Partially Premixed Ignition for a Bluff-Body Flameholder under Various Igniter and Inlet Conditions

Yuxuan Zhang, Jinghua Zhang, and Xiaomin He*

ABSTRACT: This study applies experimental methods to investigate the partially premixed ignition characteristics of a bluff-body flameholder with a pilot stage. The ignition fuel–air ratio (FAR) under different igniter and inlet conditions is obtained, while the ignition process is recorded with a high-speed photography device. Numerical simulations are carried out to investigate the relationship between the flow field, fuel distribution, and ignition process. The results show that a higher total capacitance energy storage of the igniter, inlet Mach number, or total pressure inside the combustion chamber will help increase the ignition performance, accelerate the development of the flame, and shorten the ignition delay. The flame propagation routine of the flameholder is controlled by several pairs of symmetrical recirculation zones behind the flameholder structure and the specific uneven fuel distribution caused by the flow field. This study provides a detailed understanding of the ignition process for the bluff-body flameholder.

1. INTRODUCTION

For flame stabilization provided by recirculation zones, various structures including cavities,1,2 steps,3 and bluff-bodies have served as a classic design5,6 in the context of premixed7–9 and partially premixed combustion10,11 applications. The flame stabilizing principle of the bluff-body is to generate recirculation flow inside the wake zones to extend the residence time of reactants and achieve a stabilized flame.12 Based on flow field and combustion measurements, recent studies have acquired a deeper understanding of the flow–flame coupled dynamics13–15 and lean blow-off (LBO) or near LBO characteristics16–17 for the bluff-body stabilized flame.

In the aviation propulsion field, bluff-body structures mainly exist in the form of V-shaped bluff-body flameholders. To meet the evaporation requirement of liquid fuels under non-premixed conditions and the high-velocity incoming airflow of the combustion chamber, the bluff-body flameholders have a relatively large width. Meanwhile, the flameholder could form a significant negative pressure gradient and a more expansive recirculation zone by designing the back end as a concave shape. The corresponding design results lead to the V-shaped flameholder with a reliable structure that is widely adopted in various afterburners and ram combustors, such as the Revolutionary Turbine Accelerator (RTA) hyper combustor designed by General Electric.18,19 However, a problem exists for V-shaped flameholders; the insufficient fuel–air mixing around the wake region limits the ignition performance under lean conditions. Various optimized designs appeared to enhance the fuel–air mixing process. These include using irregular edges to strengthen the fuel–air interaction in the shear layers20,21 or applying the partitioned combustion concept to create an isolated “pilot combustion stage”. The latter method leads to pilot flameholders with a significantly enhanced ignition performance, especially under extreme conditions such as high inlet velocities and subatmospheric pressures. Among the pilot flameholders, commonly used examples include the evaporating flameholder used in the afterburner of the SPEY engine, which enhances the fuel evaporation rate through the evaporation pipe,22 and the film-evaporating flameholder, which can form a fuel film on the flameholder wall to strengthen the atomization ability through air-assisted breakup.

Many relevant studies have examined bluff-body-based flameholders. Huang et al. conducted experimental studies on the performance of the V-shaped flameholder under non-uniform inlet conditions by changing the velocity peak and non-uniformity. The researchers obtained the flame propagation routine of the flameholder, which can form a fuel film on the flameholder wall to strengthen the atomization ability through air-assisted breakup.
velocity distributions. Miao et al. developed a Z-shaped evaporating flameholder and studied its flow pattern and ignition/LBO characteristics under normal pressure conditions. Cheng and Fan focused on improving the lean ignition and blow-out performance of the evaporating flameholder by proposing a crescent-shaped evaporation pipe design. In this design, the ignition boundary and flame stability significantly increased, especially under low temperature and high inlet velocity conditions. Each of the above studies was conducted under normal pressure conditions, while the performance of bluff-body flameholders under subatmospheric conditions remains unknown. Furthermore, although a large amount of data on the ignition boundary has been obtained, a complete analysis of the ignition process from the perspective of the flow field and fuel distribution is lacking, hindering the application of the bluff-body flameholders.

To achieve a detailed view of the ignition process, a typical flameholder with a pilot stage was studied for this work. The study extended the measurement of ignition performance to subatmospheric pressure conditions, and the lean ignition fuel–air ratio (FAR) under different inlet pressures, temperatures, and Mach numbers was measured. In addition, the images during the ignition process of the evaporating flameholder were obtained through high-speed photography. These images enable the analysis of the flame propagation process from the perspective of flow structure and fuel–air coupling distribution with numerical methods. The ignition delay under different parameters was also compared. A more thorough understanding of the ignition and flame propagation process for the bluff-body flameholder was obtained by this study.

