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RESEARCH

Wear Behavior of Graphic Brush for Motors in the High Humidity of Tropical Climate with Current

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A B S T R A C T

The motor with commutator brushes pair is widely used in industrial equipment. During operation, the brush and commutator of the motor will wear out, especially in humid tropical monsoon conditions. The commutator brushes pairs operate in both loading conditions: Mechanic and Electric. The temperature, velocity, spring pressure, current, material, and environmental conditions, especially high humidity of ambient air, directly affect the wear of commutator brushes pair. This paper presents studying results on the wear behavior of graphite brushes when used in conditions changes as relative humidity and current. Initial experimental results showed that relative humidity had influenced brush wear. The wear rate increases by 1.8 to 2 times when humidity increases from 51% to 99%. The wear graphs of the brushes depend on current more than relative humidity with tropical climate characteristics. The specific wear rate changed about 2.88 times in this study.

1. INTRODUCTION

The commutator-brushes pairs are widely used in electrical motors. The commutator includes many connected segments on the ring, usually made of copper and separated by mica insulation. Brush material is often carbon graphite because of low friction, low wear rate, and good conductivity when in contact with the commutator. Carbon graphite brush sliding against a copper commutator with the current in the motor. Therefore, the wear of the commutator-brush pair during operation is affected by: Mechanical, electrical, and environmental, and the wear amount directly affects the life and reliability of the commutator-brush pairs. There are new materials, including five types: Carbon, carbon-graphite, graphite, electrographic, and metal-graphite, which improve electrical characteristics and prolong brush life. Many studies showed that [1–8] thermal field, arcing, and electrical discharge influent the wear rate of the brush surface, and the proportion of electrical wear ranges from 1/2 to 2/3 of the total wear of the brushes. According to many studies [9–12]. The third body in tribology and numerical wear optimization is a new demonstrated method. It is used to wear prediction and analyze the properties of sliding contact between commutator brush surfaces of the electrical machine. Wae-Gyeong Shin et al. have investigated the wear behavior of copper-graphite brushes in a small brush-type DC motor. The study result found that: The contact pressure and sliding velocity of the brush change with and without current then brush wear greatly varies with electrical current. This shows that joule heating increase when the high current [13]. Jau-Wen Lin et al. have studied the contact friction temperature between the copper ring and carbon graphite brush surfaces without current. The study result showed friction with temperature and wear rate had a relationship. The high temperature in contact friction softens the debris, a brush, and copper particles mixture. It adhered and formed flattened areas [14]. Wae-Gyeong Shin et al. found that the temperature changes and the direction of current flow at the brush contact site have influenced the brush wear. Moreover, it tends to be accelerated by temperature increases when current is supplied. The contact resistance and voltage drop in the contact site are the main reasons for temperature change [15]. Du Sanminget al. show that wear rate increases in the high-speed dry sliding of copper-graphite composite against GCr15 steel when increasing current [16].

Vera Deeva and Stepan Slobodyan have analyzed the model of the third body, and through simulation show that the lifetime of the electrical brush depended on the third body position relative to the slip ring axis [17]. M. Grandinet al; showed that when the amount of metal in the graphite composite increase, the wear rate decreases. This result was obtained from the study of copper-graphite composites sliding against copper with a contact current [18]. AlesˇTurel et al have studied the electrical contact resistance and wear of a dynamically excited metal–graphite brush. The result showed that the wear rate increased with the rotating speed at low current and low ambient temperature. In contrast, the contact resistance decreased with an increased ambient temperature, electrical current, and rotating speed. The results were founded when studied electrical contact resistance and wear of a dynamically excited metal–graphite brush [19]. Hao Zhaohase studied electrical current, apparent contact pressure, sliding velocity, and electrical sliding wear behavior of Cu–Ti3AlC2 composites. The results showed that wear rate and contact voltage drop rise with increased current. The wear rate first reduces and then increases when apparent contact pressure increases. The wear rate of the sliding pair is influenced by the lubricating film on the contact surfaces under each test condition. When the sliding speed increases, the wear rate reduces first and then increases while the contact voltage drop regularly increases [20].

