JASMAC

Conference of the Japan Society of Microgravity Application

OR2-3

炭素繊維配合方向の異なる炭素繊維強化プラスチックの下方燃え拡がり挙動

Downward flame spread over carbon fiber reinforced plastic with different carbon fiber orientations

松川直生 [1], 松本圭佑 [2], 小林芳成 [3], 高橋周平 [4]

Naoki MATSUKAWA[1], Keisuke MATSUMOTO[2], Yoshinari KOBAYASHI[3], and Shuhei TAKAHASHI[4]

1 岐阜大学大学院自然科学技術研究科エネルギー工学専攻，Department of Energy Engineering, Graduate School of Natural Science Technology, Gifu University,

2 岐阜大学大学院自然科学技術研究科エネルギー工学専攻，Department of Energy Engineering, Graduate School of Natural Science Technology, Gifu University,

3 岐阜大学工学部機械工学科，Department of Mechanical Engineering, Faculty of Engineering, Gifu University,

4 岐阜大学工学部機械工学科，Department of Mechanical Engineering, Faculty of Engineering, Gifu University,

1. Introduction

Flame spread over solid materials has been extensively studied to investigate the effects of shape, thermophysical properties, and ambient atmospheres on the flame spread characteristics, such as flame spread rate, flammability limit, and so on. For example, Fernandez-Pello et al. investigated the effect of thickness of materials on flame spread rate [1]. Takahashi et al. examined the effect of ambient atmospheres and found that the flame spread rate reached the maximum under oxygen and argon mixtures [2]. These studies address polymers—e.g., polymethyl methacrylate (PMMA)—which are thermally isotropic mono-materials. Such materials have low thermal conductivity of less than 1 W/m/K, and therefore the solid-phase heat transfer is very small. However, there are some objects where the solid-phase heat transfer should be considered, for example, electrical wires consisting of polymer insulations and a metal core [3]. Flame spread over the electrical wires has been studied, while that over flat high-thermal-conductivity materials has not been well understood.

In recent years, carbon fibers (CFs) attract a lot of attention and are used extensively because they have superior properties, e.g., high strength, high electric conductivity, and low thermal expansion. Carbon fiber reinforced plastics (CFRPs) are an example of composite materials that consists of the CFs and applied to a variety of products. The CFs are found to have very high thermal conductivity, and therefore the CFRPs are also a high-thermal-conductivity material. Although the literature on flame spread over the CFRP is very limited, Kobayashi et al. [4,5] found that the preheat zone of CFRP is much larger than that of PMMA ones due to the high thermal conductivity of the CFs.

As for the CFRP, the thermal properties are found to vary with the CF orientation. Probably the flame spread behaviors and characteristics would also change depending on the CF orientation. This work then studied the flame spread over the CFRP with an emphasis on the effects of the CF orientation. Thermally thin CFRP sheets were fabricated and combusted in buoyant flow with variable oxygen concentrations. The flame spread rate and the length of the solid-phase preheat zone (i.e., the solid-phase preheating length) were measured by processing direct and IR movies. The effects of the CF orientation is discussed via those flame spread characteristics.

2. Experiment

2.1 Carbon fiber reinforced plastic sheets with different carbon fiber orientations

The CFs are classified into two main types: polyacrylonitrile (PAN)-based CFs and petroleum pitch-based CFs. Their chemical structures are different, thereby resulting in different physicochemical properties. The pitch-based CFs have higher thermal conductivity than the PAN-based ones, and therefore the solid-phase heat transfer is greater in the flame spread over pitch-based CFRPs. This study then selected the pitch-based CFRPs as a test sample. A variety of differently oriented CFRP sheets, as illustrated in Fig. 1, were fabricated by laminating two unidirectional CF sheets impregnated with epoxy resins, i.e., prepregs (Nippon Graphite Fiber, NT91500-525S) in different direction and curing them in a high temperature furnace (Yamato Scientific, FO810) at 403 K (130 ℃) for one hour. Carbon fiber orientations of those CFRP sheets are symmetric for longitudinal direction of CFRP sheets. Specifications of the used prepreg are listed in Table 1. The prepared CFRP sheets can be categorized as "thermally thin" because of the high thermal diffusivity of ~2.3×10^2 mm^2/s. In the flame spread tests, epoxy resin sheets with a thickness of 0.5 mm were also combusted to compare their flame spread behaviors and investigate the effects of conductive heat transfer through the CFs. The epoxy resin sheets were the same as that used in [5].

