Short Length Wire as an Electrical Fuse

Mahan Fallahpour , Sharif University, fallahpourmahan@gmail.com

ARTICLE INFO

Former participant in IYPT

New Edition of the published paper in No 1, 2023

Accepted by Ariaian Young Innovative Minds Institute , AYIMI

http://www.ayimi.org ,info@ayimi.org

ABSTRACT

This study focuses on the phenomenon of a compact wire segment's functionality as an electrical fuse. Fuses are pivotal for electrical safety, designed to melt and disconnect when excessive current flows. The primary objective is to analyze the factors affecting the time until fuse disruption. Two key parameters are examined: the current magnitude and the wire's melting point. The study also investigates the impact of resistance, an indirect factor, and physical wire attributes like length and width, assuming a constant current. This research enhances our understanding of fuse behavior, advancing electrical safety and engineering practices for reliable operation.

Keywords : *: Compact Wire Segment, Fuse, Constant Current , Electrical Engineering*

1. Introduction

The conducted study represents a rigorous scientific investigation aimed at addressing a complex problem posed by the 35th International Young Physicists' Tournament (IYPT). The focal point of this research revolves around a fundamental inquiry, stated as follows: "Under what conditions and to what extent does a concise segment of wire function as an electrical fuse? Elucidate the intricate interplay between different parameters and their influence on the temporal characteristics of fuse disruption." The pivotal terminology encompassing this research comprises "the fuse," signifying the wire segment with potential electrical fuse properties, "the time taken," indicative of the temporal interval leading to fuse disruption, and "blow," denoting the critical juncture at which the fuse's functionality is compromised. In the realm of electrical engineering and physics, the phenomenon of a short length of wire acting as a fuse holds profound implications. By meticulously examining the intricate dynamics at play, the study endeavors to unravel the underlying principles that dictate the fuse's behavior. This involves a comprehensive exploration of variables encompassing wire material composition, wire gauge, current magnitude, and ambient temperature, all of which distinctly contribute to the intricate mechanism leading to the fuse's eventual disruption. The research methodology employed entails a meticulous combination of theoretical analysis, empirical experimentation, and computational modeling. Theoretical insights gleaned from fundamental principles of electrical conductivity, Joule heating, and material science provide a robust foundation for understanding the underlying processes that govern the fuse's behavior. Empirical experiments, carried out under controlled conditions, scrutinize the effects of varying parameters on fuse disruption time, elucidating the nuanced relationships between these variables. Furthermore, computational simulations using advanced numerical methods serve to validate and extend the experimental findings, offering a predictive framework to extrapolate the behavior of the fuse under a broader spectrum of conditions. The synergy between theoretical analysis, empirical experimentation, and computational simulations fosters a comprehensive understanding of the intricate interactions at the heart of the fuse's behavior. In conclusion, this research endeavor stands as a testament to the dedication of scientific inquiry.

2. Theory

In accordance with the scientific method, the investigation centers on the critical process of fuse disruption. A central prerequisite for fuse blowing is the fusion of the conducting element, a transformation driven by the heat generated within the wire due to current flow. This pivotal heat generation underscores the significance of the produced current in this context. Leveraging the reasonable presumption that the wire functions as an ohmic conductor, the heat evolved within the wire during the passage of a current (I) is represented by RI^2t, with t denoting the elapsed time since the current's initiation.

The velocity of fuse disruption is intricately tied to both the magnitude of current coursing through it and the material constituting the fuse. Distinct materials exhibit diverse melting points, even when possessing equivalent resistance. This variation in melting points underscores the importance of material selection, as it profoundly influences the threshold at which the wire succumbs to fusion. The fusion mechanism pivots on the synergy between current, the wire's resistive properties, and the material's specific heat characteristics. Through this systematic analysis, the study enhances our understanding of the intricate amalgamation of current, resistance, and material properties, unraveling the nuanced phenomenon of fuse disruption.

2.1. Effect of Current

The impact of current on this phenomenon is pivotal, as elucidated by the Ri^2 formula governing heat generation. The magnitude of current directly influences the heat produced within the wire, amplifying the chances of fuse disruption.

A fundamental insight lies in the RI^2t formula, underscoring the current's quadratic effect on heat generation. This signifies that even small increments in current lead to disproportionately higher heat output, rendering current a dominant factor in determining the fuse disruption time.

