An Experimental Study on Effects of Sample Orientation on Non-Piloted Ignition of Thin PMMA Sheets

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Introduction

Localized ignition of solid materials due to external radiant energy and the subsequent transition to flame spread are of importance to prevent fire hazards, and to understand the complex coupling of chemical, thermal, and fluid dynamics in solid combustion. Therefore, several investigations relevant to ignition behavior over solid materials (thermally thick PMMA) have been conducted with or without external flow [1-5]. In actual room fires, the surface of solid materials is always subjected to radiation from the fire in various directions (e.g., ceiling, wall, and floor). Therefore, it is important to investigate the influence of the sample orientation angle on localized ignition behavior and subsequent transition to flame spread over thin solid materials. With respect to the influence of sample orientation angle on ignition, it has been numerically predicted that under conditions of low radiant flux, the ignition delay time should significantly vary with a change in the sample orientation angle [6]. This study examines the validity of the predicted results and also extends current understanding of the ignition behavior over a relatively thin PMMA sheet.

The goal of the present study is to characterize the variation in the flame ignition delay time as a function of sample orientation angle with different laser energy levels, and to gain a better understanding on how buoyancy can affect the flame ignition and the subsequent flame behavior by changing the sample orientation angle.

Experimental apparatus and method

Figure 1 shows a schematic of the experimental apparatus. A CO_2 laser with ≈ 4 mm diameter beam was used as an external radiative heat source to ignite the sample. The total laser power Q_{ex} was varied up to about 26.1 W. The laser was controlled with a shutter. The sample was rotated at angles between -90° and 90° relative to the normal to the surface of the optical table. The laser was always aligned and irradiated normal to the sample surface through the use of a rotating mirror angle, regardless of the sample orientation angle θ. θ was varied from -90° to 90° at intervals of 15° (Here, sample orientation angles of -90 °, 0 °, and 90° correspond to ceiling, wall and floor configurations.). The distance from the CO_2 laser source to the middle of the sample was 400 mm to maintain a constant laser beam path length. The laser power was measured as a function of laser irradiation time by a thermal power meter placed behind the sample to determine the time when a small hole was formed due to consumption of the sample surface. PMMA samples (45 mm square × 0.2 mm thickness) were used as a thin solid material [7]. In the present study, the duration of the laser irradiation was set to 10 seconds. This time was sufficient to generate a hole in the PMMA sample with ≈ 4 mm diameter laser beam. If, after 10 seconds of laser irradiation ignition was not achieved on the irradiated (frontside) or the non-irradiated (backside)

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of the sample surface, such a test was defined as a not-ignited case. To measure the flame ignition delay time, photo detectors were set up near the frontside and backside of the sample surface. An air jet, controlled with a solenoid valve, was used to extinguish the flame. All features of the experiment (i.e. laser shutter, solenoid value, and data acquisition) were controlled, using a custom LabVIEW program[2]. The sampling frequency of output data from both the photo detector and power meter is 1kHz, and the number of data points was 10,000.

To obtain the images of flame ignition and the subsequent transition to flame over the frontside, a Hi-8 video recorder at 30 frames per second was used in the present study. The images were recorded from the side view of the irradiated front surface and digitized by a PC-based image processor.

