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Research Article

Numerical Investigation of the Thermal Effect of Material Variations on the Brake Disc

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ABSTRACT

Braking is one of the most critical systems for ensuring the safe driving performance of motor vehicles. Among the components that constitute the braking system, the disc is the one with the highest risk of wear. When the braking system is engaged, the physical contact between the brake pad and the disc leads to the generation of high pressure and high temperature. This released heat shortens the material's lifespan. The wearing or fracturing of the brake disc can result in a significant safety vulnerability. Therefore, it is desired for the discs to have better heat dissipation to increase their longevity. In this study, two different designs of brake discs were first examined thermally using the computational fluid dynamics (CFD) method. Subsequently, numerical analyses were conducted under the same boundary conditions by selecting the disc geometry with superior heat dissipation performance and using different materials. The results obtained from the analyses were compared and interpreted. The materials utilized in the study were grey cast iron, carbon steel, stainless steel, and carbon-carbon composite. As a result, it was observed that the carbon-carbon composite exhibited higher resistance to elevated temperatures.

1. Introduction

Braking systems utilized in contemporary industrial applications hold paramount importance in ensuring the secure cessation and controlled operation of vehicles or machinery. The performance of these braking systems is of utmost significance concerning the safety of drivers or operators and represents an indispensable factor that cannot be disregarded. Consequently, possessing comprehensive knowledge concerning the thermal and flow characteristics of brake discs becomes imperative for the enhancement of the design and performance of such systems. Brake discs constitute fundamental constituents of a braking system, serving the primary purpose of halting the motion of vehicles or machinery[1] . A brake disc system comprises a rotating brake disc and a device termed the brake caliper. The brake caliper exerts pressure on the brake pads in motion on the brake disc, thereby effectuating the deceleration or complete cessation of movement of the vehicle or machinery [2]. Disc brakes were initially experimented with in racing cars at the beginning of the second half of the 20th century. In the subsequent years, the utilization of disc brake systems gradually expanded to other motor vehicles, and they eventually found widespread adoption. Additionally, disc brakes began to be employed in military vehicles as well [3,4]. Over time, numerous braking systems have emerged and been employed in various vehicles. However, when performance comparisons were made, it became evident that the disc brake system stood out as the most effective, thus becoming the most prevalent system [5]. With the increase in its utilization in the market, disc brake systems began to be mass-produced in France in 1955 through the assembly line method. Presently, these systems are actively used in a wide range of vehicles, including trains, automobiles, motorcycles, trucks, trailers, forklifts, and nearly all similar forms of transportation. One of the most significant advantages of these systems compared to other braking systems is their longer lifespan due to less wear and tear [6].

When brake discs first entered serial production, only gray cast iron was utilized. Gray cast iron, known for its high heat resistance, was frequently used in the automotive industry. Due to its significant thermal resilience, gray cast iron is preferred in any situation where thermal endurance is crucial and can be considered a cost-effective material. Nowadays, apart from gray cast iron, stainless steel, carbon fiber, and carbon composite materials are commonly employed [7].

With the continuous advancement of technology, expectations from any mechanical system are increasing. One of these expectations is the reduction of energy consumption. Minimizing fuel usage is one of the methods to mitigate one of the world's major issues, global warming. For this reason, the weight of vehicles becomes a crucial parameter. Therefore, the adoption of stainless steel and subsequently carbon fiber brake discs in the market can be attributed to the desire to reduce the weight of vehicles [8]. Another factor to consider when using any material in mechanical systems is its cost. Designing a system without taking economic factors into account would render it impractical in the market. Due to the high cost of brake discs made from carbon fiber material, carbon-carbon composite brake discs are more commonly preferred, considering their physical properties are in close proximity to carbon fiber. Analytical studies have shown that carbon-carbon composite brake discs exhibit excellent thermal stress resistance and perform effectively in braking

