions during the maintenance of a system for metal or metal oxide particle production was carried out. These particles can be used in a wide range of

applications such as catalysts, cosmetics, paints and nanowire growth. Particles consisting of, or incorporating metals or metal oxides, may to various degrees dissolve inside the human body and give rise to metallic ions, which can render toxic effects (Nel et al., 2009; Cho et al., 2011; Braakhuis et al., 2014a). The enhanced reactivity at the nano-scale also imposes a higher risk. For instance, Au in bulk form is non-reactive but at the nano-scale it may act as a catalyst for chemical reactions.

In Paper IV, the production and purification of carbon nanotubes was monitored for particle emissions. Carbon nanotubes are typically used in materials for increased mechanical strength, durability or conductivity. Their resemblance to asbestos fibers makes carbon nanotubes a class of engineered nanoparticles that attracts considrable attention in nanotoxicology (Donaldson et al., 2011). The shape of carbon nanotubes means that they, as asbestos fibers, can align with the air streamlines inside the respiratory tract and reach the pulmonary region even with fiber lengths considerably longer than 10 μm. Even though their toxicity has not been definitely confirmed, there are indications that some types of carbon nanotubes may induce negative human health effects, such as respiratory inflammation and production of reactive oxygen species (Vesterdal et al., 2014; Oberdorster et al., 2015). Different types of carbon nanotubes include single-walled carbon nanotubes (SWCNTs) and multi-walled carbon nanotubes (MWCNTs) depending on if they consist of a single or multiple rolled graphene layers. With regards to human health effects, MWCNTs are of particular interest because of their higher rigidity compared to SWCNTs.

The same type of engineered nanoparticles may show slightly different human health effects depending on how the particles are produced. This is because the level and type of impurities on the produced particles may vary. In the production of carbon nanotubes, the use of different catalyst materials may be a part of the production method. Thus, the catalyst material can exist in, or on, the produced nanotubes (Hsieh et al., 2012; Oberdorster et al., 2015). Another important factor is how engineered nanoparticles become airborne, whether as free nanoparticles or as larger agglomerates. Knowledge from emission assessments, as presented in Papers III and IV, can be applied to similar production processes in order to predict the occurrences and characteristics of particle emissions and exposure.

A current issue with the assessments of particle emissions in occupational environments is to differentiate emitted particles from background particles. Scanning electron microscopy (SEM) or transmission electron microscopy (TEM) analyses are in many cases necessary to achieve a selective identification of engineered nanoparticles (ENPs). Both SEM and TEM require particle sampling and deposition on filters or substrates. This can induce risks for artifacts as the sampled particle characteristics can change during analysis or sampling and storage of filters or substrates. For example, an organic coating on emitted particles cannot be analyzed through electron microscopy since such coatings disappear during the analysis process. In Papers III and V, a laser vaporization aerosol mass spectrometer (LV-AMS) was utilized for the selective sampling of nanoparticles, both during

emission assessments and in-situ characterization. Based on this, one suggestion is to develop methods or instruments that can simultaneously be used for both emission assessments and production quality assurance. This can increase the means of achieving a balance between increased production and gathering the information necessary for improved exposure assessments.

4 Methods

Several different analysis instruments and techniques are needed for detailed characterization of aerosol particles. The analysis techniques implemented in the research presented in this thesis are summarized in Table 1. The optimal aerosol instrument would simultaneously characterize gases and the chemical composition, size, morphology and concentration of particles, and be able to do so in real time. Such an optimal aerosol instrument is yet to be developed, but a promising technique is aerosol mass spectrometers (Kuhlbusch et al., 2011). The laser vaporization aerosol mass spectrometer (LV-AMS) is an example of such a technique and was implemented in two of the papers included in this thesis.

The particle analysis techniques used in the thesis research are divided into two groups: *direct reading instruments* (DRIs) that sampled particles directly from a gas, and *subsequent analysis*. The latter group includes gaseous analysis and sampling of filters that were analyzed gravimetrically, chemically or by microscopy subsequent to sampling and storage.

Table 1.
Instrumentation and analysis techniques used in the five papers included in this thesis.

Paper	I	II	III	IV	V
DRIs					
LV-AMS or AMS	x		x		x
APM or CPMA	x				x
APS		x	x	x	
CPC			x	x	x
SMPS or DMPS	x	x		x	x
Dusttrak			x		
TEOM	x				
Gaseous analysis (NO_x, CO, CO_2)	x				
Subsequent analysis					
Filter, gravimetrical analysis	x				
Filter, chemical analysis	x	x			x
Filter, optical microscope analysis		x			
Filter, SEM (-EDX)			x	x	
Filter, TEM	x		x		
Gaseous analysis (VOC, PAH)	x				

4.1 Instrumentation

4.1.1 Laser vaporization aerosol mass spectrometer

Aerosol mass spectrometers during the last decade have become useful tools in atmospheric research (McMurry, 2000; Sullivan and Prather, 2005; Nash et al., 2006; Canagaratna et al., 2007). Depending on the operational principle, this type of instrument allows time-resolved chemical composition and quantitative characterizations of aerosol particles. An example is the high resolution time-of-flight aerosol mass spectrometer (AMS, Aerodyne Inc.) (DeCarlo et al., 2006). This thesis explores new applications for the AMS beyond atmospheric research. These new applications are the selective sampling of particles emitted during the maintenance of equipment used for the production of engineered nanoparticles, and in-situ characterization of produced engineered nanoparticles.

In the AMS, an aerosol is sampled through an aerodynamic lens which focuses the particles into a narrow beam (Jayne et al., 2000). The focused particles are accelerated across a vacuum chamber and impacted on a heated tungsten vaporizer, typically heated to 600 °C. At this temperature, non-refractory species are flash vaporized and the molecules formed can be ionized. Ionization is performed by using 70 eV electron ionization. The ions formed are extracted into a high resolution time-of-flight mass spectrometer where they are separated and detected based on their ion time of flight.

By modulating the focused particle beam with a mechanical chopper, the particle time of flight (PToF) across the vacuum chamber can be determined. This time is proportional to the vacuum aerodynamic diameter (d_{va}) of the particles and is used to determine the particle mass size distribution of the sampled particles. In the size-resolved mode, called the PToF mode, the mechanical chopper is continuously rotating (140 Hz). The chopper has a small slit (2%) which allows the particle beam to pass through once per chopper cycle. The PToF is defined as the elapsed time from passing the chopper to detection in the mass spectrometer, which is possible since the ion time of flight in the mass spectrometer is two orders of magnitude faster than the PToF (Drewnick et al., 2005). The chopper can also be used to repeatedly allow the particle beam to pass through (opened) or block it (closed) in specified intervals. This is called the mass spectrum (MS) mode and allows characterization of the average chemical composition of particles, without size information but with a higher sensitivity than the PToF mode. The closed position of the chopper is used to determine the instrumental background, which is subtracted from the signals achieved with the chopper in open position.

To be able to detect refractory species, an intracavity Nd:YAG laser, operating at a wavelength of 1064 nm, can be incorporated into the standard AMS as a second

vaporizer (Onasch et al., 2012). Such an instrument, with the addition of a laser vaporizer, is typically referred to as a soot particle aerosol mass spectrometer (SP-AMS), since the original intention of its development was the detection of soot particles. In this thesis the SP-AMS is referred to as a laser vaporization aerosol mass spectrometer (LV-AMS) which, according to the author of this thesis, better reflects the wider applications of the technique. The laser vaporizer is positioned perpendicular to the particle beam, close to the tungsten vaporizer, and can be used to vaporize species that are internally mixed with species that absorb the laser light, such as soot, metals and some metal oxide particles.

Quantification with the AMS and LV-AMS

A few challenges exist for full quantification with the AMS. The research reported in this thesis does not deal with these challenges, but they are presented here since they are important for the future development of the LV-AMS.

In the AMS, vaporization and ionization are performed separately and the number of ions formed (signal strength in Hz) is directly proportional to the total particle mass (Jimenez et al., 2003). The AMS can therefore be used for quantitative measurements of aerosol particles, a function that is more limited when using other techniques that rely on simultaneous vaporization and ionization through laser desorption (Allen et al., 2000).

The collection efficiency (*CE*) of the AMS is defined as the fraction of the sampled particles that reaches the vaporizer and becomes vaporized (Canagaratna et al., 2007). For ambient aerosols, a *CE* of 0.5 is typically the optimal value (Middlebrook et al., 2012). For the AMS, the *CE* consists of three separate factors according to:

$$CE = E_L * E_B * E_S \qquad (1)$$

where the inlet and aerodynamic lens transmission factor (E_L) is dependent on losses in the sampling inlet and lens, the particle bounce factor (E_B) is dependent on the fraction of particles not being vaporized due to particle bounce off the vaporizer and the beam divergence factor (E_S) is dependent on the fraction of particles that misses the vaporizer. Since the tungsten vaporizer is significantly wider than the particle beam (regardless of particle shape), E_S can be assumed to be unity in the standard AMS (assuming correct alignment of the particle beam).

At the inlet and in the aerodynamic lens, nanoparticles are lost due to diffusion while bigger particles are lost due to impaction. With a standard lens, particles between ~0.04 and 1.5 µm in diameter are focused but sampling efficiencies close to 100% (E_L = 1) are achieved for particles between ~0.1 and 0.6 µm (DeCarlo et al., 2006). In this size range, E_B is the dominant factor. It depends on particles that, due to their inertia prior to impaction on the vaporizer, bounce off the vaporizer without being vaporized or subsequently ionized. For liquid particles the bounce effect is often negligible while for solid particles, depending on their morphology, the *CE* may

range from 0.20 to 1 due to differences in E_B (Matthew et al., 2008). Spherical and solid particles tend to bounce off the vaporizer to a larger extent compared to heavily aggregated particles due to the lower surface area available for adhesion.

Quantification becomes more complex for the LV-AMS, since a fourth factor is introduced to the *CE* according to:

$$CE = E_L * E_B * E_S * E_V \qquad (2)$$

where the absorption cross section factor (E_V) is dependent on incomplete vaporization due to possible limitations in the absorption cross section at 1064 nm for the particles sampled. Another current quantification issue with the LV-AMS is the overlap mismatches between the particle beam and the laser beam (E_S), since the particle beam is typically wider than the laser beam (Salcedo et al., 2007; Onasch et al., 2012). Spherical particles give the narrowest particle beams; they do not diverge from the particle beam center line as much as irregular particles do. Hence, E_S for spherical particles is closer to unity than heavily aggregated particles when the laser vaporizer is utilized. A way to improve quantification with the LV-AMS is to implement a beam width probe, which can be used to measure the divergence of the particle beam, and thus can be used to evaluate the fraction of the particles that hits the laser vaporizer (Willis et al., 2014).

For quantification, the mass specific ionization efficiency of species, *s* (mIE_s, *ions/pg*), also needs to be known. Theoretically, this is determined by the ionization cross section of species, *s*, at 70 eV. In practice, it is determined by measuring an ionization efficiency, relative to a calibration aerosol (RIE_s). Ammonium nitrate is the defined calibration aerosol when the tungsten vaporizer is used, and Regal black (REGAL 400R Pigment Black, Capot Corp.) when the laser vaporizer is used. The reason for choosing Regal black is that it is a carbon black that is fairly soluble in water (can be nebulized), and that the particles produced are as compact as possible (less particle beam divergence compared to other black carbons). After the ionization efficiency has been determined, the particle mass concentration (C_s) can be calculated from the summed ion rate of species, *s* (I_s), by:

$$C_S = \frac{\sum_i I_{s,i}}{CE_S \cdot RIE_S \cdot mIE_{NO_3} \cdot Q_{AMS}} \qquad (3)$$

where Q_{AMS} is the AMS sampling flow rate. When calibrating the AMS or LV-AMS, rather than the true mass-based ionization efficiency, it is the product of the CE_s and the mIE_s for the particle type used that is determined.

4.2 Particle emission and exposure characterizations

This section presents an overview of the methods applied in Papers I through IV. Extensive descriptions of the methods are found in each corresponding paper. The different emission and exposure characterizations described in this thesis can be divided into chamber exposure studies and field emission measurements. Chamber exposure studies have the advantage that specific work tasks and particle emissions or exposures can be isolated. This enhances the possibilities to correlate different types of exposures with observed health effects. Chamber studies should be designed to mimic real occupational environments, which are the environments studied in field measurements.

4.2.1 Human exposure to diesel exhaust (Paper I)

This diesel exhaust human exposure study was carried out in a project entitled "Health Effects of Combined Exposure to Diesel and Noise" (DINO). The overall aim of the project was to determine the influence of exposure to diesel exhaust, traffic noise and the combined effects from these two exposure factors on human health. The methods for the generation of diesel exhaust, exhaust dilution and exhaust physical and chemical characterization are within the framework of this thesis.

Diesel exhaust was generated from an idling light duty diesel car (Euro II) without any particle trap. The exhaust was extracted through a heated tube from the tailpipe of the car and diluted in two stages in a specially designed dilution system. The primary dilution allowed quick dilution of the exhaust, while the secondary dilution could be used to achieve desirable concentrations inside an exposure chamber. The residence time between the primary and the secondary dilution was in the order of 2 s. A two (or multiple) stage dilution system allows particle transformation processes (nucleation and condensation) to take place in a way shown to be relevant for exhaust emissions into the atmosphere (Giechaskiel et al., 2005). The dilution factor in the primary dilution was 10-15, which is typically used in laboratory measurements of engine exhaust (Ronkko et al., 2006). The total dilution ratio before the exhaust entered the chamber was 30. For standardization purposes, other types of dilution systems, such as the one described by the particulate measurement programme (PMP) are used (Giechaskiel et al., 2010). A dilution system that fulfils criteria such as the PMP, is required for legislative purposes and emission controls; but since such systems are designed to remove volatile material, they are not fully relevant for studies of human health effects.

