*H. He, et al., Int. J. Comp. Meth. and Exp. Meas., Vol. 5, No. 1 (2017) 87–95*

# FLAME PROPAGATION OVER ENERGIZED PE-INSULATED WIRE UNDER LOW PRESSURE

H. HE, Q.X. ZHANG, L.Y. ZHAO, J. LIU J.J. WANG & Y.M. ZHANG
State Key Laboratory of Fire Science, University of Science and Technology of China, P. R. China.

## ABSTRACT

Flame spread along the energized polyethylene (PE) insulated copper wire under low pressure was investigated experimentally to gain a better understanding of electrical wire fire in aircraft and space habitats. Three types of sample wires, with the same insulation thickness and different core diameters, were used in this research study. First, a simplified model was developed to quantitatively explain the impact of lower pressure on the flame propagation over the energized wires. As with the pressure decreased, both of Grashof number (Gr) and Reynolds number (Re) were decreased and the air-flow diffusion played a gradual and dominant role in the combustion process. Mainly caused by the decrease of natural convention, the heat loss turned to be reduced, resulting in the reduction of oxygen flow and the formation of carbon black was inhibited. Second, several experiments were conducted to investigate the flame spread along the energized wires in a walk-in hypobaric chamber. The experimental results showed that, with the decrease of pressure, the flame height was reduced, the flame shape turned to be spherical, and the blue area showed increased. But the flame shape was reduced gradually along the wire, till extinguished when the pressure set out below a critical value. The accumulation of melt insulation increased and the dripping behavior occurred easily under lower pressure. Moreover, the influence of overload current on the flame spreading velocity was also presented. This work was useful for a further study on the fire risk of electrical wires under low pressure.

*Keywords: electrical wire, flame propagation, flame spread, low pressure, overload current.*

## 1 INTRODUCTION

With the increase of electrical wires used in aircraft and space capsule, there are a lot of possibilities of fires accident potentials. Once on fire, a huge disaster is often caused. For example, the Swissair Flight 111 in-flight fire, which was most likely caused by the electrical arcing in the ceiling void cabling, resulting in loss of all 229 lives on board [1]. For fire safety in this specific environment, flame propagation along the electrical wires under low pressure is one of the hot research topics.

Various tests have been developed to study the fire performance of electrical wires [2]. Fujita *et al*. [3–6] focused on the flame propagation of electrical wires in microgravity. They studied the effects of both internal and external parameters, including wire initial temperature, core diameter, ambient oxygen concentration [3], low external flow [4], and sub-atmospheric pressure [5] on wire combustion under gravity and microgravity. The effect of microgravity environment on the ignition of electrical wire with short-term excess electric current was also studied [6]. From the effects of heating time, heating lengths, environmental pressures and oxygen concentration on wire ignition, Huang *et al*. [7] founded a model of ignition-to-spread transition of externally heated electrical wire systematically. Nakamura *et al*. [8] also studied the flame spread behavior for the horizontally-placed polyethylene (PE) insulated Ni-Cr wire under reduced pressure from atmospheric (101 kPa) to sub-atmospheric levels (~20 kPa). The typical ‘teardrop’ flame was gradually modified to round and the flame luminosity turned to be weak as the total pressure decreases. The similarity of observed spread trend in sub-atmospherics pressure to that in microgravity was discussed as well. Hu *et al*. [9] examined the flame spread over electric wire with high thermal conductivity metal

ISSN: 2046-0546 (paper format), ISSN: 2046-0554 (online), http://www.witpress.com/journals
DOI: 10.2495/CMEM-V5-N1-87-95

core at different inclinations in both naturally normal (Hefei city with altitude of 50 m; 100 kPa) and a reduced (Lhasa city with altitude of 3,650 m; 64 kPa) ambient pressure atmosphere. Cahill [10] conducted several tests to study the electrical short circuit and overload current on wires in commercial transport category aircraft. Babrauskas [11] summarized the well-known factors that lead to the ignition of low-voltage PVC wiring.

