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RESEARCH ARTICLE

Thermal behavior of disc brakes, impact of pad geometry and braking conditions – an experimental study

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Abstract

This study experimentally investigates the influence of brake pad slot geometry on disc–pad interface temperature and braking efficiency under controlled dry braking conditions. While most prior work emphasizes disc design and material composites through simulations, this research addresses the gap with an experimental test rig capable of quantifying thermal characteristics and stopping performance. Two pad configurations were examined: solid pads with 100% contact area and slotted pads with 90% contact area. Disc surface temperatures were measured at three radial positions (T1: 110 mm, T2: 100 mm, T3: 90 mm) using non-contact thermocouples, while braking duration was evaluated via high-resolution video analysis. Tests were repeated five times across braking pressures of 4–12 bar and simulated speeds of 20–120 km/h, with initial disc temperature stabilized at 18 ± 1 °C. Results show that slotted pads significantly lowered interface temperatures compared to solid pads, with maximum reductions of 25.8% at T1, 22.9% at T2, and 20.9% at T3. Braking time improved by 5% to 20 km/h and 9.52% to 120 km/h using slotted pads. The pronounced temperature gradient at T1 is attributed to higher sliding velocity and centrifugal heat concentration at the outer radius. Uncertainty analysis confirmed error margins of ±2 °C and ±0.1 s. These findings prove the mechanical advantages of slotted pads including enhanced airflow, reduced thermal stress, and improved stopping performance, offering practical insights for perfecting disc brake thermal management and efficiency.

Keywords: Disc temperature, slotted pad, braking time, dry braking, thermal distribution

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1. Introduction

The increasing emphasis on vehicle safety has driven the automotive industry to continuously improve braking system design. Among braking system components, brake pads play a pivotal role by ensuring effective frictional contact, enabling rapid deceleration, and influencing noise, wear, and thermal stability [1–4]. Their geometry significantly affects heat dissipation, vibration, and wear characteristics at the pad–disc interface [5, 6]. Elevated surface temperatures during prolonged braking can induce brake fade, thermal cracking, fluid vaporization, and accelerated wear, thereby undermining both safety and system reliability [7–10]. Therefore, it is essential to accurately forecast the rise in temperature within the braking system during the early stages of design. A significant number of researchers have concentrated their efforts on the design of disc rotors [11–16], perfecting materials [17–22] and using environmentally friendly composites [23–33] to enhance thermal stability. However, brake pad geometry has received comparatively less attention.

The implementation of different brake pad surface configurations such as slots, grooves, blocks or perforations has proved an ability to change friction distribution and airflow, after affecting thermal response and braking stability [34, 36-38]. Nevertheless, a significant portion of this understanding is derived from numerical simulations, which, while informative, often rely on idealized assumptions that do not reflect actual operating conditions [19, 35].

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Several recent works have tried to address pad geometric effects experimentally. Wang and Fu [34] showed that altering friction-block arrangement (while holding contact area fixed) reduced peak disc temperature by 5% and stress by 10%. Belhocine [35] applied finite element method to model stress and temperature field for different pad configuration. The study showed that the deformation in the disc's outer layer was significant; the presence of grooves in the pads negatively affects the brake's mechanical properties, while a pad without grooves shows a more uniform stress distribution. Mohammed Chaqouri et al. [36] and Wu Gang et al. [37] proved that pad geometry controls localized contact pressure and cooling, affecting thermal uniformity. Similarly, Talati and Jalalifar [39] and Grkić et al. [40] confirmed that heat flux concentration is highest near outer radii due to sliding velocity effects.

Material and structural adjustments to brake disc are the preferred methods among researchers for evaluating the thermal performance of brake systems. Nejat et al. [41] proved a remarkable enhancement in heat transfer, ranging from 8.54% to 15.38% for optimized airfoil vanes as opposed to straight designs, with added analysis of a scaled version showing a 17–29% improvement in heat dissipation. Furthermore, Javid Karbalaei Mehdi et al. [42] presented a refined vane shape using Class Shape Transformation and Territorial Particle Swarm Optimization, achieving increases in convective heat dissipation of 38.44% and 45.21% at angular velocities of 40 rad/s and 80 rad/s, respectively. At the same time, Zhen et al. [43] set up an integral-transform method to address a 3-D transient temperature model, confirming that temperature gradients are highest at the beginning of braking. Added research by Qi fe Jian and Yan Shui [44] showed radial variations, with peak temperatures occurring at the center during intense braking, while Haydar Kepekci et al. [45] examined different disc materials, such as gray cast iron and carbon ceramics, along with composite brake pads. The findings showed that the surface temperatures of carbon-ceramic discs ranged from 290 to 650 K, while gray cast iron displayed temperatures between 295 and 500 K, showcasing their varying heat dissipation abilities. Experimental evaluations of wire-woven-bulk diamond (WBD) cored brake discs suggested their appropriateness for high-performance settings [47]. However, a study of in-wheel braking systems revealed that inadequate natural convection resulted in problems like thermal buckling and fractures. The connection between disc edge temperature, pad dimensions, and cover angle highlighted the significance of design elements in addressing these thermally induced challenges [48, 49].

