Experimental Study on Spreading Flame over Inclined Electrical Wire with AC Electric Fields

S. J. Lim[1], M. K. Kim[2], J. Park[3*], O. Fujita[4], S. H. Chung[5]

[1] Interdisciplinary Program of Bio-mechanical Engineering, Pukyong National University, Korea
[2] Environmental and Energy Systems Research Division, Korea Institute of Machinary and Materials, Korea
[3] Dept. of Mechanical Engineering, Pukyong National University, Korea
[4] Division of Mechanical and Space Engineering, Hokkaido University, Japan
[5] Clean Combustion Research Center, King Abdullah University of Science and Technology, Saudi Arabia

1 Introduction

Much research efforts have been devoted to advance space technologies in various fields, in that space development is being extended from artificial satellite, manned and unmanned spacecraft, and international space station to exploration of the moon and Mars. It will be continued for development of space residence and factory. Thus, a wire fire, caused by electrical wires through unexpected overheating and/or electric short, has been one of the important research subjects for space development. Representative accidents are the Apollo I distaster and the fire in Mir space station during space development program. Electrical wire fire is also one of the main causes for building and household fires as well as aircrafts. In this regard, researches have been conducted to understand the influence of various factors in flame spread such as types of inner core material and outer insulator, gravity level, and ambient flow and pressure [1-6].

However, once wire fire occurs due to electric short and the wire is subsequently down, it can be under influence of electric fields with one electrode configuration of open circuit during flame spread. In case of AC, the frequency in practical systems can vary, 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. In such a case, abundantly charged carriers can interact with the electric fields in reaction zone. However, few studies on the effect of AC electric fields on flame spread over electrical wire have been found in the literature [7, 8]. The previous study showed that flame spread rate varied with applied AC frequencies and voltages significantly [7]. Flame spread behavior near the end of wire with AC electric fields was reported as well, in that the intensity of electric field can be concentrated near the wire end due to the convergence of electric flux [8].

Flame spread over an electrical wire may be very sensitive to the wire inclination angle in normal gravity, in addition to applied electric fields. Nonetheless, the effect of applied electric fields on flame

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

spread over inclined electrical wire has not been reported yet, and this may be covered by the present study.

2 Experiment

Figure 1 shows schematic illustration of experimental apparatus, which consists of a wire, a wire holder, an AC power supply, and a video camera. Polyethylene (PE) insulated electrical wire (NiCr wire) was used, having 350 mm in length, 0.5mm in diameter, and with 0.8mm 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 of wire was connected to a spring in order to prevent bending of wire due to thermal expansion during flame spread.

The flame was initiated by an igniter which was placed over an air cylinder. In order to minimize the interaction between the ignition system and applied AC electric fields, the igniter was removed away from the wire after ignition. A programmable logic controller (PLC) was adopted to control the time sequence of experiment. The details of the experimental procedure were reported previously [7, 8]. The wire length, excluding the portion connected to the wire holder, was 213mm. Experimental data for the initial 70 mm from one end and the final 10 mm were excluded due to ignition transient and the effect of the wire holder, respectively. Therefore, the available length for flame spread was 133mm. The test section was surrounded by nonconductive meshes to minimize external disturbances. A video camera was triggered to capture spreading flame, and the recorded flame images were analyzed by using a Matlab-based code. The averaged flame behavior was obtained from six trials, and the variations were represented as error bars.

The AC power supply (Trek, 10/10B-FG) was used to apply electric fields to the wire. The applied frequency (f_{AC}) and voltage (V_{AC}) were varied in range of 0 ~ 1000 Hz and 0 ~ 5 kV (RMS), respectively, and inclination angle of the electrical wire varied in range of -90° (Downwardly spreading flame) ~ 70° (Upwardly spreading flame). One end of the wire was directly connected to high voltage terminal of the AC power supply. The other terminal of the power supply was connected 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.