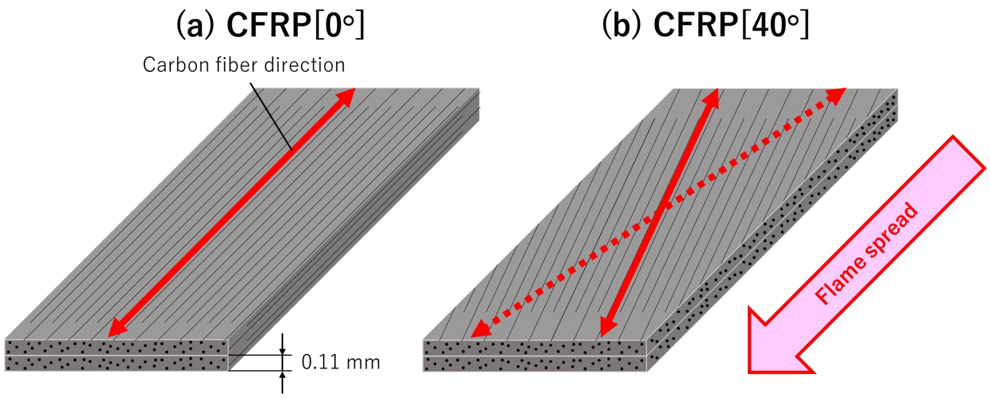

Fig. 1 Schematic of carbon fiber reinforced plastic (CFRP) sheets with different carbon fiber orientation: (a) CFRP [0°], and (b) [40°].

Table 1 Specifications of unidirectional carbon fiber sheets impregnated with epoxy resin.

Manufacturer / Model	Nippon Graphite Fiber / NT91500-525S
Type of carbon fiber	Mesophase pitch-based continuous carbon fiber
Type of thermosetting resin	Epoxy resin
Thickness	0.11 mm
Fiber areal weight	150 g/m^2
Resin content	25 wt%
Thermal conductivity	500 W/m/K

2.2 Apparatus for downward flame spread tests

The fabricated CFRP sheets were cut 120 mm long by 30 mm wide and inserted vertically into a stainless-steel sample holder (Fig. 2). Note that this work studied downward flame spread to facilitate an analysis as much as possible. The size of combustion part was 120 mm long by 20 mm wide. A 0.5-mm-thick nichrome wire was equipped with the sample holder to ignite the CFRP sheets. The nichrome wire was energized with 150 W (20 V × 7.5 A) and then turned off once a self-sustaining flame spread was recognized. Locating the sample holder with the CFRP sheets in the glovebox allowed oxygen concentration in the atmosphere to vary. The flame spread tests were conducted in variable oxygen concentrations at a total pressure of 0.1 MPa. Pressure and oxygen concentration were constantly monitored during the flame spread tests via a manometer (SIBATA, DM-1) and an oxygen meter (JIKCO, JKO-25LD3), respectively. Note that the glovebox was so large ($1 \times 1 \times 1$ m^3) that a decrease in oxygen concentration due to combustion was small enough to be negligible. This work defined "flame spread" if a flame could spread and reach the point which was 4 cm above from the bottom edge of the CFRP sheets and "no flame spread" if a flame was extinct before reaching the above point. Flame spread behaviors were recorded via a video camera (Sony, HDR-CX470), and the in-plane temperature distribution during flame spread was visualized via an infrared camera (Nippon Avionics, InfRec S25). The flame spread tests were repeated at least three times for each condition to quantitatively assess the experimental uncertainty.

