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A simulation study of airborne wear particles from laboratory wheel-rail contacts

Hailong Liu [a,*], Lage Tord Ingemar Jonsson [a,b], Pär Göran Jönsson [a]

[a] KTH-Royal Institute of Technology, Division of Applied Process Metallurgy, Department of Materials Science and Engineering, SE-100 44 Stockholm, Sweden
[b] FOI, Swedish Defence Research Agency, Division of CBRN Defence and Security, SE-901 82 Umeå, Sweden

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ABSTRACT

Laboratory measurements of airborne particles from sliding contacts are often performed using a tribometer located in a ventilation chamber. Although knowledge of particle transport behavior inside the chamber is required because it can influence the analysis of measurements, this knowledge is lacking. A numerical model was built based on the same geometry as a pin-on-disc measurement system to explain particle transport behavior inside the chamber and to determine the deviation between real amounts of generated and measured particles at the outlet. The effect of controlled flow conditions on the airflow pattern and particle transport inside the chamber was studied for different experimental conditions. Calculations show that a complex airflow pattern is formed by the spinning disc, and that it differs for each rotational speed. Simulation results reveal that particle transport in the chamber is governed mainly by the airflow pattern. The deposition velocity in the chamber was estimated and the possibility that part of the generated particles would remain in the chamber was studied. This led to an approximate estimation of particle loss rate. A comparison between experimental and simulated results with respect to the particle mass flow rate close to the outlet yields a reference factor of 0.7, which provides an indication of the difference between measured and real values.

Introduction

Air quality is a topic of great interest and concern for many people worldwide. Several researchers have reported that airborne particle concentration is one of the main criteria used to evaluate air quality. Insufficient knowledge on and potential severe health effects of airborne particles from non-exhaust traffic emissions (e.g., wear processes from brakes, wheel–rail contacts, and tire road interfaces) has led to an increase in recent attention being given to these particles (Gianini et al., 2012; Valavanidis, Fiotakis, & Vlachogianni, 2008; Karlsson, Nilsson, & Möller, 2005; Sysalova & Szakova, 2006). A large number of experimental methodologies have been developed to study airborne wear particles (Harrison, Jones, Gietl, Yin, & Green, 2012; Iijima et al., 2007; Kukutschová et al., 2011; Olofsson, Olander, & Jansson, 2009a). Laboratory ventilation chamber setups are a common and efficient method to measure concentrations and size distributions of particles generated from different wear contacts such as wheel–rail contacts and brake systems (Olofsson, Olander, & Jansson, 2009b; Wahlström, Söderberg, Olander, Jansson, & Olofsson, 2010; Kukutschová et al., 2011). However, particle monitoring values are obtained from samples at the chamber outlet in pin-on-disc measurement systems. It is necessary to determine whether a sufficient number of wear particles and their properties can be captured using the applied methods. It is also difficult to determine the exact portion of total measurable particles captured and to determine what happens to the remaining particles.

A numerical simulation approach would be beneficial to illustrate particle transport and dispersion inside a ventilated chamber. Various studies have been conducted to explain particle transport and dispersion in enclosed environments (Lu, Howarth, Adam, & Riffat, 1996; Zhang & Chen, 2006; Lai & Chen, 2006; Zhao, Chen, & Tan, 2009). These studies concluded that particle deposition and migration in a ventilation chamber are influenced mainly by particle properties, ventilation conditions, and airflow patterns. Ultrafine particles (sub-0.1 μm) experience a long residence time inside ventilation chambers as found by measurement and simulation results (Lai & Chen, 2006). Therefore, a portion of released ultrafine particles cannot be captured at the outlet in a short time. For fine and coarse particles, the large particle size leads to a high

* Corresponding author. Tel.: +46 0 765588252.
E-mail address: hailongl@kth.se (H. Liu).