Brake pad geometry is crucial because it governs how heat is generated, distributed, and dissipated at the interface, while also affecting wear, NVH, and cost-efficiency. This makes pad geometry a first-order parameter in thermal performance, while disc material and structural modifications primarily serve to manage heat once generated, through enhanced conduction, capacity, or dissipation. From a practical standpoint, pad geometry optimization is also more cost-effective and adaptable compared to redesigning disc alloys or structures. Moreover, pad geometry directly affects convective cooling and thermal recovery. Slots and grooves function as micro-channels, promoting airflow through the interface and aiding in the removal of wear debris. These geometric adjustments can substantially improve fade resistance and braking stability without the need for costly disc material substitution or complex structural redesigns. Thus, investigating brake pad geometry is not only necessary but also strategically helpful for enhancing thermal characteristics and overall braking performance in a manner that balances functionality, manufacturability, and cost.

2. Preparation of disc-brake experimental dynamo-meter test rig

Design and development of experimentally test rig was also an important stage of the research as the temperature of the surface of the disc could be measured with high accuracy under a range of operating conditions. The information on how the experimental set up was set up, on the instruments and techniques used to measure it, on how the interface of the disc and pad was modeled, the geometry of the disc and the test pad, was handled and the details are presented in individual sections as explained below.

2.1. Description of the test rig and its measuring instruments

The test rig features several key components: 1. Disc brake assembly includes an air-ventilated braking system. 2. The braking unit is equipped with a master cylinder that generates the necessary pressure. 3. The driving unit forms a motor capable of reaching up to 2800 rpm, which powers the brake assembly. 4. An electronic speed control unit (ECU) is integrated with a position sensor to check and adjust the shaft speed as illustrated in Figure.1.

Figure 1. Experimental test set up

Measuring the temperature change on the disc surface is quite challenging. Long-term temperature readings on the contact surface are nearly impossible due to the nature of the friction process. Additionally, automotive brakes run under harsh conditions, which lead to factors like wear, water presence, corrosion, and so forth. As shown in [15], thermocouples are the most efficient instruments for measuring temperature during breaking. Non-contact infrared thermocouples were employed to assess the temperature of the disc surface at specified locations. A speed sensor is found near the shaft to measure the speed of the rotor. A video recording device was employed to assess the duration of the braking process. All measurement instruments are connected to the data acquisition system.

2.2. Description of disc-pad interface and brake pad geometry design

To comprehensively measure and analyze temperature distribution level at disc-pad interface the surface of the disc was selected under three points at 110 mm (T1), 100 mm (T2) and 90 mm (T3) distance to the center of the disc as seen in Figure 2.

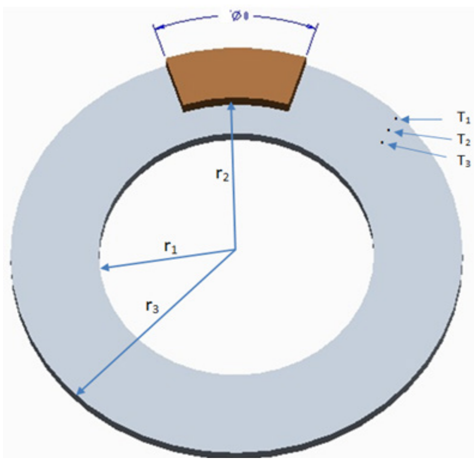
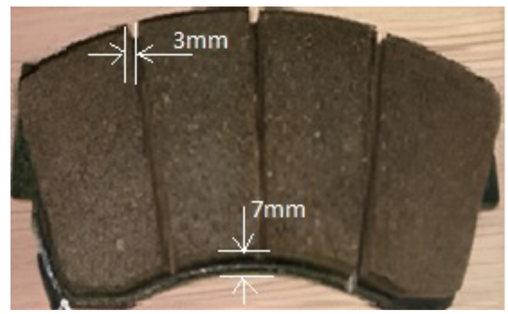


