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CONTENT

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AN OVERVIEW OF NON-EXHAUST BRAKE EMISSION MEASURING METHODS

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Abstract *Non-exhaust emission is the type of particle emission that is not caused by a combustion process, but by the wear of different parts of a vehicle's systems. One of the sources of non-exhaust particulate emission is the braking system where the wear of friction pairs is present. There is growing number of studies that analyse brake wear with reference to the size and concentration of non-exhaust emissions, especially PM_{10} and $PM_{2.5}$ particles. An overview of various measuring techniques and devices for measuring the concentration of the formed particles by brake wear was performed in this paper. Pin-on-disc tribometers and brake inertial dynamometers are most commonly used for such tests. It is important to mention that for testing the emission of particles caused by brake wear, it is necessary to make certain modifications and design additional housings that retain the emission product. The authors have used different methods for measuring or collecting particles, which is also shown in the paper. In addition to laboratory testing methods, some authors used real vehicles whose brakes were also inserted into the housing, which prevents the entry of particles from the environment. The paper also presents a newly proposed inertia dynamometer for measuring non-exhaust particles who is development on the Faculty of Engineering.*

Keywords *Brake, emission, dynamometer, measurement, non-exhaust.*

1. INTRODUCTION

The problem of particles caused by brake wear is one of the current problems today after solving the problem of particle formation by combustion of fuel in the engine [1]. Modern technology of electric vehicles today does not emit particles by combustion in the engine, but one of the particles' source is certainly the braking system. The braking system belongs to the so-called non-exhaust group of particle sources, bearing in mind the fact that these particles are not emitted by combustion of fuel or some other substance, but purely by wear of friction pairs of brakes. Particle emission is very harmful because these particles contain various materials that are harmful to human health and the environment [2, 3]. Particles can be classified according to their size. So the most commonly measured particles that are formed by brake wear are PM_{10} and $PM_{2.5}$, but the concentration of formed PM_1 particles is also

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increasingly measured. The reason is that the harmfulness of particles is higher if their diameter is smaller, i.e. PM_1 particles are more harmful than particles of larger diameters, such as PM_{10} and $PM_{2.5}$ particles [4, 5].
Today, when this is a current problem, as well as air pollution and therefore, more and more authors are researching this area. In their research, the authors use several methodologies, but also different devices that have been modified in order to be able to measure the particles formed by the wear of a friction pair of brake pad and brake disc.
The aim of this paper is the analysis and presentation of measuring devices used by different authors with the aim of measuring the concentration of particles generated by brake wear. An installation for measuring particles, which is in the development phase at the Faculty of Engineering, University of Kragujevac, is also presented in the paper.

2. THE MOST COMMONLY APPLIED METHODS AND THEIR FEATURES

Numerous authors who have examined brake wear have applied different test methods. The most commonly used methods or better said devices are pin-on-disc tribometers, inertial brake dynamometers and road testing. Devices or methodologies used to test the particle concentration are shown in Figure 1. It is important to note the fact that tribometers and inertial dynamometers belong to laboratory test methods, while road tests are performed on the road and on a real vehicle. However, some authors investigating the concentration of the formed particles use real vehicles with the aim of testing the formation of particles by brake wear in laboratory conditions.
It is important to note that each of the applied methods has specifics, i.e. test conditions differ in each case. When a pin-on-disc tribometer is applied for testing brake wear and particle formation, it is not possible to apply a pad on the tribometer that would have the same dimensions as on a real vehicle, while the disc could certainly be made of brake disc material. However, such devices may have different combinations of test conditions in terms of different pin and disc contact speeds and pressures.
Compared to the pin-on-disc tribometer, inertial brake dynamometers represent a much more realistic type of testing the formation of particles by brake wear. Such devices also belong to the laboratory type of devices with the use of brake pads and disc brakes that are actually applied to the vehicle. Brake dynamometers can very well simulate real vehicle braking and can even simulate different braking conditions (temperature, speed, pressure, air flow, etc.).
Road tests are the most realistic type of test; however the test itself is very complex. This type of testing, when it comes to particles caused by brake wear, is especially complex because there are other sources of particles on the road, so it is necessary to separate the particles generated by the braking system. This problem is much easier to solve in the case of tribometers and a brake dynamometer.

