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Effect of Reduced Ambient Pressures and Opposed Airflows on the Flame Spread and Dripping of LDPE Insulated Copper Wires

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Highlights:

- Effect of pressure and opposed flows on flame spread across copper wire was studied.
- Pressures ranged from 40 to 100 kPa and opposed flows were 10 or 20 cm/s.
- Flame spread was found to increase with pressure and decrease with faster flows.
- Dripping of LDPE insulation from wire was also studied under described conditions.
- Mass dripped was found to decrease with pressure and increase with faster flows.

Abstract:

The effect of ambient pressure on flame spread and insulation dripping of copper-cored, LDPE-insulated wires exposed to opposed airflows was investigated to increase understanding of electrical wire fire hazards in spacecraft environments. Utilized wire samples consisted of 0.64mm-diameter copper cores surrounded by 4mm-outer diameter LDPE insulation sheaths. The wire characteristics were selected for comparison with future experiments planned in the International Space Station (ISS) with similar wires. Environmental pressure was varied from sub-atmospheric (40 kPa) to atmospheric (100 kPa). Wires oriented horizontally were exposed to opposed airflows with speeds of 10 or 20 cm/s. Results showed that flame spread rates increase with pressure and decrease with increasing opposed flow speeds. Melted and burning insulation left behind by flame spread dripped with a frequency that increased with pressure; the total mass dripped decreased with pressure. It was also found that lower flows produced more frequent dripping with less total mass dripped, and higher flows produced the opposite. Coincidingly, as the mass of dripped insulation increased, the flame spread rate decreased. Comparison of present results with those from studies with different wire samples show that the effect of environmental parameters on flame spread and insulation dripping depends strongly on core conductivity and core/insulation diameters. Consequently, care should be taken in extending results obtained from specific wire tests to other wires without justification.

Keywords: electrical wires, reduced and atmospheric pressures, opposed flow, flame spread rate, insulation dripping

1. Introduction

Electrical wires are potential sources of fire ignition and spread in spacecrafts, aircrafts, vehicles, and structures [1]–[4]. Therefore, it is important to understand the burning behavior of electrical wires in their operating environments. Of interest here is the potential for fires in spacecrafts, which can be originated by electrical wires and have disastrous consequences. Furthermore, cabin environments for NASA's next generation of spacecrafts are planned to operate under reduced pressure and increased oxygen concentration conditions [5], and further study on the effect of such environments on wire flammability is desired.

Flame spread is one of the burning mechanisms used to assess the flammability of materials because after a material is ignited, the rate of heat released by the fire is dependent on its rate of spread. In addition, dripping of molten burning materials, although not normally considered as a material flammability parameter, is important in the propagation of a fire because the dripping material can ignite materials underneath or create pool fires. Furthermore, since dripping is caused by gravity there is a fundamental difference in the propensity for a molten burning material to spread a fire in normal gravity, in the absence of gravity, or in reduced gravity, as in a spacecraft or space habitat. Thus, it is relevant in the study of wire flammability and dripping to assess their fire hazard in spacecraft environments.

In wire combustion, the relevant parameters can be loosely grouped into three categories: the characteristics of the wire (the dimensions and makeup of the core and insulation), environmental conditions (airflow speed, ambient pressure, oxygen concentration, external radiant heating, strength of gravity, and even electro-magnetic fields), and geometric parameters (direction and inclination of flame spread relative to flow speed and gravity). These variables, together with the fact that different insulations have different combustion characteristics and that the interaction of the conductive core and insulation affects the burning of the wire, make the study of wire flammability very complicated. For this reason, wire flammability studies often use "laboratory" wires which are assembled from a metal rod for the core and plastic tubes for the insulation, which is the case in this study.