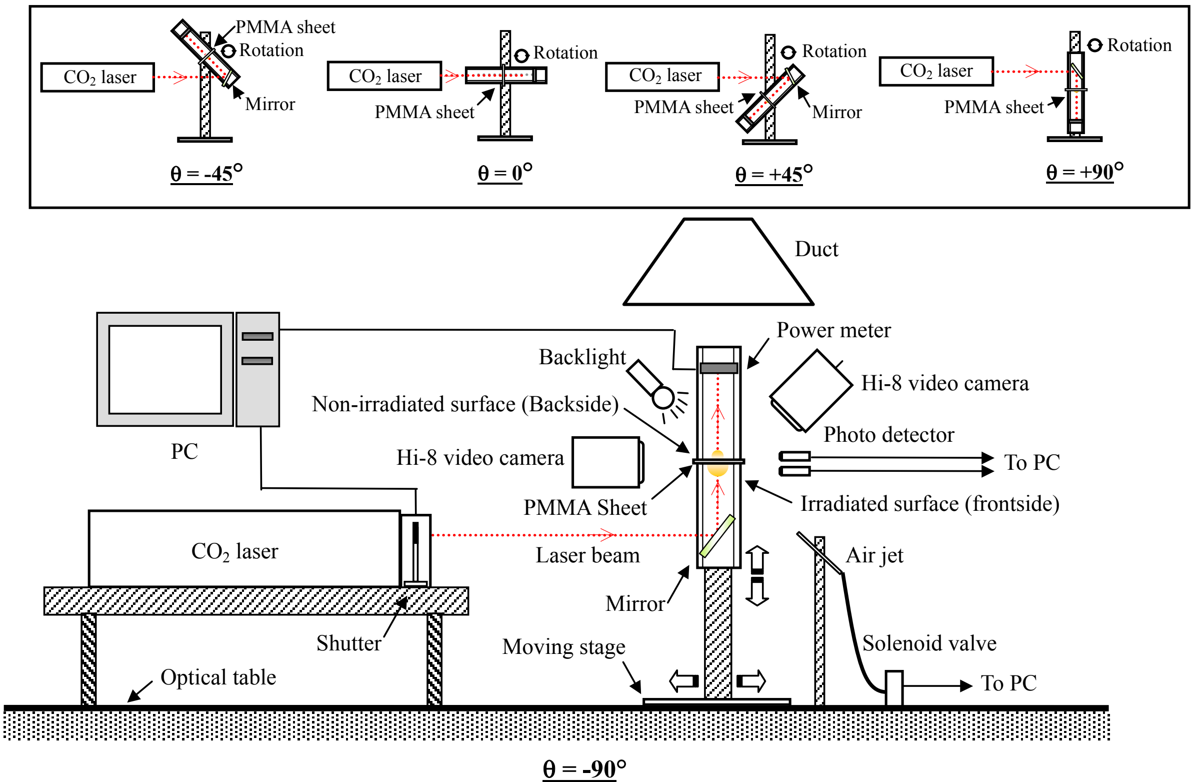

Figure 1 Experimental apparatus

Result and Discussion

Figure 3 shows images of ignition on the frontside and the transition to subsequent flame spread on backside with Q_{ex} = 26.1 W, θ = -90°, 0° and +90°. For θ = -90° (ceiling case), a diffusion flame with a hemspherical shape was clearly observed after the onset of the ignition on the frontside. As the surface continued to be irradiated by the laser beam, the size of the hemspherical diffusion flame became small due to consumption of the sample and approached the sample surface due to upward buoyancy force. After the flame attached to the sample surface, a small flame on the backside appeared with some delay. The flame intensity on the frontside simultaneously increased due to heat feed back from the ignition on the backside. A similar trend with external flow has been observed in microgravity [7]. Eventually, a bright flame on the backside was observed and its height became large. This was due to the entrainment of fresh ambient air generated by the

2 Certain commercial equipment, instruments, or materials are identified in this paper to specify adequately the experimental procedure. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology.

buoyant force to the flame base on the non-irradiated surface. At θ = 0° (wall case), after the frontside ignition, a vertical diffusion flame was formed by the upward buoyancy force. A hole on the sample surface formed similar to that of -90° (floor case). Eventually, a small flame appeared through the hole on backside. When θ = +90°, a conical diffusion flame was observed on frontside after ignition. Although the flame moved close to the sample surface, similar to that of θ = -90°, the speed of the approach to the surface was slightly lower compared with that of θ = -90° because of upward buoyancy force. A small flame was observed on the backside, but the flame size remained nearly unchanged, most likely because the buoyant hot products generated by this small flame pushed the small flame upward. Furthermore, the prevention of enough oxygen supply due to upward buoyancy force caused the intensity of the small flame on the backside to become less bright, compared with that of θ = -90°. These results indicate that buoyancy can act or counteract the flame motion on both surfaces after the ignition.