Nguyen Anh Tuan et al. have studied the influence of Vietnam's climate with relative humidity varying from 60% to 100% RH on the wear of steel materials pairs in the sliding friction. The results show that the wear amount of the material pairs changes depending on the variation of relative humidity. The amount of wear increases rapidly as the relative humidity rises [21]. Z.L. Hu et al, have investigated an electrographite brush sliding against a copper commutator. The results showed that the oxide layer's thickness on the sliding surface and the wear rate of brushes rise with the current. The brush's wear rate at 50% relative humidity (RH) is less than at 10% RH, and the oxide film layer can be used as a lubricant [22]. Ueno et al, show that the brush wear is high, at high humidity (RH = 80%) and low humidity (RH = 20%). The brush wear rate is the lowest around 60% relative humidity. The brush wear increases with decreasing temperature, at 80% humidity [23].

The studies on the wear behavior of the commutator brush pairs were briefly reviewed. The main influential factors of brush wear included temperature, velocity, spring pressure, material properties, current, and environmental conditions. The brush wear was associated with both mechanical wear and electrical wear. Not many studies were realised about the influence of environmental conditions on brush wear. Some studies were realized in high humidity with steel wear [21], and low humidity with brush wear [22,23].

In these studies, the wear amount (mass loss) of the graphite brush was measured, and the wear rate (WR) and specific wear rate (SWR) were calculated. The WR and SWR were calculated by the following formula (1 &2)[24].

$$WR = \frac{\Delta V}{L} = \frac{\Delta M}{\rho . S} \ (\mathrm{mm^3/m}) \qquad (1)$$

$$\mathrm{SW}R = \frac{\Delta M}{\rho . F . S} \quad (\mathrm{mm^3/N.m}) \qquad (2)$$

Where:

ΔV is the wear volume (mm^3),
ΔM is the wear mass loss of the samples (g),
S is the sliding distance of the samples (m),
ρ is the density of the samples (g/mm^3),
F is the normal force applied to the samples (N).

This paper presents graphite brush wear study results affected by various factors, including current and environmental relative humidity. A commutator–brush wear test machine was designed and manufactured. The wear mass loss was measured, and the wear and specific wear rates were calculated at temperatures of 40^{0}C and a velocity of 2.77 m/s.

2. EXPERIMENTAL

2.1. Test set-up and procedure

Wear tests of commutator brushes pairs were performed using a self-made tribometer. The principle diagram of the experimental apparatus is displayed in Fig. 1. Fig. 1a presents the test apparatus and electrical circuit applied for the commutator brushes pairs. The commutators were installed to the main shaft driven by a 0.27 kW motor and n = 1450 rpm. Four commutator brush pairs are testing together. The graphite brush was sliding on the surface of the copper commutator with the current. A current flowed from the first brush to the first commutator, the second commutator, and the second brush. The diameter of the commutator was 36.5 mm. The contact area of the brush was 13 x 6 mm^2. The average load of the brush onto the commutator was provided by a constant-force spring applied with 0.02 MPa. The average load of the brush onto the commutator was provided by a constant-force spring applied with 0.02 MPa. In this experiment, the amount of wear is small, so the wear layer height is small. Therefore, the spring compression force does not change significantly, and all brushes are affected the same, so the effect of the change in spring force can be ignored. With various currents, the constant commutator velocity is 2.77 m/s (rotated speeds – 1450 rpm). The graphite brushes were tested wear in the time of 10h. The current was changed from 5 to 10 A. The tropical air environment was a temperature of 40°C and relative humidity from 51 to 99%. The brush's worn surfaces were measured using a small weight scale. The electrical circuit inputs the DC part through a power resistance and then passes these contacts of commutator brush pairs. The variation of power resistance changed the current. In addition, the wear mechanisms involved, the worn surfaces of brushes, and the commutator were observed during the experiment. The composition of the worn surfaces can be an oxide layer, a mixture of brush and copper particles, and humidity film, which is the third body in tribology.

