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Research Paper

Theoretical Analysis of the Motorcycle Front Brake Heating Process during High Initial Speed Emergency Braking

Andrzej Borawski[1], Dariusz Szpica[2], Grzegorz Mieczkowski[3], Eliza Borawska[4], Mohamed M. Awad[5], Rizk M. Shalaby[6], Mohammed Sallah[7]

[1] Faculty of Mechanical Engineering, Bialystok University of Technology, 45C Wiejska Str., 15-351 Bialystok, Poland, Email: a.borawski@pb.edu.pl

[2] Faculty of Mechanical Engineering, Bialystok University of Technology, 45C Wiejska Str., 15-351 Bialystok, Poland, Email: d.szpica@pb.edu.pl

[3] Faculty of Mechanical Engineering, Bialystok University of Technology, 45C Wiejska Str., 15-351 Bialystok, Poland, Email: g.mieczkowski@pb.edu.pl

[4] Faculty of Mechanical Engineering, Bialystok University of Technology, 45C Wiejska Str., 15-351 Bialystok, Poland, Email: eliza.borsztejn@wp.pl

[5] Mechanical Power Engineering Department, Faculty of Engineering, Mansoura University, Mansoura 35516, Egypt, Email: m_m_awad@mans.edu.eg

[6] Physics Department, Faculty of Science, Mansoura University, Mansoura 35516, Egypt, Email: rizk2002@mans.edu.eg

[7] Physics Department, Faculty of Science, Mansoura University, Mansoura 35516, Egypt, Higher Institute for Engineering and Technology, New Damietta, Egypt, Email: msallahd@mans.edu.eg

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Corresponding author: A. Borawski (a.borawski@pb.edu.pl)

Abstract. Motorcycles are a common mode of transport. They are used both for a conventional purpose - as a way to cover the distance from A to B, but more and more often they are a way of recreation. The choice of bikes is huge on the market: from scooters, threw small city bikes, to high-speed performance or racing machines. High speeds is closely related to high kinetic energy of movement. In case of emergency stopping, the brakes may overheat and cause fading. In this study, it was decided to check how the initial speed affects the motorcycle brake heating process. FEM was used for this purpose.

Keywords: Mechanical engineering, Brakes, Simulation study, Friction heating, FEM.

1. Introduction

Motorcycles are a very specific group of vehicles. They can be a peaplecarriers as well as a delivery vehicles (e.g. delivery of purchases or meals). However, they are most often used for recreational purposes [1]. Various groups of models could be found here, such as: choppers, crusiers or superbikes [2]. The last ones are capable of tremendous speeds and, thanks to their low mass, generate impressive acceleration. Braking systems are extremely important in such solutions.

Most motorcycles manufactured today use disc brakes. The main element of this type of design is the disc, spinning alongside the wheel, and the brake pads, connected with the hub via a calliper [3]. As the pad is pressed against the disc, kinetic energy transforms into heat because of friction. The energy, in the form of heat is then released into the atmosphere [4]. The friction force largely depends on the materials used in the production of the friction pair [5]. Brake discs are often made of grey cast iron, as it is characterised by good thermal conductivity and anti-vibration capacity [6]. Newest disc solutions, especially in sports vehicles, utilise composite materials based on ceramics [7].

As for the brake pads, they are composites [8] made of a binding agent and other components (usually about 15-20 different substances). These may include materials which affect the coefficient of friction (e.g. copper, steel, cast iron), improve mechanical strength (various fibers), as well as fillers [9]. The binding agent is usually resin [10, 11]. However, resin has low resistance to high temperatures. Literature reports on attempts to modify the chemical composition of resins, yet even the best results indicate that temperatures of 400-500 ^{o}C lead to degradation of resin, which may cause abrupt loss of braking ability, and consequently endanger the health and lives of road users [12, 13].