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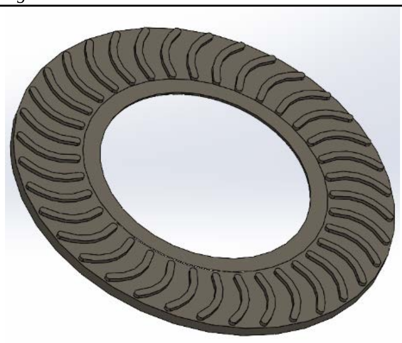
systems [9]. The design and material selection of brake systems are crucial since they are one of the most important systems in motor vehicles. The primary requirement for brake discs is to be resistant to wear. Wear or fractures occur as a result of sustained exposure to a certain pressure. The stress factor can arise both under load and as a result of interactions with high temperatures. Therefore, the heat distribution on the disc needs to be examined from a system safety perspective. If the thermal flow on the disc is not uniform or if certain points reach excessively high temperature values, modifications need to be made to the system [10].

Analyzing the flow on the disk correctly is the first step to be taken. Nowadays, instead of experimental systems, CFD methods are used to save both time and money. With the increasing popularity of CFD methods, experimental studies have lost their popularity. When academic literature is examined, it is observed that flow analysis conducted using CFD methods shows a very good agreement with experimental results, provided that correct boundary conditions are used [11]. When examining various brake system studies conducted for both academic and industrial purposes, it can be easily seen that the CFD method is an appropriate approach. In the literature, there are numerous studies on the heat distribution of brake disks. Grzes and Kuciej examined the thermal and wear distributions of a railway vehicle's brake disk. In their three-dimensional study, they analyzed five different composite materials. As a result, they demonstrated that the thermal wear resistance of brake components can be increased by using different materials [12]. Jafari and Akyüz conducted a numerical study using different parameters to determine the ideal design of radial vane brake disks. They employed the finite element method in their analysis and found that the most influential parameter on brake disk cooling is the ventilation gap. Through their analysis, they observed that increasing the ventilation gap from 8 mm to 14 mm resulted in a 21% reduction in the cooling time of the disk. This suggests that a larger ventilation gap improves the cooling efficiency of the brake disk [13]. Tauviqirrahman and their colleagues conducted a study on the modification of groove hole angles to optimize the heat distribution in brake disks. Additionally, they examined the thermal performance of the disks using the CFD method with different materials. They utilized carbon-ceramic, stainless steel, and gray cast iron in their analysis. As a result, they found that the ideal groove hole angle for the brake disk is 0 degrees, and the best temperature distribution is achieved in the disk made of gray cast iron material. This suggests that optimizing the groove hole angles and using gray cast iron material can lead to improved thermal performance in brake disks [14]. Wang and their colleagues investigated the geometric parameters of ventilated channels used in brake disks to study their thermal properties. As a result of their research, they found that the wing diameter and the number of wings have a more significant impact on thermal performance compared to the wing height [15]. Shrivastava and their colleagues examined the temperature distribution at the plate interfaces of a vehicle brake disk using a 3-dimensional model. They chose cast iron as the material for their numerical analysis. By analyzing three different geometries: slotted disk, drilled disk, and slotted-and-drilled disk, they found that the slotted-and-drilled disk provided the best heat distribution [16]. Pinca-Bretotean and their colleagues conducted thermo-mechanical studies using the CFD method and experimental methods with their originally designed brake disk geometry. As a result, they observed that the results obtained through numerical methods were in good agreement with experimental data. Consequently, they expressed that the use of experimental setups for thermal calculations of brake disks is not necessary. In other words, their study demonstrated that CFD simulations based on their original brake disk design were reliable in predicting thermal behavior, and the need for experimental setups to estimate thermal performance in brake disks could be minimized [17]. Mithlesh and their colleagues investigated the service life and thermal properties of ventilated brake disks using the CFD method and proposed some modifications. The main modifications suggested were related to the hole diameter of the disk and the contact area between the brake pad and the disk. Through their analysis, they found improvements in stress and thermal properties in brake disk designs with larger hole diameters. In summary, their study indicated that making modifications to the brake disk design by increasing the hole diameter can lead to enhancements in both stress distribution and thermal characteristics, potentially improving the overall performance and lifespan of ventilated brake disks [18]. Dubale and their colleagues selected three different brake geometries to investigate the thermo-mechanical behavior of brake disks. They conducted three-dimensional analyses using CFD methods. While comparing the different brake profiles, they preferred various parameters such as maximum surface temperature and thermal deformation. As a result, they observed that grooved-type brakes were more efficient compared to other designs. They stated that this design's heat distribution was better than the others, leading to a significant reduction in thermal deformations. In conclusion, their study indicated that using grooved-type brakes can result in improved efficiency and reduced thermal deformations due to better heat distribution compared to other brake designs [19].