A climate cabinet was used to control the humidity and temperature of the cabinet where the commutator brushes pairs tester system was placed. The system motor was placed outside the cabinet (Fig 1b).

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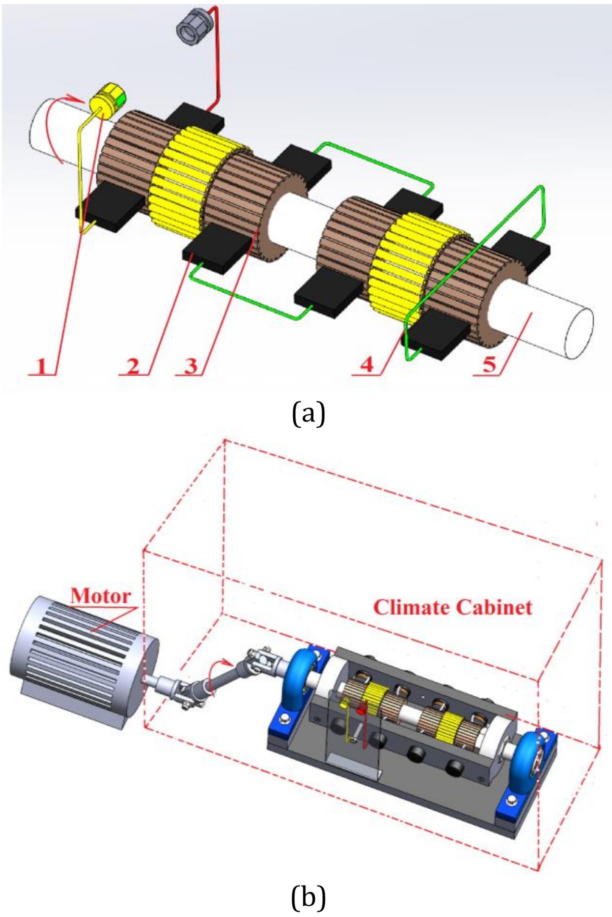

Fig 1. (a)- The test apparatus and electrical circuit applied, (b)- Experimental apparatus. 1- Connector, 2- Brush, 3- commutator, 4- line connection, 5- Main shaft.

The study's main experimental parameters for to wear behavior of the graphite brushes are in Table 1.

Table 1. Experimental parameters.

No.	Main experimental parameters	Value
1	Mass of brush to start M_b (g)	8,4
2	Speed of comuntator n (rpm)	1450
3	Temperature T(^{0}C)	40
4	Relative humidity RH(%)	51, 75, 99
5	Electrical current I(A)	5; 7.5; 10
6	Experimental time (h)	10
7	Mass loss of Wear amount ΔM	$M_b - M_e$

2.2. Materials

The copper commutator shown in Fig. 2b is a cylinder body consisting of 32 bars with a diameter of 36.5 mm and a length of 24 mm. The graphite brush size shown in Fig. 2a is 13.8 mm × 6.8 mm × 17.8 mm (width x height x length), and the contact surface is slightly curved. The copper material is composed of 99.9%Cu and 0.1% impurities. This commutator – brushes pair is often used for brush in the DC motor (the equivalent of 417A, Makita).

The copper commutator's average roughness values (Ra) were about 0.16 μm, respectively, and the micro-hardness of 130 HV. The electrographite brushes are 72% flake graphite, 8% carbon black, and 20% pitch. They were graphite at 2200^{0}C. The main properties of brushes are listed in Table 2.