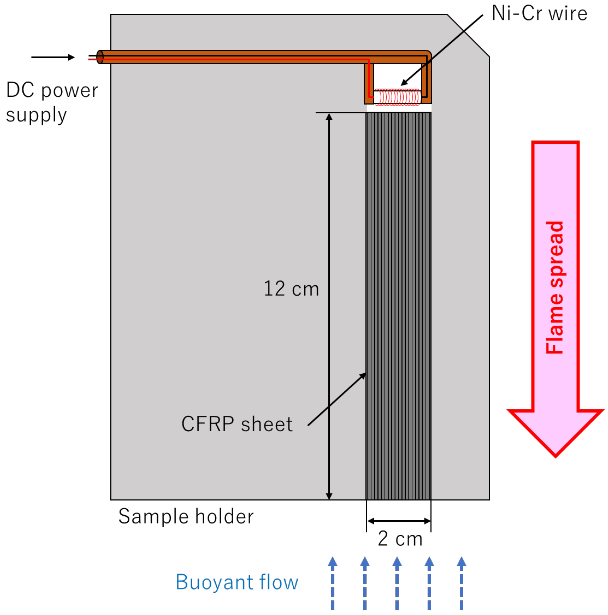

Fig. 2 Schematic of sample holder for buoyant flow downward flame spread tests.

3. Results

3.1 Flame spread behaviors

Figure 3 shows direct and IR images of the flame spread behaviors over the CFRP sheets [0°], [10°], [20°], [30°], and epoxy resin sheets as a reference. Note that oxygen concentration was the limiting oxygen concentration (LOC) of the five tested samples, as discussed in the following section, and the temperature shown in a color bar is a reference temperature where a black body was assumed, because the correct emissivity of the surface of the CFRP sheets was unknown. As seen in the direct images in Fig. 3, yellow luminous flames were observed for all the sheets, which indicates that much soot was produced. For the CFRP in Fig. 3(a)-(d), sooted CFs were left in the burnout region, while epoxy resin sheets in Fig. 3(e) did not remain after a flame spread. This indicates that the flame that spread over CFRP was driven by the pyrolysis of epoxy resins, not carbon fibers. This makes sense because the pyrolysis temperature of CF and epoxy resin are quite different, 850 K and 670 K, respectively. As seen in IR images of Fig. 3(a)-(e), the preheat zone of the CFRP sheets (the area between red and green) was much larger than that of the epoxy resin sheets. In addition, the leading edge of preheat zone (the boundary line between green area and sky blue area) gradually rounded with an increase in CF orientation angle. This is easily understood by comparing the IR images of CFRP [0°] with those of CFRP [30°]. This indicates that CF orientation controls the solid-phase heat transfer and is important for fire safety because the flammability could be estimated from the CF orientation. Comparing the attached time and the position of flames among Fig. 3(a)-(e), the flame spread of the CFRP was much faster than that of the epoxy resin because of the high thermal conductivity of the CFs (see Table 1). In other words, the CFs act as a heat conductor to facilitate the flame spread. The difference in quantitative flame spread characteristics between the four CFRP sheets is discussed in Section 3.3.

