HiSST: 4th International Conference on High-Speed Vehicle Science Technology
22 -26 September 2025, Tours, France

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Investigation of Flameholding Limits and Mechanisms in a Cavity Flameholder under Supersonic Flow

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Abstract

This study experimentally investigates fuel injection, atomization, mixing, and flameholding mechanisms in a supersonic cavity combustor, focusing on the influence of fuel mass flow rate on flame stability. Cold-flow and hot-ignition experiments were conducted with integrated flow visualization and pressure measurements to examine the relationship between cavity flow structures and combustion behaviour. In the cold-flow experiments, schlieren imaging revealed that at a mass flow rate of 3 g/s, the injected fuel is effectively entrained into the recirculation zone, achieving sufficient mixing, whereas at 4.5 g/s and 6 g/s, significant fuel retention within the shear layer reduces atomization efficiency and results in locally fuel-rich conditions. Under hot-ignition conditions, stable flameholding was observed at 3 g/s, while higher flow rates led to fuel accumulation and unstable combustion. These findings demonstrate the strong correlation between fuel mass flow rate, atomization efficiency, shear-layer dynamics, and flameholding stability, offering experimental insights into flame stabilization mechanisms for future supersonic combustor design.

Keywords : *Supersonic combustor, Cavity flame holder, Ignition, Recirculation zone*

1. Introduction

With the rapid advancement of supersonic propulsion technology, scramjets (supersonic combustion ramjets) have been recognized as one of the most promising air-breathing engines due to their high specific impulse, structural simplicity, and elimination of onboard oxidizer storage. Nevertheless, achieving reliable combustion in scramjets remains a formidable challenge. The extremely high flow velocities inside the combustor limit the available residence time for fuel atomization, mixing, and ignition to only a few milliseconds, making flame stabilization one of the key technical obstacles for practical applications.

Among the various approaches proposed to stabilize combustion, cavity flameholders have received widespread attention because of their simple configuration and ability to enhance mixing with minimal total pressure loss. A cavity generates a low-speed recirculation zone that retains fuel, prolongs residence time, and promotes ignition. The shear layer formed at the cavity–freestream interface induces vortices and flow instabilities, which strongly interact with the recirculation zone and play a decisive role in stabilizing the flame.

Depending on the cavity length-to-depth ratio (L/D), flameholders can be classified into two types. According to Yakar et al. [1], cavities with L/D < 7–10 are categorized as open-type, while those with L/D > 7–10 are closed-type. The distinction arises from the penetration depth of the shear layer: in open-type cavities, the shear layer extends from the front wall to the rear wall, spanning the entire cavity length; in closed-type cavities, the shear layer cannot reach the rear wall and instead interacts with the cavity bottom, forming a bow shock and redirecting the flow outward. When vortices induced by shear-layer disturbances impinge on the rear wall, compression waves propagate within the cavity, driving shear-layer oscillations and vortex shedding, which eventually lead to flow-field resonance and a quasi-equilibrium state.

Previous studies have also investigated the effects of rear-wall angle and L/D on cavity performance. Zang et al. [2] used RANS simulations to show that rear-wall tilting toward the freestream reduces pressure oscillations associated with shear-layer impingement. Gruber et al. [3] combined schlieren photography with numerical simulations to examine the influence of L/D and rear-wall angles, reporting that smaller rear-wall angles mitigate cavity-induced pressure fluctuations. Wang et al. [4] further demonstrated that larger L/D ratios combined with smaller rear-wall angles improve mass exchange between the mainstream and cavity flow. Additionally, Kim et al. [5] observed that increasing both L/D and rear-wall angle increases total pressure losses, while an open-type cavity with L/D = 3 provides a favorable balance between mixing enhancement, combustion efficiency, and pressure penalty.

As for flow-field structures, when high-speed airflow passes over the cavity, a primary recirculation zone typically forms near the cavity bottom and rear wall. This region provides a large interface with the shear layer and dominates the mass exchange with the mainstream, while a secondary recirculation zone near the front wall facilitates localized interactions with the primary zone. Gruber et al. [3] reported that increasing L/D and decreasing rear-wall angle can enlarge the primary recirculation zone, thereby enhancing overall mass exchange. In addition to geometry, fuel injection strategies strongly affect cavity flameholding performance. The position, angle, and number of injectors alter the interaction between injected fuel and the cavity shear layer, thereby influencing both atomization quality and the extent of fuel entrainment into the recirculation zone [6]. While many previous investigations have focused on cavity geometry or gaseous fuel injection, relatively fewer studies have examined liquid-fuel injection in combination with cavity stabilization. In particular, the coupling between liquid-fuel atomization, shear-layer dynamics, and cavity recirculation structures under supersonic conditions requires further experimental clarification.

