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Research Paper

Axial Unipolar Eddy Current Brake Performance Characteristics Against Heat Increase in Rotor

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Abstract

The development of transportation technology in the automotive sector such as electric vehicles is increasingly advanced. One technology that is needed quite a lot is the development of supporting technology for electric vehicle braking. The use of regenerative braking on light electric vehicles such as 2-wheeled vehicles is not efficient because of its low weight. The use of Eddy Current Brake (ECB) can be a solution for braking support needs. This is because the ECB is a braking system that has the advantage of a lightweight design but still relies on the frictionless principle. However, in addition to its advantages, the eddy current brake is still in the early stages of its research with efficiency that still needs to be developed. In the discussion of the ECB, heat generation is one of the interesting topics to be discussed. Specifically, the study of the characteristics of the unipolar ECB axial performance on heat generation events has not yet been discussed. So this article aims to discuss these events with a simulation process and simple mathematical calculations. Design optimization is done to get the best value. As a result, the use of eddy current brakes with conductor disks using slots, can improve the performance of the ECB on the torque side and cooling side. Thus, this article is a good contribution to the sustainability of ECB research in both the general and automotive fields.

Keywords: Eddy current brake; Regenerative brake; Friction brake; EV brake

1. Introduction

The development of vehicle technology leads to the use of electric motor-driven vehicles, in General Electric vehicles have a different character from conventional vehicles. Electric vehicles tend not to have engine brakes when decelerating, making engine brakes affect regenerative brakes developed in electric vehicles. Regenerative brakes depend on the load of the vehicle, regenerative brakes are suited for heavy vehicles. The use of 2-wheeled electric vehicles is still low in regenerative efficiency due to the weight of the vehicle. This shows the need for other braking support systems in 2-wheeled electric vehicles such as motorcycles. Eddy Current Brake (ECB) is an electric braking system that uses Eddy current principle for the braking processes [1]. ECB has been widely applied in many applications in lightweight applications, especially over-speed protection devices in a drive system. An example is applicated to the turbine to regulate the turbine speed from the critical speed [2]. In addition, the use of ECB can be used in high-speed vehicles that have a large enough weight such as high-speed trains [3], [4]. ECB has several advantages, such as a compact design but offers advantages such as a regenerative brake, namely the friction brake principle so that it is able to support the braking process on electric vehicles. However, in addition to having advantages, there are still many studies that must be done regarding the ECB system, such as the ECB study of the increase in heat in the rotor.

Heat generation analysis is needed in the application to ensure the safety of the system. When the braking action, it absorbs kinetic energy or potential energy, or both when used. For mechanical brakes, the energy was converted to heat by friction and released into the environment. Excess heat will occur if the generated heat exceeds the system's capacity to release heat, which can damage the utilized components [5], [6]. The braking system's development can be broken down into contact and non-contact phases [7]. Contact brakes typically make use of friction, which converts energy into heat and can wear down to the point where it needs to be replaced or maintained at some point. It is common practice to combine engine brakes and friction brakes, as well as friction brakes with other braking systems, in order to extend the braking system's useful life [8].

The strength of the magnetic field can be changed to alter the ECB's performance. Performance adjustments can be made by adjusting the coil's current in an electromagnet-based ECB system. As well as utilizing the given current setting, the air hole setting can likewise influence the presentation of the ECB [9]. The density of the magnetic field that emerges in the gap between the magnetic source and the conducting plate will change as a result of changes in the air gap. The ECB's braking performance will also be affected by the location of the magnetic field source, which is in addition to the air gap [10]. The analysis of radial and linear designs remains the focus of the study of heat analysis on the ECB at this time. Also, there are as yet many examinations as audits that talk about the ECB framework overall [9] and concentrate on how the preparation of the ECB will be made [10], [11]. Journals that discuss the effect of using rotor materials (aluminum, Cu, or ferromagnetic metals) on braking torque [12] have proposed several updates. Giving notches on the outer layer of the rotor [13]. The expansion of long-lasting magnets to the stator to build the size of the attractive field [14]. the addition of a structure made of back iron to improve magnetic conductivity [15] or a construction made of ferrous metal that is coated with a non-ferrous metal [16] Configuration of a Halbach permanent magnet on an ECB permanent magnet [3], [17]–[19]. The purpose of this article is to examine the evolution of ECB design and modeling in order to comprehend the characteristics of the heat produced by the ECB braking process. The comprehension of the intensity qualities of the ECB slowing down process has not yet been done. As a result, this study makes a significant contribution to optimizing the ECB's use as a braking system in the automotive industry.

