A review of cavity-based trapped vortex, ultra-compact, high-g, inter-turbine combustors

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A review of cavity-based trapped vortex, ultra-compact, high-g, inter-turbine combustors

Dan Zhao^{a,*}, Ephraim Gutmark^b, Philip de Goeij^c

^a Department of Mechanical Engineering, College of Engineering, University of Canterbury, Private Bag 4800, Christchurch 8140, New Zealand

^b Department of Aerospace Engineering and Engineering Mechanics, University of Cincinnati, PO Box 210070, Cincinnati, OH 45221-0070, USA

^c Department of Mechanical Engineering, Technische Universiteit Eindhoven, P.O. Box 513, MB 5600, Eindhoven, Netherlands

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ABSTRACT

Trapped vortex combustor (TVC) is different from conventional swirl-stabilized combustors. It takes advantages of a cavity to stabilize the flame. When the cavity size of a TVC is well designed, a large rotating vortex can be formed in the cavity. The vortex cannot shed out the cavity and is thus named a “locked” or “stable” vortex. One of the main challenges for TVC design is fuel injection. Typically, fuel can be injected directly into the cavity or from the diffuser upstream. Injecting from the diffuser leads to the fuel being mixed with the air before it enters the combustor. When the fuel is injected directly into the cavity, it is desirable to supply the fuel in such way that the locked vortex in the cavity is reinforced. Furthermore, the fuel-air mixing in the cavity will be promoted, as the bypass air is directly added into the cavity. Since the recirculation zone anchored in the cavity is not exposed to the main incoming flow, stable combustion is achieved, even in the presence of a high speed main flow as typically expected in Ramjets and Scramjets. A well-designed trapped vortex combustor (TVC) enables a better fuel-air mixing, a better stabilized flame, lower emission, ultra-compact and high efficient combustion to be achievable. As a promising combustion concept, intensive scientific research has been conducted on TVC in the application areas of aerospace propulsion, power generation and waste incineration. In this work, we will firstly introduce the fundamental concepts, the development and evolution history of TVCs. The combustion, aerodynamics, and aeroacoustics features of trapped vortex combustion are then described. This includes reviewing and discussing the cavity flow/aerodynamics, fuel-air injection and mixing, trapped vortex combustion, emission and combustion of alternative fuels, and aeroacoustics characteristics. The ‘spin-off’ application of trapped vortex combustion concept for the design of ultra-compact and high-g combustors, inter-turbine burners, in-Situ and flameless TVC reheat combustors are then reviewed and discussed. Various practical applications of trapped vortex combustion concept in gas turbines, ramjets, scramjets and waste incinerators are discussed and summarized. Finally, the challenges and future directions of the design and implementation of TVCs are provided.

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* Corresponding author.

E-mail address: Dan.Zhao@canterbury.ac.nz (D. Zhao).

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1. Introduction

For propulsion and power generation systems, control of combustion emission and stable combustion are two of the most critical requirements [1], in addition to developing effective cooling technologies and innovative composite materials. Due to its impact on environment and health, controlling combustion emissions such as unburned hydrocarbons [2], carbon monoxide, particulate matter, oxides of sulfur and NO_x (nitrogen oxides) has been an active area of great public concern since 1970's. Thus the combustion-involved industries have undergone rapid changes in the combustion technologies used to meet the increased emission standard [1]. Carbon dioxide was initially not considered as pollutants in 1980's. However, those combustion products are found to contribute to global warming a few decades ago. This leads to extensive international attention and efforts to reduce greenhouse emissions too. In addition, the reduction of NO_x emissions has been receiving more and more attention due to its toxicity, it is a precursor to acid rain and chemical smog, and it has direct impact on the ozone depletion in the stratosphere. To reduce NO_x emissions, the dry low emissions (DLE) approach [3] was introduced in the late 1980's. DLE approach as shown schematically in Fig. 1(a) also minimized the need for costly onsite requirement. The continued development of DLE approach gave rise to NO_x emissions from industrial gas turbines being reduced to the levels between 2 and 25 ppm.

The majority of industrial gas turbines are not able to achieve NO_x emissions below 5 ppm. The implementation of expensive exhaust gas after-treatment, such as selective catalytic reduction (SCR) [4] is needed. The SCR technology means that highly toxic ammonia needs to be injected into the exhaust stream to neutralize these remaining emissions. However, such technique is not only very costly, but also creates environmental hazards [4]. In addition, SCR requires the storage and handling of ammonia. Generally, thermal NO_x is formed in the primary zone of the combustor. The highest gas temperature and the associated thermal NO_x emissions occur. A decrease in the maximum temperature achieved at more lean conditions, gives rise to reduced thermal NO_x emissions [1,5]. However, the CO emission is increased, as the combustion chamber approaches 'lean extinction' [5].

In order to meet more and more stringent NO_x emissions as shown in Fig. 1(b) (< 5 ppm in the absence of SCR), industrial combustors must be operated near the lean extinction limit [6]. As the lean extinction limit is reached, the combustor temperature is too low and the flame is very weak, and sudden 'flameouts' may occur [7]. In addition, these combustors are more susceptible to combustion instabilities [8,9]. These instabilities occur, when unsteady heat release is 'constructively' coupled with the acoustic disturbances in

the combustion system to produce large-amplitude limit cycle oscillations (also known as combustion instability) [8,9]. Combustion-driven oscillations [10,11] caused serious damages to the gas turbines and aero-engines since early 1990 s [1]. Intensive research has been conducted in the industrial gas turbines community to balance extremely low emissions, with engine flameouts and the limit cycle fluctuations.

The other critical requirement for propulsion and power generation systems is 'stable combustion' [12]. It is often achieved by using recirculation zones to provide continuous sources of ignition, by well mixing the combustion products with the fresh fuel and oxidant reactants. Conventionally, swirl vanes [3], bluff-bodies [7] and rearward-facing [9] steps are used as effective approaches to establish a recirculation zone for flame stabilization. There is a broad literature that has been established on these approaches. Interested readers can refer to the excellent review papers [3,7,9] or any textbook on combustion [13].

To meet these two critical requirements of low emissions and stable combustion, the concept of trapped vortex combustion (TVC) [14,15] can also be applied. It is fundamentally different from conventional swirl-stabilized combustion as shown in Fig. 1(a) [3,16]. The TVC concept [17,18] employs a cavity to stabilize the flame (see Fig. 1(c)). The actual stabilization mechanism associated with the TVC is relatively simple (see Fig. 1(c)). A conventional bluff or forebody is located upstream of a smaller bluff body, which is commonly referred to as an aft-body. The flow over the first bluff body separates and develops shear layer instabilities. These instabilities in most circumstances are responsible for initiating a blowout [19–21]. The alternating array of vortices are conveniently trapped or locked between the two bodies [22]. If the aft-body or the second bluff body is absent, a regular dump-plane with a separation vortex behind the step [9], which can be applied to stabilize the flame. This is similar to the TVC concept. In the TVC concept, the cavity design plays a critical role. If the cavity size is designed properly, then a large vortex can be created and filled inside the cavity [22,23]. The vortex will rotate smoothly. It does not shed out of the cavity and thus "safely locked" in the cavity [23,24]. Fuel and air may be injected directly into the cavity to promote the fuel-air mixing in the cavity. Furthermore, injecting the fuel properly into the cavity may reinforce the 'locked' vortex. The hot recirculation zone is well 'locked' in the cavity. And it does not expose to the main flow. This enables a stable combustion being achieved, even in the presence of a high speed main flow. Thus TVC shows great potential to provide effective flame stabilization even at extremely lean conditions.

