

Analysis of Contamination Protection for Brake Rotor

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ABSTRACT

Contamination protection of brake rotors has been a challenge for the auto industry for a long time. As contamination of a rotor causes corrosion, and that in turn causes many issues like pulsation and excessive wear of rotors and linings, a rotor splash protection shield became a common part for most vehicles. While the rotor splash shield provides contamination protection for the brake rotor, it makes brake cooling performance worse because it blocks air reaching the brake rotor. Therefore, balancing between contamination protection and enabling brake cooling has become a key critical factor when the splash shield is designed. Although the analysis capability of brake cooling performance has become quite reliable, due to lack of technology to predict contamination patterns, the design of the splash protection shield has relied on engineering judgment and/or vehicle tests. Optimization opportunities were restricted by cost and time associated with vehicle tests. Studies were done for various ways of analyzing the contamination qualitatively and quantitatively and are presented in this paper. Combining the technology presented in this paper along with the existing brake cooling analysis capability shall enable the optimization of the splash shield design for both the contamination protection and brake cooling.

CITATION: Lee, H., "Analysis of Contamination Protection for Brake Rotor," *SAE Int. J. Passeng. Cars - Mech. Syst.* 9(3):2016, doi:10.4271/2016-01-1930.

INTRODUCTION

As brake rotors are made out of cast iron and they are prone to corrode, protecting brake rotors from contaminating particles has been one of the major concerns for the automotive brake engineering community. To provide the best contamination protection for brake rotors, simply covering the rotor completely using a shield would be the best option. However, because the brake performs better at cooler temperatures, providing adequate brake cooling air to the rotor is critical as well. Due to these contradicting requirements, designing the splash protection shield became quite complicated despite it being a simple structure. How to analyze the brake cooling has been developed well and the brake cooling analysis has been an industry standard work for years. However, how to evaluate the contamination protection for the rotor has not been well established despite the fact that the methodologies for vehicle soiling analysis have been advanced quite well during the last few years.

To find a best analytical way of designing the splash protection shield for the brake rotor, previous studies about vehicle soiling are reviewed. Summarizing previous work, water management / soiling / contamination analytical studies are composed of the multiphase flow, liquid-wall interaction, build-up of a liquid film on the surface and its development along the surface, and the film break-up and its entrainment. For the brake rotor soiling analysis, it is possible to simplify the physics we need to take into account by focusing on which area of the shield is important to protect the contamination of the rotor.

Sources of Brake Rotor Soiling

It is necessary to think about the origin of the contamination because it may require a different approach for each source of the contamination. Three general sources of the contamination for exterior soiling are wind-driven rain, foreign-soiling, and self-soiling [e.g. 1]. Foreign-soiling results from the road spray generated by other vehicles. Self-soiling is due to the rolling wheels on a wetted road. The water on the road is collected by adhesive forces exerted by the tire and sprayed radially and tangentially into the air. The amount of standing water will have an impact on choosing an appropriate analysis method. Wind-driven rain has a minimal impact on the brake rotor contamination and was ignored in this study.

Multiphase Flow Analysis

The methods to simulate vehicle soiling due to solid and liquid particles tend to differ and this review was focused on the liquid case. There are two approaches when multiphase flows are solved: the Euler-Euler and the Euler-Lagrange. For the Euler-Euler approach, both phases are treated as interpenetrating continua. For the Euler-Lagrange approach, the liquid is modeled as Lagrangian points of discrete mass moving through gas modeled as continuum. It is typical that the Euler-Euler approach requires much finer spatial resolutions than the Euler-Lagrange approach. Other than a few academic papers dealing with simplified structures [2, 3], most papers dealing with vehicle soiling problems have used the Euler-Lagrange approach [4, 5, 6, 7, 8, 9].

Phase Coupling Modes of Euler-Lagrange Approach

How the phase coupling is handled between particles and gas flow, and between particles in the Euler-Lagrange approach makes a meaningful difference in the vehicle soiling analysis. One-way coupling, which means that gas flow has an impact on particles' behavior but not vice versa, enables to separate the analysis of aerodynamic field and the particle tracking, which is accomplished using a fixed airflow field. Majority of previous publications have used this approach when the vehicle soiling was studied [4, 5, 6, 7, 8]. The assumption behind this one-way coupling Euler-Lagrange approach was that the particle is sparse and its influence on the gas flow should be minimal. However, the question remains for which level of sparseness guarantees this assumption valid.