To illustrate, consider a copper wire with a resistance of 0.1 ohms and a melting point suitable for this analysis.

When subjected to a higher current of 20 amperes, the RI^2t demonstrates that the heat generated is proportional to ($0.1*20^2*t$), resulting in a significant increase in heat production. Conversely, at a lower current of 5 amperes, the heat generation is governed by ($0.1*5^2*t$), yielding notably less heat. This divergence in heat accumulation between the two scenarios leads to a substantially shorter fuse disruption time for the higher current case, exemplifying the exponential relationship between current and heat generation in determining the temporal aspects of the phenomenon.

$$V = RI \tag{1}$$

$$P = \frac{W}{t} = \frac{q.\Delta V}{t} = I\Delta V = IV = \frac{V^2}{t} \tag{2}$$

2.2. Physical Parameters: Length, Width

The distinct roughness and length of a wire significantly impact the phenomenon's duration. Increased roughness elevates wire resistance due to augmented surface area, leading to intensified heat generation for a given current, hastening the fuse's disruption. Conversely, greater wire length escalates overall resistance, extending the time needed to accumulate sufficient heat for disruption. These effects arise from the intricate interplay of resistance, current, and surface characteristics, influencing the delicate balance between heat production and dissipation, ultimately dictating the temporal evolution of the phenomenon.

2.3. Melting Point

The time frame of the phenomenon is intricately influenced by variations in wire material and their corresponding melting points. Altered wire materials with diverse melting points distinctly affect the thermal characteristics of the system. Materials with higher melting points necessitate more substantial thermal energy accumulation to achieve the critical threshold for disruption, thus prolonging the phenomenon's duration. Conversely, materials with lower melting points require comparatively lesser energy accumulation, resulting in a shorter temporal span for disruption. This temporal modulation arises from the interaction between specific heat capacities, melting point temperatures, and the heat generation mechanism, underscoring the pivotal role of material selection in shaping the phenomenon's time course.

2.4. Other Parameters

Beyond the discussed parameters, ambient temperature and wire cross-sectional area exert substantial influence on the phenomenon's duration. Elevated ambient temperatures expedite heat transfer and reduce the time needed for heat accumulation, thus shortening the phenomenon's duration. On the other hand, a larger cross-sectional area lowers wire resistance, augmenting the heat generation rate and promoting faster disruption. Additionally, the wire's purity level and crystal structure influence its electrical and thermal conductivities, which directly affect heat generation and dissipation dynamics. Altogether, these unexplored parameters further underscore the intricate interplay between various factors in governing the temporal characteristics of the phenomenon.

3. Basic Theory

When an electric current traverses the wire, it engenders a conversion of electrical energy into heat, denoted as electrical power (P_{elec}). This generated heat is subject to intricate dissipative mechanisms. A portion of this thermal energy is transferred to the surrounding environment through convective processes, constituting convective power loss.

$$p_{convection} = hA\,(T\text{-}T_{amb}) \tag{3}$$

Simultaneously, another fraction of the heat dissipates through conduction, a process governed by the transfer of thermal energy within the wire's material itself. The comprehensive theoretical framework underlying these heat transfer dynamics provides insights into the complex interplay of convection, conduction, and electrical power, illuminating the mechanisms shaping the wire's thermal behavior during the phenomenon (Fig. 1).

$$P_{elec} - P_{conv} = \text{mc.}\frac{dT}{dt} \tag{4}$$

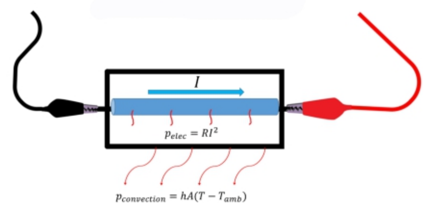


Fig. 1: Current in Fuse

3.1. The Conditions for the Creation and Non-creation of the Phenomenon

As the temperature elevation ensues consequent to the traversal of electric current through the wire, a concomitant augmentation in the convective current materializes. In cases where this thermal process unfolds gradually, a state of thermal equilibrium ($P_{elec}=P_{conv}$) is attained within the wire, characterizing a consistent temperature profile.

$$(T_F = T_{amb} + \text{R}I^2/hA) \tag{5}$$

Should this resultant equilibrium temperature remain below the material's melting point, the phenomenon remains quiescent. Conversely, if the attained equilibrium temperature surpasses the material's melting point, the stage is set for the observable manifestation of the phenomenon.