The present study addresses this gap by systematically investigating the cold-flow and hot-ignition characteristics of a cavity combustor with liquid fuel injection. A direct-connected supersonic facility was used to simulate Mach 2 flow, and JP-4 was injected into a cavity with L/D = 3 at different mass flow rates (3, 4.5, and 6 g/s). Schlieren visualization, thermocouple measurements, and pressure sensing were employed to reveal the relationship between fuel atomization, mixing efficiency, and recirculation dynamics. Cold-flow experiments were conducted to examine atomization and shear-layer interactions, while hot-ignition experiments were performed to assess flameholding stability.

The results demonstrate that fuel mass flow rate exerts a decisive influence on cavity flameholding behavior. At 3 g/s, fuel is effectively entrained into the recirculation zone, leading to stable flameholding. At higher mass flow rates, however, excessive fuel accumulation in the shear layer suppresses mass exchange with the freestream and causes unstable combustion. By combining cold-flow and hot-ignition data, this study provides new insights into how fuel injection conditions couple with cavity-induced flow structures, thereby clarifying the mechanisms that govern successful flame stabilization in liquid-fueled supersonic combustors.

2. Experimental Setup and Methods

2.1. Flow Conditions and Cavity Configuration

A direct-connected wind tunnel was employed in combination with a cold-air supply system and an air preheating system to adjust the freestream conditions to a total temperature of 770–800 K and a total pressure of 230 psi. Hydrogen was injected into the secondary combustion section to further heat the airflow, raising the total temperature to approximately 1700 K to simulate the operating conditions of a scramjet combustor. The experiments were conducted in a Mach 2 supersonic flow using a cavity design proposed by Gruber et al. [3], as shown in **Fig. 1**, with a length-to-depth ratio (L/D) of 3 and a rear-wall angle of 22.5°, in order to establish a favorable recirculation structure.

JP-4 was selected as the fuel and injected through three 0.9 mm diameter orifices located on the cavity front wall, with an injection angle of 45°. The fuel mass flow rates were set at 3 g/s, 4.5 g/s, and 6 g/s, respectively. The experimental program consisted of two parts: cold-flow observations and hot-ignition tests. The detailed configuration is illustrated in Fig. 1, where the red line indicates the cavity front wall, and the blue arrows represent fuel injection directions.

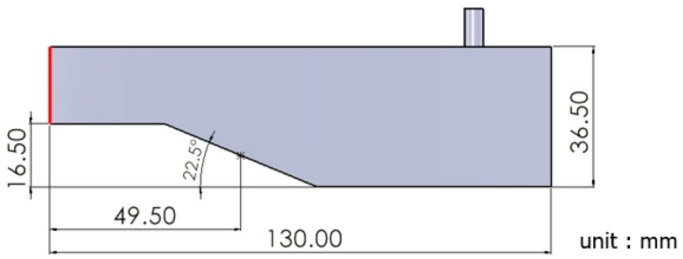

Fig 1. Cavity Configuration

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2.2. Measurement Methods

Temperature and pressure measurements were conducted to characterize both transient and steady-state flow conditions in the cavity combustor. The overall sensor arrangement is illustrated in **Fig. 2** and F**ig. 3**.

For ignition, a swirl-type igniter (blue circle) was installed 11 mm upstream of the cavity front wall to initiate combustion during hot-ignition experiments. The oxidizer-to-fuel ratio (O/F) was controlled within a range of 1–9, with a standard condition of O/F = 4 achieved by supplying 8 g/s of hydrogen peroxide and 2 g/s of W2 fuel, giving a total flow rate of 10 g/s.

Type-R thermocouples (purple circles) were employed for temperature measurements. They were mounted at three streamwise stations—27 mm, 58.42 mm, and 80.5 mm downstream of the cavity front wall—and distributed across the cavity floor, ramp wall, and downstream region. This arrangement provided nine measurement points in total (T1–T9), as shown in Fig. 2. The thermocouples were sampled at 10 Hz to capture average temperature evolution during both cold-flow and hot-ignition tests.

Static pressure measurements were obtained using high-frequency pressure sensors (green circles). In the cold-flow experiments, three measurement points (Ps-1, Ps-2, Ps-3) were located at the cavity floor, ramp wall, and downstream region. For hot-ignition experiments, three additional points (Ps-4, Ps-5, Ps-6) were included to capture pressure variations under combustion conditions. The pressure sensors were sampled at 1000 Hz to resolve both mean and unsteady fluctuations.