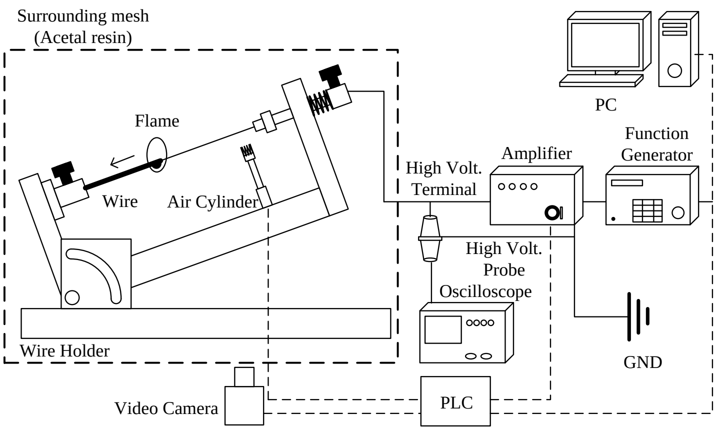
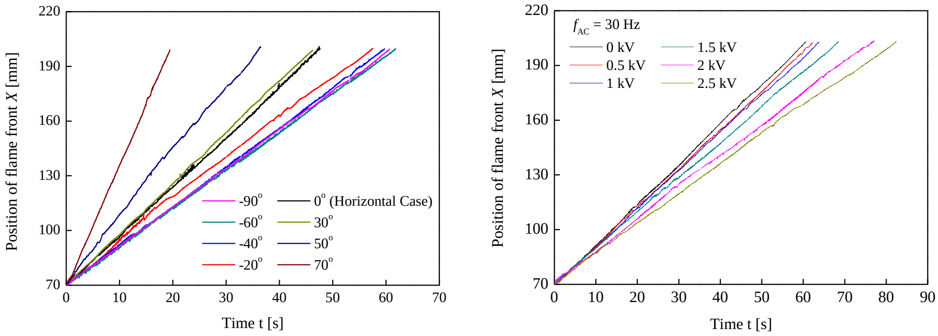


Figure 1. Schematic illustration of experimental setup

3 Results and Discussion

3.1 Overall feature in flame spread

Figure 2 shows (a) the temporal position of flame front X with time, after the ignition transition at various inclination angles of the wire in the absence of electric fields, and (b) that with voltage at a fixed frequency f_{AC} of 30 Hz and an inclination angle θ of -30°. Note that the negative sign in inclination angle means downwardly spreading direction. The flame position varies linearly with the



(a) (b)

Figure 2. Temporal position of flame front at (a) various inclination angles of the wire in the absence of electric fields and (b) voltages at f_{AC} = 30 Hz.

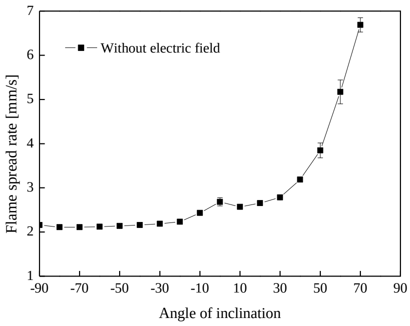
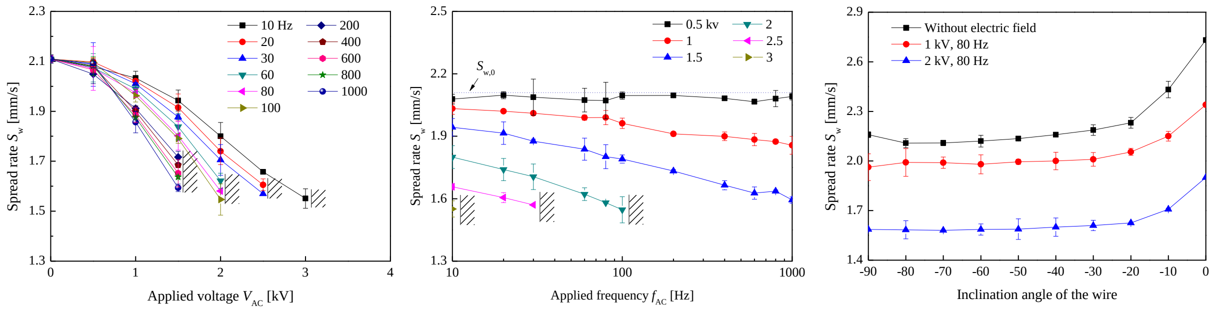


Figure 3. Flame spread rate with inclination angle in the absence of electric fields.

time in all cases. Thus, the flame spread rate is defined as the time rate of change in the temporal position of flame front. As shown in Figure 2(a), the spread rate for downwardly spreading flame without electric fields initially becomes slower compared to the horizontal case, and then is nearly constant for θ ≤ -40°, while that of upwardly spreading flame increases significantly in increase of inclination angle. When the applied voltage increases, the spread rate decreases for downwardly spreading flame at fixed frequency and inclination angle as shown in Figure 2(b).

3.2 Flame spread rate for downwardly and upwardly spreading flame

As mentioned above, the spread rate varies in terms of various factors such as inclination angle as well as applied voltage and frequency. Figure 3 shows the spread rate with inclination angle of the wire in the absence of electric fields. For downwardly spreading flame, the spread rate decreases from θ = 0° to -20°, and then it becomes nearly constant with inclination angle up to θ = -90°, while for upwardly spreading flame, the spread rate increases significantly with inclination angle after having a minimum at θ = 10°.



