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Review

A Review on Flame Stabilization Technologies for UAV Engine Micro-Meso Scale Combustors: Progress and Challenges

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Abstract: Unmanned aerial vehicles (UAV)s have unique requirements that demand engines with high power-to-weight ratios, fuel efficiency, and reliability. As such, combustion engines used in UAVs are specialized to meet these requirements. There are several types of combustion engines used in UAVs, including reciprocating engines, turbine engines, and Wankel engines. Recent advancements in engine design, such as the use of ceramic materials and microscale combustion, have the potential to enhance engine performance and durability. This article explores the potential use of combustion-based engines, particularly microjet engines, as an alternative to electrically powered unmanned aerial vehicle (UAV) systems. It provides a review of recent developments in UAV engines and micro combustors, as well as studies on flame stabilization techniques aimed at enhancing engine performance. Heat recirculation methods have been proposed to minimize heat loss to the combustor walls. It has been demonstrated that employing both bluff-body stabilization and heat recirculation methods in narrow channels can significantly improve combustion efficiency. The combination of flame stabilization and heat recirculation methods has been observed to significantly improve the performance of micro and mesoscale combustors. As a result, these technologies hold great promise for enhancing the performance of UAV engines.

Keywords: flame stabilization; micro combustors; micro channel combustion; UAV combustor; bluff body; premixed combustion; combustion efficiency

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1. Introduction

Recent developments in the civil aviation and defense sectors have been focused on enhancing the capabilities of unmanned aerial vehicles (UAVs) and drones, with significant progress being made in the fields of electronics, autonomous systems, and control. Despite these advancements, modern UAVs still face the challenge of limited endurance due to low power densities and payload carrying capacities with low energy potential power sources. In order to address these limitations, combustion engines have emerged as a potential solution for powering UAVs. The engine technology available today, which has demonstrated great progress in developing efficient engines for both subsonic and supersonic operations in the passenger aircraft and defense sectors, could be adapted for small, powerful engines that do not compromise efficiency or performance in UAVs. The design and development of UAV combustion engines is an active area of research, as these engines must be compact, lightweight, and efficient to enable long-range flights and extended flight times. UAV combustion engines typically use gasoline, diesel, or alternative fuels such as biodiesel or propane, and may incorporate advanced technologies, such as turbocharging or direct fuel injection. Another area of research in UAV combustion engines is reliability and durability, as these engines must be able to withstand the harsh environments and high stress levels associated with UAV operations. Researchers are exploring new materials, manufacturing techniques, and testing methods to improve the durability and performance of UAV combustion engines. As such, researchers and the industry have turned their attention towards the development of microscale combustion engines to power UAVs. However, developing such small-scale combustors comes with several challenges that require innovative solutions, including flame stabilization and heat recirculation. Most microscale combustors are designed to operate with a lean mixture in a premixed laminar flame, further emphasizing the need for innovative solutions to ensure reliable engine operation. Ultimately, the successful development of reliable microscale combustion engines could replace batteries and provide a portable power source for UAVs [1]. These developments can improve the opportunities for developing hybrid UAV engines, which can provide additional power during takeoff and climb. This allows the combustion engine to operate at a more efficient level during the cruise phase.

Micro aerial vehicles, which are used for combat missions at higher altitudes, require small and powerful engines that can meet the demands of these challenging applications. However, developing such engines is a fundamental challenge that requires special attention. To address this challenge, recent research has focused on the development of micro combustors, which are small-scale combustion systems that can provide the necessary power for micro aerial vehicles. This article comprehensively reviews the latest research on micro combustor development, covering both experimental and numerical studies conducted on micro-mesoscale combustors. The article also explores the potential of micro-electromechanical system (MEMS) technology for the development of small-scale systems, although it emphasizes that the combustion characteristics of microchannel combustors require special attention. One key challenge that needs to be addressed is combustion instabilities, which can be mitigated through the development of flame stabilization technologies specifically designed for small-scale combustors. The development of micro combustors is of great interest to the combustion community due to its wide range of applications, including UAVs, thrusters, portable power devices, micro propulsion, and micro gas turbine power generation [2]. To develop efficient systems, researchers need to address the thermal effects, flame wall–interactions, and combustion dynamics of micro combustors, which have a limited combustion residence time that may result in significant heat losses due to wall interactions. While there has been significant progress in developing micro combustors over the past decade [1–12], summarized in several review articles, this review focuses on the evolution of UAV combustors and provides insight into the development of current flame stabilization techniques. It also highlights the developments in the literature on flame stabilization, addressing heat recirculation, and turbulence modeling, which are critical to the development of efficient and effective micro combustors. This review article provides an overview of the current state of research on unmanned aerial vehicle (UAV) combustion engines by discussing the unique requirements of UAV engines, including the need for lightweight, compact, and efficient designs. The article is structured to provide an overview of the different types of fuels used in UAV combustion engines, including gasoline, diesel, and alternative fuels. Figure 1 shows the number of publications on the various advancements and developments made in the field of flame stabilization, heat recirculation, and turbulence modeling in micro combustors for micro aerial vehicles. Note that most of the research on UAV micro combustor studies in scaling the current engines and modifying existing configurations began in 2010, and that a detailed review using Scopus and the Web of Science database in September 2022 discovered new publications on micro-meso combustors.

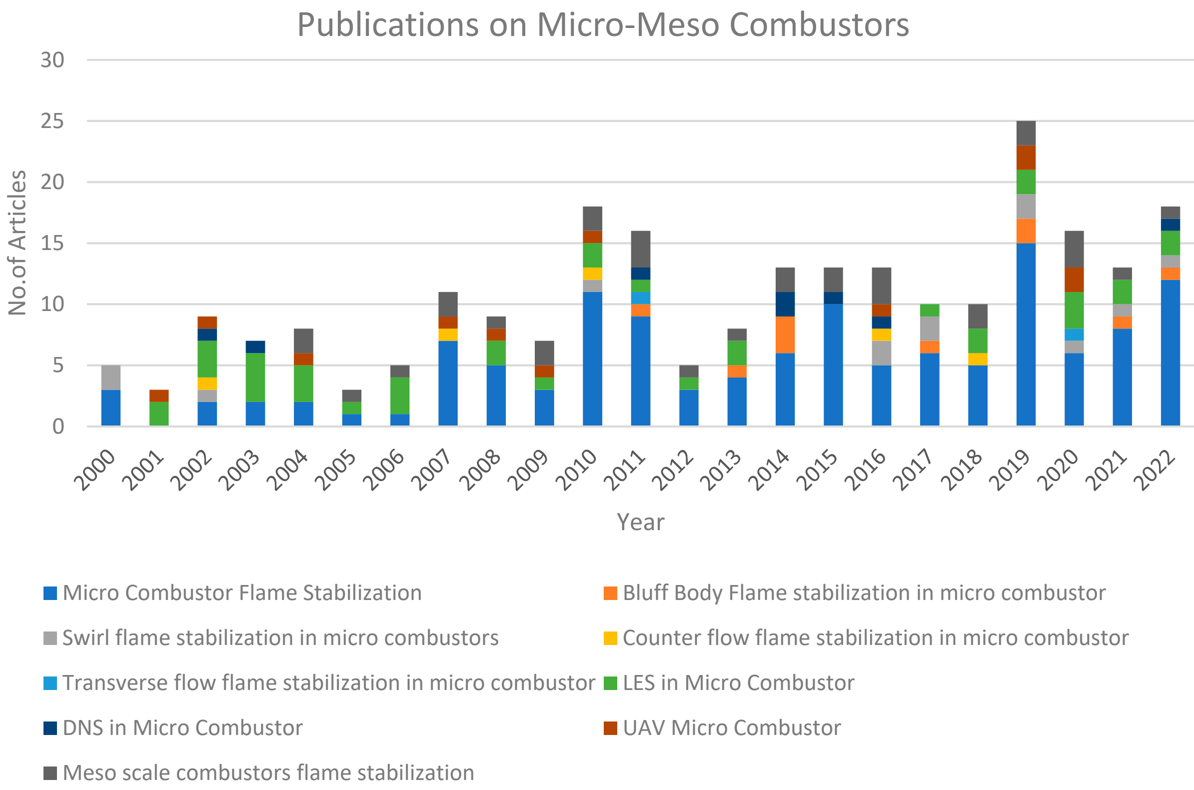


Figure 1. The number of publications containing "Micro-meso Combustors" research studies published during 2000 and 2022 (Source: Scopus database; Date of search: September 2022 Micro-Meso Scale Combustion).

In high velocity reactant streams, flames can be stabilized under specific circumstances, and understanding these circumstances together with flame blow-off limits is crucial for developing practical combustion engines. The investigation of micro combustion is also crucial for developing small UAV engines due to the complex flame instabilities that they exhibit. To address these instabilities, various flame stabilization methods have been explored, including the bluff body, swirler, counterflow stabilization, transverse flow, and two-stage flame stabilization [13]. Two-stage flame stabilization involves creating a stepped combustion channel coupled with a suitable stabilization method. Different configurations, such as rearward-facing step triple cylinder configurations [14], have extended the use of stepped micro combustors with an axial separation gap, such as the two-stage flame stabilization achieved by creating a stepped combustion channel coupled with the well-suited stabilization method. Different configurations are used with two-step flame stabilization with rearward-facing step triple cylinder configurations [14]. These concepts extended the use of stepped micro combustors with an axial separation gap, which has shown wider flame stability near stoichiometric mixtures [15]. Bhupendra et al. optimized the length, number of steps, and flow rates of a three-step rearward-facing configuration and found that flame stability is achieved at the down-stream end of the recirculation zone [14]. They also showed that the modification of the third step improves the upper flammability limit at high flowrates. Additionally, Bij et al. conducted detailed numerical studies on a mesoscale channel using a lean hydrogen mixture at near blow-off conditions and found a complex sequence of flame dynamics [16]. Although the flame burns continuously, a periodic pattern of local extinction at the wake reattachment zone with subsequent re-ignition and re-generation of the flame by the maintained flame segments behind the bluff body was observed. The periodic pattern of local extinction and recovery persisted for several cycles above the extinction limit (U = 20.6 m/s), and total extinction was observed only when the flames linked to the bluff body failed to re-build their bulk flame and scaled it down towards total extinction.

The presence of a bluff body in microchannels has been shown to create a recirculation zone that extends the residence time of mixed gas and enhances the rate of chemical reactions. In the study by Zhang et al., the use of hollow hemispherical bluff bodies with methane/air resulted in a significant increase in methane conversion along the inlet flow direction, leading to an increase in inlet velocity [17]. Specifically, the bluff bodies increased methane conversion by 3 mm as the inlet velocity was increased from 0.008 m/s to 0.02 m/s. This is due to the formation of a recirculation zone behind the bluff body, which can effectively enhance the mixing of fuel and air. However, it is of importance to note that the blow-off limits increase initially with an increase in inlet velocity, and then gradually decrease, which implies that there is an optimal inlet velocity that can maximize flame stabilization in micro combustors with bluff bodies. Wan et al. conducted an experimental study on premixed hydrogen/air flames in a bluff-body micro combustor and investigated the blowout limits at different equivalence ratios [18]. The results of their study showed that the stable combustion range of the hydrogen/air mixture was greatly expanded by the micro combustor with a bluff body. Moreover, it was observed that the blow-off limits increased as the equivalence ratio increased in lean hydrogen/air mixtures. This is primarily because the amount of heat release is increased not only by increasing the equivalence ratio, but also by enhancing the residence time of lean hydrogen/air mixtures behind the bluff body.

Fan et al. proposed the use of a Swiss-roll combustor with a bluff body to improve the blow-off limits of flames [19]. They showed that the reduction of the flame stretch effect, which is caused by the turbulence generated by the flow around the bluff body, can improve the blow-off limits. The geometric design of the combustor can also greatly extend the flame blow-off limit and enhance its performance. The use of a Swiss-roll combustor can promote better mixing of the fuel and air, leading to a more stable combustion and a higher blow-off limit. Numerical simulations have also been used to examine the blow-off limits and the impact of solid materials on the flame structure in Swiss-roll combustors with bluff bodies [19–21]. Comprehensive analyses have shown that the flame blow-off limit in Swiss-roll combustors with bluff bodies is dependent on several factors, including the rate of heat loss to the environment, the length of the recirculation zone behind the bluff body, and the rate of heat recirculation through upstream walls. The position, size, and shape of the bluff body, as well as the diameter of the channel, the thickness of the dividing walls, and the type of fuel mixture, can all have a significant impact on the flame stability of the micro combustor. Fan et al. reported that the lengths of the recirculation zones for a silicon carbide (SiC) combustor, quartz combustor, and stainless steel (SS) combustor are 4.35, 3.4, and 3.37 mm, respectively, and these lengths have a significant impact on the blow-off limits of flames in the Swiss-roll combustors [19]. Without a bluff body, the flame experiences a higher strain rate at the combustion chamber exit, which can cause flame splitting and reduce the blow-off limit. The SiC combustor has the smallest blow-off limit because it has the greatest heat loss ratio, which is an important factor in determining the flame stabilization ability of the combustor. This confirms that the heat loss effect is the main determinant of the flame stabilization ability of this novel combustor because the current configuration combines a traditional Swiss-roll design with a bluff body. In addition to the heat loss effect, the length of the flow recirculation zone and the rate of heat recirculation through upstream walls also play important roles in determining the blow-off limit of the flames in this combustor. Among the three combustors, the SiC combustor achieves the smallest blow-off limit while the quartz combustor has a medium-length recirculation zone, a considerable heat recirculation effect, and a moderate heat loss rate.

The use of alternative fuels in micro engines has gained significant attention in recent years due to their potential to address concerns related to environmental sustainability and energy security. Micro engines, which are typically used in small unmanned aerial vehicles (UAVs), require fuel with high energy density and low weight to achieve efficient and longlasting flight. Alternative fuels, such as biofuels, hydrogen, and synthetic fuels, have been studied as potential substitutes for conventional fossil fuels in micro engines. Synthetic fuels, which are produced from carbon dioxide and renewable energy sources, offer similar energy density and compatibility with existing engine technologies as conventional fossil fuels. This makes them a viable option for use in micro engines without the need for significant modifications to the engine design. Gurbuz et al. conducted studies on impact of euro diesel-hydrogen dual fuel combustion on performance in small UAV turbojet engines [22]. The results of the study showed that the euro diesel-hydrogen dual fuel system improved the performance of the UAV engine in terms of power output, specific fuel consumption, and thermal efficiency. Additionally, the use of the dual fuel system reduced the emissions of carbon monoxide, nitrogen oxide, and particulate matter, which are harmful to the environment. The study also analyzed the economic feasibility of using the dual fuel system and found that it had the potential to reduce the operational costs of the UAV engine by up to 10% [22].

1.1. Mesoscale Combustion Systems

Miniature power generation systems are popular in micro aerial vehicles, space applications, microthrustors for satellite orbital control, small-scale power generation systems, and heating, and cooling applications [23–27]. They face unique design challenges due to their small size and limited surface area. One of the main challenges is maintaining flame stability, which becomes more difficult as the size of the system decreases. In addition, the small surface area of the system makes it more susceptible to heat loss, which can affect its overall efficiency. There have been many studies conducted on flame dynamics in mesoscale channels, which have resulted in several innovative solutions. These solutions focus on promoting flame stability through different methods, such as using geometrical modifications, combustors with porous media, catalytic combustion, and two-stage flame stabilization. Wan et al. conducted both experimental and numerical studies in mesoscale channels with wall cavities [28], which have demonstrated that introducing cavities into the channel walls can greatly improve flame stability compared to straight channels. The results also indicate that the existence of wall cavities can help maintain stable flames even at high inlet velocities, which is important for applications where high flow rates are needed.

There have been numerous studies exploring the use of vortex flow to stabilize flames in narrow channels [29–32] where the stabilization of flame is often a challenge due to their limited space and high velocity. The results of these studies have shown that utilizing vortex flow can significantly improve heat recirculation, flame stability, and overall combustion performance. Shimokuri et al. developed a mesoscale system consisting of a combustor coupled with thermoelectric devices [29] that was designed to improve thermal input by enhancing heat transfer in the narrow channel. Experimental results have shown that introducing vortex motions into the channel can lead to higher thermal input by improving heat transfer, which suggests that the use of vortex flow can be an effective way to increase the thermal efficiency of mesoscale combustion systems.

Wu et al. conducted a study to investigate the impact of vortex flow on the stabilization of non-premixed flames in combustors of different sizes [30]. The study also introduced an asymmetric injection method, which resulted in increased chemical efficiencies for both methane (97%) and hydrogen/air mixtures (85%) and helped to stabilize the flame through vortex combustion. This finding suggests that asymmetric injection combined with vortex flow can be an effective strategy for improving the efficiency of combustion systems, particularly in cases where non-premixed flames need to be stabilized in different-sized combustors.

Recent studies have found that using Swiss-roll configurations with circular, rectangular, and helical shapes can be an effective way to simultaneously address both flame stabilization and heat recirculation in a single configuration [31,32]. Kim et al. investigated small Swiss-roll combustors with double spiral-shaped channels and found that the flame speed is affected by pressure, temperature, and equivalence ratio [31]. Geometrical modifications and gas injection have been found to have a significant advantage over other methods for addressing flame stability in mesoscale combustors. However, recent studies have also focused on the use of porous media to enhance heat transfer by promoting heat circulation within the combustor. Vijayan et al. conducted experimental studies on a ceramic combustor with propane/air and studied flame–acoustic interactions [32]. They found that flame–acoustic interactions had a more significant effect on flame dynamics than flame–wall interactions. The studies showed different regimes of flame dynamics, including whistling flames, rich instabilities, lean instabilities, silent flames, and pulsating flames. These findings suggest that porous media can be a promising approach for enhancing heat transfer and addressing the challenges associated with flame stability in mesoscale combustion systems.

1.2. Micro Gas Turbine Engines

In order to power UAVs, micro combustors must meet the same operational requirements as standard gas turbine combustors. As engine technology becomes more adaptable, the size of existing engines will change to meet thrust-to-power levels, thrust-specific fuel consumption (TSFC), sustainable combustion characteristics, and high bypass ratios. This section discusses the necessary technology modifications and operational requirements for scaled engines that can power future UAVs. Micro gas turbine engines face unique combustor performance issues due to their small size. To address these issues and increase performance, research into combustion has opened up new avenues. While the flammability limits are determined by fuel/oxidizer mixture and combustion conditions, flame stability, heat transfer, ignition, and combustor wall cooling are the most important aspects to consider for improving the design of micro combustors. Similarly, the design of micro combustors is subject to the same primary constraints as those of larger-sized counterparts, such as the need for a low-stress, cooling system, minimal weight, and an overall shape and size that is compatible with the rest of the engine layout [33]. Several methods are being investigated to achieve stable combustion processes, and knowledge obtained from micro power generation systems complements these developments. Studies have been conducted on bluff-body flame stabilization, catalytic combustion, swirl recirculation, and two-stage flame stabilization. It has been found that material selection significantly impacts heat recirculation in combustors, and primary and secondary air zones play a key role in cooling combustor walls. Micro gas turbine engines with propellers and jet configurations are being considered, with a hydrogen/air mixture serving as the primary fuel. Figure 2 illustrates the wide range of operating conditions in gas turbine combustors, including jet engine and rotor configurations and load characteristics. These engines operate with a wide range of power outputs in aircraft and power generation applications.

