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Thermal Analysis of Simplified Railway Brake Blocks with Different Designs

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Abstract
The main problem with braking and stopping a railway vehicle is that the brake can heat up to a high temperature in a very short time. The dissipation of the generated heat is an important task, because the high thermal loads can cause cracks and deformation on the brake block. In this article, a simplified brake model is presented, on which both tribological experiments and finite element simulations were performed. The test results show good agreement with the heating conditions of real railway brake blocks on basis of literature. Microscopic examination of previously used real brake blocks clearly shows the different levels of heat load on the friction surface parts of the brake blocks. Instead of the currently used cast iron brake blocks, printed test specimens were made from metal powder material suitable for additive manufacturing. For better heat conduction, various shaped copper inserts were placed into the test specimen. It is also shown that if even a few percent of a material with good thermal conductivity are placed in the test specimen with appropriate geometry, the thermal conductivity of the test specimen can be significantly improved. Our goal is to use numerical simulation to find a geometric design that will most effectively remove heat from the higher temperature parts of the friction surface.

Keywords
FEM simulation, railway brake block, railway brake temperature

1 Introduction

1.1 Literature review

Nowadays, rail transport plays an increasingly important role in the European Union, both in freight and passenger transport, further strengthening Europe's efforts to reduce CO_2 emission. Increased rail transport also results in an increase in the frequency of railway brake block failures. Brake block wear and failure also have a significant impact on the wheels of railway wagons, as the brakes of freight wagons act directly on the tread of the wheels, as can be seen in Fig. 1.

In Fig. 1, the arrangement of the brake system can be seen, the main parts of the system were signed with numbers in the following order:

1. brake blocks;
2. the block holders;
3. brake mechanism;
4. and wheel.

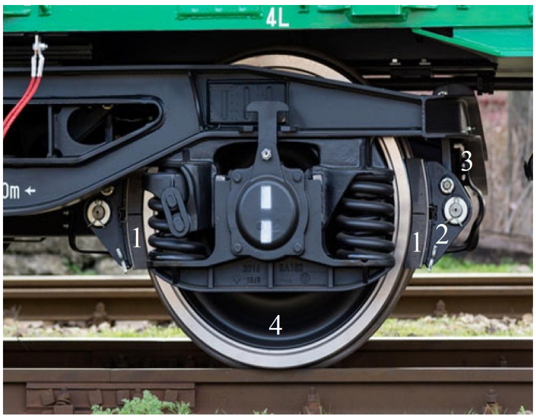

Fig. 1 The arrangement of a conventional brake system of a freight wagon (Appoh et al., 2021)

Braking causes wear not only on the brake block but also on the wheel tread. As a result of wear, the conicity of the tread changes. The accuracy of conicity is an essential

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condition for smooth driving in curves (assuming good condition of the rails). Failure of the wheel or brake of freight wagons imposes high costs to the operators, due to the reworking of the wheels or the withdrawal of the wagons from traffic (Vaerst, 2015, UIC, 2013).

During braking, the brakes convert the kinetic energy of the railway wagons into thermal energy. The heat is generated at the contact surface of the brake block with the wheel (Teimourimanesh et al., 2010). One part of the generated heat is transferred to the wheel and the other part is transferred to the brake mechanism through the brake block. Several experts investigated the heat distribution between the two contacting elements (Jálics and Jálics Sr, 2024; Vernersson, 2007), and how the distribution is influenced by the material grade or the design of the brake system. In current rail transport, several types of materials are used for brake blocks (cast iron, various composite materials). The biggest difference between the two types is that the composite versions operate with significantly lower noise than the cast iron versions. This is because the composite versions have a lower coefficient of friction, which eliminates the phenomenon of stick-slip. This is the phenomenon that causes certain structural elements of the brake and bogie to vibrate and therefore responsible for the sound effects (the sound of stringed instruments can also be attributed to this same phenomenon (Jálics and Jálics Sr, 2024)). This unwanted vibration exposes structural elements to fatigue and can loosen bolted connections, even if they are secured against loosening (Alsardia and Lovas, 2024). Of course, the resulting vibrations also spread towards the rail, which also contributes to the noise of the railway traffic (Kuchak et al., 2021).