In general, although several previous works have been focused on the ignition and flame propagation of electrical wires, there are limited studies of the energized wires still, which are more common and could be more dangerous. Especially under low pressure, as the natural convection weakened, drop occurred easily due to the inadequate combustion and heat accumulation; hence, wire fire risk is also increases. Therefore, in this present research article, the flame propagation over energized electrical wire under low pressure was investigated. A simplified relationship was developed to quantitatively explain the impact of lower pressure on the flame propagation. An experimental study was performed in a low-pressure chamber to validate the effects of ambient pressure on wire flame propagation. The results of this study could be useful for the widely used electrical wires in aircraft.

## 2 EXPERIMENTAL

Figure 1 shows the experimental apparatus, which consisted of three parts: a wire sample holder, two constant current sources (CCS), and an ignition part. The sample holder consisted of a base, holder, Bakelite plates, compression spring, wiring terminal, coil heater, and sample wire. The dimensions of the base were 300 mm (L) × 60 mm (W) × 15 mm (H). The base and holder were made of stainless steel, and the Bakelite plates were used as an insulation material to avoid a short circuit. The compression spring on the left was used to keep the wire sample straight and tight during the whole process. The coil heater, which was made of Nico-chrome, can be used as an ignitor when energized. The ignition part was free on the base, and it was set to maximize the available wire length. CCS 1, had a measuring range of 0–21 A with an accuracy 0.1 A, and was used to adjust the current of the sample wire. CCS 2 (measuring range 0–7 A with an accuracy 0.01 A), was used to precisely control the current imposed on the coil heater. A front-view video camera (SONY NEX-5R, 50 fps) was used to

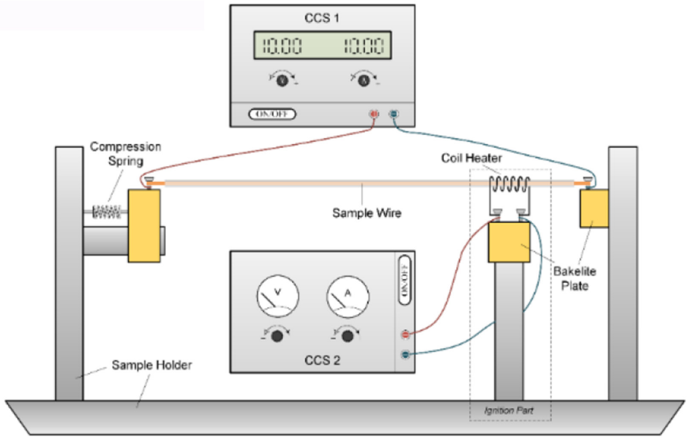

Figure 1: Schematic of the experimental apparatus.

record the process. The characteristic parameters of the flame propagation were obtained by image processing.

Three types of polyethylene (PE)-coated copper wires (Table 1) with different diameters but the same insulation thickness were used. The ratio of core section area (representing the electrical resistance and the rated current) was about 1:2.5:5. A walk-in hypobaric chamber with adjustable inner ambient pressure was used to simulate the low pressure environment. This chamber reduced pressure by extracting the inner air fixed in a vacuum pump, and the design work scope was kept 0.25~1.0 atm. All of the experiments were conducted between 20°C and 25°C ambient temperature and 70%–80% relative humidity. Generally, at least five repeated tests were conducted under the same conditions to minimize error.

## 3 RESULTS AND DISCUSSION

### 3.1 The relationship between ambient pressure and wire flame propagation

Under low pressure, the heat loss from wire to ambient environment through the natural air flow is reduced, which resulted in a higher temperature of the conductor balance, and the wire is more likely to be ignited. This effect can be analyzed qualitatively by analyzing the heat transfer of a cylinder in natural convection. If ambient air is taken as the ideal gas, the mathematical relationship between Grashof number, *Gr*, and Reynolds number, Re, can be summarized as [12]:

$$Gr = \frac{\rho^2 g\beta\Delta T L^3}{\mu^2} = \frac{g\beta\Delta T L^3}{\mu^2}\left(\frac{P}{R_{air}T}\right)^2 = \left(\frac{g\Delta T L^3}{\mu^2 R_{air}^2 T^3}\right)P^2 \tag{1}$$

$$\mathrm{Re} = \frac{\rho U L}{\mu} = \frac{P}{R_{air}T}\frac{g^{1/2}L^{3/2}}{\mu} = \frac{g^{1/2}L^{3/2}}{\mu R_{air}T}P \tag{2}$$

