Effect of core metal on flame spread and extinction for horizontal electrical wire with applied AC electric fields

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Abstract

The effect of metal core on flame spread behavior over polyethylene (PE)-insulated electrical wire was experimentally investigated by varying applied AC voltage ($V_{AC}$) and frequency ($f_{AC}$). The present experimental results with Cu-core were compared with those conducted previously with NiCr-core. Flame spread rate (FSR) with Cu-core for the baseline case with no electric field was larger than that with NiCr-core. Both FSR and flame size were appreciably influenced by applied AC electric fields and behaved differently for Cu- and NiCr-cores. For Cu-core, FSR behavior could be classified into four regimes as $f_{AC}$ increases: increasing FSR (regime I), decreasing FSR (II), and again increasing FSR (III) and decreasing FSR (IV). While for NiCr-core, it has been categorized into two regimes I and II. FSR behavior was qualitatively similar to that of flame width in regimes I, II, and IV. While such a relationship was not satisfied in regime III, which can be attributed to the formation of molten PE film in the burnt wire side as well as the formation of globular molten PE in front of spreading flame edge, emphasizing the important role of complex molten PE behavior. Molten PE dripping was observed for NiCr-core, while for Cu-core, such dripping was not observed. Electrospray and di-electrophoresis phenomena occurred with Cu-core along with a formation of molten PE film on the burnt wire side via continuous di-electrophoresis phenomenon from molten PE droplet. When the frequency was excessive, flame extinction occurred via two routes: appreciable reduction of flame size (both for Cu- and NiCr-cores) and detachment of molten PE (for Cu-core). These extinction frequencies were correlated well with the voltage.

Keywords: Flame spread; electrical wire; Cu-core, AC electric field; metal core.

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1. Introduction

Electrical wire fires, initiated by unexpected overheating and/or short circuit, could result in the ignition of neighboring combustible materials and thereby leading to a massive fire in buildings, households, industrial complexes, airplanes, and spacecrafts. In this regard, fundamental characteristics of wire fires have been extensively studied, especially focused on flame spread rate (FSR), considering various factors such as core and insulation materials, wire and insulation thicknesses, ambient flow, pressure, and gravity [1–15]. The safety of electrical wires used in space are tested based on the NASA code [16].

Previous studies typically do not consider the effect of electric field applied to a wire [1–16]. When an electrical wire catches a fire due to electric short, electric fields can still be applied. Then, the spreading flame can interact with the electric field formed around a wire. A limited number of studies have been conducted on the effect of electric field on spreading flames over electrical wires, showing appreciable modification in FSR with applied AC electric field [17–20]. The ionic wind effect [21], arising from the acceleration of charged particles by the Lorentz force, was identified as one of the major contributors influencing flame size and shape of spreading flames, thereby FSR.

It has been shown that electric fields influence the dynamic behaviors of molten insulator, such as fuel-vapor jet, internal circulation, dripping of molten insulator [17], formation of globular molten insulator leading to flame extinction [18], electrospray phenomenon [18, 19], and di-electrophoresis phenomenon [20]. These are important for fires, e.g., in cable tunnels/trays for electricity or tele-communication, since electrical wires are closely packed. Although the importance of applied electric fields on flame spread has been reported previously, the studies have only been focused on NiCr-core [17–20], even though it is not practical for electricity transmission since the electrical resistivity of NiCr is about $O(10^2)$ larger than Cu.
In this work, the effect of metal core on flame spread with applied AC is reported by adopting Cu-wire. Polyethylene (PE) insulated electrical wires are studied since it has been used extensively for the understanding of fundamental physics [1,2,4,5,8,9,13,14,17−20]. The results on FSR are compared with existing NiCr-core data to identify the effect of core material. Note that the thermal conductivity of Cu is about 34 times larger than that of NiCr, thus expecting significant influence by thermal conduction through the wire, thus flame spread behavior. Several interesting phenomena, such as electrospray, di-electrophoresis, formation of globular molten PE, and formation of molten PE film will be discussed. FSRs obtained experimentally and calculated for Cu- and NiCr-cores are compared and the thermal balance mechanism [2,5,17-20] in explaining FSR behavior is discussed.