2. Methods

2.1. Design Optimation and Simulation

Before designing the ECB, it is necessary to calculate the braking requirements that will be used. The braking requirement is assumed to be the braking torque requirement given by the ECB. The ECB design is needed at an early stage to assess the capacity and performance of the resulting design before the next stage of optimization and design characterization is carried out according to its needs. The initial design process is carried out using the general ECB design which has been widely used in research. Then the simulation process is carried out to obtain the braking torque value. After the simulation results are known, the values obtained are calculated using mathematical equations.

Eddy currents produced by magnetic induction are used by the ECB to function. Eq. (1) [4] depicts the calculation used to determine the ECB's energy value. The wellspring of the ECB attractive field can emerge out of an extremely durable magnet or a winding that is invigorated. Eq. 1 is used to derive the magnetic field density from the magnetic field flux per unit area.

$$B = \frac{\Phi_m}{(1 + 2k_{ff})w_{st}d} \tag{1}$$

Where B is the thickness of the attractive field in the air hole, m is the extent of the attractive transition created, w_{st} is the cross over surface region of the stator or attractive field source, and d is the profundity coordinate. An induced current will be produced by the value of the magnetic field in a changing conductor. The speed at which the attractive field changes in a guide turning on its hub is relative to the rotational speed of the guide. The conductor's rotational speed is inversely proportional to the magnitude of the induced current. The induced current grows in proportion to the rotational speed. According to Eq. (2), the product of the magnitudes of the magnetic field density and the rotational speed determines the magnitude of the induced current produced by the conducting disk rotating on its axis.

$$J_e = \sigma \cdot a \cdot (\omega \times B_c) \tag{2}$$

A material's resistivity also known as its electrical conductivity is a one-of-a-kind property. The temperature of a material has a significant impact on its electrical resistance. Using the material's resistivity, which can be determined using Eq. (3).

$$\sigma = \frac{1}{\rho_o(1 + \alpha T)} \tag{3}$$

Where ρ_o resistivity at zero degrees Celsius and changes in conductivity per Celsius. Research in general is to analyze the heat generation of an ECB braking process. After analyzing the heat generation, proceed with making design changes and modifications carried out using simulations. By using the simulation will be able to describe the magnetic field and heat distribution that is formed. The simulation model built is based on real testing. The simulated braking torque should be close to the real test results, with an error rate of less than ten percent. This research was conducted using the finite element method using a stator in the form of an electromagnet and a rotor disc in the form of a disc brake made of aluminum and iron with a stator made of iron. The finite element method carried out is divided into several processes that review the magnetic properties, heat generation and heat release that occur. In the review process based on the results shown by the ECB, calculations and comparisons with the braking requirements of motorized vehicles were also carried out. So we will get a design that fits your braking needs. In the process, a review of the braking torque will be obtained using magnetostatic simulations and continued using Ansys. Changes made to the design is to add kerf on the surface, this aims to increase the area of contact that occurs. In addition, the addition of grooves will be able to provide an increase in braking performance caused by the emergence of a magnetic field concentration that arises during the braking process.

This study uses changes in the number of slots and air velocity variations used as shown in **Figure 1**. The process carried out before performing the simulation is to collect data on the ECB design that does not use a cooler on the disk surface. The data collection is used as a reference in the simulation process to be carried out. In this simulation, data in the form of torque and working temperature will be obtained. Before performing the simulation, there are several things that need to be considered, namely the domain, boundary conditions, meshing, and material properties as shown in **Table 1**.

