Flame Spread over Electrical Wire with Applied AC Electric Fields near the End

S. J. Lim[1], J. Park[1*], M. K. Kim[2], S. H. Chung[3], O. Fujita[4]

[1]*Dept. Of Mechanical Engineering, Pukyong National University*
San 100, Yongdang-dong, Nam-gu, Busan 608-739, Korea
[2]*Environmental and Energy Systems Research Division, Korea Institute of Machinery and Materials, 104 Sinseongno, Yuseong-gu, Daejeon 305-343, Korea*
[3]*Clean Combustion Center, 4700 King Abdullah University of Science and Technology*
Thuwal, 23955-6900, Saudi Arabia
[4]*Division of Mechanical and Space Engineering, Hokkaido University*
Sapporo 060-8628, Japan

1 Introduction

An electrical wire fire can be catastrophic disaster. One example is the Apollo 1 accident during space development program. In this sense, it is essential to establish fire safety code for space development. Also, fire safety code in ground can be as important as in space, because electrical wire could be main causes for building and household. Various experiments have been studied to understand the influence of various factors in flame spread such as type of inner core, gravity level, ambient flow, and pressure [1-5]. However, wire fire is caused by unexpected overheating and/or electric short, meaning that the wire can be under the influence of electric fields induced by voltage applied to the wire during the flame spread. In the reaction zone of flame, there are abundant charged particles such that it can be affected by applied electric fields, and behavior of the flame spread can be modified by interaction between them. In the case of AC, the range of used frequency and voltage depending on various systems can be varied, e.g., 50-60 Hz for utility power generation and typically about 400 Hz in aircrafts, which can vary 360-720 Hz and even over 1 kHz at full throttle. Thus, the influence of electric fields on flame spread over the electrical wire requires a detail study, while studies on the effect of applied electric field in flame spread over electrical wire are limited. In the previous study, overall flame spread behaviors with applied AC electric fields were investigated over Polyethylene-insulated electrical wire [6]. It was found that the flame spread behavior is appreciably modified by applied voltage and frequency. The study adopted a single-electrode configuration of an open circuit, with one end of wire directly connected to high voltage terminal of an AC power supply and the other terminal to a building ground. Since the wire length was much longer than the wire

*** Correspondence author**
E-mail : jeongpark@pknu.ac.kr
Tel. : +82-51-629-6140
Fax. : +82-51-629-6126

thickness, the induced electric field was assumed to be axisymmetric and uniform along the wire. Near the wire end, however, the intensity of electric fields is concentrated due to the convergence of electric flux. Then the flame spread rate can appreciably vary near the wire end, such aspects have not been investigated yet. In this study, experimental observations on flame spread over electrical wire insulated by Polyethylene (PE) with applied AC electric field will be reported, focused on the flame spread rate near the end of wire.

2 Experiment

Figure 1 shows the schematic of the present experimental apparatus. It consists of a wire, wire holder, AC power supply, and a video camera. Polyethylene (PE) insulated electrical wire (NiCr wire) was tested, having 350 mm in length, 0.5mm in diameter of wire, and 0.8mm in diameter of PE insulator. The wire was installed on a wire holder made of nonconductive acetal resin. One end of a wire was fixed to the wire holder and the other end was connected to a spring in order to prevent bending of wire due to thermal expansion during flame spread. The flame was initiated by hot-wire igniter placed on an air cylinder. To minimize the interaction between the ignition system and applied AC electric fields, the igniter was retreated away from the wire after ignition. A programmable logic controller (PLC) was adopted to control time sequence of the experiment. The details of experimental procedure were reported previously [6]. The wire length, excluding the portion connected to the wire holder, was 230mm. Experimental data for the initial 73mm from the igniter was excluded by ignition transient, and data for the final 5mm was excluded to eliminate the interaction between flame and wire holder. Therefore, the available length for flame spread was 152mm. The test section was surrounded by nonconductive meshes to minimize external disturbances. A video camera was triggered to record spreading flame, and the recorded flame images were analyzed by a Matlab-based code. The averaged flame behavior was obtained from up to 7 trials, and the variations were indicated as error bars.