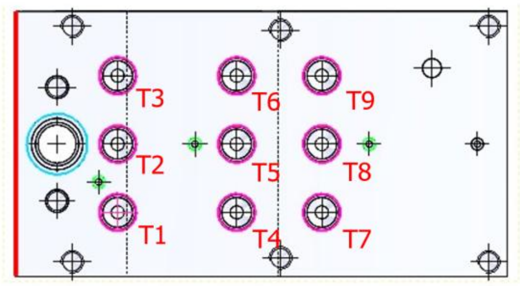

Fig 2. Thermocouple Configuration

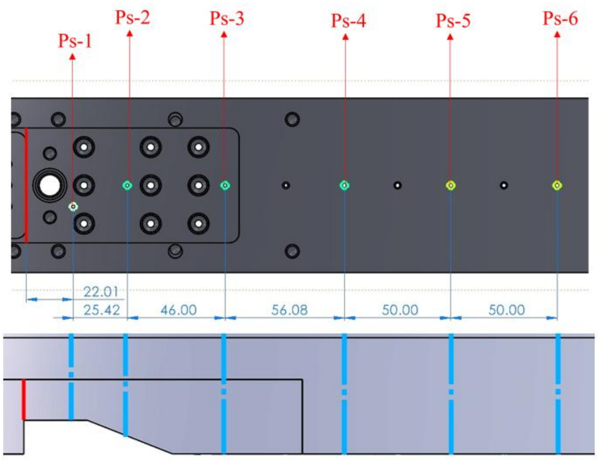

Fig 3. Pressure Sensors Locations

2.3. Optical Diagnostics

Optical diagnostics were employed in both cold-flow and hot-ignition experiments to capture flow-field structures, fuel distribution, and flame behavior inside the cavity combustor. Different imaging systems were applied depending on the test conditions, as illustrated in the following descriptions.

In the cold-flow experiments, schlieren photography was used to visualize shock waves, shear layers, and fuel atomization behavior. This technique relies on light refraction caused by gas density gradients and was combined with a Phantom V711 high-speed camera (Vision Research Inc.), which provided time-resolved imaging of compressible flow features. For each condition, 1000 consecutive images were recorded after fuel injection stabilized. Averaged frames were processed to reveal overall flow structures, while instantaneous frames were retained to study unsteady features.

In the hot-ignition experiments, flame structures and combustion zones were documented using a Canon R50 digital camera operating at 4K resolution and 120 fps. This system enabled clear visualization of flame morphology and its evolution during combustion, providing essential information on flameholding behavior within the cavity.

3. Results and discussion

3.1. Cold-Flow Experiments

Under cold-flow conditions without ignition, as shown in **Fig. 4**, the relatively low momentum flux caused the injected fuel to remain mostly trapped near the shear layer, failing to effectively penetrate the main flow region. As the fuel mass flow rate increased, the atomization performance gradually deteriorated.