The exposure chamber was a 22 m^3 stainless steel chamber where up to three people at a time could reside and be exposed. In total, 18 people were exposed to different

levels of diesel exhaust and traffic noise over 3 hour sessions. Comprehensive characterization of particles and gaseous components were carried out in order to characterize as many particle properties as possible that could be relevant for the exposure. Particle size distributions and number concentrations were determined by a scanning mobility particles sizer (SMPS), and particle mass was determined with a tapered element oscillating microbalance (TEOM, model 1400a, R & P Inc.) and by gravimetrical analysis of filters. The TEOM was the reference for the particle exposure. The target for one exposure day was an average mass concentration of 300 µg/m^3 measured by this instrument. The mass of individual particles (m_p) was determined through a tandem setup consisting of a differential mobility analyzer (DMA) and an aerosol particle mass analyzer (APM). The size-resolved particle mass was used to calculate the effective density ($\rho_{eff(I)}$) of the particles according to:

$$\rho_{eff(I)} = \frac{m_p}{\frac{\pi}{6} d_m^3} \qquad (4)$$

The surface area concentration of particles were estimated by using a model described by Rissler et al. (2012). The model assumes an indefinite small contact point between complete spherical primary particles and has been compared to other models by Svensson et al. (2015). A condition that must be true for the model to be valid is that m_p, as a function of d_m, can be described by a power function, as diesel exhaust particles can (Park et al., 2003). The model requires information on the m_p, primary particles size (d_{pp}, measured via TEM) and particle number size distribution measured with SMPS. The total deposited dose in the respiratory tract was calculated by:

$$Dose = TDF * C_{in} * t * Q \qquad (5)$$

were TDF is the total deposited fraction based on experimental data for diesel exhaust particle respiratory deposition (Rissler et al., 2012); thus, the effect on respiratory deposition from particle shape, density and composition was considered. C_{in} in equation 5 is the inhaled particle concentration, t is the time of exposure and Q is the inhaled volume flow.

Chemical analyses of the diesel exhaust particles were achieved by AMS measurements and filter sampling. The filters were analyzed for organic and elemental carbon content and particulate polyaromatic hydrocarbons (PAHs).

4.2.2 Hairdresser's exposure during hair bleaching (Paper II)

Twelve female hairdressers participated in the exposure study which aimed at characterizing particle emissions during hair bleaching. Each hairdresser carried out three separate bleaching sessions in a ventilated 22 m^3 stainless steel chamber. Six

of the hairdressers used a regular bleaching powder and the other six a powder labeled as dust free. Bleaching was carried out on wigs of real human hair that had been fitted to a heated manikin. Using a heated manikin made it possible to capture the effect that heat convection, induced by a person (the customer), could have on the hairdresser's exposure.

The bowl that was used to mix the bleaching powder and hydrogen peroxide was fixed on a moveable table inside the chamber. The amount of bleaching powder that the hairdressers used was pre-defined (90+45 g) and was the same for all exposure sessions. The amount of hydrogen peroxide used was determined by the hairdressers themselves and was on average 120 g. A sample inlet for an aerodynamic particle sizer (APS, model 3331, TSI Inc.) was positioned above the mixing bowl. The averaging time of the APS was 5 s. A filter cassette for 37 mm open-face filter sampling was placed next to the APS sample inlet. The sampling location above the mixing bowl was denoted as "mixing". During each bleaching session the hairdressers were fitted with a 37 mm open-face filter cassette and a pump worn in a harness. The filters were always placed at the right collarbone of the hairdressers and directed downwards with an angle of about 45° from vertical. This sampling location was denoted as "personal". A third sampling location, denoted as "background", was positioned in one of the corners of the chamber and included measurements with an APS, with a 5 s averaging time, and a 37 mm open-face filter cassette. The filters used for sampling in the mixing, personal and background locations were nitrocellulose filters (0.8 µm pore size, Millipore) and were analyzed for total persulfate mass through ion chromatography with a modified method described by Leino (1999). The open-face filter sampling flow rate in the background and in the mixing location was 10 lpm. In the personal sampling location the sampling flow rate was 7 lpm. These flow rates ensured sufficient volumetric sampling to collect enough persulfate mass for analysis.

Complementary experiments were carried out subsequent to the exposure study in which two filters were attached to a hairdresser, one on the left collarbone and one on the right. Everything else was the same as during the exposure study in order to determine if the position of the filter on the hairdresser (left or right collarbone) influenced the results.

4.2.3 ENP production facilities (Papers III & IV)

Two different types of facilities for ENP production were characterized. The first was a research facility that carries out small scale production. The ENPs produced are primarily metal nanoparticles used as seed particles for nanowire growth. The second facility was used for the production and purification of carbon nanotubes (CNTs). This facility produces CNTs on a small but commercial scale. The engineered nanoparticles that are intentionally produced and exist inside the

production lines in the two different facilities are denoted here "as-produced". The measurement strategies at the two facilities were similar and included a first screening step to evaluate the potential of the ENP emissions. The screening step was conducted by visiting the facilities and measuring particle levels with a simple device – a handheld photometer (Dusttrak, model 8520, TSI Inc.) – during the production of ENPs. Comprehensive measurements were then carried out. The methods applied during these measurements are described below.

Metal nanoparticle production facility (Paper III)

Emissions of particles during the maintenance and cleaning of a metal nanoparticle production system were characterized. The production system consisted of a spark discharge generator (SDG_P) (GFG 1000, Palas) and a heated tube furnace (HTF). The two generators were connected in parallel (see Figure 1 in Paper V for a schematic). The as-produced particles from the SDG_P and the HTF were aggregates with typical GMDs of 0.02-0.04 and 0.05-0.1 µm (d_m), respectively. The primary particle sizes were 0.005-0.015 µm (d_{pp}) independent of which generator that was used. Downstream the generators a sequence of a differential mobility analyzer (DMA), a sintering furnace and a second DMA were connected. The two separate DMAs were used to size select particles before and after sintering. During sintering, as-produced aggregates were heated to a temperature at which they start to collapse. At a high enough temperature (~500-1000 °C depending on the base material of the particles) the aggregates form near-spherical particles. As-produced particles after sintering were 0.02-0.04 µm by using the SDG_P, and 0.04-0.06 µm (d_m) by using the HTF.

The particle generator setup was installed in a ventilated cabinet (dimensions 2×1×2 m) inside a ISO 7 cleanroom laboratory (dimensions 6×3×3 m). The ventilation rate in the closed cabinet (as during production) was 227 h^{-1}. Maintenance and cleaning of the SDG_P and HTF were carried out inside the cabinet, with the cabinet doors opened and the worker positioned close to the expected emission source. Cleaning of the DMAs was carried out outside the cabinet.

An APS (model 3321, TSI Inc.) was used to measure the particle size distributions and total number concentrations of emitted particles in the size range of 0.5-20 µm (d_{ae}). The averaging time was set to 10 s and the flow rate was 1.0 lpm. A photometer (Dusttrak, model 8520, TSI Inc.) was used to estimate the total particle mass concentration (PM2.5) and a condensation particle counter (CPC) (P-Trak, model 8525, TSI Inc.) was used to determine the total number concentration of particles > 0.02 µm. The averaging time of the Dusttrak and the P-trak was 1 s for both and the flow rates were 1.6 and 0.75 lpm, respectively. The P-trak data were recalculated to 10 s averages in order to be able to compare to the APS data. Particle sampling with the above described DRIs were carried out through sampling probes held close to the expected emission zone (i.e., next to the maintenance procedure being carried out). Based on the probe lengths, flow rates and inclination angles, the penetration

efficiency through the sampling probes was expected to be more than 90% for both 0.02 (d_m) and 5 µm (d_{ae}) particles. In addition to the DRIs, filter samples were collected for subsequent analysis. Filter sampling was carried out with open-face 37 mm filter cassettes with polycarbonate filters (0.4 µm pore size, Nuclepore) with a sample flow rate of 2.9 lpm. The filters were positioned in parallel to the DRI sampling probe inlets during sampling and subsequently analyzed with SEM or SEM-EDX.

Carbon nanotube production facility (Paper IV)

Carbon nanotubes (CNTs) were produced in the facility by an arc discharge reactor. With this method other carbonaceous nanoparticles such as cones and plates can be produced as well, but production of such particles only occurred occasionally in the facility. The production took place in two separate but adjacent laboratories, denoted as the production and the sieving laboratory. Production was followed by purification of CNTs which was performed in a third laboratory. A schematic of the facility and a description of the work tasks performed during the production and purification of CNTs can be found in Paper IV.

The desired product during production was multi-walled carbon nanotubes (MWCNT). According to the operators of the facility, the produced material consisted of 55 wt% CNTs and 45 wt% other carbonaceous material. The final material after purification consisted of 80 wt% CNTs and 20 wt% other carbonaceous material. TEM analysis of the bulk material produced showed that the individual MWCNTs had a mean length of 1.7 µm (d) with a distribution ranging between 0.3 and 6.1 µm (d) (Hedmer et al., 2014). The diameters of the tubes were between 0.002 and 0.05 µm (d).

The strategy for characterizing particle emissions during production and purification of CNTs was similar to the strategy used in the metal nanoparticle production facility. Sampling probes were held close to the expected emission zone for each work task. In the emission zone, an APS with a flow rate of 1 lpm and a CPC (model 3022, TSI Inc.) with a flow rate of 0.3 lpm were used. Both instruments were set with a 5 s sampling time and the time periods for averaging were determined according to the duration of each work task monitored. 37 mm polycarbonate filters (0.4 µm pore size, Nuclepore) for SEM analyses were also used for the sampling of particles in the emission zone. These filters were fitted in filter cassettes with respirable cyclone inlets (BGI4L, BGI Inc.). The flow rate was 2.2 lpm. Size selective sampling was found to be necessary due to the high levels of incidental carbonaceous material emitted during some of the work tasks. Open-face filter sampling would overload the filters and the possibility for counting CNT-containing particles with SEM would be jeopardized. Background sampling was performed in one of the corners of each of the laboratories. In the background location, an SMPS was used with an aerosol flow rate of 1 lpm and a sheath air flow rate of 6 lpm (0.01-0.51 µm sampling interval). The SMPS consisted of a DMA (model 3071, TSI Inc.)

and a CPC (model 3010, TSI, Inc.) with a scan time of 3 min. An APS with the same sampling settings used as the one in the emission zone was also used in the background.

The average length of the as-produced MWCNTs is below the fiber criteria (length > 5 µm, > 3:1 aspect ratio) defined by WHO (WHO, 1997). But reports from some toxicological studies indicate that CNTs shorter than those fulfilling the fiber criteria can induce health effects (Mercer et al., 2011; Porter et al., 2013). As a result, and because CNTs can also be emitted as parts of larger agglomerates, a different approach than the one based on the fiber criteria was chosen for identifying and quantifying CNTs. The approach was to divide any CNTs or CNT-containing particles into three different particle types based on their size, shape and surface structure. To do this, the length and the width of the particles were measured by SEM analysis. The length was defined as the longest straight path between two points of a particle. The width was defined as the longest straight path perpendicular to the defined length. Type 1 particles were fiber-shaped particles with an aspect ratio > 3:1. Type 2 particles were lumps classified as impurities with CNTs sticking out from the lumps. Type 3 particles were particles that contained mostly impurities but with CNTs embedded in the surface structure.

Other sampling techniques were used as well during the above described emission measurements including: personal filter sampling of respirable dust for gravimetrical analysis, CNT counting and the determination of elemental carbon (EC) content. The results from these sampling techniques are not included in this thesis but can be found in Hedmer et al. (2014). Tape sampling for assessments of surface contaminations in the CNT production facility were also carried out and are presented in Hedmer et al. (2015).

4.3 Selective and in-situ characterization of ENPs (Papers III & V)

An LV-AMS (see section 4.1.1 for instrument details) was used for selective sampling of emitted particles during the maintenance of the metal nanoparticle production setup. This is the first time such an instrument has been used for occupational particle emission assessments. The LV-AMS was positioned next to the maintenance activity being carried out and it sampled from the same sampling probe as the P-trak (described in section 4.2.3). The averaging time of the LV-AMS was 10 s in MS sampling mode with 5 s open and 5 s closed chopper duty cycle. The LV-AMS measurements were compared to mass concentrations estimated by a photometer (Dusttrak, model 8520, TSI Inc.). The Dusttrak was used with a PM2.5 inlet at a flow rate of 1.6 lpm.

The LV-AMS was also used for in-situ analysis of as-produced metal nanoparticles. This was done to demonstrate the technique of aerosol mass spectrometry to a new research field: nanotechnology. The LV-AMS was connected directly to the metal particle production system described in section 4.2.3 and according to the schematic shown in Figure 1 of Paper V. Combined with the particle size selection by the DMA, several key particle properties were characterized, including time and size-resolved particle chemical composition, amounts of impurities, effective density and degree of oxidation.

5 Results and discussion

This section presents the main findings from the papers included in this thesis. First, the two chamber human exposure studies are summarized that together describe the complexity of particles and how particle characteristics can differ depending on the source from which the particles are emitted. Then, the results are presented from the emission measurements at facilities for production of engineered nanoparticles. This is followed by a discussion on how methods for particle emission and exposure assessments in such facilities should be designed. The laser vaporization aerosol mass spectrometry is introduced as a method for both occupational particle emission measurements and for in-situ analysis of engineered nanoparticles.

Comprehensive and selective methods for particle characterizations are needed in order to uncover possible mechanisms behind health effects from particle exposure, and to protect people from being exposed to hazardous levels of particles. In this thesis, the importance of characterizing particles according to their size, shape, surface structure and chemistry is emphasized.

5.1 Chamber exposure studies

5.1.1 Environments with diesel exhaust exposure (Paper I)

The characterization of both gases and particles are important in studies of human exposure to diesel exhaust. The gaseous components include a mix of hazardous species, such as CO, NO_x and PAHs, all of which should be monitored. This should be done not only to better evaluate any observed health effects, but of course, not to exceed the exposure limits that are defined in ethical approvals. This thesis presents the results from the particle characterization in Paper I. Methods for the gas phase analysis of major gaseous components (e.g., CO, CO_2, NO_x) in chamber exposure studies are often straightforward, but the characterization of particles often lacks comprehensiveness. While reading this section, always bear in mind that exposure studies including diesel exhaust particles also involve exposure to gaseous components above typical ambient levels. The levels of CO, NO and NO_2 in the exhaust characterized in this thesis are in the higher range compared to other exposure studies with similar particle mass concentrations (300 $\mu g/m^3$).

Recalculated to 8 h averages, the levels of CO and NO_2 were below the Swedish 8 h occupational exposure limits (Arbetsmiljöverket, 2011a) given for exhaust fumes. The results from the gas phase characterization, including volatile organic compounds and polyaromatic hydrocarbons, can be found in Paper I.

In the absence of a particle trap, diesel engine exhaust contains soot particles in the ultrafine and fine size fraction. It has been established that soot particles, independent of source, typically consist of several smaller primary particles that together form an aggregated or agglomerated structure (Kittelson, 1998; Burtscher, 2005). The soot particles characterized in Paper I were not an exception.

The count median diameter (CMD) of the diesel exhaust particles was 89 nm (d_m) with a mean primary particle diameter of 28 nm (d_{pp}). The diesel exhaust particle size distribution consisted of a single mode (Figure 3) with a small trace of nucleation mode particles. This is different from two other diesel exhaust exposure studies (Barath et al., 2010; Rissler et al., 2012) that reported bimodal distributions, including nucleation mode particles along with the soot accumulation mode particles. The diesel engine system and the dilution of the diesel exhaust define the particle size distribution achieved (Giechaskiel et al., 2010). In most diesel exhaust exposure studies, summarized by Hesterberg et al. (2010), mass concentration is treated as the major exposure metric and information on particle size is inadequate. This induces problems when any of the health effects observed in different studies are to be interpreted and compared, because particle size and number concentrations in different exposure studies can vary significantly.