The operational conditions of conventional gas turbines are restricted by the capabilities of the turbine material and the cooling requirements of the combustor walls. Consequently, modern gas turbines can only operate with a lean premixture, with the equivalence ratio ranging from 0.45 to 0.6 [34]. The combustor inlet temperature in conventional gas turbines ranges from an ambient temperature at ignition to approximately 450 °C at base load. The flow velocity at the burner inlet varies significantly, with only approximately 15% at ignition compared to the base load. The extremely low equivalence ratio can be as low as 30% of the base load equivalence ratio. However, due to the combination of their parameters, highly flexible systems can result in flame blow-off from single burners and increased non-uniform temperature distribution at the turbine inlet, which in turn increases hydrocarbon fuel emissions.

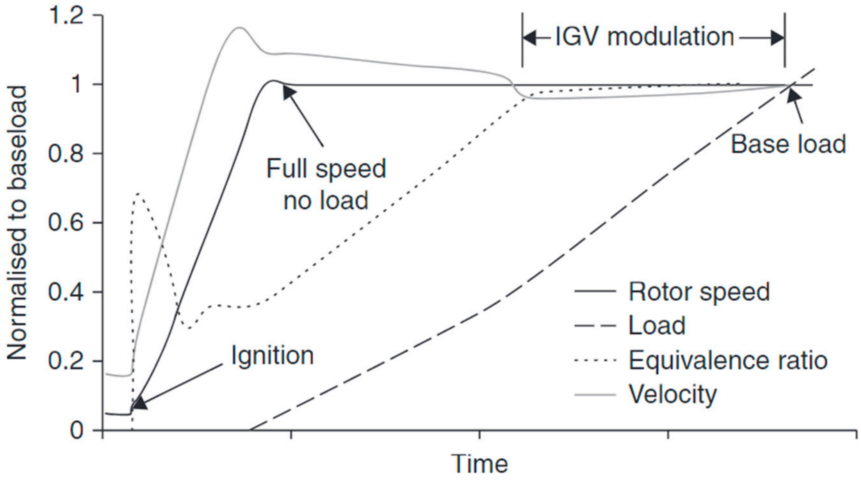


Figure 2. Gas Turbine Engine combustors with wide range of operating conditions, Reused with permission from [34]. Copyright © 2013 Elsevier Ltd.

The operational conditions are crucial in understanding the flame stability when the size of the engines is changed to a micro scale. In a previous study by Jeschke et al., a rotating combustion chamber was proposed, which demonstrated an improved thrust-to-weight ratio for small jet engines [35]. The study introduced the gas generator concept with a backward-facing step to ensure the mixing of fuel and air to achieve a homogeneous temperature distribution. These modifications resulted in the highest flame speeds with the shortest combustion chamber length. Zelina et al. conducted research on developing compact combustors with high swirl in a circumferential cavity by studying the effect of tapping a vortex. Their experiments, which used JP-8 and FT fuels, demonstrated that trapping a vortex can increase the flammability limits of the combustors [36]. The study conducted by Liu et al. focused on improving the performance of a micro gas turbine combustor by addressing flame stability issues. Based on optimization studies, modifications were made to the swirler blade angle and preliminary mixing hole location, resulting in significant improvements in performance and reduced emissions [37]. Liu et al. conducted an investigation into the flow characteristics of a micro gas turbine combustor using axial-staged jet stabilization technology combined with swirl combustion [38]. They found that the central recirculation zone did not vary significantly when the secondary fuel was injected, and the outflow velocity progressively decreased. As a result, the temperature along the central axis and at the exit decreased together with the pressure loss. However, the temperature at the annulus hole increased, while the temperature distribution at the outflow became increasingly uniform [38]. The study by Badum et al. focused on an ultra-micro gas turbine with 300 W for UAV applications [39]. They conducted numerical studies using porous inert media combustion and found that the use of cavity flow allowed for effective heat transfer management.

Mehra et al. experimentally tested a silicon micro gas turbine model with a six-wafer combustion system. The study reported exit gas temperatures in the range of 1600–1800 K using ethylene/air mixtures [40]. Additionally, stable combustion was achieved with hydrogen/air combustion and a recirculation jacket, resulting in 1600 K exit temperatures and a flame stabilization time of 0.42 ms with minimum residence time. Peck conducted experiments using two different models to investigate the stabilization of flames with a catalyst [41]. The experiments were conducted with JP-8 fuel in both a partially filled catalyst combustion chamber and a fully filled catalyst combustion chamber. The results of the study showed variations in combustion characteristics in both configurations, but detailed investigations showed better efficiency with the particle catalyst combustion chamber.

2. Recent Progress in Engine Development

UAVs have become increasingly popular in recent years due to their technological advancements and their ability to be remotely controlled or operated autonomously. The integration of artificial intelligence (AI) technology in UAVs has enabled them to perform a wide range of tasks with high precision and efficiency. The history of UAVs can be traced back to as least 1849, when unmanned explosive balloons were used as moving targets. However, it was during World War II that several developments in the usage of unmanned flying objects were made [42]. Since then, UAV technology has continued to evolve, and today, they are widely used in various industries and applications, ranging from military to civilian including underwater operations, scientific research, surveillance, emergency response services, and goods transportation. To support these diverse missions, future UAVs will require powerful engines that can improve their capabilities, such as endurance and payload carrying capacity, to ensure that they can carry out their tasks effectively and efficiently.

In the United States, the Department of Defense (DoD) has classified UAVs into five groups based on their size, maximum gross weight, and operational characteristics. This classification system helps to standardize UAV design and performance specifications and to understand the different classes of engines required to power them. The five categories of UAVs based on size and weight are listed in Table 1. Over the past four decades, significant research efforts have been focused on improving rotary engines by modifying various engine types, including 2-stroke and 4-stroke piston engines, diesel engines, and Wankel rotary engines. Despite these efforts, however, rotary engines still face certain limitations, such as weight-to-power ratio constraints, cooling challenges with the combustion systems, and performance limitations. These limitations have prevented rotary engines from being widely adopted as the primary power source for UAVs, where high power and efficiency are critical for extended flight times and payload capacity.

Table 1. UAV classification according to the United States Department of Defense [43–46].

UAV Category	Maximum Gross Takeoff Weight (MGTW) [lbs]	Size	Airspeed [Knots]	Normal Operating Altitude [ft]
Group 1	0–20	Small	<100	<1200 Above Ground Level
Group 2	21–55	Medium	<250	<3500
Group 3	<1320	Large	<250	<18,000 Mean Sea Level
Group 4	<1320	Large	Any airspeed	<18,000 Mean Sea Level
Group 5	<1320	Largest	Any Airspeed	<18,000

In recent years, there has been a growing trend of using jet engines to power UAVs that are equipped with propellers and designed to support vertical take-off and landing (VTOL) operations. To increase the endurance and efficiency of these modified micro engines, researchers have been exploring new ignition and combustion technologies that can enhance their performance. Recent research has shown that automobile gasoline engines, which have the ability to run on heavy fuels, such as kerosene and JP5 jet fuels, have yielded the longest flight times for Group 2 unmanned aerial vehicles (UAVs) [47]. This trend has also expanded to include the development of military systems that can meet the high-end requirements of Group 4 and 5 flights, which are expected to become transport aircraft soon and have the same size as manned flights. To achieve this, there is a need for UAV engines that are lighter in weight, have a low TSFC, have equal fleet payload capability and endurance capability, and are cost-effective [48].

The suitability of existing engines for UAV applications is a topic of debate among experts. Engines, such as turbojets, turbofan, and turboshaft, with a thrust range of 200 to 1500 lbs, require a detailed study of their performance characteristics. Fighter engines typically have a low bypass ratio and high specific thrust, while transport engines have low specific thrust. A modified design with a specific thrust ranging from 25 to 90 lbf/lbm/s and a TSFC close to 0.7 is likely to be of interest in UAVs. The use of advanced materials is also crucial in the development of efficient engines with better combustion systems. To overcome the challenge of the weight-to-thrust ratio, materials with superior mechanical properties, such as superalloys made with aluminum (Al) and titanium (Ti) for strength and rhenium (Re) for increasing high-temperature strength, are under consideration [49]. Efforts are being made to enhance fuel injection and combustion precision, improve combustion efficiency, and achieve higher thrust per unit of fuel. These advancements can potentially increase the endurance and payload capacity of UAVs, leading to longer flight times and improved operational capabilities. The ultimate objective is to develop jet engines that are more reliable and efficient and can cater to the diverse requirements of the different industries that utilize UAVs for various applications.

Technology Readiness Level

The turbofan engines, developed by Rolls Royce, are used in the Global Hawk, Triton, and Embraer 145 UAVs, which have an endurance range of over 30 h, can fly at an altitude of 65,000 ft, and have a payload carrying capacity of 910 kg [50]. The M250s turboshaft engines power the MQ-8 Fire Scout, MQ-8B, and Northrop Grumman vertical take-off UAVs, which are classified as Group 4 systems and operate in both the U.S. Navy and the U.S. Marine Corps [51]. The Adour engine, which is a type of turbofan engine with two rotating parts (twin spools) that rotate in opposite directions (counter-rotating) and operate at 5000 to 8000 lb of thrust, was chosen to power UAVs of the European unmanned combat air vehicle demonstrator program [52]. The PW545B turbofan engine, developed by Pratt & Whitney, has a reverse flow annular combustion chamber with a bypass ratio of 4.1:1 and powers the general-purpose atomic Predator C "Avenger" [53]. Additionally, Group 2 and 3 UAVs are powered by two-stroke and four-stroke engines, such as the Rotax 914 F/UL, a four-stroke engine with a turbocharger that powers the Predator and Harfang UAVs [54]. Table 2 provides a detailed review of modern UAVs and their engine specifications. This study emphasizes the importance of developing low-cost, effective, and simple engines for non-defense and commercial use of UAV systems.

Table 2. Few significant UAV/Drone Engines and its specifications [43–47,50,55–62].

UAV/Drone	Engine Type	Fuel *	Endurance [h]	Payload [kg]
MQ-1C Gray Eagle	HFE-180HP heavy fuel Engine	Diesel, Jet Fuel	42	227
Mojave	Rolls Royce M250	JP-4 Aviation Kerosene, Jet fuel	25+	1633
MQ-9 Reaper	Honeywell TPE331-10	Jet A, A1, JP-1,4,5,8	27	1361
Predator C Avenger	Pratt & Whitney PW545B turbofan	Jet Fuel	20	2948
Predator XP	Heavily Modified Rotax 914 Turbo	4-Stroke engine Gasoline	35	147
Global Hawk, Triton, The Embraer 145	Rolls-Royce AE 3007 Turbofan	JP-8, Jet Fuel	30	910
RQ-7 Shadow 200	AR741-1101 Single rotor Wankel-type spark ignition engine	Aviation Gasoline	6	25.4

Table 2. *Cont.*

UAV/Drone	Engine Type	Fuel *	Endurance [h]	Payload [kg]
Northrop Grumman X-47C	Pratt & Whitney Canada JT15D-5C High Bypass turbo fan	Jet fuel	6	4500
MQ-8 Fire Scout	Rolls-Royce 250-C20 W	Jet Fuel	12	1338
Harfang	Rotax 914 F	Gasoline, Octane AKI, Octane RON	26	250
Nishant	ALVIS AR-801	Gasoline	4.5	45
RQ-21 Blackjack	EFI Piston Engine	Gasoline	16	18
RQ-4 Global Hawk	Rolls-Royce AE3007H turbofan engine	Jet Fuel	36	860
CQ-10 Snowgoose	Rotax 914 piston engine	Gasoline	19	227
Scan Eagle	two-blade propeller, Piston engine	Heavy fuel (JP-5 or JP 8) or C-10 gasoline engine	20–28	5
RQ- 5A Hunter	Moto-Guzzi	Gasoline	30	125
Elbit Hermes 450	UEL R802/R902 (W) Wankel engine	Regular grade Mogas or AVGAS (100LL)	20	180
Watchkeeper	Rotary Wankel water-cooled engine	Aviation Gasoline	16+	150
Kronshtadt Orion	Rotax 914 engine	Gasoline	24	250
CH-4 Chang Hong	Lark HFE unit Wuhu-based Anhui Haery Aviation Power	Heavy Fuel	30	115
Rustom H	NPO-Saturn 36MT engines, Turbo prop	Aviation Gasoline, Jet fuel	24	350
Wing Loong-3	Turbo Prop Engine	Jet Fuel	40	2300
Sperwer A, B	Bombardier-Rotax 582/562UL	RON 90 Octane, AV Gas 100 LL	12–24	50–100
Bayraktar TB2	Rotax 912 engines	Gasoline, Octane AKI, Octane RON	24+	150

* Fuels for Military Applications and Domestic Applications are different.

3. Combustion Challenges

The size of the combustion chamber is a crucial factor in developing efficient small-scale engines. Although advancements in power generation applications have helped understand flame dynamics in UAV engines, engines mounted on aerial systems must meet weight-to-power ratios, low TSFC, and high efficiencies. Micro combustors, however, experience strong combustion instabilities due to limited residence time, high inlet velocities, and flame structure. To address these challenges, vortex interactions have been considered to stabilize flames by enhancing mixing, extending flame fronts through obstacles and swirlers, and creating step cavities. Flame stabilization studies have extensively investigated different methods that use combined stabilization strategies. During the past 30 years, turbulent combustion studies have made significant progress in understanding highly turbulent regions of flows and fluctuations in flames [63]. Vortex shedding behind the bluff body, swirler, step cavity, and counter flows lead to improved mixing and ignition, resulting in aerodynamically stabilized flames. Figure 3 illustrates vortex structures in unstable combustion with different combustor configurations.

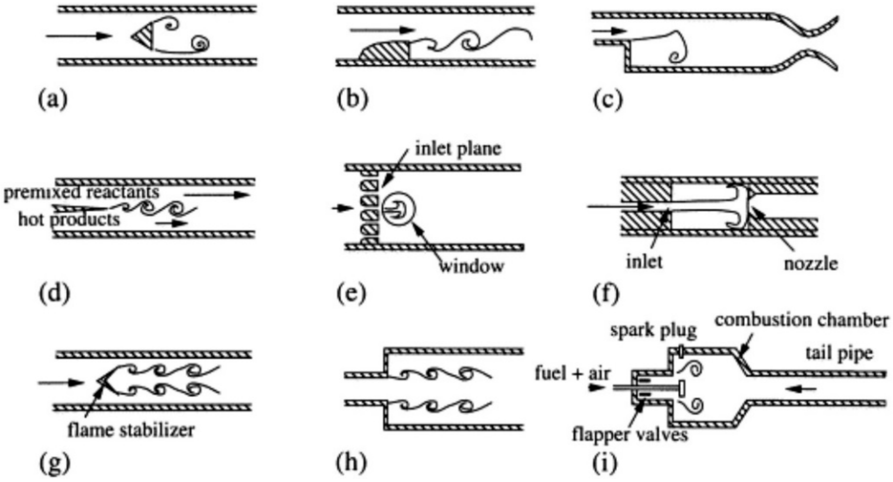


Figure 3. Observation of vortex structure in unstable combustion with different configurations: (**a**) High frequency "screech" instability; (**b**) Low frequency instabilities in a backward facing step geometry; (**c**) Low frequency instabilities of a dump combustor; (**d**) Large scale vortices in a premixed shear layer; (**e**) Vortex driven instability in a multiple jet dump combustor; (**f**) Vortex driven oscillation in a single jet dump combustor; (**g**) Organized vortex motion in a premixed ducted flame modulated by plane acoustic wave; (**h**) Control of a dump combustor using organized vortices; (**i**) Vortex motion during the injection phase of a pulse combustor. Reused with permission from [63]. Copyright © 2000 Elsevier Ltd.

The swirl-induced vortex breakdown method is a common technique used in modern gas turbines to stabilize flames [64]. This method can also be applied in micro combustors to reduce combustion lengths by utilizing recirculation zones for mixing and ignition, and to improve flame stability through the formation of toroidal recirculation zones [65]. The swirl number is an important factor in designing an efficient combustor, and studies have shown that a critical swirl number greater than 0.6 is necessary for better flame structure. Bluff bodies are also commonly used to stabilize flames in microchannels due to their aerodynamic properties. Two-stage flame stabilization of lean premixed flames has been investigated for micro combustors and has shown improvements in heat recirculation and combustion efficiency. Various experimental and numerical studies on flame stabilization techniques have been conducted, and a detailed overview is presented in Table 3, including industrial applications and key findings.

Table 3. Different micro combustion and power systems and its development.

