Electrical Tracking, Erosion and Fire Retardancy Performance of Silicone Rubber Insulation Containing Aluminum Trihydrate, Graphene and Glass Fiber Additives

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***Abstract*—Silicone rubber composite is a priority electrical insulating material used in high-voltage outdoor insulation applications. Low electrical tracking/erosion and poor flame resistance performance of silicone rubber once ignited, substantially reduce its working life. This paper attempts to investigate tracking/erosion performance of room temperature vulcanized (RTV) silicone rubber along with flame retardant parameters using aluminum trihydrate (ATH), graphene nanosheets (GN) and milled glass fiber (GF) additives. The inclined plane test (IPT) was performed in line with criteria defined in IEC 60587 using step-up tracking voltage method while flame retardancy is evaluated according to ASTM E 1354.0 using a cone calorimeter. Results suggest 30% of ATH assists in improving physical tracking/erosion resistance of pristine silicone elastomer rubber by impeding development of leakage current and a great reduction in maximum average temperatures on the surface of RTV2. Further improvement in performance of RTV2 is achieved through introduction of 1% of GN and 5% of GF as seen in RTV4. Moreover, 30% of ATH reduces heat release rate and smoke production rate, and this trend is improved with the introduction of GN/GF. RTV4 has pop up as the most promising silicone rubber composite with excellent electrical tracking, erosion, and flame resistance performance relative to its counterparts in this study.**

***Index Terms*—Dry band arcing, electrical tracking, heat release rate, leakage current, silicone rubber, smoke production rate.**

I. Introduction

HYDROPHOBIC silicone rubber is widely engaged in manufacturing of composite insulators and anti-pollution coatings for high-voltage networks [1]–[4]. Relatively, composite materials offered multiple positive attributes such as lightweight, excellent contamination flashover performance, easy transportation and superb resistance against vandalism compared to old ceramic and glass materials-based insulation technology [5], [6]. However, in the presence of contamination, silicone material may track and erode due to serious dry band arcing (DBA) on the material's surface. Such electrical carbonized tracking and erosion results in serious consequences and could challenge integrity of electrical network assets. Furthermore, silicone materials are combustible once ignited and keep burning despite having good inherent flame resistance [7]. Therefore, it is highly critical to improve electrical tracking/erosion and fire retardancy of silicone materials concurrently to be used in wildfire-prone areas, globally.

Regarding silicone materials' electrical tracking/erosion resistance, numerous researchers investigated and explained the mechanism of this issue through introduction of ceramic inorganic particles [8]–[11]. El-Hag *et al*. [12] compared erosion resistance of silicone rubber by incorporating silica with different particle sizes. It is reported the introduction of nanoparticles with 10wt% induced resistance against degradation equivalent to 50wt% micron particles. Recently, Sindhu *et al*. [13] explored dry band arcing impact on silicone elastomers using micro and nano ATH and it is reported only 2wt% nano ATH interestingly rendered better resistance to tracking/erosion relative to 30wt% of micron size ATH. Moreover, Zolriasatein *et al*. [14] investigated the role of nano-silica particles on electrical tracking performance of RTV coatings. Results exhibited RTV composites with 1 to 3wt% of nano silica didn't ignite, which demonstrated its excellent resistance against tracking. Sun *et al*. [15] explored ceramifiable technology using ATH and low-melting glass additives. Outcomes suggested that ceramifiable layer offered excellent resistance to carbonized tracking and erosion of silicone material along with excellent mechanical and hydrophobic

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characteristics. Fairus *et al*. [16] compared tracking/erosion performance of silicone/ethylene propylene diene monomer blend using nano-sized aluminum oxide and titanium dioxide particles. Results revealed that 1 vol% of aluminum oxide imparted excellent tracking performance to blends relative to 2 vol% of titanium dioxide-filled composites. Moreover, tracking failure time and thermal conduction ability of both blend composites measured relatively higher than pristine polymer blend. Meyer *et al*. [17] developed a relationship between leakage current third harmonic component and surface temperature in the electrical tracking and erosion test. Another study by Meyer *et al*. [18] explained thermal conductivity of the silicone composites significantly contributed to better tracking/erosion performance. Du *et al*. [19] reported excellent tracking/erosion performance of silicone composites using boron nitride (BN) particles and it is discussed thermal dissipation due to excellent thermal conductivity of silicone/BN composites resulted in impressive improvement.