Numerous researchers conduct studies on the brakes heating process and temperature profiles as a result. Such studies, however, generally focus on other types of vehicles, with the majority concerning on passenger cars [14, 15], as well as trains [16,17] , aircraft wheels [18, 19], trucks and their trailers [20-23], or even agricultural machinery [24, 25]. Unfortunately, testing of motorcycle brakes is rare and concerns mostly aspects other than heating. For example, systems supporting braking [26] or loss of control prediction [27] have been studied. Much research manuscripts are related to the ABS [28-30] and anti-skid [31] systems. In the cited manuscripts informations related to the braking process simulations could be found, but the main subject of research is the process itself and the physical phenomena occurring in it, e.g. pressure changes in the system or the transfer of the center of gravity. Some researchers consider the motorcycle braking system as a separate, complex system and investigate the behavior of

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its individual elements or the course of delayed motion [32-36]. The heating research is very modest. García-León et al. developed a mathematical model of the braking process and performed a simulation, however, they considered only one case for a low initial speed [37]. Zurin et al. has shown simulation results, however, there are no detailed data on the model or material data used [38].

This work is therefore a response to a knowledge gap and an attempt to develop mathematical describtion of the motorcycle braking process and the related friction heating of the working elements of brakes. On the basis of the model, simulation tests for various initial speeds will be performed.

2. Simulation Tests

2.1 Object and methodology of research

For the purposes of this manuscript, a motorcycle popular in Poland was selected, the brakes of which will be the subject of research. The most important technical data of the selected vehicle are presented in Table 1. Samples were taken from the brake system components to determine the necessary thermo-physical properties: heat capacity, termal conductivity, density and coefficient of friction. The tests were carried out at Mansoura University laboratory. Results are summarized in Table 2. Coefficient of friction between disc and pad turns out to be 0.39.

Table 1. Selected technical data of the vehicle.

Parameter	Value
Top speed	263 km/h
Engine capacity	599 cm^3
Wheelbase	X_1=1400 mm
Front brake disc	2x 310 mm
Front tire	120/70/ZR17
Total weight	m=170 kg
Center of gravity	H=806mm, X_1=610 (Fig. 2)

Table 2. Thermo-physical properties of prepared samples.

Pad			Disc		
Thermal conductivity ($W/m{\cdot}K$)	Heat capacity at constant pressure ($J/kg{\cdot}K$)	Density (kg/m^3)	Thermal conductivity ($W/m{\cdot}K$)	Heat capacity at constant pressure ($J/kg{\cdot}K$)	Density (kg/m^3)
154	1487	3341	48	488	7890

The first step in the simulation research was to develop a CAD model of tested elements. They have been simplified compared to the real parts. The simplification consisted in changing the geometry in such way as to remove elements that did not have a significant impact on the test results, but could significantly densify the mesh and extend the experiment duration. The developed model was covered with a mesh. It consisted of nearly 36k elements (pyramid shaped), which gave about 64.5k noods (Figure 1).

COMSOL software was used for the tests. Beginnig of simulation is the moment of brakes initiation. Total simulation time is 10 s with step 0.05 s. Two probes were used to analyze the results: 1) in the geometric center of the contact plane 0.02 mm into the pad material, 2) in the geometric center of the contact plane 0.02 mm into the disc material.

2.2 Initial and simplifying assumptions

Each simulation study is associated with an attempt to describe reality using mathematical equations. It has some limitations, because the exact reproduction of every detail is extremely difficult, and the resulting solutions required enormous computing power. Therefore, it is a common practice to adopt certain simplifications that allows to reduce the degree of difficulty of mathematical considerations without simultaneously burdening the obtained results with significant errors. For the purposes of this study, it was assumed that:

- the coefficient of friction between the disc and the pad is constant (while in fact it is temperature dependent),

a) b)