Several previous studies have investigated the effect of these parameters on wire burning, including various wire characteristics [6]–[9], environmental conditions [6], [10]–[17], and geometries [8], [18], [19]; however, there are only a limited number of studies examining the effect of ambient pressure, specifically sub-atmospheric, on flame spread [15], [19]–[22]. This research is important because it has previously been found that low pressure environments can approximately mimic results found in micro-gravity environments [16], [17], [21]. Among the studies that have examined the effect of pressure on wire flammability, Nakamura *et al.* [19] found flame spread rate to increase with decreasing pressure for wires with nichrome cores. However, in the same study, iron wires were also examined, and it was found that the spread rate along these wires remained constant with varying pressure, showing that flame spread behavior at different pressures can vary for different core materials. Zhao *et al.* [20] performed experiments with wires containing copper cores, and found that the flame spread rate decreased with decreasing pressure. Hu *et al.* [22] studied the flame spread of both copper and nichrome wires, and it was again confirmed that flame spread over nichrome wires increases with decreasing pressure. The results for flame spread over the copper wires were more interesting, however, as it was found that there was an initial decrease in flame spread rate with pressure, and further decreasing the pressure resulted in an increase in flame spread rate. Additionally, the effect was found to be less prominent as the core diameter increased, with a solely decreasing flame spread rate as pressure decreased being observed for a copper core with a diameter of 0.80 mm, as opposed to wire diameters of 0.30 or 0.50 mm in the same study [22]. Considering the results of these previous studies, particularly those providing results for copper-cored wires, it is thought that additional research concerning the described variables will bring more clarity to the available findings.

Additionally, it is important to look at the combined effect of low-velocity opposed airflow and ambient pressure on flame spread because space crafts designed for human crews typically have low flows of 6 – 20 cm/s generated by their HVAC systems [23]. At the present, only one study has examined such a combined effect [19], where it was found that, for nichrome wires, flame spread rate decreased at higher opposed flows and increased with decreasing pressure, and for iron wires, the flame spread at first decreased but then remained constant for increased opposed flows and also increased with decreasing pressure. However, the work in this study [19] did not include any analysis of wires with high-conductivity cores; therefore, one of the goals of the present study was to examine the combined effect of sub-atmospheric, ambient pressure and opposed airflows on flame spread over wires with a high conductivity core, such as copper. The insulation dripping off these wires was also analyzed under these conditions, since it has been shown that it affects the rate of flame spread and burning of insulated wires. The results of the present work are also relevant for comparison with future experiments planned in the International Space Station (ISS) with similar wires [24], which is the primary objective of this work.

2. Material and Methods

2.1 Experimental Apparatus

The experimental apparatus used in this study is shown in Fig. 1 and Fig. 2. The setup was used to facilitate flame spread tests of Low-Density Polyethylene (LDPE)-insulated, copper-cored wire samples under various environmental conditions, including ambient pressure and opposed flows. For this study, the wire samples were suspended horizontally in the middle of a flow duct with a cross section of 128x128 mm^2 and a total length of 255 mm, all contained within an air-tight pressure vessel with access to fresh air and the ability to remove exhaust to keep the experimental environment consistent throughout the length of each test. Within the duct, the sample tip was located approximately 95 mm from the upwind end of the flow duct where uniform air entered the duct from a flow laminarizing and straightening section. Air was used as an oxidizer, and the pressure was varied from 40 to 100 kPa, with an average standard deviation of 0.2 kPa, in intervals of 20 kPa. The pressure range was selected due to design and equipment constraints. The opposed flows were set to speeds of either 10 or 20 ± 0.5 cm/s parallel to the wire. The flow speeds were selected because they are similar to those generated by the HVAC system in a manned aircraft.

For the described experimental setup, the air was provided from a tank of pressurized air, fed by a compressor. The mass of insulation material dripped was determined by collecting the drips in a pan placed underneath the sample and weighing the mass after the test was completed. Windows on the sides of the flow duct and chamber provided optical access, which allowed for video recording using a Nikon D3200 camera with a DX AF-S NIKKOR 18 55 mm 1:3.5-5.6G lens. The recordings were taken at 30 fps with an incandescent white balance, ISO of 200, exposure time of 1/60, and aperture setting of F6.3. Subsequent video analysis allowed for measurement of the flame spread rate across each sample as well as the drip frequency.