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Nomenclature

Latin symbols

A	inner surface area in a chamber (m^2)
A_p	project area of particle (m^2)
C	mean particle concentration (kg/m^3)
C_D	drag coefficient of a spherical particle
C_m	particle mass concentration (kg/m^3)
C_μ	eddy-viscosity coefficient
d_p	particle diameter (m)
D_B	Brownian diffusivity (m^2/s)
D_B^+	dimensionless Brownian diffusivity
D_p	drag function
D_T	temperature diffusivity (m^2/s)
D_T^+	dimensionless temperature diffusivity
g_i	gravitational acceleration (m/s^2)
J	particle mass transfer rate ($kg/(m^2\,s)$)
k	kinetic turbulent energy (m^2/s^2)
l_e	eddy size (m)
n	total number of particles per unit volume (N/m^3)
m_p	mass of each particle (kg)
$\dot{m}_p$	mass flow rate of measured particles (kg/s)
p	pressure (Pa)
P_r	production term in Eqs. (4) and (5) (m^2/s^3)
R_a	roughness (m)
Re_p	particle Reynolds number
r	particle radius (m)
$S_\emptyset$	source
Δt_e	eddy life time (s)
Δt_r	particle transit-time (s)
$u_{i,j}$	velocity (m/s)
u_τ	friction velocity (m/s)
u_{pi}	particle velocity in the *i* direction (m/s)
U_i	continuous-phase instantaneous velocity (m/s)
u_i'	velocity fluctuation component (m/s)
v_d	deposition velocity (m/s)
v_d^+	dimensionless deposition velocity
V	chamber volume (m^3)
$\dot{V}$	air flow rate (m^3/s)
V_p	particle volume (m^3)
$\bar{V}_{py}^c$	particle convective velocity in the *y* direction (m/s)
$\bar{V}_{py}^{c+}$	dimensionless particle convective velocity in the *y* direction
x_{pi}	particle position
y^+	dimensionless wall-normal distance

Greek symbols

ρ_M	mass density (kg/m^3)
μ_D	dynamic viscosity ($kg/(m\,s)$)
μ_T	turbulent viscosity ($kg/(m\,s)$)
ν	kinematic viscosity (m^2/s)
ε	dissipation rate of kinetic turbulent energy (m^2/s^3)
β	particle loss coefficient for deposition in ventilated chambers (s^{-1})
$\emptyset$	scalar
τ	particle relaxation time (s)
τ^+	dimensionless particle relaxation time
ρ_p^0	particulate material density (kg/m^3)
ρ_f	fluid density (kg/m^3)
∇p	continuous-phase pressure gradient

Sub/superscripts

+	dimensionless dependent
B	Brownian diffusion
d	deposition
f	fluid
i	index *i*
j	index *j*
p	particle
py	particle in the *y* direction
T	turbulent, temperature

settling velocity and a larger inertia effect, which increases the fraction deposited (Hinds, 1982). In general, these works were performed with a particle release within the inlet air and an assumed uniform particle concentration distribution in a scaled space. However, the situation is different in airborne wear particle measurement systems. During laboratory experiments, particles are generated internally (e.g., by contact between the pin and the disc) and the particle concentration at the outlet is measured instantaneously after particle generation. Therefore, it is essential to know the variation in particle concentration distribution within the chamber during the measurements.

A numerical model was developed for ultrafine particle release in a ventilated chamber. The purpose of the work is to provide a clear understanding of ultrafine particle transport behavior inside the chamber of a laboratory measurement setup, and to establish whether there is a deviation between the generated amount and size distribution of particles and the particles measured at the outlet. The simulation could be used to increase the accuracy and understanding of measurements.

Mathematical model

A mathematical model was built to simulate a real size pin-on-disc machine located in a sealed chamber. A numerical method, computational fluid dynamics, was used to predict airflow field and particle transport. Turbulent flow was predicted using the Chen–Kim turbulence model (Chen & Kim, 1987). A deposition model from Ni, Jonsson, Ersson, and Jönsson (2014) was used to predict particle deposition, and a Lagrangian method (Ludwig, Fueyo, & Malin, 2006) was used in the particle tracking simulation to investigate the limiting size of particles to becoming airborne inside the chamber.

Model description and assumptions

The following descriptions and assumptions are made in the formulation of the mathematical model:

- The computational domain is shown in Fig. 1. It is limited to a three-dimensional (3-D) sealed box (660 mm × 450 mm × 360 mm).
- In each case, a grid system (769,785 cut-cells) is used with a Cartesian quadrilateral shape in the computational domain (as shown in Fig. 2).
- According to laboratory measurements, most particles are less than 0.1 μm in diameter. Therefore, these ultrafine particles are assumed to have the same transport behavior as the scalable source term (C1). The source is released from the 3-D object, 'PIN', at a constant rate (as shown in Fig. 1).