The AC power supply (Trek, 10/10B-FG) applies electric fields to the wire. The applied frequency (f_{AC}) and voltage (V_{AC}) were varied in range of 10-1000 Hz and 0-4 kV (RMS), respectively, and were monitored by an oscilloscope through a 1000:1 probe (Tektronix, 6015A). One end of wire was directly connected to high voltage terminal of the AC power supply and the other terminal to a building ground, such that it could be regarded as an open circuit. Then, the induced electric fields in space could be assumed to be distributed between imaginary infinite ground and high potential wire.

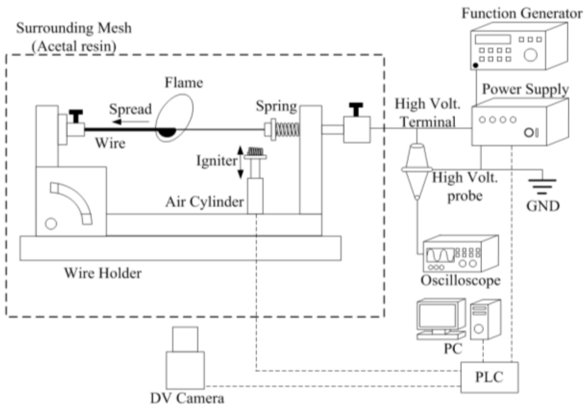
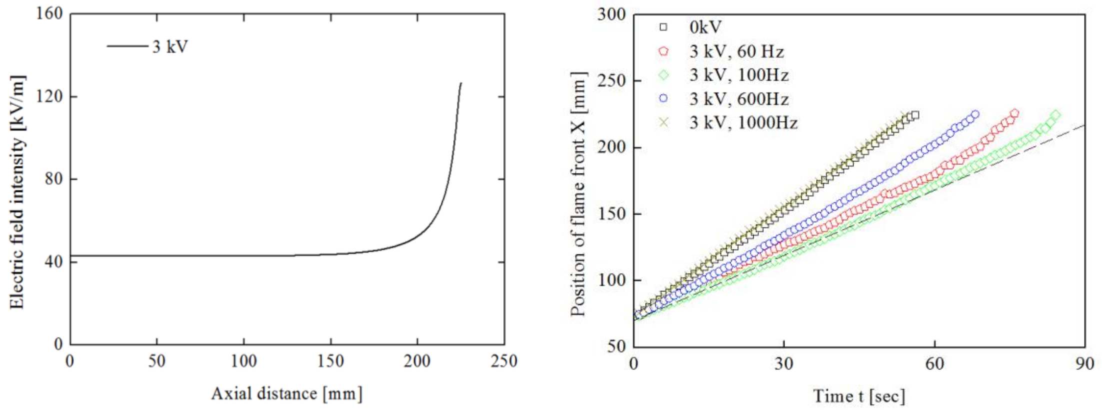


Figure 1. Schematic illustration of experimental set up

3 Result and Discussion

3.1 Overall feature in flame spread

In the present single-electrode configuration of open circuit, the intensity of electric fields is concentrated near the wire end due to the convergence of electric flux. The intensity of electric fields,



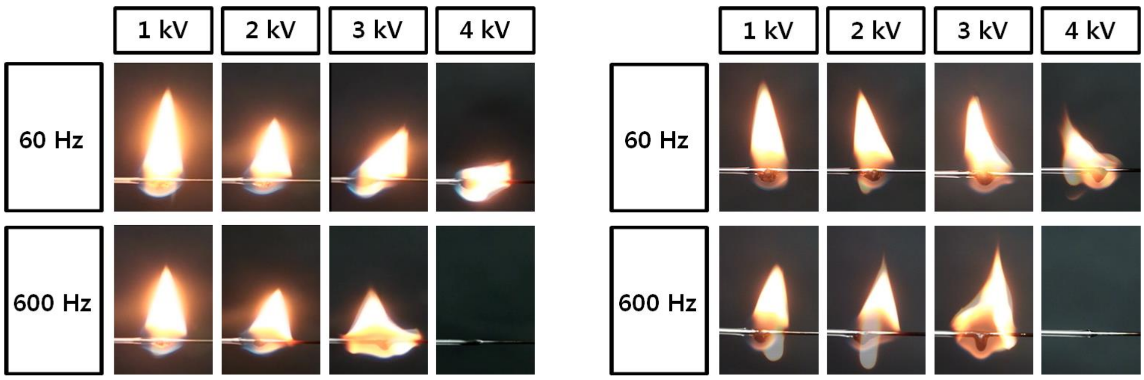
(a) **(b)**

Figure 2. (a) Electric fields intensity with axial distance for V_{DC} = 3 kV at the radial distance of 3.0mm, (b) Temporal position of flame front at various applied AC frequency for V_{AC} = 3 kV.