As far as combustibility of silicone materials is concerned, Yoon *et al*. [20] explored fire resistance performance of silicone composite materials using ATH and MDH particles. Results suggested surface temperature substantially declined in ATH, MDH carrying composites. Zhou *et al*. [21] reported solely 39%-ATH-filled silicone rubber could offer impressive importance in flame retardancy but, it improved with addition of 1% red phosphorous in the composites because of compact homogeneous char formation. Using ceramifiable characteristics, Zhixi *et al*. [22] investigated fire retardancy of silicone rubber using ATH, MDH, zinc borate and glass frits. The study showed the limiting oxygen index (LOI) improved to 34.8% in zinc-borate-filled composites. Hanu *et al*. [23] introduced the mica, glass frit and iron oxide particles' impact on thermal stability and combustion efficiency of silicone rubber. Experimental findings exhibited mica-15% and glass frit-5% offered excellent thermal stability to silicone rubber while replacing glass frit with iron oxide resulted in a substantial reduction in heat release rate and superior heat barrier.

Intumescent additives are also widely engaged in improving heat barrier and flame retardancy of silicone rubber [24], [25]. Liu *et al*. [26] incorporated 5% expandable graphite (EG) in a silicone rubber matrix and achieved a V-0 level of UL-94 and LOI of 33%. Jiaji *et al*. [27] investigated thermal conductivity and flame retardancy of natural rubber using boron nitride doped EG microspheres with PMMA shells. It is reported with introduction of additives, the HRR and SPR significantly declined whereas, thermal conductivity achieved 205% higher than pristine natural rubber. Wang *et al*. [28] reported the effect of different ratios of ATH and EG on flame retardancy and electrical and mechanical properties. Results suggested ATH and EG with a ratio of 1:1 had the highest LOI achieved while resistance against flame increased with increasing contents of EG.

In our previous work [29], dielectric, mechanical, fire and hydrophobic properties of silicone rubber are discussed using ATH, GN and GF additives. Electrical tracking/erosion investigations are critical for a newly formulated silicone rubber to be used in high-voltage outdoor insulation applications. Hence, in this work, we prepared silicone rubber composites with ATH, GN and GF and correlate physical tracking, erosion, leakage current and infrared thermal profiles in IPT with the HRR and SPR.

II. Experimental

A. Raw Materials

DC Products, Australia supplied pristine room temperature vulcanized (RTV) silicone rubber (Momentive, RTV615) in two parts. RTV615 elastomer is a polydimethylsiloxane (PDMS) based with a density of 1.01 g/cm^3. PDMS molecule [Si(CH$_3$)$_2$–O–]x has a repeating unit of [SiR$_2$–O–]x and belongs to the class of symmetrical dialkyl polysiloxanes. Australian company Redox provided ATH with a 5.0 μm average particle size. Australia's Allnex Composites provided milled glass fibers (GF) that were made using E-glass and ranged in length from 50 to 210 μm. First Graphene, Australia supplied PureGRAPH®5 graphene nanoplatelets (GN) with a 5.0 μm average size. Fig. 1(a) is illustrating morphology of ATH, GN and GF on the micron level.

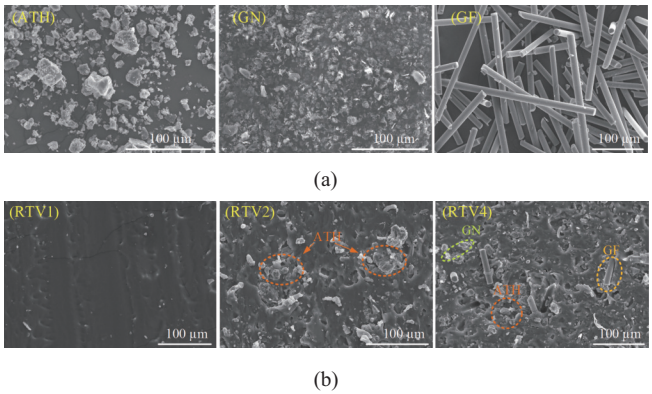

Fig. 1. SEM images of (a) surface morphology of additives (ATH, GN and GF) and (b) microstructure of selected composites.