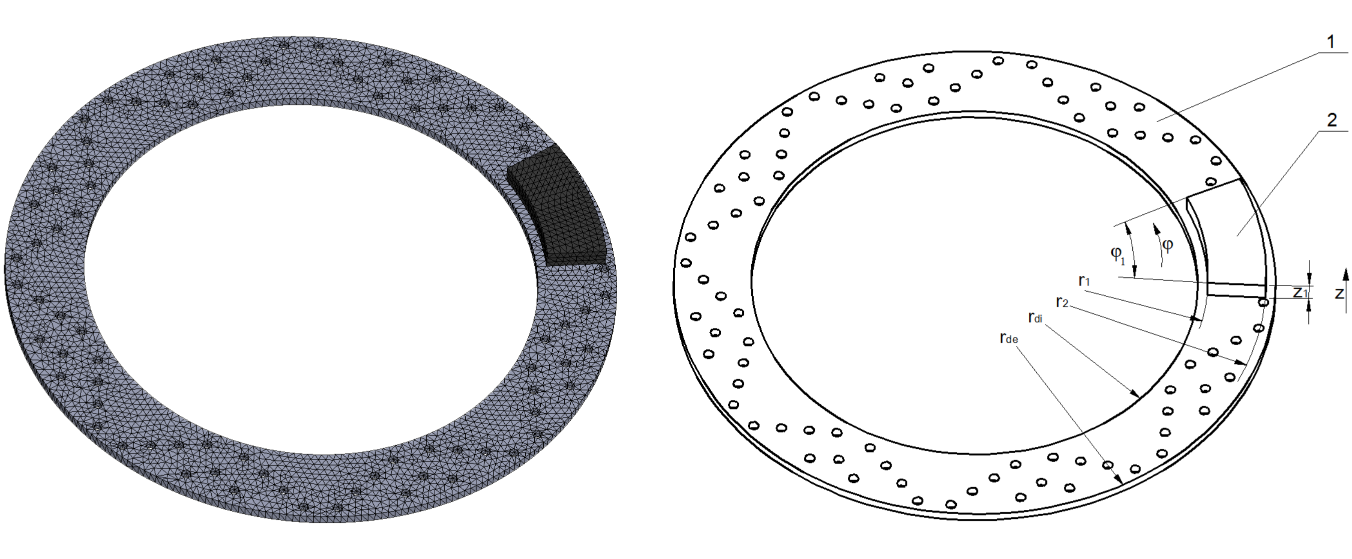

Fig. 1. CAD model of object of research: a)covered by mesh, b)with geometry markings.

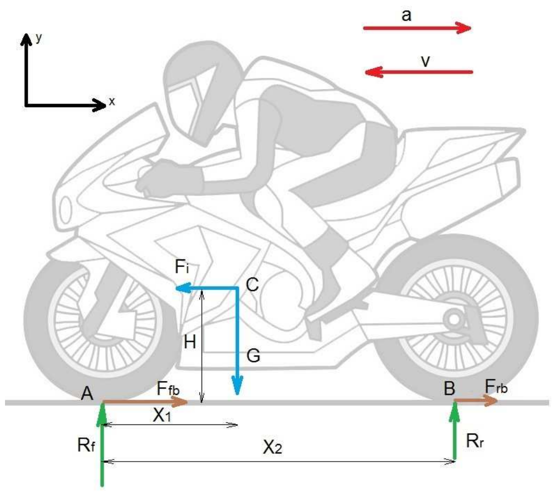

Fig. 2. The system of forces acting on the braking motorcycle.

- contact occurs with the entire surface of the pad (in fact only about 20-30 % is in contact [39]),
- contact pressure is constant and homogeneous (in fact, due to plastic deformation, the pressure distribution on the surface is uneven [40]),
- external factors (wind, road bumps, etc.) do not affect the course of the braking process,
- braking takes place without slip and the coefficient of friction of the tire to the surface is 1,
- the contact pressure builds up immediately (the rising slope is vertical, when in fact it increases with time),
- initial speed will be 100, 150, 200 and 250 km/h.

The choice of initial speeds resulted from the capabilities of the motorcycle in question and it was to take into account the cross-section of speeds over 100 km/h. Moreover, it turned out to be necessary to determine the maximum allowable braking deceleration, since excessive braking could cause a loss of stability by completely relieving the rear wheel as a result of the inertia force (Figure 2).

