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A Review of Fundamental Combustion Phenomena in Wire Fires

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Abstract:

Electrical wires and cables have been identified as a potential source of fire in residential buildings, nuclear power plants, aircraft, and spacecraft. This work reviews the recent understandings of the fundamental combustion phenomena in wire fire over the last three decades. Based on experimental studies using ideal laboratory wires, physical-based theories are proposed to describe the unique wire fire phenomena. The review emphasizes the complex role of the metallic core in the ignition, flame spread, burning, and extinction of wire fire. Moreover, the influence of wire configurations and environmental conditions, such as pressure, oxygen level, and gravity, on wire-fire behaviors are discussed in detail. Finally, the challenges and problems in both the fundamental research, using laboratory wires and numerical simulations, and the applied research, using commercial cables and empirical function approaches, are thoroughly discussed to guide future wire fire research and the design of fire-safe wire and cables.

Keywords: Electrical wire; Laboratory wire; Cable; Insulation and core; Fire Modelling

1. Introduction

Statistics show that about one-quarter of total residential fires involve electrical malfunction [1], and about 5% of home structure fires are initiated in the electrical wire and cable insulation [2]. Fundamentally, the insulation and jacket layers of wire and cable are made of plastic materials, and if heated by external and internal heat sources, pyrolysis gases can be released to support combustion (**Figure 1**). Electrical wires and cables are also potential fire risk in aircraft and have the potential to cause catastrophic disaster. For example, the investigation of the Swissair 111 accident in 1998 revealed that the crash of aircraft was caused by the fire which was initiated by an arc from the harness of wire [3]. The wire is also a likely cause of fires in space exploration activities, as many electric devices and wires are used in spacecraft [4]. So far, at least five minor incidents of electrical short circuits or component overheating have been reported on Space Shuttle missions, although no fires have occurred [5]. Several thousand kilometers of electrical cables are used in nuclear power plants (NPPs) to control and power the pumps, turbines, transformers, heaters, etc., and these cables pose a significant fire risk [6]. For example, during the accident of Browns Ferry NPP in 1975, over 1600 cables were damaged by the fire and caused short circuits between energized conductors, resulting in serious system misfunctions [7].

The research into wire fire phenomena and its application for the prevention of wire-related ignition and fire hazards has continued for several decades. The relevant work can be classified as fundamental and applied research. Most early works are all applied research using industrial tests, and the wire fire phenomena did not catch attention by the combustion community until the early 1980s. Bakham *et al.* [8, 9] first used the simplified **laboratory wires** which were made by coating polymethyl methacrylate (PMMA) and polyethylene (PE) on the copper (Cu) and glass rods of about 1 mm thick, to study the flame spread and extinction behaviors in the wire. They also first studied the effect of insulation thickness, core size and material, ambient temperature, and wire orientation, measured the temperature profile of core, and noticed the influence of melting and dripping [10] in horizontal, upward, and downward flame spread. To date, this pioneering work remains the most important reference for the fundamental combustion research in wire fire. However, in the next 20 years, very few research had continued the approach of using simplified laboratory wires, that is, made of metal rod and plastic tube. Instead, many controlled experiments and empirical models were conducted for commercial cables to understand the real cable fire behaviors [11–14].

Nomenclature

Symbols

a	strain rate (s^{-1})
A	cross-section area (mm^2)
B	mass transfer number (-)
Bo	Bond number (-)
c	specific heat (kJ/kg/K)
d	diameter (mm)
Da	Damkohler number (-)
E	activation energy (kJ/mol)
g	gravity acceleration (m/s^2)
G	thermal conductance (W-m/K)
Gr	Grashof number (-)
h	convection coefficent (W/m^2-K)
ΔH	the heat of reaction (MJ/kg)
I	electrical current (A)
L	external heating length (m)
Nu	Nusselt number (-)
m	mass (g)
$\dot{m}$	mass-loss rate (kg/s)
$\dot{m}''$	mass loss flux (kg/m^2-s)
n	index (-)
M_{dr}	mass of one drip (mg)
N	number (-)
P	perimeter (m) or pressure (Pa)
Pe	Peclet number (-)
$\dot{q}''$	heat flux (kW/m^2)
r	radius of wire
R	universal gas constant (J/mol-K)
R_e	electrical resistance (Ω/m)
V_f	flame-spread rate (mm/s)
t	time (s)
T	temperature (°C)
U	airflow speed (m/s)
W	flame width (m)
x	wire axial direction
Y	mass fraction (%)
Z	pre-exponential factor (s^{-1})

Greeks

α	Thermal diffusivity (m^2/s)
γ	surface tension (Pa)
δ	thickness (mm)
θ	inclination angle (^{o})
ρ	density (kg/m^3)
σ	surface tension (Pa)
λ	thermal conductivity (W/m-K)
Λ	non-dimensional number (-)
ν	kinematic viscosity (m^2/s)
μ	dynamic viscosity (Pa·s)
φ	equivalence ratio (-)
χ	cable classification number (-)
χ_r	radiative heat loss fraction (-)

Superscripts

*	critical

Subscripts

a	ambient
b	burning
c	core
cp	between core and insulation
dr	dripping
e	electrical
f	flame
F	fuel
g	gas
ig	ignition
J	Joule heat
m	melting
o	outer
p	plastic insulation
py	pyrolysis
sr	surface reradiation

Abbreviations

CEMAC	CE MArking of Cables
ETFE	ethylene-tetrafluorpvco-ethylene
FEP	fluorinated ethylene propylene
FIGRA	fire growth rate (W/s)
HRR	heat release rate (kW)
LOC	limiting oxygen concentration (%)
NiCr	nickel-chromium
NPP	nuclear power plant
NRC	Nuclear Regulatory Commission
PE	polyethylene
pHRR	peak heat release rate (MW)
PMMA	polymethyl methacrylate
PVC	polyvinyl chloride
SS	stainless steel
TGA	thermogravimetric analysis
THR	total heat release (MJ)
TI	thermal inertia (kJ^2/m^4-K^2-s)

Until the early 2000s, several researchers, particularly from Japan, re-adopted Bakham's fundamental approach and conducted more extensive studies on the ignition, flame spread, extinction, and suppression using laboratory wires [15–32]. These research work have focused on the influence of environmental variables, such as pressure, oxygen concentration, airflow, and gravity level, on the fire behaviors in thin wires of about 1 mm thick, as shown in Fig. 1(b-c). Since the 2010s, the wire fire becomes a fairly hot topic in combustion which attracts more research efforts from other countries (e.g. [33–51]), so that other aspects, such as fire emission, the effect of the electrical current, and phase-change processes, have been explored. At the same time, some bench-scale commercial cables have also been studied under a controlled environment (e.g. [52–58]), which help bridge the gap between fundamental studies on laboratory wires and large-scale fire tests on commercial cables. Nevertheless, the total number of research papers on wire fire barely exceeds 100, and many fire phenomena and dynamics are still far from clear, such as the scale effect, melting and dripping processes. Particularly, there is a lack of numerical work to describe the wire fire phenomena, verify the experimental data, and quantify the controlling mechanism.

Essentially, what makes the combustion phenomenon in wire fire unique is its default combination of the combustible polymer insulation and the inert metallic core. The fact that **the thermal conductivity of metallic core is 2-3 orders of magnitude greater than the polymer insulation** can significantly alter the heat-transfer process in wire fire, from the ignition, spread, and extinction to the phase-change processes of polymer insulation and the emission of combustion products. Such a strong heat transfer in the metallic core can also enhance or weaken the impact of environmental factors, such as gravity, pressure, and airflow on fire. Moreover, the metal core can produce Joule heat to self-heat the wire, which is particularly severe under poor-contact or short-circuit circumstances, posing a significant fire risk. For this reason, many studies have focused on the role of solid-phase conductive heat transfer in various aspects of wire fire. On the other hand, the default cylindrical shape of electrical wire also makes the fire dynamics very different from most other flat or irregular shape fuels.

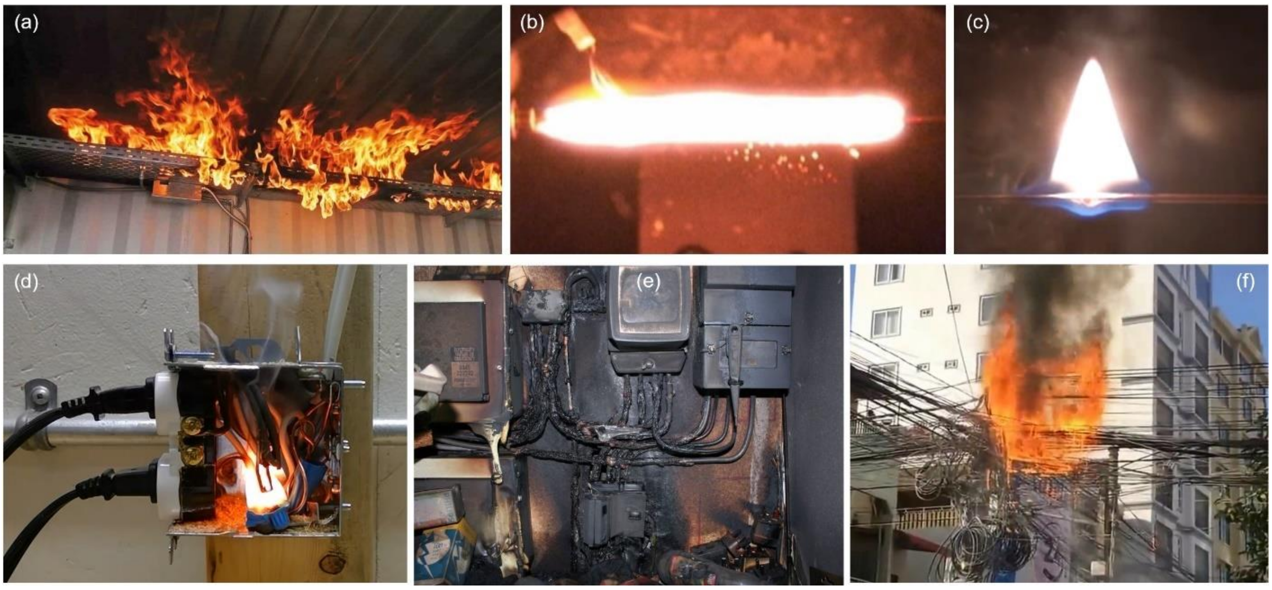

Figure 1. Typical wire fire accidents (a) in a ceiling wire tray [59], (b) overload ignition in microgravity [18], (c) flame spread over a thin laboratory wire [60], (d) fire starts at the wiring connection [61], (e) fire damage caused by loose wiring connection [62], and (f) in tangled wires above the street [63].

The purpose of the present review article is two-folder, firstly, to systematically develop the fundamental physics behind the wire fire phenomena for both scientific studies and engineering applications, and secondly, to review the literature of current works and approaches for future research on this subject. Throughout this review, attention is focussed on the understanding of ignition, flame spread, extinction in wire fire with given information on wire configurations (e.g. the dimension, orientation, and material) and environmental conditions (e.g. airflow, oxygen concentration, and pressure), thus eliminating at this stage any complications in large-scale fires of commercial cables. The review of fundamental combustion phenomena in the fire of *ideal laboratory wires* (or *research wires*) will help understand more complex fire phenomena in commercial cables and the corresponding fire hazards, but no attempt is made directly towards providing industrial guidelines to "fire-safety" wires and cables.

2. Wire fire dynamics

For transmitting power of a voltage of 10 kV or higher, wires are non-flammable because no insulation is used. The low-voltage commercial cables often include multiple wires and several layers of insulation, metallic shield, and jackets (**Figure 2**a). Ideally, the simplest wire sample can be manually assembled by mating a single layer of the plastic tube and a metal core, which fits the research purpose of controlling parameter. As illustrated in **Figure 2**b, the wire has a diameter of d_o, a core diameter of d_c, and an insulation thickness of $\delta_p = (d_o - d_c)/2$. Despite the simple structure, these laboratory wires still manifest very complicated fire behaviors. Thus, only the qualitative analysis is provided in this review to help understand wire fire phenomena. In this section, we focus on the effect of the core on fire of the simplest wire samples under normal environmental conditions.

To evaluate the absolute thermal effect of the core, we may first introduce the parameter of thermal conductance (G_c) to includes the effect of core size (d_c) and thermal conductivity (λ_c)

$$G_c = \lambda_c A_c = \lambda_c \frac{\pi}{4} d_c^2 \tag{1a}$$

By considering the thermal conductance of insulation (G_p), the relative contribution of conductive heat transfer along the wire axis ($\bar{G}$) can be expressed as

$$\bar{G}_c = \frac{G_c}{G_c + G_p} = \frac{\lambda_c d_c^2}{\lambda_c d_c^2 + \lambda_p \left(d_0^2 - d_c^2\right)} \tag{1b}$$

Table 1 lists the thermal properties of the common metals for wire core and polymers for wire insulation. For wire with a Cu core of 5 mm and PE insulation layer of 3 mm, it can be calculated that $\bar{G} = 99.9\%$, and even using a low conductivity nickel-chromium (NiCr) core, $\bar{G} = 96.9\%$. Apparently, the heat transfer through the core is dominant in the axial direction. On the other hand, to evaluate the difficulty of heating, the thermal inertia ($\rho c k$) [64] of each wire component should be considered,

$$TI = \rho c \lambda \tag{1c}$$

which is thermally thick along the axial direction of wire. As shown in **Table 1**, the thermal inertia of metal core material is about $10^2 - 10^3$ times greater than the polymer insulations.

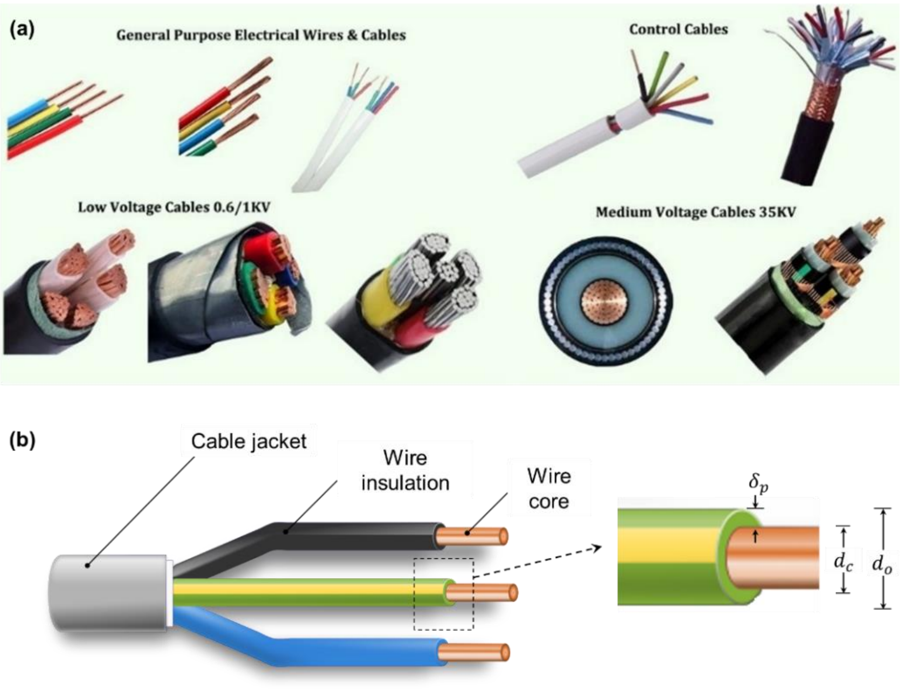

Figure 2. (a) Typical electrical wire and cables (http://todayview.co/ideas/), and (b) characteristics of a basic wire.