2. Experiment

The apparatus consisted of an electrical wire and wire holder, an AC power supply, and a visualization setup. Details on experimental procedures were reported previously [17–20]. Polyethylene (PE)-insulated electrical wire (0.8 mm in diameter with 0.5 mm diameter copper core) with 213 mm in length was used. Initial 70 mm and final 50 mm were excluded due to ignition transition and potential interaction with the wire holder, respectively, leaving 93 mm available for data taking. The wire was horizontally installed on the wire holder made of non-conductive acetal resin. One end of the wire was connected to a fixture and the other end to a spring to prevent bending by thermal expansion during flame spread. The wire and holder were surrounded by acetal mesh screen (90×90×90 cm) to prevent outside disturbances. One end of the wire was connected to the high-voltage terminal of the power supply and the other terminal of the power supply was connected to a building ground, creating an open circuit. The AC voltage ($V_{AC}$) and frequency ($f_{AC}$) were varied over the ranges of 0–7 kV and 10–1000 Hz,
respectively, considering the AC frequency could reach 700 Hz, e.g., in airplanes. Details on ignition procedure and data analysis from images captured were reported [17–20].

Figure 1. Representative flame images of spreading flames at various voltages and frequencies for Cu-core along with baseline case with no electric field.

3. Results and discussion

3.1. Overall features of flame spread

Representative flame images are shown in Fig. 1, when the flames were in the range of $95 \leq X_f \leq 116$ mm, where $X_f$ is the distance from ignition point. Several phenomena are highlighted in supplementary materials (SM) 1 and 2. The results show that size, shape, and inclination angle of flame are appreciably modified by the electric field. Note that the flame for the baseline case with no electric field is nearly vertical, due to buoyancy effect.

For 1 kV, the flame leans slightly toward the burnt side and the size gradually decreases up to 400 Hz. At $f_{AC} = 800$ Hz, sequential images and movies shown in SM1a and 2a exhibit that a single-peak flame (0 s) splits into double-peak flame (1.14 s) as part of molten PE is migrating toward burnt wire region, increasing the flame width appreciably. As the second peak flame burns out (1.88 s), it becomes single-peak flame again (2.35 s). This is associated with a dielectrophoresis phenomenon generating secondary molten PE drop, as observed previously for NiCr-core case [20].
For 3 kV, the flame height (width) decreases (increases) gradually to 200 Hz. The flame leans toward the burnt wire at 10 Hz, the flame spreads with the double-peak flame mode at 80 Hz. A globular molten PE is formed near the flame front at 200 and 400 Hz (red circles) and the flame height is reduced appreciably (SM1b1 and 2b1). The close-up images of molten PE (SM1b2 and 2b2) exhibit appreciable amount of soot deposition onto the molten PE, continuous migration of a part of molten PE toward the burnt wire via di-electrophoresis, and formation of thin long film of molten PE with appreciable soot deposition. At 800 Hz, the flame fluctuates appreciably at both end regions (although shown only near the front part), while the flame height (width) is still small (large) (SM1c and 2c).

For 4 kV, the flame leans toward the burnt wire at 10 Hz. At 80 Hz, the flame height (width) deceases (increases) appreciably due to the formation of globular molten PE near the flame front (red circle). At 200 Hz, both the flame height and width increase appreciably again (close-up image and movie in SM1d and 2d). A series of fine droplets eject from the surface of molten PE, which is associated with an electrospay phenomenon [18–20]. Note that with AC electric fields applied to Cu-core, a dripping phenomenon of molten PE is not observed at all conditions, different from that with NiCr-core [17–20]. When the frequency increases to 400 Hz, the flame is extinguished. For 7 kV, the spreading flame is slanted toward the burnt wire at 10 Hz and is extinguished at 80 Hz.