One attractive feature of TVC is that it can be applied to handle a high inlet velocity (supersonic or hypersonic) [25,26]. This high velocity flow can also be associated with hydrogen-rich fuels, when

Fig. 1. (a) Schematic of conventional and DLE (dry low emission) combustor (b) NO_x emission (c) trapped vortex combustion (TVC).

it is operated under lean premixed conditions. It is quite challenging to burn high hydrogen content fuels, since the flame speed of hydrogen [27] is approximately 6 times that of natural gas. To prevent flashback, the main flow velocity needs to be much larger than the flame speed. However, this high flow velocity [28] creates problems in establishing and maintaining the swirl-stabilized effect. The problem becomes more complicated in the design of lean premix combustors, since flashback of the flame into the fuel injector causes severe damages to the hardware and leads to engine failure. However, the TVC technology may be a good candidate [25,26,29] to provide a stable combustion with a lower pressure drop/loss and lower acoustic emission resulting from cavity resonance and downstream edge [30,31], even with a high inlet velocity flow.

Another critical feature of TVC design involves transporting and mixing [32] the hot combustion products from the vortex locked in the cavity into the main flow stream. This can be achieved by using wake regions generated by bodies, or struts [33,34], immersed in the main flow. By using geometric features to ignite the incoming fuel-air mixture [35], instead of aerodynamic features, the trapped vortex combustion is less sensitive to unstable combustion. This is particularly important near the lean flame extinction limit, where small flow fluctuations may give rise to flame extinction. In a TVC system, very stable, yet more energetic, primary/core flame zone is resistant to external flow field disturbances [36]. This enables the lean and rich blowout limits being extended. Previous review [20] has shown that the TVC configuration can withstand through-put velocities below or above Mach number 1.0 (even in hypersonic engines). In addition, TVC configuration has a larger flame-holding surface area. Thus the TVC concept facilitates the design of more compact

combustors (even ultra-compact [37]) with a shorter flame but a higher combustion efficiency and a lower emission [38]. However, the extremely hot recirculation zone with allied primary combustion in the cavity leads to a high surface temperature gradient in the transition region. The associated high thermal gradient gives rise to a higher stress level, even buckling and bending problems. This means that effective cooling techniques [39] and innovative materials [40–43] are needed for the design of flame-holding cavities. Inadequate cooling may lead to excessive material temperature with decreased reliability and durability. Thus cooling the cavity [39] and developing innovative ceramic matrix composite materials [40,41] will remain two of the key challenging technologies for the design and application of TVCs. A number of cooling techniques such as convective, film and effusion cooling, which are applied in modern and future gas turbine engines, and their applications are well reviewed and discussed in Ref. [39].

TVC may become the next-generation combustion technology [22], as conjectured by General Electric [44], National Aeronautics and Space Administration (NASA) [45], Air Force Research Laboratory (AFRL) [14] and Innovative Scientific Solutions Inc. [36]. During the past 4 decades, trapped vortex combustion has gained more and more attention, as a promising flame-holding technology in subsonic and supersonic engine systems. However, there are outstanding questions concerning the design and effectiveness application of TVC concept in practice such as

- 1) What are the optimal cavity dimensions and its geometry that yield the most effective flame-holding capability with a minimum pressure loss.

- 2) What are the optimal configurations and locations of the fuel and air injections that lead to the best mixing, flame-holding and combustion performances.
- 3) What are the effective cooling technologies to avoid excessive heat transfer to the cavity walls and to decrease the pressure losses and the drag penalties?
- 4) If TVC is applied in propulsion systems operated at supersonic/hypersonic flight conditions, then what are the effects of shock wave, and how to maximize the residence time?

These questions need to be addressed by academic researchers and industrial R&D engineers, and motivate extensive researches on trapped vortex combustors (TVCs). Numerous experimental and numerical investigations are conducted on TVCs to have a better understanding of the fundamental mechanisms and to improve the design for practical applications. In the following sections, (i) the fundamental concepts and development history of TVCs, (ii) the characteristics of flame-holding cavities such as aerodynamics, vortex combustion, and aeroacoustics [46–48], (iii) the derived concepts of TVCs such as ultra-compact, high-g, inter-turbine, in-situ and flameless TVC reheat combustors, (iv) the application of TVC in different industries, (v) the challenges for TVC design and implementation, (vi) several suggestions on future work on TVCs are described.

2. Concepts and development history of trapped vortex combustor

The trapped vortex combustor (TVC) concept was proposed by AFRL (Air Force Research Laboratory) in 1990s or late 1980s [14]. A series of follow-up studies [46–48] was conducted on aero-engine flame stabilization. These initial studies were financially supported by AFRL, the US Navy, and the Strategic Environmental Research Development Program (SERDP) [49]. Fundamental studies, development and application of TVC in aero-engines [24,42], land-based power generation systems [44] are motivated by more and more stringent NO_x emission standards and how to prevent the onset of self-sustained combustion instability [2,9,11] associated with lean premixed engines.

Before describing the physics and features of a TVC, it is useful to briefly outline the essential features of a conventional gas turbine combustor [51]. A simplified swirl-stabilized combustion system [3,15] is considered as shown in Fig. 2(a). It has a primary recirculation zone that is established by a swirler located around the fuel injector. Some of the hot combustion products are transported back towards the combustor face and ignite the incoming fuel and air, as they are mixed in the combustion chamber. In this way, continuously combustion and stable flame are provided. Combustion stability is achieved by the recirculation zones in the forward corners of the combustor. If the inlet air flow velocity is quite high, the swirl

number is increased. And the primary recirculation zone becomes unstable, depending on the swirl number. This will lead to poor flame stability and lower combustion efficiency. For this, a diffuser is applied to slow down the combustion inlet air and to avoid an unstable primary zone being created. The air used for combustion is typically considered to be the primary airflow. Excessive air is provided and injected through perforated liners [52,53] into the combustion chamber for cooling and achieving lean combustion. Such cooling flow is known as a 'secondary' air flow. The 'secondary' air is used to mix and to shape the temperature profile of the exhaust gases, as it enters the turbine vanes. This 'secondary' air is also used to dilute and decrease temperature, which is so high as to cause damages to the turbine vanes.

A trapped vortex combustion system is schematically shown in Fig. 2(b). The similarities and significant differences between a TVC and the conventional swirler-stabilized combustor can be clearly observed by comparing Fig. 2(a) and (b). The cavity employed in the TVC configuration [55] is properly sized so that it has a stable recirculation zone over a wide range of main airflow conditions. This can be achieved by applying a relatively low-pressure drop across the combustor. The fuel and air are injected directly into the cavities to reinforce the vortex [56]. Based on the cavity fuel and air injections, there is a cavity equivalence ratio. On the other hand, an overall equivalence ratio is defined as the total fuel and air injected in the engine system. Ignition of the main combustor is achieved, as the main fuel and air mix with the hot products from the pilot flame. The recirculation zones behind the struts [57] function like flame-holders that are similar to those used in afterburners. The rapid mixing in the wakes behind the struts promotes a rapid combustion. In addition, the struts help to distribute the exit gases so that an acceptable radial profile and pattern-factor can be achieved without using liner jets [52,53]. Because the pilot flame is shielded from the main flow by the cavity, stable and efficient combustion can be achieved [58], even in the presence of a high inlet velocity flow.

