JASMAC
Conference of the Japan Society of Microgravity Application

PS37

遠心力が加わるポリエチレン被膜電線上の火炎の燃え拡がりに及ぼす回転半径の影響

The effects of rotational radius on flame spread over LDPE-insulated wire in centrifuge

石川昇龍 [1]，金野佑亮 [1]，橋本望 [1]，藤田修 [1]，
Shoryu Ishikawa[1], Yusuke Konno[1], Nozomu Hashimoto[1] and Osamu Fujita[1]
[1] 北海道大学大学院工学院，Graduate school of Engineering Hokkaido university #1

1. Introduction and Background

Manned space exploration programs in Moon and Mars are planned by space agencies over the world. For instance, Artemis program led by NASA aims to send human astronauts to the Moon and Mars in 2020s and 2030s respectively. The competition for deep space explorations among the countries become more intense than ever, as it brings us state-of-the-art scientific discoveries and technologies and is related to the economy, and security. In near future, humanity will stay frequently in space, where gravity level and oxygen concentration are different from those on Earth. Ensuring the safety of stay in space is important. Fire in the spacecrafts or in the habitation modules is a potential threat to the safety of people. Previous research suggests that some materials might be more flammable in microgravity than on the ground. Sacksteder et al. showed that the minimum oxygen concentration required to burn the thin cellulose paper is lower under low-gravity conditions than under gravity on the ground.[1)]. Thus, flammability test of materials used in spacecrafts become vital to ensure the fire safety in space. For example, NASA-STD-6001B examines whether the material used in the spacecraft is adequate or not in terms of flammability. However, the NASA-STD-6001B test are conducted on the ground, which cannot evaluate the flammability of the materials in spacecraft environment. Consequently, flammability tests under micro- or low-gravity environments are crucial for the fire safety. The authors started FLARE-3 project with JAXA which aims to evaluate the flammability of materials under low-gravity environments. By utilizing centrifugal force under micro-gravity environments such as International Space Station (ISS), the pseudo low-gravity environments will be generated, and flammability tests will be conducted. The authors expect that the Coriolis force affects the combustion process of the materials in ISS experiments. In addition to that, gas flow induced by centrifugal force and Coriolis force in the experimental vessel would be complicated. It is therefore worth to conduct experiments on the ground to investigate the effects of Coriolis and centrifugal force on the combustion before bringing experimental samples to ISS and running experiments.

The previous research by authors involves combustion experiments with low density polyethylene (LDPE) coated copper and nichrome wires to gain the insight into the limiting oxygen concentration for both samples under hyper gravity conditions, flame spread rate (FSR) as a function of centrifugal force and the differences between highly conductive copper wire and less conductive nichrome wire[2]. It turned out that FSR for flames over copper wire is drastically reduced due to the flame tilt, whereas that over nichrome wire is not. Moreover, the relative importance of Coriolis force increases with a decrease in centrifugal force. However, the previous research has raised a question of how the rotational radius affects on the flame over the wire. There are numerous pairs of rotational radius and rotational speed that realize a certain level of centrifugal force. Thus, in this study authors conduct combustion experiments of the wire samples changing the rotational radius while keeping the same centrifugal force at the wire sample location.

2. Overview of the experiments

2.1. Experimental apparatus

Figure 1 shows schematic of the centrifuge used for the experiments. Figure 1(a) indicates the utilized sensors in the experiments and the placement method of samples. Cylindrical, transparent vessel rotates at constant angular velocity realizing hyper-gravity environment at the sample location. The wire sample is placed parallel to the rotational axis and hold by an upper and a lower plate. Two circle windows on the upper and lower surface of the chamber enables us to exchange the used sample with new one. The acceleration sensor, the oxygen pressure sensor, total pressure sensor are mounted on the rotating vessel which send data to the datalogger. Figure 1(b) shows view angle of two cameras. Flames are tilted by centrifugal and Coriolis force; therefore, two cameras are needed to observe the bi-directional inclination of the flames. The camera observing the flame tilt toward the circumferential direction is named "Front Camera", while the other one observing the flame tilt toward the radial direction is named "Side Camera".