The composite brake blocks have lower friction coefficient than the cast iron version, but at the same time they generate a lower braking torque, which results in a longer braking distance and a lower payload. The low friction coefficient can be compensated by a higher clamping force, which is limited by the material grade of the contacting surfaces. There are two types of composite brake blocks: LL-type and K-type. The LL-type can be installed in place of the cast iron without any modifications, while the K-type requires the replacement of the brake cylinder as well. The advantage of the K-type is that its friction coefficient is higher, and the temperature varies less with sliding speed than in the case of the LL-type (Abbasi et al., 2014; Faccoli et al., 2019; Fec and Sehitoglu, 1985; Ficzere, 2024; Srivastava et al., 2016; Wasilewski, 2017; 2018). The price of composite brake blocks is significantly higher than traditional cast iron brake blocks. In fact, the only thing that speaks in favor of composite brake blocks is their quiet operation.

After studying the relevant literature, it can be concluded that some researchers tried to gain knowledge through experiments, while others used some computer simulation methods, regarding how much of the heat from friction goes into the wheel and how much into the brake block. Knowledge of the magnitude of the resulting temperature and the temperature distribution is essential in order to reduce the failure frequency of railway braking systems.

Vakkalagadda et al. (2015) experimentally investigated the heating conditions of brake blocks using a test rig built for this purpose. During their investigation, they examined LL-type, K-type and cast iron types. The conclusion was that using cast iron allows the least amount of heat to enter the wheel, meaning it has the best heat conduction properties. Vernersson et al. (2012) used a classic tribological test method, the pinondisc method, in their experiment. They tested different brake block materials at elevated temperatures. As a result of their experiment, they determined that in the case of composite materials, the value of wear increases proportionally with increasing temperature up to 500 °C, but above 500 °C, wear increases significantly. In the case of cast iron materials, they show similar characteristics to composite materials up to 500 °C, but above 500 °C the value of wear decreases with increasing temperature. The reason for this is the changing wear process. Somà et al. (2021) measured the temperature during braking with a temperature sensor built into the brake block of a real freight wagon. The results obtained in this way were used to validate the FEM simulations. The input data for the FEM simulation was determined by calculation. Their experiment and simulation showed good match. Békési and Váradi (2013) investigated the heating and wear of brake blocks on a test bench with a scale of 1:4. The wheel involved in the study did not follow the conical profile of railway wheels but was cylindrical. Their experimental results were also used to develop a finite element method. Continuing their work, Fekete and Váradi (2013a; 2013b) created a finite element model that examined a complete wheel-brake block system in a finite element program transient thermal environment, where the temperature dependence of the material properties was also taken into account. When building the geometric model, they followed the existing test rig design as closely as possible. The built finite element model showed a very good approximation to the real measurements. In a series of tests conducted by Felhő et al. (2024), the friction between a rotating ring and a stationary disc was studied, thereby simplifying the investigation of the connection between the brake block and the wheel. The rotating ring simulated the wheel (made of steel), while the stationary disc simulated the brake block. In their experiment, the stationary disc was made from real railway brake blocks, both cast iron and composite materials. The purpose of their measurement series was to generate input data for finite element simulations.

Purely numerical simulations can be divided into two groups, one using a 2D model, the other using real 3D body models. Vernersson (1999) created a 2D plane deformation model in a finite element environment. In his simulation he searched for the conditions and locations of hot spots. His results were partly in good correlation with operational experience. Petereson (2002) also created a 2D finite element model, where both the wheel and the brake block were modeled. He applied heat input to the contact surfaces and heat removal to the other surfaces. Thuresson (2004) also used a 2D finite element model, treating the brake block as an elastic body and the wheel as a rigid body. He also took into account the degree of wear while determining the heat development. By performing a series of simulations, he was able to determine good initial parameters, such as the friction coefficient and the thermal conductivity. Békési and Váradi (2013) used brake test rig experiments to create a 3D finite element model. Their goal was to find a relationship between temperature and wear rate. Bolló et al. (2025) investigated the thermal conductivity of railway brake materials using a numerical simulation based on the work of Felhő et al. (2024). By appropriately choosing the input parameters of the simulation environment, the calculated results closely approximated the experimental results.

