Investigation of particle detachment from the rotating wheel in indoor environment

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Abstract. There are various wheels are required for indoor activities, such as spinning bike wheels in the gym, various mechanical equipment wheels in the factory. Obviously, these rotational movements of wheels will cause the detachment of particles adhering to the wheel. This common phenomenon is regarded as an important contributor to particulate matter concentrations in indoor environment. The work performed in this study mainly focused on the description and understanding of the process of particles detachment from the rotating wheel into the air. A set of theoretical models were proposed to clarify particle detachment mechanisms. Since the detachment occurs when the sum of external force moments exceed the maximum adhesion resistance moment, different forces acting on the particles should be considered before the particles detached. There are adhesion forces between the particles and the wheel surface, hydrodynamic forces acting on the particles and centrifugal forces due to the rotating wheel. In order to verify models, the corresponding experiments were carried out and the experimental results were quite consistent with the calculation results of models. Results showed that adhesion force, hydrodynamic drag force and centrifugal force were important and critical detachment diameters of particles adhering to the wheel can be influenced by these forces. Effects of different relevant parameters on these forces, including surface roughness, wheel speed, particle size were analysed. Higher roughness, larger particle and faster wheel speed are more conducive to the detachment of particles.

Keywords: Particle Detachment; Rotating Wheel; Theoretical Model; Experimental investigation; Indoor Environment

1. Introduction
The indoor environment is affected by many factors, such as the human behaviour, changes in the external environment and the moving objects in contact with particles, etc. Among the third factor mentioned above, the various wheels in the room such as the spinning bike wheels in the gym, mechanical equipment wheels in the factory are also a major factor when evaluating the indoor environment. Because these wheels are often covered with particles, for particles in the air deposit on them, or particles stick to the wheels from the ground. The rotational movements of wheels cause the detachment of particles and the increasing of particulate matter concentrations. High particulate matter concentrations have negative impact on the air quality. People spend approximately 87% of their time indoors and the probability of contracting infectious diseases is positively related to the exposure of particulates. Therefore, it is significant to study the particles detachment caused by the rotating wheel for further improving indoor environment.

Different forces acting on the particles should be considered before the particles detached. Particle adhesion and detachment from substrate have been studied by many researchers previously. Johnson, Kendall and Roberts [1] developed the well-known JKR adhesion model to include the effects of the surface energy and surface deformation on the particles in contact with a flat surface. Derjaguin, Muller and Toporov [2] developed an alternative DMT adhesion model by assuming the same contact profile as elastic Hertzian contact. However, JKR and DMT models are only suitable for predicting the van der Waals force between smooth particles and surfaces. Soltani and Ahmadi [3] considered the
effects of surface roughness and showed that even small amount of roughness significantly affects the pull-off force needed for particles detachment. In addition to the effect of surface roughness on particle adhesion and detachment, the aerodynamic behavior of air near the substrate also plays an important role [4]. Different from the particles on the substrate, the centrifugal force acting on particles should be considered in addition to the adhesion and hydrodynamic force for particles adhering to the rotating wheel. Research describes the mechanism of particles detachment from the rotating surface is rarely reported.

Spherical particles can detach from the flat surface by three ways: rolling, sliding and lifting. The removal of particles is more easily achieved by the rolling motion, rather than other mechanisms [5, 6]. In this study, the rolling motion was considered and the detachment occurs when the sum of external force moments exceed the maximum adhesion resistance moment for particles adhering to the wheel. Theoretical models describe the process of particle detachment from the rotating wheel were established and corresponding experiments were carried out. The influences of different relevant parameters were analysed, including surface roughness, wheel speed, and particle size.

2. Detachment models
In this section, models of particle detachment from the rotating wheel are proposed. Forces and torques acting on particles adhering to the wheel were briefly outlined and the detachment mechanism was described.

2.1. Adhesion force
The JKR adhesion model accounts for the effects of surface energy and elastic deformation of a sphere in contact with a flat surface [1]. On the basis of the JKR model, the nominal contact radius is:

\[ a_{JKR} = \left( \frac{9\pi d_p^2 \gamma}{4E^*} \right)^{1/3} \]  

(1)

where

\[ E^* = \left( \frac{1-v_1^2}{E_1} + \frac{1-v_2^2}{E_2} \right)^{1/2} \]  

(2)

where \( \gamma \) is the surface energy of adhesion and is estimated as \( \gamma = (\gamma_1\gamma_2)^{1/2} \), with \( \gamma_1 \) and \( \gamma_2 \) as the surface energy of surface and particle, respectively. \( d_p \) is the particle diameter. \( E^* \) is the composite Young’s modulus. \( E_1 \) and \( E_2 \) are Young’s modulus, and \( v_1 \) and \( v_2 \) are the Poisson ratio for the surface and particle, respectively.