Table 1. Physicochemical properties of common polymer insulations and core metals [65, 66] where thermal properties are evaluated near the room temperature, and ΔH > 0 represents endothermic [20].

	ρ (kg/m^3)	λ (W/m/K)	c (kJ/kg/K)	$\rho c\lambda$ (kJ^2/m^4-K^2-s)	T_m (°C)	ΔH_m (MJ/kg)	T_{py} [66] (°C)	ΔH_{py} (MJ/kg)
PVC	1200	0.19	1.37	0.31	100 - 260	0.03	270	1.7
PE	927	0.23	1.55	0.33	105 - 110	0.50	387	1.8
Cu	8954	398	0.400	1425	1085	-	-	-
Al	2700	204	0.9	496	660	-	-	-
SS	8000	13.8	0.384	42	1400	-	-	-
NiCr	8400	11.3	0.45	43	1400	-	-	-
air	1.18	0.026	1.07	3×10^{-5}	-	-	-	-

Because of the electrical current (I), the wire core will be heated by the Joule heat as

$$\dot{q}'_J = I^2 R_e \tag{2}$$

where R_e is the electrical resistance of core per unit length. The contribution of Joule heat, in general, is small under the normal operation, but it becomes significant in the events of a short circuit (large I) and poor contact (large R_e). In addition, when the high-frequency AC current flows through the core, it may interact with the ions from the flame [37, 45].

The wire is a typical cylindrical fuel. Compared to the flat fuel, the convective heat transfer is enhanced around the cylindrical fuel [67, 68], which is stronger for a smaller wire diameter (i.e., thin wires) as

$$h \propto \frac{1}{d_o^n} \qquad (n>0) \tag{3}$$

The enhanced convection is two-folder, i.e., both the convective heating from the flame or the hot plume and the convective cooling from the environment will be enhanced [11, 16, 69–74]. Such a curvature effect is particularly strong for diameter below 5 mm, while becoming weak if the diameter of the cylinder is larger than 2 cm [8, 70].

2.1. Ignition

Like most of the polymer fuels, the piloted or spontaneous ignition occurs on the electrical wire, once it is heated by the external heat source [75, 76]. Nevertheless, the ignition of an electrical wire has two unique features:

I. the metal core produces the Joule heat, which heats the insulation and may even directly lead to an ignition during the event of the short circuit [18, 30], and

II. the metal core changes the heat transfer process, if the wire is exposed to an external heat source from the environment or an internal heating from the core [31].

Figure 3 illustrates three basic heating protocols relating to the ignition of electrical wire,

(a) the convective or radiant heating from the external source such as the flame or the hot smoke,
(b) the local heating from the core to insulation, if core is directly heated by the flame or by the Joule heating at the poor connection point, and
(c) internal heating from core due to the Joule heat during the short circuit or overload.

For the heating protocol (a), the core acts as the *heat sink* because of its large thermal inertia ($\rho c\lambda$ [64]) and the cooling effect along the longitude direction [31]. On the other hand, for the heating protocols (b) and (c), the core acts as a *heat source* to assist the heating of insulation. In reality, the wire could be heated under all three heating protocols at the same time [50], and the heating process could be transient.

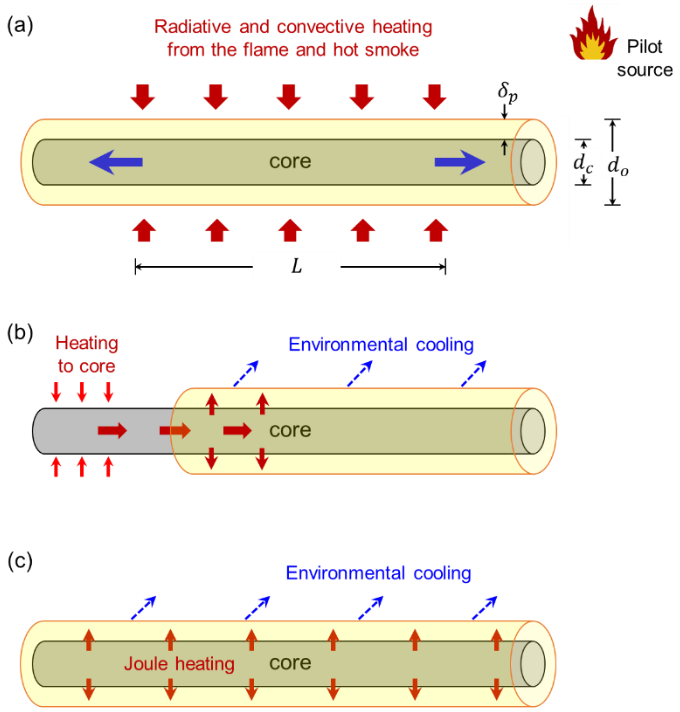

Figure 3. The schematic diagram for the ignition of wire under (a) the external heating, (b) the end heating from the core to insulation, and (b) the Joule heating during a short circuit.

Because the metal core usually has high thermal conductivity, its temperature tends to be uniform across the cross-section. The thickness of polymer insulation is relatively thin (usually less than 5 mm), so the heat transfer in the radial direction may also be ignored. Then, if we further ignore the non-uniform heating in the angular direction, the temperature profile of insulation (T_p) and core (T_c) during the ignition process could be solved by

$$\rho_p c_p A_p \frac{\partial T_p}{\partial t} = \lambda_p A_p \frac{\partial T_p^2}{\partial x^2} + P_p \dot{q}''_{e,net} + \dot{q}'_{cp} \tag{4a}$$

$$\rho_c c_c A_c \frac{\partial T_c}{\partial t} = \lambda_c A_c \frac{\partial T_c^2}{\partial x^2} + I^2 R_e - \dot{q}'_{cp} \tag{4b}$$

where x is along the wire axis; subscript p and c represent the polymer insulation and metallic core, respectively; ρ, c, A, P, and λ are the density, specific heat, cross-section area, perimeter, and thermal conductivity, respectively.

The Joule heating is represented by $I^2 R_e$. The net heat transfer between wire insulation and environment, $\dot{q}''_{e,net} = h(T_p - T_a)$, could be either heating or cooling depends on the local environmental temperature (T_a). The heat transfer between insulation and core, $\dot{q}''_{cp}$, could be estimated as

$$\dot{q}''_{cp} = \lambda_p \frac{T_c - T_p}{d_c \ln(d_o/d_c)} \tag{5}$$

If the wire is thin and the heating rate is low, a uniform cross-section temperature could be assumed (i.e., $T \approx T_c \approx T_p$). Note that for many wires and cables, the thickness of insulation is comparable to diameter of core, so that simplifying the heat conduction as $\dot{q}''_{cp} = \lambda_p (T_c - T_p)/\delta_p$ can leads a large error.

The boundary conditions of Eq. (4) change with the heating scenarios illustrated in **Figure 3**. Once the wire insulation is heated above its pyrolysis point (T_{py}), the released pyrolysis gases start to mix with the air. As a flammable mixture is produced, ignition can occur spontaneously or be piloted [76] by a nearby flame and glowing hot spots which occur in the locations of short circuit and poor contact. These gas-phase processes are particularly important in the short-term overload ignition.

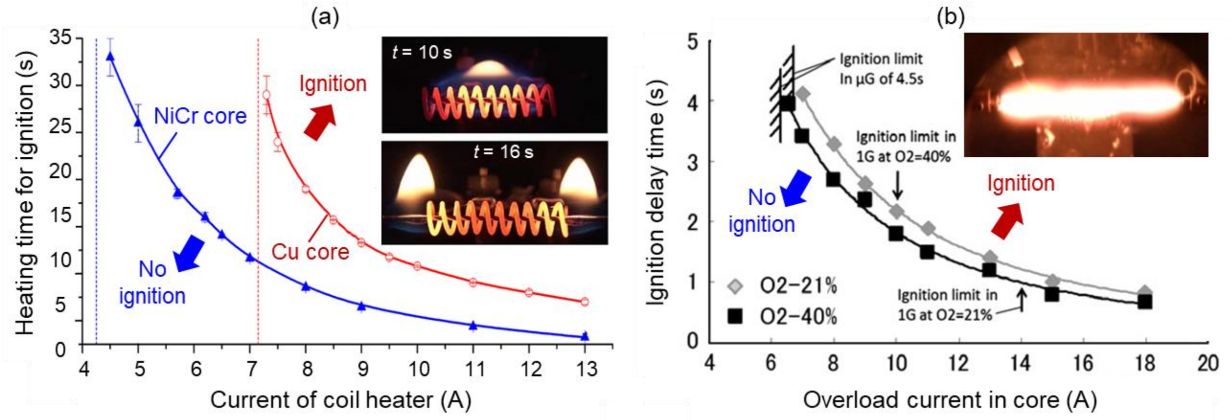

Figure 4. Ignition delay time of (a) by a local heating coil for 1-mm PE wires with NiCr and Cu cores [31], and (b) by the overload current under microgravity [30].

2.1.1 Ignition by external heating

Because of the enhanced convective cooling, Eq. (3), it may be difficult to heat a thin wire (~1 mm) up to the pyrolysis point by the external radiation alone. On the other hand, because of the enhanced convective heating, the ignition of thin wire by the flame or hot gas becomes easier. If the external heating is local with a length of L (**Figure 3**a), the overall heating should overcome conductive cooling from core [31, 41] as

$$\dot{q}'' \ge \frac{P_o}{L}\left(T_{py}-T_a\right)\sqrt{h\lambda_c d_o} \qquad (6)$$

where $\dot{q}''$ is the net heat flux from the environment under the heating protocol (a) or the core under the heating protocol (b). **Figure 4**(a) shows an example of the ignition delay time changing with the current of a local hot coil, where the hot coil acts as both heating and pilot source. Because the core acts as a *heat sink*, the ignition delay is longer for Cu-core wire than that for NiCr-core wire.

If the external heating is global ($P_o/L \to 0$), the delay time of piloted ignition can be estimated by a simple equation for the thermally-thin material [76] as

$$t_{ig} \approx t_{py} = \frac{\left(\rho_p c_p A_p + \rho_c c_c A_c\right)\left(T_{py}-T_\infty\right)}{\dot{q}''_{e,net}} \qquad (7a)$$

where the core acts as the *heat sink* due to its larger thermal inertia. With a pilot source, the gas-phase mixing and chemical processes may be ignored, and then, ignition will occur, once the insulation reaches the pyrolysis point. It is apparent that the ignition delay time decreases as the overall heating flux is increased. Other parameters such as the oxygen level, pressure and gravity could change also affect the ignition delay time [31].

On the other hand, the ignition will not occur, if the external heating is not strong enough to bring the insulation to its pyrolysis point, or if there is no pilot source. Moreover, if the heating rate is slow, the polymer insulation could melt, drip, or flow away from the core before reaching the pyrolysis temperature. Due to the removal of fuel, ignition will not occur either [31].

2.1.2 Overload ignition

In the fault of a short circuit, the overload current can generate a significant amount of Joule heat to ignite the electric wire within a few seconds. The unique ignition process under the heating protocol (c) has been extensively studied in [18, 22, 30, 34, 35]. During the short circuit, the Joule heating is almost uniform along the wire axis ($\partial T/\partial x \to 0$). The core is quickly heated by the current, showing a glowing red. Meanwhile, the core also quickly heats the insulation layer and produces pyrolysis gases at the interface between insulation and core. These local high-pressure pyrolysis gases quickly penetrate the molten insulation either in a bubbling process, which was observed for PE insulation [17], or through a bursting jet, which was observed for FEP insulation [35]. During a short gas-phase time (t_g), hot pyrolysis gases will mix with air and go through exothermic oxidation, and eventually, lead to a gas-phase thermal explosion, i.e., ignition.

The delay time of such a quick ignition process can be estimated as

$$t_{ig} = \frac{\left(\rho_p c_p A_p + \rho_c c_c A_c\right)\left(T_{ig} - T_\infty\right)}{I^2 R_e - \dot{q}_e''} + t_g \tag{7b}$$

where a uniform temperature is assumed for the entire wire. Under a fixed overload current, a thin wire is easier to ignite, because of larger electrical resistance and smaller thermal inertia. For such a short ignition event (~1 s), the pyrolysis (or heating) time could be comparable to the mixing and chemical time in the gas phase [76]. The overload ignition event is also short enough to be tested in the drop tower that helps understand the ignition behavior under microgravity for the application of spacecraft fire safety.

As expected, the ignition delay time increases as the overload current is decreased, and **Figure 4**(b) shows the example measurements in the microgravity drop tower [30]. Continuously decreasing the current, eventually the insulation could be melted and pyrolyzed without ignition. Note that this equation can only give a qualitative comparison with the experiment [77]. Because of the complexity of real ignition phenomena, even if the detailed 1-D heat transfer and gas-phase processes are modeled, the prediction is qualitative in nature [22].

2.1.3 Ignition sustainability

Under the heating protocol (a), the ignition source could be local or not strong enough. Then, even if flaming ignition occurs, the ignition may not be sustained to stabilize a flame spread due to the cooling of the core. To ensure the transition from ignition to flame spread, additional external heating may be required, because core acts as a *heat sink* to cool down the ignition zone and quench the weak flame [31]. Under the heating protocol (b), if the distance between the hot spot and insulation is large, the heating becomes weak, as modeled in [78]. As observed from the experiment [24], the insulation could be pulled away from where the core is hot by the Marangoni surface tension force [79, 80], so it becomes difficult to sustain the ignition due to the fuel removal. More studies are needed to understand the transition between ignition and flame spread.

In short, the ignition of a wire is complicated by different roles of the core under different heating protocols. For a commercial wire or cable, the ignition behavior is more complex, because of the multiple layers of insulation and sheath as well as their various material properties. For example, County and Garo [55] studied the external heating for a multi-layer commercial cable and found that the piloted ignition delay time and external heat flux follows $\left(t_{ig}\right)^{-1/2} \propto \dot{q}_e''$. Gong *et al.* [52] found that under external heating, the outer polyvinyl chloride (PVC) sheath layer would char and smolder, and these smoldering hot spot acted as a pilot source to ignite the pyrolysis gases released from inner PE insulation layer.