B. RTV Composites' Synthesis

Initially, all particles were dried overnight in the laboratory oven. Step 1: pertinent amount of RTV part A was taken in a polyethylene cup and ATH was mixed in part A for 90 s using a mechanical sharp blade mixer. Step 2: GN mixed in the cross-composite matrix followed by GF for 90 s each. Step 3: The required amount of RTV part B (A:B = 10:1) was mixed and stirred in the composites for a shorter period of 30 s to avoid curing of the matrix in the polyethylene cup. Step 4: The matrix cups were passed through the degassing phase. The matrix was degassed until no air bubble was seen at the top of the surface. Step 5: The matrix was poured into preheated molds. The molds were kept in a laboratory oven for 1800 s at a temperature of 150 °C. A schematic diagram for the fabrication of the RTV composite is given in Fig. 2. The prepared composites were thoroughly washed with ethanol and dried before performing all measurements. Table I illustrates each RTV composite with RTV part A/B and additives contents. Fig. 1(b) exhibits the SEM microstructure of the selected RTV composites. It can be seen ATH is distributed homogenously in the RTV2 and RTV4 whereas,

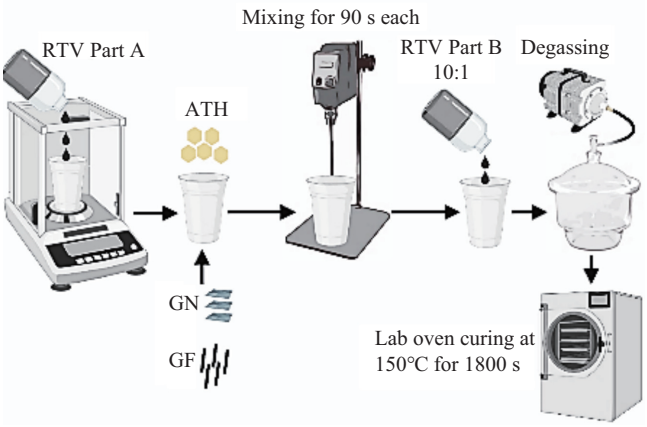

Fig. 2. Schematic for the RTV composites' preparation.

TABLE I
COMPOSITION OF RTV COMPOSITES STUDIED IN THIS PAPER

Name	RTV part A (%)	RTV part B (%)	ATH (%)	GN (%)	GF (%)
RTV1	90.90	9.10	–	–	–
RTV2	63.60	6.40	30.0	–	–
RTV3	62.70	6.30	30.0	1.0	–
RTV4	58.20	5.80	30.0	1.0	5.0
RTV5	57.30	5.70	30.0	2.0	5.0

GF is captured in the 3-D distribution pattern in RTV4. GN is added by only marginal 1% content in the RTV4 and homogenously distributed in the composites. It is seen GF constructs a 3-D network by holding the ATH and GN between GF filaments.

C. Characterization and Measurements

SEM (Hitachi S3400, Mito, Japan) was used for the microstructure analysis of additives and RTV composites. Accelerated high voltage (HV) of the instrument was controlled at 20 kV. Moreover, RTV composites were coated with a thin gold layer on the target side to make them conductive.