In above equations as dynamic viscosity coefficient μ and characteristic length *L* are indepent of pressure, while gravitational acceleration g and general gas constant $R_{air}$ are not variables. Therefore, the relationship between *Gr*, Re and the ambient pressure can be modified as:

$$Gr \propto P^2,\ \mathrm{Re} \propto P \tag{3}$$

Equation (3) demonstrates the linear relationship of pressure with *Gr* and Re. Re changes linearly with the pressure while *Gr* is propartional to square power of pressure, indicating that decrease in pressure will result in the reduction of both *Gr* and Re, but effect of pressure

Table 1: Configuration of wires used in this study.

| Type | Wire diameter $d_c$ (mm) | Insulation thickness $\delta_p$(mm) | Sample diameter $d_0$ (mm) | Rated current (A) | Core section area $S_c$ (mm$^2$) |
|---|---|---|---|---|---|
| A | 0.50 | 0.15 | 0.80 | 0.78 | 0.79 |
| B | 0.80 | 0.15 | 1.10 | 1.96 | 2.01 |
| C | 1.10 | 0.15 | 1.40 | 3.80 | 3.80 |

will be more outshined on Re than *Gr*. The diffusion plays a primary and dominated role in the transmission of the combustible mixture. For instance, operating a small cylinder such as the wire, the relationship between Nusselt number, *Nu*, and Grashof number, *Gr*, is given as [13]:

$$Nu = 0.794\ Gr_{(D)}{}^{1/15},\ 10^{-8} < Gr_{(D)} < 10^{-7}. \tag{4}$$

Consequently, the mathematical relationship between Nusselt number *Nu* and ambient pressure *P* is reconstructed as:

$$Nu \propto \mathrm{P}^{2/15}, \tag{5}$$

where Nusselt number *Nu* is the defined as the ratio of heat convection and heat conduction, eqn (5) illustrates that lowering in pressure will result in reduction of heat loss by natural convection of wire ensuring influences on wire flame morphology and flame propagation velocity.

## 3.2 The flame morphology for the energized wire under low pressure

Figure 2 shows the flame morphology for the wire without load under low pressure. As the pressure decreased, the flame height came down and the shape of flame turned to be spherical. In the blue flame region, the fuel particles were mainly converted into polycyclic aromatic hydrocarbons (PAHs) [14, 15]. Aromatic compounds are responsible for the flame color dominated by emissions spectra, while light blue flame is due to the lower concentration of soot particles. The ratio of blue flame area and the total flame area was closely related to the flame temperature, flame height, and flame radiation, which can be used to characterize the full amplitude of burning. The bright yellow region was the area due to the soot formation and oxidation. The carbon black contents formation and consumption is continued while the unburned parts can break through the flame edge and some sporadic flames were formed. With the decrease of ambient pressure decreased, the blue flame area continued to expand gradually. This might be due to the decrease of buoyancy driven oxygen flow and the formation of carbon black, which was hindered. In agreement with eqn (5), the heat loss by convection was reduced under low pressure. Meanwhile, the heat loss by radiation reduced with the decrease of wire flame power as well. These two functions caused in the changes of flame morphology under low pressure. Remarkably, the volume of melt insulation increased with the decrease of ambient pressure. This might be was the reason of incomplete burning and the accumulation of melt insulation.

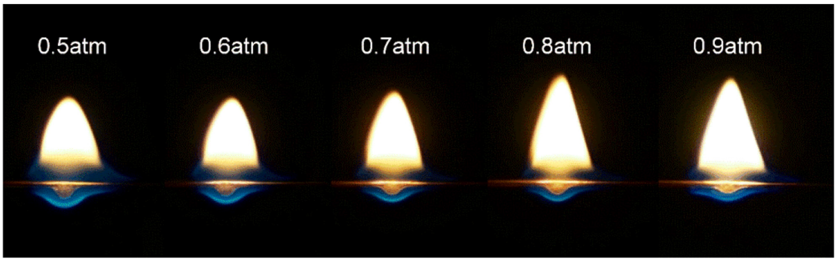

Figure 2: The flame morphology for the wire without load under low pressure.