calculated with FEMM v-4.2 [7], in absence of flame at the radial distance of 3.0 mm, with axial distance for V_{DC} = 3 kV is shown in Figure 2(a). Calculated result shows that the intensity of electric fields appreciably increased at near the wire end and such effect will affect the flame spread rate. Figure 2(b) shows the temporal position of flame front X with time t and the time zero was defined just after the ignition transition. The flame spread rate, which is the time rate of change, become slower initially with the frequency increase for f_{AC} = 60 Hz and 100 Hz and then faster for f_{AC} = 600 Hz and 1000 Hz. It is similar to our previous study [6]. The flame position varies nearly linearly for the baseline case, while the cases for f_{AC} = 60, 100 and 600 Hz are initially linear, as marked by dashed line for f_{AC} = 100 Hz. However, this tendency deviates from the linear trend as time proceeds.

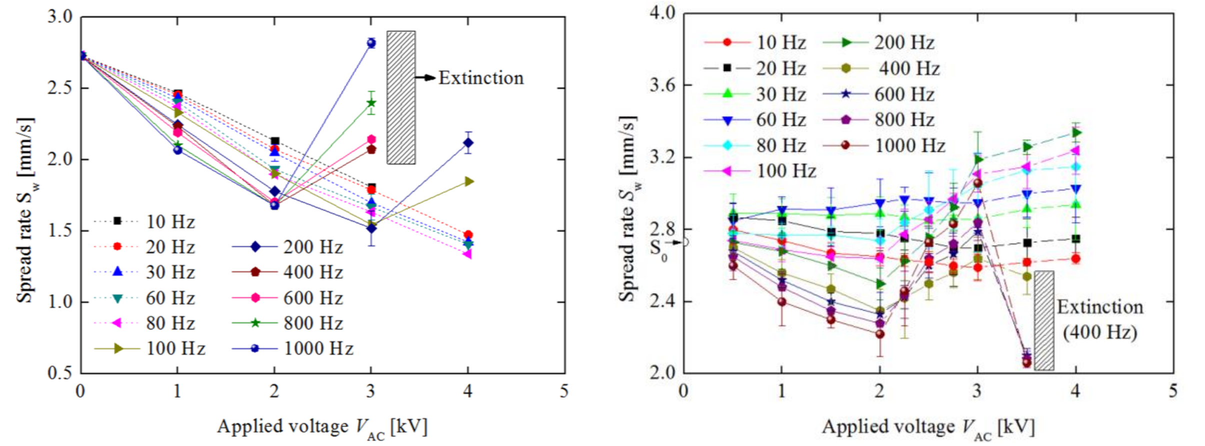
Figure 3 shows the flame images obtained at (a) X = 150$\pm$1 mm during the linearly-varying regime and (b) X = 220$\pm$1 mm near the wire end of wire by changing the voltage at f_{AC} = 60 Hz and 600 Hz. The flame spreads from right to left. As previously reported [6], the flame leans forward to the burnt side during the linearly-varying regime in Figure 3(a). As shown in Figure 3(b), while, the flame shapes are appreciably modified near the wire end with applied electric fields. For example, at f_{AC} = 60 Hz, the flame leans toward the unburned side and the flame height decreases with the increase of applied voltage. The flame width, which is a covered wire length by the flame in horizontal direction, increases. At f_{AC} = 600 Hz, the flame leans toward the burnt side and both the flame height and width increase appreciably with the applied voltage. Further increase of voltage to 4 kV causes the flame to be extinguished before reaching the location X = 220 mm.

3.2 The flame spread rate with AC near the wire end



(a) **(b)**

Figure 3. Flame images (a) at X = 150$\pm$1 mm during the linearly-varying regime and (b) X = 220$\pm$1 mm during near the wire end with applied various voltages and f_{AC} = 60 Hz and 600 Hz.