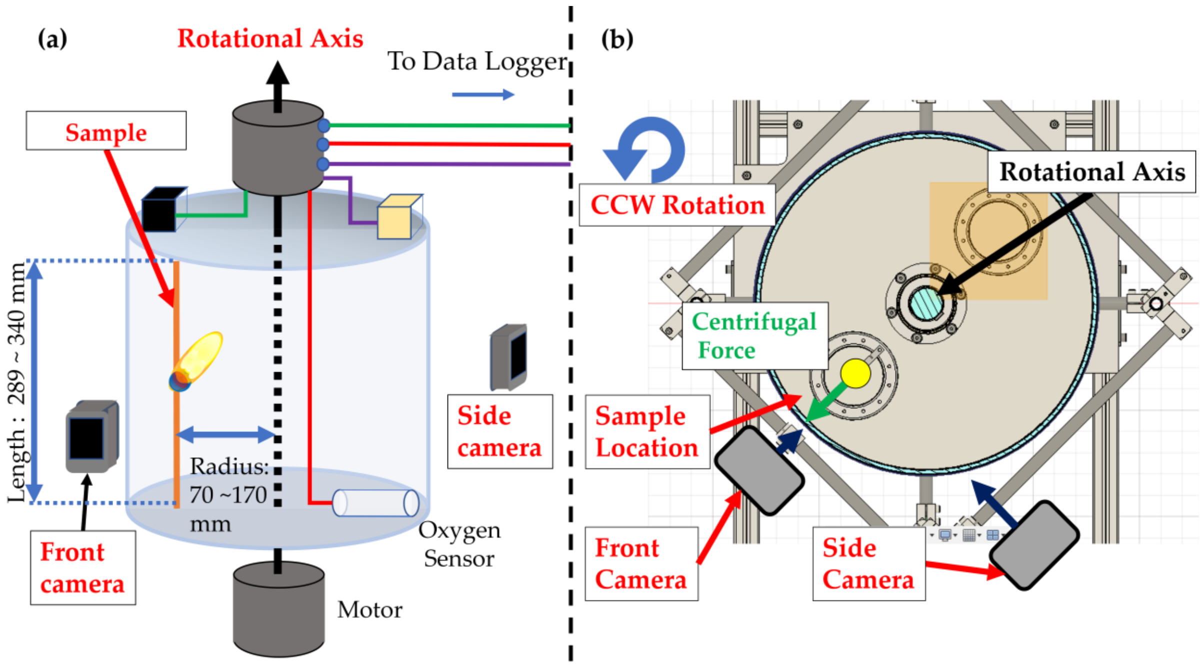

Figure 1 Components in the experimental apparatus, (a) and location of "Front camera" and "Side camera", (b).

2.2. Experimental procedure

First, the wire sample is fastened by the upper and lower plate and tensioned by a spring to avoid the deflection of the wire due to thermal expansion during flame spread process. Next, a vacuum pump exhausts the gases inside the vessel and prevent combustion products affecting on the ongoing experiment. After repeating the vacuuming process, the vessel powered by a motor start to rotate. Coil-shaped igniter, made of canthal wire ignites the wire sample after gases in the vessel achieve the rigid-body rotation. Two cameras record the flame spreading downward with 29.97 FPS. Furthermore, data from the oxygen, the total pressure, and acceleration sensor are recorded by a datalogger every 0.1 seconds.

2.3. Experimental conditions

Figure 2 is the image of how the samples are placed in the experimental vessel. The total pressure and the oxygen volume fraction in the vessel is fixed at $100\ kPa,\ 21\%$ respectively. The location of the wire sample is $r = 70\ mm$ and $r = 170\ mm$ where $0.5\ G,\ 1\ G,\ 2\ G$ centrifugal force is applied. Centrifugal acceleration, $\alpha_{centrifugal}$ is given as follow:

$$\alpha_{centrifugal} = r\omega^2, \quad (1)$$

where r is the distance between rotational axis and wire sample and ω is the rotational velocity of the experimental vessel. Two rotational velocities were set for locations so that the magnitude of the centrifugal force at the sample location does not change. To confirm the reproducibility of the experimental data at experiments are repeated three times at each condition.