For this purpose, the equations of the balance of forces and moments acting on the vehicle were used:

$$\begin{cases} \sum Mi_a = F_i H - GX_1 + R_r X_2 = 0 \\ \sum Fi_y = G - R_f + R_r = 0 \end{cases}, \tag{1}$$

and because:

$$F_i = ma\,, \tag{2}$$

$$G = mg\,, \tag{3}$$

it finaly gets form:

$$\begin{cases} \sum Mi_a = maH - mgX_1 + R_r X_2 = 0 \\ \sum Fi_y = mg - R_f + R_r = 0 \end{cases}. \tag{4}$$

Using the stability condition, which is:

$$R_r > 0, \tag{5}$$

maximum allowed deacceleration can be calculated by transforming the equasion:

$$R_r = \frac{-maH + mgX_1}{X_2} > 0 \Rightarrow \frac{gX_1}{H} > a \tag{6}$$

This allows the maximum permissible deacceleration to be calculated, which after substituting the data is:

$$a < 7.42[m/s], \tag{7}$$

and it was this value that was used for further calculations.

2.3 Mathematical description of braking process

Model development began with the determination of brakes' retardation power. It can be calculated as a negative value of the derivative of the kinetic energy of a moving motorcycle:

$$P = \frac{d}{dx}\left(\frac{mv^2}{2}\right); 0 \le t \le t_2, \tag{8}$$

or:

$$P = -mR^2\omega(t)\alpha; 0 \le t \le t_2. \tag{9}$$

If the braking deceleration is constant, the angular velocity can be written as:

$$\omega(t) = \omega_0 + t\alpha; 0 \le t \le t_2. \tag{10}$$

Assuming that braking will take place at the limit of stability, it can be stated that only the front wheel will brake. This wheel is equipped with two brake discs. The tests will cover one of them, so 50% of the total braking force will be taken into account. Therefore, the braking force for one disc will be written as:

$$F_b = 0.5 \cdot F_{tb}. \tag{11}$$

Heaving above in mind the retardation power can be described as:

$$P = -0.5 \iint F_{f/u} \cdot dA_s \cdot v_d. \tag{12}$$

Value of linear disc speed can be calculated from:

$$v_d = \omega(t) \cdot r_d(r), 0 < t < t_2, r_1 < r < r_2, \tag{13}$$

while contact surface area for one of pads can be expressed as follows:

$$A_s = \frac{\varphi_1}{\pi}(r_2 - r_1), \tag{14}$$

The braking retardation power could be also defined by the equation:

$$P = F_{f/u}\omega(t) \iint r_c \cdot dA_s, 0 < t < t_2. \tag{15}$$

where:

$$r_c = \frac{2\pi}{A_s}\int_{r_1}^{r_2} r^2 dr = \frac{2(r_2^3 - r_1^3)}{3(r_2^2 - r_1^2)}, r_1 < r < r_2. \tag{16}$$

Solution of following equasion of heat conduction will allow us to determine transient temperature distribution:

$$\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} + \frac{1}{r^2}\frac{\partial^2 T}{\partial \varphi^2} + \frac{\partial^2 T}{\partial z^2} = \frac{1}{K}\left(\frac{\partial T}{\partial t} + \omega\frac{\partial T}{\partial \varphi}\right), r_1 < r < r_2, 0 < \varphi < 2\pi, 0 < z < z_1. \tag{17}$$

at boundary conditions as follows:

$$K\left.\frac{\partial T}{\partial z}\right|_{z=0} = h[T_a - T(r,\varphi,z)], r_1 < r < r_2, 0 < \varphi < 2\pi, 0 < z < z_1, \tag{18}$$

$$K\left.\frac{\partial T}{\partial r}\right|_{r=r_1} = h[T(r,\varphi,z) - T_a], r_1 < r < r_2, 0 < \varphi < 2\pi, 0 < z < z_1, \tag{19}$$

$$K\left.\frac{\partial T}{\partial r}\right|_{r=r_2} = h[T_a - T(r,\varphi,z)], r_1 < r < r_2, 0 < \varphi < 2\pi, 0 < z < z_1, \tag{20}$$

$$\left.\frac{\partial T}{\partial z}\right|_{z=z_1} = 0, r_1 < r < r_2, 0 < \varphi < 2\pi, 0 < z < z_1. \tag{21}$$