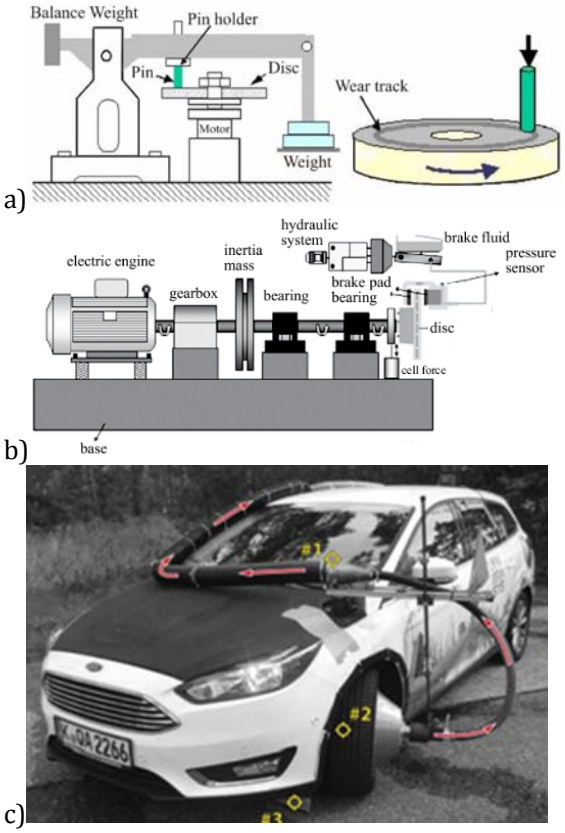

Fig. 1. Different methods for testing the concentration of particles formed by braking, a) pin-on-disc tribometer, b) inertia brake dynamometer, c) road measurement [5-8]

Having in mind the problem of the presence of particles that do not occur due to brake wear, during the test it is necessary to enable the measurement of only the particles formed by

the brakes. This is solved by isolating the brake itself in a closed housing from which the particle measuring device draws air with brake wear particles. In this way, the particle measuring device retracts and measures only the particles formed during the braking process, while the other particles remain outside the housing and the device does not retract those particles. The appearance of the housing itself is different depending on the experimental installation used for measurement. Of course, as it is necessary for air to enter the housing, at the very beginning where the air enters from the outside, there is an element for purifying the air from particles, mainly an HEPA (High Efficiency Particulate Air) filter.

When it comes to the characteristics of the device used, it mostly depends on the author himself, i.e. what is the topic of his research and what are the possibilities of the installation itself. Thus, most measuring installations can measure the rotation speed of the disc, the contact pressure between elements of the friction pair, individual temperature of the brake disc and the brake pads, the temperature in contact surface, pressure in the measuring installation, deceleration of the disc, different loads, etc. Furthermore, other devices can be connected to the measuring installation, such as the humidity control device inside the housing in which the disc brake is located, but again depending on what is being tested and what conditions the researcher wants to achieve during the test.

The most important device during such tests when particles are the subject of research is certainly the device for measuring the concentration of particles. Mostly different authors use different devices, although all devices have in common that they are intended for analysis and measurement of particle concentration. Different authors also use different measurement methodologies, i.e. different modes of particle measurement. Thus, some authors use measuring devices, i.e. modes for measuring the number of formed particles classified according to their sizes or particle concentration $\mu g/m^3$. Some research also uses multiple devices to measure particles in multiple modes.

Some of the solutions used in measuring and testing brake wear, as well as various solutions used by other authors are presented later in this paper.

3. APPLICATION OF TRIBOMETER IN MEASUREMENT OF PARTICLES FORMED DURING BRAKING

Numerous authors use various constructive solutions of tribometers to test the wear rate, especially of new materials in brake pads and their behavior in terms of the stability of the coefficient of friction.

Wahlström et al. applied a tribometer solution shown in Figure 2 to test brake wear and particle formation. In this case, in order to collect only the particles that are formed by the wear of the pin and the disc, the tribometer is located inside the housing (marked with a black bold line) and thus prevents the measurement of non-wear particles. In order to inject air from the outside into the housing, i.e. outside the housing, an HEPA filter of class H13 EN 1822 is placed at the inlet, as well as the compressor before the filter itself, while the air flow was measured using the TSI® air velocity transducer model 8455. Three devices were used for particle measurement and analysis, namely Dekati® Electrical Low Pressure Impactor (ELPI +), TSI® Optical Particle Sizer (OPS) model 3330 and TSI® Condensation Particle Counter (CPC) model 3772.