In this study, two different brake disc geometries were designed and compared under the same boundary conditions, taking into account their thermal properties. According to the heat dissipation values obtained as a result of the comparison, the design with better performance was selected and numerical analyses were carried out for different materials. The results of the numerical analyses were compared and interpreted and conclusions were reached. The aim of this study is to understand the effects of material changes on their thermal properties by subjecting brake discs to Computational Fluid Dynamics (CFD) flow analysis and to offer suggestions. There are many studies in the literature about brake discs. However, the materials used in the analyses carried out within the scope of this article are different. Drag force, which is one of the aerodynamic factors that affects the amount of fuel consumed by vehicles while driving, is related to the weight of the vehicle. For this reason, it is known that vehicles began to be manufactured from lighter materials. Another desired factor is to increase the efficiency of the intended use while reducing the weight of the material. For this reason, we investigated the suitability of using carbon-carbon composite as a disc material in vehicle braking systems. We wanted to contribute by doing a study that does not exist in the literature. According to the results we obtained from the numerical analyses we conducted throughout the study, the use of carbon-carbon composite provides great advantages in terms of both thermal dissipation and wear.

2. Material and Methods

In this study, Computational Fluid Dynamics (CFD) has been used. The CFD method is becoming increasingly popular with each passing day. Setting up an experimental apparatus is considered a significant disadvantage due to its high cost, the need for a large area, and the time-consuming data collection process. However, by using the CFD method, significant advantages can be gained in terms of both time and cost. In recent years, this method has been employed in many studies [20]. When performing any calculation with the CFD method, it is essential to first draw the geometry. In this study, two different disk designs were created for use. These are the curved channel disk and the droplet channel disk. The channels inside the disks serve to direct the airflow, preventing excessive heating and minimizing wear. Increasing the airflow accelerates the cooling of the disk. The prepared geometries are detailed in Figure 1 and Figure 2.



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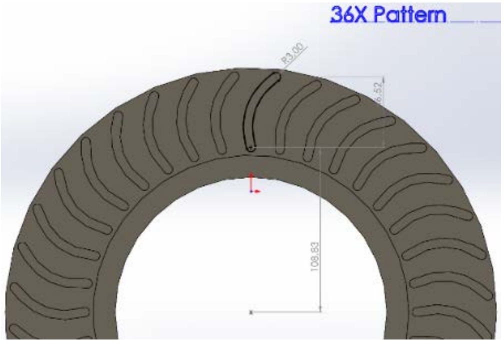

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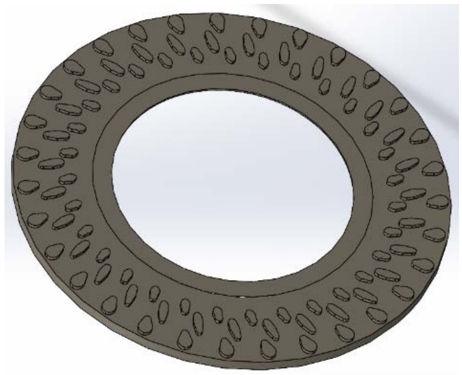
Fig. 1. Curved channel; a) General view, b) Dimensional view



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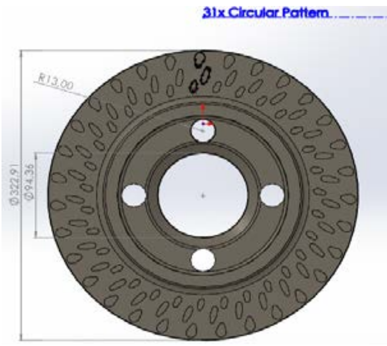


b)

Fig. 2. Droplet Channel; a) General view, b) Dimensional view

The prepared geometries have undergone a process called "meshing." The purpose of applying this process is to obtain more accurate results from the conducted analyses. In order to increase the accuracy and precision of the obtained results, the mesh structure needs to be of high quality and have a sufficient number of elements [21]. The mesh file created for use in the analyses in this study has approximately 12 million grid points. The mesh structure consists of triangular and pentagonal elements. The visual representation of the prepared mesh file is shown in Figure 3.