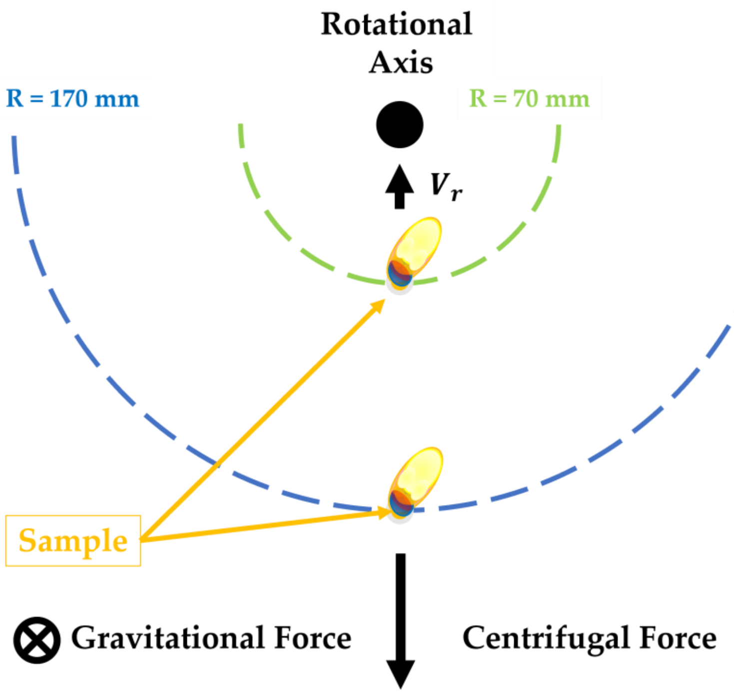

Figure 2 Location of the wire samples

2.4. Analysis method

Videos captured by two cameras are analyzed by a software developed by authors. It detects the upstream edge of the flame, traces the time-evolution of the location of the upstream edge and finally converts from pixel scale to length scale. Figure 3 shows time history of the flame front position during the flame spread and the determination method of the flame spread rate. Using least square method, authors derived the regression line whose inclination is FSR. In addition to the FSR analysis, the location of flame tip, the downstream edge of the flame is analyzed. Here, a point on a contour of a luminous flame where the curvature is maximum is regarded as a flame downstream edge. Wire vector can be obtained by linking the upper end and lower end of the wire while, flame vector is a vector connecting a flame upstream and downstream end. The angle between the wire and the flame, α is obtained by the inner product of these vectors divided by magnitude of both vectors as described in equation (2).

$$\alpha = \arccos\left(\frac{\vec{f}\cdot\vec{w}}{|\vec{f}|\cdot|\vec{w}|}\right) \tag{2}$$

As shown in Figure 4, $\vec{f}$ and $\vec{w}$ are flame vector and wire vector, respectively. The distance between the flame upstream edge and flame tip is the magnitude of $\vec{f}$. α_c and α_r are defined as the inclination angle by Coriolis force and centrifugal force, respectively. By using $\vec{f}$, α_c and α_r, the horizontal component of the length of flame vector can be calculated. d_r, d_c is the horizontal component of flame vector in the radial direction and circumferential direction as indicated in equation (3), (4). Authors performed the analysis every 30 frames, almost one second to observe the overall behavior of a flame in an experiment.