2.2. Flame Spread

Evaluation of the fire hazard of wire requires the determination of the flame spread rate. Compared to flame spread on a polymer, the existing of the metal core makes the fire spread behaviors over wires more complex. The core not only changes the heat transfer process but also modifies the flow of molten insulation. Moreover, because the wire is a typical cylindrical fuel, its flame-spread process shows a clear difference from the flat fuel. In terms of the flame configuration, the flame tends to surround the entire surface of wire, rather than attach to top side like the flat fuel. Except for in microgravity and around a vertical wire, the shape of flame around the wire is asymmetric. Compared to the flat fuel, the enhanced convective heating from the flame could be important, particularly for thin wires, as indicated by Eq. (3).

Despite that the flame spread on the wire has more complex fire phenomena and heat-transfer processes, some researchers have attempted to apply qualitative heat transfer equations to calculate the rate of flame spread, and then compare with experimental results quantitatively. Unfortunately, such an analytical approach is not only questionable by nature, but also requires the tuning of parameters and additional measurements from experiments. In fact, for the simplest flame spread over a PMMA plate, the state-of-art fire model is not able to give a prediction on the rate of flame spread that is comparable to the experiment.

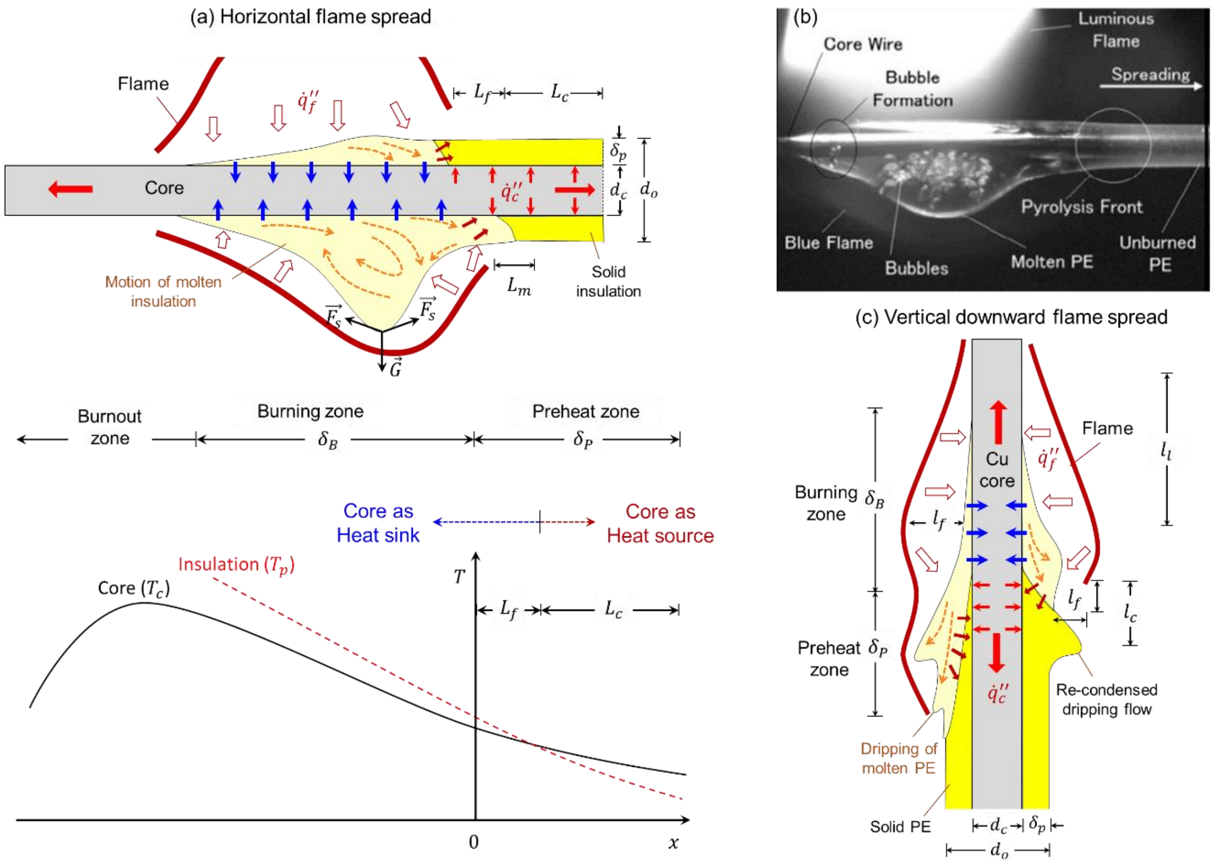

Figure 5. The schematic diagram for (a) the flame spread over the horizontal wire, together with the photo (b) [19], and (c) the vertical downward flame spread [23].

In this review, only the qualitative analysis is provided to help readers understand the unique fire spread behaviors in the wire. The flame spread on an electrical wire shares the same nature with other flame spread phenomena, and it can be viewed as the continuous ignition of polymer insulation in the fire inception [77, 81]. As illustrated in **Figure 5**, we define $x = 0$ at the flame leading edge and allow the coordinate to move with the flame. Then, the *preheat zone* locates at $x > 0$, and the *burning zone* locates at $-W < x < 0$, where the flame width is W. After flame spreads over, ideally no fuel is left on the core, defined as the *burnout zone* ($x < -W$). In the burnout region, the core is directly heated by the hot flame, so it reaches its peak temperature. If the flame is very strong like in high oxygen concentration, the thin wire core may break during the flame spread [31].

Choosing the preheating zone ($x > 0$) as the control volume, the classical qualitative expression for the rate of flame spread may be adopted

$$V_f \approx \frac{\dot{q}''L}{\rho_p \delta_p c_p \left(T_{py} - T_a\right)} \qquad \text{(Thin insulation)} \qquad (8a)$$

$$V_f \approx \frac{\dot{q}''^2 L}{\rho_p \lambda_p c_p \left(T_{py} - T_a\right)^2} \qquad \text{(Thick insulation)} \qquad (8b)$$

where $\dot{q}''$ is the total heat flux from the burning zone to the polymer insulation in the preheat zone; L is the effective heating length; ρ_p, c_p, λ_p and δ_p are the density, specific heat (including heat of melting), thermal conductivity, and characteristic thickness of the polymer insulation, respectively. Clearly, the flame spread rate will increases as the heating effect is increased, pyrolysis temperature is decreased, and the ambient temperature is increased [15]. For wires of thin insulation (< 2 mm), flame spread increases with the decreasing thickness of insulation [8, 9],

Despite the preheat zone is chosen as the control volume, the heating that drives the flame spread ($\dot{q}''L$) comes from the burning zone upstream. Specifically, there could be three major components from

(1) the flame in the gas phase ($\dot{q}_f'' L_f$, convection and radiation),

(2) the metallic core in the solid phase ($\dot{q}_c'' L_c$, conduction), including the Joule heating if there is current,

(3) the molten insulation in the liquid phase ($\dot{q}_m'' L_m$, Marangoni convection).

The effective heat flux ($\dot{q}''$) and heating length (L) of each heating component varies with the wire configurations (material, orientation, size, etc.) and environmental conditions (pressure, gravity, airflow, etc.). The effect of Joule heating on the flame spread is, in general, small unless the overload current is applied [36, 50]. Note that none of three heating components is constant, but all vary in the axial and angular direction of the wire. In general, all heating components become smaller as moving away from the flame. Therefore, a quantitative evaluation of each heating component is not possible with this simple analytical equation, but it requires a detailed numerical model including the finite chemistry and phase-change behaviors.

2.2.1 *Opposed flame spread*

On Earth, the fires are generally driven by natural convection, and if there is wind, the mixed convection controls. Depending on the airflow direction, the flame spread can be categorized into the opposed-flow and concurrent-flow spreads [76]. For the horizontal flame spread, it behaves close to the opposed flame spread. For the opposed-flow flame spread, the effective heating length from the flame is small ($L_f \sim$ O(1) mm) and decreases with the airflow speed as

$$L_f \sim \frac{\alpha}{U} \tag{9}$$

where α is the gas diffusivity, and U_a is the velocity of opposed flow or buoyancy flow if buoyancy is dominant. Experiments have shown that gas-phase temperature quickly decreased below 400 °C within in 3 mm ahead of the flame leading edge, while in microgravity the heating length could be above 10 mm [16].

Within the flame heating length ($0 < x < L_f$), the flame directly heats the insulation to a temperature higher than the core temperature, so the core acts as a *heat sink*. At $x > L_f$, the temperature profile of core is higher than that of insulation, so the core acts as a *heat source*. Thus, even within the preheat zone, the core can act either as the heat sink or heat source at a different location. Such temperature profiles of core and insulation in the preheat zone have been measured in [8, 21, 23], and an example is shown in **Figure 6**. We can estimate that the flame heating length is on the order of 1 mm where $T_p > T_c$, and it becomes smaller under a larger opposed airflow, agreeing with the prediction of Eq. (9). Because of the large core thermal conductance, the heating length of the core (L_c) is larger and can be on the order of 1 cm.

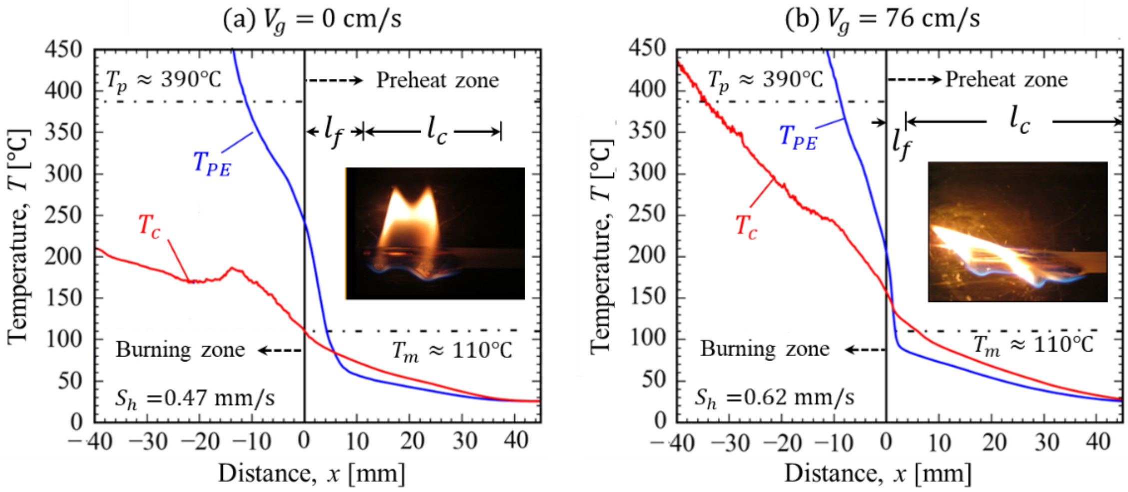

Figure 6. The temperature profile of copper core and LDPE insulation (horizontal wire) under the opposed airflow of (a) 0 cm/s, and (b) 76 cm/s where the wire diameter is 9 mm and the core diameter is 5.5 mm [23].

Note that even if the heating length of the core is larger, its overall heating contribution to flame spread is not necessarily dominant, because the flame heat flux could be larger ($\dot{q}''_f > \dot{q}''_c$). Bakhman *et al.* [8] showed that for a horizontal wire of 0.5-mm core and 0.15-mm PE insulation, the rate of flame spread is 2.5 mm/s with the glass thread core while increasing 40% to 3.5 mm/s with the Cu core. Apparently, the 40% increment in the spread rate comes from Cu core heating. Such increment in flame spread becomes only 10~20% if replacing the Cu core to the iron core [29] or increasing the wire diameter to 10 times larger [21].

In the preheat zone, the polymer insulation reaches its melting point as heated by the flame and core, but it has very little mobility. In the burning zone, the polymer insulation is heated by the strong heat flux from the flame, its temperature quickly increases (see **Figure 6**). Note that in the burning zone, the polymer temperature does not stay on its pyrolysis temperature, but continuously increases during the pyrolysis process until burnout. The thermogravimetric analysis (TGA) shows that strong pyrolysis takes place from 380 ℃ to 500 ℃ for PE, and from 170 ℃ to 750 ℃ for PVC [52]. Because both the viscosity and surface tension of melts decrease significantly as the temperature is increased [82], the molten insulation has good mobility within the burning zone surrounded by the flame. Thus, there is a clear circulation flow inside the molten polymer (see **Figure** 5a-b) [45] and the dripping of melts (discussed more in Section 2.4). Therefore, there is also strong convective heating from the hot liquid polymer in the burning zone to solid polymer in the preheat zone. As the size of the molten layer is very smaller or comparable to the wire diameter, the natural convection is small ($Gr \sim L^3$). On the other hand, the temperature gradient within the small burning zone is large, so that the Marangoni convection should dominate the liquid circulation and heating. So far, the contribution of this liquid-phase convective heating component is still unclear, and their effective heating flux ($\dot{q}''_m$) and heating length (L_m) has not been quantified.

The *downward flame spread* is a special case of the opposed-flow flame spread (**Figure** 5b), where the uprising airflow is caused by the buoyancy. If the molten insulation has high mobility, driven by gravity, the hot molten insulation will tend to flow downward along with vertical wire and beyond the leading edge of the flame. Such a hot dripping flow results in strong heating from the liquid phase ($\dot{q}''_m L_m$) to the preheat zone. It has been found that such heating from the melting flow is the dominant heating component that controls the rate of downward spread [21, 23]. Therefore, if a stronger downward dripping flow is generated from the burning zone, the rate of downward spread becomes faster [83]. For a core of larger thermal conductance, it will cool and resist the molten insulation in both the burning zone and the preheat zone. In other words, the core acts as a *heat sink* to slow down the flame spread. Moreover, there is positive feedback between the intensity of dripping flow and the size of the fire, so the downward flame spread will continuously accelerate rather than reach a steady state.

2.2.2 Concurrent flame spread

For the concurrent-flow (forward) flame spread, the direction of flame-spread and airflow collides with each other. The most common example is the upward flame spread driven by uprising buoyancy flow (**Figure** 7a). Then, the flame length defines the preheat zone. Because the insulation is directly heated by the hot flame, its temperature remains higher than the core temperature. Therefore, the core acts as the *heat sink* in the concurrent flame spread, different from the *heat source* in the downward flame spread. Lu *et al.* [84] confirmed the *heat-sink* effect of the core in the horizontal wire under a forward wind, and they also found that the *heat-sink* effect increased as the wind velocity and flame length was increased. Tewarson and Khan [11] tested the upward flame spread over 35 commercial electrical cables with copper or aluminum core where the flame spread rate was found to be smaller with a larger core size. Despite that the molten insulation may not burn out within the flame while flowing downward along with the core, its effect on the upward flame spread is negligible, because the direction of molten flow is opposite to that of flame spread.