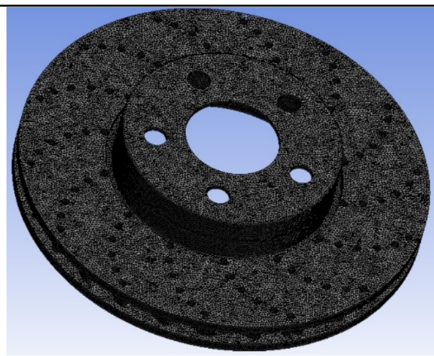


Fig. 3. General view of mesh prepared.

2.1. Mathematical Background

In this study, calculations were performed using the Finite Element Analysis (FEA) approach and Computational Fluid Dynamics (CFD) method. The computations were carried out by the computer using formulas embedded within the employed software. The formulas used in this study are related to braking force, contact pressure between the brake disk and pad, and the generated and distributed heat. The braking force is given by Equations (1) and (2) [22].

$$\dot{W} = -\frac{d}{dt}E_c = -\frac{d}{dt}\left(\frac{mV^2}{2}\right) = -mV\frac{dV}{dt} \quad \text{(1)}$$

$$\dot{W}_b = \frac{\dot{W}}{n} = -\frac{1}{n}mV\frac{dV}{dt} \quad \text{(2)}$$

The calculation of the contact pressure between the brake disk and pad is given by Equations (3) and (4) [22].

$$P = \frac{Q_b}{\mu V} \quad \text{(3)}$$

$$Q_b = \frac{\dot{W}_b}{A} \quad \text{(4)}$$

"μ" represents the coefficient of friction, and "Q_b" represents the heat ratio. The heat dissipation is given by Equations (5) and (6) [22].

$$\frac{1}{r}\frac{\partial}{\partial r}\left(kr\frac{\partial T}{\partial r}\right) + \frac{1}{r^2}\frac{\partial}{\partial \theta}\left(k\frac{\partial T}{\partial \theta}\right) + \frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right) + \dot{q} = \rho c_p\frac{\partial T}{\partial t} \quad \text{(5)}$$

If the thermophysical properties are constant, the temperature gradient in the θ direction can be neglected to a negligible extent while the disk is rotating [22].

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right) + \frac{\partial^2 T}{\partial z^2} + \frac{\dot{q}}{k} = \frac{1}{\alpha}\frac{\partial T}{\partial t} \quad \text{(6)}$$

The amounts of generated and distributed heat are calculated according to Equations (7) and (8).

$$W_{prod} = \int_0^{t_0} \dot{q}_{prod}\,dt \quad \text{(7)}$$

$$W_{diss} = \int_0^{t_0} \dot{q}_{diss}\,dt \quad \text{(8)}$$

2.2. Disk Materials

Different materials were used in the drawings made with CAD software and the analyses performed using the CFD method. These materials were selected as gray cast iron, stainless steel, carbon-carbon composite, and 1020 steel. Gray cast iron is an iron-carbon alloy composed mainly of iron, carbon, and silicon. Due to its high compressive strength, it is widely used in casting processes. It is preferred in components in the automotive industry such as brake discs and exhaust mufflers due to its sound and vibration absorption properties. Additionally, its heat resistance makes it suitable for applications such as stove grates, ovens, and casting molds [23].