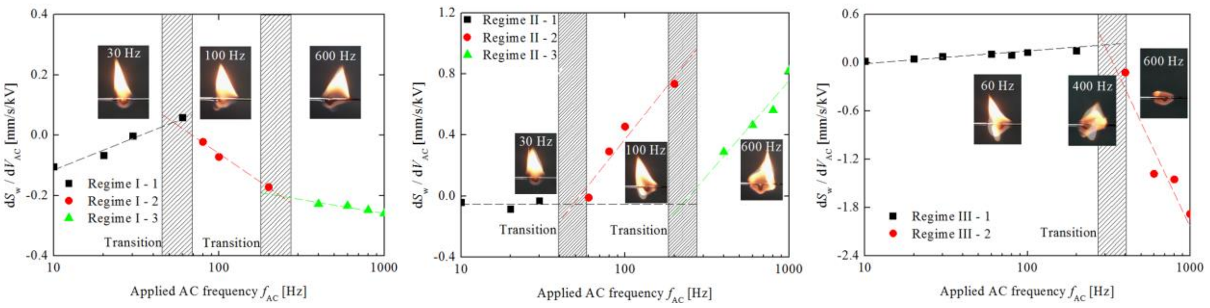
(a) (b)

Figure 4. Flame spread rate with applied voltage at several frequencies in (a) the linearly-varying regime and (b) near the wire end.

The flame spread rate, $S_w = dX / dt$, as a function of voltage at several frequencies in case of linearly-varying regime and nonlinearly-varying regime of near the wire end is shown in Figure 4 with the error bars. In Figure 4(a) which is linearly-varying regime, the spread rate decreases with voltage and frequency for frequency $f_{AC} \leq 80$ Hz and then increases at V_{AC}= 4 kV for $f_{AC} \geq 100$ Hz and V_{AC}= 3 kV for $f_{AC} \geq 400$ Hz. These behaviors are consistent with our previous study [6]. In Figure 4(b), on the other hand, the result exhibits complex behavior depending on the voltage and frequency. For f_{AC} = 10 Hz and 20 Hz, S_w decreases up to 3 kV and then slowly increases up to 4 kV. For f_{AC} = 30 Hz, S_w increase slightly up to 2 kV, decreases up to 3 kV, and then increases up to 4 kV. For f_{AC} = 60 Hz, S_w increases up to 2.25 kV, decreases up to 3 kV, and then increases up to 4 kV. For 80 Hz $\leq f_{AC} \leq$ 200 Hz, S_w decreases up to 2 kV, and then increases up to 4 kV. For 400 $\leq f_{AC} \leq$ 1000 Hz, S_w decreases up to 2 kV, increases up to 3 kV and decrease sharply up to 3.5 kV by the dripping of molten PE, and then the flame was extinguished after 4 kV. Such behaviors of flame spread rate near the wire end are quite different from that in linearly-varying regime as shown in Figure 4(a). The variation of spread rate has piecewise linear tendency up to 2 kV. For V_{AC} = 2-3 kV and 3-4 kV, also, the linear tendency is observed. In this regard, the dependence of spread rate on voltage, dS_w/dV_{AC}, was determined as a function of frequency by linear fitting for each voltage range.