Figure 3 elaborates the flame morphology for the energized wire under 0.5 atm. The flame height increased obviously with the loading current raising. The blue flame area remained unchanged while the volume of melt insulation increased. For the wire type A, when the current is greater than 8 A (10 times that the rated current), the volume of molten insulation could reach a certain limit resulting in drops occurring. The hot molten or burning polymer may ignite nearby combustibles, expand combustion range, and increase the fire risk.

### 3.3 The flame propagation for the energized wire under low pressure

The flame propagation for the energized wire under low pressure was a steady process. As shown in Fig. 4, the flame leading edge position changing with time, for the wires under 0.7 atm and at a current of 6 A. The position varied linearly with time, and its slope represents the flame propagation velocity.

Figure 5 shows that the flame propagation velocity is changing with the ambient pressure. For the wire type A, with the pressure increases, the curve has an increasing trend, even some fluctuates still exist. For the type B and C, the flame propagation velocities increase almost linearly with increasing the pressure. Remarkably, for the wire type C, pressure below than 0.7 atm, the flame reduced to extinction gradually when the flame propagates along the wire

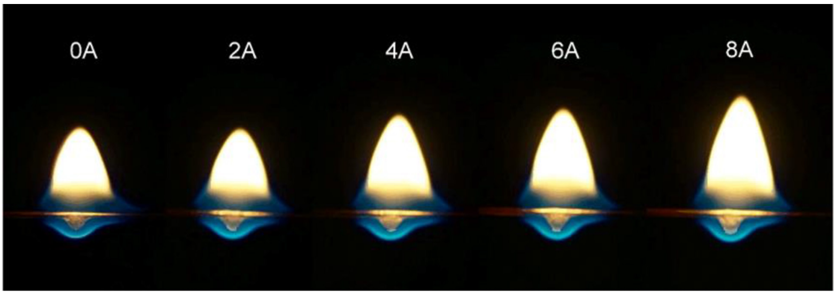

Figure 3: The flame morphology for the energized wire under 0.5 atm.

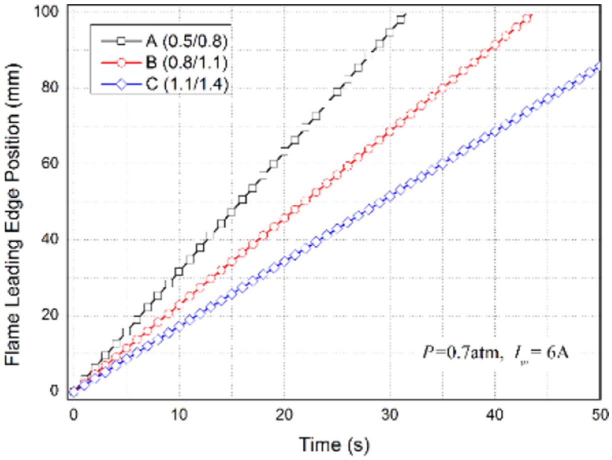

Figure 4: Flame leading edge position for the energized wire under 0.7 atm.

after ignited by external radiation. For the three types of wire under same ambient pressure, the one with the minimum core (type C) has the maximum propagation velocity.

Figure 6 indicates that the flame propagation velocity increases with the rising of current under a specific pressure. For the wires, drop occurred when the current rose above than the exceeding limit. This might be due to the decrease in burning rate under low pressure and melt droplets could accumulate easily. For the wire type A, under 10 times than the rated current, it burned fiercely with the fastest propagation speed with a rapid increased molten insulation, resulting in the formation of droplets easily.