Stainless steel is an alloy that contains elements such as iron, carbon, and chromium, and sometimes nickel and molybdenum. The chromium content provides stainless steel with resistance to corrosion and rust. It finds a wide range of applications in various industries, including the food industry, medical devices, surgical instruments, architectural embellishments, kitchen utensils, and automotive exhaust systems. Its high strength and corrosion resistance make it a suitable option for marine applications, shipbuilding, and chemical processes. In the field of biomedicine, stainless steel is commonly used in medical implants, prosthetics, and other medical devices. In architecture, stainless steel is utilized for decorative purposes, providing an aesthetic appearance in modern buildings, bridges, and sculptures [24]. Carbon-carbon composite is a high-performance material, which is a combination of carbon fiber or carbon fabric reinforced with a carbon matrix. Due to its high-temperature resistance and lightweight nature, it finds applications in the aerospace industry for rocket motors, spacecraft, and supersonic aircraft. It is preferred in applications where high temperatures are involved, such as brake discs, sports car brakes, aircraft brakes, and thermal protective shields. Its electrical and thermal conductivity properties allow its use in electrodes, high-power electrical devices, and laser rods [25]. 1020 steel belongs to the low carbon steel class and contains elements such as iron, carbon, manganese, and sulfur. It is widely used in structural components of machinery, such as machine parts, shafts, gears, bolts, and nuts. Its weldability and cost-effectiveness make it a preferred choice in the construction sector for steel pipes, structural steel, and various reinforcement materials. Its suitability for cold drawing enables its widespread use in the automotive industry for upholstery pipes and the production of lightweight steel components. Additionally, 1020 steel is utilized in numerous applications, including shafts, pumps, hydraulic cylinders, and structures supporting polymer components [26].

In this study, the heat distributions of the disks obtained from the analyses using these materials have been examined and interpreted. The objective of this study is to comparatively investigate which material provides better heat distribution. The recommended brake disk material for high-performance vehicles such as race cars will be suggested. The physical properties of the materials used as disk materials in this study are provided in Table 1.

Table 1. Physical properties of materials

Properties	Cast Iron	Stainless Steel	C-C Composite	Steel 1020
Density (kg/m3)	7100	7750	1800	7870
Young's Modulus (Gpa)	125	190	95	190
Possion's Ratio	0.25	0.3	0.31	0.29
Thermal Conductivity (W/m-K)	54.5	26	40	52
Specific Heat (J/kg-K)	586	500	755	470

2.3.Mesh Dependence

Before performing any analysis using CFD, the mesh independence of the geometry to be studied should be checked. The purpose of this process is to keep the number of grids to be created at the optimum number while meshing. Since increasing the number of grids will prolong the solution time, it is not preferred to have a high number. A low number of grids is not preferred because it will negatively affect the accuracy of the solution. For this purpose, mesh files with different grid numbers are created and analyses are performed using the same boundary conditions. Then, by comparing the results obtained from these analyses, the number of meshes to be used in the study is determined. This process is called mesh independence. In this study, six mesh files 7,352,000; 8,985,888; 9,846,000; 10,312,000; 11,986.33, and 12,242,777 grids were prepared. The hexagonal type was preferred as the mesh structure. It was assumed that all boundary conditions in the analyses performed using the created mesh files were the same. A PC with "Intel (R) Core (TM) i7-4710HQ CPU @ 2.50GHz, quad-core" was used in the calculations. The brake disc temperatures obtained as a result of the mesh independence calculations for the drop channel geometry are given in Table 2. When the results in Table 2 were examined, it was decided to use the mesh structure containing 11,986.33 grids throughout the study.

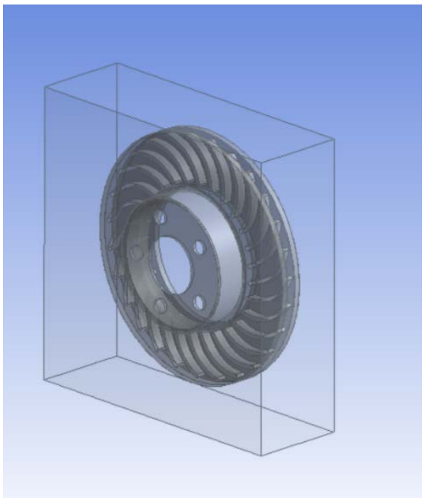
Table 2. Comparison of Mesh Types

Mesh Type	Grid Number	Temperature [oC]	Computational Time
Coarser	7,352,000	246	4 hour 30 min
Coarse	8,985,888	243	6 hour 20 min
Normal	9,846,000	241	7 hour 30 min
Fine	10,312,000	239	9 hour 50 min
Finer	11,986,33	237	11 hour 10 min
Very Fine	12,242,777	237	26 hour 30 min