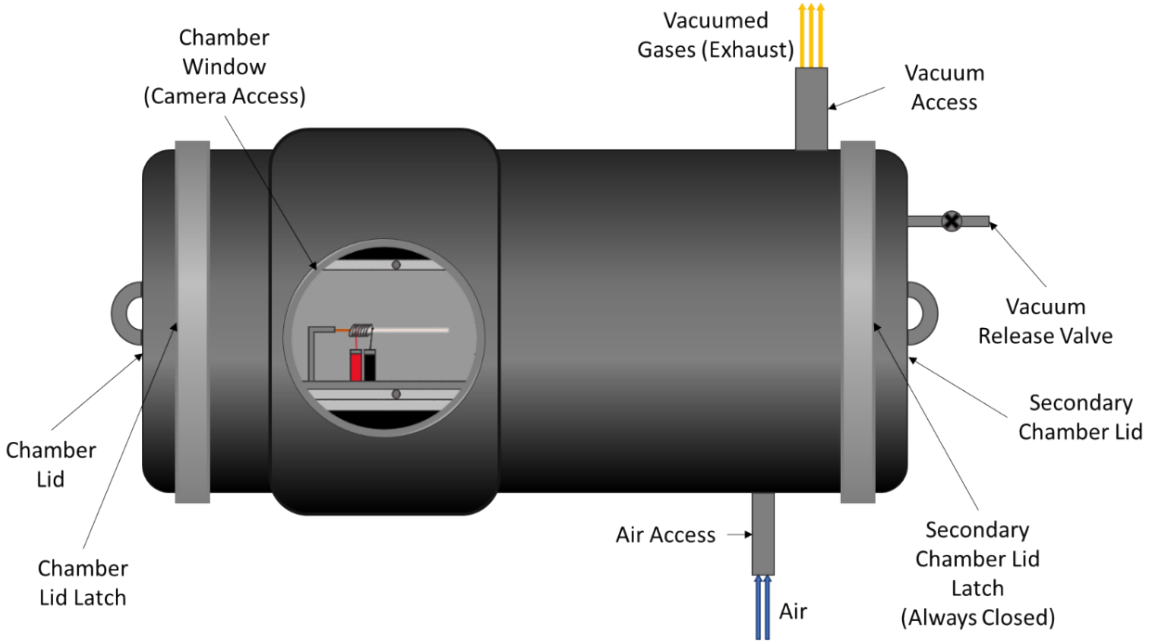

Fig. 1. External view of pressure chamber experimental setup.