This article presents a part of a project supported by the European Union. The aim of the project is to design a composite structure with better thermal conductivity than the current, traditionally cast iron railway brake blocks. 3D metal printing is used for production, taking advantage of the speed and geometric freedom offered by technology. The project involves 10 researchers working in three areas. One part of the research group determines the heat transfer properties by measuring test specimens of different material grades (including real brake blocks) (Felhő et al., 2024). Another part of the group reproduces them by numerical simulations in the ANSYS environment (Bolló et al., 2025). Our goal is to use numerical simulation to find a geometric design in a simplified brake model that will more effectively dissipate heat from the higher-temperature parts of the friction surface.

2 The test environment

The measurements are carried out on the Multi-specimen test device (Fig. 2) by Falex NV, the Belgian partner of this project. During the measurement, the specimen is clamped in a holder and a ring is placed on top, which rotates on the specimen (from 0 rpm, accelerated in three steps to 500 rpm, then operated there for 600 s) (Bolló et al., 2025). The rotating ring is pressed against the stationary specimen by a force equivalent to the weight of a 4.5 kg mass. During the tests, the coefficient of friction, the rotation speed and at 3 locations the temperature of the specimen were measured (at the top of the specimen, at the bottom of the specimen and at the clamp below the specimen). The rotating ring is pressed against the stationary specimen by a force equivalent to the weight of a 4.5 kg mass.

Outliers were removed from the measurement data received from Falex NV and the remaining data was averaged. This was necessary to be able to compare the results from the finite element simulation to the measurement. If the boundary conditions of a finite element simulation are the same, then no matter how many times we run the simulation, the result will always be the same. That is, the measurement series (9 pieces per material grade) had to be compiled into one data. The average value of the measurement results of the cast iron material is shown in Fig. 3. The ordinate of the diagram shows the measured temperature value in °C, and the abscissa shows the measurement time in seconds. The resulting curve is a sigmoid-type curve (logistic curve), which Szabó (2024) also draws attention to in his publication. The significance of this is that in the case of sigmoid curves, it is enough to know the curve up to its inflection point, and the rest can be calculated. In other words, there is a possibility to shorten the time of the experiments, which can save significant machine time and work hours.

Somà et al. (2021) presented the results of temperature measurements performed on a railway freight wagon during

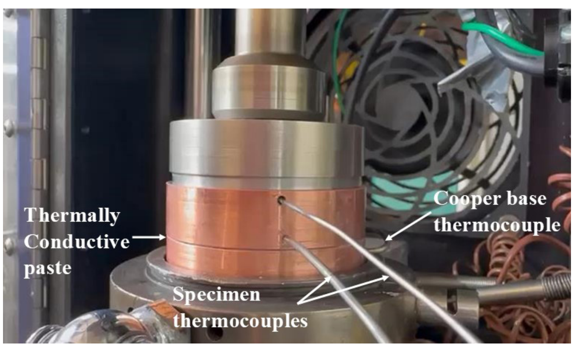

Fig. 2 The experimental setup with a copper specimen at Falex NV (Bolló et al., 2025)