2. RESULTS AND DISCUSSION

A flameholder designed with the idea of partitioned combustion, an evaporating flameholder, is applied for the experiment. As shown in Figure 1, the fuel is injected inside the flameholder onto a filming plane, after which the droplets enter an evaporation pipe used to premix and pre-evaporate the fuel. The incoming air enters the pilot zone via a set of inlet slots located on the front of the flameholder.

Figure 2 shows the comparison of ignition performance of several typical flameholders used in afterburners. The flameholders all work at atmospheric pressure and an inlet Mach number of 0.15. It can be seen from the experimental result that, due to the design of pilot stage combustion, the ignition equivalent ratio of evaporating flameholder is only 1/4 to 1/5 of that of flameholders without pilot stages, such as V-shaped flameholders and sucking flameholders. Meanwhile, its ignition performance is better than or equal to the cavity-based flameholders. This is because under the concept of regionalized combustion, the ignition process occurs inside the pilot stage. With the protection of the recirculation zone created by the flameholder, the high-speed incoming flow is separated from the pilot stage, resulting in a significant reduction in heat dissipation, and the initial flame kernel formed after ignition is then harder to be blown out. As a result, the ignition performance is effectively improved.

During the experiment, various inlet parameters were changed, including the inlet Mach number, inlet total temperature, and total pressure. As shown in Table 1, most of the experiments were conducted under subatmospheric pressure conditions. The inlet Mach number ranges from 0.1 to 0.2, the inlet temperatures are 500 and 900 K, and the total pressure ranges from 0.03 to 0.1 MPa.

The ignition process of the flameholder is intricately linked to the air and fuel characteristics inside the combustion zone. To acquire the corresponding flow field and fuel distribution, multiple numerical simulations were performed, including flow field simulation and fuel atomization process simulation. Figure 3 illustrates the simulated physical structure.

During the ignition of the evaporating flameholder, the initial fire kernel and flame propagation process are confined to the inside of the pilot stage. Therefore, the cavity’s local fuel–air ratio (FARlocal) is used to evaluate the ignition performance of the flameholder.

![Figure 1. Flameholder used in the experiment.](image1)

![Figure 2. Ignition performance between different flameholders.](image2)

| Table 1. Parameters during the Experiment |
|------------------------------------------|
| property                          | range          |
| combustor total pressure (MPa)        | 0.03–0.10      |
| inlet air static temperature (K)      | 500/900        |
| inlet Mach number                     | 0.1–0.2        |
| Reynolds number (10^5)                | 0.495–2.202    |
| capacitance total energy storage (J)  | 3–20           |
The FAR\textsubscript{local} is calculated by the pilot fuel flux and the incoming air flux entering the inlet slots at the front edge of the flameholder. In this study, the local air flux of the flameholder was obtained through numerical simulation. As seen from the results listed in Table 2, the flux ratio is around 14 for an evaporating flameholder. In other words, about 7–8% of the total inlet air would flow into the flameholder and participate in the ignition process. Meanwhile, increasing the total pressure, decreasing the inlet Mach number, or decreasing the total inlet temperature will cause a rise in the air flux ratio.

2.1. Ignition Boundary. Figure 4 shows the change of the ignition FAR of the evaporating flameholder under different total pressures, with a constant inlet temperature of 500 K, a Mach number of 0.15, and the igniter’s capacitance energy storage of 3–20 J. The ignition local FAR increases significantly under subatmospheric conditions. Higher energy storage of the igniter will decrease the ignition FAR, but this change is much less significant when compared with the change in total pressure.

For the combustion chamber with a premixing/pre-evaporation atomizer as the fuel supply device, the initial flame kernel formation mainly stems from the evaporation time. During the ignition process of a heterogeneous, polydisperse mixture at a high turbulence intensity, Ballal and Lefebvre reported a relationship based on the quenching distance $d_q^{0.5}$ as

$$d_q = \frac{0.32 Pr \rho (1 - \Omega) \text{SMD}^{1.5} \omega/0.5}{Z \omega \log (1 + B_s) \rho_s^{0.5} \rho_a^{0.5}}$$  \hspace{1cm} (1)

The minimum ignition energy, $E_{\text{min}}$, is defined as:

$$E_{\text{min}} = C_p \rho \Delta T_u \frac{\pi}{4} d_q^4$$  \hspace{1cm} (2)

In the above equations, $\omega$ is the root mean square (RMS) of turbulent fluctuating velocity, $B_s$ is the mass transfer number, $Z$ is the droplet distribution coefficient, $\Delta T_u$ is the temperature difference between the fuel and the flame, and $\phi$ is the ignition equivalence ratio.