For thin wires, the rate of concurrent flame spread can reach steady-state [43, 47] like other thin fuels, despite potential downward dripping flows (**Figure** 7a) [42]. Like other thin fuels, the rate of concurrent flame spread increases with the flow speed to a peak value and no longer varies until blow off [23]. For thick wires, the concurrent flame spread may not reach steady-state. Instead, the flame will keep accelerating until the entire wire is ignited. Additionally, if the wire is inclined from the vertical direction, as shown in **Figure** 7(a), the flame spread rate will decrease, mainly because the dominant heating from the flame is reduced. As the wire inclination is increased, the flame heat flux decreases due to the increasing flame stand-off distance or flame detachment, and the flame heating length also decreases. Further inclining the wire towards the horizontal direction, the heating length of flame will decrease, while the increasing heating length of core becomes dominant, so that the effect of the core will change from the *heat sink* to the *heat source*. It is difficult to identify such transition via experiment. The real wire is often not perfectly inclined but bends naturally. It is expected that the effect of the core will change when flame spread in these curved wires. So far, there is no related study in the literature.

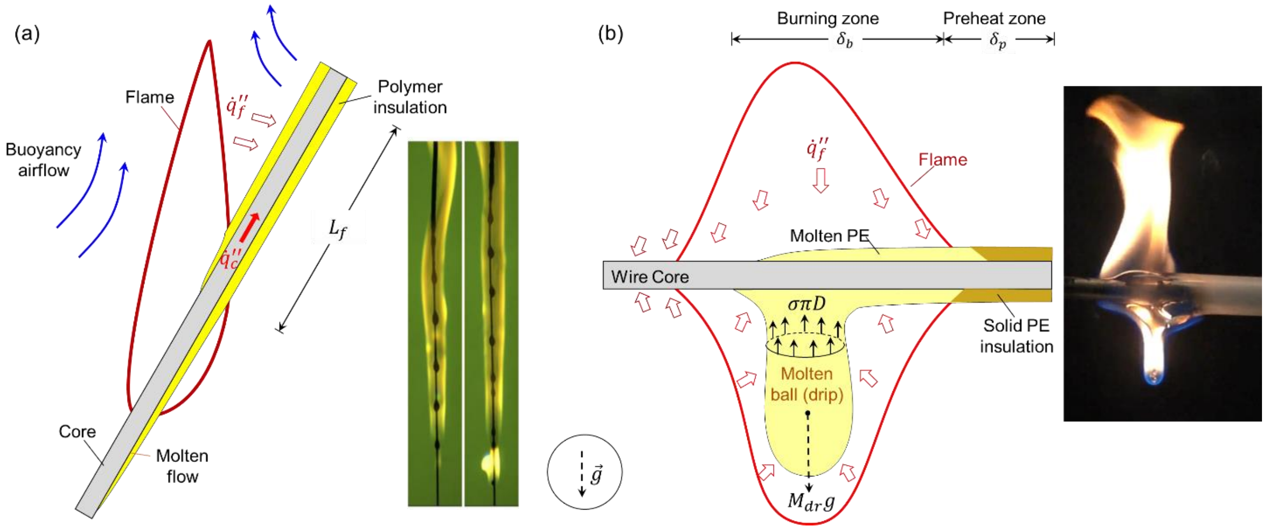

Figure 7. Diagram of (a) upward flame spread over an inclined wire where photos showing the dripping flow are from [42], and (b) the molten ball in the burning zone [56].

If the core thermal conductance is large, such as using a Cu core, a noticeable layer of insulation could be left behind (discussed more in Section 2.3). Huang *et al.* [85] observed two stable flame-spread models on a horizontal wire of 3.5-mm and 5.5-mm core, (1) a strong flame spread without remaining if the ignition is strong, and (2) a weak flame spread with a thick layer of remaining if the ignition is weak. The rates of flame spread for these two models are comparable. Further increasing the diameter of the core and decreasing the thickness of insulation, the flame spread becomes impossible [9], because of the cooling effect of the core (discussed in Section 2.4). Therefore, the role of the core in the flame spread is also not universal, but changes with the mode and scenario of flame spread. In the horizontal flame spread, the core acts as a *heat source* to accelerate the flame spread. In the dripping-controlled downward flame spread, by cooling the dripping flow, the core acts as a *heat sink* to slow down the flame spread. In the concurrent flame spread, the core can also act as a *heat sink* because of the larger thermal inertia.

2.3. Burning

The existence of core also significant changes the burning rate of wire insulation as well as the heat release rate from wire fire. During the flame spreads over a wire, the insulation layer will first melt in the preheat zone, and then, the molten insulation will (1) burn (or pyrolyze) within the flame, (2) drip away from the wire, and (3) remain and re-condense on the core surface. Their mass fraction of each component could be expressed as

$$Y_i = \frac{\dot{m}_i}{\dot{m}_m} = \frac{\dot{m}_i}{\rho_p A_p V_f}, \qquad Y_b + Y_{dr} + Y_r = 1 \tag{10}$$

where subscript *m*, *b*, *dr*, and *r* represents the melting, burning, dripping, and remaining, respectively. The rate of melting in the preheat zone is proportional to the flame spread rate. The burning of insulation contributes to the direct heat release of wire fire. Meanwhile, the flame can also accompany with the dripping and ignite nearby fuels, potentially extending the fire hazard. For wire with a larger core conductance, the cooling effect of the core is strong, so that a large amount of insulation could remain after flame spreads over the wire [85].

The overall burning rate ($\dot{m}_b$) and burning flux ($\dot{m}''_b$) in the wire may be qualitatively estimated [31] as

$$\dot{m}_b = W\left(\pi d_o\right)\dot{m}_b'', \quad \dot{m}_b'' = \frac{h_f}{c_g}\ln\left(1+B\right) \tag{11}$$

where W is the flame width; h_f is the convective heating coefficient of flame; c_g is the specific heat of gas, and B is the mass transfer number. Fundamentally, the value of B quantifies the ratio of the heat source to the heat sink in the burning zone [23] as

$$B = \frac{Y_{O_2}\left(\Delta H_f/\varphi\right)\left(1-\chi_f\right) - c_g\left(T_{py}-T_a\right)}{\Delta H_{py} + \left(\dot{q}_{sr}'' + \dot{q}_{cp}'' + \dot{m}_{dr}'' H_m\right)\big/\dot{m}_b''} \tag{12a}$$

where χ_f is the flame radiative heat loss fraction; Y_{O_2} is the oxygen mass fraction, and ΔH_{py} are the heat of pyrolysis and combustion, respectively; φ is the combustion equivalence ratio; H_m is the enthalpy of the molten insulation; $\dot{q}_{sr}''$ is the fuel surface re-radiation in the burning zone, and $\dot{m}_{dr}''$ is the mass loss flux of dripping.

In the burning zone of wire, the insulation is directly heated by the flame, so it has a higher temperature than the core (see **Figure** 6a). Therefore, the value of $\dot{q}_{cp}''$ is positive, and it indicates the *heat-sink* effect of the core. As seen from Eq. (5), $\dot{q}_{cp}'' > 0$ reduces the local burning flux, and for a core with a higher thermal conductance, $\dot{q}_{cp}''$ is larger. On the other hand, if the core has a larger thermal conductance, the flame width or the size of the burning zone (W) is found to be larger [29]. It is mainly because the core cools the molten insulation and reduces its mobility. As the cooling from the core is increased, the molten insulation would rather stay on the core burning for a longer period than drip away from the core. Such *heat-sink* effect of the core is confirmed by the measurement of mass fractions [23], that is, a smaller dripping fraction (Y_{dr}) and a larger burning fraction (Y_b) for a core with a larger thermal conductance. Therefore, it is possible during flame spread, the wire of a larger core thermal conductance has a small local burning flux ($\dot{m}_b''$), while a large overall burning rate ($\dot{m}_b$).

The dripping phenomenon is not unique to the wire fire, but it has not been well studied in the fire community [10]. It is because of the difficulty in designing controlled experiments and developing the sophisticated numerical model. For the experiment, the major difficulty comes from that the viscosity of thermoplastics has strong temperature dependence, so it is hard to measure its non-uniform temperature distribution within the melts. For the same reason, the molten insulation has the best mobility within the flame, whereas the burning (pyrolysis) process also becomes strongest. One criterion for dripping to occur is that the gravity of the accumulated molten ball exceeds its surface tension force (**Figure** 7b) so that the mass of drip (M_{dr}) or the Bond number (Bo) should satisfy

$$M_{dr}g = \rho_{dr}\left(\frac{\pi}{6}D^3\right)g \ge \sigma_{dr}\left(\pi D\right) \quad \text{or} \quad Bo = \frac{\rho_{dr} g D^2}{\sigma_{dr}} \ge 6 \tag{13}$$

where ρ_{dr}, D, and σ_{dr} are the bulk density, diameter, and surface tension of the droplet or molten ball, respectively.

However, in addition to the heating from the flame, the dripping process in the wire fire is further complicated by the strong cooling from the core. It is found that the mass of the single drip is larger from a larger-conductance core [21]. On the other hand, the mass of a single drip is sensitive to the insulation material, while insensitive to the size and core of the wire, which is in the range of 2~5 mg for PE. Such a phenomenon is not well understood yet. As the wire is inclined from horizontal to vertical, the dripping flow will be formed rather than the detached drip, and control the downward flame spread. Then, the viscosity of molten insulation (μ_m) plays more an important role in the intensity of dripping flow. The dripping phenomena have been studied numerically by a limited number of pioneering studies [86–89], but developing a sophisticated model with three phases and finite chemistry is still quite challenging. More research is desired in order to understand the phase-change processes in wire fire. For example, it is important to rank the key parameters of dripping frequency, the mass of drip, and the dripping fraction to quantify the hazard of dripping.

2.4. Extinction

To sustain fire on the condensed or liquid fuel, the flame should be strong enough to pyrolyze or vaporize the fuel, and the environmental conditions should be suitable to sustain a diffusion flame. If this feedback loop can no longer be sustained, extinction occurs, as illustrated in **Figure 8**. For example, the burnout of fuel will lead to extinction. The detailed extinction mechanism of a diffusion flame has been reviewed in [90, 91]. We will, therefore, only focus on the effect of the core on the extinction of wire fire.

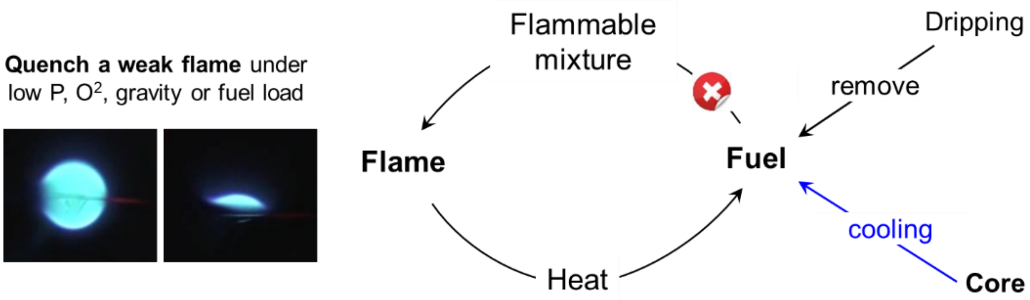

Figure 8. Illustration of the effect of the core on quenching a flame [60].

2.4.1 Quenching

Extinction will take place when the flame is too weak to sustain the pyrolysis reaction in the solid phase. Such a process may be called as quenching [92], while note that it is different from the quenching in a premixed flame. Bakhman *et al.* [9] found that there was a minimum insulation thickness for a flame spread on the thin laboratory wire, i.e., the critical thickness for extinction, and such extinction phenomenon is unique in wire fire. Near the quenching limit, the flame becomes very weak. The similar weak flame is also observed if the pressure, oxygen concentration, and gravity level is decreased. As discussed above, the overall effect of the core in the burning zone is usually cooling. A conclusion may be drawn, that is, when the flame is weak on the wire, the core always acts as a *heat sink* to promote the quenching. In terms of the fire safety, reducing the thickness of insulation can reduce the amount of fuel in wire and even help prevent the flame spread, but it also poses a risk of poor electrical insulation and vulnerability to the environmental weathering. Therefore, the design of fire-safe wire should balance the fire safety and electrical performance.

This quenching behavior may be explained a critical burning flux ($\dot{m}_b''*$) or a critical mass transfer number ($B*$) as

$$B* = \frac{Y_{O_2}\left(\Delta H_f/\phi\right)\left(1-\chi_f\right)-c_g\left(T_p-T_a\right)}{\Delta H_p+\left(\dot{q}_{sr}''+\dot{q}_{cp}''+\dot{m}_{dr}''H_m\right)/\dot{m}_b''*} \tag{12b}$$

As the burning becomes weak and approaches to the critical value, the effect of surface re-radiation ($\dot{q}_{sr}''$) and core cooling ($\dot{q}_{cp}''$) becomes very strong. As seen from Eq. (5), a larger of core thermal conductivity (λ_c) and a thinner insulation (δ_p) result in a larger value of $\dot{q}_{cp}''$. Eventually, the heating from the flame can no longer balance the cooling from the core, so the extinction occurs, and the minimum insulation thickness can be determined.

Near the quenching limit, it has been observed in an experiment that extinction often happens right after a single drip of the molten ball [29, 56]. It is because the dripping behaves as a *heat sink* by suddenly removing the hot fuel from the burning zone [15]. This phenomenon can also be explained by Eq. (12b) where $\dot{m}_{dr}''$ quantifies the dripping flow, and such effect becomes strong when the burning rate is small. The intensity of dripping flow depends on the viscosity and surface tension of insulation materials [20].

2.4.2 Blow off

Because producing sufficient fuel is only the necessary condition, not the sufficient condition to sustain the flame [77, 90], Eq. (12b) cannot explain the role of the core in all extinction phenomena. If the environmental airflow is strong, extinction can also occur even when the flame and burning are strong, and such extinction is often called as the blow-off. The blow-off of a diffusion flame may be explained by a critical Damkohler number ($Da*$) which represents the ratio of the gas-phase residence time (t_r) to chemical reaction time (t_{ch}) [77, 93]

$$Da* = \frac{t_r}{t_{ch}} = \frac{\alpha_g}{U^2} Y_F Y_{O_2} Z \exp\left(-\frac{E}{RT_f}\right) \tag{14}$$

where α_g, ρ_g and U are the diffusivity, density, and flow velocity of airflow, respectively; Y_F and Y_{O_2} are the mass fraction of fuel and oxygen, respectively; R is the universal gas constant; T_f is the flame temperature; Z and E are the pre-exponential factor and activation energy of 1-step global flame chemistry, respectively. As the external flow velocity is increased, the diffusion or residence time decreases to be comparable with the chemical time, so that blow off occurs. Such a critical flow velocity is called the blow-off velocity.