To gain a better understanding on how the sample orientation angle can influence the ignition on the frontside and the subsequent flame behavior on the backside, the variation in the frontside ignition delay time t_f, onset time of backside flame t_b, and hole formation time t_o is shown in figure 4 as a function of sample orientation angle θ with different laser energy Q_{ex}. Each data point represents 5 repeats on average. In the case of Q_{ex} = 16.0 W, the frontside ignition delay time t_f gradually increased as θ increased from -90 ° to -45°. When θ exceeded -45°, the frontside ignition did not occur. The hole formation time t_o was almost constant and independent of the change in θ. These trends were qualitatively similar to those observed using numerical simulations [6]. Except for θ = -45°, the backside flame appeared with some delay after the formation of a hole at the center of the sample surface. The motion of frontside ignition to the subsequent backside flame through the hole opening has also been shown in our recent work using high-speed photography [8]. As contrasted with the trend of t_f, the onset time of backside flame t_b slightly decreased up to θ = -45°. When θ exceeded -45°, the frontside ignition was not achieved and subsequently no backside flame was observed. Under conditions of higher laser energy with Q_{ex} = 17.3 W, t_f gradually increased as θ increased up to -30° similar to the Q_{ex} = 16.0 W results, and the value of t_f became shorter than that of Q_{ex} = 16.0 W. When θ exceeded -15°, an unstable region was observed, in which sometimes the front side ignition appeared but not always up to θ = +15°. In this region, the backside flame was also induced depending upon the appearance of the frontside ignition. With a further increase in θ, the frontside ignition began to appear again and the value of t_f remained nearly constant and became insensitive to θ. The result quantitatively agrees with the result of numerical simulation [6]. t_o was shorter than that of Q_{ex} = 16.0 W because of higher laser energy, but it remained nearly unchanged regardless of θ, similar to that of Q_{ex} = 16.0 W. With respect to the backside flame, t_b gradually decreased up to -15° and then became constant as θ exceeded 15°**,** similar to that of Q_{ex} = 16.0 W. In the case of Q_{ex} = 26.1 W, the frontside ignition was observed under the entire range of θ, and t_f became insensitive to θ. On the other hand, t_b gradually decreased and became constant, as similar to Q_{ex} = 16.0 and 17.3 W. These results suggest that the variation in the laser energy does not influence the onset of the backside flame, despite the fact that laser energy significantly affects the frontside ignition delay time. To provide insight into the open question on whether or not laser duration time becomes important to the onset of backside ignition, the change in laser duration time implemented in the previous work [7] is required to our future work. In addition, a study of the influence of PMMA thickness on the onset of backside flame is also required. As to the reason for the significant variation in the frontside ignition delay time, depending upon θ at low laser energy, the difference of buoyant MMA (monomer vapor) motion on the frontside with changing θ is expected to play an important role in the variation in frontside ignition delay time [6], although, at the present stage of our research, we have yet to address in detail how the buoyant MMA motion interacts with frontside ignition. A flow visualization method, based on the density variation such as schlieren technique [9], is being implemented to investigate the interaction of the laser beam with buoyant MMA vapor.

Summary

The influence of the sample orientation angle on the ignition and the subsequent flame motion over both sample surfaces has been experimentally investigated, using a CO_2 laser as an external radiant source in normal gravity, with a focus on how the ignition delay time varies with the sample orientation angle θ and laser energy Q_{ex}. The results are summarized as follows:

Time resolved images of the ignition and the subsequent flame motion showed that buoyancy force driven by the diffusion flame on frontside (on irradiated surface) significantly altered the backside (on non-irradiated surface) flame motion at positive (-90°) and negative angles (+90°).

When the frontside ignition was not achieved, the backside flame did not appear. In addition, the backside ignition did not appear before forming a hole on the sample surface. These observations did not depend on laser energy and sample orientation angle.

The most interesting result of this study was the variation in onset of backside flame with increase in θ. At relatively low laser power (Q_{ex} = 16.0 W), the frontside ignition delay time gradually increased with an increase in θ up to -30°, whereas the onset time of the backside flame decreased gradually. For θ > -45°, frontside ignition and the subsequent backside flame were not observed. As the laser power increased from to Q_{ex} = 17.3 to 26.1 W, the frontside ignition and the subsequent backside flame appeared for θ > -30°. The frontside ignition delay time did not vary under the range of angles considered. As compared with the frontside ignition delay time, the onset of the backside flame decreased with increasing θ up to about 0° and became insensitive for positive angles, regardless of laser energy. The trend of the frontside ignition delay time within the range of laser energy and sample orientation angle conditions we have studied, qualitatively agreed with the results predicted by numerical simulation, and we could confirm the validity of the results obtained by numerical simulation.