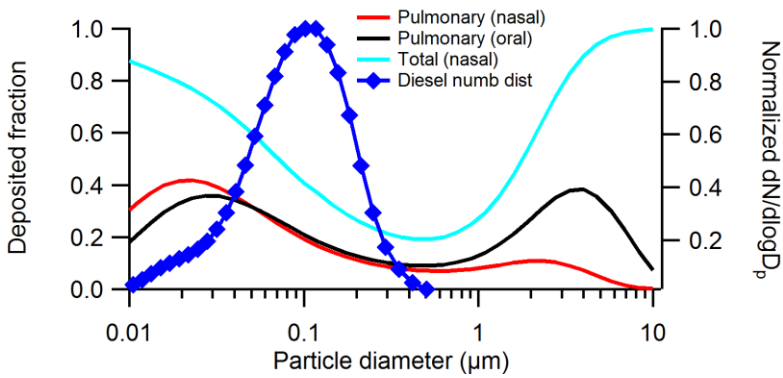

Figure 3. Average particle number size distribution (d_m) of the diesel exhaust particles characterized in Paper I. The distribution is shown together with the deposition models (MPPD) for pulmonary and total deposition with different breathing patterns (nasal or oral breathing) (see section 2.4 for details and limitations).

The average size of the soot particles characterized in Paper I was such that the pulmonary and total depositions were not the highest possible according to the present respiratory deposition models. A number size distribution shifted towards

smaller particle sizes would (theoretically) lead to a higher deposited fraction in terms of particle number, and possibly to different magnitudes of potential health effects. The presence of nucleation mode particles can significantly increase the deposited dose in terms of particle number, even if the deposited dose in terms of mass is the same (Rissler et al., 2012).

The effective densities of the diesel particles are presented in Figure 4 as a function of mobility diameter (d_m). As the aggregated particles grow larger, their shapes become more complex. This is visible as a decrease in effective density with increasing mobility diameter. In Figure 4, mass distributions estimated from SMPS measurements are also shown. By assuming unity density of all particles, the estimated mass concentration from SMPS measurements was overestimated by 261% compared to the reference method (TEOM). By accounting for the size dependent effective density, the mass concentration calculated from SMPS measurements was 276 µg/m^3 and differed only a few percent from the concentration obtained with the TEOM.

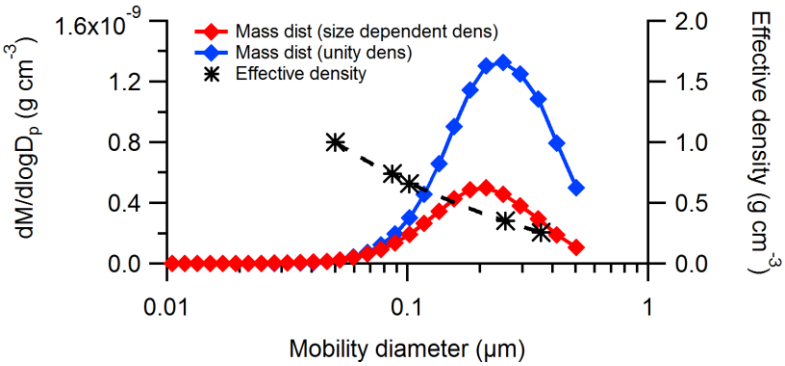

Figure 4. Size dependent effective density determind from DMA-APM and mass distributions obtained from SMPS number size distributions, with either assumed unity density or size dependent effective density (fitted power function $\rho_{eff(I)} = 15.73 \cdot d_m^{-0.69}$).

In contrary to mass concentration, surface concentration is underestimated when spherical particles are assumed instead of aggregates. The surface area of the diesel exhaust particles was determined from the mass per particle, determined with DMA-APM, and the primary particle diameter. By assuming an indefinitely small contact between primary particles, the estimated total deposited dose in terms of surface area of the aggregates was up to 37% higher compared to if spherical particles were assumed. Typically, methods for the characterization of particle surface structure and size dependent effective densities are not available in chamber exposure studies. Techniques exist, based on diffusion chargers, to determine the pulmonary and tracheobronchial deposited surface areas of spherical particles smaller than 400 nm, but the response of such instruments for aggregated and agglomerated particles needs to be further investigated (Asbach et al., 2009). Particle surface area is

considered to be important for the toxicity of inhalable particles. Thus, methods for accurate estimations of this metric will improve the ability to compare the results from different diesel exposure studies.

The chemical content of the particles is important and influences the toxicity and hygroscopicity of the particles. An aerosol particle is often considered to consist of a solid nucleus (non-volatile mass fraction) with condensed coatings or impurities (volatile mass fraction) on top. Fresh and aged (oxidized) aerosols may have different potential hazardousness since the coatings covering the solid nuclei can have different chemical compositions. The mass spectra obtained from AMS measurements showed that the diesel exhaust particles contained organic components with an O/C ratio of 0.08. This is in line with the fact that the characterized particles were directly emitted from the diesel source and that no aging (oxidation) of the aerosol had occurred. Atmospheric and aged diesel exhaust would have had a higher O/C ratio (0.2-0.8) due to more coating of oxidized organic species on the soot particles (Aiken et al., 2008). From OC/EC filter measurements, a high contribution from the elemental carbon (soot) to the total carbon (82%) showed that the total organic matter on or in the particles was about a fifth of the total particle mass.

Idling and transient driving of vehicles give rise to slightly different types of emissions. Idling frequently occurrs in cities (and in occupational environments), making this a relevant engine mode to study with regards to human health effects. The passenger car used in Paper I was not equipped with any diesel particulate filter, which today is standard in new diesel powered cars. Despite that, emissions of particulate matter from diesel powered vehicles is still an issue to consider. This is partly because older vehicles without filters will be present on the streets and used for some time to come. Secondly, heavy diesel powered vehicles (e.g., trucks, busses and tractors) are typically not equipped with any particulate filters. The particles emitted from the idling passenger car used in Paper I possessed similar characteristics as fresh soot particles found in urban environments (Rissler et al., 2014). The diesel exposure study, of which Paper I is a part, is primarily relevant for environments where exposure to fresh diesel exhaust, containing soot particles and low mass fractions of volatile material, may occur. Exposure to aged (oxidized) aerosols in the atmosphere can have different human health effects, since aging in the atmosphere can alter the particle characteristics (Wittbom et al., 2014).

5.1.2 Hairdresser salons during hair bleaching (Paper II)

The first step in a hair bleaching session is the mixing of bleaching constituents. Dust-free powder formulas are designed to minimize the emissions of particles during the mixing. The results from Paper II show that this was true for the powders used during the exposure study. No particle emissions were observed during the

mixing of the dust-free powder, making this the preferred choice for hairdressers to minimize their exposure to airborne persulfate. Figure 5a shows the average number size distribution of particles emitted during the mixing of the regular bleaching powder and hydrogen peroxide. The average diameter of the distribution is 5 µm (d_{ae}), which means that a significant fraction of the emitted particles, in terms of number concentration, can be deposited in the pulmonary region.

The key finding in Paper II was that the levels of persulfate, measured by personal sampling on the hairdressers, were higher compared to the levels measured directly above the mixing location. This was the case independent of if regular or dust-free powders were used and was in contrast to other studies that reported emissions of persulfate only during mixing (Albin et al., 2002; Berges and Kleine, 2002).

Further measurements, to confirm the above key finding, showed that particles consisting of, or containing, persulfate were emitted during application and that the emissions comprised about 20% of the total persulfate mass emitted during the entire hair bleaching sessions with regular powder. The shape of the particles can be described as ellipsoids with an average length of 23 µm (d) and a width of 15 µm (Figure 5b). The shape and average size of the particles were similar when both regular and dust-free powders were used. The definition of coarse particles covers particles with sizes smaller than 10 µm (d_{ae}). Thus, particles larger than 10 µm (d_{ae}) are in this thesis denoted as "supercoarse" particles.

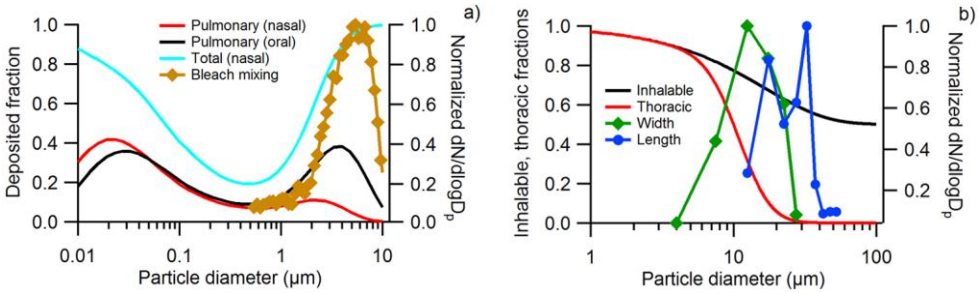

Figure 5. a) Average number size distribution (d_{ae}) of particles emitted during mixing of regular bleaching powder and hydrogen peroxide. The distribution is shown together with the deposition models (MPPD) for pulmonary and total deposition with different breathing patterns (nasal or oral breathing) (see section 2.4 for details and limitations). **b)** Number size distributions of the width and length (d) of the particles emitted during application of hair bleach. Particles with these size characteristics were emitted when both regular and dust-free powders were used. The distributions are shown together with the inhalable and thoracic fractions.

Coarse, and in this case supercoarse particles, are troublesome to sample due to their large inertia and gravitational settling. A close proximity to the emission source will enhance the ability to capture such particles. Even the side of the hairdresser that is selected for personal sampling affects the results. Paper II shows that if the left side of the hairdresser tends to be closer to the hair being bleached, the sampled level of

persulfate is higher, approximately twice as high, on the left side compared to the right.

Particles larger than 10 µm (d_{ae}) have a low probability of reaching the pulmonary region and are therefore predominantly deposited in the airways above this region after inhalation (Figure 5b). It is worth mentioning in this context that others have experimentally shown that such large particles can reach and be deposited in the pulmonary region as well, even though the possibility is very low (Svartengren et al., 1987). Emissions of supercoarse particles can be important for the total exposure, and correct methods to capture them are necessary. It is also important to remember that the equivalent diameter relevant for respiratory deposition of coarse particles is d_{ae}. The d_{ae} of the particles observed to be emitted during application can be different from d, which is the diameter determined from microscopy measurements in this thesis research. Based on the shape (near-spherical) of the emitted particles and the material density of persulfate (~2 g/cm^3), it can however be estimated that the d_{ae} of the emitted particles is close to d ($d_{ae} = d \cdot (\rho_p/\rho_0)^{1/2}$).

The discrepancy between the findings in Paper II and the studies of Albin et al. (2002) and Berges and Kleine (2002) regarding persulfate emissions during application can be due to different sampling methods. The use of respirable sampling means that coarse and supercoarse particles are not sampled. Thus, samplers for the total dust or inhalable size fraction are recommended in exposure assessments in hairdresser salons. This thesis also emphasizes the importance of close proximity sampling methods. Only 1 meter away from the emission source, the measured level of persulfate mass can be more than 10 times lower, and possibly even below the detection limit. Since the average wind speed inside the chamber was low, the motions of the hairdresser had a major impact on the release of supercoarse particles and their trajectory in the air.

In Paper II, a higher sampling flow rate than the standard flow rate for open-face filters was used. The particle deposition mechanisms that affect the sampling efficiency of large particles from still air are sedimentation (due to settling velocity) and impaction/interception (due to inertia). If the sampler is facing upwards, and if the sampler inlet velocity is low, particles not originally in the sampled streamline can settle into the sampler and an overestimation of large particles may arise (Hinds, 1999). A downward facing sampler, with low inlet velocity, can give an underestimation of large particles. This is because particles cannot travel upwards (without external forces) and need to be sucked up and into the sampler inlet. With the sampler in a horizontal position, no bias due to settling velocity exists. When using downwards facing samplers, a high flow rate is desired to avoid underestimation of large particles. On the other hand, a sampling inlet velocity that is too high leads to a decreased sampling efficiency of large particles. At higher sampling velocities, particles have a higher inertia and may to a larger extent be impacted on the sampler walls or even be "thrown away" from the sampler. By extrapolating the results of Liden et al. (2000) and Su and Vincent (2004), it can be

expected that the sampling efficiency of 20 µm (d_{ae}) particles, when sampling with 37 mm thin-walled samplers facing downwards, is similar at flow rates between 2 and 10 lpm and that the efficiency is above or close to 90%. For particle sizes larger than 20 µm (d_{ae}), the sampling efficiency with open-face filter sampling drops rapidly and other sampling methods, like IOM samplers that sample inhalable dust, should be used. With IOM samplers, more than 30% of the sampled particles may end up on the sampler itself and not on the filters (Liden et al., 2000). In the results of Paper II, open-face filter sampling was found to be optimal in order to collect as much material as possible for chemical analysis. According to the Swedish work environment standards, total dust sampling is also determined by open-face filter sampling.

This thesis does not examine whether the supercoarse particles, identified as being emitted during the application of hair bleach, contribute to why some hairdressers experience respiratory symptoms during hair bleaching. We conclude in a manuscript to be submitted to a scientific journal that similar asthma-like symptoms (dyspnea and chest tightness) were evident among the hairdresser's independent of if they used the regular or the dust-free powder. The symptoms observed were mild but significant. An increase of biomarkers (i.e., white blood cells and cytokine IL-8) were also evident in the hairdressers after exposure. The emissions that occurred during application when the two different powders were used were similar, not only considering the emissions of supercoarse particles during application, but also considering emissions of ammonium and hydrogen peroxide, which are two other airway irritants. Ammonium levels in the air, as will be presented in the prepared manuscript, were at the level of 3-5 mg/m^3 for both types of powders, which is well below the 8 h exposure limits in Sweden (14 mg/m^3). Hydrogen peroxide was not measured during the exposures. The levels of hydrogen peroxide in the air in hairdresser salons that have been reported (Geyssant et al., 2006) are far below the threshold limits used in Sweden; and other research has shown no airway effects in rabbits, despite levels far above threshold limits (Mensing et al., 1998). In the exposure study described in this thesis, the amounts of both bleaching powders and hydrogen peroxide used by the hairdressers were monitored to ensure that they were similar during all exposures. Thus, the levels of hydrogen peroxide in the air were most likely similar during all of the exposures.