The blow-off mechanism of a diffusion flame attached to a condensed fuel is more complex than that in a gas-burner. It is because the external flow velocity not only changes the characteristic flow time but also changes the feedback between flame and fuel surface [90]. In general, if a larger flame is attached to a larger burning area, it is more difficult to blow off the flame. When the flame is strong, the effect of the core becomes negligible. It has been found that the blow-off velocity is insensitive to the core material when the flame spreads over the horizontal wire under both opposed and concurrent flow [23, 27, 84]. Meanwhile, the blow-off velocity is clearly larger for wire with thicker insulation, for example, it is 150 cm/s for the 2.25-mm thick insulation (**Figure 9**a) [23] and only 40 cm/s for the 0.15-mm thick insulation (**Figure 12**d) [93]. On the other hand, if the flame is weak, e.g., under a low-oxygen ambient, it can be even blown off by the buoyancy flow introduced by itself [94, 95]. As seen from Eq. (12b), when the flame around the wire is weak, the cooling from the core will further reduce the burning flux, reducing the flame spread rate and eventually blow off the flame easier [23, 93].

In addition, the flame can also be blown off by a crossflow. If the flame is attached to a flat fuel, it will be pushed by the crossflow toward the fuel, like a ceiling flame [96]. Comparatively, for the flame attached to the cylindrical wire, it can be blown to the downwind side (**Figure 9**b) and becomes relatively easier to blow off. For a 0.8-mm thick vertical wire, the blown-off velocity under the horizontal wind is found to be 40 cm/s [43], similar to that under the opposed flow [27]. Such critical blow-off velocity increases as the angle (θ) between wind and wire deviate from 90° (vertical) and may be explained using a constant critical strain rate (a^*) [43] as

$$a^* \approx \frac{U^* \sin\theta}{r} \tag{15}$$

where the U^* is the blow-off velocity, and r is the radius of the wire. For a 0.8-mm thick wire, $a^* \approx 536$ s^{-1} is found. So far, the dependence of this critical blow-off strain rate on the wire size and material is still unclear.

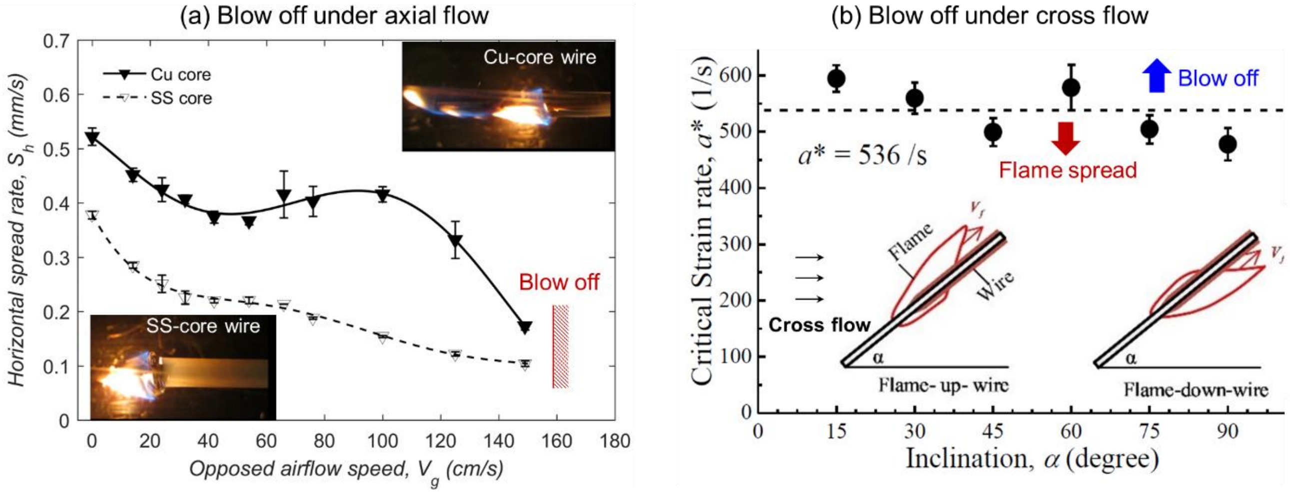

Figure 9. (a) flame spread rate and blow-off limit under axial airflow [23], and (b) critical strain rate for blowing off the flame over an inclined wire under cross flow [43].

2.5. Derived wire fire hazards

The existence of the metallic core and electrical current can result in some unique fire hazards that are derived from or coupled with the wire fire. For example, arcing, hot particle shower, dripping (**Figure 10**), and even explosion, can be generated from or with wire fires. When the insulation is burning in the fire, the electrical insulation is no longer guaranteed, and the hot flame may even melt the metal core and break the connections [60]. These broken wires could hang in other electrical devices to triggering another fire or cause electrocution of residence or firefighters. Moreover, arcing [97, 98] and hot particle shower [99] could be generated if the exposed cores touch each other or discharge through the air, as shown in **Figure 10**(a-b). It is also possible the irons from the flame could promote the discharge behaviors and explosion.

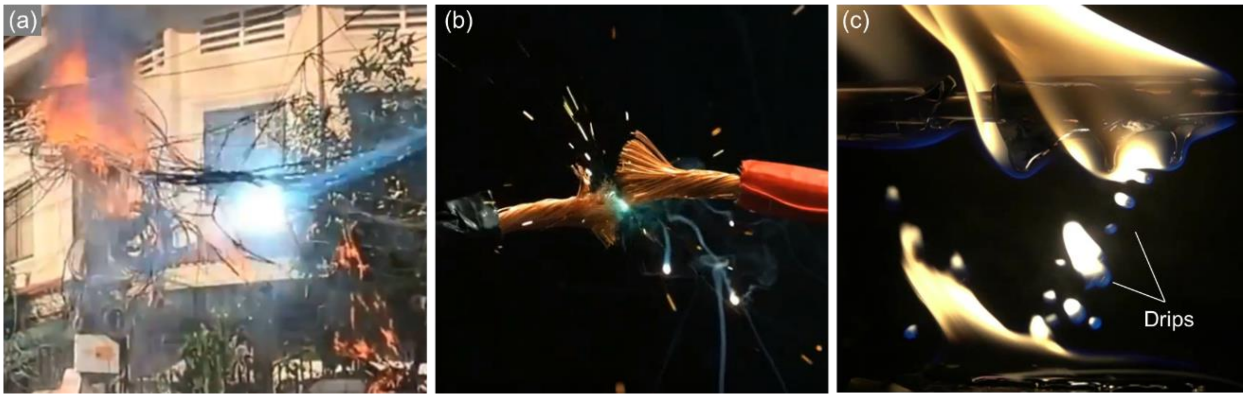

Figure 10. (a) Arcing in the cable fire [63], (b) hot-particle shower from arcing [100], and (c) drips with flame produced from the wire fire [10].

The interaction between flame and high-voltage high-frequency power transmission is still poorly understood. Not only the electrical field can change the size of the flame and molten ball, but the flame can also trigger the arcing because fundamentally the flame sheet is a weak plasma [37, 45, 98]. Additionally, the dripping produced from wire fire could carry a flame to sustain a pool fire below (**Figure 10**c) or ignite other nearby fuels, which can quickly extend the fire hazards [10, 87]. The risk and hazard of wire fire should be thoroughly considered with other derived and coupled hazards, but there is a shortage of related research in the literature.

3. Effect of Material and Environment

The wire fire behaviors will change if the wire material and environmental condition are changed. As reviewed in **Section 2**, the heat transfer through core plays a vital role in the uniqueness of wire fire. Comparatively, the influence of insulation material is not well addressed in the literature. In human's space exploration activities, the environmental conditions, such as the level of gravity, ambient oxygen concentration, and pressure used, differ a lot from the normal condition on Earth, so that the risk and hazard of wire fire have been re-evaluated. Over the last two decades, many studies have aimed to understand how wire fire changes in these different environmental conditions. We will review these works in this section.

3.1. Insulation materials

The insulation layer is the fuel in wire fire, and it is made of various common plastic materials, such as PE, PVC, fluorinated ethylene propylene (FEP), and ethylene-tetrafluorpvco-ethylene (ETFE). Like in many other fire events, if the insulation polymer material has a higher pyrolysis point (T_{py}), or is doped with fire-retardant additives, or can release flame-retard chemicals, it is more difficult to sustain a flame in the wire. Nevertheless, one uniqueness of wire insulation lies in that there is a strong heat transfer between insulation and core. Such a heat transfer process is most important for thin insulation, as well as, the thin region attached to the core if the insulation is thick. Because of the cooling from the core in the burning region, a small layer of insulation could remain, and the mobility of molten insulation will be affected. For the insulation of a larger viscosity and surface tension, the dripping phenomena will be limited, and under the overload ignition, pyrolysis gases between the insulation and core become difficult to penetrate the insulation [35]. The color and transparency of insulation can affect its radiation absorption, and for transparent insulation, the core could also be heated by the transmitted radiation [20]. During the day-to-day usage, the wire insulation could be frequently heated under a low-intensity Joule heat and degrade under the ultraviolet radiation. Such an aging process will alter the flammability of insulation that deserves more detailed investigations [101, 102].

Because the core changes the heat transfer during the ignition process, the smoke emission during the pyrolysis process will also change. The characteristic of smoke emission is important regarding *early fire detection and alarm* because many fire accidents start from the wire or electrical faults. It has been found that the particle concentration in pyrolysis smoke is larger when the core temperature is heated up by a large current [40]. Whether the core affects the emission from the wire flame is still not studied. For charring insulation like PVC and FEP, it could sustain the smoldering combustion [52, 103] and release toxic smokes after the flame spreads over [104]. Unless there is an overload current, the cooling effect of core tends to suppress the smoldering of insulation.

The other uniqueness of wire insulation is that there could be multiple insulation and jacket layers in real wires (**Figure 1**), and the materials used for internal and external insulation and protection layers are often very different. Under external heating, the pyrolysis process and emission of the external layer are dominant. On the other hand, for the Joule heating, the internal insulation attached to the core will be first heated and release pyrolysis gases. However, as confined by the outer layers, these pyrolysis gases generated internally may not be quickly leaked out or leak in a distance away from the heat source, which has the potential to delay the detection of wire fire. Therefore, depending on the heating sources (internal core or external flame), the primary fuel that releases pyrolysis gases (for fire detection) or supports the flame (as the fire load) may be different for wires of multiple insulation layers. To date, the interactions between different wire insulation materials, such as the phase-change process, smoldering, expansion, and breakage [52], are barely touched in the literature, and more works are desired in this area.

3.2. Oxygen Concentration

The standard atmosphere of the Space Shuttle and the International Space Station (ISS) is a mixture of 21% oxygen (O_2) in nitrogen at 101 kPa total pressure. However, control tolerances permit O_2 concentration to rise to higher values. The spacecraft atmosphere is altered to 30% O_2 at a total pressure of 70 kPa to accommodate crew preconditioning prior to extravehicular activities [4]. The potential change of O_2 concentration in a spacecraft environment motivates many fire experiments using laboratory wire tested under various O_2 concentration [16, 20, 23, 25, 31, 56, 93, 105].

As the O_2 concentration is increased, the pyrolysis temperature of some polymer insulations like PE and PVC will significantly decrease because of faster oxidative pyrolysis [52, 106], and the flame temperature and heat flux increase because of fast oxidation chemistry in the gas phase. Therefore, under a higher O_2 concentration, smaller energy is required to heat the wire insulation upon the pyrolysis point and release a smaller amount of pyrolysis gas. Such a phenomenon has been observed for ignition under both the overload current [18] and the external heating [31] (see **Figure 11**). If the O_2 concentration is very small, ignition will not occur as the gas-phase chemistry is too weak to sustain a flame, defining the limiting O_2 concentration (LOC).

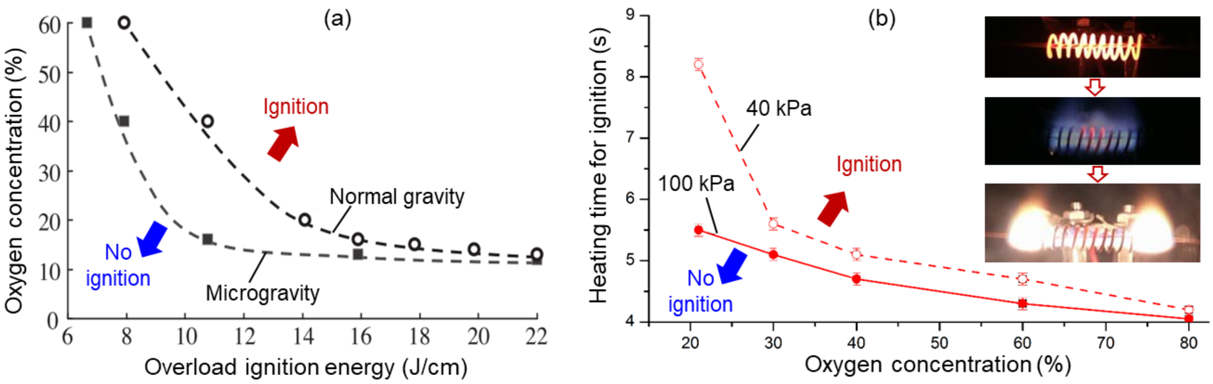

Figure 11. Effect of oxygen on the ignition of wire, (a) the minimum ignition energy in overload heating [18], and (b) the minimum heating time by a hot coil [31, 60].