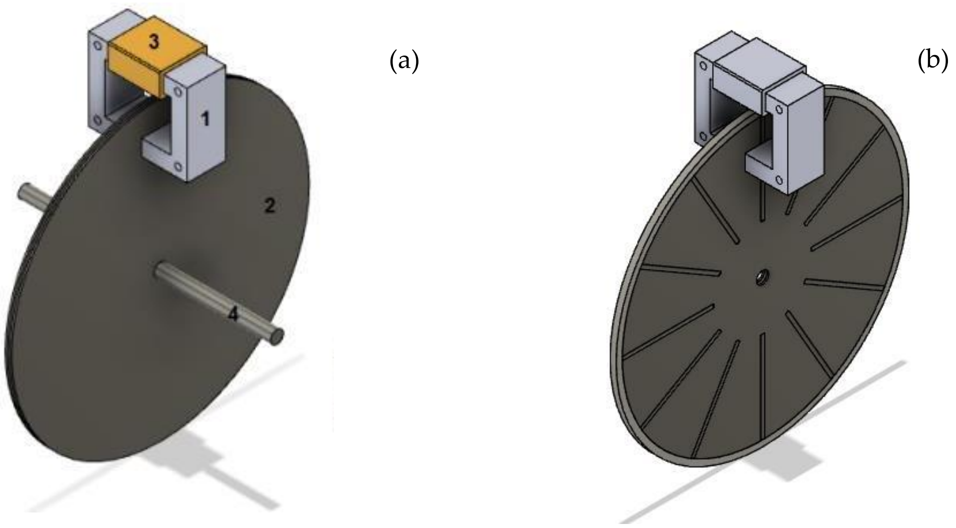

Figure 1. ECB disk: (a) without slot; (b) using slots

Table 1. Design and properties of simulation process

Variable	Unit	Value
Electric current (i)	A	20
Number of coils (n)	-	360
Length of pole shoe (a)	mm	30
Width of pole shoe (b)	mm	12.5
Total length of winding core (l)	mm	248
Center to pole shoe center gap (r)	mm	83.5
Air gap (t)	mm	0.5
Thickness of disk (d)	mm	5
Radius of disk brake (r')	mm	120
Relative permeability of aluminum (μ_{al})	-	1.000022
Relative permeability of iron (μ_{fe})	-	400
Aluminum conductivity (α)	Ωm	2.06 x 10^{-7}

To find out the results of the simulation are in accordance with the real results or not, validation of the simulation process used is carried out. One of them is by changing the settings used in the simulation process in the form of the mesh used. Meshing is the process of dividing the geometry into small elements so that each element can be applied to uniform boundary conditions and material properties. Meshing is important for conducting simulations, because it will affect the final result of a simulation. The research process can be seen in the Figure 2.

The research was continued by taking braking torque data along with heat generation which was then carried out to collect data regarding design changes with the aim of obtaining a cooling performance analysis based on the addition of slots on the surface of the rotor with a half-circle slot type conductor disk by making a comparison between without slots and with additional slots. In this case, the heat generation seen is in the active region which is experiencing a critical point from the ECB braking process. Active region is the area of the conductor perpendicular to the magnetic face whose magnitude is influenced by the dimensions of the magnet and the area of the conductor perpendicular to the magnetic face used. Illustration of active region is shown in Figure 3a. While, Figure 3b present the active region obtained from the simulation results.