Otherwise it can be said, that during the action of the brakes, the following amount of heat is released through convection and radiation [31]:

$$q_d = -h(T - T_a) - \varepsilon\sigma(T^4 - T_a{}^4), \tag{22}$$

The relation between the convention coefficient and the speed of the vehicle is described as follows [41]:

$$h = \frac{0.037K}{2(r_{de} - r_{di})}\left(\frac{2r_c\rho v}{\mu}\right)^{0,8} \cdot \left(\frac{C_p\mu}{K}\right)^{0,33}. \tag{23}$$

3. Results and Discussion

The main research results were temperature profiles illustrating the braking process in terms of thermal conditions. Figure 3 shows the course of brake pad, and Figure 4 is for the brake disc.

As it can be seen, there are clear differences between the initial speeds in the graphs. In both cases, the highest temperature was recorded when braking from 250 km/h. In that case the brake pad reached just over 459 K (185 °C). It appeared 5.4 s from the start of braking. The disc in the same study turned out to be cooler. It reached 455 K (181 °C) in 5.6 seconds. The difference is therefore small and is mainly due to different thermo-physical properties of both materials. An interesting fenomenon can be seen on the temperature profile of the pad when the motorcycle comes to a complete stop. The temperature of the material increases despite the lack of a heat source (friction movment). For braking from 250 km/h, this increase was just over 2 K. The reason for this phenomenon is the heat transfer from the disc to the pad as a result of convection. This phenomenon is noticeable in all examined cases, but it is particularly interesting in the case of incident no. 1. The thermal energy supplied from the disc causes the pad material to heat up to a temperature higher than that resulting from friction. The increse is not large, it is approx. 1 K. The lowest temperatures were of course recorded for the initial speed of 100 km/h. The pad heated up to the temperature 336 K (62 °C), and the disc to 332 K (58 °C).

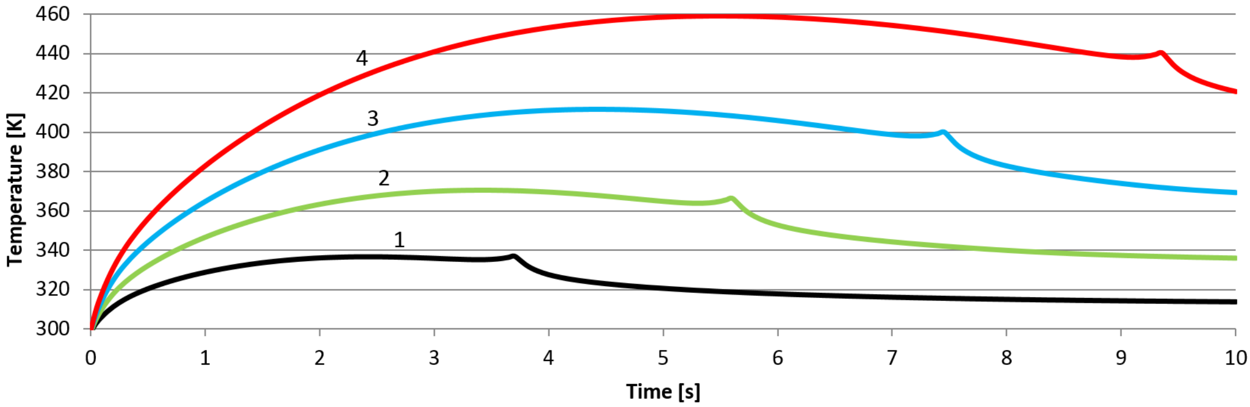

Fig. 3. Course of heating process of brake pad :1- initial speed 100 km/h, 2- initial speed 150 km/h, 3- initial speed 200 km/h, 4- initial speed 250 km/h.