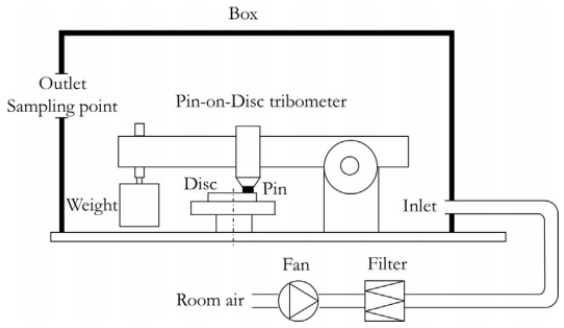

Fig. 2. Example of a solution for a device for testing the formation of particles using a pin-on-disc tribometer [9]

A similar solution of the measurement installation as before, in order to use a pin-on-disc for measuring particles caused by brake wear, was used in the study by Dizdar et al. [10]. Also, three particle analysis devices were used here: optical particle sizer (TSI® Optical Particle Sizer (OPS) model 3330), condensation particle counter (CPC) and electrical low-pressure impactor (ELPI).

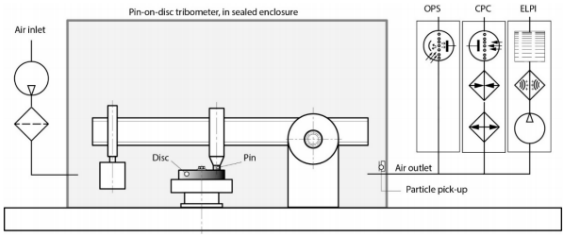

Fig. 3. Example of a solution for testing the particle formation using a pin-on-disc tribometer [10]

Mirzababaei and Filip [11] examined the effect of humidity on brake wear. Figure 4 shows the appearance of such an experimental installation. An ultrasonic Cool Mist Humidifier was used to control the humidity inside the housing.

Fig. 4. Example of a solution for testing brake wear and the influence of humidity on wear [11]

In [12], Djafri et al. presented an example of a tribometer for testing the influence of humidity on brake wear and particle formation. Figure 5 shows the installation where the housing in which the disc and pin are closed is marked with 3. Humidity and temperature are controlled in the housing itself. Meaning of the lebels in Figure 5: (1) measurement unit with a display data panel, (2) adjustment unit of test conditions (humidity and ambient temperature), (3) essay chamber, (4) disc-pin couple, (5) display screen [4].
Tribometer used to test brake wear by Cuev [13] is shown in Figure 6. An interesting aspect in this installation is the way of measuring the temperature inside the brake pads, or specifically inside the pin. In this case, the thermocouple sensor is placed inside the pin, so the temperature inside the pin is measured.

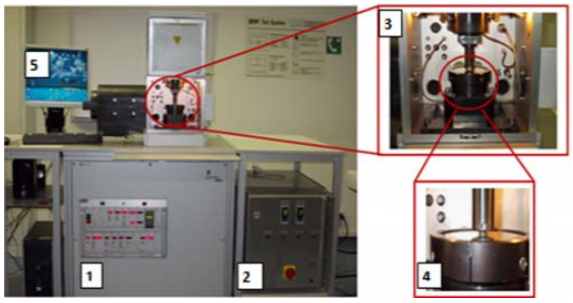

Fig. 5. Example of solution for testing particle formation using pin-on-disc tribometer under humidity and temperature control conditions [12]

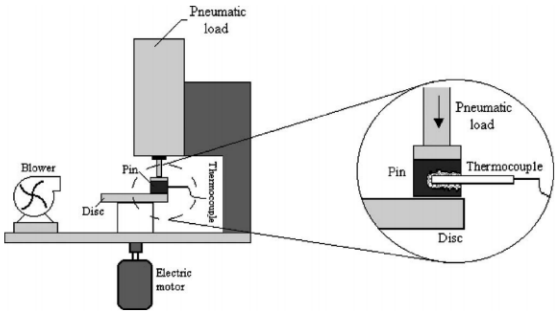

Fig. 6. Example of a solution for testing brake wear and the effect of humidity on wear [13]

4. LABORATORY TESTS OF REAL VEHICLE BRAKES

Bearing in mind the fact that Chapter 2 mentions tests performed using real brakes that are normally installed on vehicles and in the form of an inertial brake dynamometer and real vehicles only in laboratory conditions, this chapter presents such solutions that were used in testing.