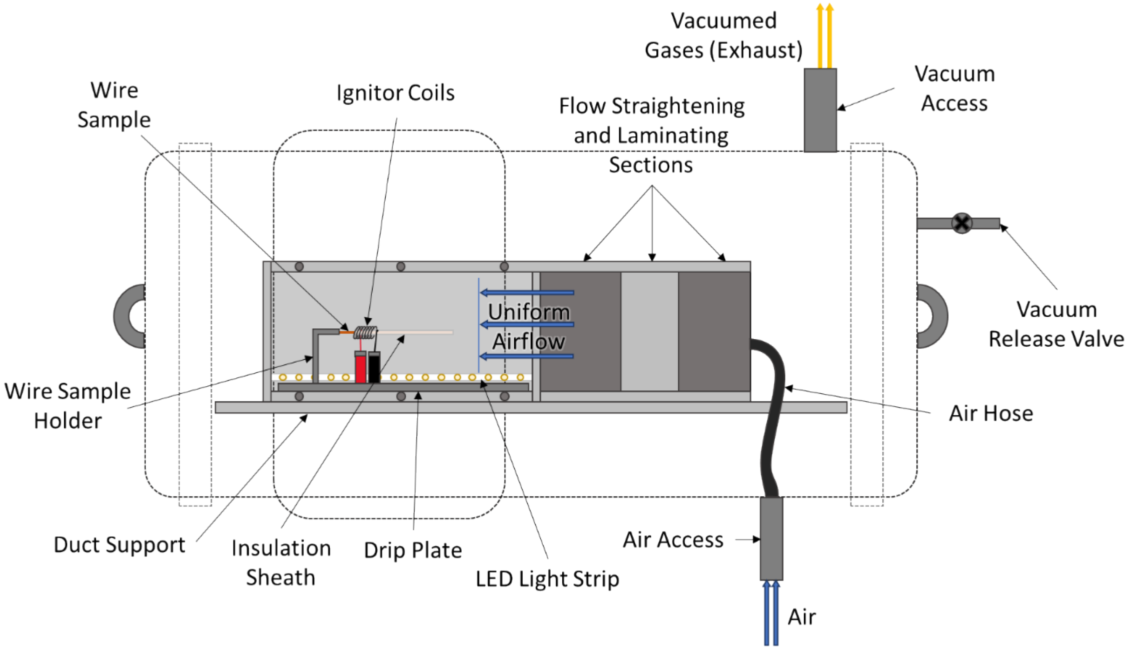

Fig. 2. Internal view of pressure chamber experimental setup.

2.2. Sample Description

All the tests were conducted with “laboratory” wires consisting of 125mm-long copper cores and 100mm-long LDPE insulation sheaths. The copper cores had diameters of 0.64 mm, and the insulation sheaths had inner diameters of 0.7 mm and outer diameters of 4 mm, as shown in Fig. 3. Relevant material properties of copper include its density of 8,880 kg/m^2, thermal conductivity of 398 W/m·K, and specific heat of 390 J/kg·K. The relatively large size of the “laboratory” wires and the insulation material, while not intended to necessarily reproduce actual electrical wires, were selected to facilitate the interpretation of the experimental results and to compare the results with future experiments to be conducted on the ISS with the same type of wires. Unfortunately, the wire characteristics do not allow for the direct comparison of the present results with wires of previous experiments, such as those of ref. [19], but the primary objective of the work is to provide normal gravity data for comparison with future microgravity experiments [24]. Also shown in Fig. 3 is that the arrangement of the insulation along the metal core for the experiments was such that their tips were aligned at one end and bare metal core was exposed on the other, allowing the bare end to be secured by the sample holder.

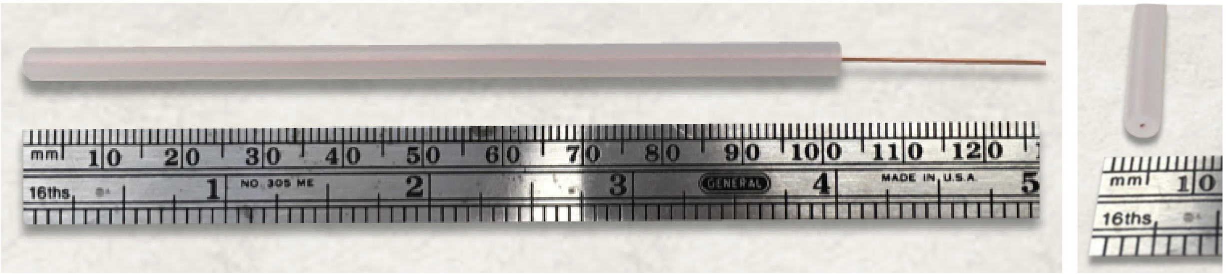

Fig. 3. Wire sample with (left) core length of 125 mm and LDPE insulation length of 100 mm and (right) 0.64mm-diameter copper core and LDPE insulation with 4 mm outer diameter.

2.3 Experimental Procedure

In all tests, the samples were ignited by a 0.64mm-diameter nichrome wire that was coiled into a diameter of about 8 mm with 6 loops and powered with a Variac power source, which was set to provide an RMS voltage of approximately 15 V, resulting in a power output of approximately 155 W. Due to the thickness of insulation on the sample, an ignition time of 35 s was used.