Hagemeier, Hartmann and Thevenin proposed a general guideline about coupling mechanisms [1]. For the volume fraction of the dispersed phase of typically less than 10^{-3} , four-way coupling is not necessary and thus particle-particle interaction such as collisions can be ignored. One-way coupling is theoretically justified when the volume fraction of the dispersed phase does not exceed a value of 10^{-6} . As the spray disperses away from the tires, the mass loadings of water decrease and coupling can be ignored. Similarly, for very large droplets near the tires, there is little interaction between the droplets and the flow. The behavior of smaller droplets near the tires would be modified if two-way coupling were included but the transport of droplets away from the near tire region can be accurately modeled without these effects. Therefore, one-way coupling is considered to be sufficient when foreign-soiling is simulated. However, self-soiling due to the tire splash may require a different approach because the volume fraction of the second phase near the tires could be much higher than 10^{-3} .

Paschkewitz [10] proposed another indicator that could be used to see whether two-way coupling would be necessary. The importance of back-coupling can be estimated using a momentum coupling parameter, which is the ratio of the particle drag to the carrier fluid momentum flux:

$$\Pi = \frac{C}{1 + St} \quad (1)$$

where C is the ratio of the mass flow rates of the disperse and continuous phases and St is the Stokes number, which is the ratio of the response times of the disperse and continuous phases, and quantifies the relative importance of particle (disperse phase) inertia:

$$St = \frac{\rho_p d_p^2 U}{18 \mu_c H} \quad (2)$$

where the p and c subscripts denote the particle and continuous phases, ρ is the density, d_p is the particle or droplet diameter, U/H is a characteristic flow time scale, and μ_c is the dynamic viscosity. If this parameter is greater than unity, the back-coupling of the particle or droplet momentum on the carrier flow field may be important.

A simple estimate of the coupling parameter near the tires is described here. Assuming an airflow rate of 20 m/s and a tire width of 250 mm (0.0625 m² frontal area near the tire), the mass flow rate is approximately 1.53 kg/s. The amount of water displaced by the tire patch can be estimated using the tire width (250 mm) multiplied by the tangential velocity (20 m/s) multiplied by the water film thickness (0.1 mm) to give the mass flow rate of 0.5 kg/s. This will give a mass loading ratio of 0.33 in the immediate vicinity of the tire. For droplets with a diameter of 0.1 mm, the Stokes number is 0.8 using the ratio of the free stream velocity and the tire height (0.7 m) as the characteristic flow time scale. These parameters give $\Pi = 0.2$, which suggests that two-way coupling may not be important. However, if the water film thickness on the road surface grows to 1 mm, the mass flow rate of water becomes 5 kg/s and the mass loading ratio will be 3.3. These parameters give $\Pi = 1.8$. For a diameter of droplet particles even smaller (20 microns), the Stokes number becomes 0.03 and it gives $\Pi = 3.2$. Table 1 summarizes this estimate. It suggests that two-way coupling is important when the contamination is calculated for locations near the tires and for small (low St) droplets.

Table 1. Influence of wall film thickness and droplet diameter and mass loading ratio on Momentum Coupling Parameter.

Water Film Thickness (mm)	Droplet Diameter (mm)	Mass Loading Ratio	Stokes Number	Momentum Coupling Parameter
0.1	0.1	0.33	0.8	0.18
0.1	0.02	0.33	0.03	0.32
1.0	0.1	3.3	0.8	1.8
1.0	0.02	3.3	0.03	3.2

Considering two-way coupling using the transient particle tracking was investigated for the simulation of wheel spray by Jilesen and et al [9]. It was claimed for the simulation of wheel spray that capturing the full transient behavior of the particles within the flow field has a significant impact on the distribution of particles within the flow field, as well as the distribution of 'hit points' on the surface. It was noted that a disadvantage of this two-way coupling approach is that its computing time takes longer since the physical time scales of the particles are directly tied to the physical time covered by the flow simulation.

Euler-Euler Approach for Brake Rotor Self-Soiling

It is recommended by commercially available RANS solvers that the Euler-Lagrange approach can be used unless the dispersed-phase volume fraction exceeds 10%. For the exterior vehicle soiling analysis, it may not be an issue to fulfill this guideline because the

particle density around the area of interest, e.g. the rear or side exterior surface, will be much less dense than the area of soiling source, the tires. However, as the purpose for self-soiling analysis of the brake rotor is to analyze the vicinity of the tires, the volume fraction of the discrete phase may cause an accuracy issue if the Euler-Lagrange approach is used. Unless the brake rotor self-soiling analysis is confined to slightly wet road surfaces, it may be necessary to consider using the Euler-Euler approach to capture the interaction between the first and second phases properly. In the Euler-Euler approach, the different phases are treated mathematically as interpenetrating continua. The VOF model (Volume of Fluid) is a surface-tracking technique applied to a fixed Eulerian mesh. It is designed for two or more immiscible fluids where the position of the interface between the fluids is of interest. It was applied to analyze tire puddling in this study. The tire puddling is used in this paper to indicate the water splash phenomena when the water film thickness on a road surface exceeds 3mm.