2.4. Boundary Conditions

CFD (Computational Fluid Dynamics) analysis is used to simulate the movement of fluids using numerical-based finite element methods. This method is employed in various engineering applications, replacing experimental studies and can be used in any area where there is fluid flow. The applications of CFD analyses range from calculating the aerodynamic loads on aircraft wings to heat transfer calculations in radiator pipes. In any CFD analysis, aside from geometry design, mesh generation, and turbulence model selection, determining the boundary conditions is another crucial parameter. In this study, the SST k-ω turbulence model was used as it accurately calculates both the flow within the boundary layer and the free flow. It performs well in high-pressure gradient flows and is commonly used in regions with high turbulence intensity. In the SST k-ω method, a combination of the k-epsilon and k-ω models is used based on the value of the local Reynolds number. This combination provides accurate results both on the wall surface and in capturing the turbulence effect in the free flow.

For all the analyses conducted in this study, the flow velocity value was chosen as 22.222 m/s, based on the legal speed limit on Turkish highways. Initially, two different brake disk geometries were used, while all other parameters remained constant. Then, the disk design with a higher heat dissipation rate was selected, and the material effect was examined. Other parameters were kept constant throughout the analysis. For an air temperature of 20°C, with $\rho = 1.225\ \mathrm{kg/m^3}$, $\mu = 1.81\mathrm{x}10^{-5}\ \mathrm{kg/(m.s)}$, and the vehicle speed $V = 22.222\ \mathrm{m/s}$, the calculated Reynolds number (Re) was determined to be 2.3x106, indicating turbulent flow. The residuals values were set to 1e-06 to ensure the accuracy of the CFD analysis results. The small value of this parameter is due to the sensitivity in the solution. The boundary conditions and the generated domain used for this study are presented in Figure 4.



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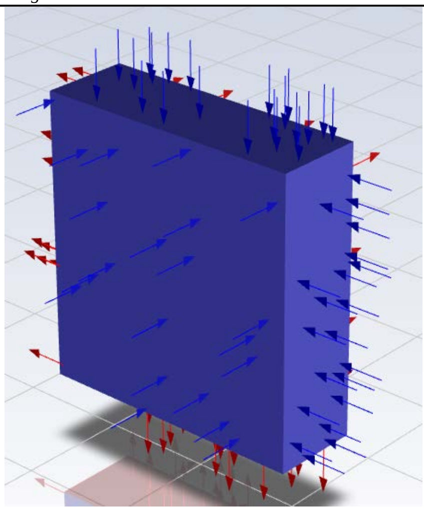

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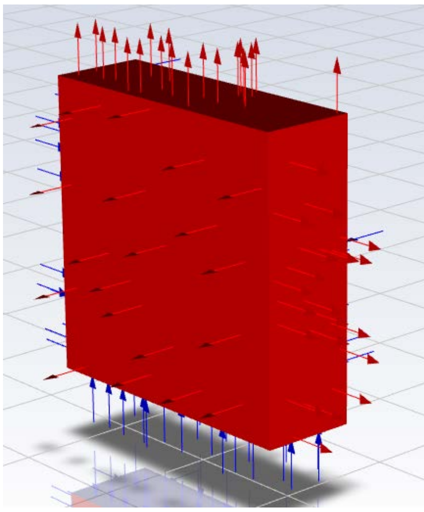