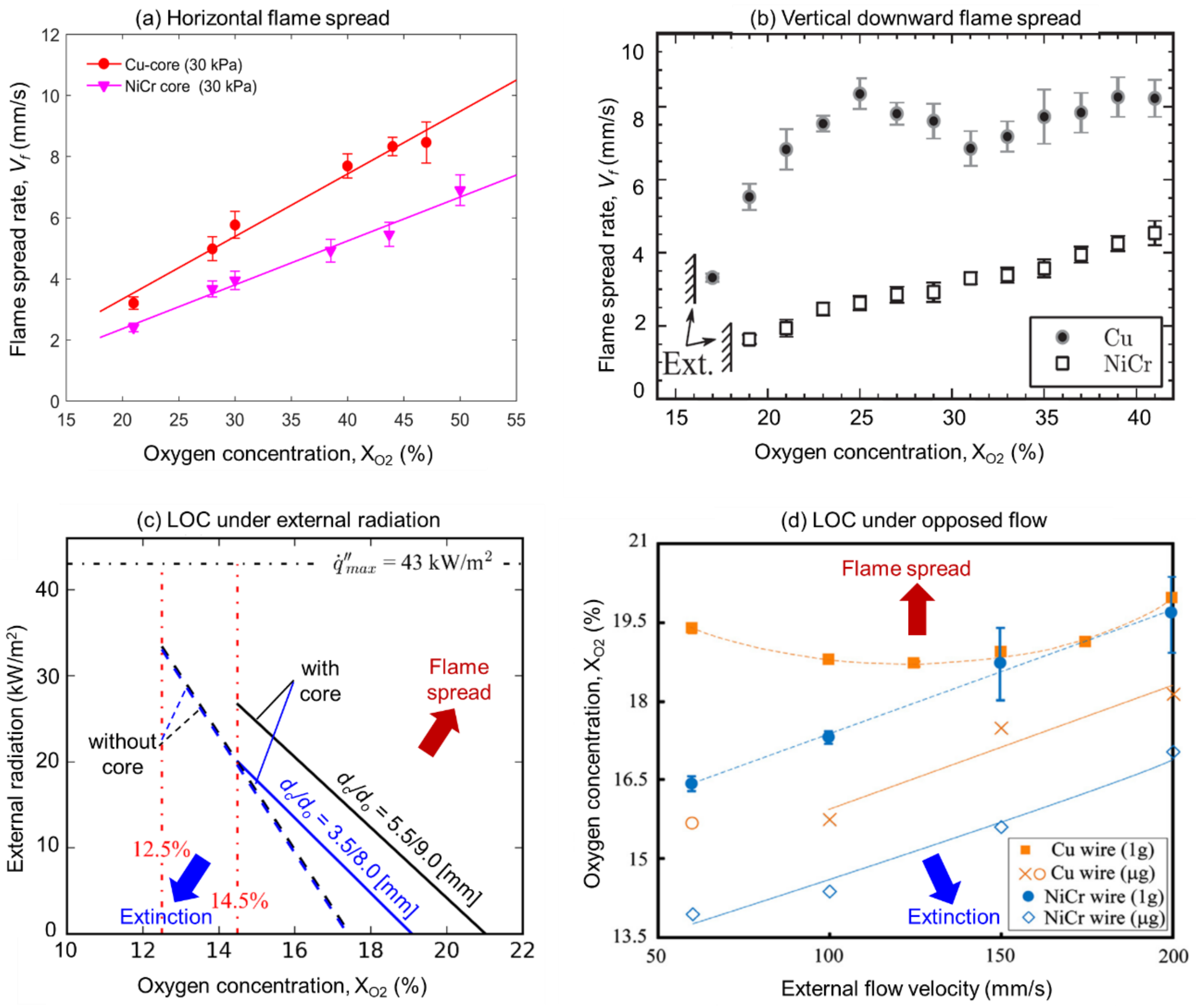

Figure 12. Rate of flame spread as a function of oxygen concentration, (a) over a horizontal thin wire [56], and (b) downward spread over a vertical thin wire [107]; limiting oxygen concentration (LOC) as a function of (c) external radiation [20], and (d) the opposed flow velocity [93].

In general, the rate of flame spread increases with O_2 concentration because of the enhanced flaming heat flux. For wire fire, such acceleration in the flame spread is further increased, because the core transfers the additional heat from the burning zone to the preheat zone. **Figure 12**(a) shows that the horizontal flame spread rate on wire increases with the O_2 concentration, and the rate of increase (i.e. the slope) is greater in a Cu-core wire than in a NiCr-core wire. Thus, in terms of the flame spread rate, increasing the O_2 concentration can increase the fire hazard of wire more than other fuels. Recently, Konno et al. [107] also observed that the rate of downward flame spread decreased with the increasing O_2 concentration in the range of 25-30%, as shown in **Figure 12**(b). This is because the reduced flame length led to a weaker core heating ($\dot{q}_c''L_c$ in **Figure 5**), and such special phenomenon also highlighted the influence of wire core. On the other hand, the limiting O_2 concentration (LOC) for flame spread under other same environmental conditions is greater for wire with a high conductance core (**Figure 12**c-d). It is because the core always acts as a *heat sink* near the quenching limit. Thus, the fire risk of wire is also smaller in an ambient of low O_2 concentration.

3.3. Ambient Pressure

Besides the spacecraft environment, the ambient of reduced pressure also occurs in the aircraft and high latitude. Fundamentally, the gas diffusivity increases with the decreasing pressure,

$$\alpha = \frac{k}{\rho c} \propto \frac{1}{P}, \quad \nu = \frac{\mu}{\rho} \propto \frac{1}{P} \tag{16}$$

Thus, reducing the pressure mainly slows down the convection and mixing processes between fuel and air. Such pressure effect is indicated by a smaller Grashof number (*Gr*) and a larger mixing length and mixing time (t_{mix})

$$Gr \propto \frac{1}{\nu^2} \propto P^2, \quad L_g \sim \frac{\alpha}{U} \propto \frac{1}{P}, \qquad t_{mix} \propto \frac{\alpha}{U^2} \propto \frac{1}{P} \tag{17}$$

Therefore, reducing the ambient pressure has a similar role as reducing gravity level, and sometimes, can be used to simulate the microgravity environment on earth [27]. The overall influence of ambient pressure on the wire is much weaker than the O_2 concentration [15, 31]. Thus, from the viewpoint of fire-safety, a lower O_2 concentration at a higher total pressure is preferable.

For the short-term overload ignition (Eq. 7b), the weakened convective cooling reduced the pyrolysis time, while the mixing time is increased. As derived from the microgravity experiment [30], the reduction in pyrolysis time should be dominant, and there may be smaller ignition energy in lower pressure, which need to be confirmed by future experiments. For the ignition by an external heat source in lower pressure, despite that the wire is easier to heat up under a lower convective cooling, the actual ignition process may become more difficult. It is mainly because the convective heating from these heat sources such as flame and coil also becomes weak [31, 46], and ignition becomes impossible below a critical pressure.

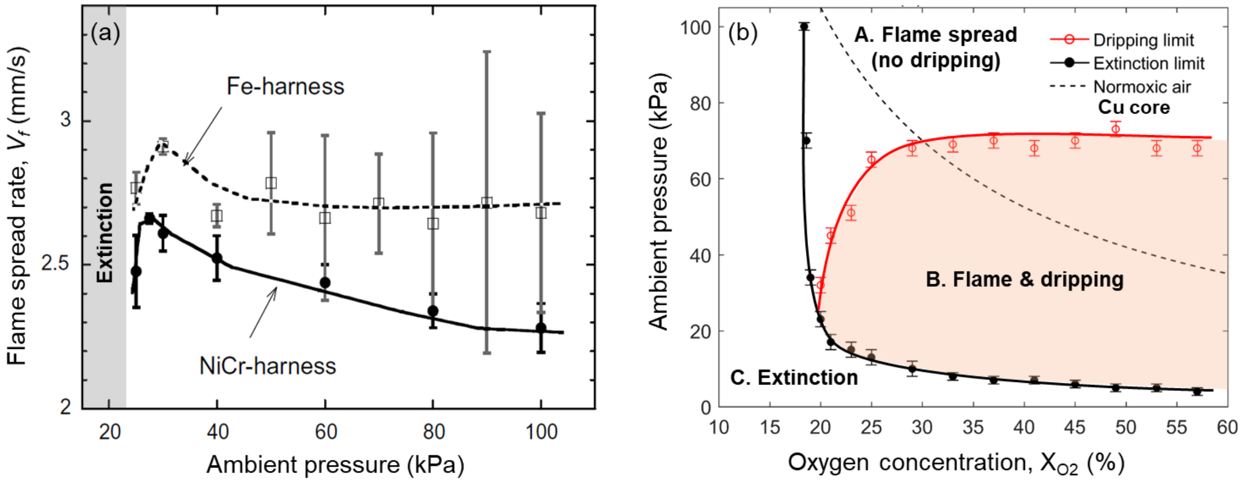

Figure 13. (a) The flame spread rate on a horizontal wire with different core materials as a function of the ambient pressure [29], and (b) limiting condition for dripping and flame spread varying with the pressure and oxygen level [56].

In general, the flame becomes weaker in lower ambient pressure. Thus, for most fuels [108–110], the flame spread rate decreases as the pressure is decreased, and eventually, the flame cannot be sustained in very low pressure (< 5 kPa). For a thin Cu-core wire, the rate of opposed flame spread is also found to increase with the pressure [15, 56]. However, Nakamura *et al.* [19, 29] observed that for a thin NiCr-core wire the flame spread increased as the pressure is decreased, as shown in **Figure 13**(a). There are two reasons: (1) the diffusive heating length of flame (L_f) becomes larger [27], and (2) the conductive heating from core becomes smaller as the flame becomes weak in the burning zone. Such a unique trend with pressure disappears if using a core metal of higher thermal conductivity (iron or copper) or in a higher O_2 concentration [29, 56]. Like other fire phenomena [111, 112], the effect of pressure on wire fire behaviors, e.g. flame spread rate, extinction limit, and dripping limit, is much smaller than that of oxygen concentration, as demonstrated in **Figure 13**(b).

3.4. Gravity and airflow

The wire is a potential fire hazard in spacecraft and human's future habitats in Moon, Mars and beyond. Many fire experiments using thin laboratory wires have been conducted in the microgravity because the overload ignition and steady-state flame spread can be achieved within a few seconds that is comparable to the time scale of drop tower (< 10 s) and parabolic flight (< 30 s). Moreover, these laboratory wires also become an exemplary fuel to help understand the fundamental theory of microgravity combustion, fire dynamics of other fuels, and fire suppression technics [15, 113]. Reducing the level of gravity, the buoyancy effect decreases and eventually disappears in the microgravity spacecraft environment [114]. Thus, the airflow and gravity level are closely connected in a way that changing the gravity inevitably alters the airflow pattern, and increasing external airflow tends to suppress the effect of gravity.

In the absence of the convective cooling, the wire becomes easier to heat up. Therefore, in microgravity, smaller ignition energy is required to achieve ignition (see **Figure 11**a). For both the overload ignition (**Figure 14**a) by Joule heating [30] and the pilot ignition by irradiation (**Figure 14**b) [24], the ignition delay time is also shorter in microgravity than in normal gravity under the same heat flux. Nevertheless, the ignition by convective heating, such as the coil heater, can be more difficult [46] because of the weak convective heating.

Without the buoyancy effect, the gas-phase heating length could controlled by the opposed flow, and it becomes very large when the opposed flow is very small. The buoyancy flow of a candle-like flame is around 30 cm/s [95, 113]; the gas-phase heating length in Eq. (9) is about $L_g \sim \alpha/U = \left(3\times10^{-4}\ \mathrm{m^2/s}\right)/\left(0.3\ \mathrm{m/s}\right) = 1\ \mathrm{mm}$. If the opposed flow is 3 cm/s in microgravity, L_g increases ten times to 10 mm [16]. As shown in Eq. (8), the increased flame heating length promotes the flame spread. As a result, the opposed flame spread over thin laboratory wire is faster in microgravity than in normal gravity (see **Figure 15**). Moreover, the limiting O_2 concentration is smaller in microgravity (see **Figure 12**d), because of in the absent of strong buoyancy flow to blow off the weak flame. Similar phenomena have also observed for thermally-thick fuels [95], suggesting that there could be a larger fire hazard in the spacecraft environment than on Earth.

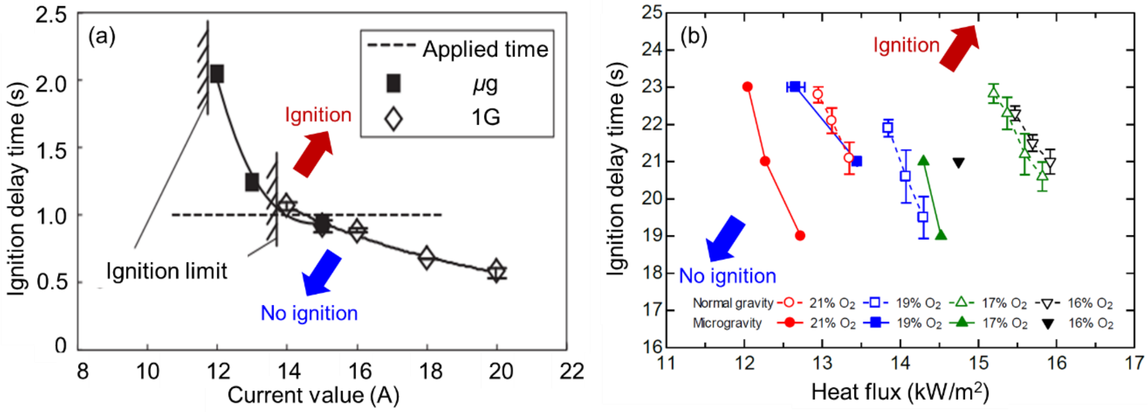

Figure 14. Comparison of ignition delay time between microgravity and normal gravity, (a) ignition by overload current [30], and (b) piloted ignition by laser spark under external heat flux [24].

Figure 15(a) also illustrates the pressure dependence in microgravity and normal gravity. In microgravity, the decrease in pressure mainly leads to a weaker flame. As the flame on wire becomes weak, the core acts as a *heat sink* to quench the flame (Section 2.4.1), so that the flame spread is more sensitive to the pressure. Comparatively, as the pressure is decreased on Earth, the increase in the flame heating length (L_f in Eq. 9b) will compensate the reduction in the flame intensity until the flame becomes very weak in very low pressure.

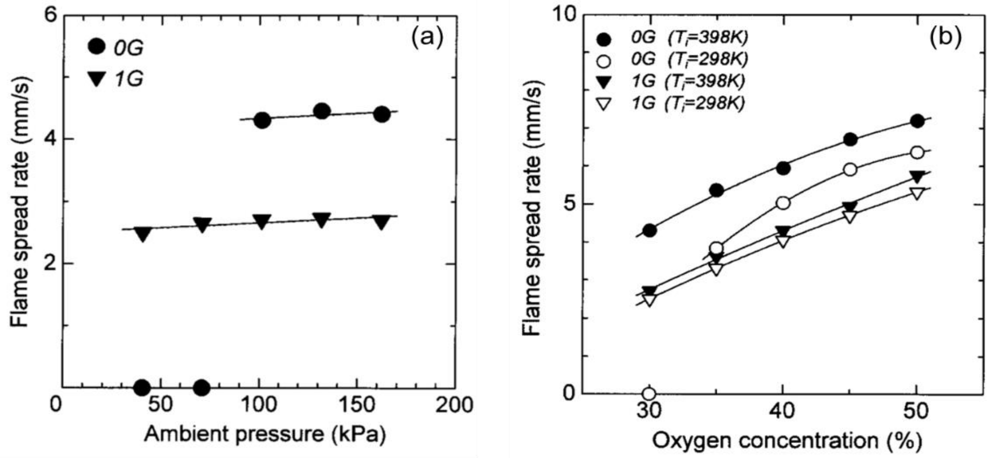

Figure 15. Rate of flame spread on a 0.62-mm ETFE-insulated Cu wires in both microgravity and normal gravity (a) pressure dependence at T_a = 125 ℃, O_2 = 30% , and (b) O_2-concentration dependence [15].

Without gravity, there is no dripping phenomenon. Instead, the molten insulation tends to accumulate in the burning zone as pulled by the Marangoni surface-tension force towards the low-temperature preheat zone, and it forms an axial symmetric ellipsoidal ball around the core. Therefore, as the size of the molten ball continuously increases, the burning rate also increases due to the increasing burning area. Under the opposed airflow, a steady-state flame spread may be reached when the burning rate equals the melting rate [17]. However, it is also possible that the flame standoff distance increases with the flame size, and the flame heat flux becomes weaker in the burning zone. If so, the rate of burning may not catch up with the rate of melting, and the scale of fire will continuously increase. Under the forward airflow, the flame spread may keep accelerating, and the flame size may keep increasing until the fire is limited by the O_2 supply [28]. So far, no long-term microgravity experiment is available for the flame spread on the wire.