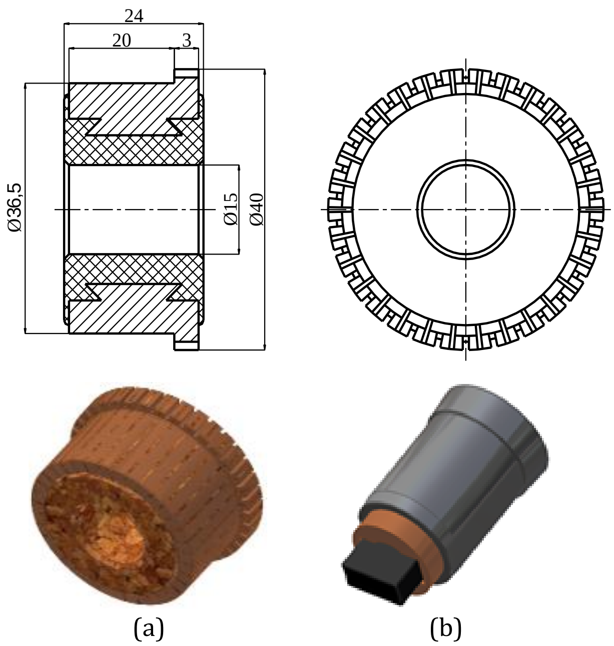

Fig 2. Shape and dimension: (a) - The copper commutator, (b) - The graphite brush 32 bars.

Table 2. Main properties of 417A electrographite brushes.

Electrical resistivity (μΩm)	Bulk density (g/cm3)	Shear strength (Mpa)	Hardness (HSC)	Max peripheral speed (m/s)	Max current (A/cm2)	Coefficient of friction
9	1.9	10	18	30	10	0.20-0.25

3. RESULT AND DISCUSSION

After every test, the mass loss M of the graphite brush was measured, and the wear rate (WR) and specific wear rate (SWR) were calculated.

These experimental results were presented, and the graphite brush's specific wear rate (SWR) depends on current and humidity at a temperature of 40^{0}C and velocity of 1450 rpm.

From data Table 3, It could be presented on the graph that the wear rate (WR) depended on current and humidity at a temperature of 40^{0}C and velocity of 1450 rpm, Fig 3.

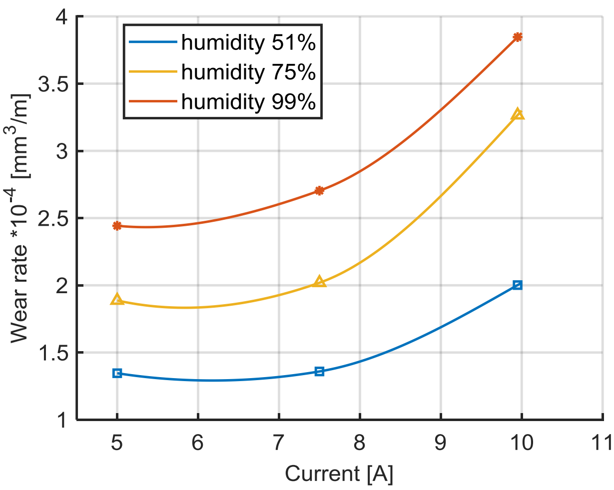

Fig 3. The effect of current and humidity on the Wear rate (WR) at 40^{0}C.

Table 3. The mass loss (M) and wear rate (WR), and specific wear rate (SWR) depended on current and humidity at a temperature of 40⁰C and velocity of 1450 rpm.

No	Experiment mode		Mass loss M (g)				Mass loss Average (g)	Standard deviation S	Volume loss Average (mm3)	Wear depth h (mm)	Wear rate WR .10-4	Specific wear rate SWR.10-4
	I (A)	RH %	Pair 1	Pair 2	Pair 3	Pair 4						
1	5	51%	0.025	0.026	0.025	0.026	0.02550	0.0006	13.42105	0.14302	1.3460	0.6730
2		75%	0.036	0.035	0.037	0.035	0.03575	0.001	18.81579	0.20051	1.8871	0.9435
3		99%	0.047	0.046	0.046	0.047	0.04650	0.0006	24.47368	0.26080	2.4545	1.2272
4	7.5	51%	0.026	0.026	0.025	0.026	0.02575	0.0005	13.55263	0.14442	1.3592	0.6796
5		75%	0.039	0.038	0.038	0.038	0.03825	0.0005	20.13158	0.21453	2.0190	1.0095
6		99%	0.051	0.051	0.052	0.052	0.05150	0.0006	27.10526	0.28885	2.7184	1.3592
7	10	51%	0.039	0.038	0.038	0.038	0.03825	0.0005	20.13158	0.21453	2.0190	1.0095
8		75%	0.063	0.062	0.063	0.062	0.06250	0.0006	32.89474	0.35054	3.2990	1.6495
9		99%	0.073	0.074	0.073	0.074	0.07350	0.0006	38.68421	0.41224	3.8797	1.9398