Based on the findings, hairdressers that do experience symptoms during hair bleaching are advised to use simple nose and mouth protections in order to detemine if their symptoms are eased by removing their exposure to coarse and supercoarse particles. Such protections have very limited filter efficiency for ultrafine and fine particles, but can remove coarse and supercoarse particles from the inhaled air.

5.1.3 Diversity of particles

The two examples of occupational settings in Papers I and II show the diversity of aerosol particles. No universal method for particle characterization exists. In the case of the hairdresser's exposure during hair bleaching, particle, or more specifically, persulfate mass concentration can be a sufficient metric for exposure assessments. During hair bleaching, mechanical work tasks can give rise to near-spherical coarse and supercoarse particles that dominate the total particle mass. In the case of diesel exhaust particles, mass concentration may not be a sufficient metric for exposure assessments due to the fine size and aggregated surface structure of combustion generated particles. Additional information on particle chemistry and particle number or surface concentration may then be required. For accurate exposure assessments, the nature of a work task and the location where it is performed are important to consider.

5.2 Occupational exposure to ENPs

5.2.1 Emissions in ENP production facilities (Papers III & IV)

The maintenance of particle production equipment by manual work tasks means that the production needs to be shut down and the equipment opened up. Opening an enclosed systems always induces a risk for unintentional emissions and exposure to airborne particles. Even though the type of ENPs and the production processes studied in Papers III and IV were different, opening of the reactors or generators was the work task found to give rise to the highest emission levels in terms of particle number concentration. If the time elapsed from shut down to opening (time allowed for flushing) is short, the emitted particles can have characteristics that are very similar to the intentionally produced particles (as-produced) since they may still be gas borne inside the reactor. This scenario can be argued to resemble the accidental release of ENPs through leakages during production, which would result in emissions of as-produced nanoparticles with size distributions similar to the distribution shown in Figure 6 (as-produced). Such particles can have a high deposition probability in the human pulmonary region, which is one of the major reasons for concern regarding ENP exposure. Note that the release of as-produced particles during production was not observed in the measurements presented in Paper III or Paper IV. The as-produced particle size distribution in Figure 6 is shown for an illustrative purpose.

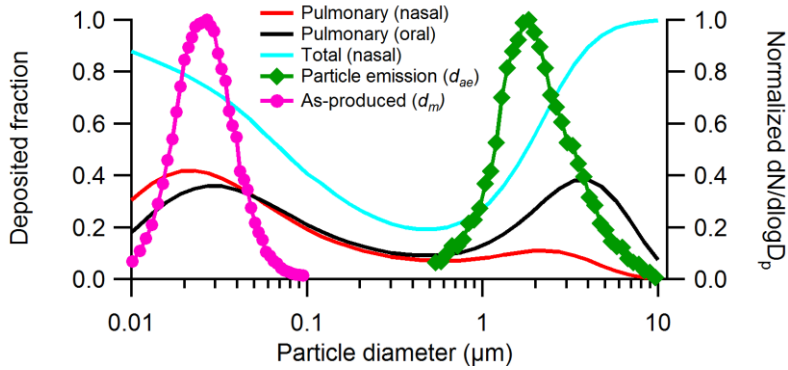

Figure 6. Average number size distributions of metal particles produced in the SDG$_P$ system (as-produced) and particles emitted during cleaning of the HTF (particle emission). The measured diameter for the as-produced particles is d_m and for the emitted particles d_{ae}. The distributions are shown together with the deposition models (MPPD) for pulmonary and total deposition with different breathing patterns (nasal or oral breathing) (see section 2.4 for details and limitations).

Metal nanoparticle production facility (Paper III)

Several short-lived events of particle emissions could be detected with the direct reading instruments (DRIs) during the maintenance of a metal nanoparticle generator setup. As previously mentioned, opening one of the generators (SDG$_P$) was found to be the work task that gave rise to the highest emission peak in terms of particle numbers. The emissions during this work task also showed a difference in particle size distribution, compared to the other emission events, because the opening of the SDG$_P$ was found to give significant emissions of particles smaller than 0.5 µm (d_{ae}). In all other emission events, the particles emitted were predominatly coarse particles between 1 and 10 µm (d_{ae}).

A typical size distribution from one of the particle emission events during maintenance of the HTF is included in Figure 6. The highest emissions during this maintenance task never reached above 130 cm^{-3} (10 s averaging time). But the size distribution coincides with the upper deposition maximum for pulmonary deposition which arguably is important to consider. Depending on the surface structure and composition of the emitted particles the deposited dose of surface or mass concentration can be significant even if the total number concentration is low.

SEM images acquired from filters, sampled during the maintenance period, are shown in Figure 7. The emitted particles were highly agglomerated with two different surface structures that consisted of individual as-produced nanoparticles. The agglomerate type in Figure 7a consists of primary particles with similar average size, 38 nm (d_{pp}), and shape as sintered as-produced particles (Figure 7c). The agglomerate type in Figure 7b has a surface structure similar to entangled as-produced particles from the SDG$_P$ (Figure 7d) with a smallest visible structure of 13 nm (d_{pp}). Emissions of similar agglomerates, consisting of as-produced particles,

have also been observed by others during the mechanical processing of nanomaterials (Peters et al., 2009; Methner et al., 2010; Zimmermann et al., 2012). But discussions are often lacking about the possibility for such large particles to induce similar effects as free nanoparticles.

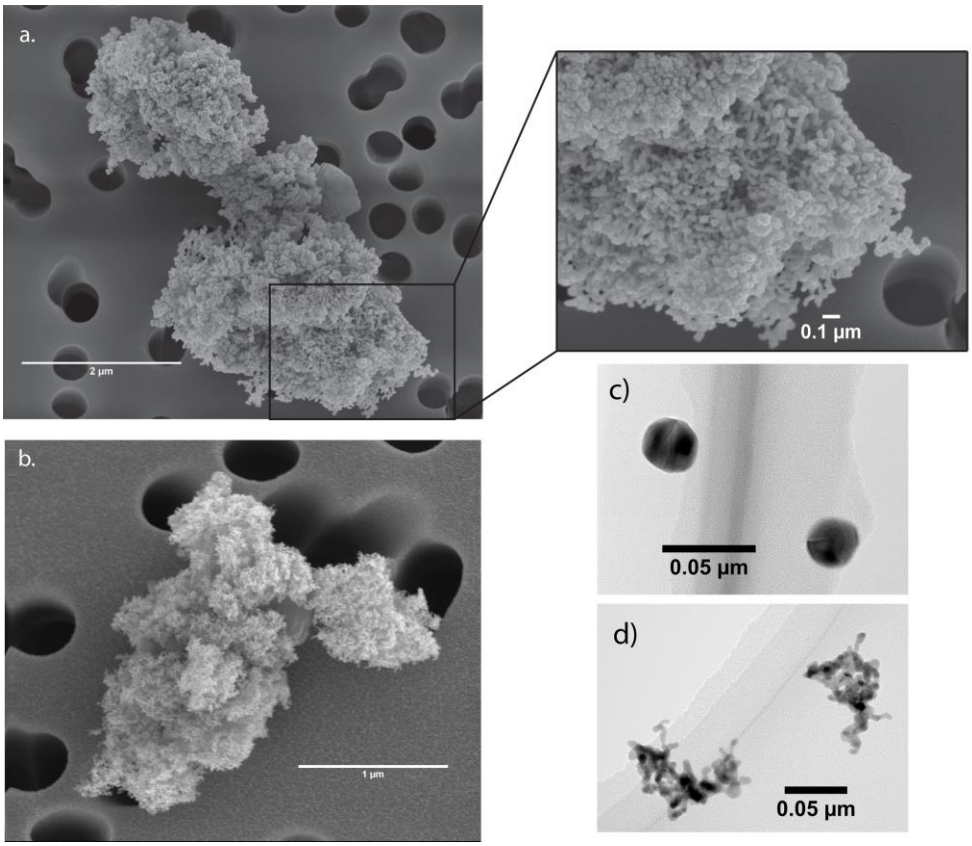

Figure 7. a-b) Typical agglomerates emitted to the air during maintenance of a metal nanoparticle production setup. **c)** As-produced Au particles produced by the SDG_P and aftertreated through sintering. **d)** As-produced Au aggregate produced by the SDG_P without sintering.

In Paper III, a spherical shape of the agglomerates were assumed in order to indicate their dominant contribution to the total particle surface area. However, an assumption of spherical particles means that the true surface area of the agglomerates, depicted in Figure 7, is underestimated. Even though they are classified as coarse, the agglomerates have surface structures that more resemble the fractal structured soot particles, characterized in Paper I, than for example the coarse particles characterized during hair bleaching in Paper II. Aggregates like soot particles are stable structures and can hardly be broken up (Seipenbusch et al., 2010). Agglomerates, on the other hand, are held together by van der Waal forces.

If these weak forces are surpassed by repulsive forces, the agglomerates may break up into smaller fragments (Jiang et al., 2009).

A 2 µm agglomerate, consisting of 10 nm (d_{pp}) primary particles can, through diffusion limited cluster aggregation (DCLA), be estimated to consist of about 30 000 primary particles (Sorensen, 2011). The structure of the agglomerates seen in Figure 7 show that they are more compact than DCLA aggregates and that 30 000 particles is therefore an underestimation. A further assumption – that the primary particles can completely, or partly, break up and act as free nanoparticles – would mean that an emission concentration of X agglomerates/cm^3 can give a true nanoparticle concentration orders of magnitude higher than X.

The possibility for deagglomeration of agglomerates, with surfaces consisting of ENPs, needs to be evaluated and should be treated as a possible fate after deposition in the respiratory tract (Methner et al., 2010; Brouwer et al., 2012; Oberdorster et al., 2015). For instance, proteins that attach to particles upon deposition in the respiratory tract play an important role in the toxicity and translocation of the particles into cells or secondary organs (Ehrenberg et al., 2009; Lundqvist et al., 2011). Gosens et al. (2010) compared single Au nanoparticles and different states of agglomeration and found no difference in pulmonary inflammation in rats. The attachment of proteins to particle surfaces can lead to the deagglomeration of some particle types (Schulze et al., 2008; Tantra et al., 2010). Balasubramanian et al. (2013) showed that Au particles deagglomerated after deposition in rats. Contrary indications show increased particle agglomeration, and reduced particle number concentration, after deposition of TiO_2 particles in lung lining fluid (Creutzenberg et al., 2012). In the above mentioned studies, however, it is not clear if the particle types studied can be considered as aggregates or agglomerates, which is crucial information that determines the binding strength within the particles. A final remark to conclude this paragraph: It is important to remember that the total number concentration of particles (agglomerates) in the air in ENP production facilities may sometimes be an inadequate metric for exposure characterization. This is because of the uncertain fates of ENP-containing agglomerates after inhalation to date.

The total particle emissions during maintenance of the metal nanoparticle production equipment in Paper III can be considered to be low. The person carrying out the maintenance was also using respiratory protection during the opening of the generators, which means that the particle exposure in this case was very low. But the risk for exposure may increase if, or when, the production is up-scaled. The results presented in Paper III should be considered in a general sense as they show that the mechanical processing of engineered nanoparticles or nanomaterials gives rise to emissions of large agglomerated particles. Such activities may induce the highest risk for unintentional human exposure to ENP-containing particles.

CNT production facility (Paper IV)

Particle emission measurements were carried out during the production and purification of carbon nanotubes (CNT). Even though the opening of the reactor was the work task with the highest average particle number concentration compared to the background (2278 cm^{-3}, for 11 min averaging), no CNT-containing particles were emitted during this work task. Instead the highest average concentration of CNT-containing particles (11 cm^{-3}, for 53 min filter sampling) occurred during the sieving and mechanical handling of as-produced material. This concentration can be compared to 0.1 fibers/cm^3, which is the current 8 h time weighted average exposure limit for asbestos fibers in Sweden (Arbetsmiljöverket, 2011a). Different criteria than those applied for asbestos fiber counting were, however, applied in Paper IV. The average number concentration, corrected for temporal background measured with a CPC during sieving and mechanical handling of as-produced material, was 45 cm^{-3} (53 min averaging). Short-lived emission peaks were evident from the DRI measurements, both from CPC and APS.

The distribution of all the CNT-containing particles that were counted for all the work tasks, according to the three different particle types defined in section 4.2.3, was 37% for type 1, 22% for type 2, and 41% for type 3. This distribution was very similar to the distribution emitted during sieving and mechanical handling, which was assessed to be a work task responsible for more than 85 % of the total emissions of CNT containing particles during a whole work shift. The average size of type 1 particles (Figure 8a) had a length and width of 1.66 and 0.26 µm (*d*), respectively, and consisted mainly of 1-15 individual CNTs stuck together in parallel. Type 2 particles (Figure 8b) had a length of 2.05 µm and a width of 1.02 µm (*d*) and contained typically 5-20 individual CNTs. Type 3 particles (Figure 8c) had a length and width of 2.61 µm and 1.69 µm (*d*), respectively, and contained 1-10 CNTs. The average sizes of all types of particles are similar to the agglomerated particles emitted during maintenance of the metal nanoparticle production equipment.

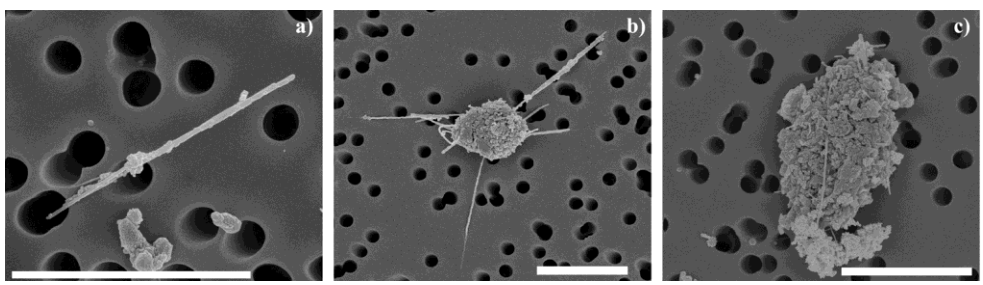

Figure 8. Different types of CNT-containing particles emitted during production and purification of CNTs. The scale bars in each image equals 3 µm (*d*). **a)** Type 1, fiber-shaped particle with an aspect ratio > 3:1. **b)** Type 2, one or more CNT fibers sticking out from a lump of solid and compact material. **c)** Type 3, lump of solid material incorporating CNTs.