In concept, the TVC seems to be simple [56]. However, it has great potential to provide better performances and lower emissions. Because of the stable recirculation zones in the flame-holding cavities, a TVC is expected to have low lean-blow-out (LBO) limits and good altitude relight capabilities. If rapid mixing can be achieved in the flame-holding cavities, then a TVC can achieve a higher combustion efficiency over a wider operating range. Low NO_x emission can be achieved through different implementation strategies. One is to rapidly mix the oxidant and the fuel. Another one is to operate a TVC as a staged system with lean or premixed combustion. When a TVC is operated at high inlet velocities, low thermal NO_x could also be achieved as a result of the reduced residence time. Finally, a TVC can be operated as rich-burn quick-quench lean-burn (RQL) combustor [58]. The cavities provide the rich-burn mode and the rapid mixing, while the main air (no main fuel) provides the quick-quench lean-burn modes. Whether these strategies can be successfully

Fig. 2. comparison between a conventional swirler-stabilized combustor and trapped vortex one. Adapted from [54].

implemented is a question that will be addressed in this review of the development history of TVC designs in the following subsections.

2.1. First generation TVC

The earliest design of a TVC [15] involves an axisymmetric configuration with only an outer cavity and no diffuser or struts employed. However, this configuration does not result in stable combustion, because the cavities were too large. A more flexible configuration was then proposed and tested, where the cavity size could be changed and the flame in the cavity can be clearly observed. This was demonstrated in the first generation TVC [35,59], as shown in Fig. 3. The two disks in tandem are used to form a cavity. And the cavity length could be changed by moving the tube attached to the cavity back face out or in. Across the back face of the cavity, propane and air were injected separately. It was found by trial and error that a stable combustion is achieved with an after-disk diameter of $0.73D_0$ and a cavity length of $0.59D_0$. Here D_0 is the diameter for the forward disk. Furthermore, a stable vortex is locked in the proper-size cavity and stable flames are observed.

To determine the optimum size of a flame-holding cavity, the rules for sizing cavities were studied [60,61] to reduce the drag of bluff-bodies in non-reacting flows. An optimal separation distance was found [61] for a ratio of afterbody-to-forebody disk diameters less than 1, where the drag was minimized. The minimum drag was found [60] to correspond to the condition where a stable recirculation zone is created. To validate the findings of the previous works [60,61] and to predict the combustor results of the 1st generation TVC, a time-dependent axisymmetric mathematical model was developed and applied [62] to examine three different size cavities, i.e. (1) undersized, (2) right-size and (3) oversized. When the cavity is undersized, the drag is relatively large because of shedding from the after-disk. However, when the cavity is properly sized, a stable vortex is formed in the cavity and in the near-wake region of the after-disk, the drag is a minimum. Also, very little fluid is entrained into the cavity. The entrainment of the main flow into the cavity of TVC is found to depend on the cavity optimum dimensions. The optimum size relatively restricts the entrainment of the main air flow into the cavity compared to the non-optimal cavities. This means that the stable cavity vortex is the best choice for flame stabilization. However, it may not be the best solution from the point of view of fuel-air mixing, as discussed in Ref. [63]. In addition, the reacting flow simulations [35,62] revealed that the dynamic vortices locked in the cavity with the air and fuel injected did not shed, even though

the cavity size was determined based on non-reacting cold-flow conditions. It is also noted that when the vortex is trapped in the cavity, the stagnation point is located at the downstream corner of the cavity. This observation is similar to that of Ref. [64]. When the cavity is too large, the vortex in the cavity is unsteady and the drag is large. In general, a cavity which is properly sized for a minimum drag for non-reacting flows is found to be the optimum size for a stable combustion in a reacting flow. The first generation TVC was found to have LBO limits considerably below those of conventional combustors and operate stably over a wide range of inlet air velocities and F/A (fuel to air) ratios [35,59].

2.2. Second generation TVC

The 2nd generation TVC is an axisymmetric can-type configuration [15]. Different from the 1st generation TVC, the 2nd generation has the cavity surrounding the casing instead of the combustor center as shown in Fig. 4(a). And there are several struts or flame holders in front of the cavity. The second generation TVC is designed to improve lean-blow-out and combustion efficiency [35,36,49], as shown in Fig. 5(a) and (b) respectively. A typical axisymmetric can-type configuration of 2nd generation TVC is illustrated in Fig. 4(a). The cavity depth is about the same as that for the optimum designs of the first generation TVC. The depths of the forward and back wall are 29.8 mm and 21.5 mm respectively. The length of the cavity is 50.5 mm, somewhat longer than that of the first generation TVC. The outer circumferential wall of the cavity is made of quartz. The diameter is about 152.4 mm. The struts result in a 50% blockage of the inlet area to the main combustor. Across the back face of the cavity, gaseous propane and air are injected. Each fuel jet is surrounded by 4 air jets. The cavity air flow is controllable and metered independently of the main airflow. To promote mixing, ignition, flame-holding and distribution of the heat for the main burner circumferential struts or splitters are used. The fuel and air are premixed at the inlet of the burner.

The most impressive aspect of the second generation TVC is its large dynamic operating range [50,55]. The overall equivalence ratio could be rapidly changed from 1 to 0.05 and then back to 1. The LBO performance of the 2nd generation TVC is shown in Fig. 5(a). Here only the cavity is fueled. The LBO experiments are conducted by establishing a flame in the cavity with a fixed main airflow rate. The fuel flow rate is slowly reduced until the visible flame in the cavity is extinguished. This process is repeated at a different main airflow rate. The 2nd generation TVC exhibited LBO limits significantly below those of an advanced combustor that uses swirl to stabilize

Fig. 3. Schematic of 1st generation TVC [54]. Courtesy of Dr. D. T. Shouse.

Fig. 4. Comparison between 2nd (a) and 3rd generation (b) TVCs with the illustration of its cavity [54]. Courtesy of Dr. D. T. Shouse.

the flame [3,15,51]. Both the advanced and TVC combustors are operated at atmospheric pressure. Fig. 5(b) compares the combustion efficiency of the 2nd generation TVC, the advanced combustor and a current combustor as a function of total fuel flow. TVC is found to be associated with a higher combustion efficiency. In general, the 2nd generation TVC exhibited excellent LBO capabilities and efficient operation over a wide dynamic range. Furthermore, this TVC is not susceptible to combustion instabilities [2,9,11], as typically encountered in lean premixed pre-vaporized (LPP) combustors.

2.3. Third generation TVC

One of main challenges is how to inject liquid fuel into the cavity in a way that can be easily implemented in practice. Since most of fuel needs to be injected near the main combustor inlet, the number of penetrations through the high-pressure case should remain to be a minimum [37,45]. Furthermore, the plumbing should be as simple as possible. This means that injecting the liquid fuel from the front face of the cavity is a good option. Thus, the key challenge is to determine the optimum locations in the cavity for the fuel nozzles and primary combustion air jets. These challenges are solved in the 3rd generation TVC. Fig. 4(b) illustrates a two/three-dimensional sector of the 3rd generation TVC designed for optical viewing and easy replacement of the cavities [15]. The cavities are built by properly placing square tubes. This design allowed the fabrication of the cavities with different patterns of air jets and pressure atomizer fuel

nozzles to be achieved easily. Illustrations of the air- and fuel-injection sites are also provided in Fig. 4(b). The struts and splitter plate act as flame holders to promote mixing and igniting the hot products transported from the cavities with the premixed fuel and air of the main combustor [50].