Authors	Type of Combustor/Power Source	Industrial Applications	Numerical/Experimental Studies	Key Findings
Kentfiled [66] 1998	Valveless Pulse Jets	UAV, MAV Propulsion applications	SNECMA/Lockwood aero valved design	Thrust augmentation flow rectifier, amplification of the thrust.
Fleming et al. [23] 2002	Small-scale thermoelectric generation	Micro air vehicles, DARPA MAV,	TEG Module testing Integration studies for DARPA	High-temperature TEG Module, Improved thermos electrical efficiency
Leach et al. [67] 2005	Millimeter scale combustor	UAV, MAVs, Missiles	Methane air mixture of two parallel plates, Heat Recirculation with detailed chemistry	Comparison of the heat recirculation and flames with Hydrogen combustors

Table 3. *Cont.*

Authors	Type of Combustor/Power Source	Industrial Applications	Numerical/Experimental Studies	Key Findings
Lloyd et al. [20] Chen et al. [68] Li et al. [21] 2005, 2008 Kim [31] Fan et al. [19] 2017 Wu et al. [69]	Swiss-roll Micro Scale Combustor	Stirling Engine, Micro heat, and Power generation, Cooling applications	Numerical Model developments, Experimental studies, Swiss-roll Catalytic combustor, 3D CFD modelling	Numerical prediction of extension limits, Heat Recirculation studies, combustion efficiency, flame stabilization, blow-off limits, system performance
Rideau [70] 2008	TR60, TR 40 New bypass Turbojet	Missiles, UAVs	Single spool Bypass Turbojet engine	Details about TR60, TR 40 Engine Demonstrator program
Minotti et al., Zhang et al. [71,72] 2009, 2022	Cylindrical Micro Combustor, Helical Fins	Propulsion, Satellite Power systems, UAVs	3D RANS Eddy dissipation Model, two-step reduced kinetic mechanisms, scaling Laws	Micro Combustor Performance, Numerical Performance of EDC, Framelet model, Micro Step flame-flow Interactions
Deshpande et al. [73] 2011	Backward-facing step Micro combustor	Micro Power Generation, UAVs	Experiment conducted with quartz micro combustors, emission measurements	Effect of geometrical configuration on flame stability limits with two-steps, three-step combustors
Wan et al. [2,13,18,19,74–79] 2012–2022	Planner Micro combustor with Bluff body	Combustion based micro power generation and UAVs	2D RANS, k-e Experiments at 40 m/s with Digital Camera Hydrogen/Air	Blow-off Limits at 0.2, 0.5, 0.6 Equivalence Ratio, Peak Temperature 1850 K
Hosseini et al. [80] 2014	Step Micro flameless combustor with bluff body	Small-Scale Power generation, Micro Thermophotovoltaic, Aviation	3D RANS, k-e EDC model, Premixed and Non premixed	Combustion efficiency enhanced due to flameless combustion, flame quenching elimination, Higher inlet velocities
Catori et al. [81] 2014	Small-Scale turbojet combustor	UAVs, Drones Gliders	Blast Atomizer Configuration CFD Miniature combustion chamber	Atomization and Mixing characteristics, Exit temperature profiles
Zhang et al. [17] 2015	Hollow hemispherical Bluff body	Power generation, military use aviation, Chemical Industry	3D with surface catalytic reaction with Deutschman mechanism Methane/air	Hemisphere bluff body enchanted blow-off limits by 2.5 times, tested at stoichiometric conditions
Kang et al. [24,25] 2015, 2019	Mesoscale Combustor with thermally orthotropic wall	Micro Propulsion systems	Parallel plate mesoscale combustor, FLIR systems, Infrared camera	Flammability limits for both pyrolytic graphite and stainless-steel plate Thermal efficiency
Lee et al. [16] 2015	Mesoscale channel with Bluff body	Power generation, Gas turbine combustors	2D Direct Numerical Simulations (DNS) Hydrogen/air	Detailed visualization of the near blow-off flame characteristics
Spytek [82] 2019	Turboshaft Engine T1310-SA100	UAV Applications	Multi-inter-turbine burner enabled configuration	Redeveloped configuration with inter-turbine burners, power output

Table 3. *Cont.*

Authors	Type of Combustor/Power Source	Industrial Applications	Numerical/Experimental Studies	Key Findings
Guo et al. [83] 2020	Swirl/Bluff-body Burner	Power generation, Gas turbine combustors	LES coupled with thickened flame model Particle Image Velocimetry (PIV) Planar Laser Induced Fluorescence (OH-PLIF) Hydrogen enriched CH_4/air	Effect of Swirl, Bluff body on hydrogen flame stabilization, Decreased Axial velocity fluctuations, attachment of the flame is weak due to lean mixture.
Zou et al. [84] 2020	Narrow channel with orthotropic walls	Microthrusters, power generation, Propulsion	DNS Studies on bluff-body stabilized flames Premixed Hydrogen/air	Heat loss resistance ability compared with isotropic combustors, Flame structure at higher inlet velocities
Sadatakhavi et al., Kankashvar et al. [85–87] 2020, 2022	Can Micro Combustor	Jet engines, UAVs, Micro has turbines	Experimental Studies, RANS Droplet Modelling, Kerosene Liquid fuel, LES studies on oxidant jets	Inner Recirculation zone and Swirl Phenomena along the liner wall, flame formation, droplet breakup, evaporation
Choi et al. [26,27] 2021, 2022	Mesoscale Swirls combustor	UAVs, Burners, Power Generation	Experimental with OH-PLIF Imaging Setup Jet A-Air, Hydrogen rich Fuels	Improve small-scale flame stability, reduce length scales, overall combustion characteristics, Lean Blow-off limits
Ghali et al. [88] 2021	Micromix Combustor	Auxiliary Power Units, Propulsion	Eddy Dissipation Model with single injection Hydrogen air	Lean mixture and influence of equivalence ratio and NOx formations
Khan et al., Zizin et al. [89,90] 2015, 2022	Micro combustor with an embedded passive fuel pumping	Micro Aerial vehicles, Power Generation	Non-Premixed Ethanol combustion, flame fluctuations	Atomization at ultra-low flow rates, Heat loss from the combustors

4. Experimental Studies on Micro-Meso Scale Combustors

4.1. Micro Scale Combustion Systems

The combustion characteristics in micro- and mesoscale combustors have been investigated through various experimental studies with different combustor configurations. The development of advanced combustion engines for UAVs is challenging due to their operational requirements, and there are practical aspects of these studies that make them distinct from conventional combustors, including thrust generation, TSFC, engine power density, safety aspects, and the use of jet fuels. Recent developments in flame stabilization have focused on using different geometrical modifications, catalysts, heat recirculation, counter flows, swirlers, and porous media flows in conventional combustors. Investigations were conducted using hydrogen/air, methane/air, and hydrocarbon/air mixtures [24,37,73,91–99]. Several studies with can-type combustors for micro gas turbines have also been reported, such as one by Sadatakhavi et al. that investigated flame behavior and predicted temperature distribution using liquid fuels [85,86,100]. The experimental setup with Amirkabir's micro gas turbine combustor is illustrated in Figure 4 with details of a swirl injector. The swirler with a swirl number of 0.86 was used to direct the flow downstream along with kerosene fuel spray using a hollow swirl injector with a spray angle of 60° [100]. Liquid fuel combustion requires a detailed understanding of flow behavior in the inner recirculation zones that support the atomization and vaporization processes.

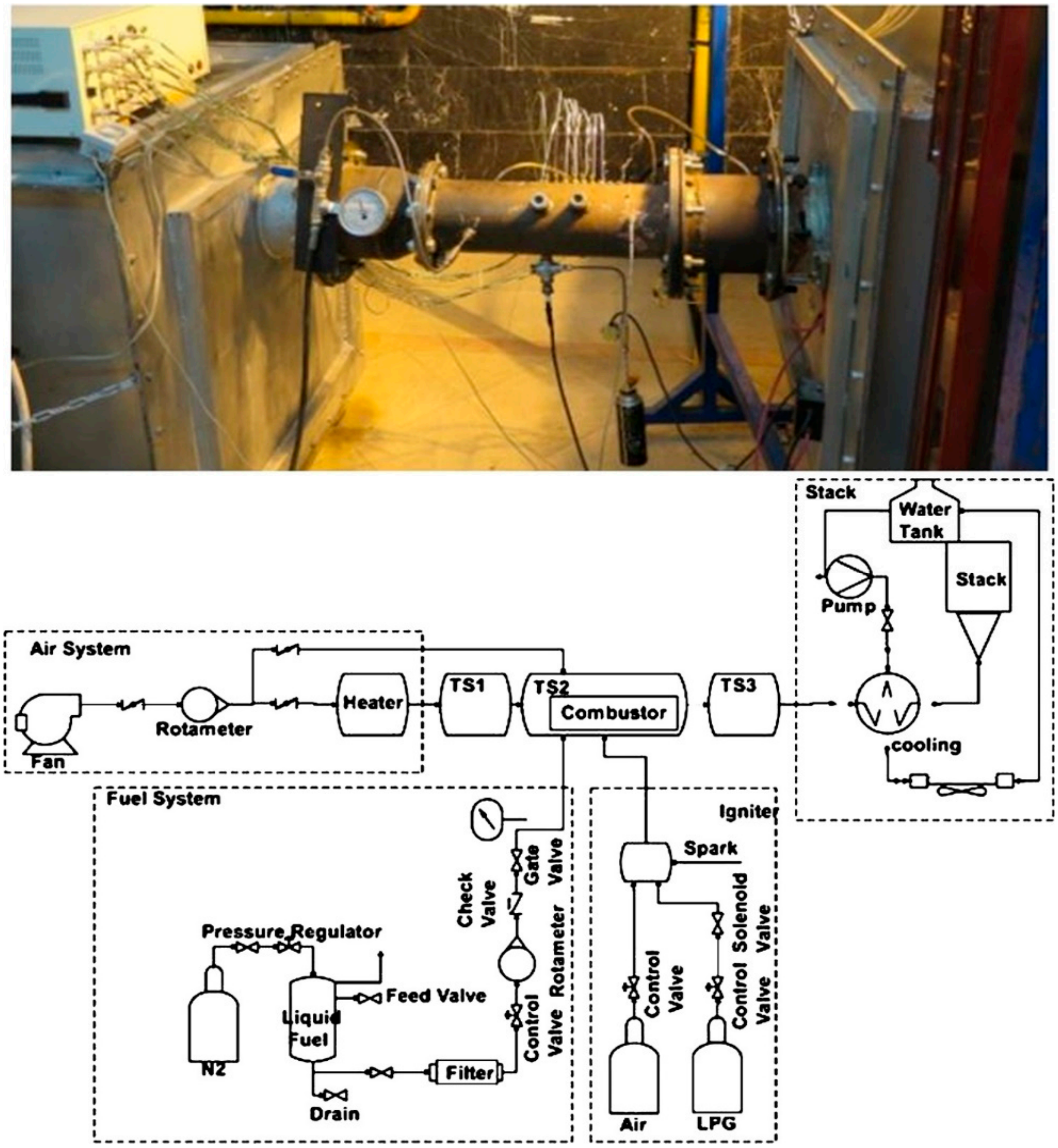


Figure 4. Experimental studies on Amirkabir's micro combustor tested liquid fuels. Reused with permission from [85,86,100]. Copyright © 2020 Elsevier Ltd.

Sadatakhavi et al. conducted experimental and numerical investigations on the characteristics of reactive and non-reactive flows [85,86,100]. They identified the atomization process in the recirculation zone by supplying fuel and air through a swirler, and Figure 5 shows the droplet profiles in the inner recirculation zone (IRZ) under both reactive and non-reactive conditions. The Sauter mean diameter (SMD) profile indicates a reduction in fuel droplet diameter due to high turbulent kinetic energy in the flow, which generates recirculation zones around the liner walls and promotes the vaporization of fuel droplets. Experimental studies have mapped the flame zones using temperature measurements in various zones of the combustor. The swirl angle enhances the efficiency of the combustor through improved evaporation in the IRZ. Similar studies have been conducted by Liu et al. with variations in swirl blade angles and combustion stage nozzles, which influenced combustion characteristics such as efficiency, stability, ignition, and temperature fluctuations [37]. Experimental studies on dry low emission (DLE)-type lean premixed combustion systems have shown that changes in swirl angles and flow characteristics improve fuel and air mixing uniformity, affecting vaporization in the IRZ and combustion performance [101]. Sahota et al. performed a study on controlled swirl flow with backward-facing steps and found that flammability limits increase significantly with incoming flow [102].

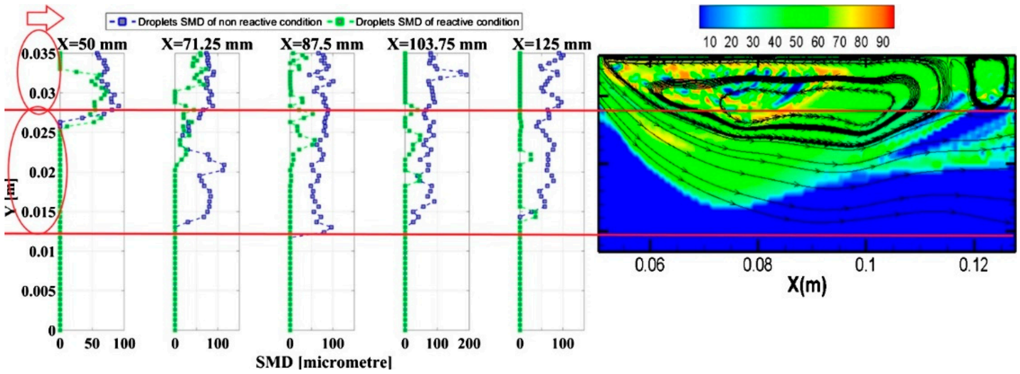


Figure 5. Droplets SMD profile and contour (in μ) in the intermediate zone in reactive and non-reactive conditions, displaying the placement of droplets in the recirculation zones. Reused with permission from [85]. Copyright © 2020 Elsevier Ltd.

Swirl was found to have an influence on the temperature profile, improving the temperature distribution for all equivalence ratios compared to no swirl. The flame position remained unchanged despite changes in equivalence ratio, but its effects were evident in an active swirl reformer [102]. Studies on can-type micro combustors with kerosene, jet fuels, hydrogen, and methane focused on flame stabilization, enhancing blow-off limits at higher velocities, and injection strategies. The fuel injection angle significantly impacted flame structure when tested with different swirl angles, and the use of a high swirl number favored flame stability [65,103]. Developing efficient atomizers to increase fuel/air mixing for lean combustion conditions is of special interest. Injection length also had a significant effect on the combustion process. Figure 6 illustrates the concept of an upward swirl combustor with lean combustion limits and temperature distributions in the primary combustion zone.

The swirl number is an important parameter for evaluating the combustion characteristics of can combustors. Kankashvar et al. [86] investigated the effect of swirl angle on flame structure and combustion characteristics using an 18-blade swirler and cone atomizer. They tested this configuration with different spray cone angles (45°, 60°, and 80°). The swirl number can be calculated using the following equation:

$$Swirl\ Number = \frac{2}{3}\left[1-\left(\frac{D_{hub}}{D_{sw}}\right)^{3}/1-\left(\frac{D_{hub}}{D_{sw}}\right)^{2}\right]\tan\theta, \quad (1)$$

where D_{hub} indicates the swirler hub diameter, D_{sw} the swirler diameter, and θ swirler vane angle.

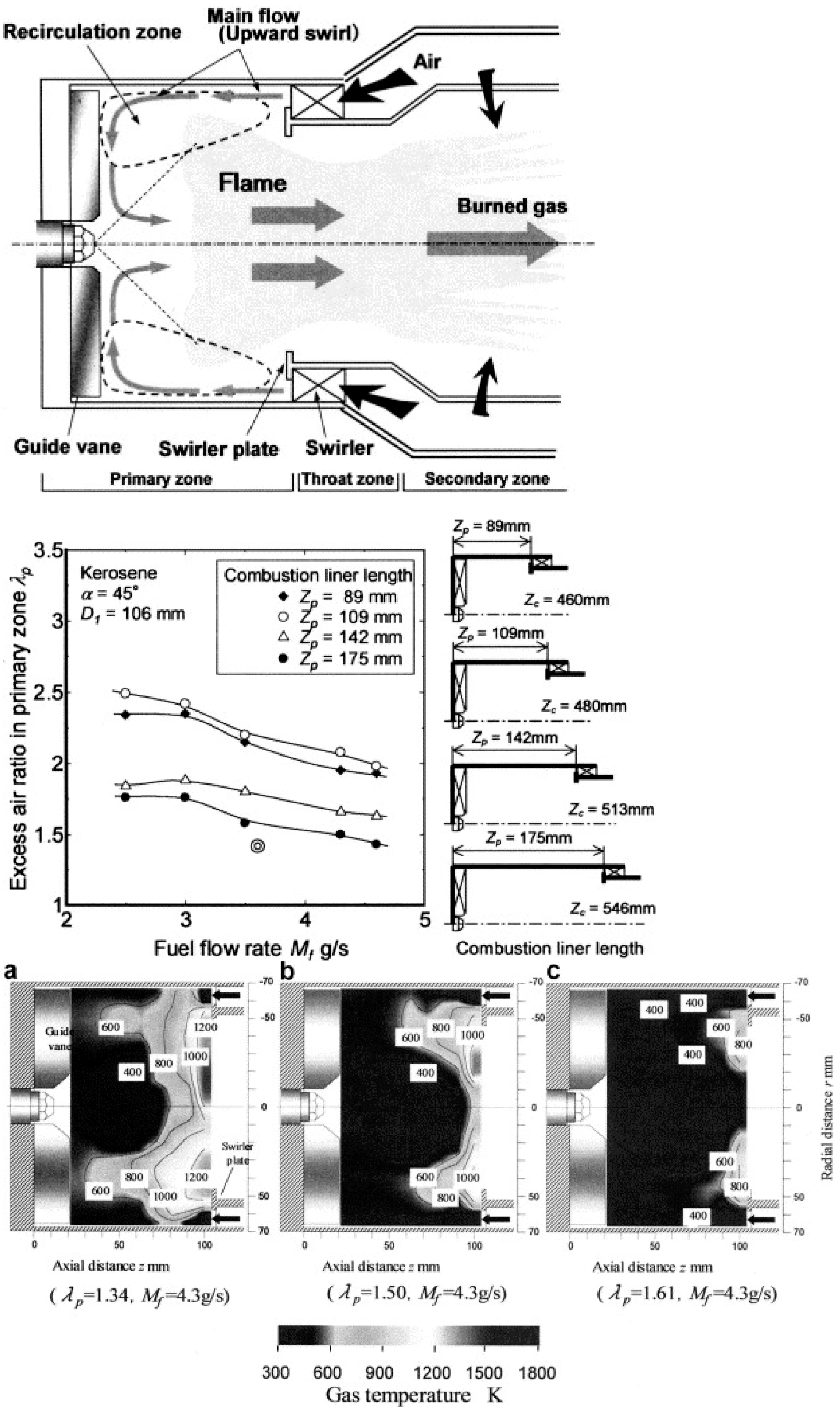


Figure 6. Concept of upward swirl combustor with lean combustion limits and temperature distributions in the primary combustion zone: (**a**) Excess air ratio (l_p = 1.34), Fuel flow rate (M_f = 4.3 g/s); (**b**) Excess air ratio (l_p = 1.50), Fuel flow rate (M_f = 4.3 g/s); (**c**) Excess air ratio (l_p = 1.61), Fuel flow rate (M_f = 4.3 g/s). Reused with permission from [104]. Copyright © 2007 Elsevier Ltd.

Furuhata et al. introduced the concept of upward swirl and conducted experimental studies using kerosene to understand the effects of swirl angle under high swirl number conditions as shown in Figure 6 [104]. In this type of combustor, the swirler is placed between the primary and secondary zones to enhance mixing and recirculation. A parametric study with four combustion liner lengths, Z_p, was performed to optimize the primary zone for efficient combustion under lean conditions, with an optimized Z_p of 109 mm showing better performance. The location of the flame is crucial for evaluating the condition of combustion with the swirler and the optimized primary zone. The swirler vane angle and throat diameter were fixed for the experimental studies to estimate lean combustion limits, and recirculating burned gas in the primary zone significantly affected emissions by enhancing the inlet conditions of the fuel/air mixture. Temperature distribution inside the combustion chamber is shown in Figure 7 for different spray cone angles, with the temperature profile at different injection angles reflecting the importance of atomization angle and novel atomizer selection. Lower atomization angles enhance fuel-air mixing in the center of the combustor, thereby inducing high flame temperatures. These studies highlight the importance of developing efficient atomizers and swirlers to enhance the combustion characteristics of can-type micro combustors.