The inclined plane test (IPT) was carried out in accordance with the IEC 60587 criterion and its schematic is shown in Fig. 3. RTV composites with a dimension of 5 cm × 12 cm × 0.6 cm were cast for IPT and mounted on a PTFE insulating support using top HV and bottom ground electrodes. A 25 kΩ resistor was also inserted in the circuit to avoid overcurrent. Moreover, the contamination solution was prepared using NH_4Cl (0.1 wt%) and a wetting component of Triton X-100 (0.02wt%) in distilled water. HV was supplied through a single phase 250 V/11 kV transformer with a variac to control energizing voltage in the circuit at power frequency of 50 Hz. A 3 kV initial voltage and contamination flow rate of 0.3 ml/min were used in the stepwise tracking voltage method (method 2: IEC 60587). Tracking voltage was increased by 250 V per hour and IPT lasted a total of 4 hours.

Leakage current (LC) was recorded by measuring voltage drop across 100 Ω as a sampling resistor as seen in Fig. 3. For this purpose, a 32-bit NI DAQ-6251 data acquisition coupled with the computer was used with a sampling rate of 1000 samples per second. The voltage drop and leakage current of composites in the IPT were measured using a Matlab program.

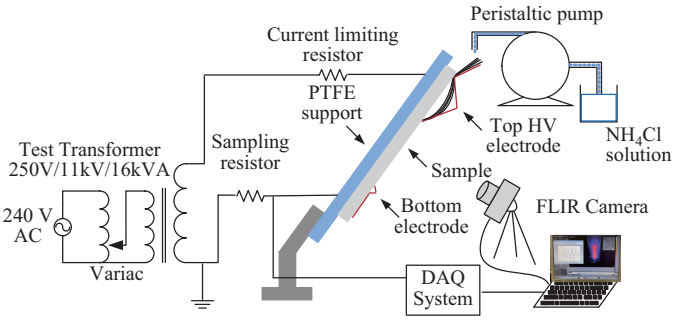

Fig. 3. Schematic diagram for IPT experimental setup.

A cone calorimeter (FFT iCone Classic, UK) was used to determine flame retardancy of RTV composites according to ASTM E 1354. RTV samples with size of 10 cm × 10 cm × 0.3 cm were tested at heat flux of 35 kW/m^2. Heat release rate and smoke production rate were analyzed from cone calorimeter data.

III. RESULTS

A. Physical Tracking and Erosion

Electrically conductive carbonous tracking and erosion pattern at the end of IPT is depicted in Fig. 4. Physical length of the carbonous pattern was analyzed using precise vernier before removal of all residual material from composites. Moreover, samples were cleaned with ethanol and distilled water and dried in the lab oven for half an hour at 100 °C. The samples were then weighed using an electronic balance to determine mass difference while digital height gauge instrument was used to compute erosion depth of the composites. Fig. 5 illustrates composites' tracking length, erosion depth, and eroded mass after IPT. It is noted that substantial reduction in tracking length, eroded mass and erosion depth is seen in the RTV4 relative to its counterparts. Tracking length is measured at 14.8 mm in RTV4 which is less than 58.7% and 27.8% relative to RTV1 and RTV2. Interestingly, erosion depth and eroded mass are also found consistent with tracking length findings. Erosion depth is measured at 1.5 mm which is lower by 67.4% and 42.3% while, eroded mass is computed at 0.13 g which is less by 91.3% and 27.7% relative to RTV1 and RTV2, respectively.

B. Leakage Current

Figure 6 is illustrating the fundamental and third harmonic component of leakage current recorded in the final two hours of IPT using the fast Fourier transform. To explore key features of data presented in Fig. 6, a method of moving average of adjacent ranges in OriginPro was used with a backward and forward offset of 50. Fig. 7 depicts the fundamental component and third harmonic component of leakage currents after moving average smoothing for the last two hours of IPT.