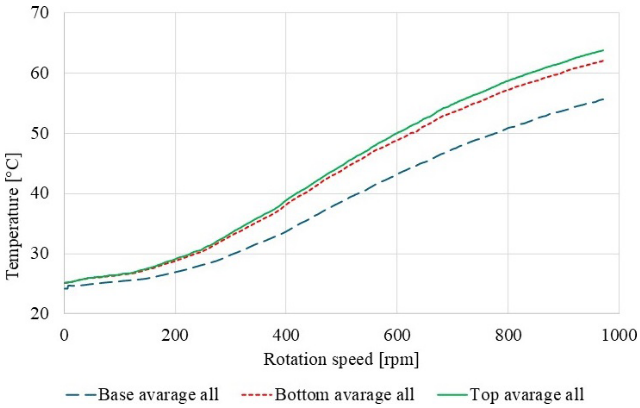

Fig. 3 Averaged results of Falex NV experiments for cast iron material

braking. The results obtained are shown in Fig. 4. By observing the fourth curve (Brake Temperature), it becomes clear that a sigmoid-type curve is also being encountered. Looking at the temperature values of the diagram, it shows approximately the same temperature as in the experiment performed by Falex NV. In other words, it can be stated that the developed laboratory experiment shows a very good approximation to the temperature relationship of real conditions. For the initial tribological and thermal testing of various brake block materials, a much cheaper, simpler and, most importantly, faster method is available.

The sigmoid curves of Fig. 3 are transformed into straight lines by linear approximation. Fig. 5 shows the temperature curve of the upper measurement point of the specimen (green).

The equation of the approximate line and the coefficient of determination indicating the goodness of the approximation were entered into Fig. 5, and the approximate line (red) was also plotted, and the R^2 value was displayed as well. Microsoft Excel program (Microsoft, online) gave the R^2 value of 0.9892, which is almost 1, which means complete identity.

Based on the approximation function, a linear characteristic for the temperature increase of the specimen surface was used in the finite element model, applied to the friction surface (Fig. 5). This further simplified the finite element model.

3 Materials and methods

The CAD model was a simple task, since cylindrical parts had to be created. The finite element model was created using the mechanical (FEA) and flow (Fluent) modules of the ANSYS software package (ANSYS, Inc., online). The first numerical calculations were performed on a cast iron specimen (Bolló et al., 2025). During the modeling, simplified geometry was used, and several options were examined until the conditions that showed a good approximation of the thermal distribution between the experiment and the simulation were finally found (Bolló et al., 2025).

In this publication, a printed test piece using additive technology from metal powder was modelled (174PH-A material grade). Our goal is to transform the previous geometry so that it has better thermal conductivity than the original, essentially creating a composite structure. Copper inserts of different shapes (99.99% pure, electrode copper) were placed into the test piece made of 17-4PH-A material to improve the heat dissipation during friction.