During each experiment, once the sample was in place, the camera was started to record real-time video. An LED light strip was used to illuminate the wire sample for approximately 3 s at the start of the experiment, so the insulation on the sample, which provided a length scale, could be more easily measured during post image-processing of the videos. Then, the Variac power source was turned on for the desired amount of time. Once the power source had been switched off, the test was allowed to continue until the flame propagated along the whole length of the wire or the burning along the wire naturally extinguished. During the tests, melting and dripping of the LDPE insulation occurred, and a drip plate was placed beneath the length of the wire sample to collect the fallen material which was weighed after the test. Six tests were conducted for each test condition.

2.4 Post Processing and Video Analysis

After the experiments were conducted, the videos were analyzed using an interactive image processing script, which had been developed previously [16], [17], to extract geometric information about the flame at regular intervals during its spread. The intervals were selected such that 50 to 80 of the recorded frames of steady flame spread were examined; edge effects were not considered. In each of the analyzed frames, the position of the leading edge of the flame was recorded. With further analysis, these locations of the leading edges were fit with a linear regression, and the flame spread rate was calculated by the slope of the regression, which was found to be linear in all cases. Using the length of the insulation sheath on the sample as a length scale, a conversion from pixel coordinates to lab scale (mm) was made. Subsequent analysis of the videos was used to determine the frequency of insulation dripping by counting the number of drips that occurred during steady spread and noting the corresponding time frame.

3. Results and Discussion

3.1 Effect of Reduced Ambient Pressure and Opposed Flow Speed on Flame Spread

Fig. 4 shows the combined effect of reduced ambient pressure and various opposed flow rates on the flame spread rate along the wire samples. In this figure, the averages of the measured data points are presented, and the included error bars represent a 95% confidence interval. This data shows a decrease in flame spread rate as the speed of the opposed flow was increased, agreeing with ref. [19], which found flame spread rate to either decrease or remain constant (depending on wire core material) as the opposed flow speed was increased. However, regarding potential error in this study, it should be noted that the average uncertainty in the flame spread rate data was calculated to be 0.06 mm/s (assuming an accuracy within 5 mm when tracking the positions of the flame front), which is comparable to the average 0.06 mm/s difference in the flame spread rate observed between the two tested flow speeds, so more testing may be need to confirm this effect.

Looking at the effect of pressure in Fig. 4, the flame spread rate along the wire insulation was found to decrease as the pressure decreased, which is consistent with some previous findings [20]. As well, the aforementioned calculated uncertainty of 0.06 mm/s in the flame spread rate is significantly less than the total variation of 0.2 mm/s in the flame spread rate across the range of tested ambient pressures. Interestingly, however, this trend showing that reducing ambient pressure resulted in slower flame spread is in opposition to the trend observed in ref. [19]. Additionally, there is only partial agreement with the results of Hu *et al.* [22], which showed that the flame spread rate along thin LDPE-insulated copper wires (0.30 or 0.50 mm diameter cores) first decreased then increased with decreasing pressure. The difference in the results may be due to the different copper core diameters used in the studies or because they were performed in the absence of a forced flow.

While the exact effects of both the pressure and flow speed on the flame spread behavior, most likely due to a combination of their effect on the rate of heat release by the flame and the thermal contact with the wire core, remain slightly ambiguous, Fig. 5 makes it clear that there is, indeed, an effect taking place. Here, it can be seen that there is a change in the flame shape and appearance for reduced ambient pressures and increasing opposed flow speeds. It is also observed from Fig. 5 that the flame became less luminous and weaker at lower pressures, which agrees with previous studies [15], [21]. Because the heat release rate decreases for weaker flames, the heat that is transferred from the flame into the wire insulation and core also decreases, thus providing an explanation for a reduced flame spread rate [22].