Rolling Tires on Vehicle Soiling

The influence of rotating tires on the aerodynamics field and in turn on the vehicle soiling has been studied extensively [7, 9, 11, 12, 13, 14, 15, 16, 17, 18, 19]. Gaylord and et al studied three different approaches accounting for the wheel rotation: a rotational velocity boundary condition; a moving reference frame; a sliding mesh [7]. Comparing with test results, they concluded that applying the rotational velocity condition did not capture the flow field near the tires well, but the moving reference frame and the sliding mesh provided relatively accurate representations. It was also found that the sliding mesh provided more detailed small-scale flow structures compared to what was calculated by the moving reference frame.

Film Modeling Approaches

If an objective of the soiling analysis requires a relatively accurate representation of the particle behavior after particles contact the wall surfaces, the film modeling becomes important. O'Rourke and Amsden proposed a discrete phase wall film model for the application on port injections for internal engines [20]. The model was later improved for splashing and a wall film inertia term [21]. Kruse and Chen adapted the wall film model O'Rourke and Amsden used to make it more suitable for the vehicle soiling analysis [6]. This new film model enhanced its behavior on wet surfaces and a wall film separation model was refined in their study as well. Jilesen et al. demonstrated the enhancement of the wall film model used in their two-way coupling wheel soiling analysis using the LBM transient soiling analysis [9]. New splashing and break-up models available in the concurrent transient vehicle soiling analysis provided improved correlation for soiling patterns on the rear exterior surface compared to the one-way coupling analysis result.

Even with all these enhancements in wall film models, the limitation still exists in some cases, as wall film models are based on a thin film assumption. When a relatively thick film is expected compared to the boundary layer thickness or to the radius of the surface

curvature, discrete-phase-film models will suffer from accuracy issues because individual particles do not pile up and cannot alter the flow field boundaries.

BRAKE ROTOR FOREIGN-SOILING

Based on the review of previous studies and the need for the analysis of the brake rotor contamination, the scope of the work for this paper was determined as follows. The paper includes both foreign-soiling and self-soiling of the brake rotor, and this section discusses foreign-soiling first.

The goal of this paper was to establish an analytical method that is capable of differentiating the performance of various splash shield designs for contamination protection, quantitatively and qualitatively. To achieve this goal, three functionalities were pursued.

- Visualize the particle accumulation pattern on the rotor or the splash shield.
- Quantify the number of particles accumulated on the surfaces of rotors and splash shields.
- Trace back the sources of the soiling (origin of particles).

Assumptions for Brake Rotor Foreign-Soiling Analysis

A traditional one-way coupling was deemed adequate for the brake rotor foreign-soiling analysis based on the review of previous studies. Regarding particle motions, it was assumed that colliding, merging, and splitting of free particles would not significantly affect the brake contamination result. For particles in contact with the wall, it was assumed that all particles in contact with the rotor or the splash shield were either trapped or rebounded. Particles splashed into smaller particles and particles evaporated right after the contact due to high rotor temperature were not considered. Travelling of particles on the surface of the splash shield was not considered because it was not important for the goal of the study.

The overall process of the brake rotor foreign-soiling analysis is shown in Figure 1.

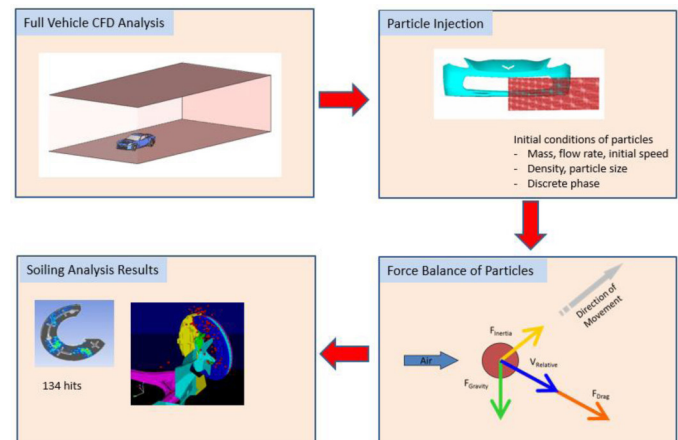


Figure 1. Analysis process of brake rotor foreign-soiling.