Figure 2. Positions of thermal monitoring points

Geometric design of the brake pads is a very important element in braking since the rotor is directly interacted with it. Surface geometry of the brake pad influences heat dissipation, wear rate, friction coefficient and noise levels significantly [34]. Such characteristics of design of the brake pads like the area of the part of friction, the thickness of its elements, the existence of slots and grooves, and also the shaping and beveling edges are crucial to a proper thermal regulation so that the brake mechanism performs optimally [35].The slot geometry was engineered to optimize thermal efficiency while ensuring an adequate contact surface for stable friction. A 10% reduction in the pad's surface area was chosen based on earlier numerical analyses [34, 36], which show that reductions exceeding 15% may negatively impact torque performance. The dimensions for the slot (3 mm in width and 7 mm in depth) were selected with three evenly spaced slots across the pad length, to guarantee the durability of the friction material along with manufacturability. The slot orientation was parallel to the direction of rotation to enhance airflow and debris evacuation. Two pairs of brake pads were created and assessed using a disc brake dynamometer. Each pad's contact surface area was changed by adding vertical slots, with measurements taken using a digital planimeter. Therefore, the brake pad featuring a single slot is classified as having a 100% contact area (CASE I-solid pad), while the pad with three slots is classified as having a 90% contact area (CASE II-slotted pad).as illustrated in Figure 3.

(a)



(b)

Figure 3. (a) Case - I. Brake pad with 100 % contact area. **(b)** Case –II. Brake pad with 90% contact area

The brake pad design incorporates vertical slots on its surface. Planimeter measures surface area of pad. Surface area for a single solid brake pad is 34.4 cm², not accounting for the slots. Thus, when considering two pads, the total area amounts to 68.8 cm², which is the standard 100% area (Case I). Each slot has an area of 1.6 cm², totaling 6.4 cm² for four slots. This results in a reduction of the pad's surface area by 9.87%, which we approximate to 10%. Consequently, the overall area of the slotted pad is 90% for Case II. Table 1 provides all the necessary information about the size of the disc and pad and mechanical properties of the pad, and the disc used in the experiments, but the influence of the materials that disc and pad were made of is not considered in the study.

Table 1. Thermo-physical properties of a disc and pad

Description	Disc	Pad
Outer diameter (mm)	230	---
Inner diameter (mm)	148	---
Thickness (mm)	12	10
Thermal Conductivity (W/m-K)	47.3	12
Density (kg/m^3)	7250	2500
Specific heat (J/kg-K)	440	900

2.3. Materials and method

Temperature readings were recorded at three radial locations: 110 mm, 100 mm, and 90 mm on the disc-pad interface, across different operating conditions in a dry braking scenario. The test conditions included braking pressures ranging from 4 to 12 bar and vehicle speeds of 20, 40, 60, 80, 100, and 120 km/h. Contact is checked between the brake pad and disc in two configurations namely; Case I (100 % contact area) and Case II (90 % contact area). The time interval between the start of the braking motion to the absolute halt of the vehicle was measured with the help of a video camera and is termed as the braking duration. The temperature of the disc surface was measured and recorded by a non-contact thermocouple gauge. The temperatures of the disc surface were recorded using a non-contact infrared thermocouple (model: OMEGA OS130A-IR). Each IR sensor features a response time of less than 100 milliseconds with temperature range of –40 °C to 500 °C and an accuracy of ±1.5 °C. The synchronization of the non-contact thermocouple with video-camera frames ensured alignment of braking times and temperature data. This setup enabled correct measurement of both thermal response and braking duration. Since the machine was relatively new, five samples were replicated and the mean value was treated as the experimental value to carry out further analysis about the reliability and accuracy of temperature data as well as in reducing the level of uncertainty in the experiment. The overall process of experiment is given below.