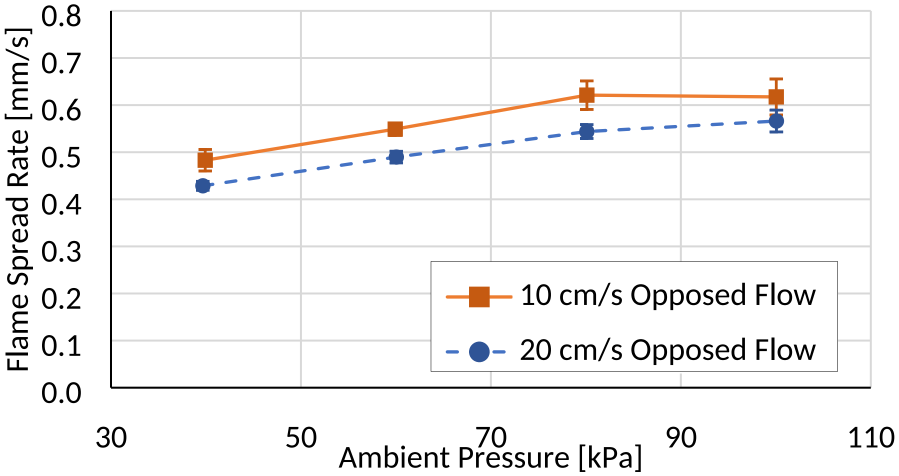

Fig. 4. Effect of reduced ambient pressure and opposed flow speed on flame spread rate over LDPE-insulated copper wire.

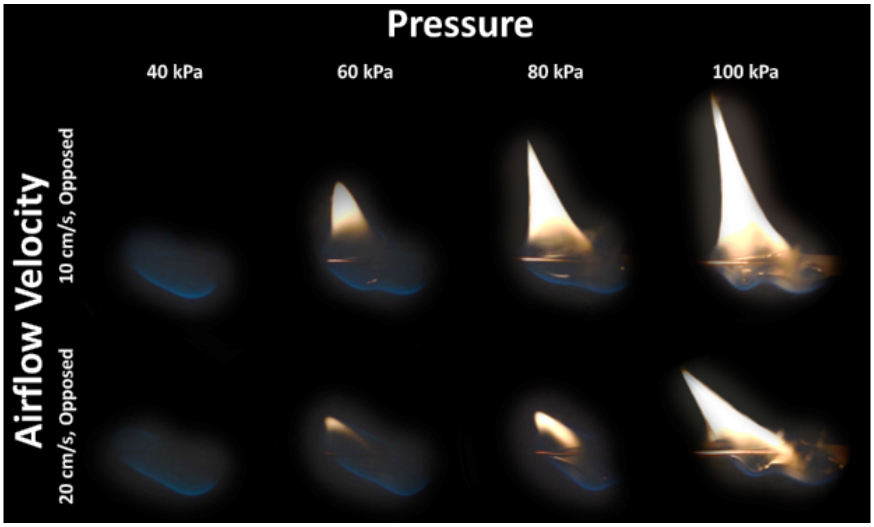

Fig. 5. Effect of reduced ambient pressure and opposed flow speed on flame appearance during flame spread along LDPE-insulated copper wire.

Also shown in Fig. 5 is that as the opposed flow speed increased, the flame leaned toward the wire in the direction of flow, as seen previously in tests with opposed flows [19]. The reduction of the opposed flow flame spread with the flow speed has been observed in previous studies with flat surfaces and was attributed to chemical kinetic effects on the flame [25]. However, as discussed in prior studies [19], the presence of the conducting core also plays a role in the heat transfer from the flame to the unburnt insulation ahead of the flame front. It is thought that the flame leaning observed when the flame is subject to opposed flows increases the heat transfer from the flame to the wire, due to their increased proximity. This increase in heat transfer from the flame, and subsequently along the core, again reduces the amount of heat transfer from the flame to the pre-heat zone ahead of the flame. The mechanisms controlling the effect of the flow velocity on the flame spread are similar to those discussed in ref. [19], thus their discussion is not repeated here; the reader is referred to the work of ref. [19] for a detailed description of these mechanisms.

3.2 Effect of Reduced Ambient Pressure and Opposed Flow Speed on Insulation Dripping

Fig. 6 and Fig. 7 show the effects of reduced ambient pressure and opposed flows on the dripping frequency and the total mass dripped of the LDPE insulation from the wire sample during flame spread, respectively. Just as in Fig. 4, in these figures, the averages of the measured data points are presented, and the included error bars represent a 95% confidence interval.