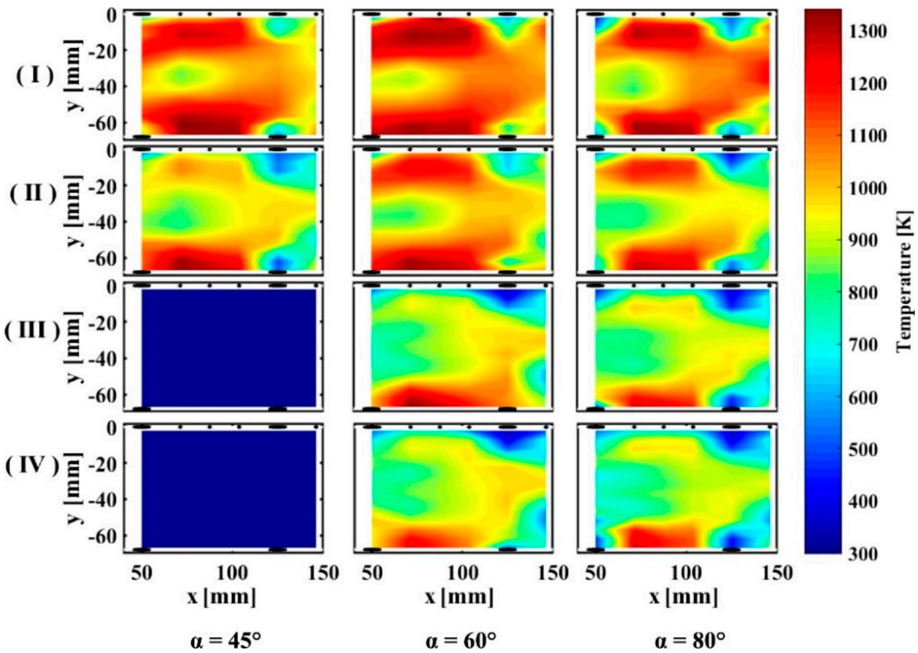


Figure 7. Temperature distribution inside the combustor with different spray cone angles and at different operating conditions: (**I**) Φ = 0.38; (**II**) Φ = 0.31; (**III**) Φ = 0.27 and (**IV**) Φ = 0.25. (For interpretation of the colors in the figure(s), the reader is referred to the web version of this article). Reused with permission from [86]. Copyright © 2021 Elsevier Ltd.

The development of efficient micro combustors has attracted significant attention from researchers, and key findings are summarized in Table 3. Various configurations with flame stabilization mechanisms have been tested using different fuel mixtures, making them suitable for different applications. Bluff-body flame stabilization studies have been conducted on various micro combustor configurations, and the flames can be stabilized at high velocities due to their downstream blunt shape, which creates a wake of eddies behind the object [105]. The shape and position of the bluff body and inlet velocities have significant impacts on the flame structure, improving the blow-off limits at high velocities [16,106–108].

Wan et al. tested different bluff-body configurations in a planar micro channel with lean premixed hydrogen/air mixtures and observed that the high-temperature zone shifted gradually with increasing velocity, and the flame was stabilized behind the bluff body [18].

Figure 8 shows the direct images of the flame at different inlet velocities of 15, 23, and 40 m/s. The bluff body established stable combustion in the narrow channels with higher heat release and chemical reaction rates. At moderate inlet velocities, there was a gradual rise in the exhaust gas temperature due to the fuel/air mixture having enough time to mix and burn completely. However, at higher inlet velocities, the exhaust gas temperature started decreasing due to incomplete combustion. Heat loss played an important role in determining combustion efficiency and exhaust gas temperature due to the large surface area to volume ratio of the micro combustors. Fan et al. investigated the effect of combustor material on the blow-off limits and flame stabilization in bluff-body narrow channels and showed that a quartz combustor exhibited better performance than stainless steel and SiC ones due to its low thermal conductivity, which favored the blow-off limit due to weak flame stretching effects [79].

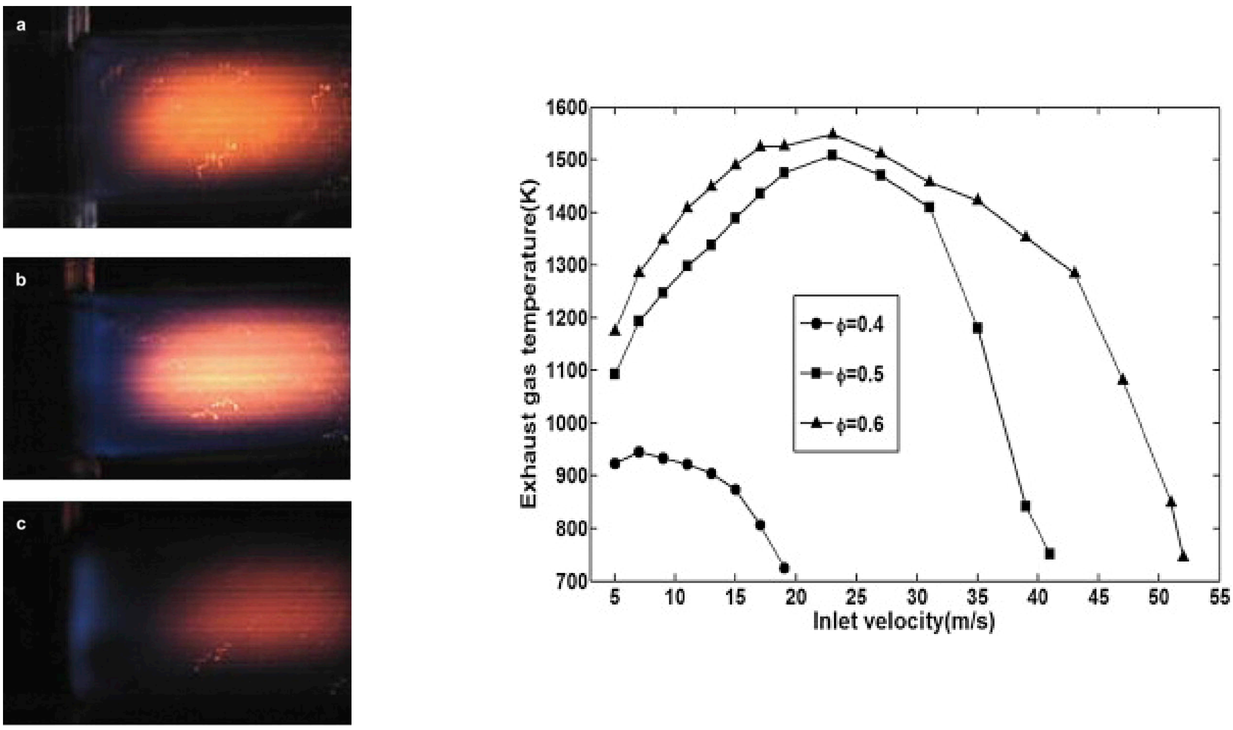


Figure 8. Flame photos for different inlet velocities at the same equivalence ratio of 0.5: (**a**) V_{in} = 15 m/s; (**b**) V_{in} = 23 m/s; (**c**) V_{in} = 40 m/s. The inlet of the combustor is on the left side. Experimental data of exhaust gas temperature versus inlet velocity for different equivalence ratios. Reused with permission from [18]. Copyright © 2012 Elsevier Ltd.

The thermal conductivities of stainless steel and SiC are greater than that of quartz, resulting in a more efficient transfer of heat. Consequently, the temperature profiles of walls made from stainless steel or SiC are significantly different from those made from quartz, mainly due to the increased heat transfer at the upstream location [79]. Thermal management is also a crucial aspect of addressing the flame stability issues that arise in micro combustors and micro thermophotovoltaic applications. Tang et al. conducted experimental studies on a propane/air heat recirculation combustor that utilized symmetrical baffles and evaluated its performance [109]. To differentiate between the inlet and burning zones, they developed an experimental model featuring two symmetrical baffles, which enhanced preheating of the cold flow and improved combustion. They observed that the equivalence ratio and baffle length had significant effects on both the heat recirculation and combustion process. Specifically, longer baffle lengths resulted in greater heat loss due to increased surface area; nevertheless, this design with longer baffles proved advantageous in terms of recirculation and mixing of the incoming propane/air mixture.

Numerous methods have been proposed to achieve combined flame stabilization and heat recirculation in micro combustors, including the use of backward-facing step, central rod, porous media flows, wall cavities, bluff body, swirl, orthotropic wall, and catalyst [15,17,18,26,93,105,110–116]. To evaluate the combustion performance, various studies have been conducted on these configurations at different velocities and equivalence ratios. For example, a study on flame stabilization with bluff body and wall cavity has shown significant improvement in combustion efficiency [13]. Kang et al. investigated the flame stability limits and thermal performance of a parallel plate combustor with orthotropic wall made of pyrolytic graphite, which exhibits a high velocity limit due to improved temperature distribution on the plate [24]. Additionally, several experimental studies have indicated that controlling flame position with bluff bodies and using combined flame stabilization methods with backward-step channels favor heat recirculation. When combined with bluff bodies and wall cavities, these methods further improve thermal efficiency by anchoring the flame behind the bluff body and recirculating it in the backward step [117].

4.2. Mesoscale Combustion Systems

Small-scale combustion systems have been modified and transformed into micro- and mesoscale combustors with varying physical length, quenching diameter, and device scale. The microscale combustors span from 1 to 1000 μm, while the mesoscale combustors range from 1 to 10 mm and have been developed using MEMS technologies to power small applications [7]. Mesoscale combustors are used in various applications, such as rotary engines, Swiss-roll combustors, thrusters, and micro aerial vehicles. They are particularly used to power micro aerial vehicles that require efficient mesoscale combustors, which are included in several different engines, such as Stirling, Wankel, rotating piston, scaled gas turbine, and conventional spark ignition and compression ignition engines. Mesoscale combustors are more commonly used as low-impulse thrusters in the range of approximately 1 mN to 1000 mN [7].

In small-scale combustion systems, a major challenge is achieving stable combustion and efficient thermal management while igniting the propellant. To address combustion instabilities, wall heat transfer, and acoustic instabilities in mesoscale systems, numerous novel designs have been developed. Experimental and numerical studies have focused on examining flammability limits, combustion characteristics, and heat losses. One such design modification is the Swiss-roll combustor, which has been introduced in Stirling engines to enhance their performance for powering aerial vehicles and generating power. The addition of catalytic beds to the Swiss-roll combustor can also help to lower ignition temperature and increase combustion efficiency [69]. Mesoscale burners with various configurations are also being evaluated to power-scaled gas turbine engines. These changes include the incorporation of new injection strategies, swirlers, and combined flame stabilization technologies that work with hydrogen/air, jet fuel, and aviation gasoline. In addition, miniature Wankel rotary engines have been developed as mesoscale engines by incorporating new cooling technologies that can operate with multiple fuels, such as gasoline, JP-5, JP-8, and Jet-A1.

The Swiss-roll combustor, initially proposed by Lloyd and Weinberg as a burner of low-heat content, has been shown to be effective even with low-grade fuels [20]. At first, researchers sought to enhance the performance of the Swiss-roll combustor by incorporating radiation shields coated with strips around the spiral. They tested these shields at various surface temperatures and observed an increase in power density of 150 W/m^2. Subsequent studies have concentrated on improving the design to achieve flame stabilization through heat recirculation [31,69,118,119]. Experimental studies by Zhong et al. on a premixed methane/air Swiss-roll combustor with three double spiral configurations of varying channel dimensions have shown stable combustion with methane/air [118]. The combustor, shown in Figure 9, exhibits an incandescent region, with combustion occurring at the center due to the narrow channel size, which preheats the mixture, resulting in high temperatures and stable flames. Gas chromatography analysis was used to determine combustion efficiency, and the results indicated incomplete combustion with H_2 and CO. It was found that the flammable ranges are significantly extended, and thermal insulation plays a crucial role in achieving stable combustion with a methane flow rate of 2.0 mg/s and a temperature of 1100 K at the center [118].

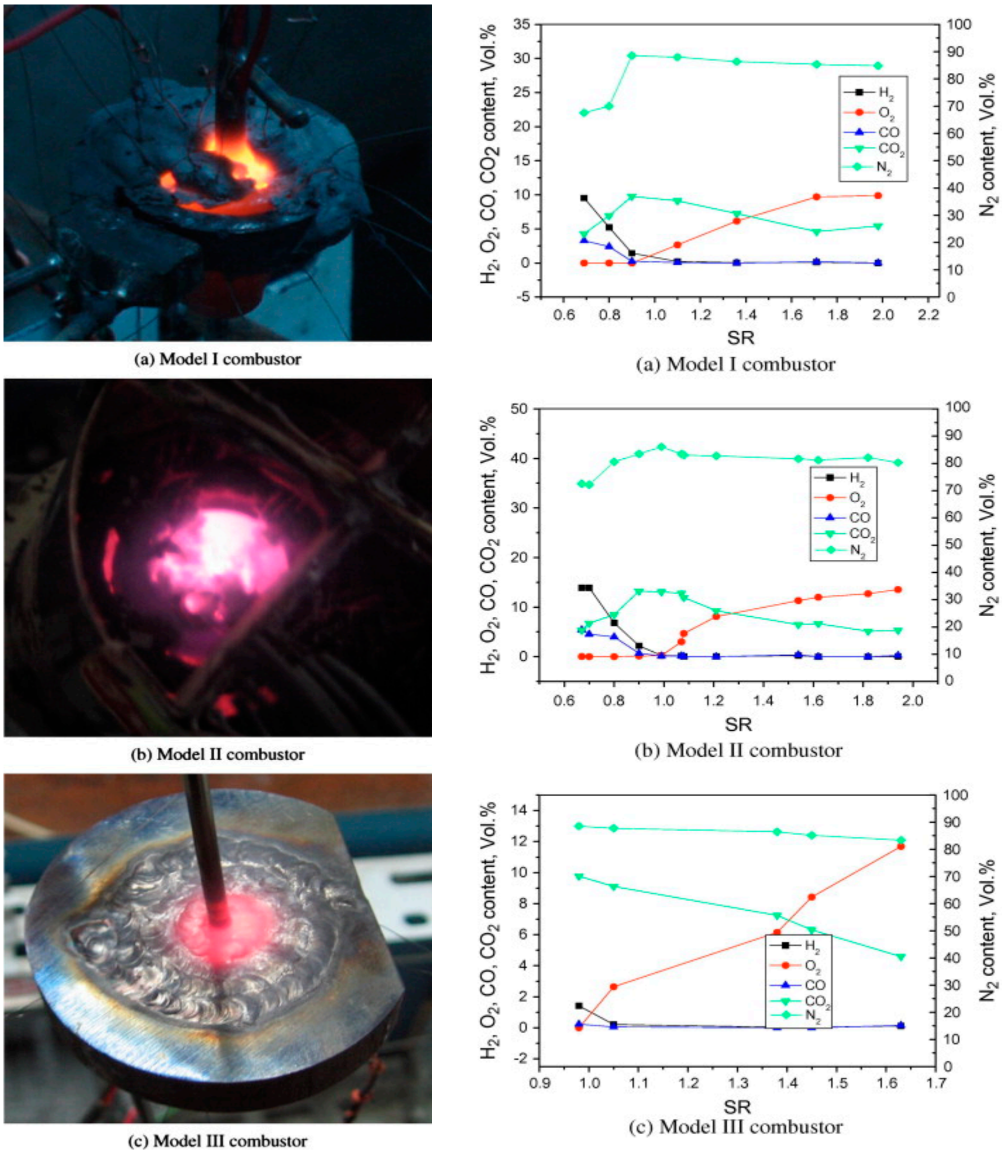


Figure 9. Photos of stable combustion in three Swiss-roll combustors. The composition of the flue gas at exit of combustors: (**a**) Model I Combustor (reactant and exhaust are separated by a 1.9 mm gap); (**b**) Model II Combustor (reactant and exhaust are separated by a 1.9 mm gap); (**c**) Model III Combustor (does not have the internal gap or external thermal insulation). (Reused with permission from [118]. Copyright © 2010 Elsevier Ltd.

In order to improve combustion performance, a proposal was made to use distributed mesoscale arrays combined with flame stabilization by a bluff body and tangential inlet flow swirl. Various fuel mixtures were evaluated for array combustors in mesoscale combustors to assess their performance [26,120–128]. Rajasegar et al. introduced mesoscale combustion arrays with an estimated combustion efficiency of 98% for lean mixtures [124]. These mesoscale burners are arranged in an array with premixed fuel/air mixture inlets separated by a bluff body and tangential inlet to produce swirl. The combined flame stabilization mechanism helps to address flame oscillations and extend the blow-off limits in the arrays.

The detailed configuration and the lean blow-off limits are illustrated in Figure 10. This configuration enhances fuel/air mixing, which ultimately reduces the length scale of the combustor. Experimental studies have been conducted on different sets of burner arrangements using OH-PLIF, chromatography-mass spectrometry, and dynamic mode decomposition to analyze flame interactions [26,125]. OH-PLIF can be used to examine flame shapes, which can be clearly seen in the processed image. The shape of the flame is significantly affected by the equivalence ratio and inlet velocity. It has been observed that, for fuel-rich mixtures, merged flames are produced at low Reynolds numbers, while for lean mixtures, a V- or an M-shaped flame is produced.