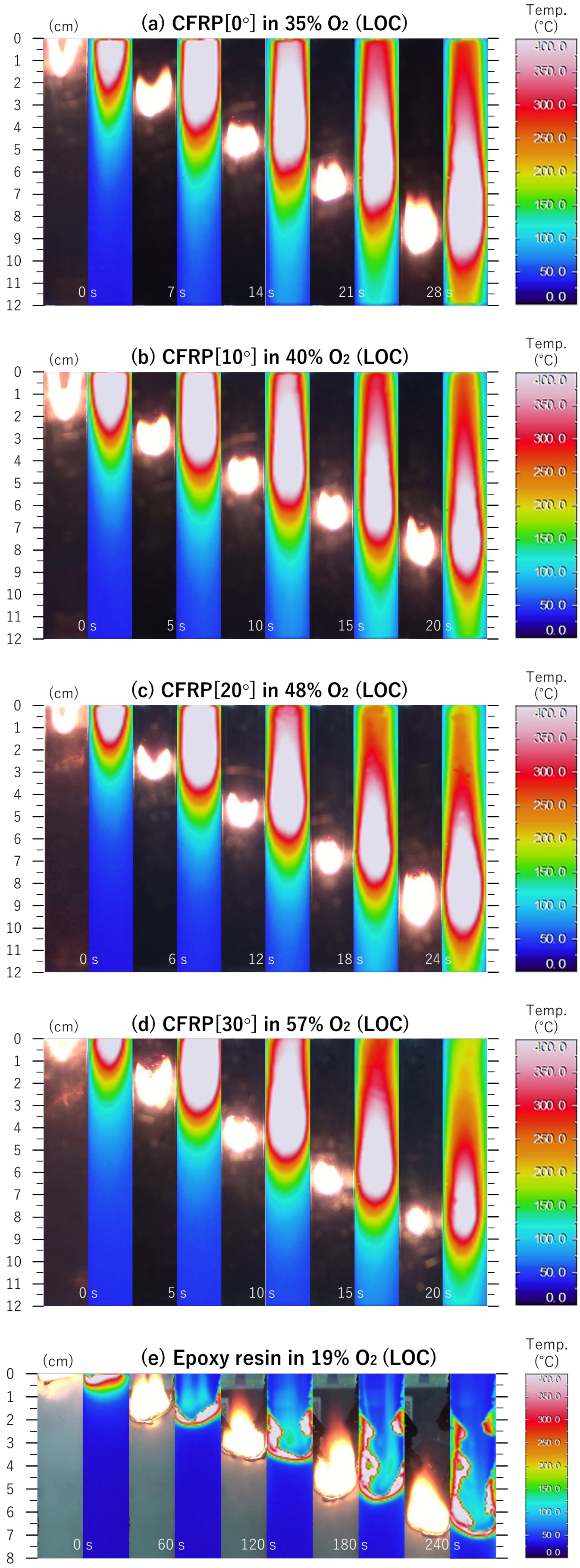

Fig. 3 Direct and IR images of buoyant flow downward flame spread at the LOCs: (a) CFRP [0°] at 35% O_2, (b) CFRP [10°] at 40% O_2, (c) CFRP [20°] at 48% O_2, (d) CFRP [30°] at 57% O_2, (e) Epoxy resin at 19% O_2. Note that the temperature shown in a color bar is a reference temperature where a black body was assumed.

3.2 Flammability: limiting oxygen concentration

Flammability of CFRP sheets is plotted as a function of CF orientation angle (i.e., the angle of prepreg relative to the other) in Fig. 4. This work defined the LOC as the minimum oxygen concentration where flame spread was achieved. The LOC significantly increased with CF orientation angle, and the CFRP sheets with an angle of more than 40° were not combusted even at 60% O_2, which was the maximum oxygen concentration achieved in this study. This is interesting that one material was found to have a variety of LOCs in a certain condition. At an angle of 40°, a flame did not spread at all and was extinct once the CFRP sheets were ignited. This fact implies that CFRP [40°] is safer than CFRP [0°] from fire. This is probably because the heat from the igniter was dispersed via the CFs and did not produce enough pyrolysates to sustain flame spread. Therefore, the flammability of CFRP varied with CF orientation angle. The flammability limit which distinguishes between flame spread and no flame spread could be approximated by fitting a linear line over the LOCs. According to the flammability limit line, a flame would go out below 60% O_2 if the CF orientation angle is more than 33.9°. This work can define the angle as the minimum CF orientation angle for fire safety, although it might be increased when further increasing the oxygen concentration. The LOC of CFRP [0°], which is the most flammable CFRP, is 35% O_2, and therefore it is reasonable that CFRPs are classified into incombustibles.

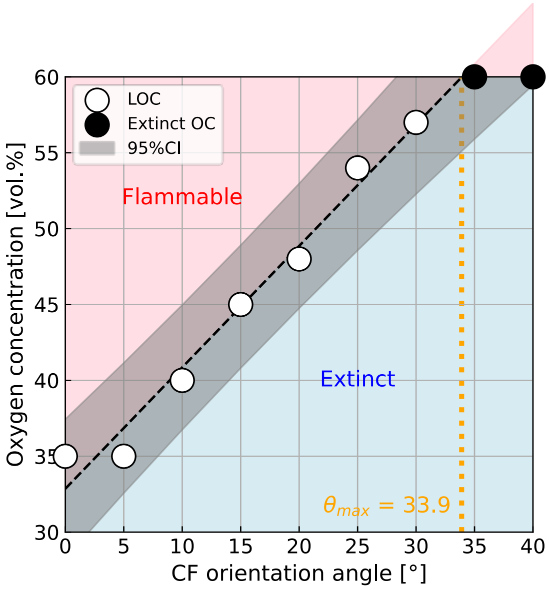

Fig. 4 Flammability of CFRP sheets in the atmosphere as a function of carbon fiber orientation angle and oxygen concentration.