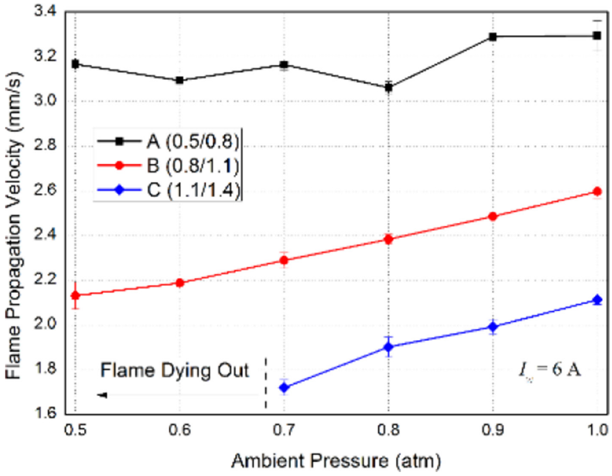

Figure 5: The flame propagation velocity changing with the ambient pressure (0.5–1.0 atm).

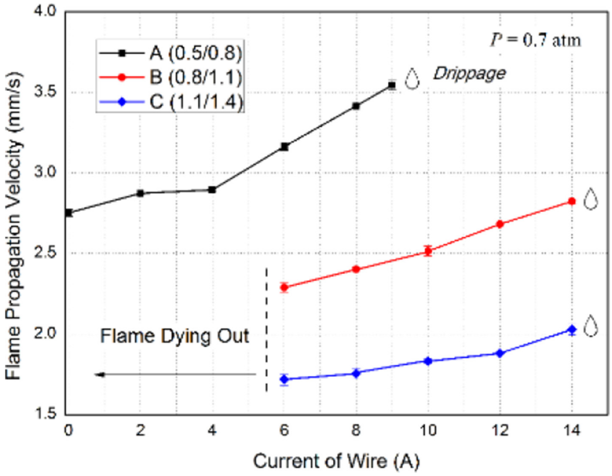

Figure 6: The flame propagation velocity changing with the current of wire (0–14 A) under 0.7 atm.

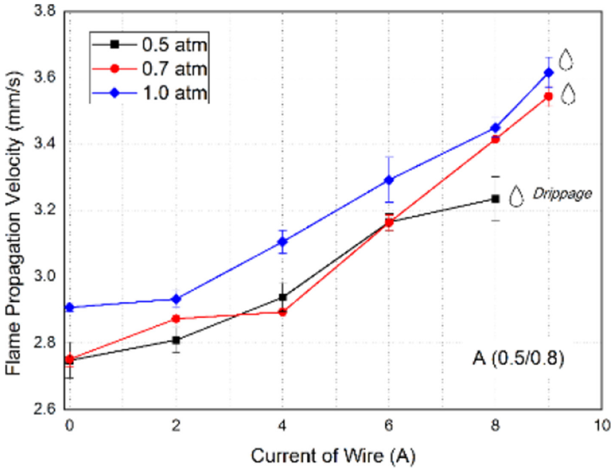

Figure 7: The relationship between loading currents and flame propagation velocity for wire type A.

Figure 7 shows the relationship between loading current and wire flame propagation velocity. Under different pressure, the curves for wire type A are in the same trend. They all have a linear growth process before the drippage and the growth rates were similar generally. Drop occurs at a current limit of 9 A for the wires under 1.0 and 0.7 atm, but 8 A was for 0.5 atm. It can be concluded that drop can easily occur under low pressure.

## 4 CONCLUSIONS

In this present study, the flame morphology and propagation under low pressure for the energized PE insulated copper wires were examined experimentally. The main points are as follows:

(1) A simplified relationship between natural convection and ambient pressure is presented, it shows that the wire heat loss is reduced under low pressure and it has influences on the wire flame morphology and flame propagation velocity.

(2) In case of flame morphology, with the pressure decreased, the bright yellow area is shift down but the light blue area is increased. Meanwhile the volume of molten insulation increases gradually.

(3) The flame propagation velocity under low pressure is obtained. The flame propagation for the energized wire shows a steady process under low pressure, but below a certain limit of pressure the flame can reduce to extinction. The flame propagation velocities increase almost linearly with increase of pressure.

(4) The effect of loading current on the flame propagation velocity is also discussed. The curves have a linear growth process before the drippage and drop can occur under low pressure easily.