The main components of brush wear are mechanical and electrical wear. This is consistent with the studies of [1-8]. In these experiments, the brush's wear rate (WR) increases as the current through the pair of brush commutators rises. The more current is, the higher the nonlinear wear rate is. When humidity increases from 51% to 99%, the Wear rate increases by 1.8 to 2 times. Mechanical wear occurs because friction at the contact surface causes the wear particles to separate from the graphite brush surface, creating carbon dust. During the working process, a thin film appears between the two surfaces of the brush, and the commutator is the third object. It is composed of graphite microcrystals, water vapor, and metal oxides. It is produced by the electrochemical action of an electric current to the brush's graphite, moist air, and a contact surface's metal. As the humidity increases, this thin film's adhesion to the surface rises, increasing its thickness.

In it, graphite plays the role of lubricant and increases wear resistance. The mechanical wear of brushes is an inverse ratio to the thickness of the thin layer, while the electrical wear of brushes is affected by current and contact voltage drop. Electrical wear occurs when current flows through poor surface contact with high resistance, causing an arcing. The higher the relative humidity, the greater the contact voltage drop on thin film, which strongly increases electrical wear. Thus the total wear rate (WR) caused by electrical and mechanical currents increases despite the increased lubricating effect of graphite.

The dependence of the SWR on the current and relative humidity of the graphite brush can be described by the following mathematical function (3) with $R^2 > 0.95$.

$$SWR= b_{03} I^3 + b_{20} RH^2 + b_{12} RH\cdot I^2 + b_{11} RH \cdot I + b_{02} I^2 + b_{10} RH + b_{01} I + b_{00} \tag{3}$$

With:

b_{00} = 0.0265; b_{01} = 0.0591; b_{02} = -0.01494;
b_{03} = 0.00075; b_{10} = -0.0043; b_{11} = 0.00079;
b_{12} = 0.00002; b_{20} = 0.00004.

Equations 3 and Figure 4 show the simultaneous influence of the relative humidity and current on the SWR of graphite brush, but it is very different in level. At the same current value, when the humidity increases, the SWR also rises, but the rise tends to decrease slightly, showing that: Although the electrical wear increases rapidly when the voltage drop across the thin layer of graphite microcrystals, water vapor, and metal oxides increases, But the lubricating effect of this thin layer reduced the magnitude of the rise of SWR. Specific wear rate has the lowest value in the area with 5A current and 51% relative humidity. The maximum value is reached in the area with a 10A current and 99% relative humidity.