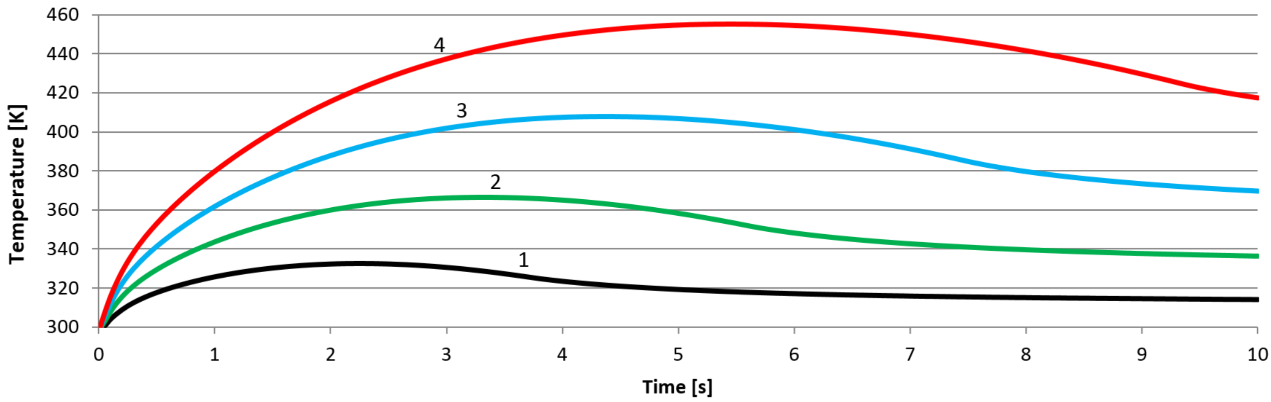

Fig. 4. Course of heating process of brake disc :1- initial speed 100 km/h, 2- initial speed 150 km/h, 3- initial speed 200 km/h, 4- initial speed 250 km/h.

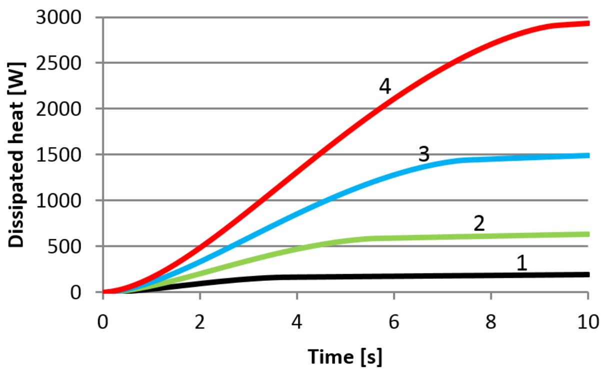

Fig. 5. Heat dissipated to athmosfere threw radiation and convection: 1- initial speed 100 km/h, 2- initial speed 150 km/h, 3- initial speed 200 km/h, 4- initial speed 250 km/h.

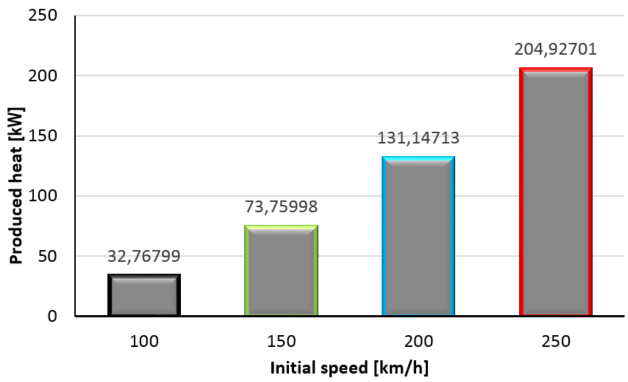

Fig. 6. Amount of heat produced in braking process

The reasons for the low maximum temperatures obtained in the tests, compared to e.g. cars, should be seen primarily in the low weight of the motorcycle. In addition, the design of the brake system, featuring two drilled brake discs, significantly reduces the heat load. Energy is released to the environment far more quickly, which was verified in the next series of results - the course of dissipated heat (Figure 5). High heat transfer rate can be seen especially in the initial phase. Performed tests also allowed to determine the amount of energy generated by friction. The results are presented in Figure 6.