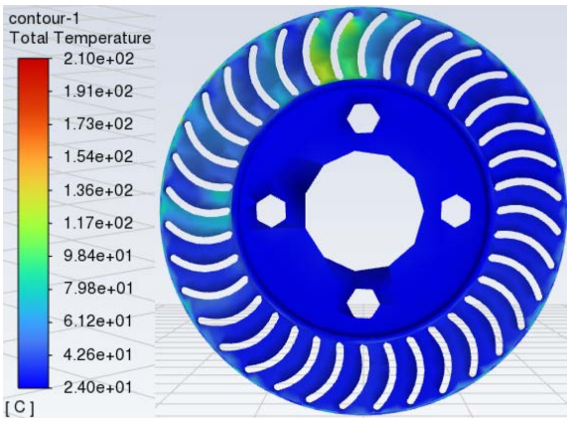
c)

Fig. 4. Boundary Conditions; a) Created domain, b) Inlet surfaces, c) Outlet surfaces

3. Results

3.1. Analysis results of different disc designs

Two different brake disc designs, which were modeled in 3D using CAD program, were subjected to numerical analysis under identical conditions and the heat distributions of the discs were examined. The results obtained from the analyzes made by choosing gray cast iron as the material are given in Figure 5.



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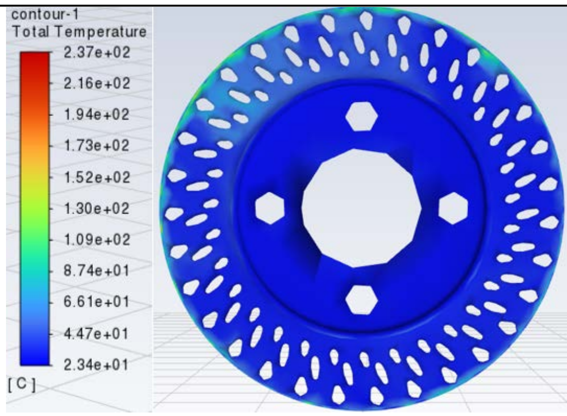

b)

Fig. 5. Thermal distribution on the disc; a) Curved channel, b) Drop channel

According to the thermal analysis of the curved channel disk configuration, the maximum temperature observed in the disk structure due to convective heat transfer was measured as 210°C. On the other hand, for the droplet channel disk configuration, the maximum temperature observed in the disk structure due to convective heat transfer was measured as 237°C. When comparing the CFD flow analyses of the two modeled configurations, the disk design with the curved channel structure demonstrated better thermal performance. This improvement is attributed to the increase in heat transfer with the widening of the ventilation channel. To avoid high temperatures on the disk surface, the curved channel disk geometry was chosen for further analysis by considering material changes.

3.2. Results of Analyses with Different Materials

One of the critical components in the braking system of vehicles is the brake disks, and subjecting them to high temperatures can lead to wear, which is an undesirable situation. Therefore, it is crucial for brake disks to have a high heat dissipation capability on their surface. To investigate which material used in disk manufacturing is more resistant to high temperatures, calculations were performed. In the numerical simulations, four different materials were used: gray cast iron, 1020 steel, stainless steel, and carbon-carbon composite. The results obtained from the calculations with different materials for the curved channel disk geometry are presented in Figure 6.

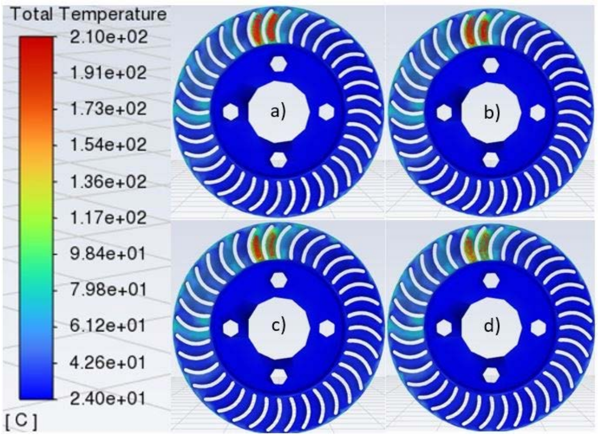

Fig. 6. Thermal distribution on the disk; a) Gray cast iron, b) Stainless steel, c) 1020 steel, d) Carbon-carbon composite