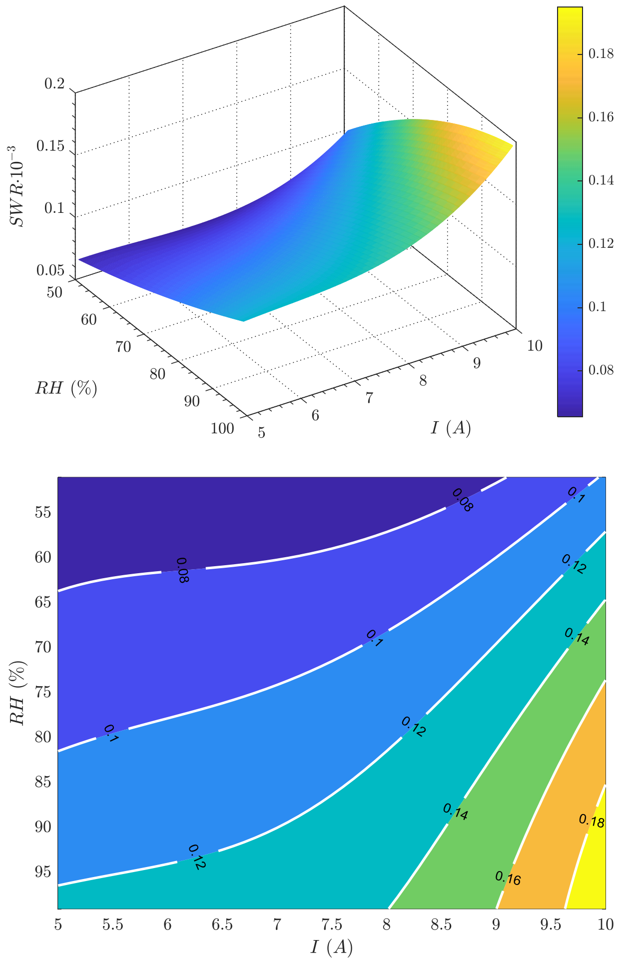

Fig 4. The effect of current and relative humidity on the Specific wear rate SWR at 40⁰C and 1450 rpm.

So SWR changes about 2.88 times. This shows that as the relative humidity increases, the lubricating effect of the third object increases. It reduces the wear of the graphite brush. On the other hand, the electrical wear of the Graphite brush strongly increases due to the rising effect of the current and the thickness of the third object. Therefore, total electrical and mechanical wear increases, but the rate gradually decreases [22]. The graph of the SWR contour lines in Figure 4 shows that the regions of SWR values can be determined according to the ranges of current I and relative humidity RH. When the relative humidity changes, the SWR can be kept stable by adjusting the current value accordingly in the contour area or can evaluate the change of SWR when keeping the current value and changing humidity. From there, the reduction of brush life can be predicted.

Contour density increases quickly in the region with I > 7.5 A and RH > 75%, showing that the brush has a large SWR and a low life. Therefore, no more than 75% of the maximum current and 75% RH should be used under actual operating conditions. In areas of high relative humidity, there is a decrease in insulation between bars because graphite adhesion increases the likelihood of an electric arc and increases current wear. Specific wear rate significant increase leads to damage do not allow the commutator - brushes pair.

4. CONCLUSION

The studies on the simultaneous influence of the current and relative humidity with characteristics of the humid tropical environment on the wear of electric motor brushes have been conducted on a brush friction pair wear test device. Based on the analysis results in this study, the following conclusions were drawn:

The relative humidity and current parameters of the experiment are simulated close to the working conditions of the brush commutator pair in actual operation at a humid tropical ambient temperature of 40⁰C and n =1450rpm.

The wear rate WR of brushes varies with variations in relative humidity and current. When humidity increases from 51% to 99%, the Wear rate increases by 1.8 to 2 times. And Specific wear rate SWR of the brush change about 2.88 times as the current increases from 5A to 10A and relative humidity rises from 51% to 99%. The change of WR and SWR is due to the mutual effect of mechanical wear and electrical wear on the contact surface between the brush and the commutator in the changes in the condition of humidity and current.

As relative humidity and current increase, mechanical wear decreases, and electrical wear increases. But the increase in electrical wear is more significant than the decrease in mechanical wear, so the total wear still rises. This can be explained by the relative humidity increases leading to the moisture film thickness increases, and it acts as a lubricant to reduce mechanical wear. On the other hand, when high humidity will increase the adhesion of graphite to the commutator and the insulation gaps between the bars of the commutator, it will generate and increase the discharge current, which is the main cause of the increased electrical wear.

The contour graph can be used to control the motor current value at suitable levels for stable brush life under conditions of high relative humidity and significant variation. Based on the levels of the contour SWR when relative humidity and current vary, it is possible to determine the expected life of brushes according to wear limit and the required reliability. It is also possible to provide the optimal set of working parameters and propose measures to improve the long life of brushes and commutator pairs in humid tropical climates.

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