4.1 Measurement of particle formation using an inertial brake dynamometer

A schematic representation of the inertial brake dynamometer in the examination of the formed particles, which is shown in [14], is specifically given in Figure 7. In this case, too, it is noticeable that the brake is located inside the housing from which the particles are collected and measured.

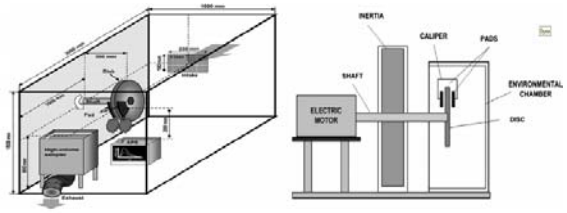

Fig. 7. Schematic representation of the dynamometer and brake housing [14]

In their study, Niemann et al. [15] applied the measuring installation shown in Figure 8. In this study, too, the disc brake is located inside the housing, and the air entering the housing from the environment is purified using an HEPA filter. This measuring installation was developed by the Institute of Environmental and Energy Technology (IUTA e.V.). For particle measuring and their analysis, an Optical Particle Sizer (TSI OPS 3330), a Fast Mobility Particle Sizer (TSI FMPS 3091), and a Condensation Particle Counter (TSI CPC 3776) were used.

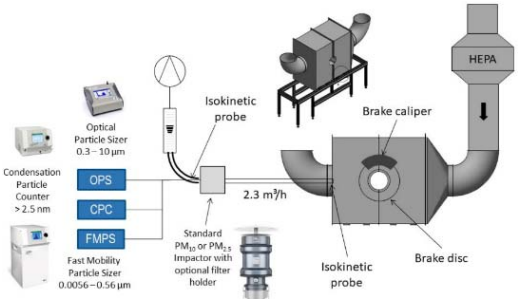

Fig. 8. Measuring installation applied in research[15]

Hagino et al. applied the installation shown in Figure 9 to investigate the concentration of the formed particles. The experimental installation is designed so that it is possible to monitor and record multiple parameters that can be analyzed and compare their impact on the formation of particles during braking.

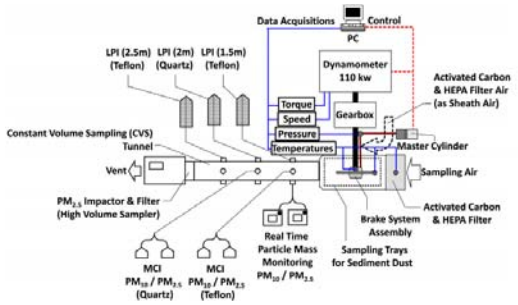

Fig. 9. Applied measuring installation in research of formed particles during braking [16]

In their study of particle formation by brake wear in the braking process, Matějka et al. applied the measuring installation shown in Figure 10. In this case, an electric low-pressure impactor ELPI+ (Decati) was used to measure the particles.

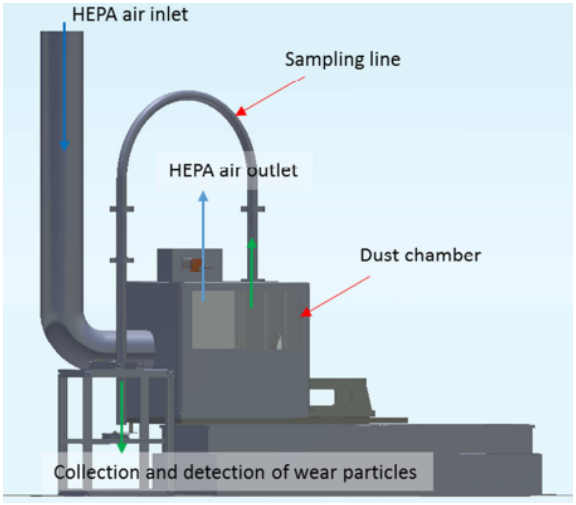

Fig. 10. Applied measuring installation for measuring particles formed during braking [17]

Figure 11 shows the measuring installation used in the research [18]. It can be seen from the figure that, in this case, clean-air flows through the brake disc which further pushes the particles towards the devices for measuring and analyzing the formed particles.