3.3 Flame spread rate

To quantitatively demonstrate that the flame spread for the CFRP sheets was much faster than that for the epoxy resin sheets, which was described in Section 3.1, the flame spread rate was measured by tracking the flame leading edge via an in-house Python image-processing code. Figure 5 shows the displacement of the flame leading edge for the CFRP sheets and epoxy resin sheets in 60% O_2. Good linearities indicate that all flame spreads for the CFRP sheets reached a steady state. Such linearity was also found in other tested oxygen concentrations. For the epoxy resin sheets, however, the tracking time was shortened with increased oxygen concentration because the flame leading edge could not be accurately identified due to dripping flow. Elevating oxygen concentration raised flame temperature to heat up and melt more resins, thereby leading to the dripping flow. The melted resins with high temperature flowed downward faster than the flame, and therefore the dripping flow heated virgin fuels to facilitate the flame spread. This work dealt with only the steady state during a flame spread because too much dripping flow led to unsteady flame spread, which is difficult to analyze. This work then tracked the flame leading edge until it could be clearly recognized and calculated the flame spread rate from 35% O_2 to 60% O_2 every 5% O_2. For the epoxy resin sheets, the flame spread rates are calculated from the 20% O_2 to 60% O_2 every 10% O_2.

The measured flame spread rates of the CFRP sheets are plotted as a function of CF orientation angle in Fig. 6(a). The flame spread rate gradually decreased with CF orientation angle. Increasing CF orientation angle primarily affects solid-phase heat transfer and consequently increases conductive heat loss through carbon fibers to directions irrelevant to the flame spread. This is verified by Fig. 3 where the preheat zones (the area between red and green) become smaller as CF orientation angle is increased. Then, the heat feedback from flame to virgin fuel via solid-phase heat transfer decreases to decelerate the flame spread. In Fig. 6(b), the measured flame spread rates of the CFRP [0°] and the epoxy resin sheets are plotted as a function of oxygen concentration. The flame spread rate of the CFRP [0°] was at least three times as high as that of the epoxy resin sheets. In fact, a direct comparison between their flame spread rates is difficult because their thickness is different, at 0.22 mm and 0.5 mm. For thermally thin solids, the flame spread rate is found to double when the thickness is half[6]. However, even if the flame spread rate of the epoxy resin sheets is doubled, the order of the flame spread rate, i.e., CFRP > epoxy resin, still holds. The difference between their flame spread rates would be largely concerned with the conductive heat transfer via CFs as well as thermal inertia. This is because the difference in the two tested sheets was only whether the CFs were contained or not.

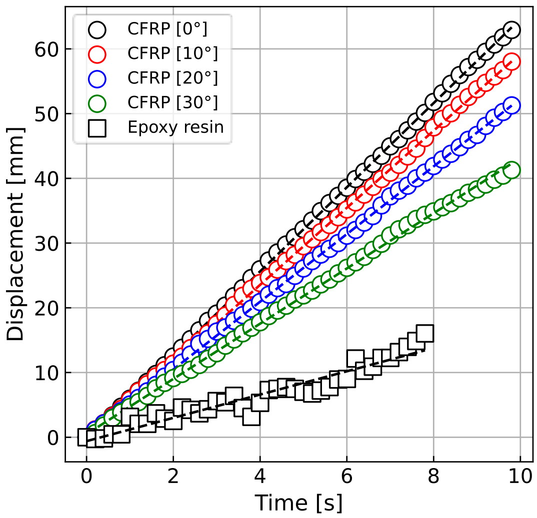

Fig. 5 Displacement of the flame leading edge in flame spread over CFRP [0°], [10°], [20°], [30°], and epoxy resin sheets in 60% O_2.