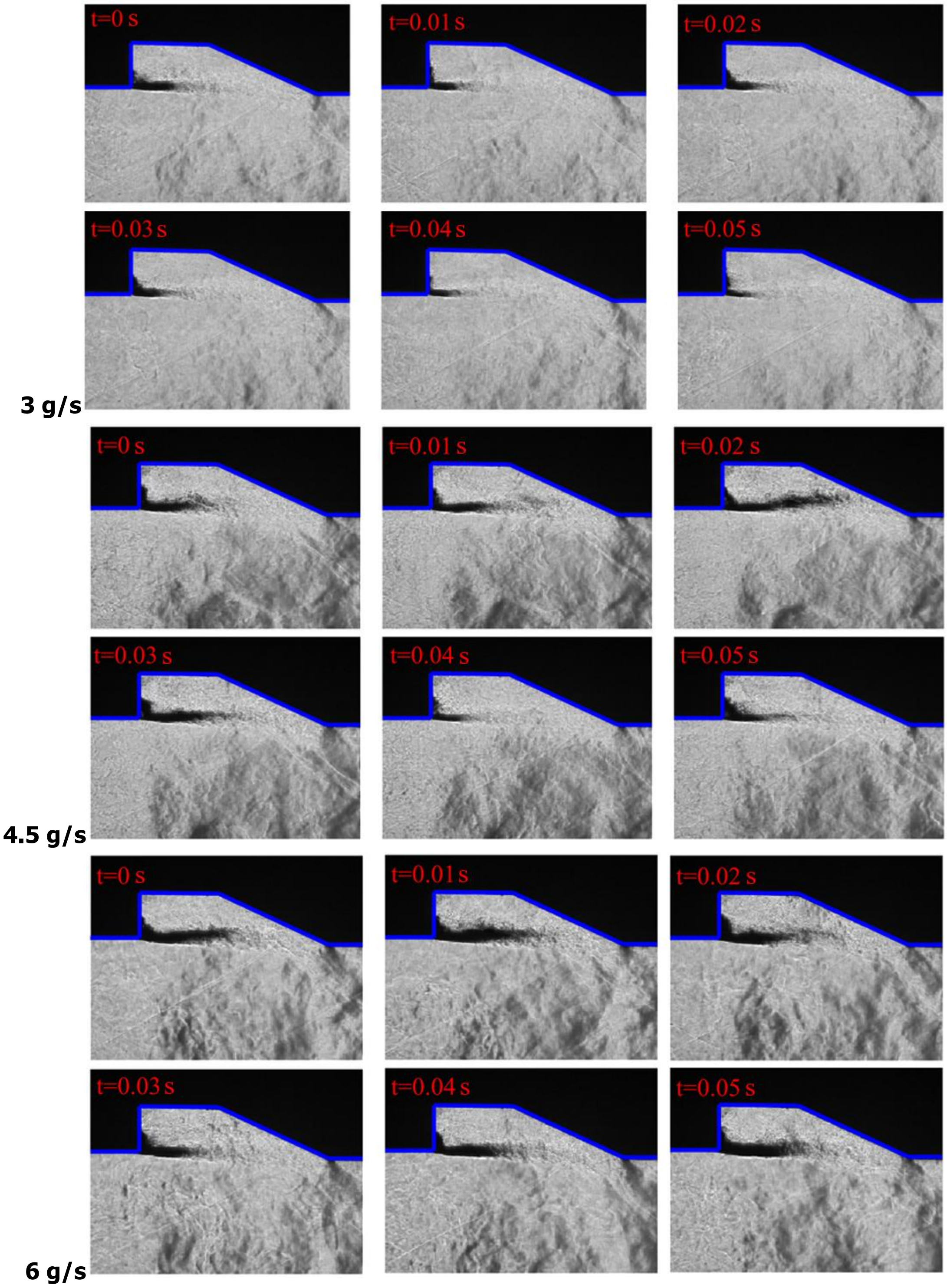

Fig 4. Instant schlieren images of cold flow at different Mass flow rates

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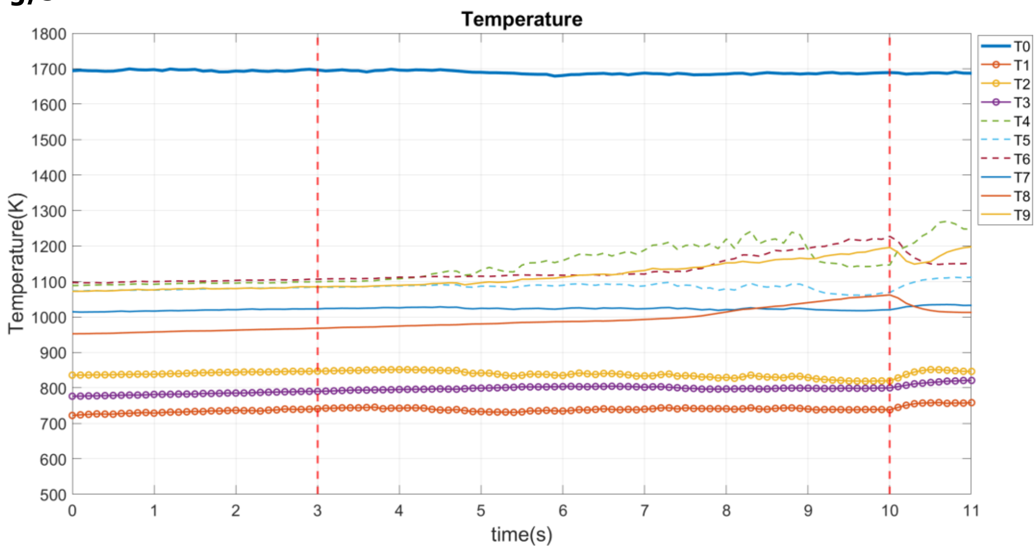
At a fuel mass flow rate of 3 g/s, the fuel was effectively entrained into the primary recirculation zone inside the cavity, resulting in more complete atomization and mixing with the mainstream air. This indicates that at lower injection momentum, the coupling between the fuel jet and the shear layer remains moderate, allowing the recirculating vortex to continuously draw fuel into the cavity and promote gas–phase mixing. When the flow rate was increased to 4.5 g/s, the interaction between the fuel jet and the shear layer became more pronounced, and the process of fuel being drawn into the recirculation zone was still visible, though the atomization performance was slightly reduced compared to the 3 g/s case. At the highest flow rate of 6 g/s, the fuel jet penetrated strongly into the shear layer but failed to sufficiently break up and atomize. Instead, a large portion of the liquid fuel was trapped within the shear layer region, forming dense clusters that significantly reduced mixing efficiency with the main flow. These observations confirm that excessive fuel momentum suppresses entrainment into the cavity and favors localized accumulation rather than uniform mixing.