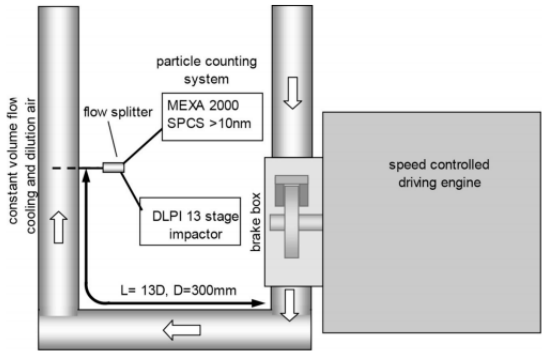

Fig. 11. Applied measuring installation for measuring particles formed during braking [18]

According to [19], the installation shown in Figure 12 can be used to measure the formed particles.

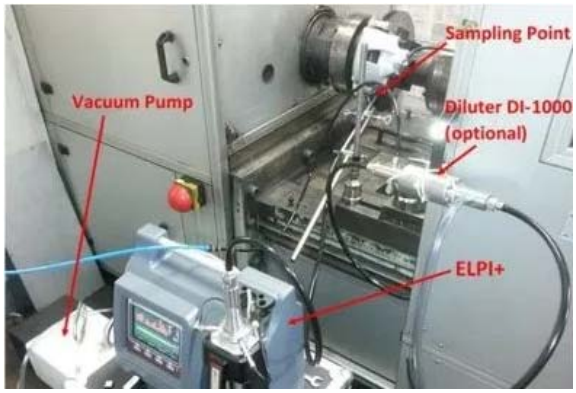

Fig. 12. Applied measuring installation for collecting the particles formed during braking [19]

One of the professional installations for brake particle emissions developed by LINK Engineering is shown in Figure 13. Such installations have a wide range of test possibilities. Such installations can simulate driving cycles, and also control conditions such as air temperature, humidity, brake cooling, and many more. Interesting in this case is the housing in which the brake is located and it is also shown in the figure.

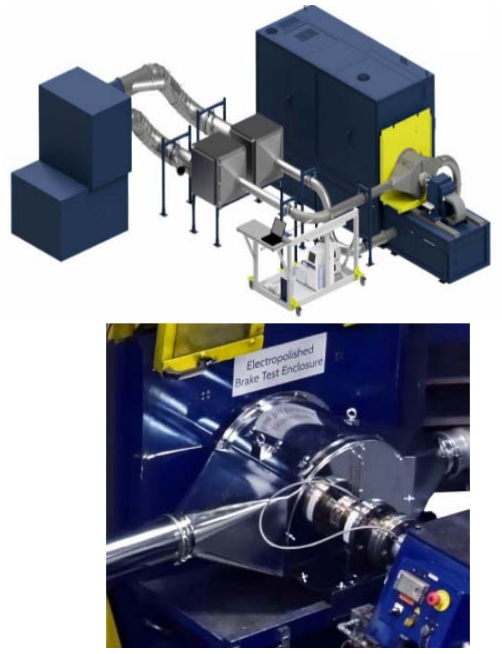

Fig. 13. Applied measuring installation for measuring particulate matter during braking [20]

Reference [13] shows a measuring installation that was also developed for measuring the concentration of particles generated by braking, but also for the analysis of particles. Figure 14 shows the disc brakes inside the housing as well as the construction of the housing, but also the construction of the air inlet and outlet to the housing.