Note that over the last 20 years, the usage of thin laboratory wires has dominated in the wire fire research. One major reason is that the ignition, flame spread, and extinction behaviors of these thin wires have a fairly short time scale, which can be examined in the short-term microgravity tests, such as the drop tower and parabolic flights (e.g. [15–18, 22, 24–26, 30, 48, 93].). In other words, the motivation or the priority of these studies is for the microgravity environment or space fire safety, rather than the understanding the fire dynamics of real wires. Thus, attentions are needed to carefully interpolate or extend the results and conclusions to other wires, especially the thicker wires, due to the complex scale effect (discussed more in Section 4.2). Today, the importance of the scale effect in wire fire has been gradually recognized, and some studies have been conducted using thicker laboratory wires [20, 21]. Nevertheless, more efforts are needed that may eventually bridge the knowledge gaps between ideal laboratory wires and real commercial wires.

4. Challenges in Fundamental Research and Implications to Commercial Wires

The research on wire fire shares many similar difficulties and challenges with other fire problems, for example, the lack of reliable numerical tools, the scaling effect, and the poor connection to the real-world application. Current researches on wire and cable fire are distinctively separated into two categories, (1) the fundamental research using laboratory wires, and (2) applied research using commercial wires and cables. These two approaches are very different, while both have some major limitations. The major limitations of the first approach lie in the unreal insulation materials of laboratory wires because most of the real wires have fire-retardant insulation, and the unreal environmental conditions because there can be a high environmental temperature and external radiation in real fire scenarios. The author had conducted an ignition test with a strong Bunsen burner for more than 20 different widely used wires in the laboratory, but none of these real wires could be ignited, mainly because all of them had fire-retarded insulation. Nevertheless, wire and cable fires have been widely observed in real fire scenarios under the external heating from hot smoke and flame. Unfortunately, these limitations are more or less neglected in the first fundamental approach.

For the second approach, most of the studies developed and conducted standard tests to measure the key fire parameters, such as the ignition delay time, flame spread limit, and the heat release rate (e.g. [6, 48, 54, 115–123]). Essentially, these standard tests treat commercial wires and cables like a PMMA sample without touching their complex structure and heat transfer processes. Then, based on these parameters, their fire risk and hazards are determined in comparison to the pure materials. However, without correlating the fire behaviors to the complex structure, it is not possible to fully understand the wire fire phenomena or guide the design of fire-safe wires and cables. So far, only a limited number of studies have tried to combine both approaches [11, 12, 19, 52]. In this section, we will discuss these specific challenges and problems that deserve more research efforts in the future.

4.1 Numerical Simulations

To investigate the wire fire behaviors, applying analytical models like Eqs. (4-8) requires the neglection of many secondary processes, such as the mixing and chemical processes in the gas phase, the temperature dependence of all thermal physical properties, and non-uniform heat flux. Nevertheless, these analytical models can still help qualitatively explain most of the experimental phenomena. For more complex fire phenomena in wire, such as dripping and radiant heating, more sophisticated numerical models are required to give a better explanation. Note that the use of numerical fire model does not ensure a quantitative comparison with experimental observations, mainly because (1) these models need more parameters as inputs while these parameters are often not well determined, and (2) many experimental measurements are not accurate and reliable enough. Thus, like all other fire phenomena, the major purpose of numerically modeling the wire fire is to help understand the underlying physics and processes that cannot be easily quantified via experimental techniques.

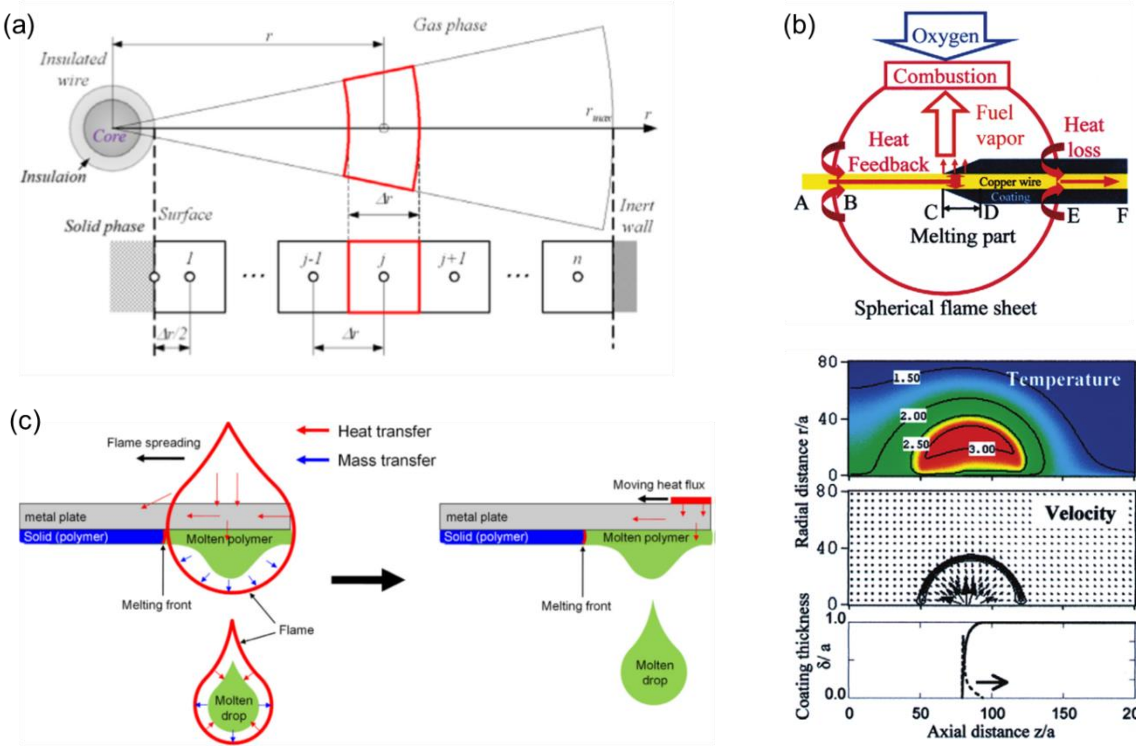

Figure 16. Illustration of the numerical model for wire fire, (a) overload ignition in microgravity [22], (b) flame spread in microgravity [26], and (c) dripping phenomena [87].

There are only a limited number of numerical models for wire fires under different levels of complexity. Leung *et al.* [78] simulated the 2-D heating process and mass-loss rate when the end of the core was heated, which is the same as the protocol (b) in **Figure 3**. The model helped determine the influence of core thermal conductivity on the pyrolysis of the insulation layer without flame. Stein et al. [124] modeled the 2-D heat transfer process within the cross-section under a uniform external radiant heat flux. For 22 commercial cables with different internal structures, modeling results show a good linear correlation between the failure time when the cable surface reaches 400 °C and the total thermal mass, $\Sigma(mc)_i$, but not verified by experiment. Huang *et al.* [31] modeled the piloted ignition process by a local external heat source by solving Eq. (4). Despite the gas-phase processes are not included, modeling results agree with the experimental results qualitatively. Nevertheless, even if more physical sub-models are included, a quantitative prediction of experiments could not be expected, because the transient heating process in the experiment could not be quantified. Takano *et al.* [18] and Shimizu *et al.* [22] proposed a numerical model to predict the overload ignition of wire in microgravity, and this model includes the radial (1-D) transport phenomena and 1-step finite chemistry in both solid and gas phases, as illustrated in **Figure 16**(a). By carefully setting the boundary conditions, this model could predict the overload ignition delay time and LOC, that were comparable to the experimental data, and help understand the influence of insulation thickness, ignition energy, and O_2 concentration on overload ignition.

The flame spread on the wire is more complex than the ignition process, because a smaller mesh size and a time step are required to simulate the gas-phase flame and solid-phase pyrolysis at the same time. In 2002, Umemura *et al.* [26] developed a 2-D transient model for the ignition and the subsequent flame spread over wire under microgravity, as illustrated in **Figure 16**(b). The model neglects the angular dependence, which is a reasonable assumption under microgravity and sets a critical temperature for insulation gasification. The modeling results also confirm that within in the flame, the copper core acts as both a heat sink (burning zone) and a heat source (burnout zone). Also, the effect of O_2 concentration and airflow on the flame spread rate is well predicted. This model is still state-of-the-art in the description of flame spread process over wires. Recently, the model of Guibaud *et al.* [118] provided a fine description of gas and soot radiation for the opposed flame spread over wire under microgravity. This model included the detailed kinetic scheme of ethylene and soot model, whereas constant rates of burning and flame spread were assumed.

The dripping process in wire fire has been studied by Kim, Hossain, and Nakamura [86–88]. As illustrated in **Figure 16**(c), as a first approximation, the heating of flame is simplified to the heating from a hot spot on the core, and the pyrolysis process is neglected in the model. The phase-change process is modeled by changing the fraction of gas, liquid and solid within each mesh. The model has successfully predicted the length of the molten front as a function of the heating intensity and inclination and quantified the volume of drip and the dripping frequency. Because in real wire fire, the flame heating on insulation is dominant for the phase-change process, a more sophisticated model, including the pyrolysis and flame, is needed in future research, despite a great challenge. In summary, there is an ardent desire for numerical work on wire fire, in order to improve our understanding of the complex phenomena in wire fire and potentially help design the fire-safe wires in industrial applications. Numerical analysis can also help understand the size effect in the wire fire, but such an approach has not yet been touched in the literature.

4.2 Scale effect

The effect of scale in wire fire has not been well investigated. Very few studies have performed well-controlled experiments on wires of various scales or scale analysis based on these limited data. The complexity of the wire's scale effect has several folders:

(1) *Complex role of the core*. As discussed above, the core can act as either a *heat sink* or a *heat source* depending on the ignition process, flame-spread configuration, and environmental conditions. Increasing the diameter of the core, the conductive heat transfer will be enhanced in general, but the role of the core may also change between heating and cooling. For example, when the flame spreads over a horizontal wire, the rate of spread increases as the core diameter is increased. However, continuously increasing the size of the core, eventually, the flame cannot be sustained as the core becomes a *heat sink* [8, 9].

(2) *Multi-dimensional heat transfer process*. The dominant heat transfer in the core is along the wire axis, which is different from the radial direction where the change of scale takes place. On the other hand, despite that the heat transfer within the thin insulation can be ignored, the thickness of insulation has a strong effect on the ignition delay and the flame spread rate. Moreover, if the insulation is thick than 5 mm, the assumption of thermally thin fuel, used in Section 2, is no longer valid.

(3) *Cylindrical shape or the curvature effect*. Changing the wire size not only modifies the heat transfer in the solid phase but also changes the gas-phase convective heating from the flame and convective cooling from the environment, as indicated by Eq. (3).

(4) *Phase change process*. Ideally, the fuel available in a wire increases almost linearly with the thickness of wire insulation. However, besides burnt, the molten fuel can flow along the wire or drip driven by the gravity, as discussed in Section 2.3. This dripping flow not only changes the heat release rate from wire fire but also controls the rate of downward spread.

As expected, not a single or a group of non-dimensional numbers is available to qualify the size effect in wire fire. In fact, a "simple" question like *how the minimum insulation thickness for flame spread changes with the diameter of the core* is not so easy to answer. Similar unknowns also extend to the ignition and flame-spread processes. For example, Bakhman *et al.* [8] found that the rate of downward flame spread with the Cu core increased about ten times as the thickness of insulation decreased to 1/10, that is, from 0.4 mm to 0.04 mm, well following the classical thermally-thin theory in Eq. (8). However, as the thickness of PE insulation increased 15 times from 0.15 mm to 2.25 mm, the flame spread only decreases to 1/7, that is, from 3.5 mm/s to 0.5 mm/s [19, 23], probably because the validity of thermally-thin assumption become weak.

Several attempts have been made to implement the convenient laboratory small-scale tests to evaluate the cable burning character obtained by standard tests. These attempts might be useful to explain the physics lied in the empirical function to connect the real standard test. The best example is the cone calorimeter test that is often used for this purpose and has been applied to various wire and cables [54, 57, 58, 125]. Other established small-scale test facilities are also developed to utilize the scaling law to mimic the large-scale test. For example, Girardin *et al*. [117] developed the scaled-down enclosure of EN 50399, and their results exhibit a nice correlation of the peak HRR, damaged length, and total heat release between full-scale prototype and small-scale model (see **Figure 17**a).

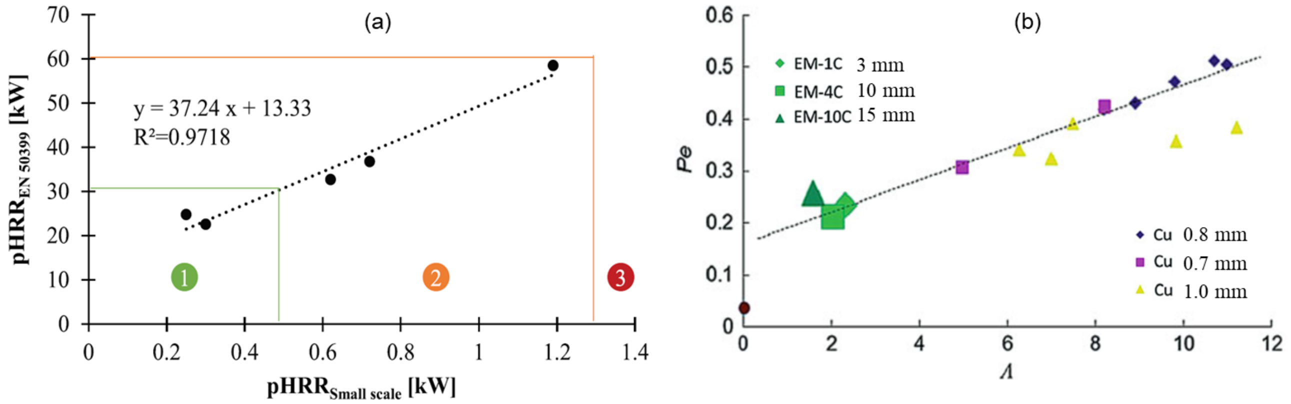

Figure 17. (a) Correlation plot for the peak of heat release rate (pHRR) for five different cables [117], and (b) the relation between *Pe* and *Λ* in Eq. (18) for various wire sizes and materials [19].

Comparatively, applying the scale analysis to predict the ignition delay time and fire spread rate is more challenging. Based on the solid-phase heat transfer analysis, Nakamura *et al.* [19] proposed a linear correlation between two non-dimensional numbers (*Pe* and *Λ*),

$$\frac{\Lambda}{Pe} = \left(\frac{2\pi d_c \lambda_p}{d_o A_c \rho_c c_c} \right) \frac{W}{V_f} = \text{const.} \tag{18}$$

which correlates the flame spread rate on wires of various size. This simple correlation can well correlate the flame spread rate over a horizontal wire of diameter over almost two orders magnitude from 0.7 mm to 15 mm (see **Figure 17**b). Note that the thermal conductivity of core (k_c) does not appear in this correlation, but implicitly affects the value of flame width (*W*) and flame spread rate (V_f) measured from the experiment. Other non-dimensional correlation and scale analysis for different ignition and extinction processes could also be developed using a similar approach and worth further research.