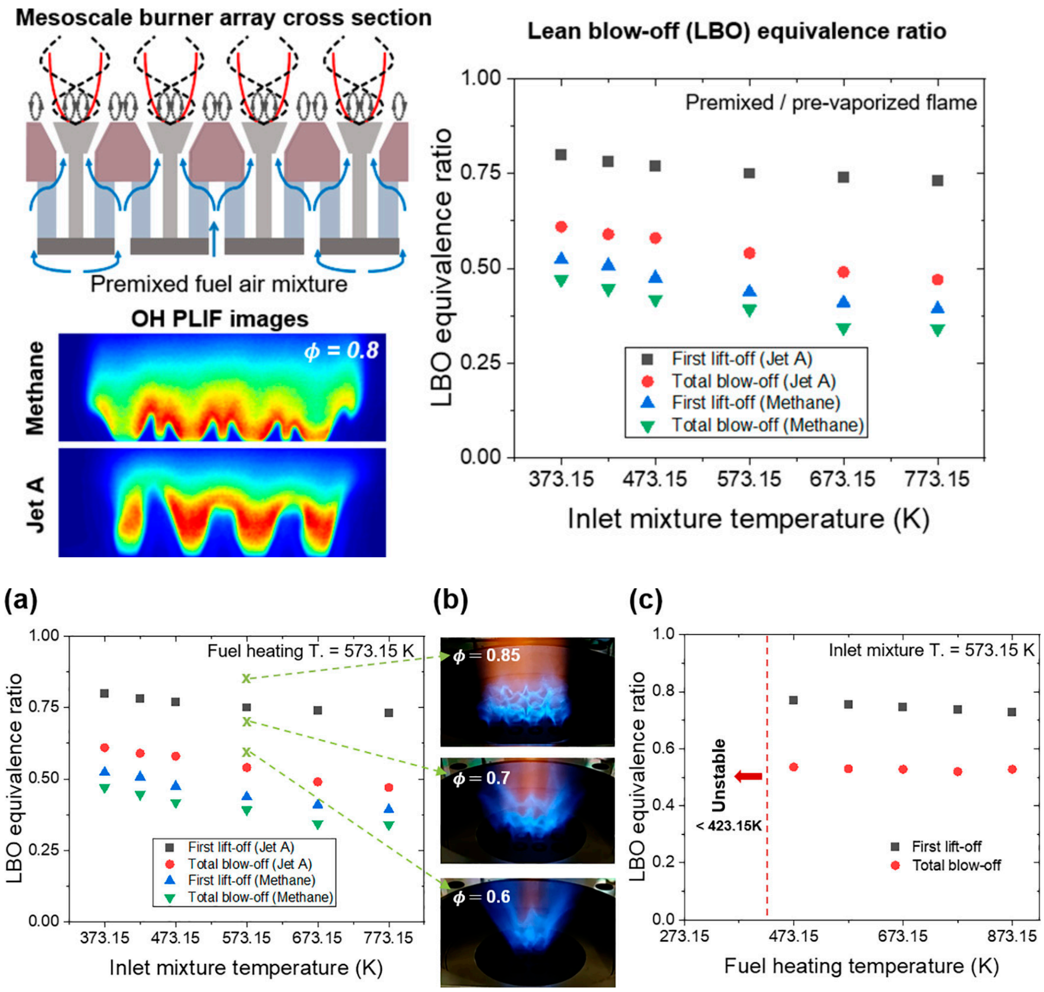


Figure 10. Mesoscale burner array cross section with Methane and Jet flames images at ∅ = 0.8: (**a**) Effect of inlet mixture temperature on the lean blow-off equivalence ratio; (**b**) Visible images of the Jet A flame array; (**c**) Effect of Jet A heating temperature on the lean blow-off equivalence ratio. "Reprinted (adapted) with permission from [26]. Copyright © 2021 American Chemical Society."

The transition from a V-shaped to an M-shaped flame is also observed with increasing equivalence ratio and inlet velocities [126], where the geometry of the burner plays a crucial role due to wall interactions at the bluff body and sudden expansion in the swirler. It is important to investigate the optimal inlet velocities for lean mixtures to achieve a stable flame and to note that the flame lifts off when the fuel flow rate is reduced at a constant air flow rate. A full-scale burner can sustain the flame at an equivalence ratio of less than 0.7, which corresponds to similar behavior in a single burner [125]. Investigating the performance of aviation fuels is significant to develop engines for different classes of aerial vehicles. Combustion stability was compared between jet fuels and conventional petroleum-based fuels for understanding thermal quenching, extinction mechanisms, and operating conditions. Choi et al. evaluated the performance of hydrocarbon fuels in small-scale systems using jet A and methane at an equivalence ratio of 0.8 in a mesoscale swirl-stabilized combustor array to improve flame stability and combustion length scale [26]. They showed that jet A is less stable than methane at lean blow-off limits, as seen in Figure 11, where the jet A flame exhibits more fluctuation with high-mode energy content compared to the methane flame.

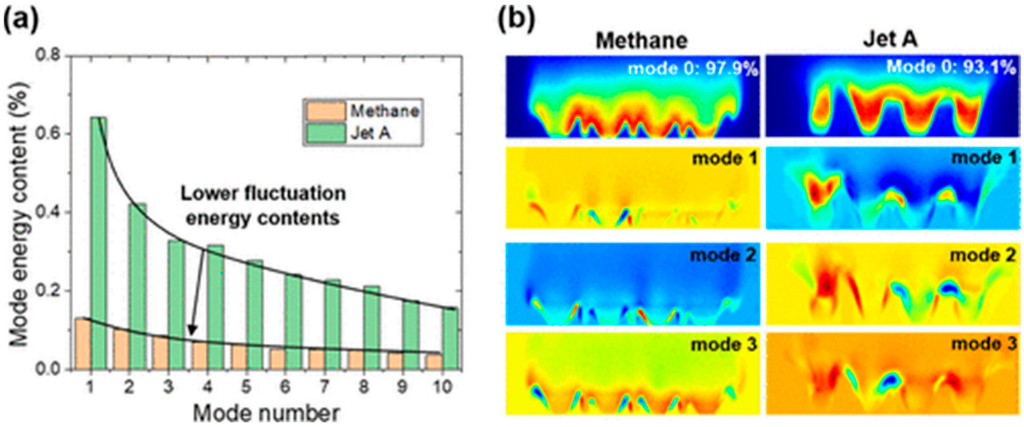


Figure 11. Snapshot of POD analysis to study mesoscale flame dynamics using two different fuels: (**a**) POD mode energy contents and (**b**) mode structures of methane and Jet A flame array. "Reprinted (adapted) with permission from [26]. Copyright © 2021 American Chemical Society".

Various types of porous media, including ceramic fiber, packed bed, SiC foam, folded stainless steel mesh, graphite fibers, sintered powder, and nickel foam, have been receiving significant attention to improve combustion characteristics [93,112,119,129,130]. Ning et al. investigated the effects of fibrous porous media on ignition distance, flammable range, and combustor performance in a Y-shaped combustor [129]. The use of porous media extended the flammability range to 0.16–0.50 m/s, while the burner without porous media had a range of 0.23–0.34 m/s. Kang et al. developed a combined porous media to enhance heat transfer characteristics in mesoscale thermophotovoltaic power generators [130]. The results demonstrated that the use of porous foam effectively improves combustor performance. In addition, Chen et al. studied the effects of porous media on flame stability and thermal performance in mesoscale burners fueled with ethanol [112]. In their experimental studies, three different configurations were tested to understand the effect of porous media with 10 pores per inch (ppi) nickel foam applied at the combustion section. The results showed that blue flames entered the porous media region, and the stable operating range of the porous media was depicted at different air preheat temperatures, as shown in Figure 12. Furthermore, two different materials of zirconia foam and nickel foam were applied at the combustion section of the mesoscale burner with liquid ethanol premixed flames to estimate the radiation output. The flame exhibited an oscillatory pattern with decreasing flow rate due to the overheating of the fuel nozzle. Figure 13 illustrates the effect of flow rate on the flame shape, showing a quasi-symmetrical flame with an inner cone and external diffusion flames readily observed with an increase in flow rate to 270 mL/min [112]. The use of porous media was found to enhance flame speed and significantly increase the radiant intensity of the mesoscale burner.

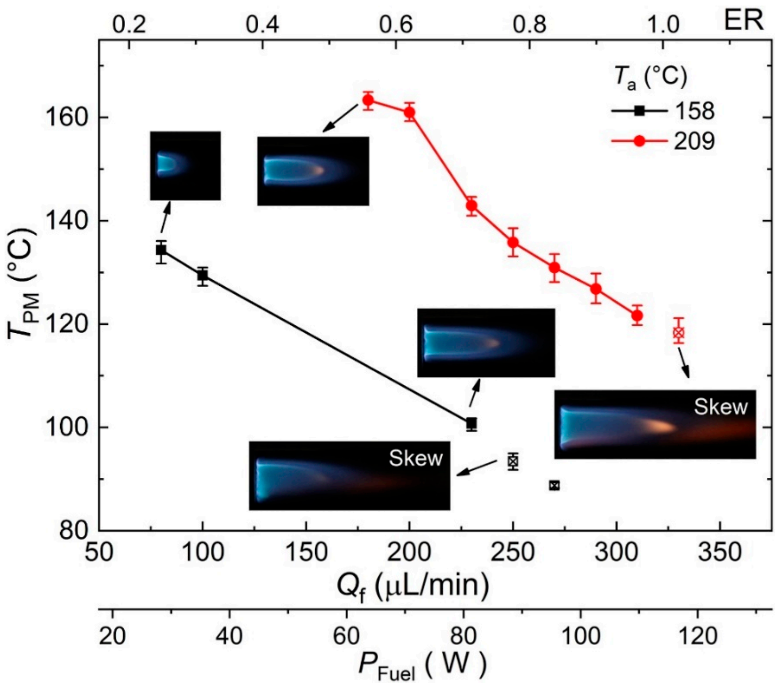


Figure 12. Stable operation range and corresponding temperature of porous media at different air temperatures. Reused with permission from [112]. Copyright © 2021 Elsevier Ltd.

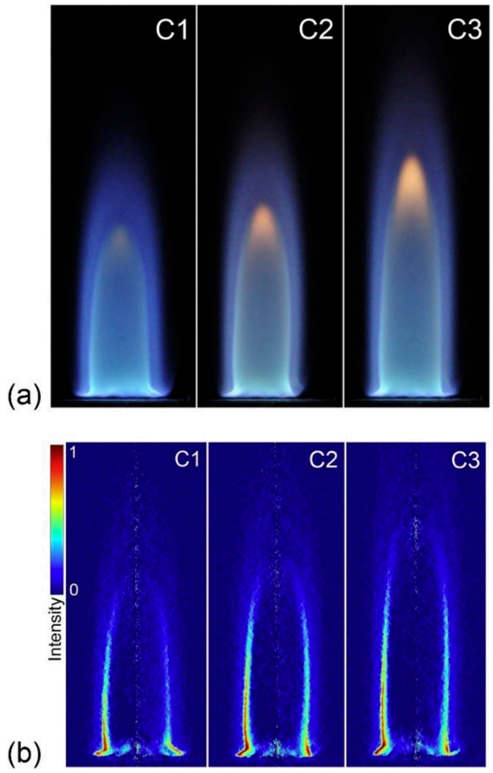


Figure 13. Photographs of free flame structure at Ta = 158 °C and 209 °C: (**a**) Direct photographs; (**b**) CH∗ chemiluminescence images with Abel transformation. (C1): Qf = 230 µL/min, Ta = 158 °C; (C2): Qf = 230 µL/min, Ta = 209 °C; (C3): Qf = 270 µL/min, Ta = 209 °C. Reused with permission from [112]. Copyright © 2021 Elsevier Ltd.

Various types of engines, such as microthrusters, rocket chips, and staged thrusters, have been developed for different operating conditions. Among them, mesoscale vortex chambers are widely used in power and propulsion applications. To achieve efficient fuel/oxidizer mixing in these combustors, the inlets are designed to have tangential oxidizer injection and perpendicular fuel injection [30,131]. Wu et al. conducted experimental studies on different mesoscale vortex stabilized combustor configurations with varying volumes and diameters [30]. Figure 14 describes the flame characteristics of the propane/air flame in the 124 mm^3 combustor with an equivalence ratio of 0.8 and the methane/oxygen-enriched air flame in the 49.1 mm^3 combustor with an equivalence ratio of 0.3. The whirling flame is observed to rotate around the luminous flame zone, but achieving stable combustion is challenging due to strong viscous loss as the chamber volume decreases. Advanced thermal recuperation has been developed for the vortex chambers and tested with hydrocarbon fuels under non-premixed conditions. Hosseini et al. investigated the combustion characteristics using two different configurations with and without thermal recuperation [80]. Thermal recuperation improves the flame stability of lean mixtures at high velocities and significantly impacts the mean wall temperature of the combustors at high equivalence ratio and high Reynolds numbers. The development of miniature thrusters for space applications with bi-propellants and solid propellants was also investigated, and their design was modified to accommodate the low volume and the mode of combustion. The electrolytic microthruster was found to be a promising option for smaller volumes ranging from 200 to 600 µm. These thrusters were developed with three layers for electrolytic reaction of a hydroxylammonium nitrate (HAN) [7]. Figure 14 depicts a three-layer configuration developed with ceramics for HAN-based propellant and combustor volume of 0.82 mm^3, with the ceramic offering high-temperature strength and shock resistance [132].

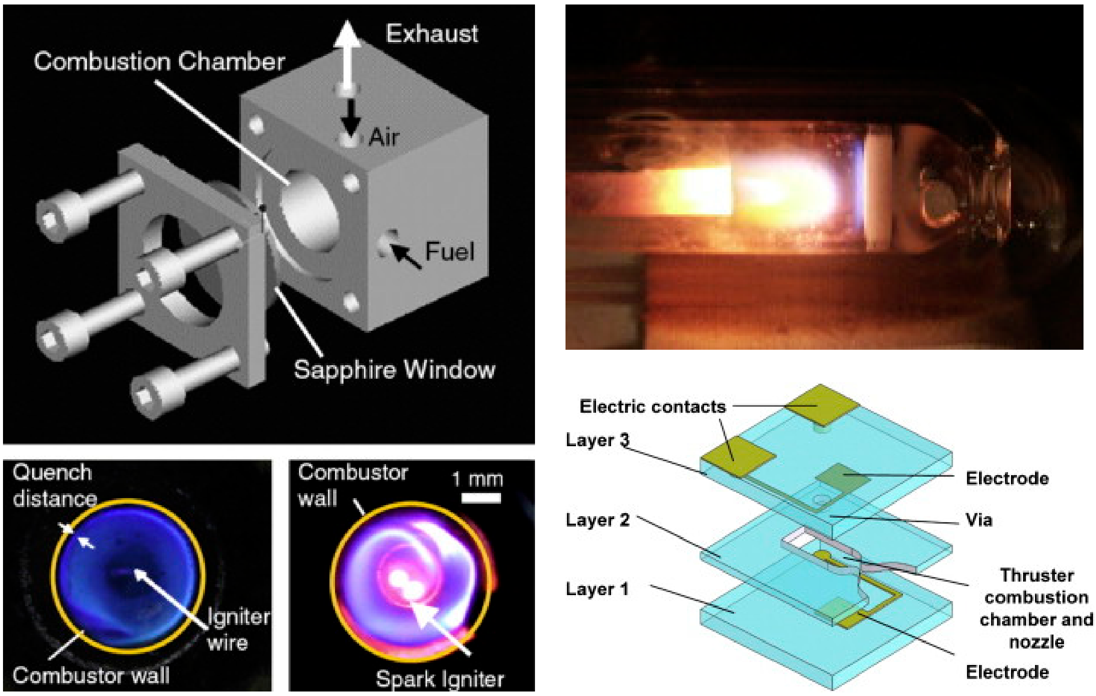


Figure 14. A two-staged mesoscale combustor consisting of a sub-millimeter scale catalytic reactor to produce radicals and recirculating flow for a mesoscale, dual-shelled main combustor. Reused with permission from [7,30,132]. Copyright © 2011 Elsevier Ltd.

The application of porous media to enhance combustor performance in thermoelectric and photovoltaic applications is a well-established technique. These developments offer improved combustion characteristics and thermal management in micro- and mesoscale channels, making them suitable for use in miniature UAV engines. Various configurations have been tested to understand the impact of the position of porous media in the combustor from the inlet to the combustor zone, and the performance of the combustor with methane/air and hydrogen/air has been extensively investigated [3,93,130,133–135]. Li et al. performed experiments on a 1 mm channel operating at low velocities with hydrogen/air premixed flames to investigate the effect of porous media on heat transfer and system efficiency. The performance of the system is influenced by the position of the porous media, and three different configurations have been evaluated: 4.5, 9.0, and 13.5 mm, each with a fixed equivalence ratio of 0.8. At higher inlet velocities, the 9 mm region, located in the middle of the combustor, exhibits higher combustion efficiency [93]. Figure 15 illustrates the variation in the wall temperature as a function of the equivalence ratio and the inlet velocities. When the porous media exist between 8 and 11 mm, with an equivalence ratio of 0.8 to 1.0 for 3 m/s inlet velocity, the combustor performs the best. Similar performance is also observed for 2 m/s, and it is recommended to use optimized porous media in combustors to achieve better efficiency under lean premixed conditions.

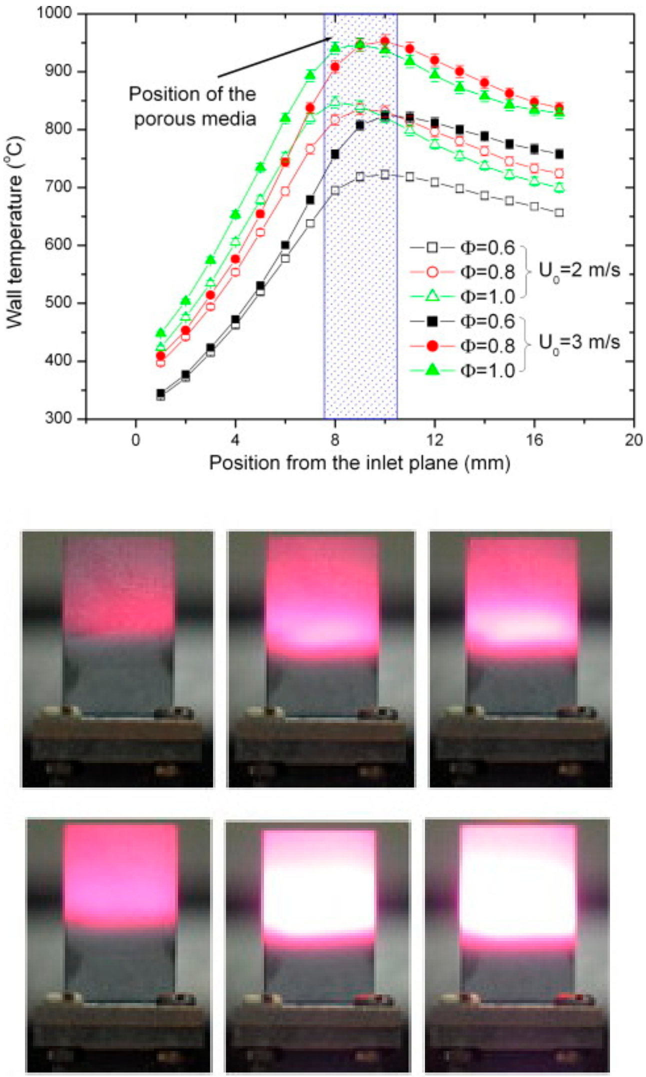


Figure 15. Experimental results, with porous media in the center (Lpm = 9 mm). Direct photo from left to right Φ = 0.6, 0.8 and 1.0; at U_o = 2 m/s and 3 m/s for upper and lower row respectively. Measured Wall Temperature. Reused with permission from [93]. Copyright © 2010 Elsevier Ltd.