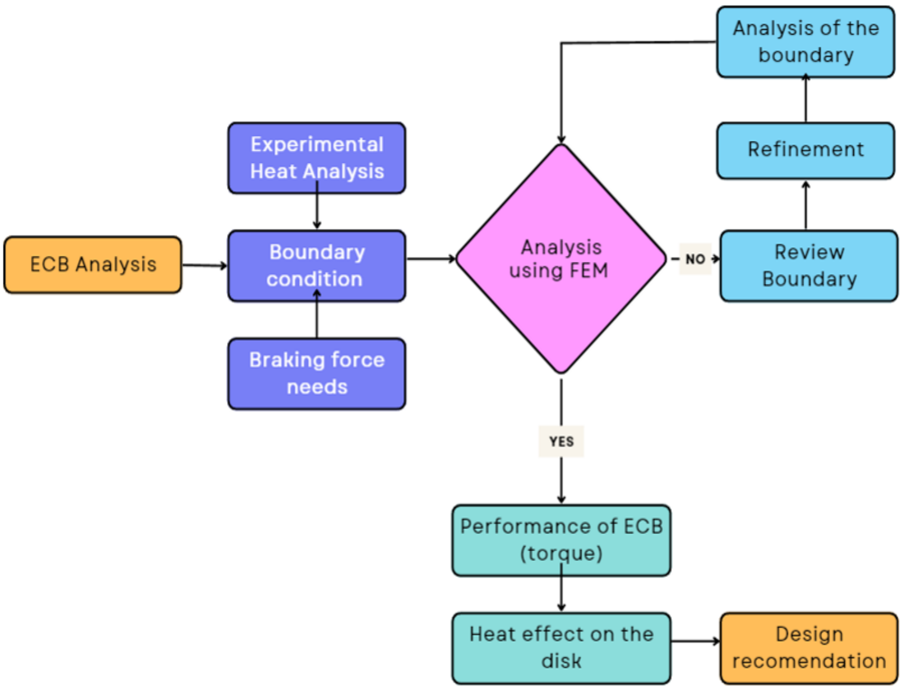

Figure 2. Research stage and procedure

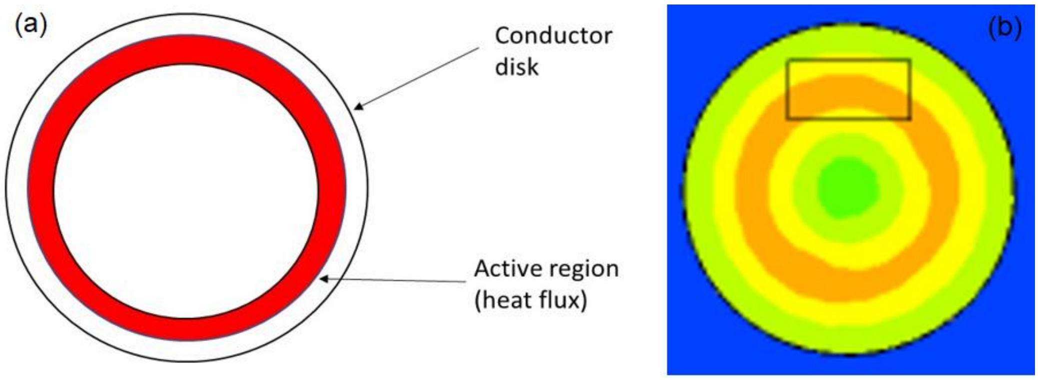

Figure 3. Active region: (a) theoritical illustration; (b) simulation result

3. Results and Discussion

Simulation research data retrieval was carried out to obtain data on braking torque and magnetic flux on the ECB. This data is used to analyze the characteristics of the effect of changing the number of slots on the performance of the ECB using an electromagnet as a magnetic source. The modeling in this simulation uses conventional braking principles. Simulation using Finite Element Method (FEM) using Ansys Electronics Desktop software by varying the number of slots used on the ECB conductor disk. Each data retrieval uses an electromagnet with a voltage specification of 12 V, a current of 20 A and uses 360 coil turns. The results show that a suitable heat distribution is obtained between the simulation and experimental processes.

In addition to being influenced by the energy conversion process from motion to heat (braking process), the position of the heat source will be centered at the bottom of the magnetic field source with the ECB's axial design. The magnetic field source also generates heat. The center or central portion of the disc being utilized will typically be the direction in which heat travels. The findings indicate that as the temperature rises, the braking procedure performs less effectively. The value of electrical conductivity will decrease as temperature rises, resulting in less effective braking. This is the same thing that happened in **Figure 4**. As the working temperature rises, the performance decreases, as depicted in **Figure 4**. If you look at Eq. 1-3, you can see that the conductivity of the conductor material decreases as the temperature rises. The induced current's value will decrease as conductivity decreases. While taking a gander at condition 4 the diminished prompted current will bring about a decline in slowing down force. As temperature rises, performance deterioration occurs simultaneously. Each change shown in **Figure 4** will typically result in a braking performance decrease of up to 10% when the temperature is increased by 5 °C. The same characteristics apply to each subsequent temperature increase.