The experimental procedure was carefully designed to examine thermal behavior of disc-pad interface during braking in the dry condition. Experiments were conducted between January and February 2025 under controlled laboratory conditions. Ambient temperature during trials was in the range of 18 ± 1 °C. The motion of a vehicle was simulated by using a motorized drive system with a starting baseline speed 20 km/h, increasing gradually to a maximum speed of 120 km/h. The assembly speed was checked using Digital Rotary Encoders with an accuracy of ±0.1 rpm. Surface temperatures were narrowly measured at every established speed range (20, 40, 60, 80, 100 and 120 km/h) with three non-contact thermocouples that were placed tactically at radial positions of 110, 100 and 90 mm to the center of the disc. The braking time, denoted as the duration during which the brakes are applied, and the vehicle completely stops, was measured using a high-resolution video camera. With such an arrangement the braking time could be measured accurately by later video playback. Repeatability of tests and limiting the error of measurements were achieved by repeating the same test five times under the same conditions and averaging the results, which were further used in analysis.

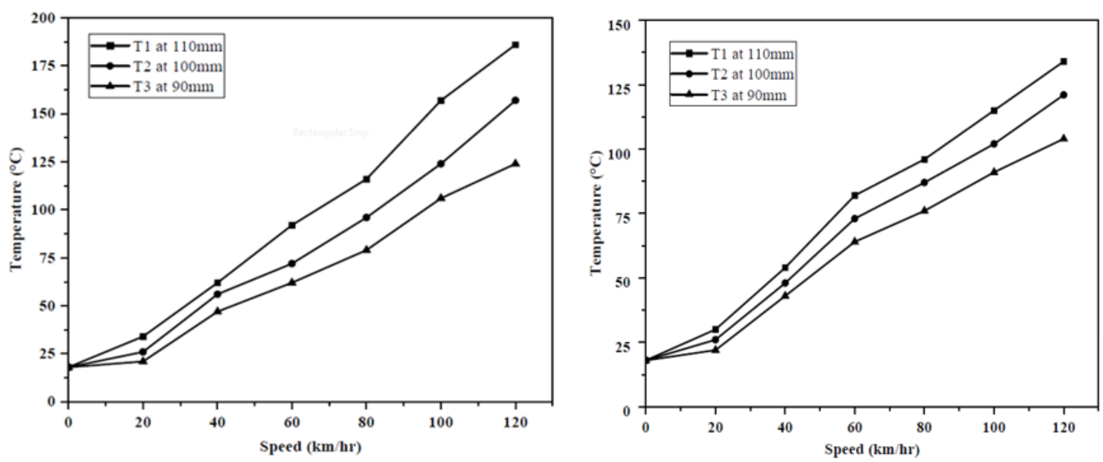
3. Results and discussion

The influence of solid and slotted brake pads on temperature of disc is decided and analyzed experimentally under various operating conditions. Some of these factors are braking force, total energy generated from braking, duration that the brake pads were in contact with brake disc, and amount of heat generated and absorbed by the brake disc during the braking process, which affect the disc surface temperature as an impact of vehicle speed and time (or duration) of braking [20]. In this part, it showed the effect of different brake operating factors on increasing the temperature of disc to the speed of the vehicle and the duration of braking.

3.1. Influence of vehicle speed on disc thermal response

The effect of vehicle speed on disc temperature and its relationship with solid and slotted brake pads is critical to braking performance and lifespan of braking systems. The temperature of the brake disc is greatly influenced by the speed of the vehicle, particularly during high-speed breaking, where a significant amount of kinetic energy transforms into thermal energy. In this study, the vehicle's speed was kept consistently from 0 to 120 km/h to evaluate the full spectrum of disc temperatures at three designated points while keeping brake pressure between 4 to 12 bars. Figure 4 illustrates the disc surface temperature measured at three distinct locations in relation to speed while gradually increasing the pressure from 4 to 12 bars. It was noted that the highest temperature occurs as the radial distance increases, corroborating the findings presented in [19], regardless of speed and braking pressure. At the outer disc radius (T1, 110 mm), the sliding velocity increases, resulting in a higher frictional power input and, as a result, greater local heat generation. Moreover, centrifugal forces tend to direct thermal loads towards the outer edge, which further worsens the temperature increase in this area. The addition of pad slots improves airflow and convective cooling at the interface; therefore, the cooling effect is more significant at T1 than at the mid-radius (T2) and inner radius (T3), where both sliding velocity and heat concentration are comparatively lower. The consistent distribution of pressure results in a uniform temperature increases across various vehicle speeds, as the work done by the friction force escalates with the radius. In the analysis of solid brake pads (CASE-I), the maximum recorded temperature, T1, reached 186°C, while the minimum temperature, T3, was noted at 124°C when running at a maximum speed of 120 km/hr. In contrast, the slotted brake pads (CASE-II) showed a maximum temperature, T1, of 138°C and a minimum temperature, T3, of 93°C. The findings achieved are highly comparable to those observed in [50].Notably, the maximum temperature (T1) for the slotted pads is 25.80% lower than that of the solid pads at a maximum speed of 120 km/hr, and the temperature (T3) is 25% lower at the same speed, demonstrating significantly improved performance compared to the results documented in [34] for the 5-friction block brake pad, where friction blocks disturbed the pad surface continuity.