3.2. Instantaneous Temperature and Time

When examining the phenomenon through a temporal lens, the temperature of the wire experiences incremental increases (RI^2dt) at each successive instant. Simultaneously, the convective heat transfer mechanism precipitates a continuous temperature loss ($hA(T\text{-}T_{amb})dt$) during each time increment. This complex interaction leads to the formulation of a differential equation that includes the dynamic relationship between temperature rise and convective heat loss.

$$(Ri^2dt - hA(T\text{-}T_{amb})dt) = mcdt) \tag{6}$$

Separation of this differential equation leads to the extraction of an analytical expression that provides the possibility of determining the final thermal state obtained by the wire in that second:

$$T = \frac{RI^2}{hA} . e^{-\frac{\alpha}{m \times c}t} + \frac{RI^2}{hA} + \mathrm{T_{amb}} \quad (7)$$

By assigning the ultimate temperature as the melting temperature within the context of this differential equation, we can discern the temporal duration requisite for the phenomenon's manifestation:

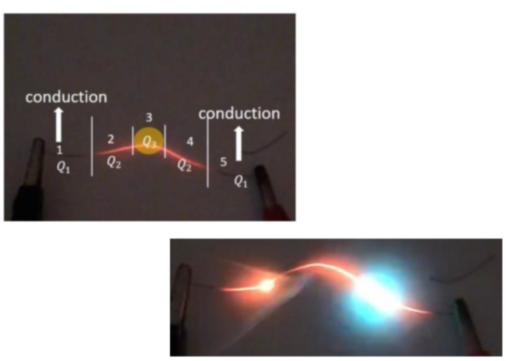
$$t_{blow} = \frac{mc}{hA} \times \ln(\frac{RI^2}{RI^2 - hA(T_l - T_{amb})}) \quad (8)$$

3.3. Place of Melting

Due to the observed conduction phenomenon, it may initially appear that the temperature of a designated region, denoted as "part 3," surpasses that of an alternate segment. This implication leads to the presumption that the point of melting should correspond to "part 3." However, this inference is misleading and lacks accuracy. Contrary to imagination, this phenomenon happens in episode 4.

The elevated heat generation within "part 4" is attributed to impurities present in the wire. Despite its proximity to the reference point represented by the "crocodile wire," conduction's impact is relatively mitigated. Consequently, within the theoretical framework, conduction is ascribed a diminished influence.

For enhanced elucidation of this phenomenon, a partition of the wire into three discrete segments is undertaken. The premise of the wire's intrinsic impurity necessitates an assumption wherein $R'' > R' > R$. Within this framework, a uniform current distribution is postulated across the entire wire over a defined temporal interval. Consequently, the segment characterized by heightened impurities manifests augmented heat generation. Empirical validation accentuates the observation of heat loss due to conduction. However, the efficacy of this heat transfer mechanism is notably curtailed owing to suboptimal propagation, consequently warranting its exclusion from the theoretical construct(Fig. 2).



$\text{Conductin } 1 \approx \text{Conductin } 5 > \textit{Conductin } 2 \approx \textit{Conductin } 4 > \textit{Conductin } 3$

Fig. 2: Melting point

4. Experiment setup

1.Amperemeter
2.Voltmeter
3.Short length of wire
4.power supply (Fig. 3)

4.1. Finding Convection Coefficient (*h*):

The determination of the convective coefficient is derived through the manipulation of Equation (2):

$$h = \frac{\frac{V^2}{(T_{max} - T_{amb})R}}{A} \quad (9)$$

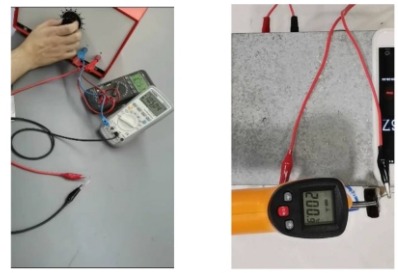


Fig. 3: Experimental setup

The acquisition of the convective coefficient (h) necessitated the selection of an elemental unit characterized by readily determinable cross-sectional area ($A \approx 0.001$) and resistance. Subsequently, the temperature differential of this chosen unit was ascertained through the implementation of a meticulously devised experimental procedure. This procedure involved the utilization of a laser thermometer to capture instantaneous temperature variations. The ensuing dataset was graphically portrayed, enabling the subsequent deduction of the convective coefficient (h): $h \approx 28$ (Fig. 4).