Lathe machining did not involve any handling of CNT-containing material, but airborne CNT-containing particles were still identified during this work task. This can be due in part to the work task being carried out in the same room as the sieving. Particles emitted during sieving can still be airborne even though the sieving finished 30 minutes prior to lathe machining. The CNT type distribution was found to be shifted towards type 3 particles (type 1: 17, type 2: 17, type 3: 66%), which may indicate resuspension of the particles. In subsequent research (Hedmer et al., 2015), we examined this further and found coarse and supercoarse (> 10 µm) CNT-containing particles on workplace surfaces in several locations, such as adjacent offices and computer mice in the production facility.

Hedmer et al. (2014) carried out exposure measurements from the same maintenance period described in this thesis. In that study, we concluded that an exposure limit based on the mass of elemental carbon (EC), as suggested by NIOSH (2013), is not sufficient for characterizing an exposure to CNTs during arc discharge production. The total number of CNT-containing particles did not correlate to the amount of EC. Only filter sampling, followed by visual identification of CNTs with SEM, as applied in Paper IV, was found to be comprehensive enough to identify CNT exposure in environments with particle production by arc discharge.

The possibility for CNT-containing agglomerates to deagglomerate after deposition in the respiratory tract should be mentioned as a continuation of the discussion in the section covering metal nanoparticles. Mercer et al. (2013) found, for example, that heavily agglomerated particles consisting of multi-walled carbon nanotubes gave rise to the translocation of single (free) nanotubes in mice after inhalation. Because of the low presence of single nanotubes in the aerosol inhaled (by mice), it can be hypothesized that the translocated single nanotubes came from slow deagglomeration of agglomerates deposited in the lung (Oberdorster et al., 2015).

The DRIs utilized in Papers III and IV proved to be efficient methods for identifying peaks of particle emissions. But this thesis shows that the highest number concentrations detected with DRIs may not necessarily be associated with any emissions of ENP-containing particles. The highest emissions of CNT-containing particles, for instance, occurred when the total number concentration was low and close to the background concentration. High background particle concentrations can make it hard to identify emissions of particles relevant for human health.

During most of the work tasks in the production and sieving laboratory, the worker was wearing a negative-pressure half-face respirator. But the worker removed the respirator as soon as any of the work tasks were finished. This means that a significant exposure may have occurred. Finding CNT-containing particles on surfaces in the facility also strengthens the conclusion that the exposure in the facility was significant. The worker in the purification laboratory handled CNT-containing material inside a fume hood but did not wear any respiratory protection. Based on the results of the particle emission characterization presented in this thesis,

and based on the personal exposure sampling presented in Hedmer et al. (2014), the precautionary measures used in the facility were found to be inadequate.

5.2.2 Remember the small giants

The majority of the occupational emission studies summarized in Kuhlbusch et al. (2011) focused on particles smaller than 1 µm. The implementation of an upper particle size limit during emission and exposure assessments, due to practical limitations, is sometimes discussed in the ENP production and safety community (Van Broekhuizen et al., 2012). According to epidemiological studies, the particle size fraction in the urban atmosphere that appears to have the highest impact on human health is PM2.5. But in occupational environments, such as those where ENPs are handled, exposure may not predominantly occur through the emission of fine as-produced nanoparticles, but rather as nanoparticles that have grown together and formed larger agglomerates. The fate of agglomerated particles that consist of ENPs after inhalation is to date unknown (Braakhuis et al., 2014b; Hedmer et al., 2014; Oberdorster et al., 2015). That is why it is important to keep them in mind and to include them in occupational emission and exposure assessments. The emissions of coarse particles, the giants among aerosol particles, typically occur in low number concentrations and may be troublesome to identify among the high numbers of incidental background particles.

Recent efforts on an international level have led to the development of measurement strategies for ENP emission and exposure assessments (OECD, 2015). These strategies are based on tiered approaches, which are beneficial to overcome the practical and economic limitations of assessments. The nanoGEM tiered approach is an example of such a strategy and is divided into three tiers, or steps (Asbach et al., 2014). In Tier 1 the task is to clarify whether nanoparticles, or nanomaterials, are being handled at a workplace. If this is the case, and if a risk for exposure is identified, tier 2 is carried out. In this tier, easy-to-use instruments, such as handheld devices for the determination of particle number or mass concentrations are used. If the risk for exposure is confirmed as likely, a more extensive emission or exposure assessment is carried out in tier 3. This includes using a range of DRI and filter sampling methods to characterize particle emissions as comprehensivly as possible. If the assessments in tier 2 do not include measurement techniques for coarse particle sampling, or if sampling inlets are not designed to allow significant penetration of coarse particles, there is a risk for missing a relevant exposure. This is particularly the case if ENPs or nanomaterials are handled manually in non-enclosed environments.

The author of this thesis recommends that methods in screening measurements (tier 2) are not simplified too much, and that it is ensured that fine, coarse and supercoarse particles that may contain nanoparticles can also be detected. The first

visit and screening measurements (with a Dusttrak) at the CNT production facility described in Paper IV made the authors of the paper believe that no or very low emissions of CNT-containing particles were to be expected. This proved to be wrong during the more comprehensive measurements. Respirable or other size selective sampling should be avoided but can be necessary if large quantities of incidental particles are present in the sampled air. This was the case in Paper IV, where respirable sampling proved to be necessary so as not to overload the filters with incidental carbonaceous material emitted during some of the work tasks.

Emissions of coarse and supercoarse (> 10 µm) particles may not only induce a risk for human health through inhalation, but also risks through resuspension into the air, dermal exposure or ingestion. The findings in Hedmer et al. (2015) show that large CNT-containing particles can be deposited on workplace surfaces far away from the production. This further strengthens the claim that coarse and supercoarse particles should be included in ENP emission and exposure assessments.

5.3 Selective and in-situ characterization of ENPs (Papers III & V)

A laser vaporization aerosol mass spectrometer was used for the selective sampling of particles during the emission assessments of metal particles in Paper III. With this method, the emissions of particles that consisted of the chemical components used for particle production in the production system were identified (Figure 9).

As with the time series from the APS measurements (see Figure 3 in Paper III), the time series from the LV-AMS revealed short-lived particle emission peaks. The highest emissions of particles smaller than 0.5 µm occurred, as described in section 5.2.1, when the SDG_P was opened up for maintenance. The main constituents of the emitted particles during this work task could be identified as Fe, Pd, Ag and Au with the LV-AMS (Figure 9). The y-axes in Figure 9 are linear which means that only the highest emission peaks are visible. Several less intense peaks, which shared similar chemical content with the major peaks within the same period, were observed with the LV-AMS. Since the LV-AMS was operated in MS-mode with 5 s closed, it is possible that the intensity (Hz) of the peaks visible in Figure 9 are underestimated, which is important to consider for quantification purposes.

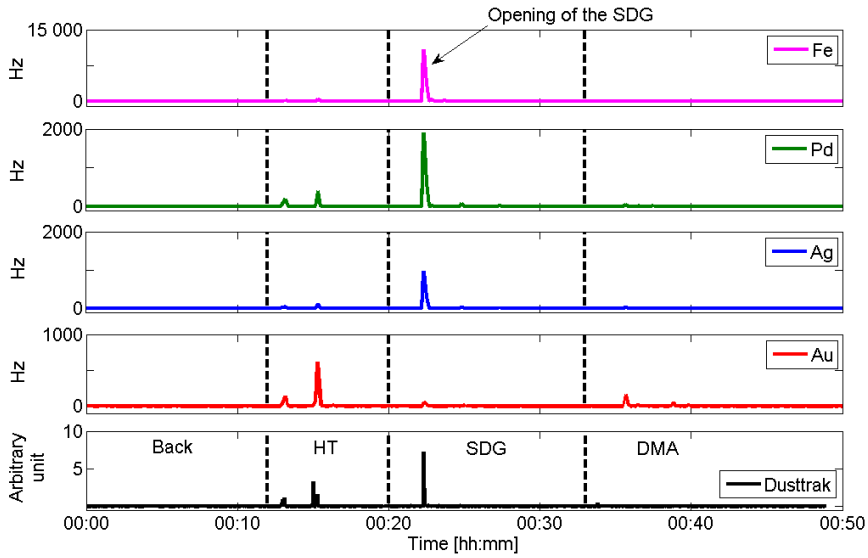

Figure 9. Time series from a photometer (Dusttrak) and the four dominating metal elements identified with the LV-AMS during maintenance of a metal nanoparticle production system. The signal strength from the LV-AMS includes all isotopes for each specific metal. The Dusttrak concentration is given as arbitrary units, but it corresponds to the total mass concentration (mg/m^3) if the response of the detected particles is assumed to be the same as the response of the calibration aerosol (Arizona test dust). The time series are divided into four sections. "Back" is background measurement with no activity; "HT" is maintenance of a high temperature furnace; "SDG_P" is maintenance of a spark discharge generator; and "DMA" is maintenance of a differential mobility analyzer.

With the LV-AMS it is possible to show that the emissions that occurred during maintenance of the high temperature furnace (HTF) were predominated by Au particles. The HTF had exclusively been used to generate Au particles, which means that the peaks identified in the APS time series could be assumed from the beginning to be Au particles. But the LV-AMS results revealed that the emissions that occurred during the maintenance of the HTF also consisted of particles containing Pd, and to a lesser extent Ag. This information would not have been possible to achieve without selective sampling.

The method of using the LV-AMS for selective sampling in emission assessments was further evaluated in Paper V. This paper introduced the LV-AMS as a technique for the in-situ analysis of ENPs and their coatings directly inside a production line. Several particle properties that are important for the quality assurance of nanoparticle production processes were characterized. These included particle size, effective density and chemical composition, which all are important characteristics for potential effects on human health as well.

An example of the benefits of in-situ and real-time selective particle sampling is shown by the results obtained when Au particles, produced from two different

methods (generators) were characterized. Even though the generators were part of the same metal particle production system, the impurities on or in the as-produced Au particles differed (Figure 10). As-produced Au particles from the HTF (Figure 10a) contained mostly aliphatic hydrocarbons, while the organics on as-produced Au particles from the SDG$_P$ were oxygenated. The ability to characterize a coating on particles is important since a particle's coating may determine how it interacts with its surrounding. In controlled particle production processes, the coating on particles may influence the efficiency of the ultimate particle performance. Particle coatings or trace elements on particles can also be important for human health since they may determine the ultimate fate of the particles once inside the body, as also briefly discussed in section 5.1.1.

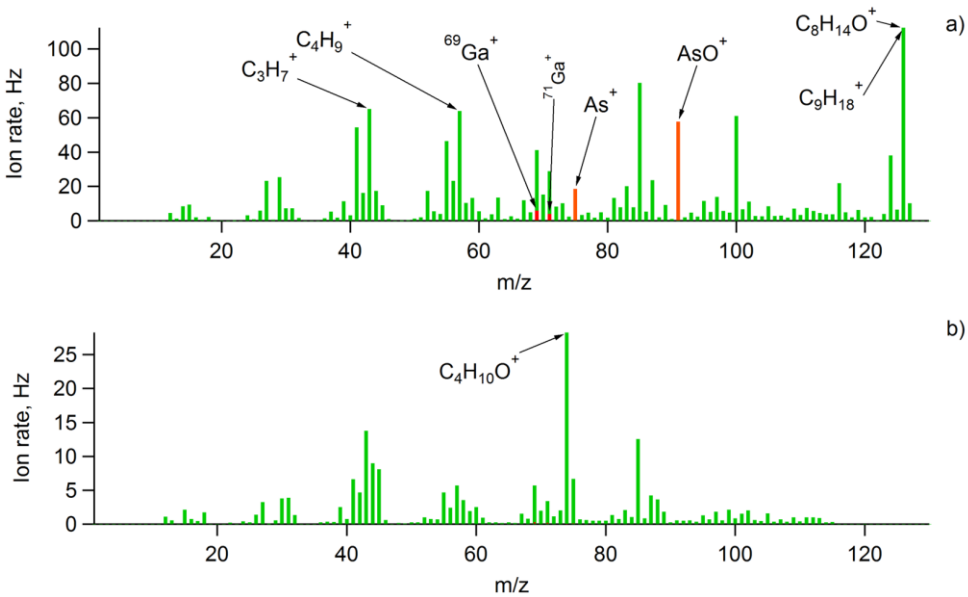

Figure 10. a) Unit resolution mass spectra of impurities present on or in 100 nm (d_m) Au aggregated particles produced with the HTF. **b)** Unit resolution mass spectra of impurties on or in 100 nm (d_m) Au aggregated particles produced with the SDG$_P$.

Prior to the maintenance period, the HTF had been used to generate Au seed particles for GaAs nanowire growth in an aerotaxy system (Heurlin et al., 2012). The mass spectra in Figure 10a show that the as-produced Au particles produced by the HTF carried impurities of Ga, As and As_xO_y. This result shows that traces of material that are supplied upstream a particle generator (Ga and As) can reach and contaminate the generator. Contaminations of upstream equipment in a nanoparticle production setup can influence the behavior of the particles since the chemical content and surface properties may be altered. Thus, real-time and in-situ analysis

of generated particles can be beneficial to keep or enhance the efficiency of a production process.

The results of Paper V show that with the SDG_P, it is possible to generate alloyed particles with a constant composition for different d_m, and that a higher sintering temperature gives a lower amount of organic impurities. On the other hand, the oxidation degree of materials prone to oxidize (e.g., Fe and Ni) increased with increased sintering temperature.

In-situ analysis of the generated particles makes it possible to optimize process parameters in order to achieve the ultimate efficiency. One suggestion is to develop instruments or methods that can be used simultaneously for both in-situ analysis of as-produced particles and for particle characterization in occupational emission and exposure assessments. Thus, the benefits for nanotechnology would be twofold: the same instruments would provide information for improvements of the operating parameters, and for the field of safe handling of nanoparticles or nanomaterials.

6 Summary and conclusions

Particles emitted in occupational environments can possess different characteristics depending on their origins. In cases when the mechanisms behind health effects from particle exposure are unknown, it is important to characterize particles with comprehensive methods. This has been shown in four different occupational settings.

It has been shown that when diesel exhaust particle surface and mass concentrations are estimated and based on number concentration measurements, considerable errors are induced if spherical particles with unity density are assumed. The estimated mass concentration was overestimated by 261 % if spherical particles with unity density were assumed, compared to if the size resolved effective density was considered. The ability to compare different diesel exhaust human exposure studies will increase significantly if methods that allow the characterization of particle size, shape, morphology, chemistry and different concentration metrics are utilized in future studies.

The use of powders labeled as dust-free, instead of regular powders, during hair bleaching was shown to be preferred in order to minimize hairdressers' exposure to airborne persulfate. But exposure to persulfate may not in fact be eliminated by using dust-free powders, since emissions of supercoarse particles (> 10 µm (d)) occurred during application to the hair, regardless of which powder was used. Sampling of such large particles is troublesome and the position for sampling is very important. Stationary sampling methods a few meters away from the hair being bleached are not sufficient in order to capture the emissions of particles during hair bleach application.