**Figure 2.** Flame front positions over time at several frequencies for $V_{AC} = 3$ kV (baseline case with no electric field is marked in black line).
Figure 2 shows the flame front positions ($X_t$) with time ($t$) at several $f_{AC}$ for $V_{AC} = 3$ kV ($t=0$ when $X_t = 70$ mm to exclude ignition transient effect). The flame front was determined by the same method of image analysis adopted previously [18−20]. The result shows that $X_t$ is reasonably linear over time even with several phenomena mentioned above, implying that overall FSR can be determined. As $f_{AC}$ increases, the slope decreases from the baseline case and then increases. This non-monotonic behavior is associated with flame size and direction of flame-leaning as well as complex nature of molten PE behaviors such as magnetic force induced vortex as well as electrophoresis together with a globular molten PE formed near spreading flame front and continuous generation of a molten PE film by di-electrophoresis phenomenon in the rear part of molten PE, which will be explained later.

![Figure 3](image)

**Figure 3.** Flame spread rate against AC frequency at several voltages (inset data for NiCr-core [20]).

### 3.2. Flame spread rate

Since $X_t$ was reasonably linear with $t$, the overall FSR, $S_w$, can be determined from $S_w = \frac{dX_t}{dt}$. Figure 3 shows the result as a function $f_{AC}$. The baseline case with no electric field, $S_{w,0}$, is marked as the dotted line. The inset is for the NiCr core case [20]. For the baseline cases, FSR for Cu-core is much larger than that for NiCr-core, emphasizing the important role of conductive heat transfer via metal core [13].

The FSR behavior against frequency with Cu-core is quite different from that with NiCr-core. For the NiCr-core, FSR generally shows decreasing and increasing trend. While for the
Cu-core case, FSR generally shows decreasing, increasing, again decreasing and increasing
trend, although the values of $f_{AC}$, where the slope of FSR changes its sign, varies with $V_{AC}$. For
better understanding, Fig. 3 is also reproduced in normal coordinate in SM 3.

3.3. Effects of AC electric field on flame and molten PE behaviors

When an electric field is applied to a wire, charged particles in a reaction zone is accelerated
by the Lorentz force. Accelerated ions can transfer momentum to neutral particles such that
bulk flow can be generated, i.e., the ionic wind effect [21]. This interaction of electric fields
with spreading flame resulted in a modification of flame shape and slanted direction of the
flame (Fig. 2) [17-20]. Since the electric field is stronger on the burnt wire side by the existence
of PE-insulation on the unburned side, a flame is typically tilted by the ionic wind toward the
burnt wire side. This results in a decrease in FSR, similar to a wire flame with counter-current,
due to decreased heat transfer toward the unburned wire. However, when the spreading flame
is tilted toward the burnt bare wire with a high thermal conductivity, say, Cu-core, the solid-
phase heat transfer from the bare wire to molten PE can increase. This results in an increase in
FSR. The overall FSR can thus be influenced by the competition between the heat transfer and
ionic wind effects.

A flame edge experiences quenching near the wire due to thermal and radical interactions,
causing the flame edge to have a premixed flame nature by a partial-premixing through the
quenching zone [17–20]. The edge propagation speed of non-premixed flame and the
stabilization of premixed Bunsen flame can be influenced appreciably by electric field [22,23].
While overall FSRs of wire flames were typically controlled by the size of diffusion flame
[17–20], due to a heterogeneous combustion nature similar to droplet or candle flames.

With NiCr-core, FSR has been qualitatively described well by the thermal balancing
mechanism among conduction, convection, and radiation [2,5,17–20]. When one (or more) of
these heat transfer modes is altered by electric fields, FSR should be adjusted to re-balance them [17–20]. An example is that when a spreading flame leans toward the burnt wire, FSR reduces because of insufficient heat transfer from the flame to PE [17–20].