The simulation process demonstrates that the braking temperature is one of the crucial aspects to take into account. During the energy conversion process, it is understood that heat generation is normal. When braking is required, the ideal temperature will be reached by utilizing the ECB heat generation analysis. The conductivity of the material used for the conductor also plays a significant role. It is evident from the phenomena depicted in **Figure 5** that temperature regulation during ECB application must be investigated. In the future, it will be necessary to improve ECB's ability to release heat in addition to its ability to generate heat.

The utilization of spaces isn't just equipped for giving extra intensity dispersal abilities, the utilization of openings likewise improves slowing down execution. The critical speed is located in the range of 400-500 rpm, as can be seen from the graph of the torque relationship. At the point when the basic speed has been passed, the slowing down force will in general diminish. This is brought about by the skin effect or the concentration of the magnetic field on the outside [5]. Due to the primary magnetic field's high frequency, the conductor's skin experiences the skin effect, which is the current density in the conductor. The presence of a secondary magnet with a significant magnetic force generated by eddy currents is what results in the skin effect [15]. As a result, the eddy currents that are formed in the conductor are pushed toward the conductor skin by the magnetic force [15]. The expansion of openings will build the contact region of the guide material. When looking at Eq. 1, it is clear that increasing the depth of the conductor area and increasing the surface area of the contact will both contribute to increasing the density of the generated magnetic field, resulting in an increase in torque during braking. What's more, the skin impact caused will likewise be unique. The pattern of heat release and distribution are shown in **Figure 6**.

The value of braking torque from the ECB can be analyzed through an analysis of the kinetic energy required during the braking process, with a theoretical approach using the assumption of 14-inch alloy wheels for braking at 750, 600, 450, 300, and 150 RPM with a load of 190kg on a vehicle with a disc diameter of 240 mm (**Table 2**). The braking distance to stop from 60 km/h to 0 km/h is 10 meters.