4.3 Modeling real cable fires

Depending on the application, real cables are consisting of multiple inner wires and several layers of the polymer coating and metallic shield. Besides the standards test on the original cable, the same tests can be applied to its every component, such as the single inner wire and the cable jacket, to explore their specific fire behaviors. Comparative experiments can also be conducted by removing or replacing some components to see the change in fire behaviors [11, 52, 126]. For example, the effect of the core is often studied by using laboratory wires and changing the core materials, and a similar approach can be applied to commercial cables. The scale of cable components, such as the diameter of core and thickness of jacket and insulation, can also be varied to understand the scale effect. Because of larger uncertainties in measuring the ignition delay, flame spread rate and failure criteria, statistical methods should be applied in the data analysis [115]. With a good database of extensive experiments in different scales, the numerical model for commercial cables, including the detailed structure and multi-dimensional heat transfer processes, could be developed and calibrated to design fire-safe cables. However, such a sophisticated model is not available yet.

There have been a few numbers of standard tests proposed and established to judge the fire performance of the cable across the world. Accordingly, rich efforts and attempts have been made to model these test results, but unfortunately, it is still far from what we expected. In the early 90's Babrauskas *et al.* [13] made a comprehensive review on fire performance of wire and cables, including a survey of the standard tests established over the countries to compare their similarities. In the review, they claimed an interesting key point for modeling task; namely "…. *Research necessary to integrate flame spread prediction over wire and cable products must be expedited in order to be able to analyze the role of wire and cable flammability with fire models*…" Although almost 30 years has been passed after that review was presented and several modeling works for burning actual cable have been made (e.g., [119, 120]), in reality, researchers still suffer from the optimum integration of various parameters and challenges to establish the comprehensive model of burning cable and simulating the standard tests. In this section, we shall briefly introduce the representative case studies and propose effective future works and strategies for establishing "better" modeling of cable fires.

4.3.1 Empirical Function Approach

The empirical function approach has been often applied to predict the overall burning character of the vertical cable tray test, which avoids dealing with the spread event. The flame spread process is not explicitly solved, whereas it is replaced by the fire performance characteristics, such as fire growth rate, and then, we can seek the way to predict the growth rate per given cable characteristics. As a representative case for this approach, the project in Europe named "CEMAC (CE MArking of Cables)" [116] was propelled in order to develop the cable burning model based on the rich database accumulated from laboratories, testing institutes, industries in European countries. The main aim of CEMAC is to provide the prediction formula to judge the classification category of the target cables covered for real European market without performing the standard test, likely prEN 50399 [83]. A new parameter χ has been proposed in order to classify the burning behavior of cables, such as total heat release (THR), peak heat release rate (HRR), fire growth rate (FIGRA):

$$\chi = \frac{c}{d^2} V_{combust} \qquad (1)$$

where d is the outer diameter [m], c is the number of conductors in the cable [-], V_{combust} is combustible volume per unit meter of the ladder [m^2]. Note that the number of conductors is counted by the isolated cores. For instance, it is counted as one when the multiple thin conductors are bundled without separated by insulation materials.

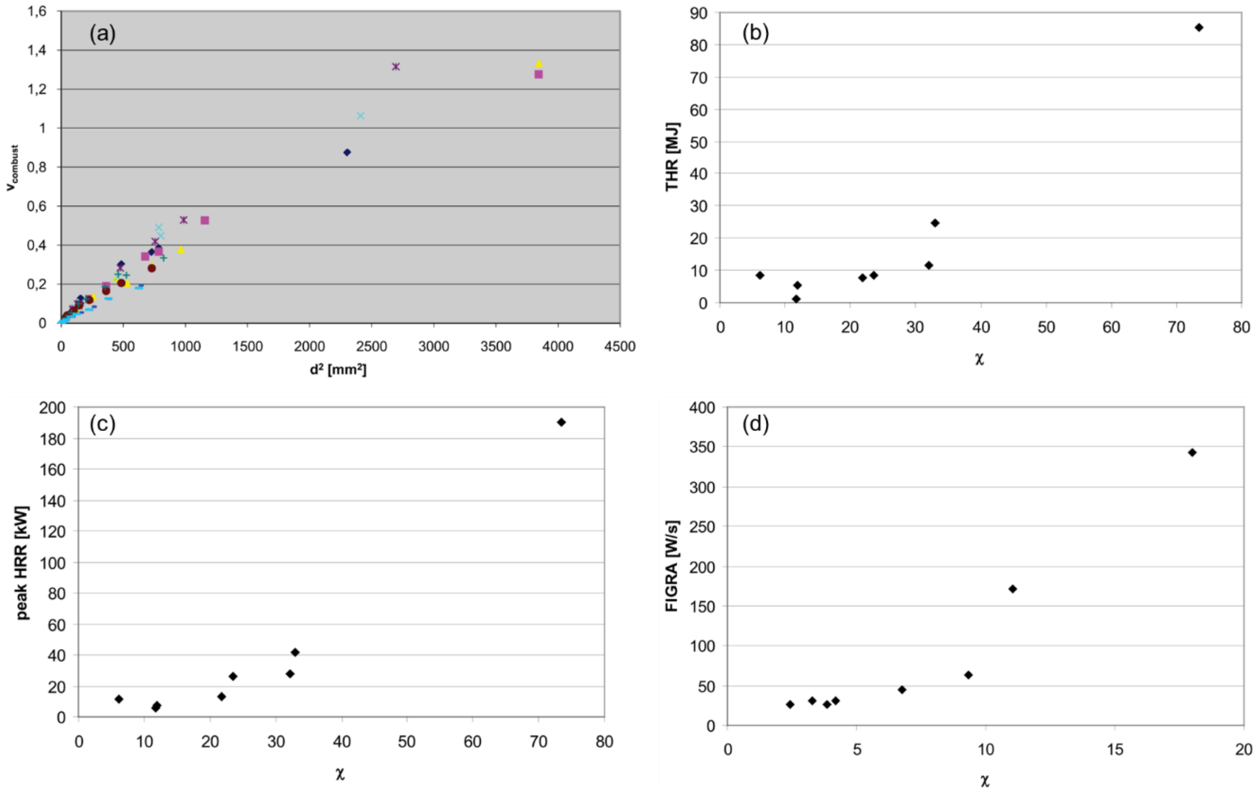

Figure 18. (a) Combustible volume per meter cable, $V_{combust}$, as a function of d^2, and the correlation between χ and (b) THR, (c) peak HRR, and (d) FIGRA for seven representative cables [116].

A linear relationship as found between V_{combust} and d^2 [116] for most of the cables considered for CEMAC project (**Figure 18**a). In addition, this report revealed that χ is well-correlated to cable combustion characters, e.g., THR, HRR, and FIGRA (**Figure 18**c-d), so that found to work in sufficient wide range (for engineering purpose) to judge which category the candidate cable shall be classified into ones determined by the existing evaluation test. In this report, an evaluation methodology for the burning character of cables larger than the tested range and generic rules for cables not included in CEMAC are also provided. Empirical function approach sounds quite engineering, whereas the above example showed its feasibility and effectiveness. A heat transfer analysis to prove the eligibility of the suggested formula would be quite useful, and eventually, a group of non-dimensional parameters, similar to Eq. (18), can be proposed to predict the fire behaviors for a range of cables types and configurations.

4.3.2 Multiple cables

In real-world applications, multiple cables are often arranged together as a bunch or into a tray, as shown in **Figure 1** and **Figure 19**. Once a fire is initiated, the interaction between fires in nearby wires become vital. For example, cables can be ignited by the flame or drips from an existing burning cable. Eventually, fire hazards can be escalated, if the whole cable tray is ignited and fire spreads to everywhere by following the direction and location of cables. So far, most fundamental studies simply neglect the interactions between wire fires, while other applied researches simplify the cable trays as a flat sample, a piled sample, or a plate wall [120–123]. Very limited fundamental studies have addressed the interaction between cable fires and the spacing effect [48, 54, 117–119].

Figure 19. The cable trays (a) in the utility tunnel, and (b) in power plants (photo credit: Miguel Medina).

Under the multi-year program named CHRISTIFIRE (Abbreviation of “Cable Heat Release, Ignition, and Spread in Tray Installations during FIRE”) led by the Nuclear Regulatory Commission (NRC) [6], NIST and University of Dayton Research Institute developed the numerical code, called FLASH-CAT (Flame Spread over Horizontal Cable Trays) to reproduce the horizontally-allocated cable tray burning experiment with 3-7 cables. More than 20 different cables were tested (**Figure 20**a). The model could reproduce the V-shaped flame spread angle under the condition of the prescribed horizontal flame spread rate referred from the experiments by Sandia National Lab, as described in NUREG/CR-6850 [117] (**Figure 20**b). On the other hand, the peak HRR and the energy release are overestimated, although the trend is captured (**Figure 20**c). The main reason for this deviation is due to the assumption that the cable shall burn at the rate of prescribed one, but in these tests, the cable fire did not grow for some cases. In other words, we still have difficulty to predict the real cable tray combustion in satisfactory level, even the spread model is prescribed.

For the case of the horizontal tray test, flames shall heat the cables neighboured and stacked in the upper trays, and then, accelerate their pyrolysis and degradation, then causes a subsequent flaming and spread processes accordingly. Once the fire propagates to the upper trays, the radiation from the flame in the upper tray would affect thermally to the cables in lower trays. In this way, fire processes in lower trays and upper trays strongly influence each other. By this nature, even slight error happened in the process at the lower trays, the error is conveyed to the event of the upper trays and back to the event in the lower trays to accumulate to cause large deviation, unless there is no dumping factor in the system. To end, simple accumulation of knowledge on single cable fire may not ensure the successful simulation of the standard test, if we miss the proper sense as stated above. Thus, more careful research works are needed to correlate the fire behaviors in a single wire with those in bunched wires.

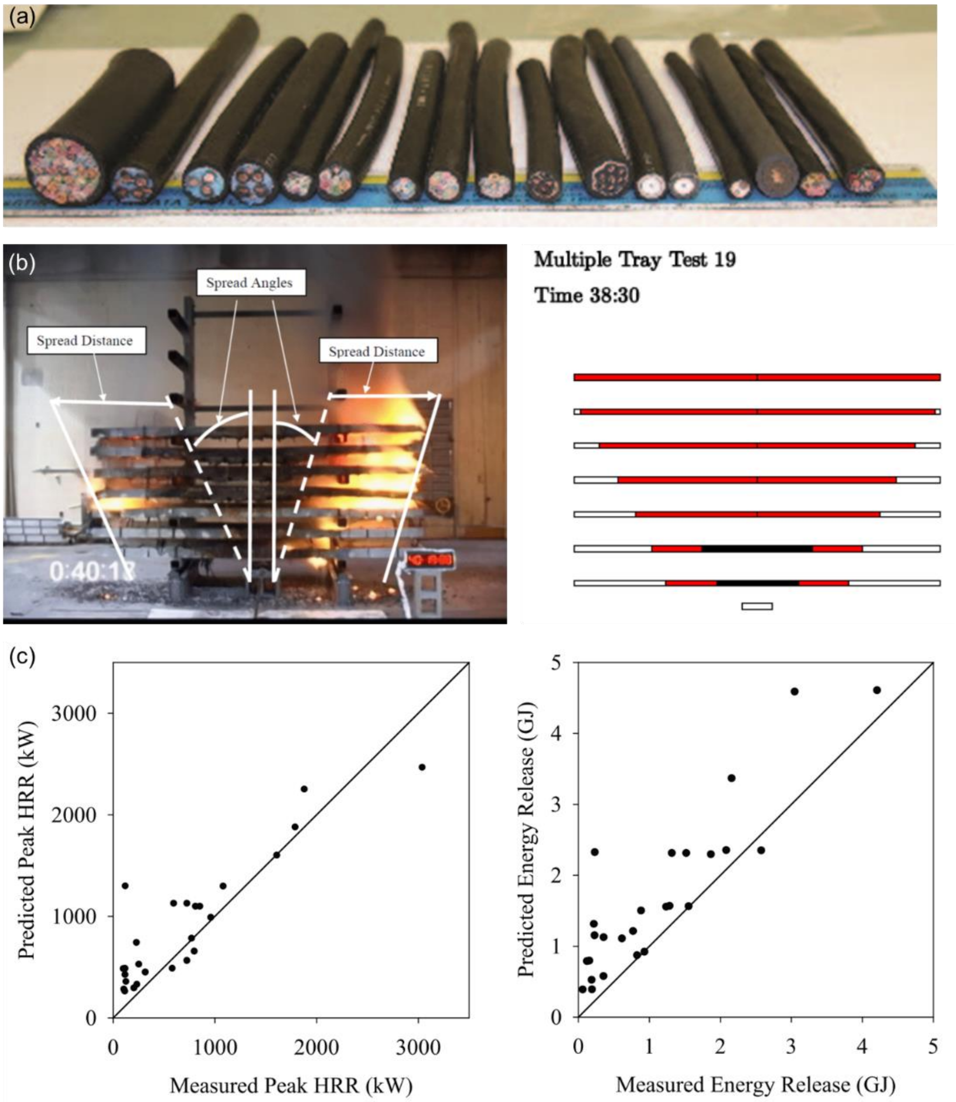

Figure 20. (a) Tested cable samples, (b) horizontal cable tray experiment comparing the experimental observation with the prediction by the FLASH-CAT, and (c) the predicted vs measured peak HRR and energy release [6].

5. Conclusions

This work reviews the wire fire phenomena and dynamics studied in the literature over last three decades. The complex role of the core, specifically whether it is a *heat source* or *heat sink*, in the ignition, flame spread, burning, and extinction, has been emphasized throughout this review. Owing to the fundamental research, especially the experimental studies using laboratory wires and the qualitative analysis of heat transfer and combustion processes, different wire fire behaviors under various fire scenarios, wire configurations, and environmental conditions have been thoroughly explored.

However, most of small-scale studies in the literature used the very thin laboratory wires that are very different from real wires and neglect the important scale effect of wire fire. Therefore, a deeper understanding of fire phenomena in real wire and cable is still quite challenging, and attempted inferences for real wire fires based on the qualitative or semi-empirical analysis of limited laboratory data are not yet convincing enough. Particularly, the scale analysis and numerical models for wire fire are lacking in the literature, and despite of great challenges, they are most needed to help explain experimental data and reveal the complicated interactions between core, flame, and insulation, such as the heat-and-mass transfer and phase-change processes. Moreover, there is still a large gap between the fundamental research using laboratory wires and applied research using commercial wires. Developing a framework to combine both research approaches should play a central role in the future wire fire research and the design of fire-safe wires and cables.

Acknowledgements

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