Coarse and agglomerated particles predominated the particle emissions during the maintenance of ENP production equipment and during the handling of ENP-containing materials. Such particles may, depending on their aerodynamic size, have a similar probability to that of free nanoparticles to reach and be deposited in the pulmonary region after inhalation. The conclusion is that methods for emission and exposure assessments in ENP production facilities should include techniques for sampling coarse particles, and even particles larger than 10 µm (d_{ae}). This is because the fate of agglomerated particles with nanostructured surfaces after inhalation is unknown. Toxicological studies should consider large agglomerates consisting of nanoparticles, as well as "as-produced" nanoparticles. The agglomerates can make a considerable contribution to the total particle surface concentration, for example,

especially if deagglomeration after deposition in the respiratory tract takes place. The knowledge from the emission assessments presented in Papers III and IV can be applied to similar production processes in order to predict the occurrences and characteristics of particle emissions and exposure.

Aerosol mass spectrometry has proven to be a promising method to achieve real-time selective sampling of particles relevant for emission and exposure assessments. Such a technique allows for the separation of emitted particles and background particles with different origins than the source of interest. Currently, the main drawbacks in using aerosol mass spectrometry in occupational emission assessments on a regular basis are the size and cost of the instrument. To date, aerosol mass spectrometry is only suitable for specialized or expert occupational assessments of aerosol particles. In addition, the development of new sampling inlets and aerodynamic lenses would be highly beneficial since it would allow sampling of particles larger than 1 µm.

It has been demonstrated that aerosol mass spectrometry is a useful method for real-time in-situ analysis of produced nanoparticles without having to extract the particles from the production line. This can be highly beneficial in the field of nanotechnology. Such techniques can be used for production quality assurance, for instance, to evaluate the effect of different impurities on the intended usage of the particles. Knowledge regarding the compositions and degrees of particle impurities can also have an important influence on the toxicity of inhaled particles, since particle impurity coatings are important for how particles interact with their surroundings.

This thesis highlights the fact that exposure to large particles can be important in some environments and should not be excluded in particle emission and exposure assessments. As the industry of nanoparticle production grows bigger, accurate exposure assessments become increasingly important. Accurate assessments should cover a wide range of particle sizes in order to find the nanoparticles that hide in the form of bigger particles.

7 Outlook

An arguably important factor to consider in occupational risk assessments is the possibility for agglomerated ENP-containing particles to deagglomerate once deposited in the respiratory tract. Research focused on this topic should examine different degrees of agglomeration, with a clear differentiation between agglomerates and aggregates. Research on possibilities for deagglomeration should also study the effects of using different serums or proteins that are relevant for the human body.

The emission of particles containing persulfate during the application of hair bleach should be studied further. Hairdressers who are known to develop respiratory symptoms during or after hair bleaching could participate in a series of studies in which they test different types of respiratory protection. This would help determine whether the elimination of exposure to coarse or supercoarse particles can eliminate or reduce the respiratory symptoms they experience. Different types of extraction systems, such as point extraction should also be evaluated in terms of lowering hairdressers' exposure to particles.

The physical and chemical properties of diesel exhaust covered in this thesis should be characterized in future exhaust exposure studies. The increased availability of such information can be used by aerosol and medical experts to improve their ability to compare the human health effects observed in different studies.

A few challenges exist in order to be able to use aerosol mass spectrometry on a regular basis for occupational particle emission characterization. AMS instrument types need to be smaller in size and less expensive. The rapid development of 3D printing may help to achieve this, since it can reduce the cost of machined parts that are currently expensive to produce. This applies particularly to parts which are hard to machine, such as aerodynamic lenses for coarse particle sampling. These lenses are also preferable for sampling carbon nanotubes and nanowires. In-situ characterization of nanotubes or wires can provide new knowledge on the growth mechanisms of these particles, which in turn may improve the manufacturing of solar cells, for example. Work to increase the understanding of the limitations of particle quantification with the LV-AMS is also needed.

Acknowledgements

I am very grateful to my main supervisor, Anders Gudmundsson, who has the formidable quality of showing you how to look at things in a simple way and not to complicate things. I have always felt welcome when I have had questions to ask.

Anders Gudmundsson and my co-supervisors Joakim Pagels and Aneta Wierzbicka: As you may remember it was not obvious for me that I would start working on a Ph.D. Thanks for keeping me around and convincing me that a Ph.D. position was the right choice to make. Joakim, thanks for introducing me to the field of aerosol science and for all the guidance you have given me. Aneta, thanks for fruitful discussions. You know what needs to be done and your comments have always improved my work.

Christian Svensson, you are a man full of ideas. You are one of the most noble people I have ever met; you always think about others. It has always been a privilege sharing an office with you. Bad boys for life!

Erik Nordin and Axel Eriksson, we have worked together in many projects and it has always been inspiring. I have always felt that we together make up a good team. Axel, as you wrote yourself in your thesis: We have put a lot of things into that AMS! Much of what I know about AMS data analysis is something that I originally learned from you.

Mehri Sanati, thanks for hiring me in your different gasification projects. Without your efforts I may have missed the opportunity of becoming a Ph.D. student.

Maria Messing, thanks for helping with electron microscopy analysis and for good and constructive comments on some of the papers included in my thesis. And of course, thanks for the time spent on the squash/badminton court and the following discussions, which nowadays has been transformed to eating burgers and pizzas.

Linus Ludvigsson, thanks for good company during field measurements and for great SEM and TEM analysis of filter samples. I will never forget that you manually counted more than 10 000 particles. Efforts like that are invaluable. The front cover on my thesis is based on a SEM image acquired by you; for that I am grateful.

Emilie Hermansson, an important part of doing science is “fikapaus”. We have not done any research together put we have “fikat” together. “Science gets a lot better with fika”. Hey, I should have put that in the conclusions!

Related to “fika”, Jessika Sellergren, thanks for introducing me to a new world, the world of coffee. Coffee on the balcony. Ahh, glorious. And thanks for helping me with the cover of my thesis. And for the pink wagon which unfortunately did not become a part of my thesis.

Erik Ahlberg, Moa Sporre and Cerina Wittbom – Thanks for all the funny conversations. You should “fika” a bit more than you do! Cerina, thanks for including me in one of your papers. You are not included in any of mine but that does not mean that you haven’t contributed to making me a better Ph.D. student.

Emilie Stroh, thanks for making people laugh, including me, like no one else. And for putting together excellent network meetings, even though you somehow can picture me as “The Phantom Blot”. I have cited one of your papers in my thesis. Can you find where? A true meerkat should be able to spot everything.

Karin Öhrvik, thanks for all the help with economy and shipment questions. Eileen Deaner, thanks for proofreading my thesis.

To all my colleagues in aerosol science at EAT including Jenny Rissler, Christina Isaxon, Mats Bohgard, Jonas Jakobsson and Jakob Lönndahl: All of you contribute to making EAT an excellent workplace. The aerosol scientists at Nuclear Physics are of course also acknowledged: Göran Frank, Johan Martinsson, Johan Friberg, Pontus Roldin, Erik Swietlicki, Birgitta Sveningsson and Adam Kristensson. To all the new Ph.D. students at EAT and Nuclear Physics – Ville, Christina, Malin, Karin and Stina – you have made the right choice and have many fun years ahead of you.

Often during my time as a Ph.D. student I have cooperated with people from AMM. To Håkan Tinnerberg, Maria Hedmer, Jörn Nielsen, Maria Albin, Monica Kåredal and all the nurses working in the emission and exposure studies included in this thesis: Thank you for your good cooperation and for providing useful comments.

A month of my time as a Ph.D. student I spent in the Boston area and at Aerodyne Inc. Tim Onasch and Ed Fortner, thanks for making that opportunity come true and for all the things you taught me about aerosol mass spectrometry.

And of course finally, thanks to my family and all my other friends not mentioned above.

References

Abbott, L. C. and Maynard, A. D., Exposure Assessment Approaches for Engineered Nanomaterials, *Risk Anal*, **2010**, 30(11), 1634-1644.

ACGIH (1997). Threshold Limit and Values and Biological Exposure Indices. Cincinnati, USA, American Conference of Governmental Industrial Hygienists.

Aiken, A. C.; Decarlo, P. F.; Kroll, J. H.; Worsnop, D. R.; Huffman, J. A.; Docherty, K. S.; Ulbrich, I. M.; Mohr, C.; Kimmel, J. R.; Sueper, D., et al., O/C and OM/OC ratios of primary, secondary, and ambient organic aerosols with high-resolution time-of-flight aerosol mass spectrometry, *Environ Sci Technol*, **2008**, 42(12), 4478-4485.

Albin, M.; Rylander, L.; Mikoczy, Z.; Lillienberg, L.; Hoglund, A. D.; Brisman, J.; Toren, K.; Meding, B.; Diab, K. K. and Nielsen, J., Incidence of asthma in female Swedish hairdressers, *Occup Environ Med*, **2002**, 59(2), 119-123.

Allen, J. O.; Fergenson, D. P.; Gard, E. E.; Hughes, L. S.; Morrical, B. D.; Kleeman, M. J.; Gross, D. S.; Galli, M. E.; Prather, K. A. and Cass, G. R., Particle detection efficiencies of aerosol time of flight mass spectrometers under ambient sampling conditions, *Environ Sci Technol*, **2000**, 34(1), 211-217.

Arbetsmiljöverket (2011a). Arbetsmiljöverkets föreskrifter och allmänna råd om hygieniska gränsvärden. Stockholm, Sweden, Arbetsmiljöverket. AFS 2011:18.

Arbetsmiljöverket (2011b). Frisörer och nagelbyggare - en regional tillsynsinsats genomförd av Arbetsmiljöverket i södra Sverige 2011. Rapport No 2012:6.

Asbach, C.; Fissan, H.; Stahlmecke, B.; Kuhlbusch, T. A. J. and Pui, D. Y. H., Conceptual limitations and extensions of lung-deposited Nanoparticle Surface Area Monitor (NSAM), *J Nanopart Res*, **2009**, 11(1), 101-109.

Asbach, C.; Kuhlbusch, T. A. J.; Stahlmecke, B.; Kaminski, H.; Kiesling, H. J.; Voetz, M.; Dahmann, D.; Götz, U.; Dziurowitz, N. and Plitzko, S. (2014). Chapter 11. Measurement and Monitoring Strategy for Assessing Workplace Exposure to Airborne Nanomaterials. Safety of Nanomaterials along Their Lifecycle, CRC Press.

ASTM International (2012). Standard Guide for Measurement of Particle Size Distribution of Nanomaterials in Suspension by Nanoparticle Tracking Analysis (NTA). ASTM E2834-12. West Conshohocken.

Balasubramanian, S. K.; Poh, K. W.; Ong, C. N.; Kreyling, W. G.; Ong, W. Y. and Yu, L. E., The effect of primary particle size on biodistribution of inhaled gold nano-agglomerates, *Biomaterials*, **2013**, 34(22), 5439-5452.

Barath, S.; Mills, N. L.; Lundback, M.; Tornqvist, H.; Lucking, A. J.; Langrish, J. P.; Soderberg, S.; Boman, C.; Westerholm, R.; Londahl, J., et al., Impaired vascular function after exposure to diesel exhaust generated at urban transient running conditions, *Part Fibre Toxicol*, **2010**, 7.

Bekker, C.; Brouwer, D. H.; van Duuren-Stuurman, B.; Tuinman, I. L.; Tromp, P. and Fransman, W., Airborne manufactured nano-objects released from commercially

available spray products: temporal and spatial influences, *J Expo Sci Env Epid*, **2014**, 24(1), 74-81.

Bello, D.; Wardle, B. L.; Yamamoto, N.; deVilloria, R. G.; Garcia, E. J.; Hart, A. J.; Ahn, K.; Ellenbecker, M. J. and Hallock, M., Exposure to nanoscale particles and fibers during machining of hybrid advanced composites containing carbon nanotubes, *J Nanopart Res*, **2009**, 11(1), 231-249.

Berges, M. and Kleine, H., Hazardous substances in the air at hairdressers' workplaces, *Gefahrst Reinhalt L*, **2002**, 62(10), 405-409.

Braakhuis, H. M.; Gosens, I.; Krystek, P.; Boere, J. A. F.; Cassee, F. R.; Fokkens, P. H. B.; Post, J. A.; van Loveren, H. and Park, M. V. D. Z., Particle size dependent deposition and pulmonary inflammation after short-term inhalation of silver nanoparticles, *Part Fibre Toxicol*, **2014a**, 11.

Braakhuis, H. M.; Park, M. V. D. Z.; Gosens, I.; De Jong, W. H. and Cassee, F. R., Physicochemical characteristics of nanomaterials that affect pulmonary inflammation, *Part Fibre Toxicol*, **2014b**, 11.

Bradshaw, L.; Harris-Roberts, J.; Bowen, J.; Rahman, S. and Fishwick, D., Self-reported work-related symptoms in hairdressers, *Occup Med-Oxford*, **2011**, 61(5), 328-334.

Brasche, S. and Bischof, W., Daily time spent indoors in German homes - Baseline data for the assessment of indoor exposure of German occupants, *Int J Hyg Envir Heal*, **2005**, 208(4), 247-253.

Brouwer, D.; Berges, M.; Virji, M. A.; Fransman, W.; Bello, D.; Hodson, L.; Gabriel, S. and Tielemans, E., Harmonization of Measurement Strategies for Exposure to Manufactured Nano-Objects; Report of a Workshop, *Ann Occup Hyg*, **2012**, 56(1), 1-9.

Brouwer, D. H.; van Duuren-Stuurman, B.; Berges, M.; Bard, D.; Jankowska, E.; Moehlmann, C.; Pelzer, J. and Mark, D., Workplace air measurements and likelihood of exposure to manufactured nano-objects, agglomerates, and aggregates, *J Nanopart Res*, **2013**, 15(11).

Brown, J. S.; Gordon, T.; Price, O. and Asgharian, B., Thoracic and respirable particle definitions for human health risk assessment, *Part Fibre Toxicol*, **2013**, 10.

Burtscher, H., Physical characterization of particulate emissions from diesel engines: a review, *J Aerosol Sci*, **2005**, 36(7), 896-932.

Canagaratna, M. R.; Jayne, J. T.; Jimenez, J. L.; Allan, J. D.; Alfarra, M. R.; Zhang, Q.; Onasch, T. B.; Drewnick, F.; Coe, H.; Middlebrook, A., et al., Chemical and microphysical characterization of ambient aerosols with the aerodyne aerosol mass spectrometer, *Mass Spectrom Rev*, **2007**, 26(2), 185-222.