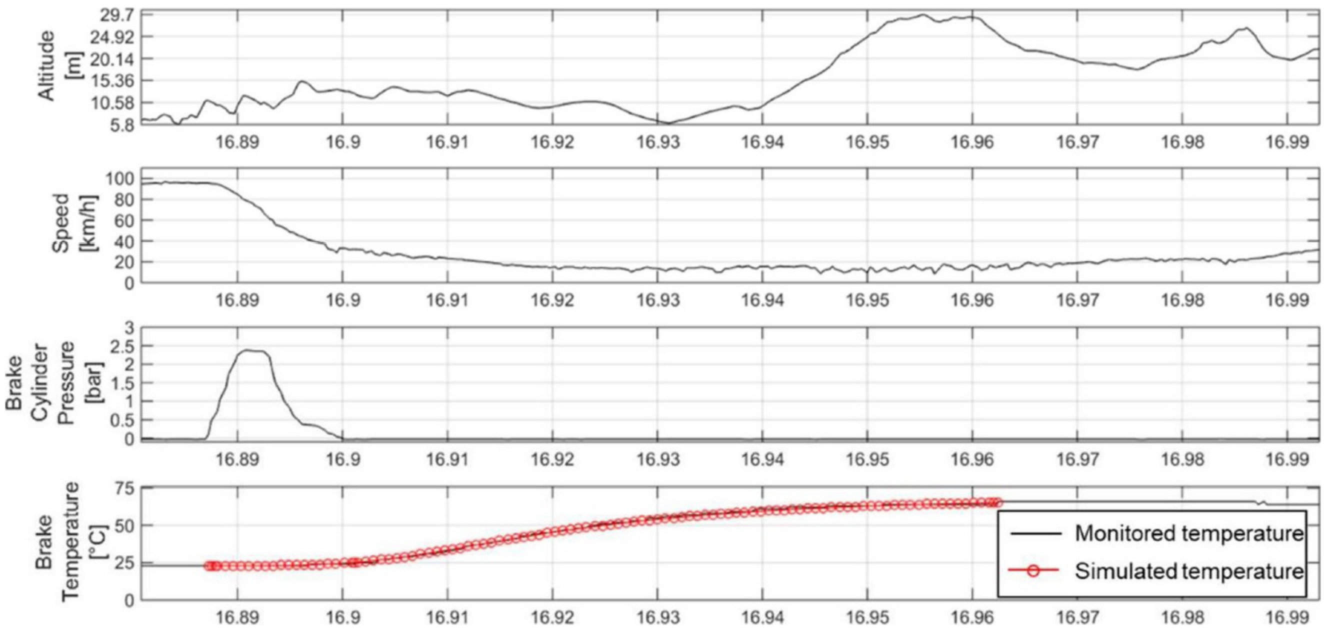

Fig. 4 Brake block temperature measurement under real braking conditions as a function of time (h) (Somà et al., 2021)

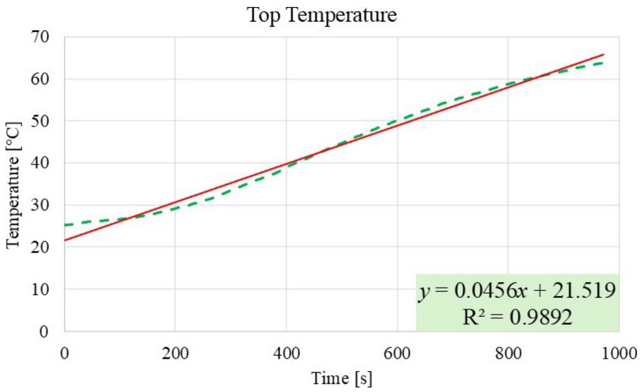

Fig. 5 Temperature change of the upper part of the specimen (green) and its approximation by a straight line (red)

The original cylindrical specimen has a diameter of 53.8 mm and a height of 15 mm. Our goal is to determine the temperature distribution in the specimen, so the rotor was not modelled, but instead the heat generated by friction on the specimen surface was entered as an input boundary condition (Bolló et al., 2025). Fig. 6 shows the contact surface of the stator and rotor (green), which is a 4.4 mm wide ring, and the temperature as a boundary condition for this surface according to Fig. 4 was specified. According to the measurement arrangement, the temperature values were investigated at two points, below the upper surface of the specimen (MP1) and above the bottom surface (MP2) (Fig. 6).

The initial test specimen was made of cast iron (EN-GJL-100), which is also the most commonly used brake block material. The test specimens made of the new material were printed from metal powder using the additive technique using the Creator 3D printer at the Faculty of Materials and Chemical Engineering of the University of Miskolc. The metal printer at our disposal is capable of producing adequate results for metal powders with a mass percentage of carbon as an alloying element below 0.6 m/m%. Therefore, 17-4PH-A stainless steel material was chosen, which can be found in the ANSYS software that was used for the simulation (ANSYS, Inc., online).