$$d_r = |\vec{f}|\cdot\sin(\alpha_r) \tag{3}$$

$$d_c = |\vec{f}|\cdot\sin(\alpha_c) \tag{4}$$

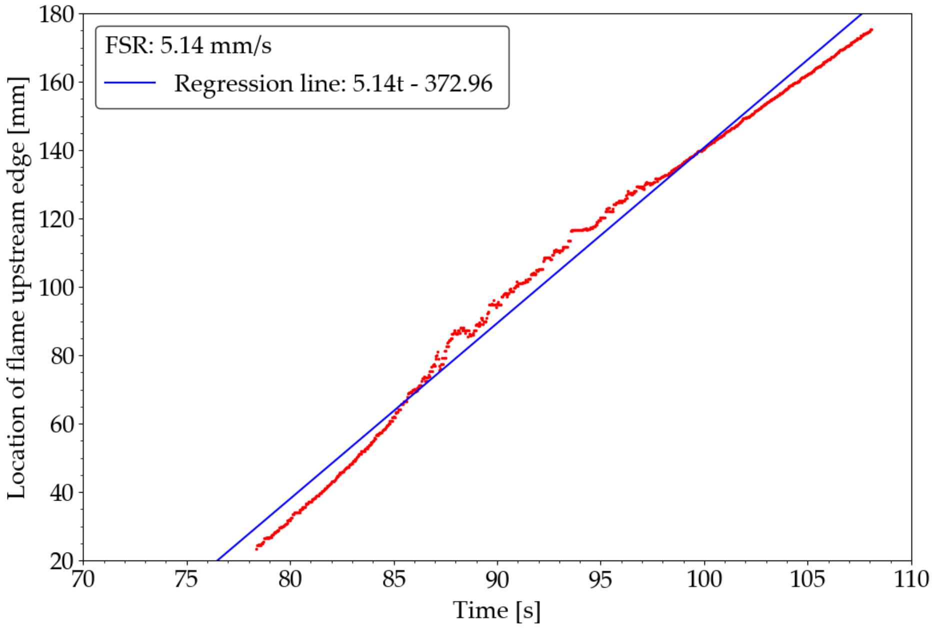

Figure 3. Determination of flame spread rate (FSR) by using least square method

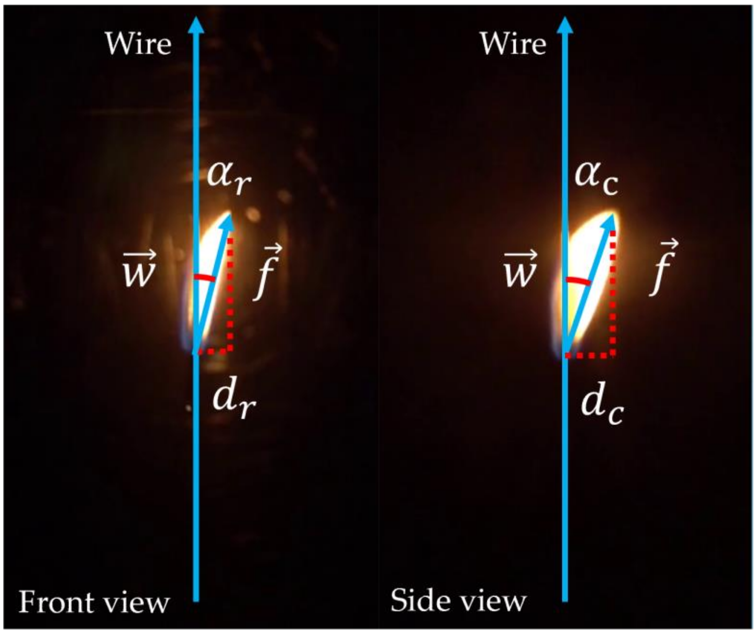

Figure 4. Defining the inclination angle between a wire and a flame by calculating inner product of wire vector and flame vector divided by the magnitude of both vectors