Chen, H.; Katz, P. P.; Eisner, M. D.; Yelin, E. H. and Blanc, P. D., Health-related quality of life in adult rhinitis: The role of perceived control of disease, *J Allergy Clin Immun*, **2004**, 114(4), 845-850.

Cho, W. S.; Duffin, R.; Howie, S. E. M.; Scotton, C. J.; Wallace, W. A. H.; MacNee, W.; Bradley, M.; Megson, I. L. and Donaldson, K., Progressive severe lung injury by zinc oxide nanoparticles; the role of Zn2+ dissolution inside lysosomes, *Part Fibre Toxicol*, **2011**, 8.

Creutzenberg, O.; Bellmann, B.; Korolewitz, R.; Koch, W.; Mangelsdorf, I.; Tillmann, T. and Schaudien, D., Change in agglomeration status and toxicokinetic fate of various nanoparticles in vivo following lung exposure in rats, *Inhal Toxicol*, **2012**, 24(12), 821-830.

DeCarlo, P. F.; Kimmel, J. R.; Trimborn, A.; Northway, M. J.; Jayne, J. T.; Aiken, A. C.; Gonin, M.; Fuhrer, K.; Horvath, T.; Docherty, K. S., et al., Field-deployable, high-resolution, time-of-flight aerosol mass spectrometer, *Anal Chem*, **2006**, 78(24), 8281-8289.

Demou, E.; Stark, W. J. and Hellweg, S., Particle Emission and Exposure during Nanoparticle Synthesis in Research Laboratories, *Ann Occup Hyg*, **2009**, 53(8), 829-838.

Diab, K. K.; Jonsson, B. A. G.; Axmon, A. and Nielsen, J., Work-related airway symptoms, nasal reactivity and health-related quality of life in female hairdressers: a follow-up study during exposure, *Int Arch Occ Env Hea*, **2014**, 87(1), 61-71.

Diab, K. K.; Truedsson, L.; Albin, M. and Nielsen, J., Persulphate challenge in female hairdressers with nasal hyperreactivity suggests immune cell, but no IgE reaction, *Int Arch Occ Env Hea*, **2009**, 82(6), 771-777.

Dockery, D. W.; Pope, C. A.; Xu, X. P.; Spengler, J. D.; Ware, J. H.; Fay, M. E.; Ferris, B. G. and Speizer, F. E., An Association between Air-Pollution and Mortality in 6 United-States Cities, *New Engl J Med*, **1993**, 329(24), 1753-1759.

Donaldson, K.; Murphy, F.; Schinwald, A.; Duffin, R. and Poland, C. A., Identifying the pulmonary hazard of high aspect ratio nanoparticles to enable their safety-by-design, *Nanomedicine-Uk*, **2011**, 6(1), 143-156.

Drewnick, F.; Hings, S. S.; DeCarlo, P.; Jayne, J. T.; Gonin, M.; Fuhrer, K.; Weimer, S.; Jimenez, J. L.; Demerjian, K. L.; Borrmann, S., et al., A new time-of-flight aerosol mass spectrometer (TOF-AMS) - Instrument description and first field deployment, *Aerosol Sci Tech*, **2005**, 39(7), 637-658.

Ehrenberg, M. S.; Friedman, A. E.; Finkelstein, J. N.; Oberdorster, G. and McGrath, J. L., The influence of protein adsorption on nanoparticle association with cultured endothelial cells, *Biomaterials*, **2009**, 30(4), 603-610.

Geyssant, E. M.; Mouchot, L.; Paris, C. and Zmirou-Navier, D., Exposure of hairdressing and bakery apprentices to airborne hazardous substances and flour dust, *Epidemiology*, **2006**, 17(6), S530-S530.

Giechaskiel, B.; Alfoldy, B. and Drossinos, Y., A metric for health effects studies of diesel exhaust particles, *J Aerosol Sci*, **2009**, 40(8), 639-651.

Giechaskiel, B.; Chirico, R.; DeCarlo, P. F.; Clairotte, M.; Adam, T.; Martini, G.; Heringa, M. F.; Richter, R.; Prevot, A. S. H.; Baltensperger, U., et al., Evaluation of the particle measurement programme (PMP) protocol to remove the vehicles' exhaust aerosol volatile phase, *Sci Total Environ*, **2010**, 408(21), 5106-5116.

Giechaskiel, B.; Ntziachristos, L.; Samaras, Z.; Scheer, V.; Casati, R. and Vogt, R., Formation potential of vehicle exhaust nucleation mode particles on-road and in the laboratory, *Atmos Environ*, **2005**, 39(18), 3191-3198.

Gomez, V.; Levin, M.; Saber, A. T.; Irusta, S.; Dal Maso, M.; Hanoi, R.; Santamaria, J.; Jensen, K. A.; Wallin, H. and Koponen, I. K., Comparison of Dust Release from Epoxy and Paint Nanocomposites and Conventional Products during Sanding and Sawing, *Ann Occup Hyg*, **2014**, 58(8), 983-994.

Gosens, I.; Post, J. A.; de la Fonteyne, L. J. J.; Jansen, E. H. J. M.; Geus, J. W.; Cassee, F. R. and de Jong, W. H., Impact of agglomeration state of nano- and submicron sized gold particles on pulmonary inflammation, *Part Fibre Toxicol*, **2010**, 7.

Hallquist, M.; Wenger, J. C.; Baltensperger, U.; Rudich, Y.; Simpson, D.; Claeys, M.; Dommen, J.; Donahue, N. M.; George, C.; Goldstein, A. H., et al., The formation,

properties and impact of secondary organic aerosol: current and emerging issues, *Atmos Chem Phys*, **2009**, 9(14), 5155-5236.
Hansen, S. F.; Maynard, A.; Baun, A. and Tickner, J. A., Late lessons from early warnings for nanotechnology, *Nat Nanotechnol*, **2008**, 3(8), 444-447.
Harling, M.; Schablon, A.; Schedlbauer, G.; Dulon, M. and Nienhaus, A., Bladder cancer among hairdressers: a meta-analysis, *Occup Environ Med*, **2010**, 67(5), 351-358.
Hashemi, N.; Boskabady, M. H. and Nazari, A., Occupational Exposures and Obstructive Lung Disease: A Case-Control Study in Hairdressers, *Resp Care*, **2010**, 55(7), 895-900.
Hedmer, M.; Isaxon, C.; Nilsson, P. T.; Ludvigsson, L.; Messing, M. E.; Genberg, J.; Skaug, V.; Bohgard, M.; Tinnerberg, H. and Pagels, J. H., Exposure and Emission Measurements During Production, Purification, and Functionalization of Arc-Discharge-Produced Multi-walled Carbon Nanotubes, *Ann Occup Hyg*, **2014**, 58(3), 355-379.
Hedmer, M.; Ludvigsson, L.; Isaxon, C.; Nilsson, P. T.; Skaug, V.; Bohgard, M.; Pagels, J. H.; Messing, M. E. and Tinnerberg, H., Detection of Multi-walled Carbon Nanotubes and Carbon Nanodiscs on Workplace Surfaces at a Small-Scale Producer, *Ann Occup Hyg*, **2015**, 59(7), 836-852.
Hesterberg, T. W.; Long, C. M.; Lapin, C. A.; Hamade, A. K. and Valberg, P. A., Diesel exhaust particulate (DEP) and nanoparticle exposures: What do DEP human clinical studies tell us about potential human health hazards of nanoparticles?, *Inhal Toxicol*, **2010**, 22(8), 679-694.
Heurlin, M.; Magnusson, M. H.; Lindgren, D.; Ek, M.; Wallenberg, L. R.; Deppert, K. and Samuelson, L., Continuous gas-phase synthesis of nanowires with tunable properties, *Nature*, **2012**, 492(7427), 90-95.
Heyder, J.; Gebhart, J.; Stahlhofen, W. and Stuck, B., Biological Variability of Particle Deposition in the Human Respiratory-Tract during Controlled and Spontaneous Mouth-Breathing, *Ann Occup Hyg*, **1982**, 26(1-4), 137-147.
Hinds, W. C. (**1999**). Aerosol Technology: Properties, Behavior and Measurements of Airborne Particles. USA, John Wiley & Sons.
Hoek, G.; Brunekreef, B.; Goldbohm, S.; Fischer, P. and van den Brandt, P. A., Association between mortality and indicators of traffic-related air pollution in the Netherlands: a cohort study, *Lancet*, **2002**, 360(9341), 1203-1209.
Hollund, L. E.; Moen, B. E.; Egeland, G. M. and Florvaag, E., Prevalence of airway symptoms and total serum immunoglobulin E among hairdressers in Bergen: A four-year prospective study, *J Occup Environ Med*, **2003**, 45(11), 1201-1206.
Hsieh, S. F.; Bello, D.; Schmidt, D. F.; Pal, A. K. and Rogers, E. J., Biological oxidative damage by carbon nanotubes: Fingerprint or footprint?, *Nanotoxicology*, **2012**, 6(1), 61-76.
Hussein, T.; Glytsos, T.; Ondracek, J.; Dohanyosova, P.; Zdimal, V.; Hameri, K.; Lazaridis, M.; Smolik, J. and Kulmala, M., Particle size characterization and emission rates during indoor activities in a house, *Atmos Environ*, **2006**, 40(23), 4285-4307.
IARC (2012). Diesel Engine Exhaust Carcinogen. Lyon, France, International Agency for Research on Cancer. Press release No. 213.
IPCC (2013). Climate Change 2013: The Physical Science Basis.

Isaxon, C.; Gudmundsson, A.; Nordin, E. Z.; Lonnblad, L.; Dahl, A.; Wieslander, G.; Bohgard, M. and Wierzbicka, A., Contribution of indoor-generated particles to residential exposure, *Atmos Environ*, **2015**, 106, 458-466.

Jayne, J. T.; Leard, D. C.; Zhang, X. F.; Davidovits, P.; Smith, K. A.; Kolb, C. E. and Worsnop, D. R., Development of an aerosol mass spectrometer for size and composition analysis of submicron particles, *Aerosol Sci Tech*, **2000**, 33(1-2), 49-70.

Jiang, J. K.; Oberdorster, G. and Biswas, P., Characterization of size, surface charge, and agglomeration state of nanoparticle dispersions for toxicological studies, *J Nanopart Res*, **2009**, 11(1), 77-89.

Jimenez, J. L.; Jayne, J. T.; Shi, Q.; Kolb, C. E.; Worsnop, D. R.; Yourshaw, I.; Seinfeld, J. H.; Flagan, R. C.; Zhang, X. F.; Smith, K. A., et al., Ambient aerosol sampling using the Aerodyne Aerosol Mass Spectrometer, *J Geophys Res-Atmos*, **2003**, 108(D7).

Kennedy, N. J. and Hinds, W. C., Inhalability of large solid particles, *J Aerosol Sci*, **2002**, 33(2), 237-255.

Kittelson, D. B., Engines and nanoparticles: A review, *J Aerosol Sci*, **1998**, 29(5-6), 575-588.

Knoeller, G. E.; Mazurek, J. M. and Moorman, J. E., Health-related quality of life among adults with work-related asthma in the United States, *Qual Life Res*, **2013**, 22(4), 771-780.

Koivisto, A. J.; Aromaa, M.; Makela, J. M.; Pasanen, P.; Hussein, T. and Hameri, K., Concept To Estimate Regional Inhalation Dose of Industrially Synthesized Nanoparticles, *Acs Nano*, **2012**, 6(2), 1195-1203.

Kuhlbusch, T. A. J.; Asbach, C.; Fissan, H.; Gohler, D. and Stintz, M., Nanoparticle exposure at nanotechnology workplaces: A review, *Part Fibre Toxicol*, **2011**, 8.

Kulkarni, P. P.; Baron, P. A. and Willeke, K. (**2011**). Aerosol measurement: principles, techniques and applications. Hoboken, New Jersey, John Wiley & Sons.

Lee, J.; Mahendra, S. and Alvarez, P. J. J., Nanomaterials in the Construction Industry: A Review of Their Applications and Environmental Health and Safety Considerations, *Acs Nano*, **2010**, 4(7), 3580-3590.

Leech, J. A.; Nelson, W. C.; Burnett, R. T.; Aaron, S. and Raizenne, M. E., It's about time: A comparison of Canadian and American time-activity patterns, *J Expo Anal Env Epid*, **2002**, 12(6), 427-432.

Leino, T., Working Conditions and Health in Hairdressing Salons, *Applied Occupational and Environmental Hygiene*, **1999**, 14, 26-33.

Leino, T.; Tammilehto, L.; Hytonen, M.; Sala, E.; Paakkulainen, H. and Kanerva, L., Occupational skin and respiratory diseases among hairdressers, *Scand J Work Env Hea*, **1998**, 24(5), 398-406.

Liden, G.; Melin, B.; Lidbom, A.; Lindberg, K. and Noren, J., Personal Sampling in Parallel with Open-Face Filter Cassettes and IOM Samplers for Inhalable Dust—Implications for Occupational Exposure Limits, *Applied Occupational and Environmental Hygiene*, **2000**, 15(3), 263-276.

Londahl, J.; Massling, A.; Pagels, J.; Swietlicki, E.; Vaclavik, E. and Loft, S., Size-resolved respiratory-tract deposition of fine and ultrafine hydrophobic and hygroscopic aerosol particles during rest and exercise, *Inhal Toxicol*, **2007**, 19(2), 109-116.

Londahl, J.; Moller, W.; Pagels, J. H.; Kreyling, W. G.; Swietlicki, E. and Schmid, O., Measurement Techniques for Respiratory Tract Deposition of Airborne Nanoparticles: A Critical Review, *J Aerosol Med Pulm D*, **2014**, 27(4), 229-254.

Lundqvist, M.; Stigler, J.; Cedervall, T.; Berggard, T.; Flanagan, M. B.; Lynch, I.; Elia, G. and Dawson, K., The Evolution of the Protein Corona around Nanoparticles: A Test Study, *Acs Nano*, **2011**, 5(9), 7503-7509.

Matthew, B. M.; Middlebrook, A. M. and Onasch, T. B., Collection efficiencies in an Aerodyne Aerosol Mass Spectrometer as a function of particle phase for laboratory generated aerosols, *Aerosol Sci Tech*, **2008**, 42(11), 884-898.

McMurry, P. H., A review of atmospheric aerosol measurements, *Atmos Environ*, **2000**, 34(12-14), 1959-1999.

Mensing, T.; Marek, W.; Raulf-Heimsoth, M. and Baur, X., Acute exposure to hair bleach causes airway hyperresponsiveness in a rabbit model, *Eur Respir J*, **1998**, 12(6), 1371-1374.