Decreasing the pressure mainly affects the ignition equivalence ratio by lowering air density, $\rho_a$. This decreases the aerodynamic force exerted by the airflow on the fuel droplets to further increase the Sauter mean diameter (SMD) of fuel droplets. As seen in the formula, lower $\rho_a$ and larger SMD both have a negative effect on the ignition equivalence ratio.

The air density is inversely proportional to the total pressure of the combustion chamber. The change in SMD could be inferred by using Kolmogorov and Hinze’s assumption regarding how the dynamic pressure generated by turbulence is the main factor of droplet breaking in turbulence flow.\textsuperscript{31} Under this assumption, the critical Weber number $W_{\text{crit}}$ is

$$W_{\text{crit}} = \frac{\rho \bar{u}^2 D_{\text{max}}}{\sigma}$$  \hspace{1cm} (3)

In turbulent flow, the dynamic pressure to break the droplets mainly comes from the velocity difference having a wavelength equal to 2 times the droplet’s diameter ($D$). According to the theory of turbulent energy levels, the following are true:

$$\bar{u}^2 = C_4 (ED)^{2/3}$$  \hspace{1cm} (4)

and

$$D_{\text{max}} = C \left( \frac{\sigma}{\rho_a} \right)^{3/5} E^{-2/5}.$$  \hspace{1cm} (5)

Under different total pressures, the only parameter affecting $D_{\text{max}}$ is the air density $\rho_a$. With the assumption of a constant distribution of fuel droplets, the SMD will be proportional to $-3/5$ power of air density $\rho_a$. As shown in Figure 4, the ignition local FAR under 0.03 MPa is approximately 0.4, which is significantly higher than the stoichiometric ratio of 0.067. As such, the poor atomization performance significantly reduces the evaporation rate. Although much fuel is injected inside the flameholder, only a small amount can vaporize into gaseous production on time and participate in the ignition process.

After analyzing the changes in air density and SMD under subatmospheric pressure, the ignition equivalent ratio, $\phi_i$, 34979

https://doi.org/10.1021/acsomega.1c05643
ACS Omega 2021, 6, 34977−34988
together with the ignition local FAR, can be inversely calculated as

\[
\text{FAR}_{\text{local}} \propto \varphi \propto \text{SMD}^{3/2} \times d_{q}^{-1} \times \rho_{q}^{-1/2} \\
\propto \text{SMD}^{3/2} \times \rho_{q}^{-1/6} \propto P^{-16/15}.
\]  

Figure 5 shows the comparison between the ignition FAR acquired by the experiment (black line) and the fitted FAR proportional to \(P^{-16/15}\). Although certain differences exist under extremely low pressure, the two curves fit well for total pressure above 0.05 MPa. This analysis explains the ignition behavior under subatmospheric pressure.

The influence of the inlet Mach number on ignition FAR is shown in Figure 6. For most igniters, the local ignition FAR decreases as the inlet Mach number rises from 0.1 to 0.2. With regard to the 3 J igniter under 0.1 MPa, the ignition FAR dropped steeply from 0.106 to 0.073 when the inlet Mach number increased. However, for the 12 J igniter, the ignition FAR only changed slightly from 0.085 to 0.069. The only exception involves the 20 J igniter, where the ignition FAR increased from 0.058 to 0.065 for a higher inlet Mach number.

For the non-premixed or partially premixed spray ignition, the ignition will fail unless the combined rate of droplet evaporation and chemical reaction exceeds the heat loss rate of the flame kernel. Based on the \(\varphi_{\text{min}}\) formula, a higher inlet Ma number would affect the ignition process by two means. First, a higher velocity would enhance the secondary breakup process of the fuel, leading to a small SMD and faster evaporation. Subsequently, this would lower \(\varphi_{\text{min}}\). Second, increasing the inlet air velocity also results in a larger turbulent fluctuating velocity, \(u'\), increasing the heat exchange between the flame kernel and the surrounding cold air and causing \(\varphi_{\text{min}}\) to rise. Influenced by these two diametrically opposite effects, the lean ignition performance varies under different igniter parameters with the increasing Mach number.

For igniters with small discharge energy, the energy provided to the fuel–air mixture is limited by the spark. The increase in the droplets’ SMD at low Mach numbers hinders the formation of an initial flame kernel. According to the principles of the secondary breakup process, mentioned above, the \(D_{\text{max}}\) is influenced only by the energy input rate \(E_{\text{w}}\), which is proportional to the square of the time-averaged velocity \(u^{2}\) and is expressed as

\[
D_{\text{max}} \propto u^{-4/5}
\]  

Assuming that SMD is proportional to \(D_{\text{max}}\), the relationship between ignition equivalence ratio and inlet Mach number could be derived as

\[
\varphi \propto \text{SMD}^{3/2} \times d_{q}^{-1} \times u^{1/2} \propto \text{Ma}^{-7/10}
\]  

Thus, for the igniter with energy storage between 3 and 12 J, the ignition performance improves for a higher inlet Mach number. The same phenomenon can be found when the total pressure is 0.05 MPa. The secondary breakup process is significantly weakened under low-pressure conditions; so, the increase of inlet Ma will make up for this deficiency.