3 Result and discussion

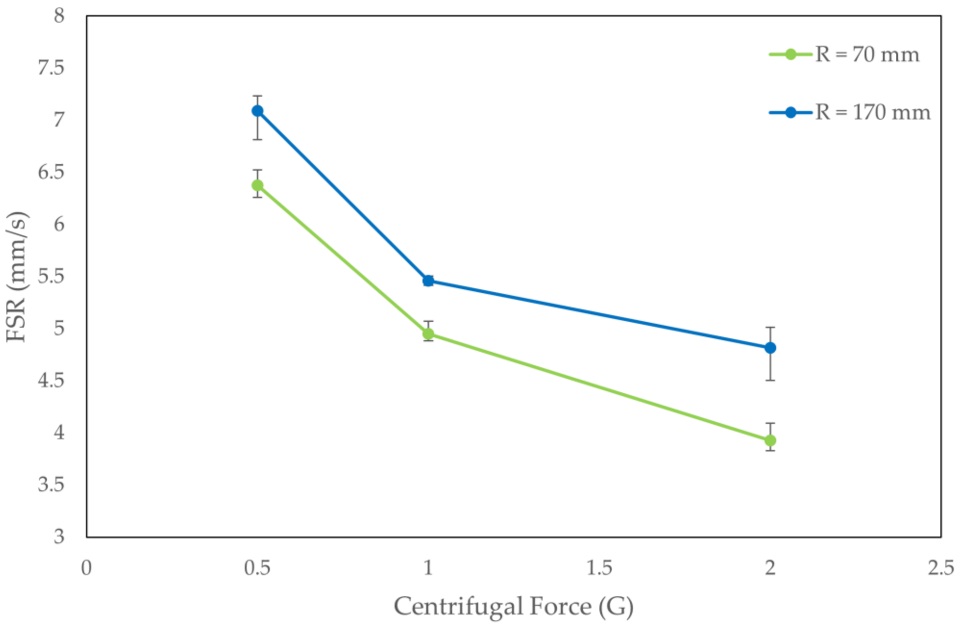

Figure 5. Flame spread rate (FSR) as a function of centrifugal force

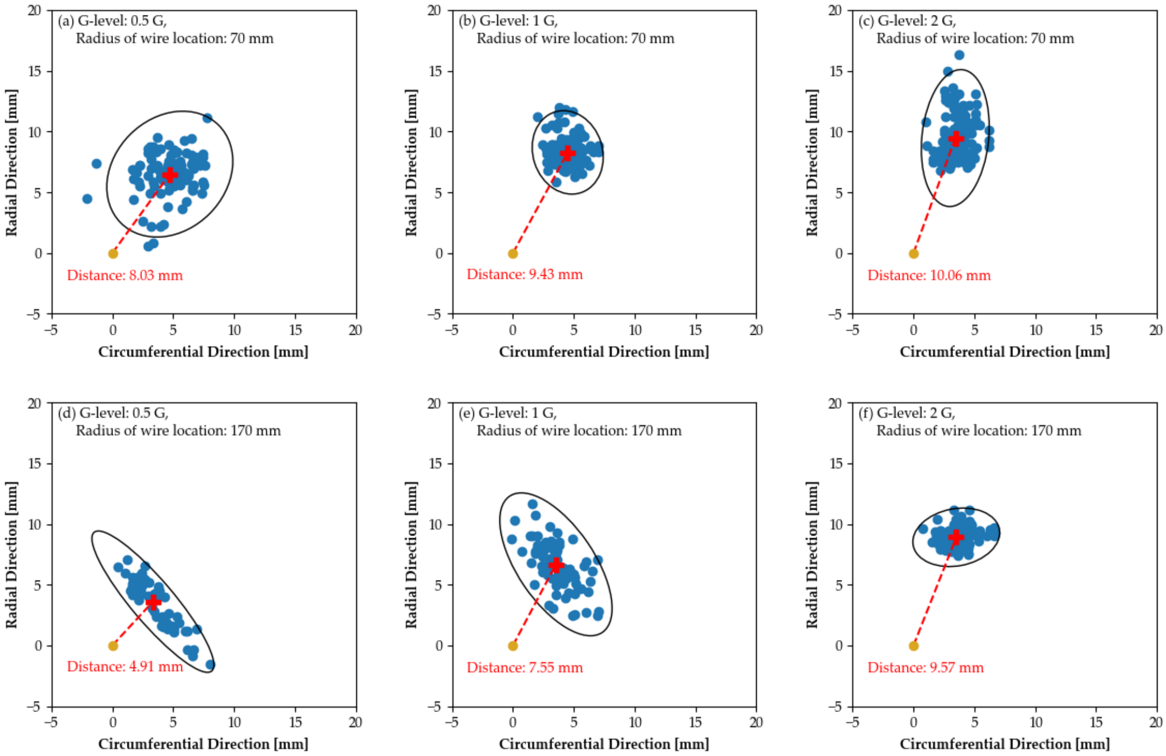

Figure 6. Scattering of the displacement of downstream edge of the flames in the radial and circumferential direction

Figure 5 shows how the FSR changes as the centrifugal force applied to the wire sample increases. The error bar ranges from the minimum FSR to the maximum FSR of each experimental condition. It reveals that FSR decreases with decreasing the rotational radius of the wire sample. FSRs over the wire at $r = 170\ mm$ are higher than those over the wire at $r = 70\ mm$.