4. Conclusion

In the paper a mathematical model of the motorcycle braking process was presented. The sports model popular in Poland was selected as the research object. On its basis, a CAD model of the working elements of the braking system was developed. Samples taken from the actual, real parts allowed to determine selected thermo-physical properties - necessary for simulation tests. COMSOL software was used in the research. The simulations were performed for various initial speeds of 100, 150, 200 and 250 km/h. In the course of the research it was found that:

- low weight and design details of the braking system ensure moderate maximum temperatures achieved by the working parts of the brakes,
- of all considered cases, the highest temperature on the pad surface was recorded when braking from an initial speed of 250

km/h (it was a value of 459 K); the top temperature on the pad surface had the lowest maximum value (336 K) when braking from a speed of 100 km/h,

- in the same cases, the disc temperature was 455 K and 332 K, respectively,
- despite the lack of mutual movement of the friction pair, the readings show that the temperature of the pad material increases near the contact surface; this is because both materials have different thermal capacities and thermal conductivities - part of the heat energy is therefore received from the brake disc and then transferred into the material.
- at the beginning, when the velocity is high, it can be seen that the heat release curve has a positive derivative value; during the process it goes to zero, then drops to negative values at the end of braking; after complete stop, it becomes linear - this is because at the beginning of braking, although the most thermal energy is generated, the cooperating materials are still cold; large temperature differences increase the energy gradients, and after the speed drops to zero and the heat source is extinguished, only energy transfer to the environment takes place.
- in the performed tests for the highest initial velocity, the temperatures reached are within a safe range, so there should be no fading phenomenon.

Author Contributions

A. Borawski initiated the project, planned the reaserch, developed mathematical model; D. Szpica conducted the simulation tests; G. Mieczkowski analyzed and described the research results, E. Borawska prepared the graphic design; M.M. Awad; R.M. Shalaby and M. Sallah collected and tested in laboratory samples of the brake disc and pad. The manuscript was written through the contribution of all authors. All authors discussed the results, reviewed, and approved the final version of the manuscript.

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Conflict of Interest

The authors declared no potential conflicts of interest with respect to the research, authorship, and publication of this article.

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Nomenclature

A	Contact point of the front wheel with the ground	T	Local mean temperature [K]
B	Contact point of the rear wheel with the ground	T_a	Ambient temperature [K]
C	Center of gravity	ε	Emissivity of material
R_f	Ground reaction to the front wheel pressure [N]	σ	Stefan-Boltzman constant [W/(m^{2}K^4)]
R_r	Ground reaction to the rear wheel pressure [N]	μ	Coefficient of friction
G	Gravity force [N]	ρ	Density [kg/m^3]
F_i	Inertia [N]	ω	Angular velocity of the wheel [RPM]
a	Braking deceleration [m/s^2]	ω_0	Initial angular velocity of the wheel [RPM]
g	Gravity deceleration [m/s^2]	t	Time [s]
v	Driving speed [m/s]	t_s	Braking time [s]
v_d	Brake disc linear speed at radius r [m/s]	α	Angular deceleration, [rad/s^2]
m	Motorcycle mass [kg]	A_s	Area of contact surface [m^2]
R	Dynamic radius of the road wheel [m]	K	Thermal conductivity [W/(mK)]
q_d	Heat released through convection and radiation [W]	h	Convention coefficient [W/(m^{2}K)]
H	Convection coefficient [W/(m^{2}K)]	$F_{f/u}$	Frictional force per surface unit [N/m^2]
φ	Angle variable [rad]	F_b	Total brake force [N]
φ_1	The angle of the pad covering the disc [rad]	F_{fb}	Front wheel braking force [N]
C_p	Thermal capacity [J/(mK)]	F_{rb}	Rear wheel braking force [N]

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ORCID iD

Andrzej Borawski https://orcid.org/0000-0001-5817-655X
Dariusz Szpica https://orcid.org/0000-0002-7813-8291
Grzegorz Mieczkowski https://orcid.org/0000-0002-8090-1671
Mohamed M. Awad https://orcid.org/0000-0001-6238-5872
Rizk M. Shalaby https://orcid.org/0000-0001-9060-7911
Mohammed Sallah https://orcid.org/0000-0003-2063-8979

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