The temperature measurements provide further evidence of this behaviour. As shown in **Fig. 5**, with increasing fuel mass flow rate, a stronger endothermic effect occurs during the atomization and vaporization process. This leads to an earlier temperature drop at the cavity bottom positions T1, T2, and T3, indicating that higher flow rate conditions promote greater liquid fuel residence inside the cavity and result in locally fuel-rich mixtures. At the inclined wall positions T4, T5, and T6, the central thermocouple recorded the most significant temperature decrease, consistent with stronger vaporization and heat absorption in regions of higher fuel concentration. The side positions, in contrast, initially showed elevated temperatures due to lower local fuel loading, where partial oxidation of vaporized fuel dominated. As vaporization progressed and the flow field gradually stabilized, temperatures at the side positions also decreased, pointing to the redistribution of fuel vapor within the cavity. For the downstream positions T7, T8, and T9, both heating and cooling trends were detected simultaneously. This suggests that oxidation reactions occurred in localized regions, while vaporization-driven cooling persisted in others, reflecting the highly unsteady and non-uniform nature of fuel–air mixing downstream of the cavity.

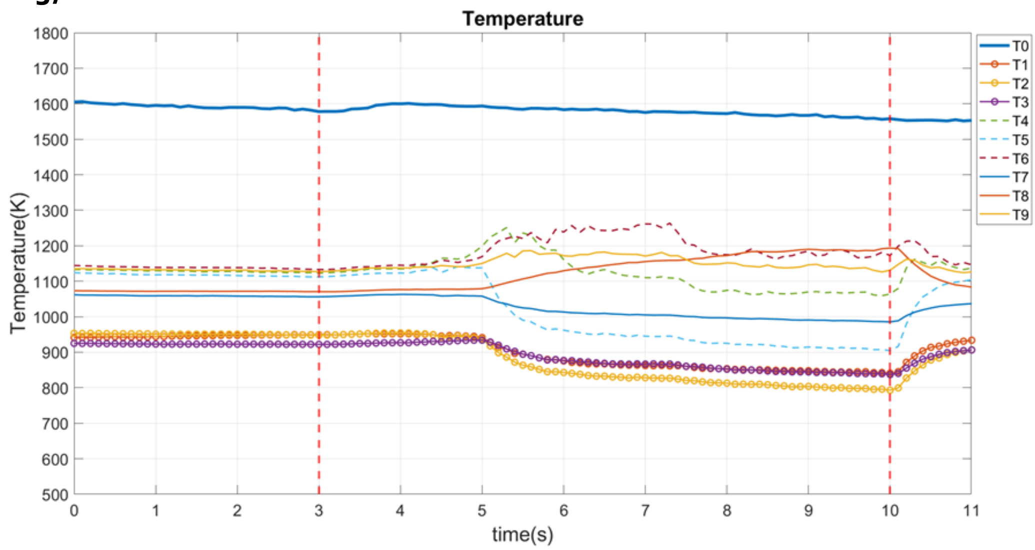
The pressure measurements corroborate these findings. As shown in **Fig. 6**, the inclined wall pressure (Ps-2) exhibited the highest value, likely due to the separation of airflow upstream of the cavity and subsequent shear-layer impingement on the inclined surface. This impingement converted flow momentum into static pressure, producing a distinct local rise [3]. The downstream pressure (Ps-3) served as a reference for the freestream static pressure, while the cavity bottom pressure (Ps-1) remained noticeably lower. The reduced cavity pressure can be attributed to the formation of a recirculation zone, where static pressure was partially converted into dynamic pressure. This mechanism ensured pressure equilibrium with the external flow but also indicated that the cavity region maintained a favorable low-pressure environment for fuel entrainment.