Peak values of the fundamental leakage current component are computed at 9.8, 10.2, 14.9, 8.7, and 17.4 mA in RTV1, RTV2, RTV3, RTV4, and RTV5, as shown in Fig. 7(a). Surprisingly, both the fundamental and third harmonic components of leakage current are significantly lower in RTV2 and

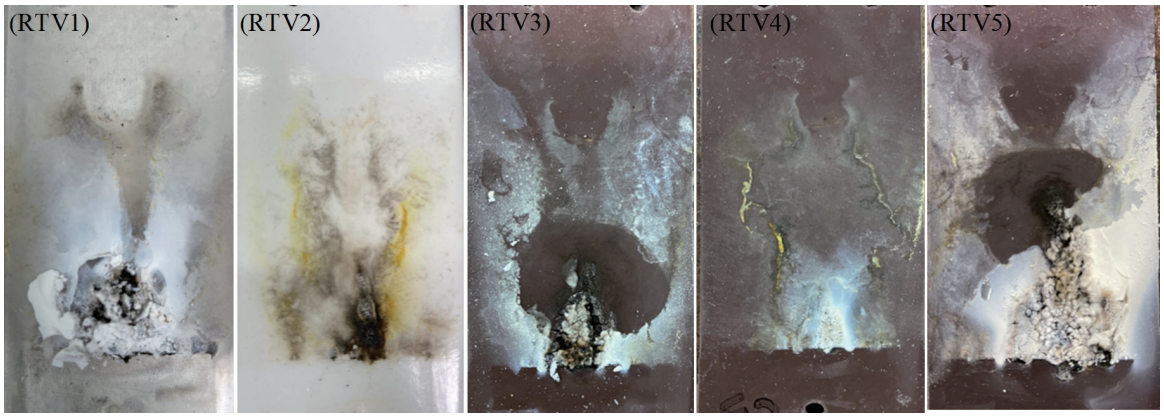

Fig. 4. Physical erosion and tracking pattern on the surface of RTV composites.

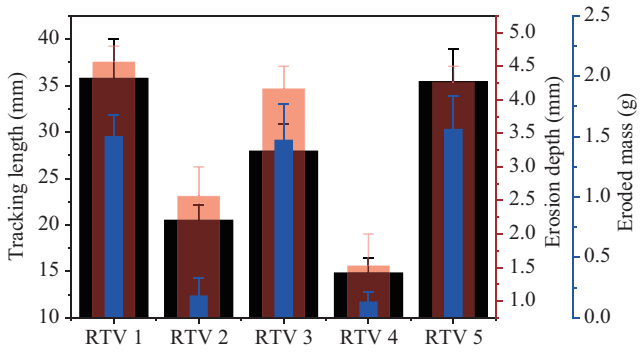

Fig. 5. Physical tracking length, erosion depth and eroded mass of RTV composites.

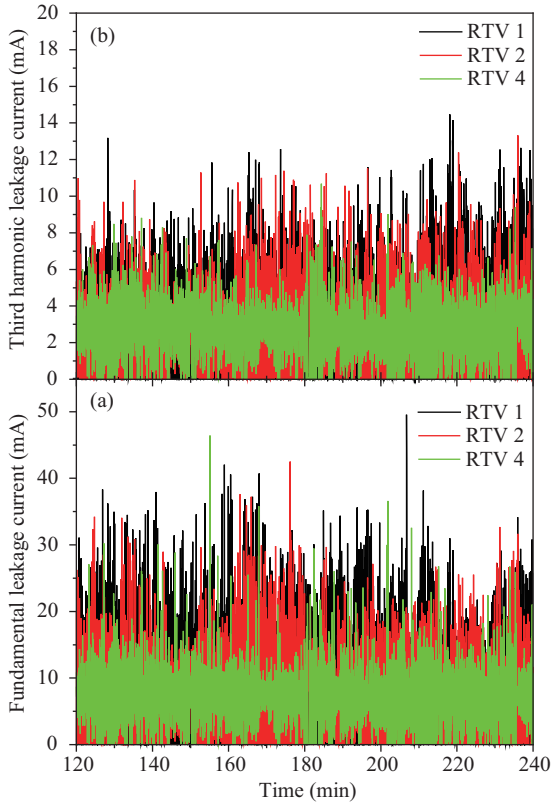

Fig. 6. The leakage current of composites (a) Fundamental component and (b) third harmonic component of leakage current as a function of time.