## 5 ACKNOWLEDGEMENT

This work was supported by the Joint Funds of the National Natural Science Foundation of China under Grant No. U1233102, the National Program on Key Basic Research Project of China under Grant No. 2012CB719702, and the Collaborative Innovation Center of City Public Safety of Anhui Province. The authors gratefully acknowledge all of this support.

## REFERENCES

[1] Jia, F., Patel, M.K., Galea, E.R., Grandison, A. & Ewer, J., CFD fire simulation of the Swissair flight 111 in-flight fire-Part 1: Prediction of the pre-fire air flow within the cockpit and surrounding areas. *Aeronautical Journal*, **110**(1103), pp. 41–52, 2006. http://dx.doi.org/10.1017/S0001924000004358

[2] Hirschler, M.M., Survey of fire testing of electrical cables. *Fire and Materials*, **16**(3), pp. 107–118, 1992. http://dx.doi.org/10.1002/fam.810160302

[3] Kikuchi, M., Fujita, O., Ito, K., Sato, A. & Sakuraya, T., Experimental study on flame spread over wire insulation in microgravity. *Symposium (International) on Combustion*, **27**(2), pp. 2507–2514, 1998. http://dx.doi.org/10.1016/s0082-0784(98)80102-1

[4] Fujita, O., Nishizawa, K. & Ito, K., Effect of low external flow on flame spread over polyethylene-insulated wire in microgravity. *Proceedings of the Combustion Institute*, **29**(2), pp. 2545–2552, 2002. http://dx.doi.org/10.1016/S1540-7489(02)80310-8

[5] Nakamura, Y., Yoshimura, N., Ito, H., Azumaya, K. & Fujita, O., Flame spread over electric wire in sub-atmospheric pressure. *Proceedings of the Combustion Institute*, **32**(2), pp. 2559–2566, 2009. http://dx.doi.org/10.1016/j.proci.2008.06.146

[6] Fujita, O., Kyono, T., Kido, Y., Ito, H. & Nakamura, Y., Ignition of electrical wire insulation with short-term excess electric current in microgravity. *Proceedings of the Combustion Institute*, **33**(2), pp. 2617–2623, 2011. http://dx.doi.org/10.1016/j.proci.2010.06.123

[7] Huang, X., Nakamura, Y. & Williams, F.A., Ignition-to-spread transition of externally heated electrical wire. *Proceedings of the Combustion Institute*, **34**(2), pp. 2505–2512, 2013. http://dx.doi.org/10.1016/j.proci.2012.06.047

[8] Nakamura, Y., Yoshimura, N., Matsumura, T., Ito, H. & Fujita, O., Flame spread over polymer-insulated wire in sub-atmospheric pressure: Similarity to microgravity phenomena. *Progress in Scale Modeling*, pp. 17–27, 2008.

[9] Hu, L., Zhang, Y., Yoshioka, K., Izumo, H. & Fujita, O., Flame spread over electric wire with high thermal conductivity metal core at different inclinations. *Proceedings of the Combustion Institute*, **35**(3), pp. 2607–2614, 2015. http://dx.doi.org/10.1016/j.proci.2014.05.059

[10] Cahill, P., Electrical short circuit and current overload tests on aircraft wiring. Federal Aviation Administration Technical Center Atlantic City NJ, No. DOT/FAA/CT-TN94/55, 1995.

[11] Babrauskas, V., Mechanisms and modes for ignition of low-voltage PVC wires, cables, and cords. *Fire & Materials*, pp. 291–309, 2005.

[12] Bergman, T.L., Lavine, A.S., Frank, P., Incropera, F.P. & Dewitt, D.P., *Fundamentals of Heat and Mass Transfer*, John Wiley & Sons, pp. 407–408, 2011.

[13] Tsubouchi, T., Heat transfer from fine wires and particles by natural convection. Reports of the Institute of High Speed Mechanics, Tohoku University, 12, 1961.

[14] Faraday, M., The chemical history of a candle. *Resonance*, **7**(3), pp. 90–98, 2002. http://dx.doi.org/10.1007/BF02896314

[15] Warnatz, J., Maas, U. & Dibble, R.W., Combustion: physical and chemical fundamentals, modeling and simulation, experiments, pollutant formation, 2006.