5. Numerical Studies on Micro Combustors

High-performance computing (HPC) resources are available for numerical investigations of various micro combustor configurations. Combustion models in commercial, in-house, and open-source CFD solvers can be used to conduct reactive flow simulations, which aid in understanding flame stabilization. To configure existing micro combustors for specific applications, a detailed investigation of their performance is required. Flame stabilization studies for different configurations can be simulated using direct numerical simulation (DNS), large eddy simulation (LES), and Reynolds-averaged Navier–Stokes equation (RANS) simulation to comprehend the influence of turbulence on the combustion process. Different fuel compositions, such as lean mixtures of hydrogen/air, methane/air, propane/air, and jet fuel/air, are used in micro combustors. The computational studies utilize well-developed reaction mechanisms specific to each fuel set. Turbulent premixed flames provide comprehensive insights regarding flame stabilization and vortex shedding into the flow field. The use of bluff bodies and swirlers induces flow fluctuations and recirculation zones behind them. Direct numerical simulations offer realistic flow configurations, which enhance understanding of micro combustion. In micro combustors with bluff bodies, strong eddies are generated, leading to local quenching and resignation [136]. A comprehension of flame/turbulence interaction is crucial to address combustion instabilities and flame regrowth in the upstream of the channel.

Various numerical simulations have been conducted to study the behavior of flames in different configurations, with a focus on resolving turbulent reacting flows. Lee et al. performed DNSs of hydrogen/air flames in a meso channel with a bluff body to understand the flame dynamics near the blow-off limit [16]. This study employed a multicomponent-reactive Navier–Stokes equations with 9 species and 19 reactions and demonstrated the complex sequence of events that occur during local extinction and recovery of the flame, including the regrowth of bulk flame by flame segments attached behind the bluff body. Figure 16 shows instantaneous snapshots at local extinction and isocontours of $Y_{H2O}/Y_{H2O,max}$ for U = 20.5 m/s. A new instability mode was observed at an inflow velocity of 20 m/s, leading to local extinction and recovery. Tanaka et al. investigated the effects of swirl and combustion on premixed flame structure and heat transfer characteristics in a micro gas turbine combustor, using VODE solver with compact finite difference filters [137]. The study analyzed the hydrodynamic behavior and flame structure for cold and reactive flows with two different swirl numbers at 15 m/s and 30 m/s. The micro combustor design was also studied for heat recirculation and heat loss from the walls, and the DNS studies considered heat flux on the walls to estimate heat transfer in the combustor. Figure 17 shows the heat flux distribution for two cases with different swirl numbers of 0.6 and 1.2. Figure 18 depicts the correlation between the flame and flow structure at high frequencies. It presents a time-series graph of pressure fluctuations at the inlet, specifically for the low swirl number case with perturbations. The figure highlights typical pressure conditions, including (a) downturn, (b) saddle point, (c) local minimum, and (d) upturn. For each of these typical pressure conditions, the figure provides volume rendering of the instantaneous heat release rate and instantaneous streamlines [137]. The results indicated that heat flux on the walls depended on oscillations at these swirl numbers. The high-fidelity DNS studies demonstrated the multiscale phenomena of micro combustors, including the characteristics of flame structure and heat transfer to the walls.

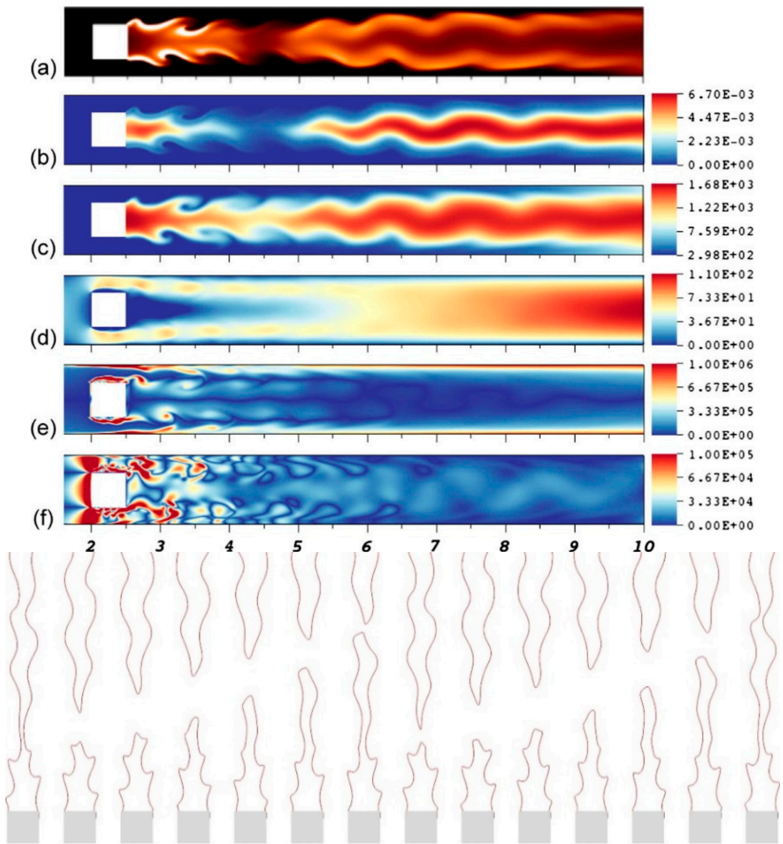


Figure 16. Instantaneous snapshots at local extinction, at t = 10.23 ms for U = 20.5 m/s: Isocontours of: (**a**) heat release rate (the color level is maximum at 1010 J/m^3 s); (**b**) Y_{OH}; (**c**) temperature (K); (**d**) axial velocity (m/s); (**e**) magnitude of vorticity (1/s) and (**f**) magnitude of ∂u/∂x (1/s). A sequence of instantaneous snapshots of the isocontours of Y_{H2O}/Y_{H2Omax} = 0.5 for U = 20.5 m/s, at an increment of 10 µs starting from t = 10.27 ms. Reused with permission from [16]. Copyright © 2015 Elsevier Ltd.

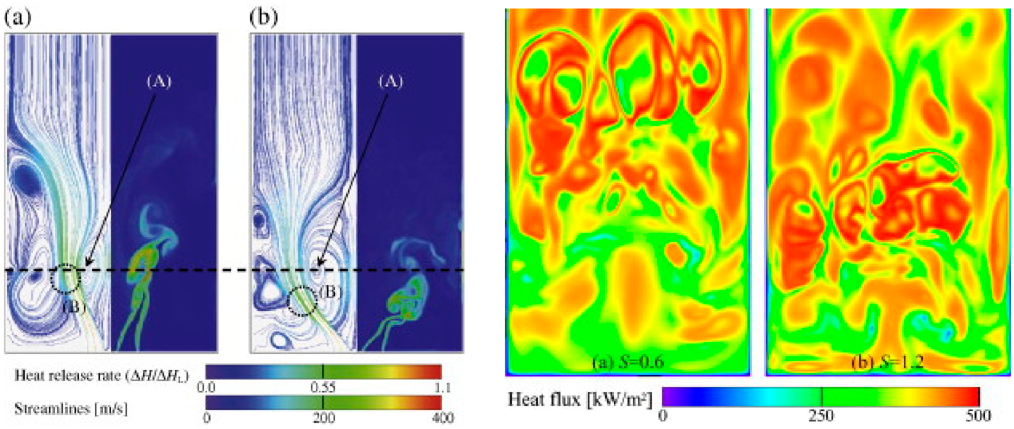


Figure 17. Streamlines obtained from time-averaged velocity (**left**) and instantaneous distributions of heat release rate (**right**) on the center plane (y = 0) for: (a) S = 0.6 and (b) 1.2 in reactive flow without inflow perturbations. The region denoted by (A) represents the central recirculation zone (CRZ) (B). Small-scale vortices appear frequently in this region as mentioned. Reused with permission from [137]. Copyright © 2011 Elsevier Ltd.

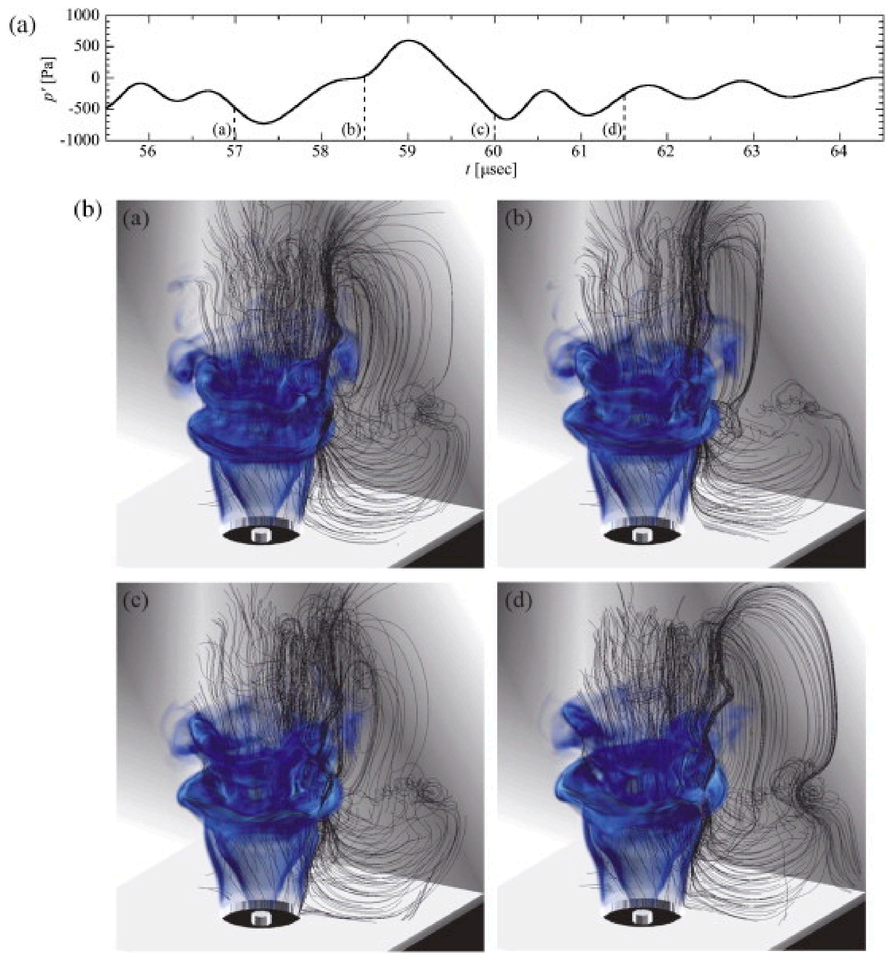


Figure 18. Relation between flame and flow structures in high frequency: (**a**) time series of pressure fluctuation at the inlet for the low swirl number case with perturbations. conditions are extracted: (a) in downturn; (b) at a saddle point; (c) close to a local minimum and (d) in upturn; (**b**) volume rendering of instantaneous heat release rate and instantaneous streamlines. In the pressure conditions (a) and (d) where absolute values of the derivative are large. In contrast, the size gets small in conditions (b) and (c) where the absolute values of the derivative are small. Reused with permission from [137]. Copyright © 2011 Elsevier Ltd.

DNS studies require significant computational resources to accurately resolve all spatial and temporal turbulence scales. Due to this limitation and the complexity of the problem, many numerical studies have been conducted using LES and RANS by modelling turbulent reacting flows. For instance, Tyliszczak et al. utilized RANS with the $k-\varepsilon$ turbulence model and LES with the wall adapting local eddy (WALE) viscosity subgrade model to investigate combustion processes in a medium-scale gas turbine [138]. They modelled the combustion process using a steady laminar framelet model with Smooke mechanism, including 16 species and 25 elementary reactions. The researchers optimized the fuel injection location using three different injection methods to alter the multipoint fuel injection, which affected the flow dynamics and temperature distribution. In another study, Benard et al. conducted a high-fidelity LES of a hydrogen-enriched methane/air flame in a quasi-cubic mesoscale whirl flow combustor using the finite volume code, YALES2, which can solve low Mach number flows with unstructured complex mesh [139]. They modelled the chemical reactions using the Arrhenius chemical kinetics approach, and the use of whirl flow topology enhanced the mixing and improved the burner performance.

Sadatakhavi et al. conducted numerical studies of a can-type micro combustor with kerosene liquid fuel using RANS with the $k-\varepsilon$. RNG turbulence model to simulate spray combustion with a high-swirl Eulerian–Lagrangian formulation [85]. They adopted the eddy dissipation concept (EDC) model to understand the importance of chemical kinetics with 12 species and 10 elementary reactions in turbulent flows. The combustion characteristics are shown in Figures 19 and 20, which represent the inner recirculation zone, intermediate zone temperature, mass fraction, and the relationship between the temperature and combustion characteristics. The inner recirculation zone enhances the mixing through swirl-like configurations and becomes effective in evaporating fuel, while the combustion becomes efficient due to the recirculation zone around the linear wall.

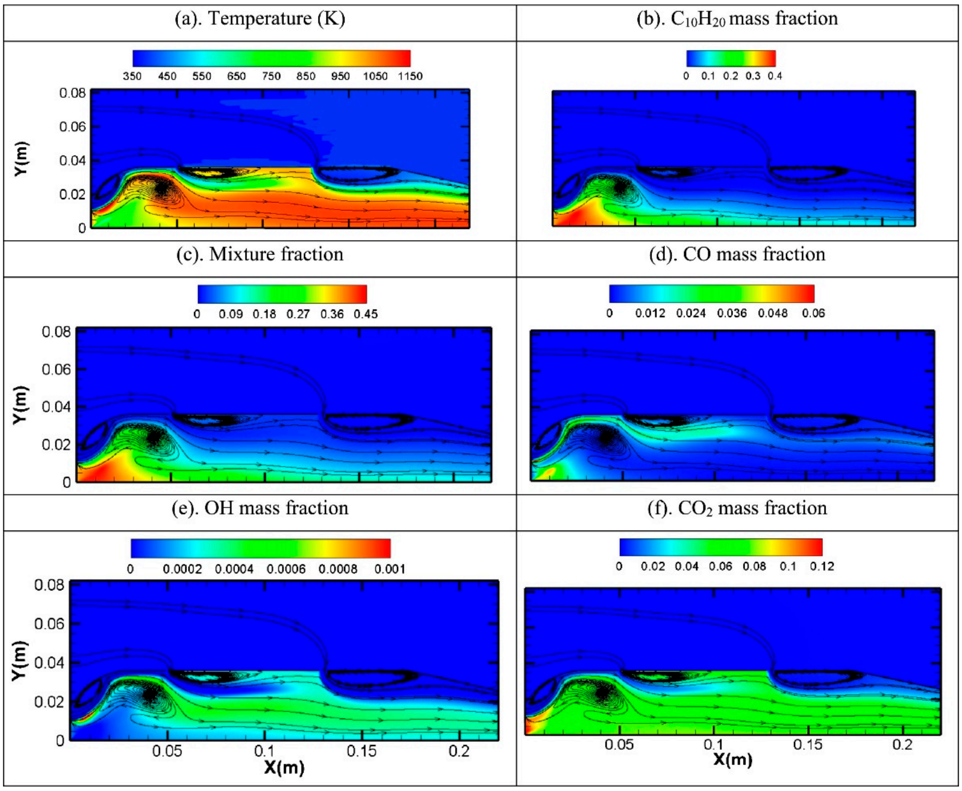


Figure 19. Contours of chamber combustion characteristics and distribution of the main species resulted from the combustion: (**a**) Temperature (K); (**b**) $C_{10}H_{20}$ mass fraction; (**c**) Mixture fraction; (**d**) CO mass fraction; (**e**) OH mass fraction; (**f**) CO_2 mass fraction. Reused with permission from [85]. Copyright © 2020 Elsevier Ltd.

In their investigation into flame stabilization, Jha et al. explored several different factors, ultimately determining that using a bluff body is one of the most effective methods to stabilize flames [13]. The study was focused on optimizing geometry-based parameters to gain a better understanding of how to stabilize flames in narrow channels. By generating a recirculation zone behind it, a bluff body can transfer thermal energy to upcoming fuel-air mixtures, helping with ignition. This recirculation zone can also increase residence time, which in turn extends and stabilizes the flame in the anchor zone. To test this theory, Jha et al. conducted a numerical study of nine different L/D ratios and optimized channel dimensions by examining blow-off limits. Bluff bodies with various shapes and configurations were placed at successive positions, the velocity and temperature profiles of nine different bluff body configurations are shown in Figure 21. The researchers found that the wall blade bluff body demonstrated superior performance under lean hydrogen/air premixed conditions. The researchers used RANS with the $k - \varepsilon$ turbulence model to conduct detailed studies on cases with three different velocities and a constant equivalence ratio of 0.5. Through geometrical modifications, performance was improved by a factor of two. In addition, the wall blade bluff body had the lowest exhaust gas temperature in all conditions, suggesting that the combustor was able to use most of the thermal energy and improve overall performance.