For the 20 J igniter, the SMD of droplets no longer remains the main factor since relatively higher spark energy could be provided to droplets. Under these circumstances, a higher turbulent fluctuating velocity will cause excessive heat dissipation between the flame kernel and the surrounding cold incoming air, making the flame kernel easier to dissipate and limiting the lean ignition performance.

Figure 7 shows the comparison of the ignition performance under different inlet temperatures (500 and 900 K). Based on Figure 7, the ignition FAR at an inlet temperature of 900 K is higher than the ignition FAR at 500 K, especially for igniters with low spark energy.

An increase in inlet temperature will affect the ignition in many ways. A higher temperature will accelerate the
evaporation process, producing richer gaseous fuel and reducing the ignition FAR. However, similar to the actual combustion chambers, the high temperature of the inlet air is acquired by gas heating. As such, a higher temperature indicates a lower oxygen content, which leads to a decreased reaction rate and a poor ignition performance. In addition, when the inlet Mach number remains constant, the absolute reaction rate and a poor ignition performance. Meanwhile, the high-velocity jets through the inlet slots provide a sufficient air feed, diluting the fuel and making the corresponding zone lean-fuel. As such, on the central section shown in Figure 9c, the fuel flows out from the evaporation pipe. Under the influence of the recirculation zone, as shown in Figure 8a, two fuel bands form along the upper and lower edges of the flameholder, leaving a crescent-shaped rich-fuel area. As shown in Figure 9b, the high-velocity jets through the inlet slots provide a sufficient air feed, diluting the fuel and making the corresponding zone lean-fuel. As such, on the central section shown in Figure 9c, the fuel flows out from the evaporation pipe along with the small hole air-jet shown in Figure 8c, directly hitting the upper and lower walls of the flameholder.

Figure 9d shows a relatively rich fuel area behind the flameholder, where the local mass fraction of the vaporized product is above 0.04 (equivalence ratio of 0.596). As seen from the figure, the fuel downstream of the flameholder is concentrated in the central and two marginal sections (left and right sides), while the rest could be considered as the lean-fuel area. This unique fuel distribution pattern significantly affects the flame propagation process after ignition.

Based on the flow field and fuel distribution, the ignition process of the evaporating flameholder could then be analyzed. Though the ignition delay time differs significantly under different inlet conditions, the flame propagation routine is similar. As such, one set of inlet condition parameters could be chosen to demonstrate the ignition process. Figures 10 and 11 show the images obtained by high-speed photography at a total pressure of 0.03 MPa, inlet temperature of 500 K, and inlet Ma of 0.15 with the energy storage of the igniter set to 12 J (same as the numerical simulation above). The subatmospheric condition is chosen to induce low flame brightness and slower flame propagation speed for clearer imaging of the ignition process.

Figure 10a shows the image at the very moment of spark ignition. The bright light of the spark discharge fills the entire image. The figure also shows the relative position of the flameholder and the discharge position of the igniter.

Figure 10b shows the image at 1 ms after ignition. The spark forms a high-brightness flame kernel, illuminating the edge of the flameholder. At 2 ms after ignition, as shown in Figure 10c, the initial flame kernel in Figure 10b has almost been blown out by the high-speed incoming airflow. The remaining flames form two distinct flame bands near the upper and lower edges of the flameholder, while no flame is observed between these flame bands. When compared with the spatial distribution of evaporated fuel obtained by numerical simulation, the positions of the two flame bands in Figure 10c correspond to the rich-fuel area near the upper and lower edges of the flameholder, as shown in Figure 9a,d. As such, after ignition, the rich-fuel bands are ignited by the initial flame kernel at the marginal section of the flameholder. Simultaneously, between these flame bands, the recirculation zone shown in Figure 8a continuously transports fresh air from downstream to keep the
location in a lean-fuel state and prevent the flame from expanding.

Figure 10d–f shows the flame distribution at 3–5 ms after ignition. Originating from the two flame bands shown in Figure 10c, a combustion zone is maintained at the marginal section under the constant fuel supply. At the same time, another spurt of flame is propagating along the evaporation pipe, penetrating through the lean-fuel zone toward the center section of the flameholder, as marked in Figure 10e. The fuel content of the corresponding position is relatively lean, preventing this spurt of flame from spreading downstream of the flameholder.