Detailed studies performed on the 3rd generation TVC showed that the main vortices in the double vortex and the single vortex configurations are safely 'trapped' in the cavities for all operating conditions. No combustion instabilities [3,11,12] have been observed from these two configurations. However, combustion instability [59] was found to be related to the location of the fuel nozzles and it has been observed for several other configurations. Some experimental results obtained from the 3rd generation TVC are summarized in Fig. 6(a)–(c) [15]. As shown in Fig. 6(a), the double vortex cavity design provided the lowest LBO limits. Certainly, all three TVC designs shown in Fig. 6 had LBO limits below those of conventional combustion systems operating at the same conditions. The comparison of combustion efficiencies is made as shown in Fig. 6(b). Again the double vortex design exhibited the highest combustion efficiency at the lowest overall equivalence ratio. The TVC designs are associated with a relatively higher combustion efficiency than the conventional combustor, whether ethanol fuel or JP-8 fuel is burned. Fig. 6(c) indicates that a TVC could have a wide operating range.

To determine the optimum location of the air and fuel injection sites in the cavities, 19 cavity configurations with different patterns

Fig. 5. Variation of (a) lean-blow-out (LBO), (b) combustion efficiency for 2nd generation TVC with comparisons with current and advanced combustors [15]. Reprinted from [15] with permission of Dr. D. Shouse and D. Burrus.

Fig. 6. Performance of the 3rd generation TVC, in terms of LBO (a), combustion efficiency (b), conversion efficiency of FBN (fuel-bound nitrogen) to NO, (d)–(f) three optimum configurations for injecting fuel and air into cavity [15]. Reprinted from [15] with permission of Dr. D. Shouse and D. Burrus.

of air and fuel injections were proposed and evaluated. In all the designs, the fuel is injected from the cavity's front face. Ethanol and JP-8 fuel are chosen in the experiment because of its low heating value. The optimum overall performances are obtained from two cavity designs as shown in Fig. 6(d) and (e). A cooling approach was also examined for the back face and corners of the cavities as shown schematically in Fig. 6(f). While a small vortex is also produced near the aft corner of the cavity, double vorticities are generated by a line of air jets located deep on the front face of the cavity and near the center of the aft face of the cavity. Locating the fuel deep in the cavity plays a critical role in achieving good idle performance. The single vortex design is shown in Fig. 6(e); the fuel injectors are located just above the centerline of the front face of the cavity. Small variations in the location of the fuel injectors have a strong effect on the combustor performance.

There are some interests in evaluating the TVC concept for a number of practical applications. The National Energy Technology Laboratory (NETL) is interested in reducing NO_x emission from power-generation gas turbine engines that burn low-Btu fuels [15]. These fuels contain fuel-bound nitrogen (FBN) [2] compounds such as ammonia. An RQL combustor approach is one possible way to stop the FBN from becoming NO_x . Experiments have been conducted with the 3rd generation TVC to determine whether the TVC, operated in a RQL mode, could stop some of the FBN from becoming NO_x . These experiments have been conducted at atmospheric conditions, with ethanol fuel supplied. Pyridine or butylamine were used as additives to simulate FBN compounds. Experimental tests were conducted with one cavity fueled and two cavities fueled. With combustion in both cavities, only about 17% of FBN was converted to NO_x . These results are quite encouraging, since these are the first FBN experiments performed with a TVC. NETL has designed an RQL/TVC

combustor [58] for conducting follow-up research at their Morgantown Laboratory.

2.4. Fourth generation TVC

The experimental studies on the 3rd generation TVC provided useful information needed to design two high pressure TVC sectors for evaluating the TVC operated under realistic pressure and inlet air temperature conditions. This is the 4th generation TVC. A double vortex and a single vortex cavity were designed in a high-pressure sector rig located at Wright-Patterson Air Force Base [15]. Also, a dual-pass and a tri-pass diffuser were designed for this rig. There are 4 TVC configurations being examined [54]. The first configuration involves a high pressure TVC including a dual-pass diffuser and a double or single vortex cavity arrangement. These arrangements are illustrated in Fig. 7(a) and (b) and are referred to as the 2P-2 V and 2P-1 V TVC.

A total of 54 fuel injectors are applied in the 2P-1/2 V TVC sector. This large number of fuel injectors facilitates good distribution and mixing of the fuel and air. A tri-pass diffuser with double vortex cavities (3P-2 V TVC) is shown in Fig. 7(c). It is constructed in essentially the same way as the 2P-2 V TVC sector. The cavity and diffuser components could also be configured for 2P-1 V and 3P-1 V TVCs. These configurations are not shown, because very few experiments have been conducted with them. This is due to the instability that resulted from single vortex cavity design [15]. The cavity fuel injectors were located deep in the cavities. Some of the fuel was transported directly into the main air stream. This burning fuel appeared to couple to the small vortex that is shed over the aft-wall corner of the cavity. This small vortex resulted from the way in which air is

Fig. 7. (a) 2-Passage dome/2 vortex cavities, (b) 2 passage dome/1 vortex cavity, (c) 3 passage dome/ 2-vortex cavities, (d) 3 passage dome/2 vortex cavities (cavity fueled only/R-Q-L mode operation). Adapted from [54].

used to cool the aft face of the cavity. A similar vortex occurs in the double vortex cavity design.

The Air Force combustion facility [49,50] where the TVC sectors were evaluated was designed with full optical access to the inside of a TVC sector. Fig. 7(d) is a photograph of the 3P-2V TVC operating with the cavities and the main fueled. It can be seen that the main fuel spray from the center air passage has collapsed. Indeed, a closer observation of the flame showed that the fuel spray has collapsed for all of the main fuel nozzles. However, the center passage created the major problem, since there was not adequate heat at the exit of the center air passage to vaporize the fuel. This problem can be solved partially by replacing the tri-passage [45] fuel spray bars with the bi-passage spray bars. Thus, only the outer main air passages are fueled.

Assessment of the performance revealed that the prototype 4th generation TVC test rig had exceeded all initial expectations. A more detailed description of the TVC sectors and the high-pressure test results can be found in Ref. [54]. Some results from the 3P-2V TVC are presented in Fig. 8. The LBO characteristics of the 3P-2V TVC is shown in Fig. 8(a). Comparison is then made between the 4th generation TVC and the blow out characteristics for two conventional swirl stabilized combustors [49,50]. The LBO limits for the TVC are found to be about 50% below those for the conventional combustors. Furthermore, the TVC LBO limits do not depend strongly on the loading parameters as those for conventional combustors. Fig. 8(b) illustrates the altitude relight capabilities of the 4th generation TVC. The TVC altitudes relight is found to be considerably better than that for swirl-stabilized combustors. Conventional combustors have a relight capability of about 9 km. There appears to be significant improvements in relight capability. Fig. 8(c) illustrates the large operating

range of the TVC. Effective combustion efficiencies above 99% were achieved for an overall equivalence ratio between 0.12 and 0.82. This represents about a 40% wider range than that typically achieved by conventional gas turbine combustion systems. Fig 8(d) shows the exit gas temperature profile across the duct height with cavity-only and with cavity-plus-main-combustor operations. Results are shown for two fuel-air ratios with the main and cavities operating. The temperature profiles are relatively flat, even with cavity only operation, which is a good indication that the struts are evenly distributing the hot products transported out of the cavities. Although the temperature profiles of rigs do not always accurately reflect those of annular combustors of the same design, the temperature data do offer the potential of achieving low pattern factors with the TVC without the use of liner jets.