Table 2 provides a comparative evaluation of Case 1 and Case 2 under varying vehicle speeds, revealing average temperature reductions of 17.86%, 14.76%, and 12.74%, respectively. These temperature drops highlight the improved thermal performance of the modified design in Case 2, which incorporates vertical slots into the brake pad geometry. The introduction of vertical slots enhances heat dissipation and airflow at the disc-pad interface, thereby mitigating the accumulation of frictional heat. This effect is particularly pronounced at higher rotational speeds, where increased sliding velocity intensifies thermal loading. As a result, the modified geometry contributes to more efficient thermal regulation under dynamic braking conditions. On the other hand, a steady rise in temperature was noted at all locations with the slotted pads, which can be attributed to effective heat dissipation, enhanced airflow, and more uniform friction distribution. The use of slotted pads enhances heat dissipation throughout the disc, particularly in the outer region, which helps to prevent overheating, minimizing the risk of brake fading and enhances overall braking efficiency. Solid brake pads generally heat up more quickly due to their limited surface area for heat dissipation, which can result in increased brake fading under extreme conditions. To ease clearer interpretation and analysis, the disc surface temperature distributions for both solid and slotted brake pads are illustrated in Figure 5.



(a) (b)

Figure 4. (a) Disc surface temperatures at different radial distances (case I-solid pads), **(b)** Disc surface temperatures at different radial distances (case II- slotted pads)

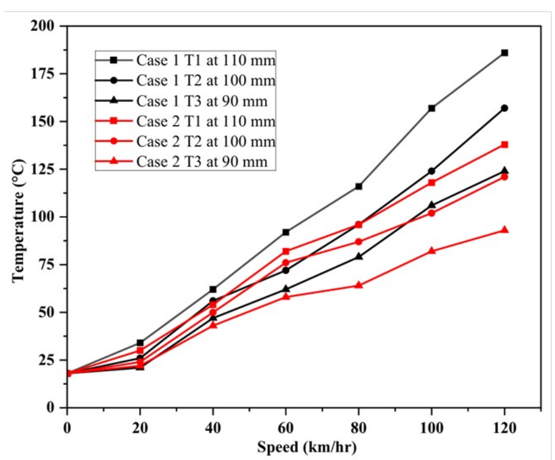


Figure 5. Disc surface temperature for case-1 and case-2

Table 2. Percentage temperature difference for both pads at various speeds

	Temperature difference (%)		
Speed (Km/hr.)	**T1**	**T2**	**T3**
20	11.76	7.69	4.35
40	12.9	10.71	8.51
60	14.58	12.64	10.77
80	17.24	15.53	14.67
100	24.84	19.05	17.17
120	25.81	22.93	20.97
Average temperature difference (%)	**17.86**	**14.76**	**12.74**

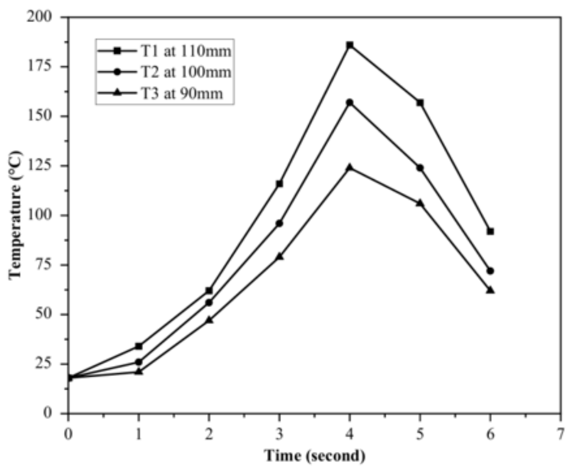
Table 2 highlights the percentage temperature differences between solid and slotted pads at three radial positions across speeds from 20 to 120 km/h. Two clear trends appear: temperature differences rise consistently with speed, peaking at 25.81%, 22.93%, and 20.97% at the highest velocity, reflecting increased thermal stress under greater braking demand.