The flame distribution at 6–8 ms after ignition is shown in Figure 11a,b. At 6 ms after ignition, the flame has reached the center section of the flameholder along the evaporation pipe. As shown in Figure 9c,d, the fuel content is relatively rich at the central section, and the flame could spread downstream to form another combustion zone (the central flame zone). As Figure 8c shows, there is, as in the marginal flame zone, a stable recirculation flow in the central section that creates two more flame bands along the upper and lower walls of the flameholder, as shown in Figure 11a. As the temperature rises after 8 ms, more fuel is evaporated, mixed, and ignited, while the brightness of the flame zones also increases.

The right side of the flameholder is obscured by the outer wall of the flameholder. As such, the camera cannot obtain the flame propagation process from the center to the right side. However, at 12 ms after ignition, the flame front continued to
expand and fill the symmetrical recirculation zone in the marginal section, as shown in Figure 11c; two flame bands could also be found at the central section, and the flame pattern is consistent with the rich-fuel zone shown in Figure 9.

At 15 ms after ignition, a self-sustaining, stable flame fills the entire combustion chamber, indicating that the ignition process is complete.

As a whole, for the ignition of the tested evaporating flameholder, the entire ignition process is shown in Figure 12.

First, the spark creates an initial flame kernel near the left side of the flameholder, further igniting the left-marginal fuel-rich area. Meanwhile, the flame spreads alongside the distribution pipe and ignites the central fuel-rich area to form another flame zone. The central flame reaches the right-marginal fuel-rich area near the right side and, eventually, completes the entire ignition process. The upper wall surface of the evaporating flameholder after the combustion test is shown in Figure 13. In the figure, the traces caused by the combustion process can be

---

**Figure 9.** (a) Fuel distribution downstream of the evaporating flameholder at the marginal section. (b) Fuel distribution at the plane, which cuts through the inlet slot. (c) Fuel distribution at the central section. (d) Relatively rich-fuel area downstream of the evaporating flameholder.
seen on the flameholder wall, divided into left, central, and right parts.

2.3. Effects of Inlet Parameters on Ignition Delay. Figure 14 shows the ignition process under different total pressures inside the combustion chamber, with the inlet Mach number kept at 0.15, the inlet temperature at 500 K, and the igniter parameter at 12 J/8 Hz. As the total pressure drops, the initial flame kernel formed under the same spark energy shrinks, together with a slower speed of flame development. However, the flame propagation process under different total pressure conditions is similar, except when the total pressure equals 0.1 MPa. In this case, the flame brightness is too high to decipher specific details. With a total pressure of 0.03, 0.05, and 0.07 MPa, the flame kernel formed two crescent-shaped flame zones in the rich-fuel area at 2 ms after ignition, while under higher total pressure, the brightness of the flame increased significantly with a greatly accelerated propagation speed.

Figure 14 shows the ignition process under different inlet Mach numbers under 0.05 MPa. Comparing the image at 1 ms after ignition, the initial flame kernel fades faster under the inlet Mach number of 0.2. This is due to the higher local velocity that strengthens the convective heat transfer between the ignited flame kernel and the surrounding unburned air. After a successful ignition, the flame propagation speed and combustion zone establishment speed are significantly faster at
higher Mach numbers due to the increase of airflow velocity and the enhancement of the fuel atomization.

Next, this study examines the effect of ignition delay. Ignition delay is defined as the time frame starting from the point of ignition and ending when the flame fills the entire flameholder. The ignition delay under different total pressures and inlet Ma is shown in Figure 16. The ignition delay under every operating condition occurs within milliseconds. When the combustion chamber’s total pressure increases, the flame propagation speed significantly accelerates. Similar to the enhancement of ignition performance, this is also caused by an increase in reactant concentration and secondary atomization performance under higher total pressure. Meanwhile, the higher inlet speed also contributes to the rapid spread of the flame.

3. CONCLUSIONS

To obtain a complete understanding of the ignition characteristics, this paper studies the ignition process of a pilot bluff-body flameholder, involving the ignition FAR, flame propagation routine, and its inherent fuel–air coupling relationship. Different igniter parameters and inlet conditions, including several subatmospheric situations, are involved in the study, from which multiple conclusions were drawn.

First, the ignition of the pilot flameholder performs at a satisfactory level, considering that the ignition local FAR typically lies below 0.1 under atmospheric conditions. The flameholder can acquire a stable ignition under a total pressure of as low as 0.03 MPa.

The study also found that the total capacitance energy storage of the igniter has a significant impact on the ignition FAR. When the total capacitor energy of the igniter increases, the single discharge energy of the spark increases, causing the ignition FAR to drop.