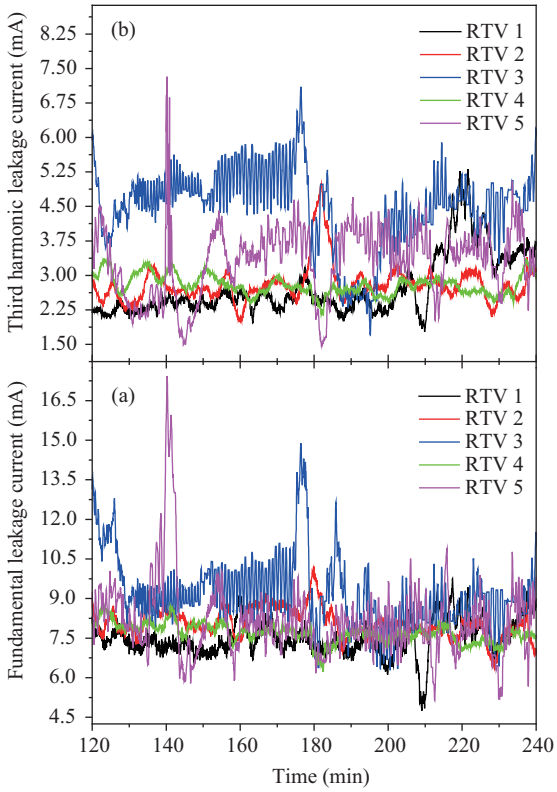

Fig. 7. The leakage current of composites (a) Fundamental component and (b) third harmonic component of leakage current as a function of time after smoothening of data using moving average method.

RTV4 compared to their counterparts. Tracking and erosion of materials in IPT are well-known to be correlated with the third harmonic component of leakage current due to joule heating effect [30]. As seen from Fig. 7(b), magnitude of the third harmonic component exits in leakage current significantly reduced in RTV2 with introduction of ATH particles in the pristine specimen. Moreover, it is found addition of 1% of GN and 5% of GF in RTV4 substantially reduced development of the third harmonic leakage current component. Interestingly, no peak in RTV 4 is seen crossing 3.5 mA while the majority of peaks are seen crossing 4.0 mA in RTV3 and RTV5 which represent the highest development of leakage current and dry band arcing, relatively. The peak third harmonic component of

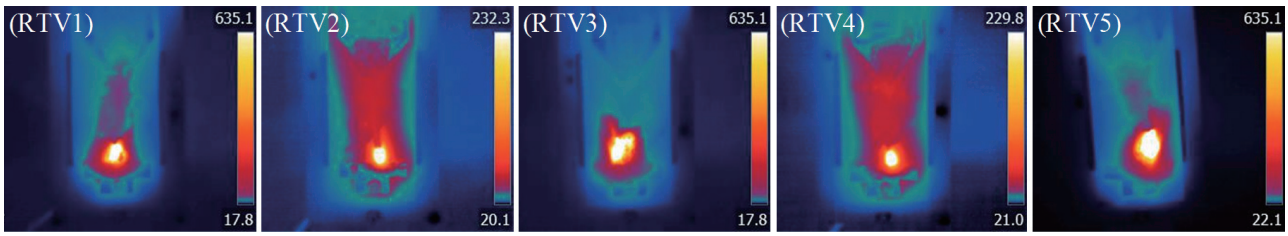

Fig. 8. Infrared thermal images of RTV composites.

leakage currents is measured at 5.3, 5.0, 7.1, 3.4 and 7.3 mA in RTV1, RTV2, RTV3, RTV4 and RTV5, respectively.

C. Temperature Profiles

DBA substantially increases surface temperature of the specimen which leads to track and erosion failure of electrical insulating materials. As a result, an infrared thermal camera was used to record thermal profile data during the final two hours of IPT. Fig. 8 shows infrared thermal images captured at peak temperature point during the IPT. Recorded data were processed by fixing a rectangular box on the sample from top to bottom electrode and average temperature was computed as explained in [31]. Furthermore, processed data was smoothed with the backward and forward offset of 50 as earlier described and is shown in Fig. 9. The maximum average temperatures on the surfaces are exhibited at 195, 147, 225, 74 and 185 °C in RTV1, RTV2, RTV3, RTV4 and RTV5, respectively. Comparatively, lower temperatures are seen in RTV2 and RTV4 with minor temperature spikes. Interestingly, the maximum average temperatures are found to be consistent with the third harmonic leakage current profiles relative to the time incurred for IPT.