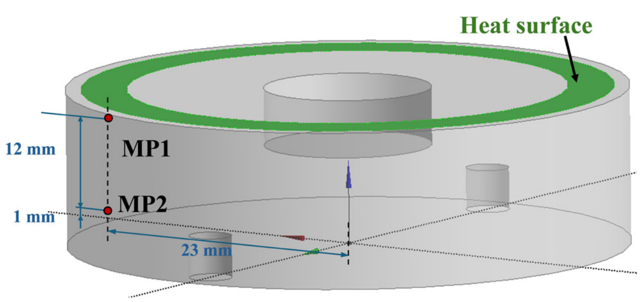

Fig. 6 Test specimen used in the initial experiment (CAD model)

Our goal is to remove heat from the surface of the formed specimen, where frictional heat is generated, as quickly as possible so that the structure of the material is not damaged. Geometry changes were made to the original cylindrical specimen. It was assumed that the thermal conductivity of the specimen would have improved. The aim was to create the macrostructural changes by adding a material, namely copper with better thermal conductivity. There are two reasons for choosing this material:

1. on the one hand copper is one of the best thermally conductive materials and if that has influence that will be significant;
2. and on the other hand its melting point allows it to be melted in the university laboratory and can poured into the hollow parts formed in the test specimen.

Macrostructural changes can involve almost any geometry change, as the specimens are created using additive technology.

To begin the thermal calculations, CAD models were created, which were equipped with copper "inserts" of

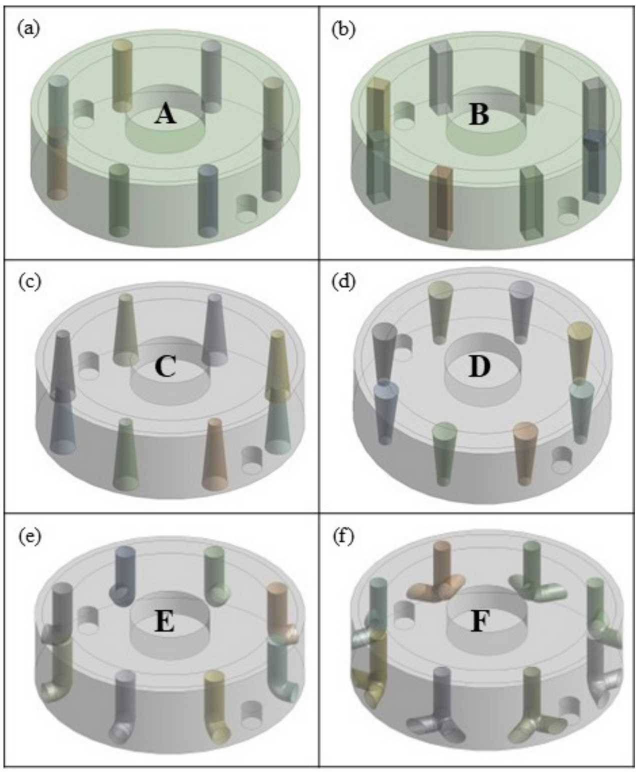

Fig. 7 CAD model of the test specimens designed for the simulation series: (a) 8 pcs 4 mm diameter cylinders, through the whole material; (b) 8 pcs circular ring-shaped blocks; (c) 8 pcs truncated cones (diameter increasing downwards); (d) 8 pcs truncated cones (diameter decreasing downwards); (e) 8 pcs 90 degree bent "cylinders" with one outlet to the cylindrical surface; (f) 8 pcs 90 degree bent "cylinders" with two outlets to the cylindrical surface

a certain size and shape compared to the original test specimen. Fig. 7 shows the planned macrostructural changes (versions A to F). The driving principle of the designs was to conduct the heat generated on the friction surface to the bottom or to the cylindrical surface of the test specimen. These solutions can also be implemented in the case of real brake block geometry. The size of the copper inserts was determined so that the volume of added copper was the same for all versions (~8 × 180 mm^3). The copper insert versions created are the following:

- Version A (Fig. 7 (a)): 8 pcs 4 mm diameter cylinders, through the whole material (reference);
- Version B (Fig. 7 (b)): 8 pcs circular ring-shaped blocks, through the whole material;
- Version C (Fig. 7 (c)): 8 pcs truncated cones (diameter increasing downwards), through the whole material;
- Version D (Fig. 7 (d)): 8 pcs truncated cones (diameter decreasing downwards), through the whole material;
- Version E (Fig. 7 (e)): 8 pcs 90 degree bent "cylinders" with one outlet to the cylindrical surface;
- Version F (Fig. 7 (f)): 8 pcs 90 degree bent "cylinders" with two outlets to the cylindrical surface.