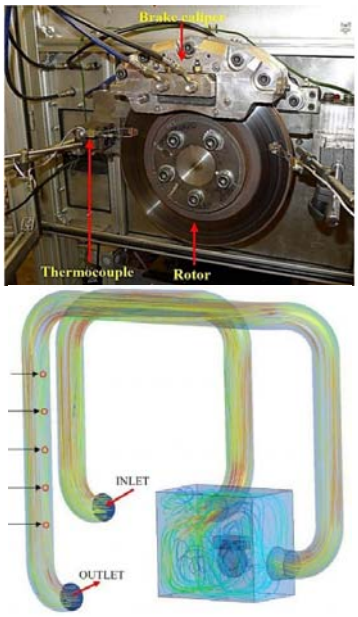

Fig. 14. Particle collection installation [21]

One of the methods for collecting particles according to [22] is shown in Figure 15. In this case, the particles created by wear are directly collected and withdrawn.

Fig. 15. Particle collection method [22]

A view of the housing in which the disc brake is located is shown in Figure 16. It can be seen in the figure that this housing is closed, as mentioned so far. This figure shows the way air escapes from the housing to the particle measuring devices.

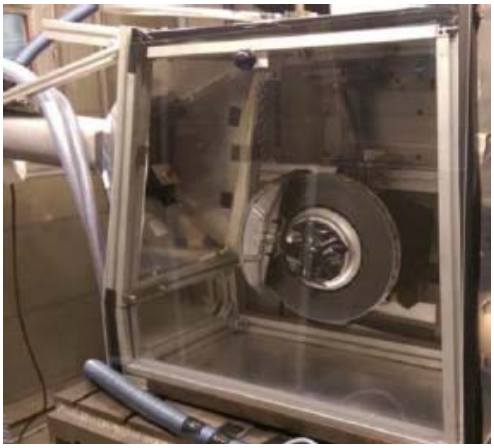

Fig. 16. Particle collection method [23]

Figure 17 shows another solution of the particle feeder. In this case, as can be seen, there is a profile that is connected to the device for measuring the concentration of particles, so with the help of this part, the formed particles are retracted and measured.

Fig. 17. Particle retraction method formed by brake wear [24]

4.2 Measurement of generated particles using real vehicles in laboratory conditions

Although research on real vehicles in laboratory conditions is very rare, at least from the aspect of particles generated during braking, Perrenoud et al. in a study [25] performed just such research. Six different vehicles were used in this research, but in laboratory conditions. An illustration of one vehicle on which the measurement of particle formation was performed is shown in Figure 18. In this case, it is noticeable that the housing is placed on the brake, i.e. on the vehicle in the part where the brake is located. Thus, only the measurement of particles created by brake wear is possible and there is no entry of particles from the environment. According to [25], the labels in Figure 18 represent: A-exposure box; B - HEPA filter and pump system; C - water cooling pump; D - pumps for collection on filters; E - DMA-CPC particle sizer and counter. Wide Range Aerosol Sampler (Grimm Aerosol Technik GmbH & Co) and condensation particle counter (DMA-CPC, Vienna U-Type, model 5.400) were used for analysis and measurement of particles.

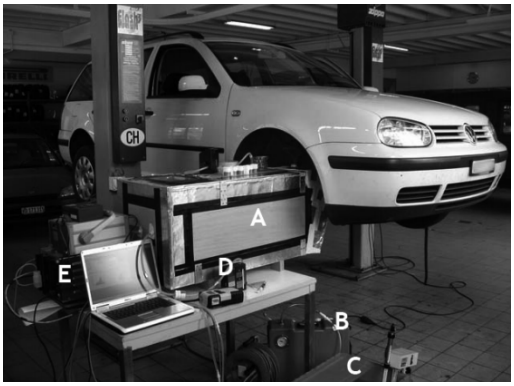

Fig. 18. Investigation of particle formation on a real vehicle in laboratory conditions [25]

A similar measurement installation was presented by Riediker et al. in his research [26]; however, he also gave an overview of some parts of the installation and the installation solutions shown in Figure 19. It is noticeable that an installation is shown in the housing that allows the retraction of particles, while the device for measuring concentration is outside the housing, but there are also sensors for measuring humidity of the air and body which enable the maintenance of a stable temperature.