(a) (b) (c)

Figure 4. Flame spread rate of downwardly spreading flame with (a) applied voltage V_{AC}, (b) frequency f_{AC} at θ = -70° and (c) inclination angle of the wire.

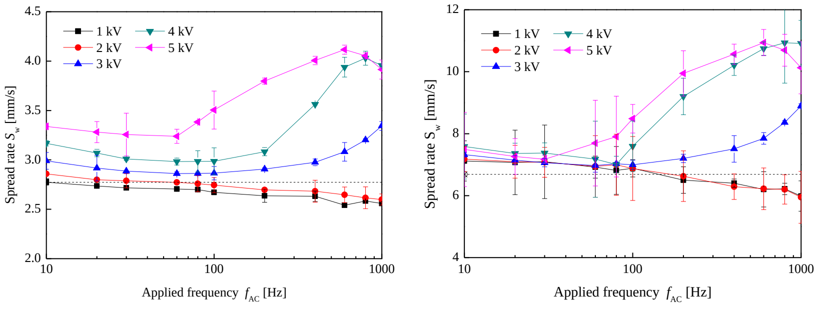


Figure 5. Flame spread rate of upwardly spreading flame with applied frequency f_{AC} for several voltages V_{AC} at (a) θ = 30° and (b) 70°.

Figure 4 shows the spread rate with applied voltage, frequency, and inclination angle. In Figures 4(a) and (b), the result shows that the spread rate of the downwardly spreading flame in the presence of electric fields decreases with applied voltage, and decreases with frequency for $V_{AC} \geq 1$ kV after indicating nearly a constant with applied frequency at $V_{AC} = 0.5$ kV. As applied frequency increases, the spreading flame over the wire was extinguished at lower applied voltage. In Figure 4(c), the spread rate decreases with inclination angle from θ = 0° to -20° and then exhibits similar values with inclination angle up to θ = -90°.

Note that for upwardly spreading flame, the flame size and spread rate become much larger than those for downwardly spreading flames. Figure 5 shows the upwardly spreading flame with applied frequency for various voltages at θ = 30° and 70°. In case of V_{AC} = 1 and 2 kV, the spread rate decreases slightly with applied frequency. For V_{AC} = 3 kV, the spread rate increases significantly with frequency for $f_{AC} \geq 100$ Hz, while the spread rate shows a maximum at f_{AC} = 600 Hz for V_{AC} = 5 kV and decreases in further increase of applied frequency.

To better understand variation of the spread rate via flame shape, instantaneous images of spreading flame were shown in Figure 6. As shown in Figure 6(a), downwardly spreading flame in the absence of electric fields leans toward the burnt side. The flame size reduces significantly from θ = 0° to -30° and then it scarcely changes with inclination angle up to θ = -90°. On the other hand, upwardly spreading flame leans toward the unburned side and the flame size increases significantly with inclination angle. With applied AC electric fields, the size of downwardly spreading flames decreases with applied voltage and frequency as shown in Figure 6(b). For upwardly spreading flame in Figure 6(c), the size of the spreading flame reduces slightly with applied frequency at V_{AC} = 1 kV. At V_{AC} = 3 kV, the flame size increases significantly for $f_{AC} \geq 100$ Hz, while that for V_{AC} = 5 kV increases up to f_{AC} = 600Hz and decreases in further increase of applied frequency.

3.3 Thermal balance mechanism

With applied electric fields, charged particles in a reaction zone can be affected by Lorenz force. Subsequently, diffusion fluxes associated with charged particles can increase and the kinetic energy,

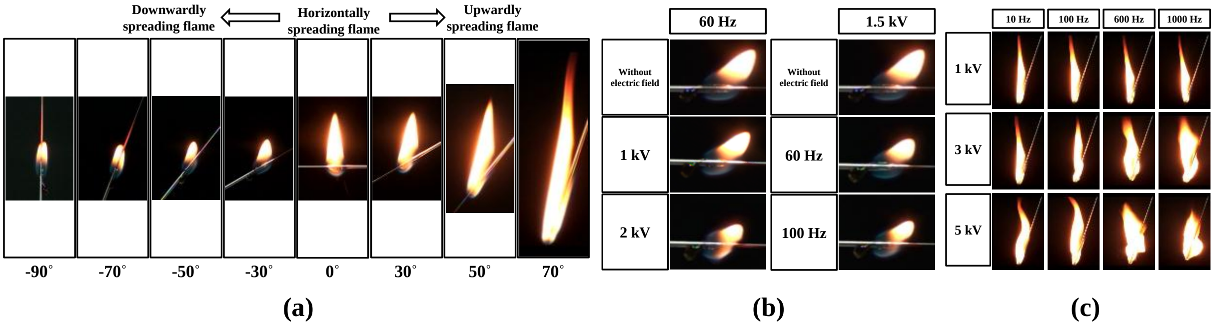


Figure 6. Spreading flame images with (a) inclination angle and applied AC electric fields for (b) downwardly spreading flame of θ = -30° and (c) upwardly spreading flame of θ = 70°.