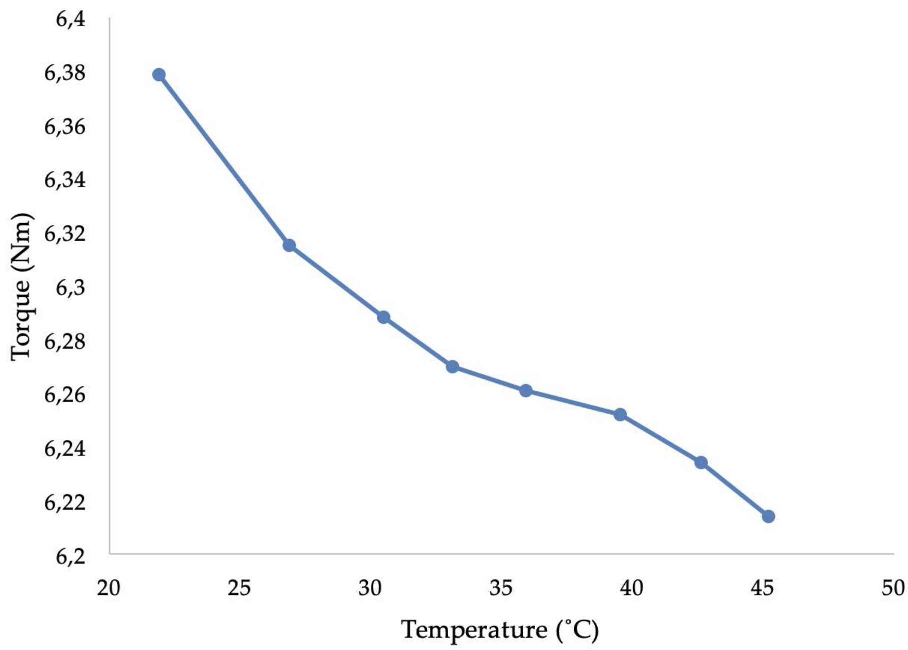

Figure 4. Torque decrease with increasing temperature

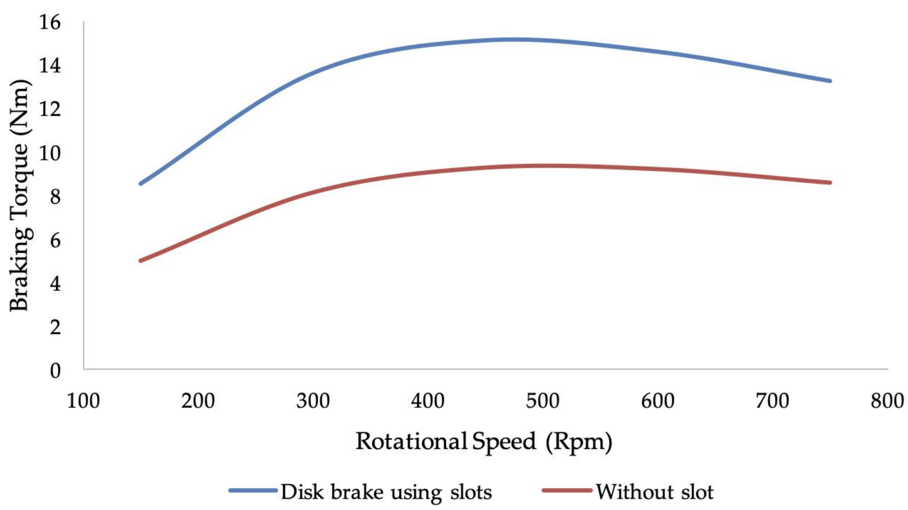

Figure 5. Comparison of the torque value against the rotating speed between a disc with slots and without a slot