In addition, under subatmospheric pressure conditions, the fuel atomization ability is greatly weakened. This limits the evaporation rate and significantly reduces the ignition performance of the flameholder. The local FAR rises to about 0.4 to achieve the ignition at 0.03 MPa. Increasing the inlet Ma will help to achieve a lower ignition FAR for igniters with a small energy storage but will degrade the ignition performance for the igniter with an energy storage of 20 J.

Meanwhile, since the high-temperature inlet flow is achieved by the gas heater, the decrease in the oxygen content of the inlet would result in poor ignition performance under a high-temperature condition of 900 K.

In the case of the evaporating flameholder, the incoming airflow leaves several symmetrical recirculation zones on the vertical section behind the flameholder. The recirculation zones on the marginal sections are relatively complete. Under the influence of the flow field, the fuel flowing out of the evaporation pipe will form a pair of belt-shaped rich-fuel areas at the marginal section, and another rich-fuel area could be found on the central section. Due to the uneven fuel distribution, the flame will propagate from the marginal section toward the center after ignition, further spreading to the non-ignition marginal section. During the ignition process, the flame shape coincides with that of the fuel-rich area obtained by numerical simulation.
Finally, subatmospheric pressure or low Ma conditions will significantly reduce flame brightness, slow down flame propagation rate, and lengthen the ignition delay.

4. METHODS

4.1. Experimental Methods. The experiments were conducted in the combustion laboratory of the Nanjing University of Aeronautics and Astronautics. The schematic overview of the experimental setup is shown in Figure 17. A single screw air compressor compressed the air, and an orifice plate flowmeter with an uncertainty of 1% measured the air flux. An electrical heater and a gas heater were used to preheat the inlet air up to 900 K, and K-type thermocouples were placed 500 mm before the experimental model to measure the air temperature with an uncertainty of 2.5%. During the test, the inlet temperature of 500 K is acquired using the electrical heater; the gas heater is only used for inlet temperatures of 900 K.

The flameholder is placed horizontally inside a 120 × 130 mm tunnel, as shown in Figure 18. Two pumps are used to supply fuel to the gas heater and the pilot class of the test section, and the fuel flux is measured by a rotameter. The ignition was achieved by a high-energy spark igniter placed at the side plate of the test section and inserted approximately 2 mm inside the flameholder. The total energy storage of the spark igniter ranges from 3 to 20 J. Finally, a high transmittance quartz glass is mounted to observe the ignition process.

The outlet of the test section is connected to a tank, further linked to three vacuum pumps capable of reducing the total pressure to 0.03 MPa in the test section. Several total pressure tubes are mounted inside the test section to measure the pressure during the ignition process. A high-speed photography system captures the ignition process with a shooting pixel of 1024 × 1024 and a frame rate of 1000 Hz.

4.2. Fuel Properties. The RP-3 aviation kerosene was used as jet fuel during the experiment. For the RP-3 aviation kerosene manufactured in Da Qing, China, the detailed components obtained from the chromatographic analysis are listed in Table 3.32 Meanwhile, different physical properties of the fuel were measured before the experiment and are listed in Table 4.

![Figure 17. Schematic of the experiment system.](image)

4.3. Numerical Methods. The steady-state continuing and momentum equations were discretized via the finite volume method, and the SIMPLE algorithm was employed for pressure–velocity coupling. The standard k-ε model was chosen as the turbulence model. In simulating the two-phase flow, the discrete phase model (DPM) is applied since the volume fraction of the liquid phase is much less than 10% of that of the gaseous phase. In addition, for the evaporation pipe with air-assisted atomization effect, the secondary atomization process cannot be ignored, and the Taylor Analogy Breakup (TAB) model is used to simulate it.

A mesh independent validation was performed before starting the numerical simulation, as shown in Figure 19a. Five different mesh sets were used to simulate the flow field behind the evaporating flameholder. Figure 19a shows the velocity distribution on a Y-direction line at the central section, 60 mm behind the trailing edge of the flameholder. As shown in the figure, with the number of grids increased to 2644k, the simulated velocity distribution no longer changes with increasing grid numbers. To ensure the independence of the mesh, a set of 3000k mesh grids was applied during the simulation. Figure 19b is the simulation method validation using the velocity data acquired by particle image velocity transmittance.