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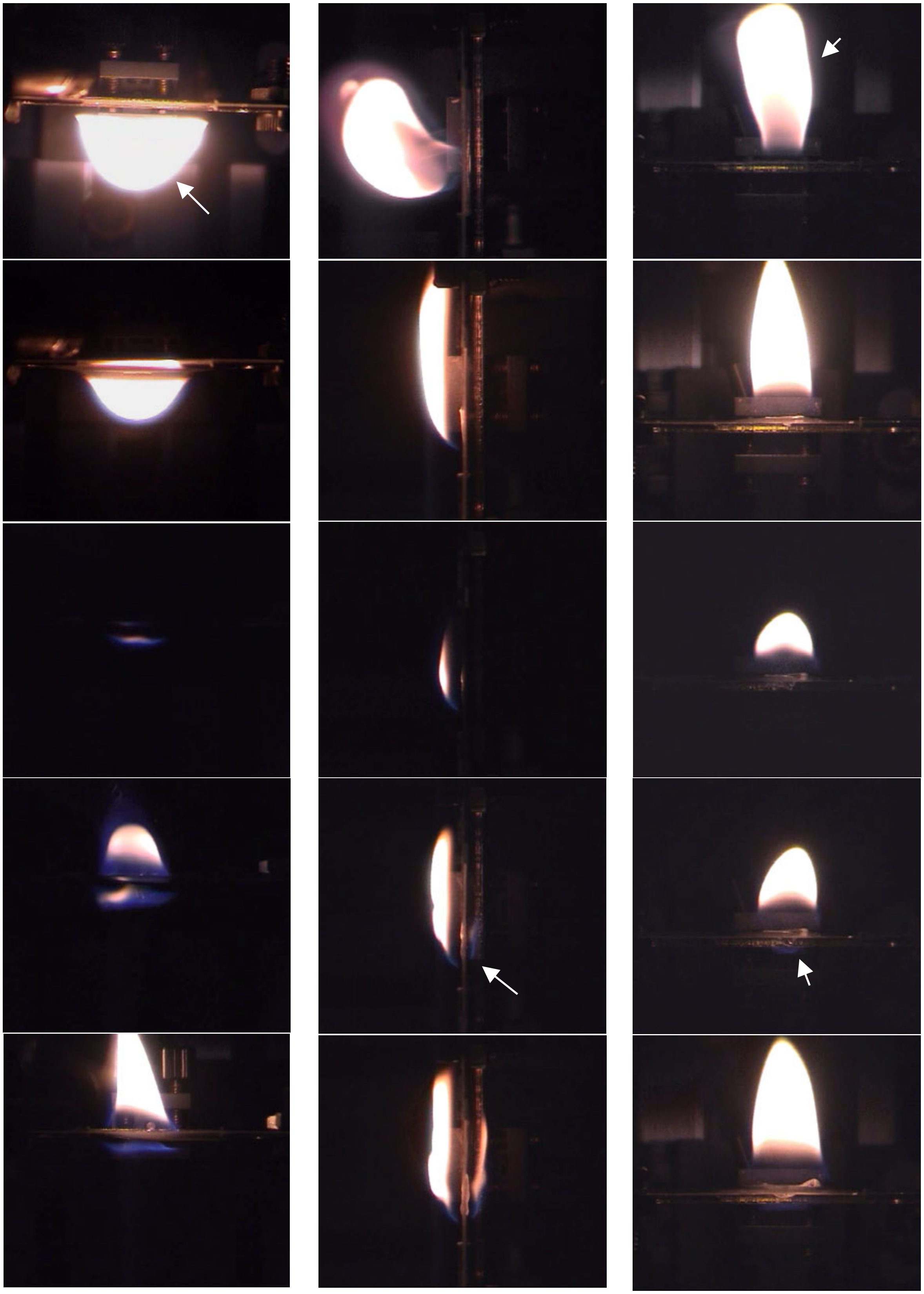