Concerning the fluctuation of both front and rear flame edges (SM1c and 2c), the mechanism of the onset of such instability is not clear yet. While an experimental observation of a hydrodynamic instability [24] could provide a clue. It has been attributed to an induced magnetic field in triggering the hydrodynamic instability. Magnetic force is expressed as

$$F_{mag} = qvB$$

where \(q\) is the charge of particle, \(v\) is the magnitude of the charged particle velocity, and \(B\) is the magnetic field, respectively. The ion drift velocity can be scaled with electric field intensity \(E\) proportional to the applied voltage as \(\nu \sim E \sim V_{AC}\) where \(V = \sqrt{2}V_{ACs}\)sin \((2\pi f_{AC}t)\). According to the Ampere’s law, the magnitude of induced magnetic field is expressed with the displacement current \(I_d\) as \(\oint B \cdot dl = 2\pi r_0B = \mu_0 I_d\) where \(r_0\) is the radius of wire and \(\mu_0\) is the magnetic constant. Here, the displacement current can be expressed as \(I_d \approx \varepsilon_0(\partial E / \partial t)(2\pi r_0L)\) where \(L\) is the wire length and \(\varepsilon_0\) is the electric constant. Therefore, \(B \approx 2\pi f_{AC}EL/c^2\) where \(\varepsilon_0\mu_0 = 1/c^2\) and \(c\) is the speed of light. The maximum electric field intensity can be estimated to be \(V_{AC}/r_0 \sim O(10^6\ \text{V/m})\). By adopting \(f_{AC} \sim O(10^2\ \text{Hz})\), \(\nu \sim O(10^2\ \text{m/s})\), and \(L \sim O(0.1\ \text{m})\), a relative ratio of the magnetic force to corresponding electric field will be \(vB/E \sim O(10^{-13})\). Thus the magnetic force is much smaller than corresponding electric field. However, as pointed out in [24], only a small disturbance may be required in triggering a hydrodynamic instability, such as shown in SM2c and 3c. The AC field induced magnetic force acting on a charged particle can be scaled as \(F_{mag} \sim vB \approx f_{AC}V_{AC}^2\). One of the convincing evidences in identifying the mechanism based on magnetic field induced vortex can be the test on the critical onset condition, whether \(F_{mag}\) maintains constant at the onset condition, that is, \(f_{AC} \sim V_{AC}^{-2}\) in the above. The onset condition
of the formation of the vortex structure is fitted to the form of $f_{AC_{cr}} \sim V_{AC}^{-2}$ as shown in SM4.

The best fit is $f_{AC_{cr}}[\text{Hz}] = 7.29 \times 10^9 (V_{AC})^{-2}[V^{-2}]$ with $R = 0.99$. This could partially substantiate the mechanism based on the induced magnetic fields, however, details will be the future study.

Interaction of molten PE with applied electric field can also influence FSR in a complex way. Soot particles formed in the fuel region of spreading flame is transported and deposited on the wire and/or molten PE via thermophoresis and electrophoresis. The amount of soot deposition increases with $V_{AC}$, promoting radiation absorption to the molten PE. Sufficient accumulation of molten PE could result in a dripping of molten PE when NiCr-core was used [17–20]. Such a dripping phenomenon did not occur in the present experimental ranges with Cu-core. Recall that the flame size was appreciably reduced when a globular molten PE is formed near spreading flame front, e.g., 3 kV and 400 Hz (SM1b1 and 2b1). Then, FSR is expected to be reduced. In this case, the rear part of molten PE continues to generate a molten PE film by di-electrophoresis phenomenon (SM1b2 and 2b2), thereby further reducing FSR, despite the increase in flame width. This may be understood based on the reduction of burning rate in 1-D droplet arrays [25,26] as the droplet spacing is reduced.

When an electric field is applied to molten PE via the wire, positive ions drift toward the surface of molten PE (for positively charged wire) and the negative ions away from the surface. The accumulated positive ions on the surface become concentrated on the outermost skin layer, and subsequently the PE surface is drawn out to form a liquid Taylor cone. When a sufficiently high electric field is applied to the wire, small droplets can be ejected from the molten PE surface in the form of electrospray [27–30] (SM1d and 2d). The occurrence of electrospray tends to reduce FSR because of mass loss of molten PE [19,20].