![Figure 18. (a) Front view of the test section. (b) Back view of the test section.](image)

Table 3. Composition (Mass Basis) of China No.3 Aviation Kerosene

| composition          | value (%) |
|----------------------|-----------|
| alkanes              | 52.2      |
| monocyclic naphthenes| 33.8      |
| bicyclic naphthenes  | 6.0       |
| tricyclic naphthenes | 0.1       |
| alkyl benzenes       | 5.1       |
| indan and tetralin   | 1.3       |
| naphthalene          | 0.6       |
| naphthalene derivatives | 0.9     |

Table 4. Main Physical Properties of Fuel

| property          | value            |
|-------------------|------------------|
| density (g/cm³)   | 801.6            |
| kinematic viscosity (mm²/s) | 4.631 |
| net heating value (MJ/kg) | 43.32 |
| ice point (K)     | 213.15           |
| flash point (K)    | 323.65           |
revealing the internal conclusion, the current simulation method is suitable for are completely consistent with the previous research; in addition, in our previous research, the same turbulence model and atomization model were used to verify a partially premixed, air-assisted fuel supply device; it was found that the spatial distribution of the liquid phase and atomized particle size are both consistent with the experimental results. In the evaporating flameholder, the form and atomization principle of the fuel supply device used are completely consistent with the previous research; in conclusion, the current simulation method is suitable for revealing the internal flow and spray field of the tested flameholder.

■ AUTHOR INFORMATION

Corresponding Author

Xiaomin He — College of Energy and Power Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China; Aero-engine Thermal Environment and Structure Key Laboratory of Ministry of Industry and Information Technology, Nanjing 210016, China; Phone: +86 25 84896770 2439; Email: hxm@nuaa.edu.cn

Authors

Yuxuan Zhang — College of Energy and Power Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China; orcid.org/0000-0001-7010-4030

Jinghua Zhang — Beijing Power Machinery Institute, Beijing 100074, China

Complete contact information is available at: https://pubs.acs.org/10.1021/acsomega.1c05643

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

This work was supported by the National Science and Technology Major Project (No. 2017-III-0008-0034). We thank LetPub (www.letpub.com) for its linguistic assistance during the preparation of this manuscript.

■ REFERENCES

(1) Zhu, Z.; He, X.; Xue, C.; Hong, L.; Zhu, Y.; Song, Y. Experimental investigations on combustion characteristics of a cavity pilot augmentor of the turbine-based combined cycle engine. Proc. Inst. Mech. Eng., Part G. 2015, 229, 2024–2034.

(2) Choubey, G.; Devarajan, Y.; Huang, W.; Mehar, K.; Tiwari, M.; Pandey, K. M. Recent advances in cavity-based scramjet engine- a brief review. Int. J. Hydrogen Energy 2019, 44, 13895–13909.

(3) Li, Z.; Moradi, R.; Marashi, S. M.; Babazadeh, H.; Choubey, G. Influence of backward-facing step on the mixing efficiency of multi microjets at supersonic flow. Acta Astronaut. 2020, 175, 37–44.

(4) Zhao, S.; Fan, Y. Analysis of flow resistance and combustion characteristics in the combined application of step and strut. Aerosp. Sci. Technol. 2020, 98, 105676.

(5) Nicholson, H. M.; Field, J. P. Some experimental techniques for the investigation of the mechanism of flame stabilization in the wakes of bluff bodies. Symp. Combust. Flame, Explos. Phenom. 1948, 3, 44–68.

(6) Winterfeld, G. On processes of turbulent exchange behind flame holders. Symp. (Int.) Combust. 1965, 10, 1265–1275.

(7) Pan, J.; Zhang, C.; Pan, Z.; Wu, D.; Zhu, Y.; Lu, Q.; Zhang, Y. Investigation on the effect of bluff body ball on the combustion characteristics for methane/oxygen in micro combustor. Energy 2020, 190, 116465.

(8) Zhang, Z.; Wu, K.; Yao, Y.; Yuen, R.; Wang, J. Enhancement of combustion performance in a microchannel: Synergistic effects of bluff-body and cavity. Fuel 2020, 265, 116940.

(9) Zhang, W.; Wang, J.; Lin, W.; Guo, S.; Zhang, M.; Li, G.; Ye, J.; Huang, Z. Measurements on flame structure of bluff body and swirl stabilized premixed flames close to blow-off. Exp. Therm. Fluid Sci. 2019, 104, 15–25.

(10) Zhao, S.; Fan, Y. Experimental and numerical study on fuel distribution and flame expansion of the enhanced flame holding devices. Energy 2020, 203, 117850.

(11) Zhao, S.; Fan, Y.; Deng, T.; Crookes, D. Influence of injection scheme on flame characteristics in partially premixed combustion. Energy 2020, 205, 118058.

(12) Longwell, J. P.; Frost, E. E.; Weiss, M. A. Flame stability in bluff body recirculation zones. Ind. Eng. Chem. 1953, 45, 1629–1633.