Taken together, the cold-flow results highlight the sensitive dependence of atomization and mixing on fuel injection rate. At lower flow rates, stable entrainment into the cavity recirculation zone promotes uniform vapor distribution and balanced temperature profiles, whereas higher flow rates disrupt this mechanism and lead to localized accumulation, strong cooling, and pressure fluctuations. These trends not only clarify the role of shear-layer dynamics in liquid-fuel mixing but also provide valuable predictive insight into the ignition and flameholding behaviour observed in the subsequent hot-flow experiments.

3 g/s



4.5 g/s



6 g/s

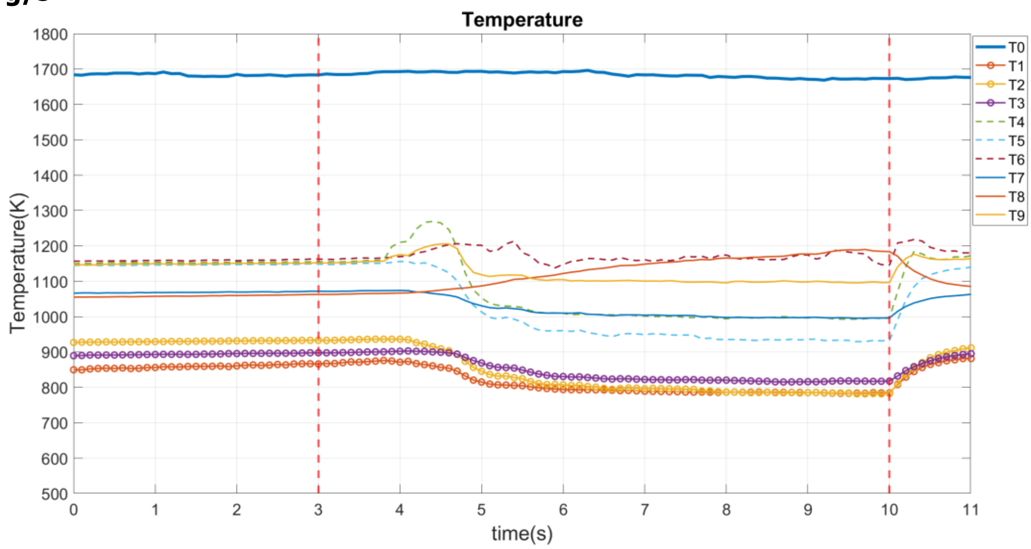


Fig 5. Temperature time-series plots of cold flow at different mass flow rates

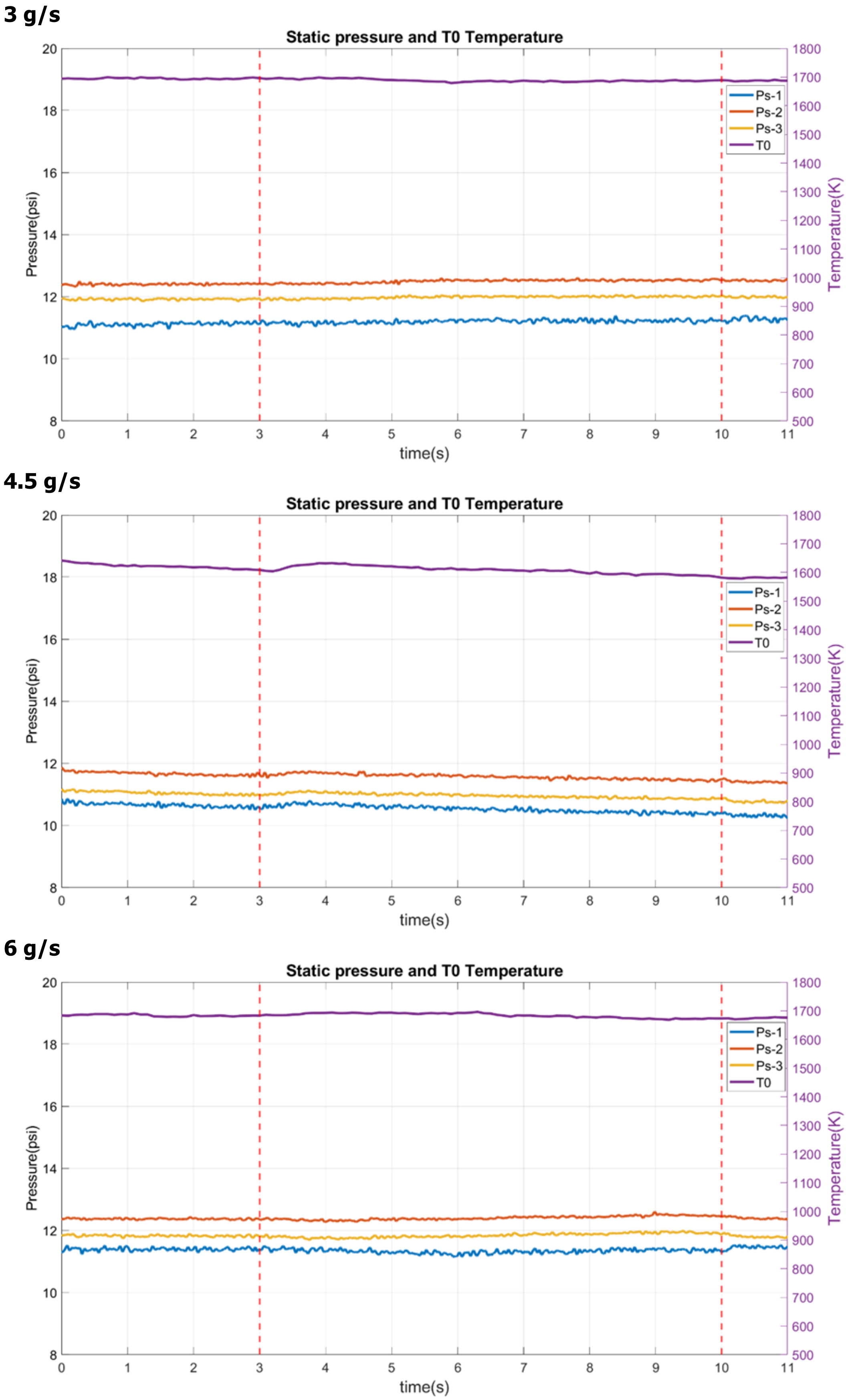


Fig 6. Pressure time-series plots of cold flow at different mass flow rates

3.2. Hot-Ignition Experiments

Under hot-ignition conditions, stable flameholding was achieved at a fuel mass flow rate of 3 g/s, while at 4.5 g/s and 6 g/s, combustion was unstable due to excessive fuel accumulation in the shear layer. This behavior is consistent with the cold-flow observations, where higher momentum flux ratios limited fuel entrainment into the cavity recirculation zone and prevented effective mass exchange with the freestream.

Tables 1 and 2 summarize the measured temperatures during ignition and steady combustion. Table 1 lists the peak temperatures recorded during igniter activation and shutdown, while Table 2 presents the average values during the stable flameholding period. At 3 g/s, the temperature traces showed a clear rise following ignition and remained relatively steady during sustained combustion, reflecting robust energy release inside the cavity. In