Additionally, a distinct radial gradient is seen, with the outermost point (T1) showing the highest average difference (17.86%), followed by T2 (14.76%) and T3 (12.44%). These results underscore the slotted pad's superior ability to dissipate heat, particularly in high-friction zones, thereby enhancing thermal stability under intensified braking conditions.

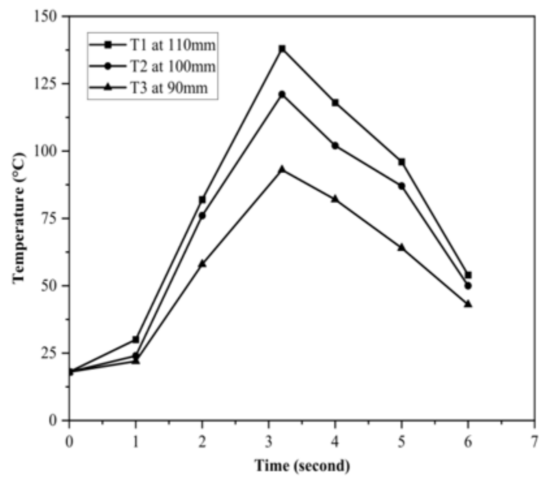
An analysis of uncertainty reveals that the accuracy of instruments (±1.5 °C for the thermocouple, ±0.1 rpm for speed, and ±0.05 s for video timing) accounts for less than 2% of the total error. Tests for repeatability prove that variation between runs is kept to a minimum, at under ±2%. Consequently, the observed differences (ranging from 5% to 15%) surpass the combined uncertainty. Mechanistically, the incorporation of slots improves convective heat transfer by directing airflow through the interface between the pad and the disc. This airflow decreases local thermal resistance and aids in the removal of debris, resulting in lower surface temperatures and diminished radial temperature gradients (T1 > T2 > T3).

3.2. Influence of braking time on thermal behavior of the disc

Figure 6 illustrates the disc surface temperatures T1, T2, and T3, measured at various radial distances over time while pressure gradually increased. The analysis revealed that the temperature peaks around the midpoint of the graph during the braking process, after which it starts to decrease. This decrease is linked to the diminishing sliding velocity between the two contact surfaces as braking persists.



(a)



(b)

Figure 6. (a) Disc surface temperature at different radial distance versus braking time case-I (100%), **(b)** Disc surface temperature at different radial distance versus braking time case-II (90%)

The maximum temperature was recorded approximately at 4 seconds after the braking process began with solid pads, while it was noted about 3.2 seconds after initiation with slotted pads at all temperature measurement sites. This can be attributed to the larger contact area of solid pads, which allows for greater heat retention, thereby delaying the peak temperature to around 4 seconds into braking. Conversely, slotted pads, because of their smaller contact area, generate higher localized pressure that increases frictional heat more rapidly, leading to a quicker rise in first temperature relative to solid pads. The solid pad reached a peak temperature of 186°C, while the slotted pad reached a maximum of 138°C. After hitting these peak temperatures, both types of pads showed a decrease in temperature. Nonetheless, it was noted that the slotted pad's temperature dropped more swiftly than that of the solid pad, a result of the slots on its surface. An area reduction in contact assists in dispersing more thermal energy without compromising braking performance, thus reducing thermal stress on the system.

3.3. Effect of increasing speed on stopping efficiency

Dependence of braking time (stopping time) on vehicle speed is a vital factor that must be considered as far as vehicle safety and performance is concerned. The duration of brakes to a vehicle depends on several factors, such as vehicle, path, and the way of driving. Speed of the vehicle, tire-road friction, braking technique of driver, braking system and its state, pressure on tire, tread depth, road surface capacity and road vertical slope are most critical. These factors influence the braking distance when decelerating and depend on the conditions under which the braking process is accelerated [51]. The braking process depends on the braking force pressed, which in its turn is directly connected with the braking force pressed and is reliant on the friction between the brake pad and the disc. Such friction depends on several factors including the temperature of the brake components.