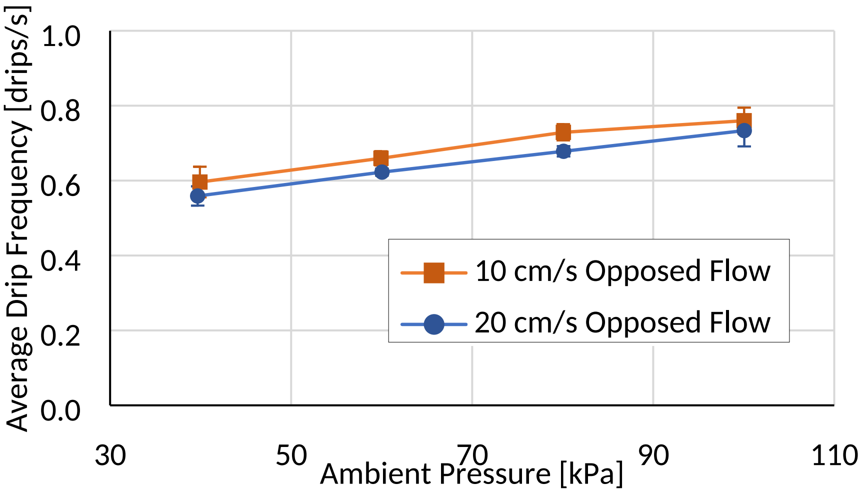

Fig. 6. Effect of reduced ambient pressure and opposed flow speed on drip frequency during flame spread along LDPE-insulated copper wire.

The trend in Fig. 6 shows that the frequency of insulation dripping decreased as pressure decreased. The average uncertainty for each test condition, assuming a discrepancy of 2 drips either above or below the actual counted value, was calculated to be 0.03 drips/s, which is considerably smaller than the total variation of 0.2 drips/s observed across the range of ambient pressures tested, but comparable to the 0.04 drips/s variation between the two flow speeds tested. Previous studies with thin wire insulation found that the insulation drip frequency increased with decreasing pressure [20], [21]. In these prior studies, thinner wires were used with core diameters of 0.50 mm, versus 0.64 mm in the current study, with thin insulation thicknesses of 0.5 mm [20] and 0.15 mm [21], versus 0.9 mm thickness in the current study. This geometry difference corresponds to substantially more insulation mass per unit length of the wires in the current study. Furthermore, some experiments were only performed on nichrome wires [20], which have a lower thermal conductivity than copper. Thus, it is not possible to directly compare the different results, and more research is needed to determine how the wire core properties, both material and diameter, as well as the amount of insulation impact the dripping behavior.

The results in Fig. 7 show that the total mass of insulation that dripped per flame spread test increased as the pressure decreased and slightly increased as the opposed flow speed increased. Here, the averages of the measured data points are presented, and the included error bars represent a 95% confidence interval. The uncertainty of this data is quite low at only 0.001 g due to the precision of the utilized mass balance. Therefore, because the difference in total mass dripped across the range of pressures is on average 0.1 g, and the average change in total mass dripped between the two tested airflows is 0.02 grams, it is observed that both pressure and flow speed have a notable effect on the mass of molten insulation dripping from the wire during flame spread.