Unequal electric field acting on permanent or induced dipoles (e.g., molten PE) could drive them to move toward the region of higher electric field intensity, that is, the di-electrophoresis
phenomenon [31–33]. The phenomenon forces flame width to increase appreciably (SM1a and 2a), resulting in increasing FSR [20].

Measured current in the single electrode configuration is in range of 0.01-0.12 (0.01-0.17) mA for NiCr (Cu) core (see SM5), resulting in the electrical power of 0.01-0.84 (0.01-1.19) W. The overall heat production can be estimated to be 29.9 (40.7) W from $\rho S_w H_L$ where the spreading rate $S_w$ is about 2.5 (3.4) mm/s for NiCr (Cu), the measured mass density per unit length of PE coating $\rho$ is $2.66 \times 10^{-4}$ kg/m, and the lower heating value of PE $H_L$ is $4.5 \times 10^7$ J/kg. Joule heating effect to overall heat production is negligible, since it is 2.8 (2.9) % for NiCr (Cu) core.

**Figure 4.** Regime diagram based on the characteristics of burning in terms of AC voltage and frequency for Cu-core; Regime I is for slanted flame toward burnt wire, II for double-peak flame, III for formation of globular molten PE near spreading flame front and film formation, and IV for fluctuating flame with electrospray.

Based on the above-mentioned phenomena along with the FSR behavior against $f_{AC}$ (Fig. 3), the regime diagram is constructed in Fig. 4. In regime I, both FSR and flame size decrease with frequency, which appears mostly at low voltages. In regime II, both FSR and flame size increase with frequency while the spreading flame is repeatedly double-peaked. In regime III, FSR (flame size) decreases (increases) with frequency. In such a situation, a globular molten PE is formed near the spreading flame front and a molten PE film is generated toward the bare wire side. In regime IV, electrospray occurs and both FSR and flame size increase with
frequency. Both the front and rear flame edges fluctuate (SM1c and 2c), which are associated with magnetic field induced vortex. In regimes III and IV, further increase in frequency results in flame extinction, which will be explained later.

**Figure 5.** Relationship between flame spread rate and flame width over the tested AC frequency range for 2 and 6 kV.

### 3.4. Flame spread rate and flame size

As mentioned, FSR was controlled mainly by diffusion flame size with NiCr-core [17–20], thus FSR correlated well with flame width. With Cu-core, FSR and flame width ($W$) versus $f_{AC}$ are shown in Fig. 5, where $W$ is defined as the wire length covered by flame (see inset photo). For comparison, the inset plots are with NiCr-core. For the NiCr-core case, FSR against $f_{AC}$ shows similar tendency as to $W$ [20]. For 2 kV with Cu-core, FSR and $W$ show similar tendencies for $f_{AC} \leq 400$ Hz (regimes I and II), while opposite tendency for $f_{AC} \geq 400$ Hz (regime III). For 6 kV, FSR and $W$ show opposite tendency for $f_{AC} \leq 60$ Hz (regime III) and similar trend for $60 \leq f_{AC} \leq 200$ Hz (regime IV). This implies that with Cu-core, a correlation between FSR and $W$ is not satisfactory in regime III, while it holds in other regimes.
In this regard, the thermal balance mechanism (details in [13]) on flame spread is re-examined. With a metal core with a large (small) thermal conductivity, e.g. Cu (NiCr), the spreading flame could be expressed as follows [13]:

\[ V_f = \left[ 2h_s r_s L_p + \frac{2h_c r_c (W - L_p)}{2\lambda c (W - L_p)} \right] \frac{(T_f - T_p)}{\rho_p (r_s^2 - r_c^2) [c_p (T_p - T_0) + L] + \pi r_c^2 \rho_c c_c (T_p - T_0)} \]  