The time of braking is greatly influenced by the type of the brake pads being used i.e. whether solid brake pads or slotted brake pads as shown in figure 7.Since both types of brake pads vary in the rate at which heat is dissipated and in the rate at which they generate friction, it can be ascertained that the solid brake pads are not ventilated, creating greater heat and reducing the rate of braking. In contrast, slotted pads prove superior performance at higher speeds, as they are more effective in dissipating heat and keeping consistent friction levels. The stopping time for solid pads is recorded at 6.3 seconds, while slotted pads achieve a stopping time of 5.7 seconds, resulting in a difference of 0.6 seconds showing better braking performance. This is increased by the fact that the slotted pads have an improved heat dissipation feature. Fig. 7 shows that surface patterns of solid and slotted pads influence the brake performance of the car at the vehicle speed ranging between 0-120km/h, with 4-12bars of brake pressures. At the speed of 20 km/h the solid brake pad had a braking dragging time of 2.4 seconds and as the speed was raised to 120 km/h the braking dragging time rose to 6.3. Compared to this, the slotted pad was seen to have a 2.28 second braking time at 20km/h, which is slightly less than a 5 % braking time as compared to the solid pad. The braking time at 120 km/h was 5.7 seconds which gives a 9.52 reduction in time when compared to the solid pad. These findings show the enhanced design of the slotted pad in terms of braking efficiency, especially under higher speeds. Comparing the results obtained with those presented in [36] a similar outcome is seen whereby at low speeds a similar performance is realized while in the present study there is a significant reduction of the braking duration at elevated speeds.

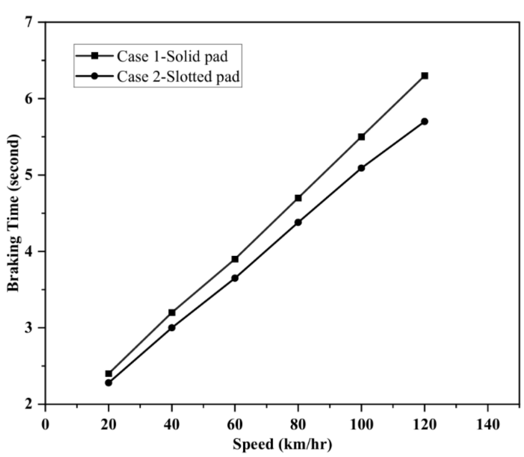


Figure 7. Braking time for solid and slotted brake pads

This decrease in braking time can be linked to the extra slots present in the slotted pads, which enhance the dissipation of heat from the brake disc, thereby reducing brake fade. This implies that a minor reduction in contact area can result in shorter braking times, improved heat dissipation, and ultimately, better braking efficiency.

4. Conclusion

Brake pad geometry, particularly the inclusion of vertical slots, markedly enhances thermal and braking performance under dry conditions. Based on the results, the following conclusions can be drawn:

- Slotted pads reduce largest disc surface temperatures by 25.8% (T1), 22.9% (T2), and 20.9% (T3) compared to solid pads.
- Stopping time decreases by 5% at 20 km/h and 9.52% at 120 km/h, proving improved braking responsiveness at higher speeds.
- The outer disc radius (T1) shows the highest temperature gradient due to centrifugal and sliding speed effects.
- Slotting promotes convective cooling, reduces thermal stress, and ensures more uniform frictional performance across the contact area.
- A 10% reduction in pad contact area can substantially enhance cooling and braking efficiency without compromising safety.

This study was limited to dry braking conditions with constant disc material and vertical slot geometry, excluding wet environments, material variations, and long-term wear effects. Future work should examine diverse slot designs and material combinations, using AI techniques such as machine learning and evolutionary algorithms to optimize thermal stability, wear, noise, and predictive brake performance.

Overall, this research underscores that the geometry of brake pads is as essential in achieving thermally stable, safe, and efficient brake systems. The results offer practical insights for engineers developing future brake pad technologies and pave the way for further optimization of disc–pad interactions.

Author contributions statement

Nilesh Kharate: Writing – Original draft, Methodology, Conceptualization. Ankur Vasava: Conceptualization, Methodology, Review and editing, Validation. Vishal Sulakhe: Review and editing.

Declaration of interests

The authors declared that they have no competing financial or personal interests related to this work. DATA AVAILABILITY The datasets generated and analyzed during the current study are available from the corresponding author upon reasonable request.

Declaration of generative AI and AI-assisted technologies in the writing process

No generative AI or AI-assisted technologies were used in the preparation of this manuscript.

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