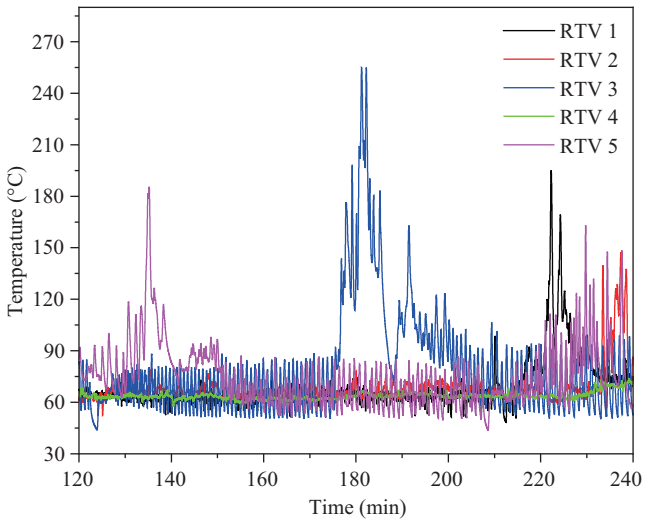

Fig. 9. Temperature profiles of RTV composites as a function of time.

D. Flame Resistance

The heat release rate and smoke production rate are analyzed for the flame resistance of the RTV specimen in this work. Fig. 10 shows the enhancement in fire resistance performance of composites with the addition of additives which reduces the heat release rate and smoke production rate. The peak heat release is measured at 217, 146, 118, 116 and 119 kW/m^2 (Fig. 10(a)) in RTV1, RTV2, RTV3, RTV4, and RTV5 whereas, the smoke production rate exhibits 0.086, 0.045, 0.024, 0.018, and 0.020 m^2/s (Fig. 10(b)) in RTV1, RTV2, RTV3, RTV4, and RTV5, respectively. It is found ATH renders a substantial impact in reducing heat release and smoke production of pristine silicone rubber while GN/GF synergically impact positively to further lowering both parameters in solely ATH-filled RTV2.

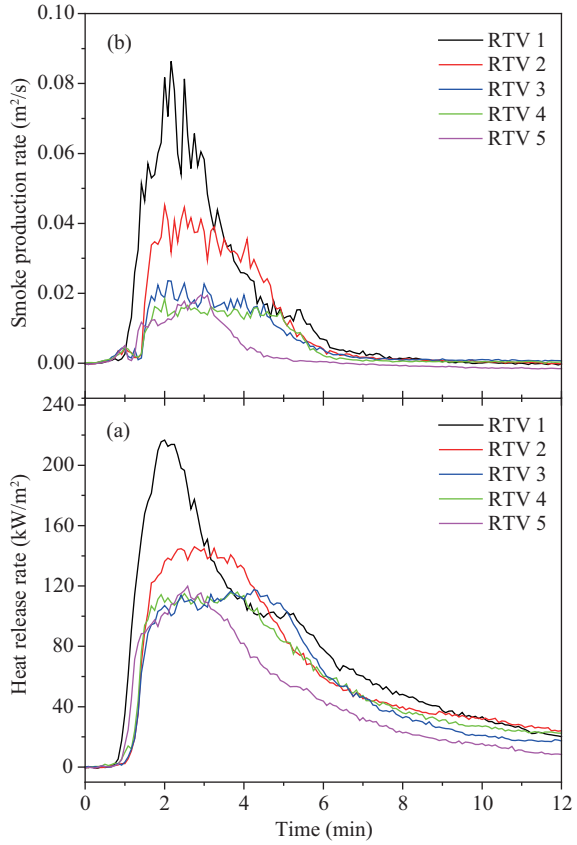

Fig. 10. (a) Heat release rate and (b) smoke production rate of specimens.