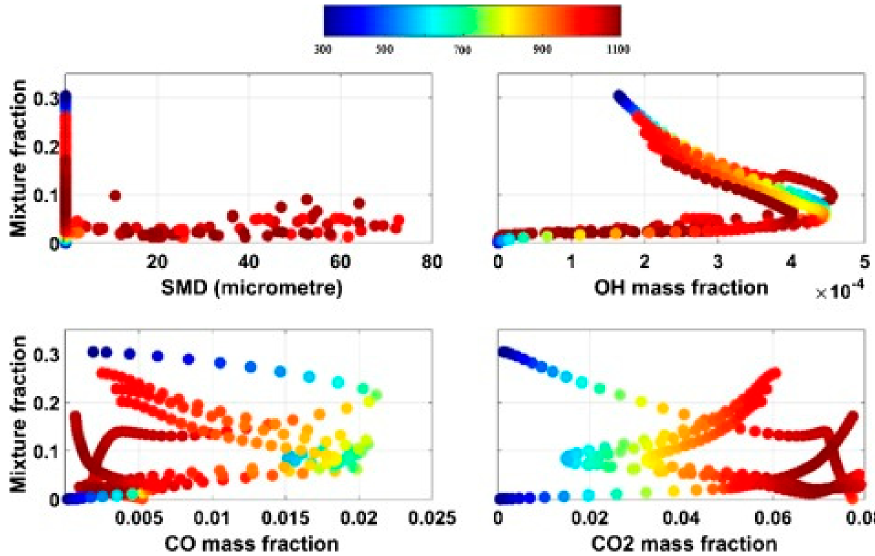
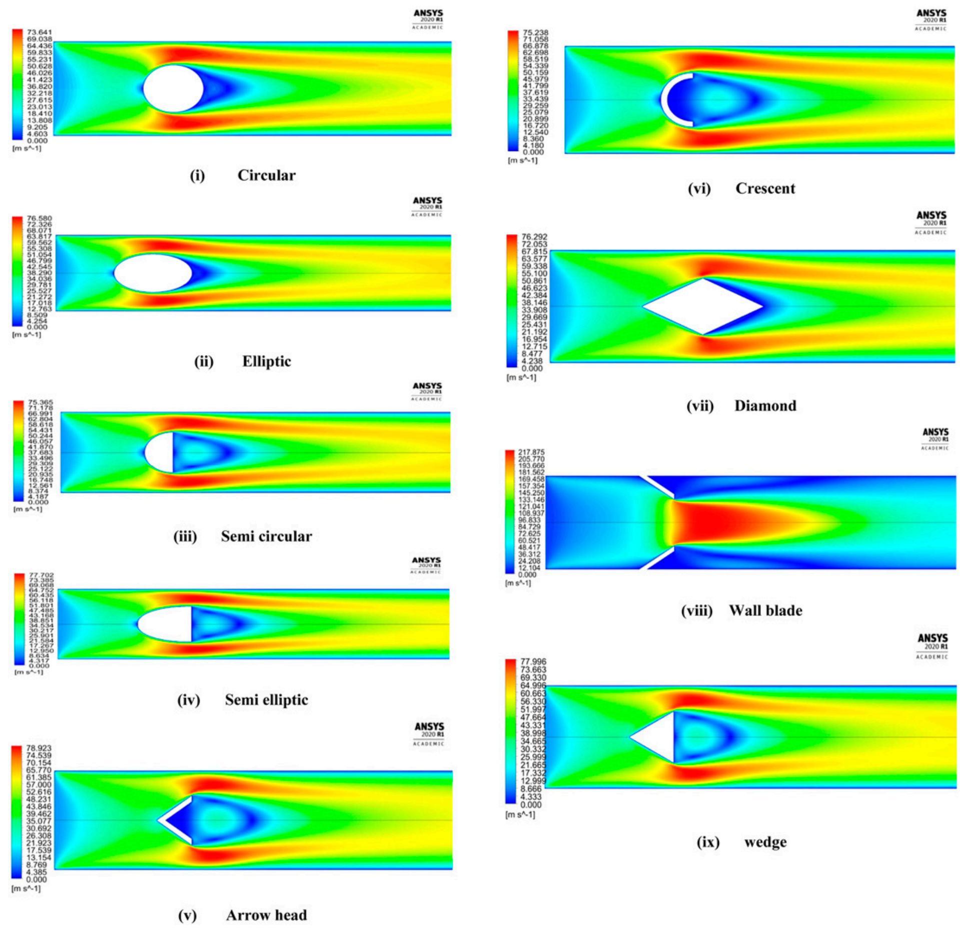


Figure 20. Scatter diagram illustrates the relationship between the combustion characteristics and temperature (in Kelvin) in the intermediate zone. Reused with permission from [85]. Copyright © 2020 Elsevier Ltd.



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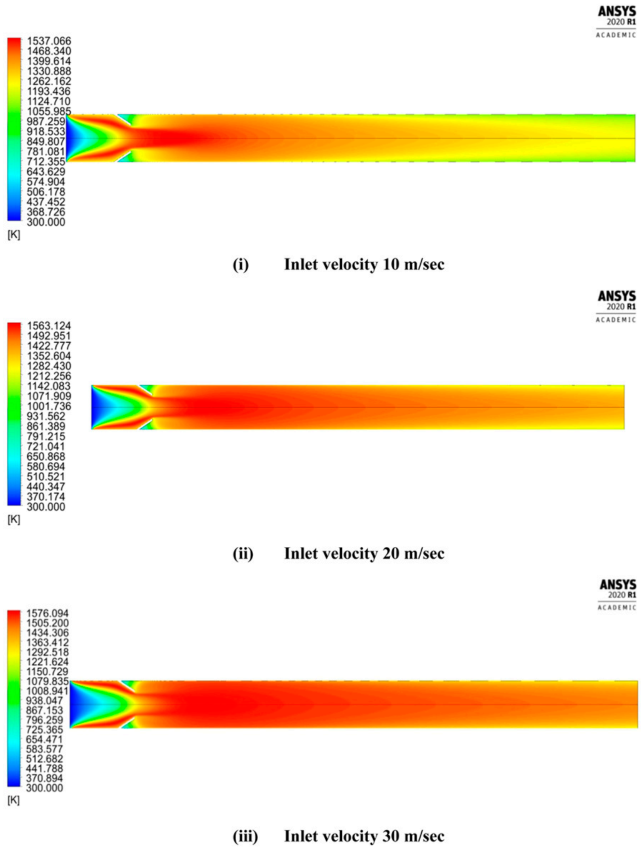


Figure 21. Velocity and temperature profiles with nine different bluff body shapes at 10 m/s, 20 m/s, and 30 m/s: (**i**) circular; (**ii**) elliptic; (**iii**) semicircular; (**iv**) semielliptic; (**v**) arrowhead; (**vi**) crescent, (**vii**) diamond; (**viii**) wall blade and (**ix**) wedge. Reused with permission from [13]. Copyright © 2022 Wiley.

Taywade et al. and Aravind et al. proposed a three-step micro combustor with an outer cap that can improve flammability limits through heat and flow recirculation [115]. Figure 22 shows a schematic of a disc combustor with an annular step, featuring two inlets: one with a radial preheating channel for the air inlet and the other with a mixed channel designed to prevent flame flashback. Numerical studies were conducted on a quartz-glass double-disc micro combustor using a methane/air mixture with the DRM-19 mechanism (21 species and 84 reactions). The annular step created a recirculation zone, anchoring the flame upstream of the combustion chamber. The intake mixture was preheated by the recirculation zone, resulting in higher flame speeds. The double disc configuration was later modified to a miniature double-layer disc combustor with porous media and Swiss-roll pre-heated channel [119], which improved thermal performance and reduced anomalous blow-off limits by decreasing heat recirculation. In addition, Mehra et al. proposed a six-wafer combustion system for a silicon micro gas turbine engine, which exhibited stable combustion for high-temperature hydrogen/air mixtures [40].

The small size of submillimeter scale combustors presents a challenging issue in terms of heat recirculation, which can lead to thermal quenching. To address this problem, numerous novel designs have been proposed for mesoscale combustors. One such design is the Swiss-roll combustor, which utilizes heat recirculation from burned gas and preheating via spiral-shaped inlet channels [31]. Fan et al. investigated a Swiss-roll combustor with bluff bodies for steel, quartz, and SiC combustors featuring rectangular spiral patterns as shown in Figure 23. Numerical studies were conducted to assess various configurations. Due to the narrow channel diameter and low inlet velocities, low Reynolds numbers were observed, and turbulence had a minimal effect on combustion performance. However, improvements are necessary to operate these channels under lean premixed conditions.

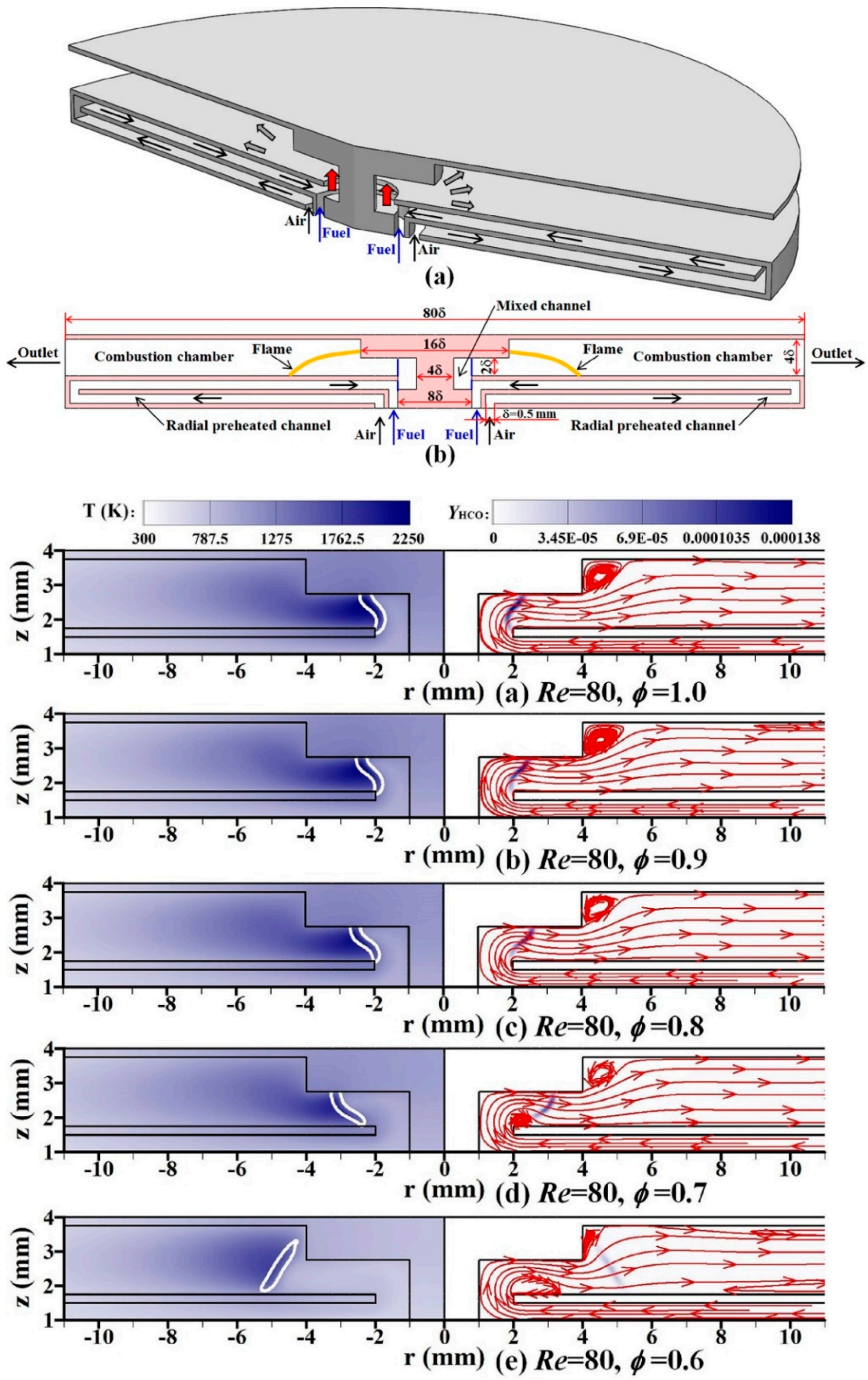


Figure 22. Schematic diagram of the micro disc-combustor with an annular step and a radial preheat channel: (**a**) Three-dimensional view; (**b**) cross sectional view. Temperature contours overlaid with 10% maximum Y_{HCO} isolines (white solid lines) (**left**) and Y_{HCO} contours overlaid with streamlines (**right**) for various ϕ values at Re = 80. Re-used with permission from [115]. Copyright © 2012 Elsevier Ltd.

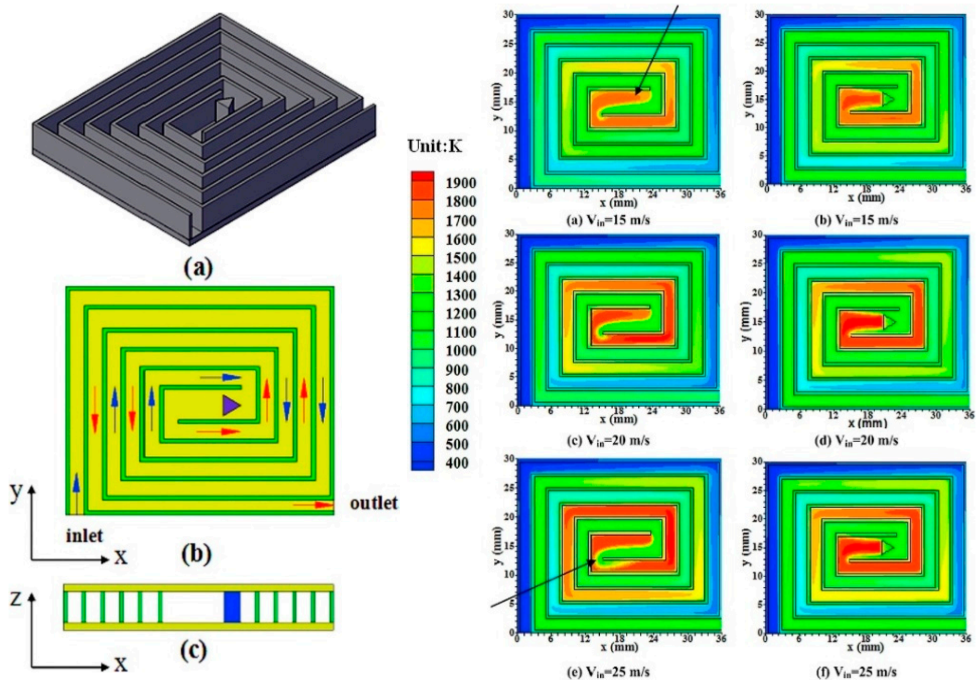


Figure 23. Microscale Swiss-roll combustor with Bluff body: (**a**) three-dimensional geometrical model; (**b**) horizontal cross-section; (**c**) vertical cross section. Temperature fields in the middle of the Swiss-roll combustors with and without a bluff body at different inlet velocities and ϕ = 0.5. Reused with permission from [19]. Copyright © 2017 Elsevier Ltd.

A Swiss-roll combustor with flow recirculation channels and a 2.5 mm side length configuration was studied using a three-dimensional model. The use of the standard $k - \varepsilon$ turbulence model and SIMPLE algorithm facilitated the coupling of pressure and velocity, and surface radiation effects were considered to calculate wall heat loss using the discrete ordinate method (DOM). Numerical studies revealed that blow-off limits were extended by 10 m/s with a wedge-shaped bluff body [19]. The Swiss-roll combustor was further modified into a double-layer disc combustor with porous media to enhance thermal performance and extend blow-off limits for methane/hydrogen/air mixtures. The fresh mixtures were preheated in the Swiss-roll configuration, and metal foam in the combustion zone supported additional preheating of unburned mixtures [119]. In addition, Wang et al. investigated a divergent channel porous burner for ultra-low calorific gas, which increased heat recovery efficiency by 18% for minimum inlet gas temperatures [140].

Small-scale power generation applications benefit from micro-step combustors, which offer superior flame stabilization. To operate combustors at high velocities and enhance blow-off limits, modifications have been proposed, such as changing the inlet configuration and using helical fins [15,113]. The use of helical fins has been found to improve combustion performance with high mass flow rates. Zheng et al. conducted numerical simulations to study the effect of helical fins on the combustion performance in a micro step combustor [72]. The swirl induced by the helical fins enhanced mixing and improved combustion efficiency due to radiant energy conversion. The simulations resolved velocity and pressure coupling as well as conjugate fluid-solid heat transfer effects. Figure 24 illustrates a schematic of the combustor with helical fins and the ignition process of the helical fin anchored flame at $V_{\text{in}} = 34$ m/s. The use of helical fins improved flame anchoring position and blockage effects at higher inlet velocities compared to simple step combustors. Similar studies were conducted with helical fins in different micro combustor configurations. The studies have shown that optimized fin positioning with a high swirl number improves the thermal performance and burning characteristics of different fuels [72,141–143].

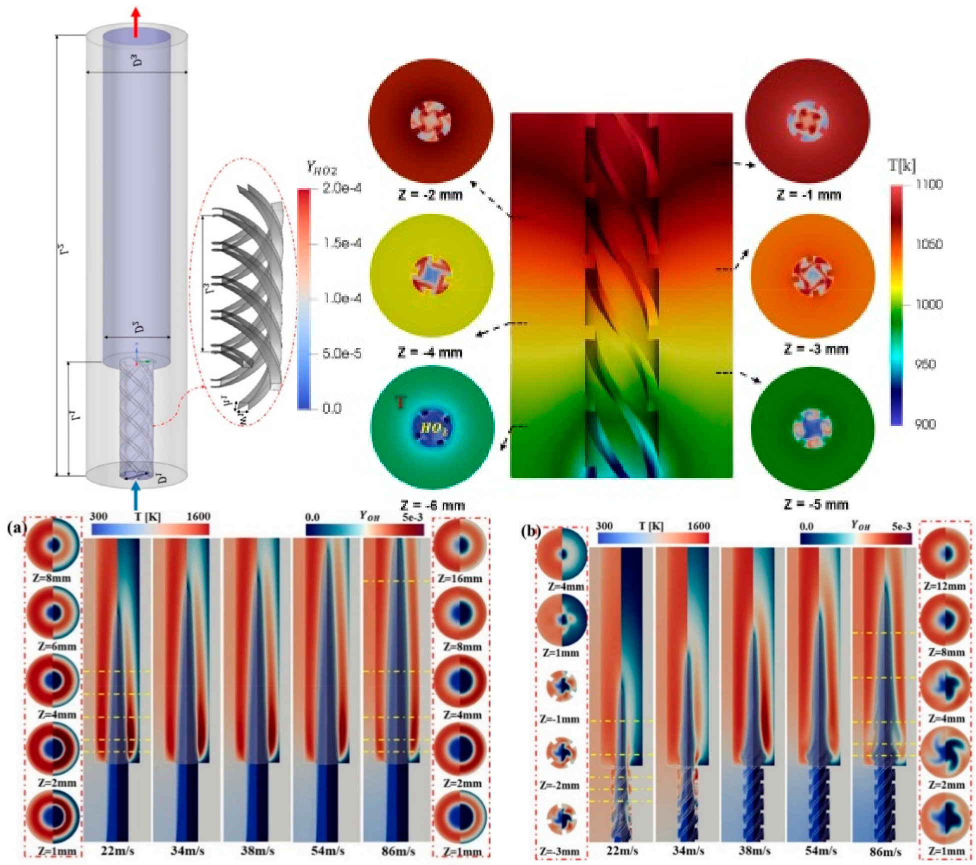


Figure 24. Schematics of the combustor with helical fins. The ignition process of the helical fin-anchored flame at $V_{\text{in}} = 34$ m/s. The wall and flow regions are mapped with temperature and HO_2 respectively in the z-slices and the inlet channel. (**left**) Temperature and (**right**) OH contours on the central plane of Y = 0 and various Z slices (the positions are indicated by yellow dash-dot lines) with overlaid flame surfaces (transparent surfaces) of (**a**) Step and (**b**) Helix combustors at increasing inlet. Reused with permission from [72]. Copyright © 2022 Elsevier Ltd.