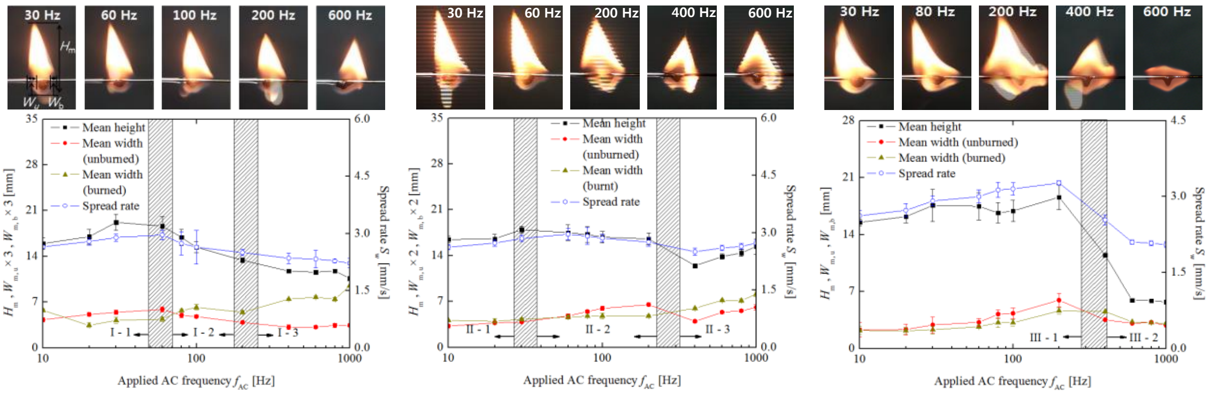
The result for each voltage range is shown in Figure 5 with flame shape photos. In the low voltage regime I of $V_{AC} \leq 2$ kV (a), three distinct sub-regimes can be identified depending on the frequency, the voltage dependence of spread rate increases up to 60 Hz and decreases up to 1000 Hz. And the spreading flame leans toward unburned side in regime I-1; the flame either leans toward the unburned side or is nearly vertical in regime I-2; and it leans toward the burnt side in regime I-3.

In the intermediate regime II of V_{AC} = 2-3 kV (b), which can be also divided into three sub-regimes depending on AC frequency, the voltage dependence of spread rate changes little up to 30 Hz, sharply



(a) (b) (c)

Figure 5. Characteristics of the flame spread rate with applied frequency in (a) regime I, (b) regime II and (c) regime III with flame shapes



(a) (b) (c)

Figure 6. The flame spread rate S_w, mean flame height H_m, and mean flame width from molten PE to burnt side W_b and unburned side W_u with applied frequency at V_{AC} = (a) 2 kV, (b) 2.5 kV, and (c) 3.5 kV, respectively with direct photos.

increases in 60 ≤ f_{AC} ≤ 200 Hz and then drastically increases again from 400 Hz to 1000 Hz. And the flame images in this intermediate voltage regime show that the flame slightly leans toward unburned side in regime II-1, is slanted toward unburned side and the flame width enlarges in regime II-2, and then leans toward the burnt side and the width is significantly widen in regime II-3. This implies that flame shape such as the height and width can affect flame spread rate appreciably [6].

In high voltage regime III of V_{AC} = 3-4 kV (c), it shows two distinct sub-regime. The slop of spread rate with AC frequency increases slowly and then decreases rapidly. In regime III-1, the flame becomes more and more inclined toward the unburned side and the width gradually increases with AC frequency. In regime III-2, the flame tends to be slanted toward the burnt side; a part of the molten PE drips frequently and the remaining molten PE subsequently sustains flame spread, increases the size of molten PE and drips again repeatedly; the number of dripping of molten PE increases significantly with the increase in AC frequency, finally leading to the flame extinction for V_{AC} ≥ 3.5 kV. Such dripping phenomenon of molten PE can be an important factor in establishing safety strategy of electrical wire.

Table 1 shows the correlation of the rate of change in spread rate with AC frequency and transition frequency in each sub-regime with the correlation coefficient.

Figure 6 shows mean flame height H_m, mean flame width from molten PE to burnt side W_b and unburned side W_u, and the flame spread rate S_w with applied frequency. The mean values are the averages during X=215-225 mm. In figure 6(a) of V_{AC} = 2 kV, the spread rate increases up to 60 Hz and then decreases up to 1000 Hz, and H_m and W_u exhibit reasonably similar tendency. Figure 6(b) and (c) show the cases of V_{AC} = 2.5 kV and V_{AC} = 3.5 kV, respectively. In case of figure 6(b) and (c), the spread rate can be understood base on the behaviors of flame height and width toward unburned side.