3.1 Finite element analysis

After the CAD models were available, the models were transferred to the ANSYS finite element program (ANSYS, Inc., online).

A 4.4 mm wide annular surface area was created on the top surface of each specimen version in the DesignModeler environment. On this surface, based on the measurement results and previous simulations, the temperature increased linearly from 25 °C to 63 °C in 20 s. The ambient temperature was 25 °C, and a fixed support was applied to the bottom of the specimen, because this constraint is the closest to the real that was used in the test. Two small pins were used to prevent any movement of the specimen during the tests. The finite element mesh on the test specimens was designed so that the skewness factor of the cells did not exceed 0.92. During the calculations, the value of the thermal error was also monitored, and it was tried not to get a value greater than 0.2. If it exceeded this value during the calculation, a finer mesh was applied.

4 Results and discussion

In the results, the temperature of the upper (MP1) and lower measurement points (MP2), and the temperature difference between the two points were retrieved for. The smaller the difference, the better the thermal conductivity of the specimen. In addition, the percentage reduction in temperature difference compared to the original geometry made of 17-4PH-A material was also examined. Table 1 summarizes the results obtained for the original geometry and various modified geometries (Fig. 7 (a) to (f)) for 17-4PH-A material.

Table 1 shows that version B and version D (see Fig. 7 (b) and (d)) dissipated the heat best from the top surface of the specimen. Compared to the original design, the temperature difference decreased by 26.7% in the case of version B and by 26.8% in case version D. In version E and version F, the heat was dissipated to the side of the specimen, so it is worth calculating the average temperature and the temperature difference between the two surfaces on the side and top of the specimen in these two cases. Table 2 contains the average temperature values obtained on the top and side of the specimen. The data clearly shows that version E (see Fig. 7 (e)) removes heat from the top 69.4% faster. In case F (see Fig. 7 (f)), the value became worse because the volume of each insert is the same (approximately180 mm3), i.e., when the heat is delivered to the side through two outlets, the diameter becomes smaller. In case of version B (see Fig. 7 (b)) (circular section-based block) the heat generated on the side also became greater, meaning the temperature difference between the two surfaces decreased by 61.7% compared to the original.

Table 1 Temperature values obtained from the simulation

Version	MP1 (°C)	MP2 (°C)	MP1-MP2 (°C)	Decrease of temperature differences (%)
Original	52.29	32.20	20.09	
A	54.77	39.91	14.86	26.0
B	54.72	39.99	14.73	26.7
C	54.02	38.51	15.51	22.8
D	55.31	40.60	14.71	26.8
E	54.62	39.65	14.97	25.5
F	54.34	39.17	15.17	24.5

Table 2 The average temperature of the top and sides of the specimen and their differences

Version	Top (°C)	Side (°C)	Top-side (°C)	Decrease of temperature difference (%)
Original	50.87	40.82	10.05	
A	57.09	48.56	8.53	15.1
B	52.47	48.62	3.85	61.7
C	51.88	46.78	5.10	49.3
D	53.43	48.72	4.71	53.1
E	51.64	48.56	3.08	69.4
F	53.41	47.89	5.52	45.0

Fig. 8 illustrates the temperature distribution on the surface of the specimens for different geometric configurations, based on the solution provided by the ANSYS program (ANSYS, Inc., online). (The temperature scale is the same for each version.) The same temperature of 63 °C is visible on the upper surface of the specimen on the ring surface. In the case of version D (see Fig. 7 (d)), where the downwardly decreasing truncated cones were placed in the specimen, the upper surface of the cone did not fit into the heated ring surface, therefore, in this version, the insert conducts heat faster towards the interior of the specimen. This probably means that this was one of the best versions compared to the original geometry.