Mercer, R. R.; Hubbs, A. F.; Scabilloni, J. F.; Wang, L. Y.; Battelli, L. A.; Friend, S.; Castranova, V. and Porter, D. W., Pulmonary fibrotic response to aspiration of multi-walled carbon nanotubes, *Part Fibre Toxicol*, **2011**, 8.

Mercer, R. R.; Scabilloni, J. F.; Hubbs, A. F.; Wang, L. Y.; Battelli, L. A.; McKinney, W.; Castranova, V. and Porter, D. W., Extrapulmonary transport of MWCNT following inhalation exposure, *Part Fibre Toxicol*, **2013**, 10.

Methner, M.; Hodson, L.; Dames, A. and Geraci, C., Nanoparticle Emission Assessment Technique (NEAT) for the Identification and Measurement of Potential Inhalation Exposure to Engineered Nanomaterials-Part B: Results from 12 Field Studies, *J Occup Environ Hyg*, **2010**, 7(3), 163-176.

Middlebrook, A. M.; Bahreini, R.; Jimenez, J. L. and Canagaratna, M. R., Evaluation of Composition-Dependent Collection Efficiencies for the Aerodyne Aerosol Mass Spectrometer using Field Data, *Aerosol Sci Tech*, **2012**, 46(3), 258-271.

Morawska, L.; Afshari, A.; Bae, G. N.; Buonanno, G.; Chao, C. Y. H.; Hanninen, O.; Hofmann, W.; Isaxon, C.; Jayaratne, E. R.; Pasanen, P., et al., Indoor aerosols: from personal exposure to risk assessment, *Indoor Air*, **2013**, 23(6), 462-487.

Nash, D. G.; Baer, T. and Johnston, M. V., Aerosol mass spectrometry: An introductory review, *Int J Mass Spectrom*, **2006**, 258(1-3), 2-12.

Nazaroff, W. W., Indoor particle dynamics, *Indoor Air*, **2004**, 14, 175-183.

Nel, A. E.; Madler, L.; Velegol, D.; Xia, T.; Hoek, E. M. V.; Somasundaran, P.; Klaessig, F.; Castranova, V. and Thompson, M., Understanding biophysicochemical interactions at the nano-bio interface, *Nat Mater*, **2009**, 8(7), 543-557.

NIOSH (2013). Occupational exposure to carbon nanotubes and nanofibers. Current intelligence bulletin 65. Cincinatti, Ohio 45226-1998, NIOSH.

Nordin, E. Z.; Uski, O.; Nystrom, R.; Jalava, P.; Eriksson, A. C.; Genberg, J.; Roldin, P.; Bergvall, C.; Westerholm, R.; Jokiniemi, J., et al., Influence of ozone initiated processing on the toxicity of aerosol particles from small scale wood combustion, *Atmos Environ*, **2015**, 102, 282-289.

Nowack, B. and Bucheli, T. D., Occurrence, behavior and effects of nanoparticles in the environment, *Environ Pollut*, **2007**, 150(1), 5-22.

Oberdorster, G.; Castranova, V.; Asgharian, B. and Sayre, P., Inhalation Exposure to Carbon Nanotubes (CNT) and Carbon Nanofibers (CNF): Methodology and

Dosimetry, *Journal of Toxicology and Environmental Health, Part b*, **2015**, 18(3-4), 121-212.

Oberdorster, G.; Oberdorster, E. and Oberdorster, J., Nanotoxicology: An emerging discipline evolving from studies of ultrafine particles, *Environ Health Persp*, **2005**, 113(7), 823-839.

OECD (2015). Harmonized Tiered Approach to Meaure and Assess the Potential Exposure to Airborne Emissions of Engineered Nano-objects and their Agglomerates and Aggregates at Workplaces. Paris, OECD Environment, Health and Safety publications.

Onasch, T. B.; Trimborn, A.; Fortner, E. C.; Jayne, J. T.; Kok, G. L.; Williams, L. R.; Davidovits, P. and Worsnop, D. R., Soot Particle Aerosol Mass Spectrometer: Development, Validation, and Initial Application, *Aerosol Sci Tech*, **2012**, 46(7), 804-817.

Park, K.; Cao, F.; Kittelson, D. B. and McMurry, P. H., Relationship between particle mass and mobility for diesel exhaust particles, *Environ Sci Technol*, **2003**, 37(3), 577-583.

Parra, F. M.; Igea, J. M.; Quirce, S.; Ferrando, M. C.; Martin, J. A. and Losada, E., Occupational Asthma in a Hairdresser Caused by Persulfate Salts, *Allergy*, **1992**, 47(6), 656-660.

Peters, T. M.; Elzey, S.; Johnson, R.; Park, H.; Grassian, V. H.; Maher, T. and O'Shaughnessy, P., Airborne Monitoring to Distinguish Engineered Nanomaterials from Incidental Particles for Environmental Health and Safety, *J Occup Environ Hyg*, **2009**, 6(2), 73-81.

Pope, C. A. and Dockery, D. W., Health effects of fine particulate air pollution: Lines that connect, *J Air Waste Manage*, **2006**, 56(6), 709-742.

Porter, D. W.; Hubbs, A. F.; Chen, B. T.; McKinney, W.; Mercer, R. R.; Wolfarth, M. G.; Battelli, L.; Wu, N. Q.; Sriram, K.; Leonard, S., et al., Acute pulmonary dose-responses to inhaled multi-walled carbon nanotubes, *Nanotoxicology*, **2013**, 7(7), 1179-1194.

Raaschou-Nielsen, O.; Andersen, Z. J.; Beelen, R.; Samoli, E.; Stafoggia, M.; Weinmayr, G.; Hoffmann, B.; Fischer, P.; Nieuwenhuijsen, M. J.; Brunekreef, B., et al., Air pollution and lung cancer incidence in 17 European cohorts: prospective analyses from the European Study of Cohorts for Air Pollution Effects (ESCAPE), *Lancet Oncol*, **2013**, 14(9), 813-822.

Ris, C., US EPA health assessment for diesel engine exhaust: A review, *Inhal Toxicol*, **2007**, 19, 229-239.

Rissler, J.; Nordin, E. Z.; Eriksson, A. C.; Nilsson, P. T.; Frosch, M.; Sporre, M. K.; Wierzbicka, A.; Svenningsson, B.; Londahl, J.; Messing, M. E., et al., Effective Density and Mixing State of Aerosol Particles in a Near-Traffic Urban Environment, *Environ Sci Technol*, **2014**, 48(11), 6300-6308.

Rissler, J.; Swietlicki, E.; Bengtsson, A.; Boman, C.; Pagels, J.; Sandstrom, T.; Blomberg, A. and Londahl, J., Experimental determination of deposition of diesel exhaust particles in the human respiratory tract, *J Aerosol Sci*, **2012**, 48, 18-33.

Rivera Gil, P.; Oberdorster, G.; Elder, A.; Puntes, V. and Parak, W. J., Correlating Physico-Chemical with Toxicological Properties of Nanoparticles: The Present and the Future, *Acs Nano*, **2010**, 4(10), 5527-5531.

Robinson, A. L.; Donahue, N. M. and Rogge, W. F., Photochemical oxidation and changes in molecular composition of organic aerosol in the regional context, *J Geophys Res-Atmos*, **2006**, 111(D3).

Ronkko, T.; Virtanen, A.; Vaaraslahti, K.; Keskinen, J.; Pirjola, L. and Lappi, M., Effect of dilution conditions and driving parameters on nucleation mode particles in diesel exhaust: Laboratory and on-road study, *Atmos Environ*, **2006**, 40(16), 2893-2901.

Rudell, B.; Blomberg, A.; Helleday, R.; Ledin, M. C.; Lundback, B.; Stjernberg, N.; Horstedt, P. and Sandstrom, T., Bronchoalveolar inflammation after exposure to diesel exhaust: comparison between unfiltered and particle trap filtered exhaust, *Occup Environ Med*, **1999**, 56(8), 527-534.

Salcedo, D.; Onasch, T. B.; Canagaratna, M. R.; Dzepina, K.; Huffman, J. A.; Jayne, J. T.; Worsnop, D. R.; Kolb, C. E.; Weimer, S.; Drewnick, F., et al., Technical Note: Use of a beam width probe in an Aerosol Mass Spectrometer to monitor particle collection efficiency in the field, *Atmos Chem Phys*, **2007**, 7, 549-556.

Salvi, S., Health effects of ambient air pollution in children, *Paediatr Respir Rev*, **2007**, 8(4), 275-280.

Salvi, S.; Blomberg, A.; Rudell, B.; Kelly, F.; Sandstrom, T.; Holgate, S. T. and Frew, A., Acute inflammatory responses in the airways and peripheral blood after short-term exposure to diesel exhaust in healthy human volunteers, *Am J Resp Crit Care*, **1999**, 159(3), 702-709.

Schmid, O.; Moller, W.; Semmler-Behnke, M.; Ferron, G. A.; Karg, E.; Lipka, J.; Schulz, H.; Kreyling, W. G. and Stoeger, T., Dosimetry and toxicology of inhaled ultrafine particles, *Biomarkers*, **2009**, 14, 67-73.

Schulze, C.; Kroll, A.; Lehr, C. M.; Schafer, U. F.; Becker, K.; Schnekenburger, J.; Isfort, C. S.; Landsiedel, R. and Wohlleben, W., Not ready to use - overcoming pitfalls when dispersing nanoparticles in physiological media, *Nanotoxicology*, **2008**, 2(2), 51-U17.

Seipenbusch, M.; Rothenbacher, S.; Kirchhoff, M.; Schmid, H. J.; Kasper, G. and Weber, A. P., Interparticle forces in silica nanoparticle agglomerates, *J Nanopart Res*, **2010**, 12(6), 2037-2044.

Silverman, D. T.; Samanic, C. M.; Lubin, J. H.; Blair, A. E.; Stewart, P. A.; Vermeulen, R.; Coble, J. B.; Rothman, N.; Schleiff, P. L.; Travis, W. D., et al., The Diesel Exhaust in Miners Study: A Nested Case-Control Study of Lung Cancer and Diesel Exhaust, *J Natl Cancer I*, **2012**, 104(11), 855-868.

Sorensen, C. M., The Mobility of Fractal Aggregates: A Review, *Aerosol Sci Tech*, **2011**, 45(7), 765-779.

Stroh, E.; Rittner, R.; Oudin, A.; Ardo, J.; Jakobsson, K.; Bjork, J. and Tinnerberg, H., Measured and modeled personal and environmental NO2 exposure, *Popul Health Metr*, **2012**, 10.

Su, W. C. and Vincent, J. H., Experimental measurements and numerical calculations of aspiration efficiency for cylindrical thin-walled aerosol samplers in perfectly calm air, *Aerosol Sci Tech*, **2004**, 38(8), 766-781.

Sullivan, R. C. and Prather, K. A., Recent advances in our understanding of atmospheric chemistry and climate made possible by on-line aerosol analysis instrumentation, *Anal Chem*, **2005**, 77(12), 3861-3885.

Svartengren, M.; Falk, R.; Linnman, L.; Philipson, K. and Camner, P., Deposition of Large Particles in Human-Lung, *Exp Lung Res*, **1987**, 12(1), 75-88.

Svensson, C. R.; Ludvigsson, L.; Meuller, B. O.; Eggersdorfer, M. L.; Deppert, K.; Bohgard, M.; Pagels, J. H.; Messing, M. E. and Rissler, J., Characteristics of airborne gold aggregates generated by spark discharge and high temperature evaporation furnace: Mass–mobility relationship and surface area, *J Aerosol Sci*, **2015**, 87, 38-52.

Tantra, R.; Tompkins, J. and Quincey, P., Characterisation of the de-agglomeration effects of bovine serum albumin on nanoparticles in aqueous suspension, *Colloid Surface B*, **2010**, 75(1), 275-281.

Van Broekhuizen, P.; Van Veelen, W.; Streekstra, W. H.; Schulte, P. and Reijnders, L., Exposure Limits for Nanoparticles: Report of an International Workshop on Nano Reference Values, *Ann Occup Hyg*, **2012**, 56(5), 515-524.

Vesterdal, L. K.; Jantzen, K.; Sheykhzade, M.; Roursgaard, M.; Folkmann, J. K.; Loft, S. and Moller, P., Pulmonary exposure to particles from diesel exhaust, urban dust or single-walled carbon nanotubes and oxidatively damaged DNA and vascular function in apoE(-/-) mice, *Nanotoxicology*, **2014**, 8(1), 61-71.

WHO (1997). Determination of airborne fibre number concentrations - A recommended method, by phase-contrast optical microscopy (membrane filter method). Geneve, World Health Organization.

WHO (2006). Constitution of the World Health Organization. Basic Documents, World Health Organization. 45.

Willis, M. D.; Lee, A. K. Y.; Onasch, T. B.; Fortner, E. C.; Williams, L. R.; Lambe, A. T.; Worsnop, D. R. and Abbatt, J. P. D., Collection efficiency of the soot-particle aerosol mass spectrometer (SP-AMS) for internally mixed particulate black carbon, *Atmos Meas Tech*, **2014**, 7, 4507-4516.

Wilson, J. G.; Kingham, S.; Pearce, J. and Sturman, A. P., A review of intraurban variations in particulate air pollution: Implications for epidemiological research, *Atmos Environ*, **2005**, 39(34), 6444-6462.

Vincent, J. H., Health-related aerosol measurement: a review of existing sampling criteria and proposals for new ones, *J Environ Monitor*, **2005**, 7(11), 1037-1053.

Wittbom, C.; Eriksson, A. C.; Rissler, J.; Carlsson, J. E.; Roldin, P.; Nordin, E. Z.; Nilsson, P. T.; Swietlicki, E.; Pagels, J. H. and Svenningsson, B., Cloud droplet activity changes of soot aerosol upon smog chamber ageing, *Atmos Chem Phys*, **2014**, 14(18), 9831-9854.

Woskie, S., Workplace practices for engineered nanomaterial manufacturers, *Wires Nanomed Nanobi*, **2010**, 2(6), 685-692.

Xu, Y. Y.; Barregard, L.; Nielsen, J.; Gudmundsson, A.; Wierzbicka, A.; Axmon, A.; Jonsson, B. A. G.; Karedal, M. and Albin, M., Effects of diesel exposure on lung function and inflammation biomarkers from airway and peripheral blood of healthy volunteers in a chamber study, *Part Fibre Toxicol*, **2013**, 10.

Zimmermann, E.; Derrough, S.; Locatelli, D.; Durand, C.; Fromaget, J. L.; Lefranc, E.; Ravanel, X. and Garrione, J., Results of potential exposure assessments during the maintenance and cleanout of deposition equipment, *J Nanopart Res*, **2012**, 14(10).