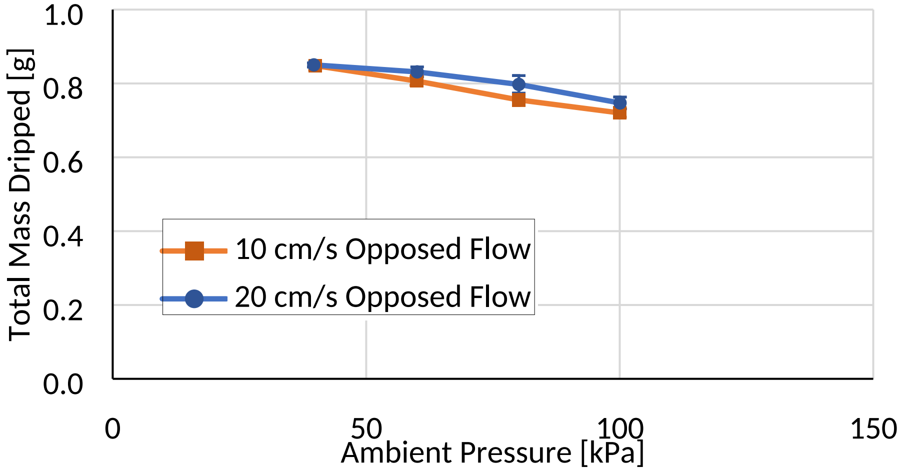

Fig. 7. Effect of reduced ambient pressure and opposed flow speed on total mass dripped during flame spread along LDPE-insulated copper wire.

Comparing the total mass of insulation dripped results with the frequency of insulation dripping from Fig. 6 in environments that were subject to different opposed airflows, it was found that slower flow speeds produced more frequent dripping with less total mass dripped. Since the flame spread rate decreased as the flow velocity increased, this result is like what was observed as the pressure was reduced. In other words, just as larger drops were observed at lower pressures, they were also observed at faster opposed flow speeds, and both conditions resulted in a substantially reduced flame spread rate.

As noted in prior studies [21], LDPE insulation is burnt less in low-pressure environments. It is thought that this effect can be attributed to the wire core acting as a significant heat sink to an already weakened flame. Regarding the core heat sink effect thought to occur at faster flow speeds, as discussed in previous studies [19], when heat is transferred to the core from the flame, a fraction is conducted ahead of the flame into the pre-heat zone helping flame spread, while a fraction, which is larger for opposed flows, is also conducted away along the bare end of the wire and subsequently lost to the ambient surroundings, which hinders flame spread. If it is assumed that the relative fraction of each is constant across these test conditions, increased heat transfer from the flame to the wire would mean more heat losses to the environment, but also a larger molten section of the preheat zone, as shown in Fig. 5. A larger molten section of the preheat zone would provide more conductive conditions for dripping, explaining the increase in total mass dripped. Thus, the phenomena of decreased flame spread rate and increased total mass dripped with increased opposed flow velocity are linked because they are both caused by an increase in flame to metal core heat transfer.

4. Conclusions

The combined effect of reducing the ambient pressure and increasing the opposed flow speed on horizontal flame spread and dripping of copper-cored, LDPE-insulated wires was examined through experiments to increase understanding of the fire hazard electrical wires pose in spacecraft environments, and to provide data for comparison with future microgravity experiments. Results showed that the flame spread rate as well as the molten, burning insulation drip frequency decrease both with decreasing pressure as well as increasing opposed flow speeds. Contrarily, it was found that the total mass dripped increased both with decreasing pressure and increasing opposed flow speeds. It is thought that these results are due to the wire core acting as a heat sink and drawing a significant amount of heat out of the flame, which affects both the rate of flame spread and the rate of insulation burning. Comparison with results from other studies with wires of different core material or dimensions show that the effect of the environmental parameters on the flame spread and mass burning of insulated wires depends strongly on the core conductivity as well as core and insulation diameters. Consequently, data obtained from specific wire tests should not be extended to other wires without justification.

5. Acknowledgements

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Figure captions

Fig. 1. External view of pressure chamber experimental setup.

Fig. 2. Internal view of pressure chamber experimental setup.

Fig. 3. Wire sample with (left) core length of 125 mm and LDPE insulation length of 100 mm and (right) 0.64mm-diameter copper core and LDPE insulation with 4 mm outer diameter.

Fig. 4. Effect of reduced ambient pressure and opposed flow speed on flame spread rate over LDPE insulated copper wire.

Fig. 5. Effect of reduced ambient pressure and opposed flow speed on flame appearance of LDPE insulated copper wire.

Fig. 6. Effect of reduced ambient pressure and opposed flow speed on drip frequency of LDPE insulated copper wire.

Fig. 7. Effect of reduced ambient pressure and opposed flow speed on total mass dripped of LDPE insulated copper wire.