2.5. High inlet velocity/pressure TVC

The potential of applying TVC such as 3P-2V configuration in ramjet and scramjet engine systems is recently evaluated via conducting high-speed experiments at NASA Glenn [48,50]. The high inlet velocities were obtained in the experiments via increasing the pressure drop across the combustor. In a ramjet, this pressure drop could be generated by ram air, not by the upstream plenum. The experiments have been conducted with cavities only fueled and at 3 fuel-air ratios. Although these experiments do not simulate a ramjet operation, they do provide some insights into the operation of the cavity at high inlet velocities. Stable cavity flames were clearly observed. And the vortex well trapped in the cavity became more intense and smaller with an increased pressure drop. Fig. 9(a) shows the variation of the measured combustion efficiency with the fuel/

Fig. 8. Performance of TVC in the configuration of 3P-2V: (a) lean-blow-out and (b) altitude relight for high pressure, (c) combustion efficiency and radial profiles, (d) the exit gas temperature profile across the duct height with cavity-only and with cavity-plus-main-combustor operations [54]. $SP = (P_3/14.7)^{0.26808} \times e^{(T_3/257.693)} \times FAR^4 \times (F_{cav}/F_{overall})^{0.291096}$. P_3 and T_3 denote the operating pressure and the inlet air temperature, FAR denotes fuel-air ratio, F_{cav} and $F_{overall}$ are the overall equivalence ratio in the cavity and the combustor overall operating equivalence ratio. Adapted from [54].

air ratio. The combustion efficiency is found to remain above 99% for a cavity equivalence ratio between 1.2 and 3.8. The efficiency for the higher inlet velocity condition was essentially over the full range of the primary equivalence ratios tested. Fig. 9(b) shows the measured NO_x emission index. The TVC gives a 55% reduction in NO_x for the advanced commercial engine cycle as compared to the 1996 ICAO standard [15]. This suggests that NO_x production can be significantly reduced with a TVC operating with a high inlet-air velocity. These promising results offer strong support that a TVC is a good candidate for powering a ramjet. A joint program is in progress with NASA Glen to further evaluate the TVC as a hypersonic combustion system.

3. Characteristics of trapped vortex combustor

TVC involves multi-physics and characteristics such as 1) cavity aerodynamics [56] and aeroacoustics [65], 2) fuel (liquid or gas) injection and fuel-air mixing [66–68], 3) vortex-combustion characteristics [69,70], 4) chemical emissions [71,72]. Extensive research has already been conducted to shed lights on the fundamental physics and mechanisms of such cavity-based flame holders. We will review and discuss the characteristics of trapped vortex combustion systems [73,74] in the following subsections.

Fig. 9. High pressure TV test rig data (a) combustion efficiency, (b) variation of LTO NO_x with pressure ratio. Adapted from [54].

3.1. Cavity flow and aerodynamics characteristics

Understanding the fluid dynamics of cavities in a cross flow (subsonic [56,75] or supersonic [23,76]) is critical to ensure appropriate fuel-air ratio in TVCs and appropriate temperature distributions downstream of the combustor. For this, a number of researchers [29,60,77] studied the flow characteristics of a stable/locked vortex after-body, since the aerodynamic drag is decreased in the presence of a cavity attached behind. When incoming air flows subsonically over a cavity created by a fore- and after-body disk, there are 4 flow regimes as shown in Fig. 10(a)–(d).

The 4 regimes include: (1) the wake backflow, (2) the unsteady cavity vortex, (3) the steady cavity vortex and (4) the compressed cavity vortex. For the 1st and 2nd flow regimes, the vortices generated between the fore- and after-body are not fully included in the cavity. They are still somehow related to the downstream recirculation zone. The vortices are under the influence of wake flow downstream of the after-body. Experimental test [60] confirmed that these vortices are unstable. When the after-body is placed at a certain distance from the fore-body such that no flow is spilled over the after-body, a stable vortex occurs and the flowing fluid in the main stream moves smoothly over the cavity. In this case, the cavity is filled with a 'large rotating' vortex [84]. Now the stagnation point in this regime is on the after-body's top surface, and disconnected with the wake. For this, the cavity vortex is found to be 'locked safely' inside. The compressed cavity vortex as shown in Fig. 10(d) is present, when the cavity length is greater than that of the steady vortex regime. The cavity vortex is elongated and compressed by the main flow. The stagnation point is on the after-body's front surface. This means that the flow in the main stream goes into the cavity directly. The direct flow impingement on the after-body's front surface gives rise to a large undesirable drag being produced from a large pressure increase. The compressed cavity vortex is found to be unstable, since

there is a strong and continuous exchange of fluid between main flow and the cavity [29,60].

The momentum ratios and cavity sizes were found to play important roles on affecting mass exchange in a subsonic TVC. The acetone PLIF Measurements [79] reveals that the vortices were locked in the cavity, as the cavity aspect ratio is varied. In addition, the fuel-air ratio and inlet Mach number were shown to influence the flame and combustion dynamics, as experimentally visualized [69] in a single-cavity trapped vortex combustor (see Fig. 11(a) and (b)). Fig. 11(c)–(h) shows the images illustrating the effects of increasing fuel-air ratio (FAR) and increasing inlet Mach number on the visible length and the physical appearance of the flames. As FAR is set to 0.008 and the inlet Mach number is increased, as shown in Fig. 11(c)–(e), the flames are all confined within the cavities. The flame length becomes shorter and the color of the flames is changed from yellow to blue. This indicates more intense combustions at high-velocity flow conditions. However, as the inlet Mach number remains unchanged but FAR is increased, the flame length is increased.

Cold-flow non-reacting tests were also conducted [69] to gain insights on vortical flow patterns within the cavity, turbulence intensity distribution and interaction between the cavity stream and mainstream. It is found that the flow in the cavity features a dual-vortex pattern, as shown in Fig. 12, whereas in the plane along with the radial strut, the single-vortex flow pattern is established in the cavity. Mixing and interaction between the cavity stream and mainstream occurs mainly in the wake regions of radial struts. Combustion tests [69] are then carried out with preheated air (473 K) at atmospheric pressure using liquid kerosene. Flame images at different operating conditions are obtained as shown in Fig. 11(c)–(h). The effects of the fuel/air ratio and the inlet Mach number on the cavity flames are examined. The flame length is found to increase as the fuel/air ratio is increased. As the inlet Mach number is increased, the flame becomes shorter and the color changes from yellow to

Fig. 10. Experimental and numerical determined 4 typical cavity flow regimes. (a) Wake back flow, (b) unsteady cavity vortex, (c) steady cavity vortex, and (d) compressed cavity vortex. Left column: Reprinted from Ref. [29] with permission of the American Institute of Aeronautics and Astronautics (AIAA) Inc. Right column: Fluent simulations [84]. Courtesy of Dr. S Chen.