Based on the thermal analysis results shown in Figure 6, it can be observed that using the same boundary conditions, the highest temperature value of 210°C was measured in the analyses conducted with gray cast iron. The temperature was 192°C for stainless steel disks, 180°C for 1020 steel disks, and 144°C for carbon-carbon composite disks. When comparing the thermal analyses with each other, it is evident that there is a 31.42% difference in heat distribution between carbon-carbon composite disks (with the best heat distribution) and gray cast iron disks (with the worst heat distribution). These results demonstrate that the specific heat values of materials are the most crucial parameters for the heat distribution and surface temperature of brake disks. The specific heat value of the carbon-carbon composite material used in this study is much higher than the other materials, which is why it exhibited the best heat distribution. Another significant parameter for the heat distribution of the disks is the thermal conductivity value. When comparing the thermal analysis results of disks made from Steel 1020 and stainless steel, it is observed that despite the specific heat value being lower in Steel 1020, the heat distribution is better. The reason for this is that the thermal conductivity value of Steel 1020 is twice that of stainless steel. If both the specific heat and thermal conductivity values of a material are high, products made from that material are expected to have good heat transfer capabilities.

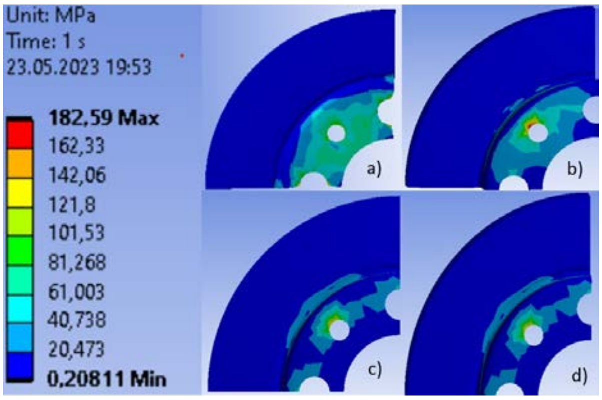

Fig. 7. Stresses distribution on the disk; a) Gray cast iron, b) Stainless steel, c) 1020 steel, d) Carbon-carbon composite

The stresses contours obtained from the analyses using the same boundary conditions are given in Figure 7. According to these results, the highest pressure value on the brake disc was obtained from the analyses made with gray cast iron and the lowest pressure value with carbon-carbon composite. When the pressure distributions on the brake disc are examined, it is seen that the obtained situation is compatible with the thermal distribution. Considering that one of the reasons for the high temperature on the brake disc is the pressure on the disc, this result is expected.

4. Conclusions

In this study, the heat distribution on the surface of brake disks using different materials was investigated. First, the channel geometry was determined, and numerical analyses were conducted with two different disk designs: curved channel and droplet channel disks. The calculations showed that the surface temperature of curved channel disks was 210°C, while droplet channel disks had a surface temperature of 237°C. Based on the analysis with gray cast iron material, it was concluded that the curved channel design was more suitable for the disk surfaces.

Subsequently, thermal analyses were performed using a CFD program with four different materials: gray cast iron, stainless steel, 1020 steel, and carbon-carbon composite. The numerical analyses were carried out under the same boundary conditions, with the fluid temperature set to 20°C, and the fluid velocity set to 80 km/h. The results of the calculations showed that the highest temperature value of 210°C was obtained with gray cast iron. The temperature was 192°C for stainless steel disks, 180°C for 1020 steel disks, and 144°C for carbon-carbon composite disks. The thermal analysis results revealed a 31.42% difference in heat distribution between carbon-carbon composite disks (with the best heat distribution) and gray cast iron disks (with the worst heat distribution).

From the numerical calculations in this study, it was evident that the most important parameters for the surface temperature of brake disk materials were specific heat and thermal conductivity. Although carbon-carbon composite is considered an ideal material for brake disk surfaces, its higher cost compared to other materials makes it less suitable for every vehicle's braking system. However, it is recommended for vehicles with high-revving engines. In high-torque sports cars commonly used today, carbon-carbon composite is found to be a suitable brake disk material.

Declaration of conflicting interests

The authors declare no competing interests.

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