The adhesion force between particles and the smooth surface is given as [1]:

\[ F_x = \frac{2E^*a_{JKR}^3}{3d_p} \]  

(3)

Surface roughness can influence the real contact area and significantly affect the adhesion force. Based on the JKR model, the adhesion force can be calculated considering the average roughness of contact surfaces as equation (4) [7]:

\[ F_x = \frac{2E^*C^{1/2}a_{JKR}^3}{3d_p} \]  

(4)

where \( C \) is the correction factor caused by the surface roughness.

2.2. Hydrodynamic force and torque
The hydrodynamic drag force acting on particles adhering to the wheel can be expressed here according to previous studies [8]:

\[ F_i = \frac{C_d \pi f \rho d_p^2 u_m^2}{8C_v} \]  

(5)
where \( \rho \) is the fluid density; \( u_M \) is the fluid velocity at the location of the mass center of the particle; \( f = 1.7009 \) is the correction factor for the wall effect [9]; \( C_c \) is the Cunningham factor taking into account the non-continuum effects. The expression for \( C_c \) is given as [10]:

\[
C_c = 1 + K_n \left[ 1.257 + 0.4 \exp \left( -1.1/K_n \right) \right]
\]  
where \( K_n \) is the Knudson number which is defined as:

\[
K_n = \frac{2\eta}{d}
\]  
where \( \eta \) is the mean free path of the fluid. (typically about 0.07\( \mu \)m under normal conditions).

In the equation (5), \( C_D \) is the drag coefficient which can be expressed as [11]:

\[
C_D = \begin{cases} 
\frac{24}{R_e} (1 + 0.15 R_e^{0.678}) & \text{when } R_e \leq 1000 \\
0.44 & \text{when } 1000 \leq R_e \leq 2 \times 10^5
\end{cases}
\]  
The corresponding hydrodynamic torque acting on the particle is given as [8]:

\[
M_t = \frac{2\pi g_w u_m d_p^2}{C_c}
\]  

2.3. Centrifugal force

The centrifugal forces acting on particles adhering to the wheel can be calculated as:

\[
F_c = \frac{mV^2}{R}
\]  
where \( V \) is the wheel speed and \( m \) is the particle mass.

2.4. Rolling detachment model

Figure 1 shows the schematic of forces and torques acting on the particle adhering to the wheel. Effect of other forces such as electrostatic force, lift force and gravity force could be considered as needed. Nevertheless, these forces are negligible compared to the adhesion force and hydrodynamic force [12]. Therefore, they were ignored in our model.

\[
M_t + F_t \frac{d_p}{2} + F_c a_{JKR} \geq F_v a_{JKR}
\]  

Figure 1. Forces and torques acting on the particle adhering to the wheel.

Particles can detach from the wheel surface by three ways: rolling, sliding and lifting. Previous studies pointed out that the removal of spherical particles is more easily achieved by the rolling motion, rather than by sliding or lifting [5, 6]. Therefore the rolling detachment of spherical particles was intensively analyzed in this paper. When the total external force moment exceeds the adhesion force moment, the particle adhering to the wheel will be detached according to these studies. Then the critical condition of detachment can be given as:
3. Experiments

The experiments were carried out to investigate the process of particles detachment from the rotating spinning bicycle, and the experimental set up and procedures are introduced below.

![Figure 2. Schematic of the experimental set up](image)

The detailed layout of the experimental facility is shown in figure 2. The wheel was fixed and mounted by the glass slide and speed measuring instrument. The wheel speeds were measured and displayed by the speed measuring instrument. In order to make the surface roughness consistent and be easy to sample and observe the particles, the glass slides for microscope were employed to conduct the experiments. The roughness of the glass slide $\sigma$ was measured by the roughness measuring instrument Veeco-Dektak 150. Three points on the glass slide were randomly selected and the average value of $\sigma$ was $5\times10^{-9}$meters under the scale of $1\times10^{-3}$meters.