contrast, at 4.5 g/s and 6 g/s, the temperature increased only briefly after ignition and then dropped rapidly once the igniter was turned off, indicating that the flame could not be self-sustained. These data confirm that only at 3 g/s could the cavity maintain combustion with a consistent temperature rise across multiple regions, while higher flow rates led to incomplete mixing and extinction.

The corresponding pressure measurements further reinforced these findings. At 3 g/s, the cavity exhibited a quasi-steady pressure distribution, reflecting a stable balance between heat release and gas expansion. However, when the fuel flow rate was increased, pressure traces displayed pronounced fluctuations and localized surges, indicating unstable feedback between combustion and the cavity flow field. Such behavior suggests that excessive fuel loading altered the recirculation pattern and induced transient oscillations that were detrimental to stable flameholding.

Finally, optical visualization using the Canon R50 camera provided direct evidence of the observed stability limits. At 3 g/s, the flame was clearly anchored within the primary recirculation zone and gradually convected downstream along the upper wall, maintaining a coherent structure throughout the stable burning period. At higher flow rates, however, flameholding could not be sustained; the visible luminosity appeared only intermittently, breaking apart into fragments that were quickly carried downstream without forming a persistent anchored flame. This further highlights that the successful establishment of stable supersonic combustion in a cavity combustor requires not only reliable ignition but also precise control of the fuel injection rate to maintain favorable mixing and recirculation dynamics.