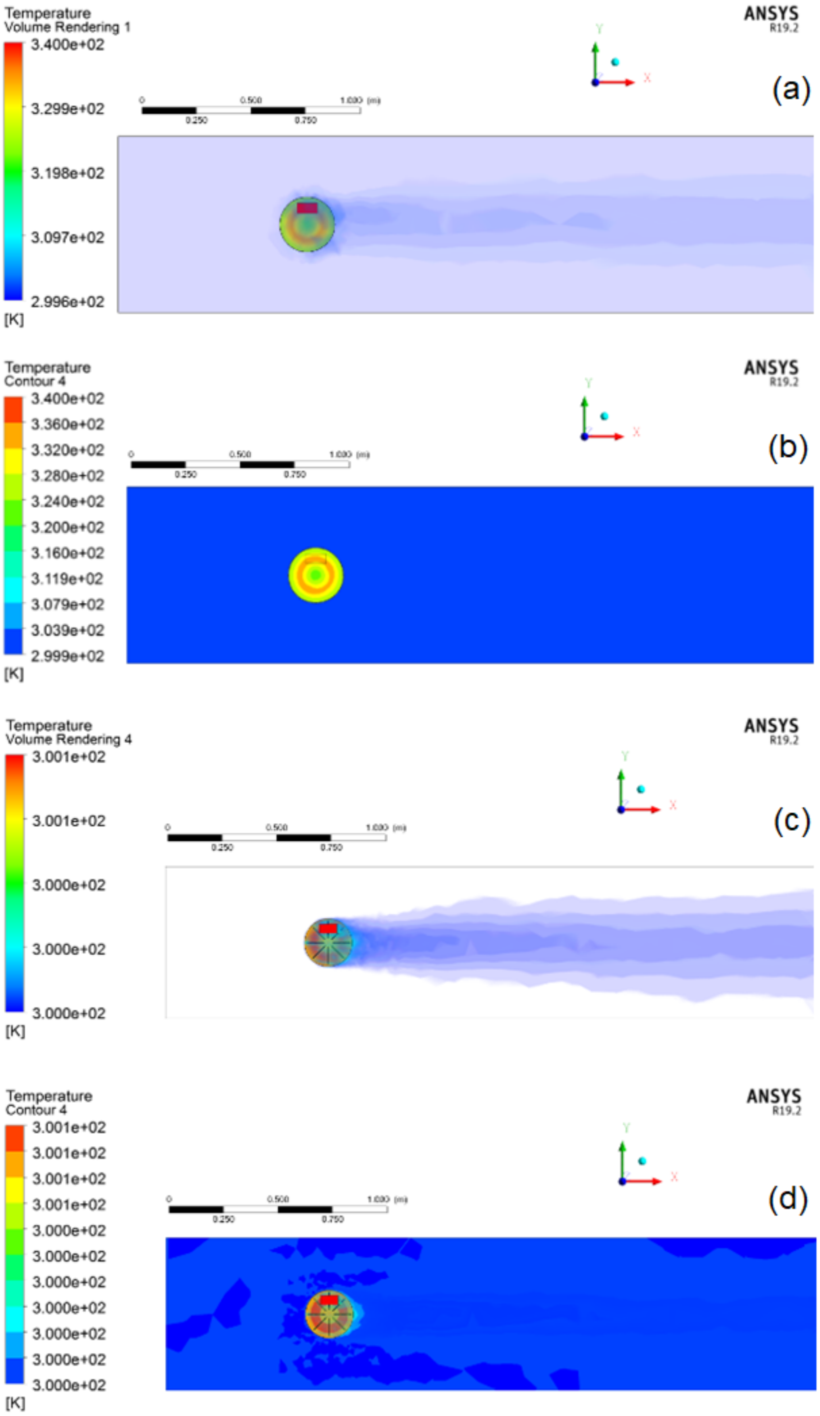

Figure 6. Pattern of heat release and distribution: (a, b) ECB disks without slots; (c, d) ECB disks with slots

Table 2. Braking energy analysis

Rotating speed (RPM)	Braking Energy		ECB support capability (%)
	Mechanical (Joule/s)	ECB (Joule/s)	
150	877	135	15.39
300	1754	431.75	24.62
450	2631	713.09	27.10
600	3508	915.62	26.10
750	4385	1031.5	23.52
	Average (%)		23.35

The ECB's braking power can only provide support of 22% on mechanical braking. It is also influenced by the different characteristics of using ECB and conventional braking. ECB has an induction value that changes with changes in rotational speed that occurs, and this is different from the phenomenon of mechanical brakes, which have the same frictional force value for various reference speeds used. The application of ECB is suitable to be braking support by braking using ECB, which would be ideal for use at high speeds, starting at speeds of 750 Rpm up to 300 Rpm.

4. Conclusion

The utilization of spaces isn't just equipped for giving extra intensity dispersal abilities, the utilization of openings likewise improves slowing down execution. The critical speed is located in the range of 400-500 rpm, as can be seen from the graph of the torque relationship. At the point when the basic speed has been passed, the slowing down force will in general diminish. This is brought about by the skin effect or the concentration of the magnetic field on the outside [5]. Due to the primary magnetic field's high frequency, the conductor's skin experiences the skin effect, which is the current density in the conductor. The presence of a secondary magnet with a significant magnetic force generated by eddy currents is what results in the skin effect [15]. As a result, the eddy currents that are formed in the conductor are pushed toward the conductor skin by the magnetic force [15]. The expansion of openings will build the contact region of the guide material. When looking at Eq. 1, it is clear that increasing the depth of the conductor area and increasing the surface area of the contact will both contribute to increasing the density of the generated magnetic field, resulting in an increase in torque during braking. What's more, the skin impact caused will likewise be unique.

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Author's Declaration

Authors' contributions and responsibilities

Writing – original draft preparation (M.R.A.P., B.W.L.); conceptualization (M.N., D.D.D.P.T., Z.A.); validation (M.N., D.D.D.P.T., Z.A., I.); supervision (M.N., and D.D.D.P.T.); All authors have read and agreed to the published version of the manuscript.

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Availability of data and materials

All data are available from the authors.

Competing interests

The authors declare no competing interest.

Additional information

No additional information from the authors.

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