(13) Karmarkar, A.; Tyagi, A.; Hemchandra, S.; O’Connor, J. Impact of turbulence on the coherent flame dynamics in a bluff-body stabilized flame. Proc. Combust. Inst. 2021, 38, 3067–3075.

(14) Geikie, M. K.; Rising, C. J.; Morales, A. J.; Ahmed, K. A. Turbulent flame-vortex dynamics of bluff-body premixed flames. Combust. Flame 2021, 223, 28–41.

(15) Nair, S.; Lieuwen, T. Near-blowoff dynamics of a bluff-body stabilized flame. J. Propul. Power 2007, 23, 421–427.

(16) Pathania, R. S.; Skiba, A. W.; Ciardiello, R.; Mastorakos, E. Blow-off mechanisms of turbulent premixed bluff-body stabilised flames operated with vapourised kerosene fuels. Proc. Combust. Inst. 2021, 38, 2957–2965.

(17) Kim, Y. J.; Song, W.; Hernández Pérez, F. E.; Im, H. G. Explosive dynamics of bluff-body-stabilized lean premixed hydrogen flames at blow-off. Proc. Combust. Inst. 2021, 38, 2265–2274.
(18) Hasegawa, H.; Shimada, Y.; Kashikawa, I.; Yoshimura, T.; Kinoshita, Y.; Kitahara, K. Experimental study of compact ram combustor with double-staged flameholders for ATR engine. 37th Joint Propulsion Conference and Exhibit; 2001, DOI: 10.2514/6.2001-3292.
(19) Lee, J.-H.; Winslow, R.; Buehrle, R. J. The GE- NASA RTA Hyperburner Design and Development. NASA/TM-2005-213803; 2005.
(20) Stwalley, R. M., III; Lefebvre, A. H. Flame stabilization using large flameholders of irregular shape. J. Propul. Power 1988, 4, 4–13.
(21) Lefebvre, A. H. Characteristics of dune-shape flameholders. 23rd Joint Propulsion Conference; 1987, DOI: 10.2514/6.1987-2106.
(22) Liu, H.; Wang, F.; Wang, J. Experimental study of the performance of special evaporating V-gutter flame-holder at low pressure. Jiangsu Gongye Xueyuan Xuebao 2004, 16, 12–14. (In Chinese)
(23) Huang, Y.; He, X.; Jiang, P.; Zhu, H. Effect of non-uniform inlet velocity profile on flow field characteristics of a bluff body. Exp. Therm. Fluid Sci. 2020, 118, 110152.
(24) Huang, Y.; He, X.; Jin, Y.; Zhu, H.; Zhu, Z. Effect of non-uniform inlet profile on the combustion performance of an afterburner with bluff body. Energy 2021, 216, 119142.
(25) Miao, J.; Fan, Y.; Liu, T.; Wu, W. Analysis of length effect on thermodynamic characteristics in a Z-shaped evaporating flameholder. Acta Astronaut. 2020, 166, 369–376.
(26) Miao, J.; Fan, Y.; Liu, T.; Wu, W. Experimental and numerical study on thermodynamic characteristics in a Z-shaped evaporating pilot-flameholder. Acta Astronaut. 2019, 162, 56–65.
(27) Cheng, X.; Fan, Y. Experimental study of lean ignition and lean blow-out performance improvement using an evaporation flameholder. Int. J. Heat Mass Transfer 2016, 103, 319–326.
(28) Xue, C. Investigation on the flow and combustion characteristics of flameholder in nonuniform field. Nanjing University of Aeronautics and Astronautics; 2014 (In Chinese).
(29) Miao, J.; Fan, Y.; Liu, T. Influence of strut on cavity at subsonic speeds: Ignition characteristics. Proc. Inst. Mech. Eng., Part G 2020, 234, 1369–1379.
(30) Ballal, D. R.; Lefebvre, A. H. A general model of spark ignition for gaseous and liquid fuel-air mixtures. Symp. (Int.) Combust. [Proc.] 1981, 18, 1737–1746.
(31) Lefebvre, A.H. Atomization and Sprays; 2nd ed.; CRC Press: Boca Raton, 2017.
(32) Fan, X.-J.; Yu, G. Analysis of Thermophysical Properties of Daqing RP-3 Aviation Kerosene. Tuijin Jishu 2006, 27, 187–192. (In Chinese)
(33) Zhang, Y.; He, X.; Jin, Y.; Zhou, Y. Research on Spray Characteristics of an Air-Assisted Multi-Point Fuel Supply Device. Tuijin Jishu 2019, 40, 1594–1605. (In Chinese)
(34) Zhang, Y.; He, X.; Zhu, H. Study on atomization performance of multi-orifice air-assisted plain jet atomizers. Fuel 2021, 286, 119428.