Table 1. Maximum temperature at igniter activation and deactivation

	Temperature at t_0 = 4			Temperature at t_0 = 15		
Case	**bottom**	**aft wall**	**downstream**	**bottom**	**aft wall**	**downstream**
3 g/s	T2 : 925 k	T4 : 1188 k	T7 : 1101 k	T2 : 1522 k	T6 : 1769 k	T7 : 1423 k
4.5 g/s	T2 : 1012 k	T6 : 1179 k	T9 : 1154 k	T2 : 1514 k	T5 : 1780 k	T9 : 1490 k
6 g/s	T3 : 921 k	T6 : 1167 k	T9 : 1144 k	T2 : 1547 k	T4 : 1834 k	T7 : 1463 k

Table 2. Average flameholding temperatures after igniter deactivation

Average temperature during flameholding			
Case	**bottom**	**aft wall**	**downstream**
3 g/s	T3 : 1310 k	T4 :1438 k	T9 : 1245 k
4.5 g/s	N/A	N/A	N/A
6 g/s	N/A	N/A	N/A

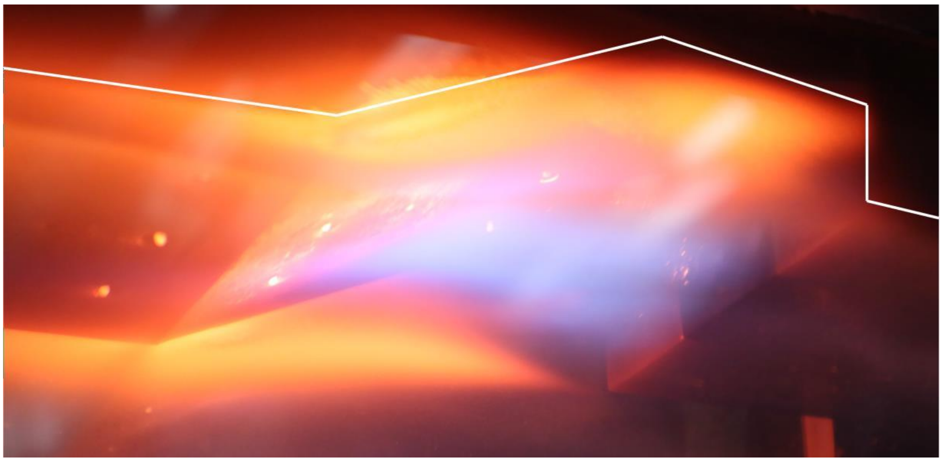


Fig 7. R50 image capturing the flameholding moment at fuel mass flow rate of 3 g/s

The cold-flow and hot-ignition results together highlight the critical role of fuel mass flow rate in determining cavity combustor stability. At 3 g/s, cold-flow measurements revealed effective entrainment of fuel into the primary recirculation zone, which promoted vaporization and mixing. This directly corresponded to the hot-ignition outcome, where the same condition yielded stable flameholding with quasi-steady pressure signals and coherent flame structures. In contrast, at 4.5 g/s and 6 g/s, cold-flow observations showed significant fuel accumulation within the shear layer and non-uniform downstream profiles, which later manifested as unstable combustion and pressure fluctuations during ignition tests.

This correspondence indicates that cold-flow diagnostics can serve as a valuable predictor of ignition performance in cavity-based combustors. Early temperature drops in fuel-rich regions, pressure rises along the cavity wall, and non-uniform vapor distribution all foreshadowed flameholding failure at high flow rates. Conversely, balanced entrainment and more uniform distributions at 3 g/s established favorable conditions for stable combustion. These results demonstrate that flameholding in supersonic cavity combustors depends not only on ignition success but also on maintaining an optimal coupling between atomization, recirculation, and shear-layer dynamics across operating regimes.

4. Conclusion

This study systematically investigated the flow-field development and flameholding behavior of a liquid-fueled cavity combustor through combined cold-flow and hot-ignition experiments. By integrating schlieren visualization, thermocouple measurements, and pressure sensing, the study clarified how fuel mass flow rate governs the interaction between atomization, shear-layer dynamics, and cavity recirculation.

The findings emphasize that only at 3 g/s could the cavity sustain stable flameholding, while both lower entrainment efficiency and excessive fuel accumulation at higher flow rates led to unstable or extinguished combustion. These results provide experimental evidence that highlights the sensitivity of cavity flows to injection momentum and the necessity of carefully controlling fuel conditions to sustain long-duration stability. Beyond identifying the stability limits, the present work also demonstrates the predictive value of cold-flow measurements for anticipating ignition outcomes.

Future work will focus on a more detailed examination of transient temperature and pressure distributions during the flameholding process, enabling finer resolution of the coupling between combustion heat release and cavity flow structures. In addition, OH* chemiluminescence diagnostics will be employed to directly visualize flame anchoring mechanisms, offering complementary insights into the stabilization process of liquid-fueled supersonic combustors and guiding the optimization of injection strategies for scramjet applications.

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