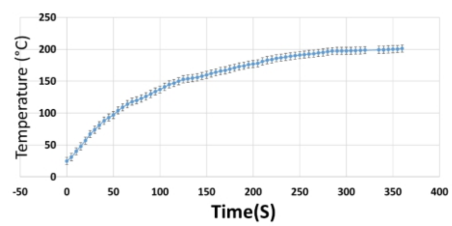


Fig. 4: Temperature vs time

4.2. Make a Fuse

Within this specific section, the primary objective is to establish an operative range for voltage and current values, beyond which the fuse is anticipated to undergo combustion. By employing Equation (2) and under the premise of equating the ultimate temperature to the melting temperature, the upper bounds for both voltage and current are deduced :

$$I < \sqrt{\frac{29680\, A_{(WIRE)}}{R}} \;,\; V < \sqrt{29680\, A_{(WIRE)}\, R} \quad (10)$$

4.3. Time of Blow vs. Length

In this designated section, a meticulous examination was conducted to scrutinize the proportionality between alterations in length and the corresponding temporal adjustments. This investigation involved subjecting wires of varying lengths to controlled testing conditions. Evidently, a noteworthy correlation emerged, revealing that an escalation in wire length correlated with an elongation in the temporal persistence of the wire under investigation (Fig. 5).

4.4. Voltage vs. Time

In this dedicated section, a systematic exploration was undertaken to assess the proportional relationship between alterations in voltage and the associated temporal variations. This analysis was conducted using wires of identical composition yet varying in length. The results unveiled a discernible pattern wherein an escalation in voltage was inversely correlated with the duration of wire persistence, leading to a reduction in the time interval over which the wire endured (Fig. 6).

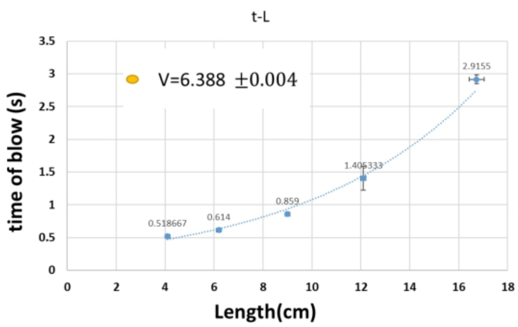


Fig. 5: Time of blow vs. Length of wire

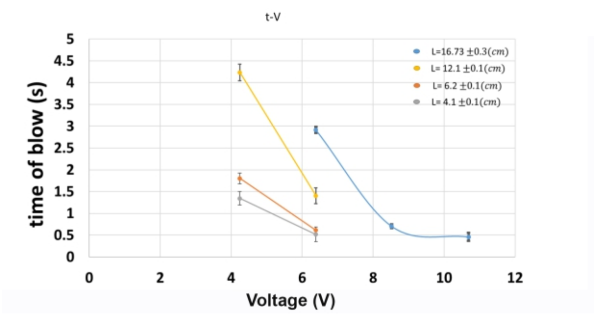


Fig. 6: Time of blow vs. voltage

5. Conclusion

Section 3.2 encompassed the utilization of Equation (7) to ascertain the ultimate temperature, while Equation (8) enabled the determination of the temporal interval necessary for wire disruption. The subsequent Section 3.3 elucidated the significant interrelation linking wire termination locations with the inherent impurity content at specific points. Moving forward, Section 4.2 engendered the establishment of a standard range for fuse voltage and current parameters through systematic analysis. Section 4.3 substantiated a direct correlation between wire length and the temporal duration of its functionality. Lastly, Section 4.4 rigorously evidenced an inverse relationship between voltage magnitudes and the temporal span of wire endurance.

References

[1] Holiday Edition 10, pages753-761.

[2] Frank P. Incropera and David P. Dewitt, Introduction to heat transfer