Fig. 11. (a) Photographs of the PIV model combustor, (b) the combustion model combustor, (c)–(h) flames photos at various Mach numbers and fuel-air ratios (FARs). Reprinted from [80,81] with permission of Elsevier.

Fig. 12. The streamlines overlaid on contours of velocity magnitude in PM, showing the vortical flow patterns in cavities at 2 different Mach numbers, (a) 0.1 and (b) 0.25. Reprinted from [69] with permission of Elsevier.

blue, indicating more intense or complete combustion. The combustion efficiency is in the range of 92%–100%. Furthermore, good flame stability is achieved, since the fuel to air ratio at lean blow out (LBO) is in the range from 0.0043 to 0.0056, as the inlet Mach number is varied from 0.15 to 0.3. However, the fuel injection in the mainstream and the combustion performance evaluation at high-temperature, high-pressure operating conditions are not studied.

The experimental measurements on a low NO_x subsonic TVC combustor [70] revealed that a stable combustion is achieved by a large recirculation zone with distributed combustion and nearly uniform temperature values that exceed the auto-ignition temperature values. Fig. 13 shows the measured velocity vectors and concentrations of the chemical species such as NO_x , O_2 , CHC , CO and CO_2 . It revealed that in the regions of higher temperatures, the O_2 concentrations are relatively low. This contributes dramatically to hinder the NO formation via the classical thermal mechanism. In the recirculation zone, the O_2 concentrations are relatively low and the CO_2 concentrations are relatively high. This clearly indicated the presence of recirculated combustion product gases originating from regions where the oxidation process is already in a more advanced stage.

LES (large-eddy simulations) [82,83] with an immersed boundary method implemented were conducted on a subsonic TVC for the non-reacting and reacting flows. The photo and schematic of the trapped vortex combustor are shown in Fig. 14(a) and (b) respectively. The combustion model is based on tabulated chemistry

associated with a presumed PDF (PCM-FPI) for premixed flames. The vortical structure of the cavity flow with PIV measurements and LES predictions are shown in Fig. 14(c) and (d). Good agreement is observed. The effect of swirling is shown in Fig. 14(e) and (f). A strong modification of the cavity flow dynamics is clearly observed. Furthermore, two coherent structures of same sizes keep the flow in the cavity, with its emptying mainly affected by the upper vortex. Fig. 14(g) and (h) illustrate the trapped vortex combustion with a beta-presumed PDF and a premixed flamelet tabulated chemistry, which is characterized by progress variable F as defined in Ref. [82] and temperature. These studies indicate that the cavity seems to be an interesting option for fuel-lean burning.

There are current interests in whether spinning motion can improve the fuel-air mixing and combustion performance in TVCs. It is found in Refs. [78,84] that stable cavity flows are achieved in a higher subsonic TVC without and with a spinning motion, as shown in Fig. 15(a) and (b) respectively. The non-reacting case was studied by conducting LES simulations via the JETCODE developed at Stanford University [78]. The 3D streamlines viewed in the relative reference frame are also obtained, as shown in Fig. 15.

3D streamlines in combustions without and with the spinning motions are shown in Fig. 16(a) and (b) respectively. Compared with 3D flow in the non-spinning case as shown in Fig. 16(a), obvious 3D flow features are clearly seen in the cavity and in the wake region as the spinning motion is involved as shown in Fig. 16(b). The flow near the combustor centerline still rotates as shown in Fig. 16

Fig. 13. Measured velocity vectors for test condition C1, and measured O_2 , CO , NO_x , HC and CO_2 concentrations for the test condition C3 at the symmetry plane inside the combustion chamber. Reprinted from [70] with permission of the American Institute of Aeronautics and Astronautics (AIAA) Inc. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 14. Photo (a) and schematic (b) of the trapped vortex combustor (c) PIV measured vortical flow structure (30 g/s), (d) LES simulated vortical flow structure over the cavity. Q-criterion ($Q = 9 \times 10^7 \text{ s}^{-2}$) colored by the velocity magnitude (m/s), (e) 20 g/s with no swirl, and (f) 30 g/s with swirl, (g) and (h) iso-F and iso-temperature contours. Reprinted from [82] with permission of Elsevier. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(b). As the rotating reference frame spins at 30,000 rpm, the rotating streamlines indicate that there is a higher spinning rate. The combustion efficiency of the TVC in the absence or presence of the spinning motion is illustrated in Fig. 16(c). The spinning motion is found to lead to an increased combustion efficiency close to the spinning disc. The improved performance can be explained by the increased fuel-air mixing resulted from the spinning motion.

Further non-reacting study [85] on investigating the TVC operated in swirling flow reveals attractive cold flow-field characteristics and the stability of the locked vortex in different swirling flow conditions. Three dimensional unsteady simulations are performed by solving the Reynolds-Averaged Navier–Stokes (RANS) equations with the commercial flow solver ANSYS FLUENT v16.1. The Reynolds Stress Model (RSM) is selected for the turbulence closure to better predict the anisotropic turbulence features encountered in highly

swirling flows. Validation with the experimental data shows that the RSM model can provide rather good agreements for flows with a swirl number up to $S = 0.98$. Numerical results of the swirling TVC reveal that the cavity vortex can still be trapped well in flows with 2 different swirl numbers, as shown in Fig. 17(a) and (b) respectively.

Due to the swirling flows, strong tangential motion is introduced into the cavity vortex, and vortex breakdown is established in the sudden expansion region of the TVC. Turbulence kinetic energy and turbulence intensity are significantly increased by around 300%. This indicates the fuel-air mixing can be dramatically improved. A flow disturbance, swirl number suddenly changing from 0.6 to 0.98, is added to the TVC to study the stability of vortices. The transient results show that the cavity vortex is quite resistant to the flow disturbances and is still trapped well in the cavity, while vortex shedding is observed in the conventional breakdown vortex region when

Fig. 15. 3D streamlines of the non-reacting flow in the combustor: LES (large eddy simulations) averaged results: (a) 0 rpm, and (b) 30,000 rpm [84]. Courtesy of Dr. S. Chen.

the flow disturbances is added. This study reveals that the TVC is a promising combustor concept for swirling flow operations, not only because of high turbulence levels that is good for mixing, but also because the cavity vortex for flame stabilization is more robust.

Supersonic flow over cavities has also been extensively studied [86–88], because of the strong relevance to the development of ram-jets [89] and scramjets [23,90]. The main idea is to create a recirculation region inside the cavity with a hot pool of radicals. This will reduce the induction time, and enables auto-ignition of the fuel/air mixture being achieved. When a cavity is exposed to a high-speed cross flow, the cavity may experience self-sustained flow oscillations [87,90]. Thus pressures, densities and velocities in and around the cavity will be fluctuating. This will lead to drag penalties. Fig. 18 shows the magnitude of pressure fluctuation on the bottom of the cavity (see Fig. 18(a)) and drag coefficient (see Fig. 18(b)) for different length-to-depth ratios L/D [23]. When the oscillatory mode inside the cavity is changed from transverse mode to a longitudinal one, there was a sharp rise of oscillatory level and drag. With increased L/D , the fluctuation magnitude is decreased, while the drag coefficient is increased significantly.