Starting from version D (see Fig. 7 (d)), it may be worthwhile to place the inserts not in the center of the annular surface, but to shift the inserts towards the center of the specimen. The rest of the research series will examine cases where the inserts are shifted from their current location to a smaller or larger radius, or the number and/or size of the inserts. In the beginning, 8 inserts were used, the number of them can be increased or decreased, or 8 pieces can be kept and increase the volume or the contact surface of the inserts. This means that the optimal arrangement needs to be found, while also taking into account that there should not be too much inserted in the formed test piece, and that it should be as simple as possible in terms of manufacturability. The volume of the test specimen without copper is 31,536 mm^3, and the volume of the inserts is 1,440 mm^3, which is 4.5%. A small amount of copper can make significant improvement in the heat conduction of the test specimen.

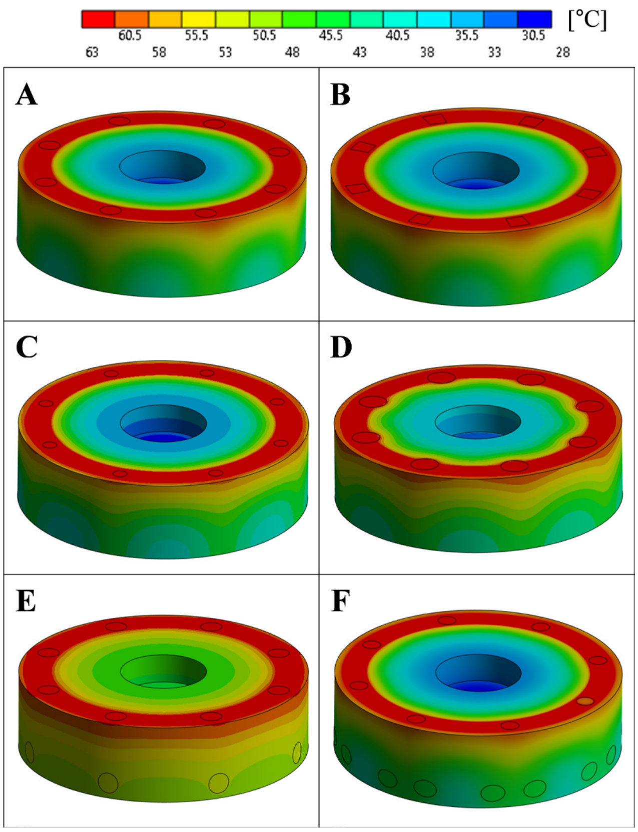

Fig. 8 Temperature distribution on the surface of the specimen from version A to version F (°C)

5 Conclusions

As a result of our research, two important conclusions can be drawn:

- The simplified experiment has a reason to exist, since with a good approximation, the same heating conditions can be created as the heating of real railway brake blocks during braking. In the applied simulations, it was possible to find the appropriate initial conditions, which can be used to demonstrate a good agreement between the test and the experiment. This allows some of the real experiments to be eliminated, thus accelerating and making research and testing cheaper.
- It can be clearly stated that it is worth adding materials with good thermal conductivity to the existing test specimen. Even with a small volume addition, a significant improvement in the change of thermal conductivity can be achieved. The geometries used in the simulation conducted heat away from the friction surface at different speeds, regardless of the fact that their volumes were the same. This opens up the possibility of designing such a brake block where, with the help of geometries providing different thermal conductivity, the deformation of the brake block caused by the thermal effect can be kept at the same level for the entire brake block.

When the most suitable design is found, the geometry using 3D printing from 17-4PH-A metal powder will be created, and the place of the inserts will be filled with 99.99% pure electrode copper. Then the results of the simulations can be compared with the values obtained during the tests to see the goodness of the new simulations. Ultimately, our goal is to transfer the macrostructural changes developed during the research to the case of a real brake block.

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