IV. Discussion

Results suggest the presence of ATH (30%), GN (1%) and GF (5%) exhibit significant impact in improving physical tracking and erosion performance of silicone rubber by reducing leakage current development and surface temperature during the IPT. Electrical tracking tends to start due to thermal accumulation and increase in localized surface temperature

which thermally depolymerizes the methyl groups in the silicone rubber structure [32]–[34]. This high-temperature deterioration results in a carbonous track formation and erosion in the target sample. Therefore, the limiting oxygen index (LOI) of composites is measured at 26, 30, 35, 36 and 38% in RTV1, RTV2, RTV3, RTV4, and RTV5, respectively [35]. It is a well-known fact thermal conductivity is directly related to tracking and erosion formation of the surface and controlled thermal stress gradient [18]. Therefore, thermal conductivity of the composites is measured using LFA447 (Netzsch). Thermal conductivity is measured at 0.329, and 0.376 W/(m·K) in RTV2 and RTV4, respectively whereas, it was measured at 0.190 W/(m·K) in RTV1. It is highly likely that RTV4 with high thermal conductivity has more capability to conduct heat out from the DBA region and maintain lower surface temperature. Hence, this mechanism expects to reduce drying and evaporation of contaminated water on the surface of composites [16]. This activity will assist in declining DBA and leakage current formation which may result in excellent tracking performance in RTV2 and RTV4. Interestingly, RTV3 and RTV5 offer thermal conductivity of 0.368 and 0.408 W/(m·K) but exhibit poor tracking/erosion and high leakage current development. It could be due to an increase in electrical bulk conductivity due to presence of GN in the composites. Electrical bulk conductivity of composites is measured at 1.954×10^{-13}, 1.642×10^{-13}, 1.985×10^{-13}, 1.953×10^{-13} and 2.476×10^{-13} S/cm in RTV1, RTV2, RTV3, RTV4 and RTV5. The excellent tracking performance of RTV4 could be due to presence of GF/GN together and it may improve rigidity and restrict segmental moment in the composites [36]. It could improve the barrier against DBA and enhance resistance against electrical discharges.

It can also be attributed to inherent flame retardancy properties of ATH and GN that RTV2 and RTV4 are excellent in tracking, erosion, and flame resistance. As ATH decomposes at 250 °C to 350 °C, it always releases its inherent water. During combustion, the amount of water released decreases [37]. Therefore, RTV2 appears with much lower physical tracking/erosion, heat release and smoke production parameters. Furthermore, the excellent flame resistance performance of RTV3, RTV4 and RTV5 could be due to carbonous char layer structure formation in presence of GN. It is believed that GN could assist in char layer formation which acts as a heat barrier [38]. Furthermore, GF could transform this barrier into a rigid and compact char structure with improved fire resistance.

V. Conclusion

Electrical tracking/erosion and flame resistance of silicone rubber was investigated using ATH, GN and GF. Physical tracking, erosion depth, eroded mass, leakage current, infrared thermal profiles, heat release rate and smoke production rate were analyzed in this work. From experimental findings, it is concluded physical tracking length, erosion depth and eroded mass of silicone rubber declined with introduction of 30% ATH as seen in RTV2. Moreover, performance of RTV5 in IPT suggested addition of 1% of GN and 5% of GF could assist in further improving tracking/erosion performance of solely ATH-filled silicone rubber. Fundamental and third harmonic components of leakage current appeared considerably lower in RTV2 and RTV4 while maximum average temperatures are found to be consistent with third harmonic leakage current findings. It is also summarized ATH substantially contributed to reducing the heat release rate and smoke production of composites whereas, GN/GF facilitated in reducing the above-mentioned parameters to a great extent in the case of solely ATH-filled RTV composites. It is concluded improvement in thermal conductivity and inherent flame retardancy of ATH/GN along with GF could assist in developing a barrier against DBA and combustibility.

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