Cavity supersonic flow can be categorized into two basic flow regimes, depending strongly on the length-to-depth ratio L/D [23]. For $L/D < 7$ –10, the cavity flow is ‘open’ (see Fig. 19(a)), since the upper shear layer reattaches to the back face. For $L/D > 10$ –13, the cavity flow is ‘closed’ (see Fig. 19(b)), since the free shear layer reattaches to the lower wall. In both cases, a shear layer is separated

from the upstream lip and reattached downstream [91]. The critical length-to-depth ratio corresponding to a transition between different cavity flow regimes depends strongly on the boundary-layer thickness at the leading edge of the cavity, the flow Mach number, and the cavity width. Larger aspect ratio cavities are associated with longitudinal oscillations [92], while small aspect ratio cavities ($L/D < 2$ –3) are dominated by transverse oscillations [93]. The drag of the cavity is increased by the high pressure at the rear faces as a result of the shear layer impingement. Large drag losses result from the pressure increase in the back wall vicinity and the pressure decrease in the front wall (see Fig. 19(b)).

A cavity with self-sustained oscillations [90,91] is defined to be unstable. And many experimental and computational studies [91] have been conducted to better understand the physics of cavity flows and the means to control their nature. The self-sustained flow fluctuations consist of two types of flow disturbances. One is characterized by broadband small amplitude pressure fluctuations typical of turbulent shear layers. The other consists of discrete resonances whose amplitude, frequency, and harmonics depend strongly on the cavity geometry and external flow conditions. Open cavities [23] were found experimentally to be dominated by transverse or longitudinal mode oscillations (see Fig. 19(a)), which depend on the Mach number M_∞ and L/D . In a short cavity filled by a single large vortex, the oscillation is excited by a transverse mode. The transition from transverse to longitudinal mode oscillation was found to occur near $L/D = 2$ at $M_\infty = 1.5$ and between $L/D = 2$ and 3 at $M_\infty = 2.5$. However,

Fig. 16. 3-D streamlines of combustor flows in the combustor: (a) 0 rpm, and (b) 30,000 rpm, (c) Combustion efficiency for the non-spinning and spinning combustor [84]. Courtesy of Dr. S. Chen.

Fig. 17. 3-D streamlines in the cavity region with (a) $S = 0$ and (b) $S = 0.6$. S denotes the swirl number. And it is defined as the ratio of axial flux of angular momentum to R times the axial flux of the axial momentum. Reprinted from [85] with permission of Elsevier.

Fig. 18. Effect of L/D on (a) magnitude of pressure fluctuations on the bottom of the cavity at $x/D = 0.33$ and (b) drag of the cavity at Mach 1.5 and 2.5 flows. Reprinted from [23] with permission of Dr. A. Ben-Yakar and R. K. Hanson.

in the long cavity filled by vortices, the oscillations are excited by longitudinal modes. The resonant frequency ω_m^l of the longitudinal mode [92] can be predicted by using the empirical formula:

$$\omega_m^l = \frac{2\pi(m-\alpha)U_\infty}{[M_\infty / \sqrt{1 + M_\infty^2 (\gamma_\infty - 1)} + 1/k]L} \quad (3.1)$$

where M_∞ and U_∞ are the free-stream Mach number and flow speed. L is the cavity length and γ_∞ is the specific heat ratio. ω_m is the resonant frequency corresponding to the m th mode. α and k are empirical constants.

Fig. 19. Flow field schematics of cavities with different length-to-depth ratio L/D in a supersonic flow: (a) open cavity, (b) closed cavity. Adapted from [23] with permission of Dr. A. Ben-Yakar and R. K. Hanson.

The transverse oscillation frequency ω_m^t in a supersonic deep-cavity flow is predicted [93] as

$$\omega_m^t = \frac{2\pi(m-\alpha-\Delta\phi)U_\infty}{[(M_\infty/c_l)/\sqrt{1 + (\gamma-1)M_\infty^2/2} + 1/k]L} \quad (3.2)$$

where c_l is defined as the normalized sound speed in the cavity, which is assumed to be equal to that in a stagnating free-stream. $\Delta\phi$ corresponding to a time delay $\Delta\tau = \Delta\phi/\omega$ is assumed to result from the effect of pressure waves reflection at the bottom wall of the cavity.

Cavity flame-holders can be designed to involve with a cone-strut or guide vane to improve flame stabilization capacity [94–96]. To achieve a stabilized flame in a $M_a = 3.25$ Scramjet combustor over a wider equivalence ratio range, a cone-strut is introduced to a cavity flame-holder. The experimental results show that the flame-holding range is broadened by approximately 50% [94,95]. A guided vane could also be designed and introduced to TVC to improve the fuel-air mixing in the cavity. Preliminary numerical non-reacting simulations show that introducing the guided vane will introduce about 5% of drag penalty. However, the combustion efficiency can be increased by approximately 14% [96].

Self-excited combustion-driven oscillations also known as combustion instability have been found [97–99] to occur in combustion systems with a cavity flame-holder, even in supersonic flow conditions. The underlying mechanism was shown to be due to the coupling between transient combustion response and unsteady flow motion in a confined volume, where acoustic pressure waves can be excited and sustained. This mechanism is typically applied to explain the combustion instability occurred in subsonic conditions. However, under supersonic flow conditions, acoustic pressure waves cannot propagate upstream. And flow oscillations generated in the flame zone can simply travel downstream and exit from the engine. Thus no feedback loop is formed, which is essential to sustain combustion and flow instabilities. However, combustion instability with frequencies of 100–400 Hz was experimentally observed in an ethylene-fueled scramjet combustor as reported in Refs [97,98]. The generation mechanism is identified to be the interaction between unsteady heat release fluctuations in the flame zone and the transient responses in pre-combustion shock and fuel mixing respectively. The onset of combustion instability in TVCs depends strongly on the flight/flow conditions and inflow stagnation temperature [98]. A series of experiments are conducted on a $M_a = 4.0$ Scramjet combustor with a cavity flame-holder confined to evaluate the effects of (1) the cavity location, (2) its length to depth ratio and (3) aft-wall angle on combustion-driven oscillations. The experiments reveal that combustion instability does occur in supersonic engines with a cavity flameholder, which is generally assumed to be unlikely to occur.

Residence time of the supersonic and subsonic flow inside a cavity depends on the mass exchange rate in and out of the cavity. In the open cavities, mass and momentum transfer mechanisms are determined by the vortex structure inside the cavity and the longitudinal oscillations. It is numerically demonstrated [100] that there was one large vortex stationed near the trailing edge of the cavity and a secondary vortex near the upstream wall. The large trailing vortex interacts with the unstable shear layer and determines the mass exchange of the cavity. As the trailing edge vortex occupies a larger volume inside the cavity, the mass exchange is increased and the flow residence time inside the cavity is decreased. It is worth noting that for some applications, supersonic cavity oscillating flow is undesirable such as weapons bay. To prevent or mitigate this oscillating cavity flow, a triangular bump or a sub-cavity can be designed near the leading edge of the cavity. Interested readers can refer to the interesting work [101].

3.2. Fuel injection and fuel-air mixing characteristics

In the trapped vortex combustor geometry, the mainstream fluid is difficult to enter into the recirculation area in the cavity (typically < 3% of the total vortex mass) [79]. This means that reactants need to be injected directly into the cavity. In this way, a very efficient turbulent mixing of reactants is achieved. This fuel-air injection strategy also compensates for the lack of oxidizer due to a low fluid exchange between the mainstream flow and vortex region. Furthermore, the vortex itself in the cavity can be strengthened by the direct injection of reactants, thus being stabilized over a wide range of the inlet airflow and fuel rates. This indicates that some form of fuel-oxidant premixing may occur in the cavity, even while the flameless combustion mode [102,103] can be combined with trapped vortex combustion.