Particles applied in the experiments were all dried an hour in the drying box at the constant-temperature of 80°C before seeded on the glass slide surface. The reproducible seeding system was built here to minimize the variance in the particles loading based on the report of the previous research [13]. This system consists of a stainless steel funnel and an deposition chamber and the details can refer to the previous study[13]. Aluminum oxide particles with a purity of 99% were investigated here for the aluminum oxide is one of the main components of particles. The wheel was rotated at a constant linear speed which varies from 2m/s to 7m/s after the particles were seeded. The wheel speed and rotating time were recorded at the same time. At last, particles still adhering to the glass slide surface were observed using the microscope when the wheel stopped rotating.

![Figure 3. Comparisons of theoretical models and experimental data ($\sigma=5\times10^{-9}$m, $x=0.001$)](image)

The predictions from the proposed models were compared against the obtained experimental data. In experiments, particles which still adhering to the glass slide surface when the wheel was not rotating would be observed using the microscope. Three positions on the slide were randomly chosen
and the largest diameter of particles was recorded. The largest diameter, namely the critical diameter of particles detachment, was compared with the theoretical calculation results.

The forces and torques acting on particles adhering to the wheel were introduced and the critical diameter of detachment was calculated in this paper. It should be noted that the fluid velocity at the location of the mass center of the particle when calculating the hydrodynamic force and torque. And in this calculation process, it was assumed to be proportional to the wheel speed which can be measured \( u_M = \alpha \times V \). As shown in the figure 3, the model predictions were compared with the available experimental data and good agreement was observed.

4. Results and discussions

Models about particle detachment from the rotating wheel were described in this study and corresponding experiments were carried out. The critical detachment diameter was calculated and the specific effect of rotating wheels on the indoor environment was quantified.

Figure 4(a) shows the variation of critical detachment diameters under different conditions. It is found that the critical diameter of particles adhering to the wheel will decrease with the increasing roughness. This situation is due to the adhesion force between the particles and wheel surface will decrease with the increasing surface roughness. Under the condition of constant external force moments, the reduction of adhesion force will make the particles more easily detached. Figure 4(a) also shows that with the wheel speed increasing, the critical diameters will decrease. It means that smaller particles are more likely to stick to the rotating wheel under higher speed. The reason is that increasing wheel speed will generate larger air velocity. The hydrodynamic force and centrifugal force moments acting on particles will increase correspondingly. The adhesion force moments are constant under different speed.

![Figure 4(a): Critical detachment diameters and force moments under different conditions.](image)

Figure 4(b) shows that external and adhesion force moments acting on particles under different conditions. The solid lines are external force moments and the dash lines are adhesion force moments. When total external force moments exceed adhesion force moments, particles adhering to the wheel can be detached from the wheel. It is seen that with the increasing of particle size, the external and adhesion force moments are increasing at the same time. It is obvious that the growth rate of external force moments is faster than that of adhesion force moments as shown in the figure 4(b). Therefore, smaller particles would still adhere to the wheel due to adhesion force moments exceed the external force moments while the larger particles would detach from the wheel under the same conditions. This figure shows the reason why larger particles are more easily detached compared with smaller particles. The wheel speed can influence the external force moments acting on particles while the adhesion force moments remain constant at the same time. Not only the external force moments, but also the growth rate will be larger at the faster speed. This figure gives the more intuitive explanation of the problem of why particles are more easily detached at faster speed. The surface roughness can influence the adhesion force moments while the external force moments remain constant at the same time. Particles
adhering to the wheel are more easily detached at larger roughness.

5. Conclusions
Models about particle detachment from the rotating wheel surface were proposed in this study and the corresponding experiments were carried out. Different forces acting on particles were considered in this paper, and calculation results show that: adhesion forces between the particles and the wheel surface, hydrodynamic forces acting on the particles and centrifugal forces due to the rotating wheel are the main forces acting on the particles and they have a direct impact on the critical detachment diameters of particles.

Effects of multiple relevant parameters on these forces, including surface roughness, wheel speed and particle size were analyzed. Results show that the roughness and the particle size can affect the adhesion force moments between the particles and the surfaces. The wheel speed and particle size can affect the hydrodynamic drag and centrifugal force moments. Therefore, higher roughness, larger particle and faster wheel speed are more conducive to the detachment of particles. That is to say, under these conditions, the particles are more easily detached and cause pollution in the indoor environment. It is expected the research of our study will be helpful for better understanding the process of particle detachment from the rotating wheel and improving the indoor environment.

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