(1)

Here, \( \rho \), \( c \), and \( \lambda \) are the density, specific heat, and thermal conductivity, respectively; the subscripts c, s, p, f, and 0 denote the core, insulator surface, pyrolysis, flame, and ambient condition, respectively; \( L \) is the latent heat (254 kJ/kg for PE [13]); \( r_c \) and \( r_s \) are the radii of metal core and insulator, respectively; \( h_c \) and \( h_s \) are the heat transfer coefficients to the bare core and insulation, respectively; \( L_p \) is the pyrolysis length; \( T_f \), \( T_0 \), and \( T_p \) are the flame, ambient, and pyrolysis temperatures, respectively.

Since the pyrolysis length is included, we examine the effect of electric fields on pyrolysis length in Fig. 6 with Cu- and NiCr-cores, defined as the distance between flame front and molten PE drop (see inset photo) [13]. The result shows that the pyrolysis length traces the trend of FSR for both Cu- and NiCr-cores. Note that the flame width could not follow the FSR trend in regime III with Cu-core (Fig. 5). This emphasized the importance of fuel pyrolysis toward the unburned side for a wire with large thermal conductivity.
Figure 6. Effect of applied electric field on pyrolysis length with Cu- and NiCr-cores.

Figure 7. Experimental and calculated flame spread rates for Cu- and NiCr (shaded region)-cores.

The effect of fuel pyrolysis is further examined by comparing the experimental FSRs with calculated ones from Eq. (1) in Fig. 7. Here, the flame, ambient, and pyrolysis temperatures were taken as 1200, 298, and 648 K, respectively, from [13] along with other thermo-physical properties.

For NiCr-core, the calculated FSRs are somewhat smaller than the measured ones, implying that the assumed flame temperature (1200K) may be underestimated. Note that when using $T_f$
= 1500 K, the quantitative values between calculated and measured FSRs are much better agreement. Note that flame temperature simply shifts the result vertically in the figure, thus quantitative comparison does not have much meaning.

For Cu-core, the calculated FSRs seem to reasonably trace the measured FSRs. Recall that for Cu-core in regime III, flame width (FSR) increases (decreases), as shown in Fig. 5. The calculated FSRs in regime III are larger than the calculated ones in regimes I, II, and III. For further understanding, the contribution ratio of core heat transfer to overall heat transfer is presented in SM6. For the NiCr core with low thermal conductivity, the contribution of core heat transfer reasonably decreases with the increases in FSR. For the Cu core, the contribution of core heat transfer is reasonably constant in regimes I, II, and IV while that in regime III, being large contribution, decreases with the increase in FSR. This could be associated with the formation of globular molten PE near spreading flame front edge and molten PE film in regime III, which could reduce FSR while the apparent flame width increases. These effects are not reflected in Eq. 1, which will be a future work. In summary, despite various electric field induced phenomena on flame and molten PE, FSR can be overall described by the thermal balance mechanism, especially emphasizing the effect of pyrolysis length.

![Figure 8](image.png)

**Figure. 8.** Characterization of flame spread rate.

Previously [18–20], electric field intensity (E) was found to play a crucial role for various flame responses. For a spreading flame, the flame edge at the unburned wire in contact with
the insulation material is expected to play an important role because of partially-premixed nature. The electric field intensity at the outer surface of the PE, $|dE/dr|_{D_{\text{out}}}$, was selected as the representative electric field intensity. Details of the calculation of $E$ was reported [20]. For several PE-insulator thicknesses with NiCr-core, the normalized FSR $S_w/S_{w,0}$ was shown to be correlated as $(S_w/S_{w,0})^{1/2} = A \times f_{AC} \times |dE/dr|_{D_{\text{out}}} \times (D_{\text{out}}/D_c)^{1.9}$ [Hz$^{0.36}$×kV/mm$^2$] [20], where $D_c$ is the core diameter. This is revisited in Fig. 8 for Cu-core for $(D_c, D_{\text{out}}) = (0.5, 0.8)$ mm, in the functional form of $(S_w/S_{w,0})^{1/2} = A \times f_{AC}^{0.36} \times |dE/dr|_{D_{\text{out}}} + B$. For NiCr-core (dotted lines), the best fit is $A = -1.76 (2.49)$ and $B = 0.99 (0.61)$ with $R = 0.90 (0.88)$ in regime I (II). For Cu-core, satisfactory correlations cannot be obtained although the slopes of various regimes (solid lines) seemingly agree with the slopes for NiCr-cases. This can be attributed to various complex dynamic behaviors of molten PE, such as electrospray, di-electrophoresis, and formation of molten PE film.