(a) -90 deg (b) 0 deg (c) +90 deg

Figure 3 Ignition motion on irradiated and non-radiated surface with changing sample orientation angle

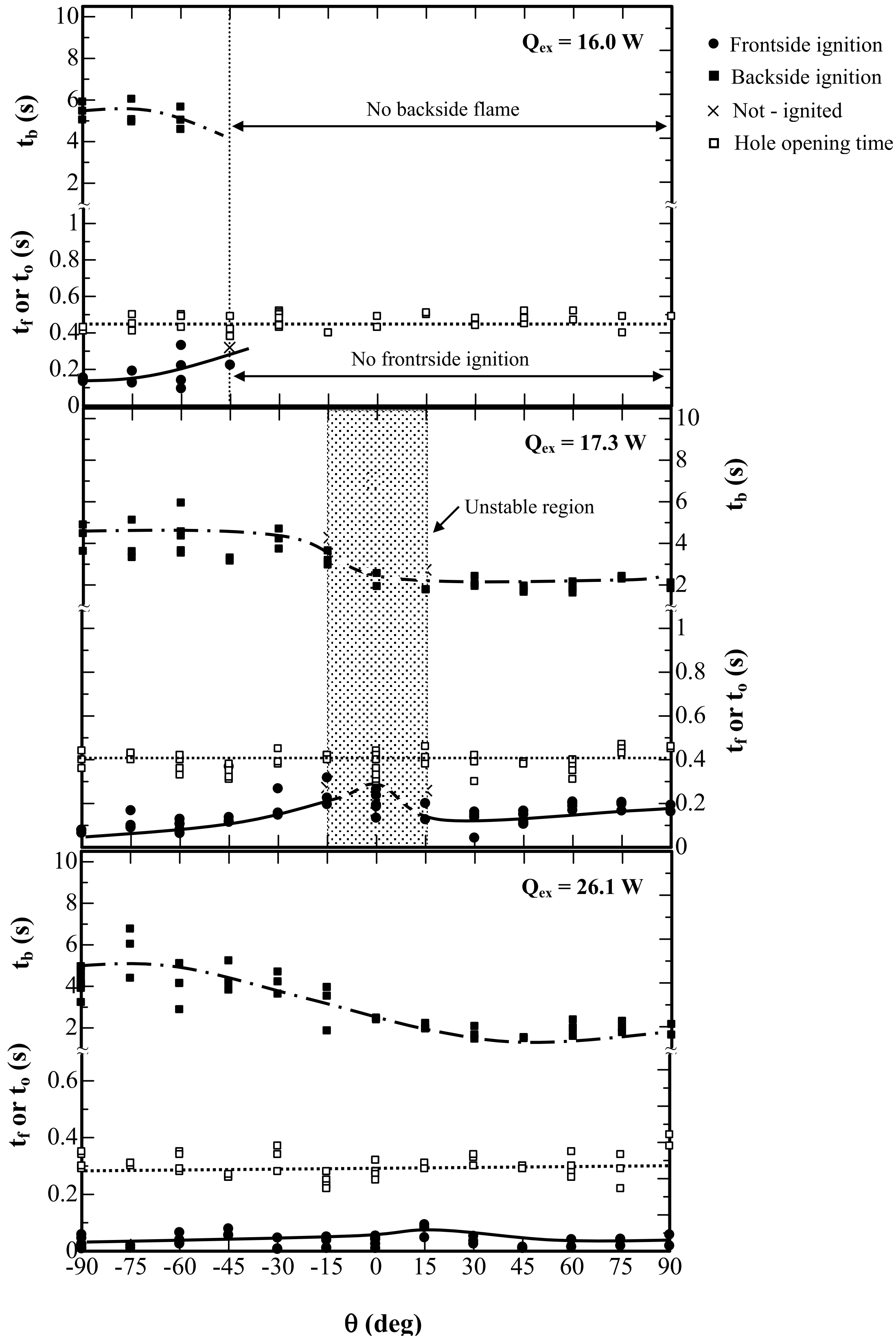

Figure 4 Variations in the frontside ignition delay time and onset time of backside flame as a function of sample orientation angle (Unstable region means that ignition was not achieved except few cases.).