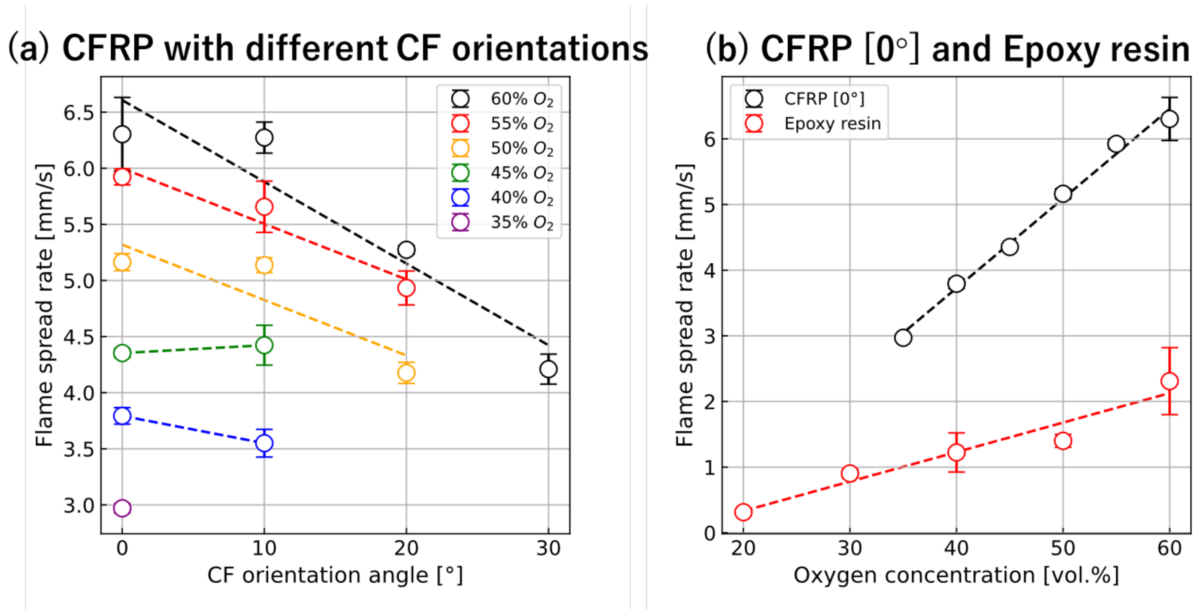

Fig. 6 (a) Flame spread rates of CFRP sheet as a function of carbon fiber orientation angle at different oxygen concentration and (b) flame spread rates of CFRP [0°] and epoxy resin sheets as a function of oxygen concentration.

3.4 Solid-phase preheating length

To understand how the CFs work in the flame spread, the in-plane temperature distribution during flame spread was visualized via the IR camera, which was explained in Section 3.1. Again, the preheat zone of the CFRP sheets was much larger than that of epoxy resin sheets. The solid-phase preheat zone in the epoxy resin sheets was almost non-existent. It clearly shows that for the CFRP sheets, the heat from the flame was conductively transferred forward via the CFs, while for the epoxy resin sheets, such conductive heat transfer was not involved due to the low thermal conductivity, ~ 0.3 W/m/K. Fundamentally, flame spread is driven via the heat transfer to the preheat zone. For the CFRP sheets, the carbon fibers acted as a heat conductor to transfer heat in the solid phase, such as the metal core of electrical wires. This additional heat transfer would accelerate the flame spread, resulting in a higher flame spread rete.