Figure. 9. Functional dependency of extinction frequency on voltage.

3.5. Flame extinction

Spreading flames were extinguished when $V_{AC}$ and $f_{AC}$ became excessive and the extinction regime diagram is shown in Fig. 9. Previously for NiCr-core [20], two types of flame extinction modes (excessive reduction of flame size and excessive mass loss of molten PE) were observed, both of which were fitted as $\log (f_{AC,\text{ext}}) [\text{Hz}] = -0.53 \times V_{AC}[\text{kV}] + 4.40$ with $R=0.99$. For Cu-core, two types of flame extinction are also observed as shown in SM 7. The former (latter)
case is fitted as \( \log (f_{AC,\text{ext}}) [\text{Hz}] = -0.54 \times V_{AC}[\text{kV}] + 5.38 \) \((-0.10 \times V_{AC}[\text{kV}] + 2.98) \) with 
\( R = 0.91(0.98) \). For the flame extinction mode via reduction of flame size with Cu-core, the 
slope \((-0.54)\) is very close to that \((-0.53)\) with NiCr-core. With Cu-core, the reduction of flame 
size is attributed to the formation of globular molten PE near the leading flame edge and the 
formation of molten PE film with a long tail in the rear part of molten PE droplet (SM7a and 
b). The other route of flame extinction is through the abrupt detachment of molten PE when 
AC frequency increases further from regime IV, where both front and rear flame edges fluctuate 
appreciably and electrospray occurs, leading to flame extinction (SM7c and d). Note that the 
abrupt detachment of molten PE during flame fluctuation with Cu-core leads to flame 
extinction, which is different from mass loss of molten PE via near-periodic dripping with 
NiCr-core.

3. Conclusions

Flame spread behaviors over electrical wire with Cu-core were experimentally studied by 
varying \( f_{AC} \) and \( V_{AC} \) and the result was compared with NiCr-core case. The following 
conclusion can be made:

1) For the baseline cases with no electric field, FSR with Cu-core was larger than that 
with NiCr-core. Electric fields significantly influenced flame shape and FSR. With Cu-
core, FSR was classified into four regimes; decreasing, increasing, and again 
decreasing, and increasing trends with \( f_{AC} \), which were attributed to flame tilting, flame 
splitting by di-electrophoresis, formation of globular molten PE near spreading flame 
edge and formation of molten PE film, and electrospray and flame fluctuation near the 
end parts of flames, respectively.

2) FSR behavior was in qualitative agreement with flame width in regimes I, II, and IV, 
while in regime III with pyrolysis length, emphasizing the importance of heat
conduction through the Cu-wire having large thermal conductivity.

3) For NiCr-core, flame extinction occurred via two routes: appreciable reduction of flame size and excessive dripping of molten PE. For Cu-core, the dripping phenomenon of molten PE did not occur. The flame extinction occurred via two routes: appreciable reduction of flame size and detachment of molten PE. For both cases, the extinction frequency decreased with $V_{AC}$.

Acknowledgements

This work was conducted under the framework of the Research and Development Program of the Korea Institute of Energy Research (B9-2431). SHC was supported by the King Abdullah University of Science and Technology (KAUST). CSY was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Science and ICT (NRF-2018R1A2A2A05018901).

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