Figure 6 shows how the flame tip moves around the sample wire seen from the direction of vertical axis of cylindrical vessel. The horizontal displacement from the origin is tilt of the flame in the circumferential direction, which means how much the flame is bent by the Coriolis force. The vertical displacement from the origin is tilt of the flame in the radial direction, which means how much the flame is bent by the centrifugal force. As the value in vertical axis increases, a flame tip become more closer to the center of the cylindrical vessel. Yellow dots at origin are the location of the wire sample. The red plus sign is average displacement of flames tip. The black solid ellipse indicates confidence ellipse (3σ) in which 99.7 % of the flame tips are if one assumes that the data follow normal distribution. The distance between a wire sample and the averaged displacement of the flame tip is written in each graph. Since each experiment was repeated three times, all the data of flame tips under the same experimental condition were combined and analyzed. The top and bottom rows are the experimental results for $r = 70\ mm$ and $r = 170\ mm$ respectively. Experimental results at 0.5 G, 1 G, 2 G are placed from the left one.

Nakamura et al revealed that heat transportation mechanisms in the flame over the highly conductive copper wire is dominated by the heat conduction through the wire core[3]. So, it is considered that the amount of heat transported to the unburnt insulation of the wire by solid heat conduction can be estimated by measuring the extent to which the flame touches the burnt core for flames that is tilted away from the wire. The much heat is transferred to the unburnt coating, the faster the FSR becomes. As shown in Figure 5, FSRs over wire at $r = 70\ mm$ are lower than those at $r = 170\ mm$. In Figure 6, the average displacement of flames at $r = 70\ mm$ are far away from the wire compared with that at $r = 170\ mm$ for the same centrifugal force condition. As the distance between a wire sample and the averaged displacement of the flame tip increases, a flame over a wire makes less contact with the burnt wire. Therefore, thermal conduction though the wire core under $r = 70\ mm$ conditions is suppressed and FSRs for these conditions are lower than FSRs for $r = 170\ mm$ conditions. As shown in Figure 6, the confidence ellipses for $r = 170\ mm$ are slenderer than those for $r = 70\ mm$ with exception of 2 G experiments. As a confidence ellipse becomes round, it means that the magnitude of Coriolis force becomes stronger relative to that of the centrifugal force. Since the rotational velocity of the vessel is higher at $r = 70\ mm$ than that at $r = 170\ mm$, the magnitude of Coriolis force seems to become more dominant at $r = 70\ mm$.

4 Conclusion

In this study, the authors conducted combustion experiments of the low-density polyethylene (LDPE) coated wire samples under pseudo-hyper-gravity environments by using centrifugal force in a centrifuge. Two important variables for the experiments were the rotational radius, r, the distance between the rotational axis and wire samples and the magnitude of centrifugal forces, G.

- Flame spread rates over the wire at $r = 170\ mm$ are higher than those over the wire at $r = 70\ mm$ because the flame under $r = 70\ mm$ condition makes less contact with the burnt wire, which reduces heat transferred to the unburnt insulator.

- The ratio of the magnitude of Coriolis force to that of the centrifugal force is higher for $r = 70\ mm$ conditions than for $r = 170\ mm$ conditions.

Acknowledgement

This study was partly supported by JAXA "Kibo" utilization feasibility study, JKA and its promotion funds from KEIRIN RACE, and JSPS KAKENHI Grant numbers JP23K13258 and JP24K21649.

References

1) KURT R. SACKSTEDER, JAMES S. T'IEN: BUOYANT DOWNWARD DIFFUSION FLAME SPREAD AND EXTINCTION IN PARTIAL-GRAVITY ACCELERATIONS: Twenty-Fifth Symposium (International) on Combustion/The Combustion Institute, (1994) pp. 1685 1692, DOI: https://doi.org/10.1016/S0082-0784(06)80816-7
2) Yusuke Konno, Shoryu Ishikawa, Nozomu Hashimoto, Osamu Fujita: Downward flame spread and extinction over electric wires placed in a ground-based centrifuge: Proceedings of the Combustion Institute Volume 40, Issues 1–4, (2024), 105199, DOI: https://doi.org/10.1016/j.proci.2024.105199
3) Yuji Nakamura, Nobuko Yoshimura, Hiroyuki Ito, Keisuke Azumaya, Osamu Fujita: Flame spread over electric wire in sub-atmospheric pressure: Proceedings of the Combustion Institute 32 (2009) 2559–2566, DOI: https://doi.org/10.1016/j.proci.2008.06.146