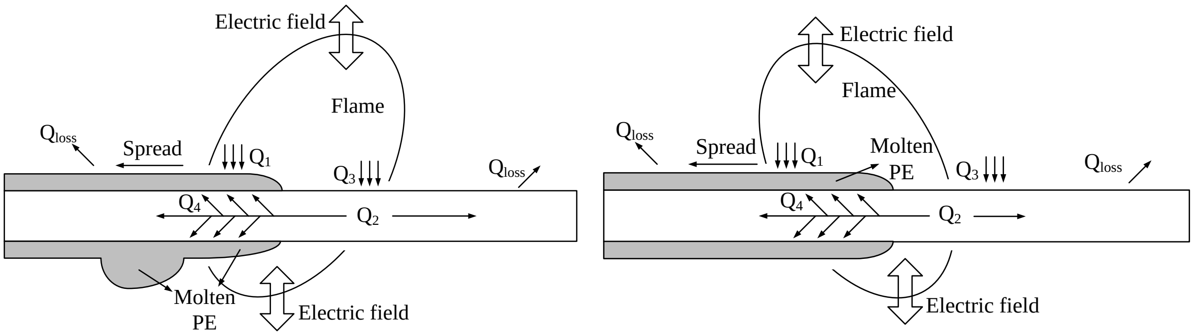


Figure 3. Schematics of thermal balance mechanism for the (a)downwardly and (b) upwardly spreading flame.

which is gained by the charged particles, can enhance the rate of chemical reaction. Accelerated ions can transfer momentum to neutral particles by random multiple collisions among molecules, and then it can generate bulk flow called ionic wind. Those effects can make flame shape changed with applied AC electric fields. Behavior of flame spread can be explained by thermal balance mechanism [5, 7].

Figures 7(a) and (b) show the schematic representation of thermal balance mechanism for downwardly and upwardly spreading flame, respectively. For downwardly spreading flame, the flame leans toward burnt side with inclination angle as shown in Figure 7(a). It reduces the heat transfer from the flame to unburned PE (Q_1). Moreover, as mentioned above, the flame size decreases significantly in the increase of inclination angle for small inclination angle such as the cases of θ = -10 and 20°, and it decreases the heat transfer from the flame to burnt wire (Q_3). Subsequently, the decrease in Q_3 causes reduction in the heat transfer to the molten PE through the wire (Q_2) and to unburned wire (Q_4). As a result, there will be reduction in the total heat transfer from the flame to PE, leading to the decrease of production and evaporation rate of molten PE. Therefore, the spread rate becomes slower. For large inclination angles, the flames exhibit similar flame size, while the flame leans toward burnt side. Whereas Q_1 decreases due to flame tilting towards the burnt side, Q_3 increases relatively, because there is no change in flame size. Thus, the flame spread rate scarcely changes. For increased voltage and frequency, the flame size decreases as shown in Figure 3(b). Then, Q_1 and Q_3 decrease, resulting in reduction of the spread rate. On the other hand, upwardly spreading flame leans toward unburned side and the flame size increases significantly in increase of inclination angle as shown in Figure 3(a). In this case, both Q_1 and Q_3 increase, thereby increasing spread rate.

4 Conclusions

Downward and upward flame spread behaviors over electrical wire, which was insulated by Polyethylene, were investigated experimentally with applied AC electric fields. The spread rate of downwardly spreading flame decreased with applied voltage and frequency except for V_{AC} = 0.5 kV and decreased with inclination angle from θ = 0° to -20°, while that scarcely changed with inclination angle from the range of inclination angle of -30° to -90°. On the other hand, the spread rate of upwardly spreading flame showed various trends with applied voltage and frequency, and increased significantly with inclination angle. The spreading flame over an inclined electrical wire with applied AC electric fields exhibited various flame shapes. Based on flame shape and the slanted direction of flame, the flame spread rate could be explained by thermal balance mechanism.

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] Kikuchi M, Fujita O, Ito K, Sato A, Sakuraya T. (1998). Experimental study on flame spread over wire insulation in microgravity. Proc. 27th In. Comb. Symp.:2507

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

[8] Lim SJ, Kim MK, Park J, Fujita O, Chung SH. (2014). Flame spread over electrical wire with AC electric fields: Internal circulation, fuel vapor-jet, spread rate acceleration, and molten insulator dripping. Combustion and Flame. http://dx.doi.org/10.1016/j.combustflame.2014.10.009