Regime	Correlation of the rate of change in spread rate, dS_w/dV_{AC}	Correlation coefficient	Transition frequency
I - 1	$-0.330 + \log f_{AC}{}^{0.217}$ $[s^{-0.217}]$	0.98	f_{AC} = 52 [Hz] f_{AC} = 248 [Hz]
I - 2	$0.669 + \log f_{AC}{}^{-0.366}$ $[s^{0.366}]$	0.99	
I - 3	$-0.0156 + \log f_{AC}{}^{-0.080}$ $[s^{0.080}]$	0.96	
II - 1	$-0.056 + \log f_{AC}{}^{0.003}$ $[s^{-0.003}]$	0.95	f_{AC} = 46 [Hz] f_{AC} = 225 [Hz]
II - 2	$-2.328 + \log f_{AC}{}^{1.351}$ $[s^{-1.351}]$	0.96	
II - 3	$-2.983 + \log f_{AC}{}^{1.247}$ $[s^{-1.247}]$	0.96	
III - 1	$-0.043 + \log f_{AC}{}^{0.080}$ $[s^{-0.080}]$	0.94	f_{AC} = 312 [Hz]
III - 2	$10.611 + \log f_{AC}{}^{-4.190}$ $[s^{4.190}]$	0.95	

Table 1. Correlations between dS_w/dV_{AC} and applied frequency f_{AC} with the correlation coefficients

4 Conclusions

The flame spread rate near the end part of polyethylene-insulated electrical wire with applied AC electric fields was investigated experimentally in range of f_{AC} = 10-1000 Hz and V_{AC} = 0-4 kV with a single electrode configuration. Temporal flame position with applied AC electric fields was nearly linearly increased in most stages of flame spread with showing the similar behavior of previous study [6]. Near the end of wire where the electric flux was concentrated, however, temporal position of the flame with AC electric fields was accelerated. Three distinct regimes for flame spread rate near the end of electrical wire existed depending on the voltage. For a fixed voltage in each regime, distinct regimes are also categorized depending on applied frequency. In regime I of $V_{AC} \leq 2$ kV, characterized value, dS_w/dV_{AC}, increased and then decreased with applied frequency. In regime II of V_{AC} = 2-3 kV, dS_w/dV_{AC} with applied frequency slightly increased, then increased and increased again. Meanwhile, that with applied frequency increased mildly and then rapidly decreased in regime III.

As observed in this experiment, the flame spread rate near the end of electrical wire could be significantly modified from that without having electric fields and those at the stage of temporal linearly-varying flame spread with applied electric fields. In this sense, the relevant fire safety codes are needed to be modified by considering the situation of fire near the end of electrical wire with having electric fields.

5 Acknowledgements

The work was supported by AEA Project/KAUST, by Space Core Technology Development Project/ NRF (2011-15), and by JAXA as the candidate experiments for the second phase utilization of JEM/ISS entitled "Quantitative Description of Gravity Impact on Solid Material Flammability as a base of Fire Safety in Space" as well as JAXA Research Working Group to promote space utilization.

References

[1] Fujita O, Nishizawa K, Ito K. (2002). Effect of low External Flow on Flame Spread over Polyethylene-insulated Wire in Microgravity. Proc. Combust. Inst. 29:2545

[2] Nakamura Y, Yoshimura N, Ito H, Azumaya K, Fujita O. (2009). Flame Spread over Electric Wire in Sub-atmospheric Pressure. Proc. Combust. Inst. 32:2559

[3] Umemura A, Uchida M, Hirata T, Sato. (2002). Physical Model Analysis of Flame Spreading along an Electrical Wire in Microgravity. Proc. Combust. Inst. 29:2535

[4] Onishi Y, Fujita O, Agata K, Takeuchi H, Nakamura Y, Ito H, Kikuchi M. (2010) Observation of Flame Spreading over Electric Wire under Reduced Gravity Condition Given by Parabolic Flight and Drop Tower Experiments. Transactions of the Japan society for Aeronautical and Space Sciences, Aerospace Technology Japan. Vol.8:19

[5] Nakamura Y, Yoshimura N, Matsumura T, Ito H, Fujita O. (2008). Opposed-wind Effect on Flame Spread of Electric Wire in Sub-atmospheric Pressure. Journal of Thermal Science and Technology, Vol.3:430

[6] Kim MK, Chung SH, Fujita O. (2011). Effect of AC electric fields on flame spread over electrical wire. Proc. Combust. Inst. 33:1145

[7] Finite Element Method Magnetics v-4.2, http://www.femm.info/wiki/HomePage.