Can-type combustors are commonly used in micro gas turbines due to their compact design. However, their performance can be improved by introducing baffles to the combustor. Suzuki et al. proposed a design with baffle plates that include a central fuel nozzle and multiple holes for air injection. Numerous studies have been conducted on the impact of these baffles on various combustion characteristics, such as heat transfer, fuel-air mixing, turbulent reactive flows, flame stability, and flow characteristics [144–148]. Results show that introducing baffle plates can significantly improve flow mixing and flame structure in the can combustors. Overall, the use of baffles enhanced flow mixing and combustion characteristics, leading to improved performance of the micro can combustor. The dimensions and shape of the baffle plates were optimized to achieve better mixing in the central region [144]. Woodfield et al. conducted numerical studies on multiple confined jets in a micro can combustor and found that dimensional modifications to the baffle plates improved performance compared to co-axial jets [146]. Yahagi et al. studied the flow structure and flame stability in a micro can combustor with a baffle plate and found that the plate enhanced flow recirculation and mixing, resulting in better combustion conditions [147].

The shape of the baffle inlet holes also played an important role in the distribution of streamwise velocity along the central line and non-circular holes helped the fast decay of the streamwise velocity [144]. It has been shown that triangular holes experienced early development of the recirculation region at the fuel jet. The axial distribution of temperature for three air inlet baffle shapes are shown in Figure 25. The central recirculation zone has shown impact on the temperature distribution; in the case of triangular holes, the rise has been from $x/D_f = 2$, whereas the square and circular holes have shown flame formation in the forward region. This effect can be seen due to the delay in activation of the reaction, which was caused by the delay in the formation of a central recirculation zone with the air fuel jets. A 3-D numerical study helps in understanding the flame lengths in different baffle shapes; however, the diameter of the combustor also has a significant impact on the flame structure [144]. The use of baffles improves combustion characteristics and helps to stabilize the flame in combustors.

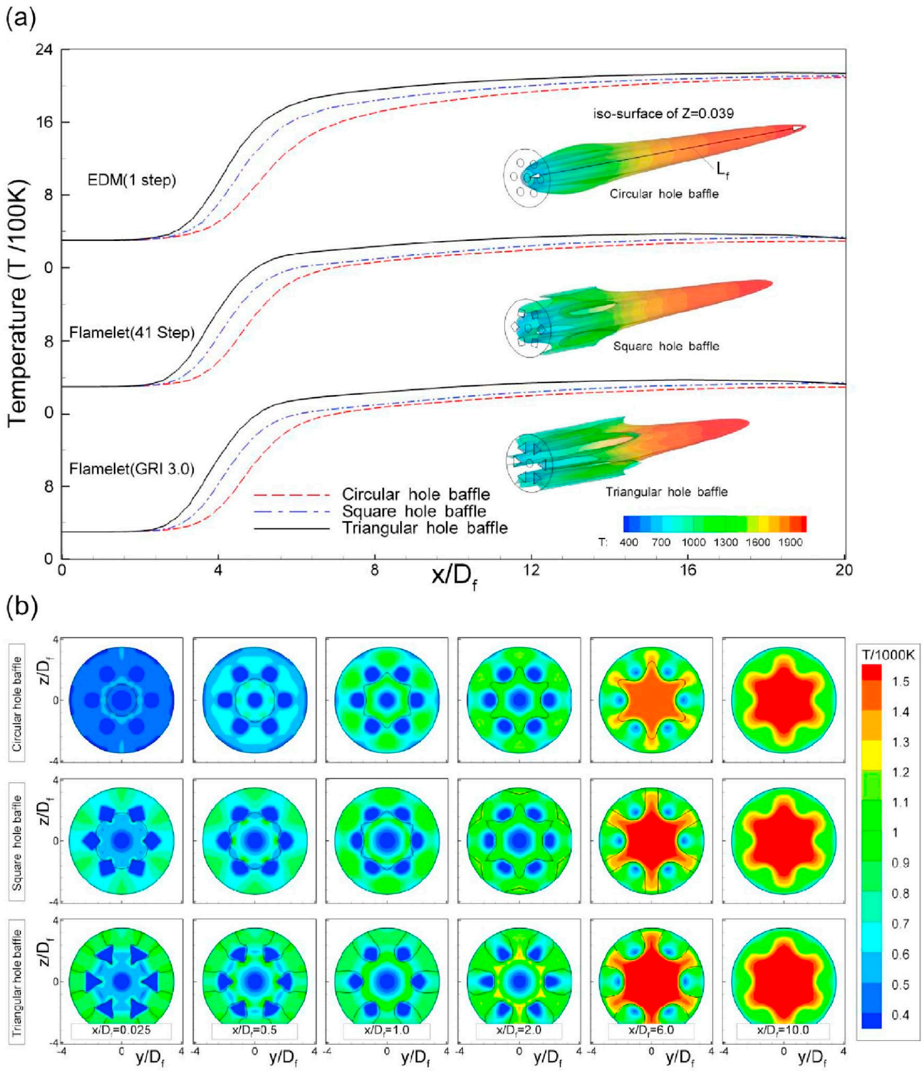


Figure 25. Axial distributions of temperature along the centerline and iso-surfaces of $Z = Zst$ for three baffles: (**a**) Temperature distributions along the centerline, and (**b**) temperature contours at several streamwise positions (Solid lines are $Z = 0.039$). Reused with permission from [144]. Copyright © 2016 Elsevier Ltd.

Kim et al. investigated a micro can combustor that incorporated a baffle plate consisting of seven holes for CH_4/air mixture [148]. They used the eddy dissipation model (EDM) and framelet model to analyze the system. The baffle design included six annular air inlets of varying shapes, such as triangles, circles, square holes, and a fuel nozzle at the center. The turbulent reacting flows were solved using three turbulent models: standard $k - \varepsilon$ (SKE), Reynolds stress model (RSM) and shear stress transport $k - \omega$ (SST $k - \omega$), along with GRI-MECH 3.0. The results showed that the baffle plate configuration with different hole shapes, along with the central fuel nozzle, improved flow mixing and combustion characteristics. The mixture fractions obtained from the framelet model with 16 species and 41-step reaction mechanism were compared with Brookes and Moss experimental data and the results obtained from the EDM model. The profiles of streamwise velocity, mixing fraction, and temperature along the centerline of the jet flow were shown in Figure 26. The framelet model performed better than the EDM model. They also observed axis-switching flow structures for air jets past the baffle plate with the square and triangular holes [148]. The use of baffle holes as inlets develops jet flow, and axis switching has an impact on spreading rate and flow mixing. They recommended using 30° rotated square holes and 15° rotated triangular holes to improve uniformity of the combustor. Based on the mixing length, 45° for square and 60° for triangular holes were recommended to improve combustion performance and thermal characteristics.

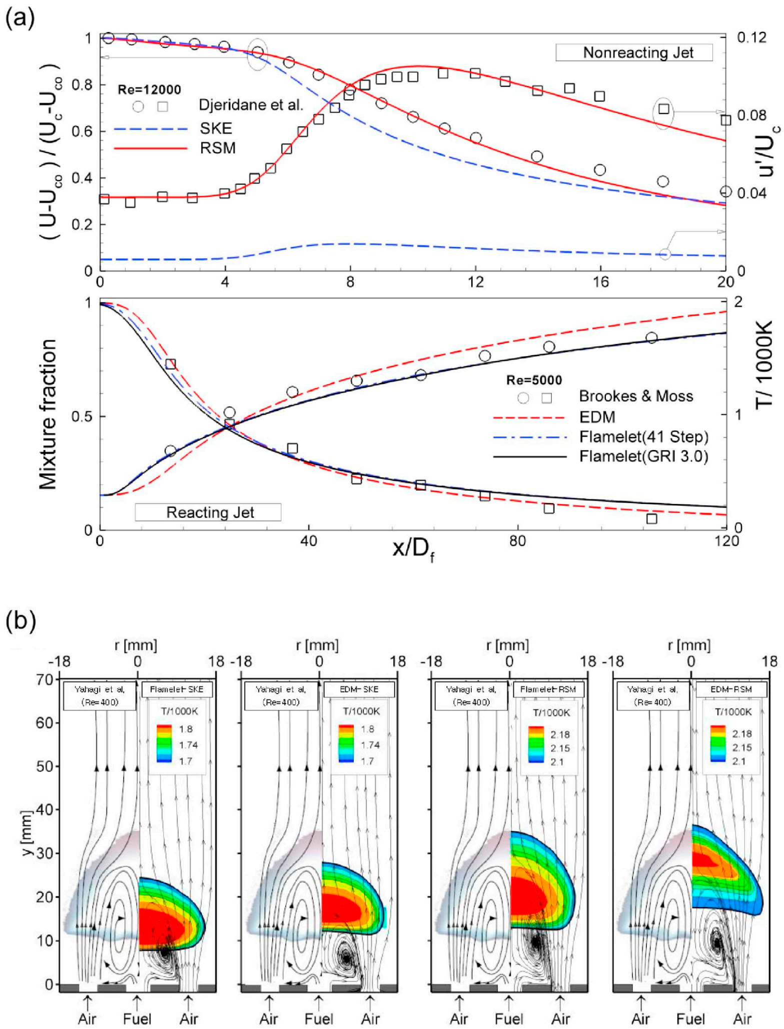
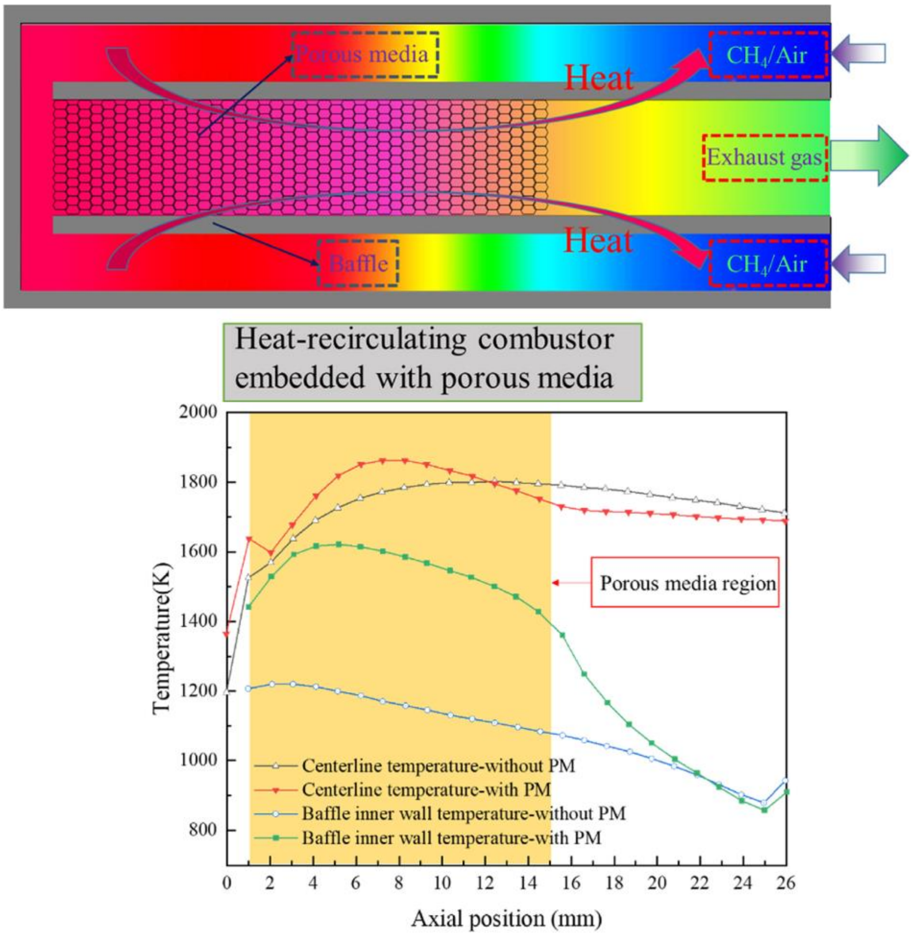


Figure 26. Comparison of predicted results and experimental data: (**a**) streamwise velocity and its fluctuation, mixture fraction, and temperature along the centerline of jet flow and (**b**) temperature and streamlines of a micro combustor. Reused with permission from [144]. Copyright © 2016 Elsevier Ltd.

The heat transfer in micro combustors is enhanced by embedding porous media, and the selection of combustor shape is important for both flame stabilization and heat recirculation. Heat recirculation using porous media is particularly useful for micro aerial vehicles, grouping array thrusters, and micro spacecraft that operate in the 1–10 mN thrust range for satellite altitude control and orbital insertion [149,150]. Experimental and numerical studies have investigated the use of porous media materials with strong thermal conductivity, such as stainless steel, ceramic, quartz, alumina, cordierite, platinum, and silicon carbide coated with platinum, and proposed various configurations with cylindrical tubes, rectangular slots, and radial microchannels [3,93,134,149].

Yan et al. used computational fluid dynamics to investigate a U-shaped micro combustor with a peripheral recirculating channel and a central channel embedded with porous media for heat recirculation. The study employed the RANS method with the $k-\varepsilon$ turbulence model and a 39-step reaction mechanism for methane oxidation. The effect of porous media material and thickness on the flame stability limits of methane/air mixture was studied, and it was found that using porous media materials such as Al_2O_3, SiC, and ZrO_2 improves flame stability and enhances heat transfer [149]. Figure 27 shows the U-shaped micro combustor with a peripheral recirculating channel and a central channel embedded with porous media. The U-shaped micro combustor had an inlet velocity of 20 m/s and an equivalence ratio of 0.5, and the thickness of the porous media was varied from 5 to 25 mm using Al_2O_3-based ceramics. The results showed that the use of porous media improved effective heat transfer to the baffle inner surface, and the central line temperatures increased by 25 mm in the thickness of the porous media. Among the three configurations tested, the SiC combustor exhibited higher baffle temperatures than its counterparts due to its high thermal conductivity; however, this effect was limited by its low operating temperatures [149]. Therefore, the use of porous media for flame stabilization can improve combustion characteristics in micro combustors with lean mixtures for a wide range of velocities.



(a) The central axis and inner baffle surface along the axial direction

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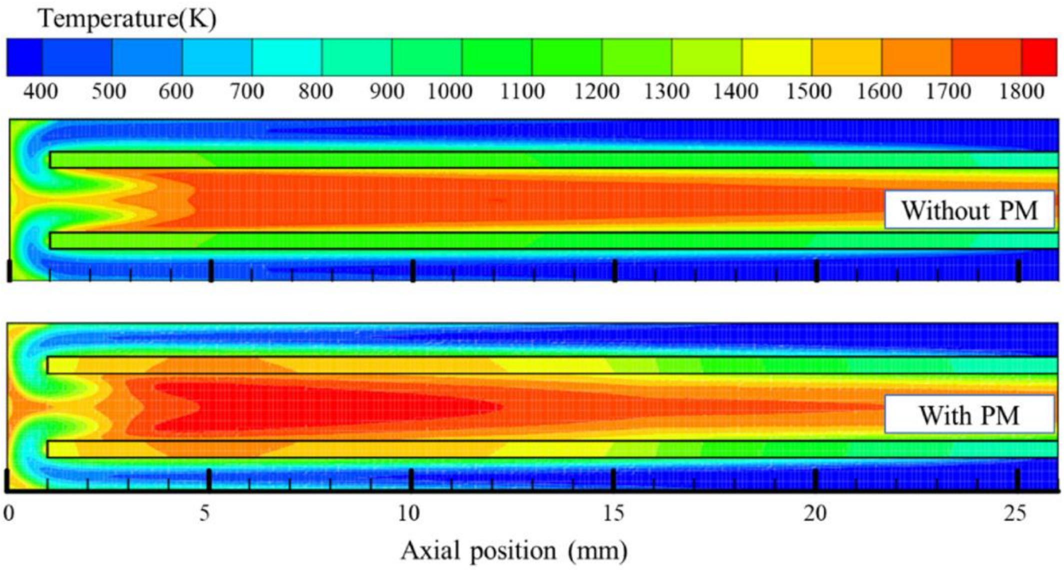

(b) Comparison of combustor temperature field distribution.

Figure 27. Heat Recirculating combustor embedded with porous media. Effect of porous media on temperature distribution of micro combustor. The central axis and inner baffle surface along the axial directions: (**a**) The central axis and inner baffle surface along the axial direction; (**b**) Comparison of combustor temperature field distribution. Re-used with permission from [149]. Copyright © 2022 Elsevier Ltd.

6. Summary and Outlook

The use of combustion-based engines to power UAVs aims to enhance the endurance and payload capabilities of vehicles. Most modern UAVs designed to meet military and defense needs utilize hybrid engines that provide several advantages, including improved fuel efficiency, reduced emissions, and quieter operations. The cost of engines remains a significant factor in the adoption of hybrid engines for commercial UAVs. Therefore, to cater to the needs of commercial operations, there is ongoing research and development focused on a variety of technologies aimed at creating low-cost, efficient engines. The progress of these technologies is continuously reviewed to identify opportunities for further improvement. The development of innovative combustors with efficient flame stabilization and heat recirculation is essential. This is particularly important in small-scale combustors where flame instabilities can occur due to the low length scales involved. Most studies established a concurrent understanding on extending the blow-off limits through geometrical modifications or by changing the flow characteristics. Micro combustor flame stabilization is a technique used in the design of UAV engines to improve their combustion efficiency and stability. In this technique, a flame stabilization mechanism is used to enhance the flame-holding capability of the combustor, which ensures that the flame remains stable and does not extinguish. Different mechanisms, such as vortex generators, bluff bodies, and recirculation zones, have been employed for micro combustor flame stabilization in UAV engines. These mechanisms improve the residence time of the fuel and air mixture, leading to better mixing and more efficient combustion. They also create low-velocity regions, increasing the residence time of the fuel and air mixture in the combustor, which results in a more stable flame structure. Bluff-body flame stabilization is a technique that shows promise in improving the performance and reliability of micro-meso scale combustors by increasing the blow-off limits by two to three times.

Some more detailed studies are necessary to achieve improved combustion characteristics with the micro-meso scale engines. However, only limited literature is available for UAV combustors based on experimentally tested miniature engines. Most of the applications are developed for power generation, propulsion, and space applications. A large part of the work focused on scaling the engines from gas turbines, spark ignition, and compression ignition engines. Advancements in engine technology have also led to the development of new types of UAVs, including vertical takeoff and landing (VTOL) and hybrid airships, which have unique engine requirements. This review merits a first step in developing a framework for flame stabilization technologies for UAVs.

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