To quantify the solid-phase preheat zone shown in Fig. 3, the length of the solid-phase preheat zone, i.e., the solid-phase preheating length, was measured by processing the IR images via another in-house Python image-processing code. The solid-phase preheating lengths of the CFRP sheets are plotted as a function of CF orientation angle for variable oxygen concentration in Fig. 7. Note that this work defined the distance from the flame's leading edge to the point where the dimensionless temperature $\Theta = (T - T_\infty)/(T_v - T_\infty)$ reached a value of 0.3 as the representative solid-phase preheating length. Assuming that the pyrolysis and ambient temperatures (T_v and T_∞) are 670 K and 293 K, respectively, then the solid-phase preheating length is the distance to the point at the temperature of 406 K. As seen in Fig. 7, the solid-phase preheating length decreased with an increase in CF orientation angle and increased with a decrease in oxygen concentration. For CFRP [0°] in Fig. 3(a), the preheat zone was thin because the low thermal conductivity of epoxy resins did not allow the heat transfer between the CFs. On the other hand, with an increase in the CF orientation angle in Fig. 3(b)-(d), the preheat zone gradually rounded and developed sideways because the CFs were also oriented horizontally. For CFRP [0°] in Fig. 3(a), a large amount of heats from a flame is transferred to the preheat zone due to the limited heat transfer to the sides. For CFRP [10°], [20°], and [30°] in Fig. 3(b)-(d), on the other hand, less heat is transferred because some of the heat is leaked in directions different from the flame spread through the CFs. The flame spread over CFRP [0°], therefore, could be sustained compared to the other CFRP sheets. As a result, CFRP [0°] had the lowest LOC among the four tested CFRP sheets, and the LOC increased with CF orientation angle. This would support the prediction that the flame spread rate of CFRP [0°] is the highest in the last section.

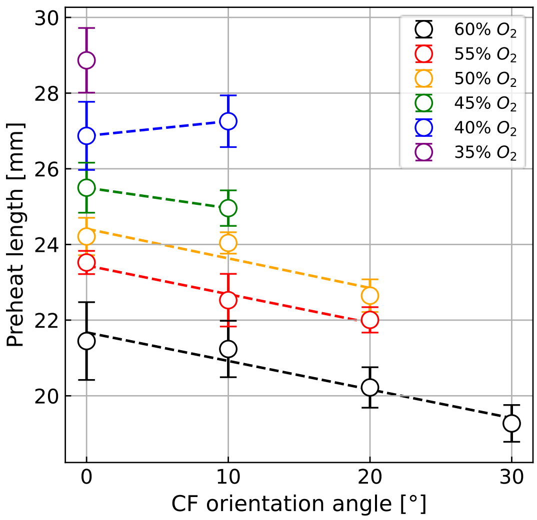

Fig. 7 Solid-phase preheating lengths of CFRP sheet with different carbon fiber orientations as a function of carbon fiber orientation angle for different oxygen concentrations.

4. Conclusions

This work experimentally studied the downward flame spread over thermally thin CFRP sheets with different CF orientations under buoyant flow. According to the visualized in-plane temperature distributions, the CFs were found to conductively transfer the heat from flame upstream. The heat-conductor effect of the CFs accelerated the flame spread. In addition, the LOC of CFRP sheets significantly increased with CF orientation angle because of the solid-phase heat transfer. Similarly, the flame spread rate depended on the CF orientation angle, and that of CFRP [0°] was the highest among the four tested CFRP sheets. These results are also produced by different heat transfer in the preheat zone. This is supported by quantifying the preheat zone and discussing the difference in the preheating length. This study therefore concludes that the CF orientation controls the solid-phase heat transfer to the preheat zone, thereby varying the flammability and flame spread characteristics. These findings from this work not only deepen our understanding of flame spread behaviors of thermally anisotropic materials and CFRPs but also help us evaluate their fire risk and hazard.

References

1) A. C. Fernandez-Pello, S. R. Ray and I. Glassman: Symp. Combust., **18**, 1, 1981, 579.
2) S. Takahashi, T. Ebisawa, S. Bhattacharjee and T. Ihara: Proc. Combust. Inst., **35**, 3, 2015, 2535.
3) Y. Konno, N. Hashimoto and O. Fujita: Combust. Flame, **220**, 2020, 7.
4) Y. Kobayashi, K. Terashima, R. Oiwa and M. Tokoro: Proc. Combust. Inst., **38**, 3, 2021, 4857.
5) Y. Kobayashi, R. Oiwa, M. Tokoro and S. Takahashi: Combust. Flame, **232**, 2021, 111528.
6) A. Fernandez-Pello and F.A. Williams: Symp. Combust., **15**, 1, 1975, 217.