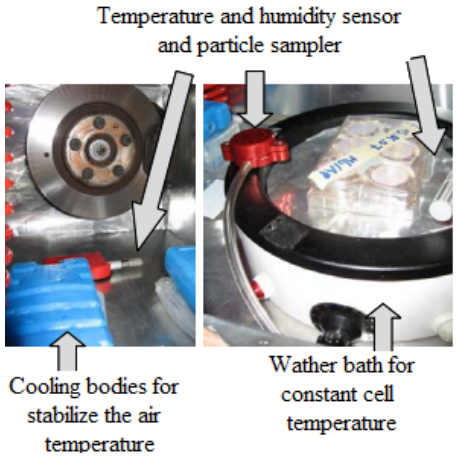

Fig. 19. Investigation of particle formation on a real vehicle in laboratory conditions [26]

5. MEASURING INSTALLATION PROJECT FOR BRAKE WEAR MEASUREMENT AT THE FACULTY OF ENGINEERING

The measuring installation at the Faculty of Engineering, University of Kragujevac will be based on the inertial brake dynamometer shown in Figure 20.

The installation is based on the fact that it is possible to change the loads during braking, which simulates different wheel loads. Thus, it is possible to simulate different types of vehicles and their axle loads, and to achieve different speeds, so different loads of one wheel of the vehicle and wheel's rotation speed can be combined as when the vehicle is on the road. At any time, it is possible to monitor the speed of rotation of the disc on the computer, i.e. the simulated speed of the vehicle. Braking with different pressures has been achieved so that it is possible to adjust the braking force. So the pressure in the brake system can be monitored on the computer too, and it is also possible to control the pressure. The installation is also equipped with sensors for measuring the temperature of the brake pads in different zones of contact.

Fig. 20. Inertial brake dynamometer at the Faculty of Engineering [27]

In order to measure the particles formed during braking, the dynamometer was upgraded with a housing in which the brake is located. The purpose of the housing is to collect the particles that were created by the wear of the brakes and to place a device for measuring the concentration of particles. It is certainly necessary for air to enter the housing from the environment in order not to create a vacuum when extracting air with the help of a device that measures the concentration of the formed particles. In order to prevent particles from entering from the environment and to avoid leading to erroneous measurement results, there is an HEPA filter at the inlet that purifies the air entering the housing.

The device used for measuring particles, i.e. particle concentration is TROTEC PC-220, which is shown in Figure 21. The device can measure the number of particles $PM_{0.3}$, $PM_{0.5}$, PM_{1}, $PM_{2.5}$, PM_{5} and PM_{10}. Bearing in mind that the device can measure particles in multiple modes, one possibility is to measure the mass of particles in $\mu g/m^3$; however such measurement is only possible for particles $PM_{2.5}$ and PM_{10}. The device enables the transfer of data from its internal memory to a computer, so it is possible to analyze data numerically or graphically using diagrams [28].

Fig. 21. Trotec PC-220

The entire projected installation is shown in Figure 22. The dashed line in the figure represents the housing from which the particles are extracted, and the concentration is measured using a Trotec PC-220. The red arrows represent the data that the researcher sets as the initial conditions, i.e. braking conditions, single wheel loads, speed and brake

pressure. The green line represents the data that is collected and controlled at the same time as the conditions that are set as the initial.

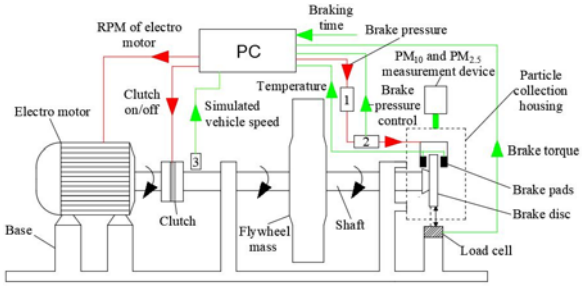

Fig. 22. Schematic representation of the proposed measuring installation for measuring particles generated by brake wear

6. CONCLUSION

Measurement installations for monitoring the concentration of particles differ from author to author, but the test method itself also differs. Measurement devices generally differ in their performance depending on what the author's aim of the research. Tribometers are most often used, but in a large number of studies, inertial brake dynamometers are also used. Certainly, different sensors are used on each installation, which can measure different parameters, but the most important devices are those for measuring and analyzing particles. These are the key devices in any installation.

The measured installation at the Faculty of Engineering, University of Kragujevac is a type of laboratory testing using an inertial brake dynamometer. The installation developed at the Faculty is a very complex installation that allows a number of different tests of vehicle brakes, but also has the possibility of different modes of operation and changing various parameters.

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