The mass injection can change the dynamic characteristics of the flow inside and around the cavity dramatically. This is numerically demonstrated [35,36] by using a third-order accurate, time-dependent CFD with chemistry code. The dynamic flow associated with an axisymmetric, center-body TVC was studied under both non-reacting and reacting conditions. The effect of mass injection in the cavity on pressure coefficient was summarized in Fig. 20. It is shown that the pressure coefficient is decreased with the injection mass. And the pressure coefficient for 180% injection becomes nearly steady. However, the frequency of the oscillations is decreased with injection mass. It was also found that the mass injection can increase the optimum cavity size (width-to-diameter ratio). As a small amount of fluid (< 50% with respect to the primary fuel and air injection) was injected into a non-optimum cavity, the flow unsteadiness was increased as shown in Fig. 20. The simulations also revealed that a thinner after-body can lead to the cavity flow being more dynamic.

The fuel-air momentum ratio is found to play a critical role on influencing the mixing and vortex structure in a cavity. This is experimentally illustrated by conducting both PLIF (planar laser induced fluorescence) [104,105] and PIV (particle image velocimetry) optical diagnostic measurements on a single cavity TVC [66]. It was found [66] that the fuel-air mixing in the cavity is enhanced as the momentum flux ratio (MFR) is decreased as shown in Fig. 21(a) and (c). This is most likely due to a favorable vortex being formed in the cavity. Comparing the scalar dissipation rates of mixture fraction with the vorticity contours revealed that a good agreement was obtained as shown in Fig. 21(b) and (d). The regions of the maximum mixing are

Fig. 20. Effect of mass injection on pressure coefficient C_p . Reprinted from [35] with permission of the American Institute of Aeronautics and Astronautics (AIAA) Inc.

observed to be along the fuel-air interface. Reacting flow PIV measurements showed that the vortex was displaced from the center of the cavity towards the guide vane. In general, the detailed measurements showed interesting features of the flow including the presence of a dual cavity structure. A better understanding of the underlying physics of the cavity flow was obtained to highlight the importance of the fuel-air momentum ratio parameter as shown in Fig. 21.

Entrainment of the main flow into the cavity was found to be a minimum in the absence of air or fuel jets, as a large, stable vortex is trapped within the cavity with an optimal width-to-depth ratio. This is confirmed by direct numerical simulations (DNS) [62] of reacting and non-reacting flows over a cavity. When air was directly injected into the cavity to drive the flow, stabilizing the vortex needs to be achieved by a larger cavity width-to-depth ratio. Similar findings were obtained for reacting flow cases [35,36]. Indirect measurements of the entrainment of cross-flow into the cavity of a subsonic TVC revealed that the entrainment of air into or out of the cavity was determined indirectly from CO emissions and LBO (lean blow-out) measurements. For high momentum ratios (i.e. ratio of cavity momentum to mainstream momentum ≈ 1) a maximum entrainment (i.e. $\sim 40\%$) was observed for a cavity length to depth ratio equal to 0.55. However, for low momentum ratios, minimum entrainment of the main flow into the cavity (i.e. $\sim 4\%$) was observed for the cavity length to depth ratios of 0.55–0.90.

Direct measurements of mixing and mass transport in a TVC are typically conducted by using PLIF [106–108]. The acetone PLIF measurements [109] was performed to quantify mixing in non-reacting flows, where the gas phase composition was within the flammability limits. Similar PLIF measurements [110] were applied to study scalar dissipation rates in turbulent opposed flows and jets. How to achieve good mixing between the cavity products and the mainstream flow is a major challenge for TVC design. A passive mixing enhancement approach was proposed in Ref. [32]. Inclined struts along with a flow guide wave as shown in Fig. 22(a) were designed and tested on a TVC operated at an atmospheric pressure condition. The measured flame images are shown in Fig. 22(b)–(e). Excellent mixing is found. And a small flame length, low pressure drop (in the range of 0.35), and low NO_x emission (1–3 ppm) are achieved. The flame stability is excellent, and combustion efficiency is reasonable in the range of 96%. The mixing improvement is due to a counter-clockwise cavity vortex resulting from the flow guide vane. The vortex is conducive to the mixing with the mainstream flow due to the rise of cavity combustion products along the inclined struts.

One of the common fuel injection schemes applied in supersonic combustors is to inject fuels upstream from the wall of the cavity flame-holder [23]. Furthermore, shock waves are generated at supersonic or hypersonic flight conditions, which affect the flow field around the cavity and the behavior of the shear layer over the cavity. The effects of shockwaves on fuel-air mixing and combustion dynamics in the supersonic cavity flame holder ($M_a = 3$) are numerically and experimentally studied [111]. A shock wave impinging near the fuel injection leads to the shear layer into the cavity flow and may quench combustion in the wake of the fuel jet due to the increased fuel concentration within the cavity. However, a shock wave impinging over the cavity gives rise to greatly enhanced mixing and stronger combustion in the cavity. This is due to the shear layer being lifted until interacting with the incident shock wave and reattaching at the rear section of the cavity.

3.3. Emissions and combustion of alternative fuels

Another attractive feature of TVC is that different types of fuels such as syngas and methane in either liquid and gas phase can be applied [112]. For conventional combustion systems, it is difficult to burn syngas, because of its varying compositions and considerably

Fig. 21. (a, c) Comparison of mean mixture fraction contours for syngas cases 1a and 3a (b, d) vorticity contours for syngas cases 1a and 3a. Reprinted from [66] with permission of Elsevier.

low calorific values. CFD studies on fuel flexibility were performed [112] to evaluate the combustion performance and emissions from a syngas-fueled TVC as shown in Fig. 23(a). Here natural gas fuel (methane) is replaced with renewable and

alternative fuels such as hydrogen and synthetic gas (syngas). The flame temperature, the flow field, and species concentrations inside the TVC were obtained as shown in Fig. 23(b)–(d). Hydrogen enriched hydrocarbon fuels combustion (see Fig. 23(b)) was shown to produce more energy, a higher temperature (14% increase when methane is replaced with methane/hydrogen mixture with 75% hydrogen fraction). The NO_x emission is increased, as the fraction of hydrogen is increased for methane/hydrogen fuel mixture (see Fig. 23(d)). The flame for methane combustion (see Fig. 23(c)) was found in the primary vortex region. However it was shifted to the secondary vortex region for hydrogen combustion.

OH species concentration in a cavity of a TVC burning syngas was measured by using PLIF. Comparison is then performed between Syngas and methane in terms of mixing and flame stabilization [113,114], as shown in Fig. 24(a) and (b) respectively. The momentum flux ratio (MFR) is found to be a critical parameter governing the combustion process and the mixture formation. At high MFR, the combustion is restricted to a mixing layer flame at the interface of the fuel and air in the cavity like in a jet diffusion flame. The syngas addition in the mainstream does not change the MFR dramatically in the cavity. Thus the flame location and extent look quite similar. This indicates that the combustor can be operated stably in the absence of syngas addition in the mainstream, and all fuel can be injected into the cavity. For methane, the mechanism of mixing is different from that of syngas due to the much lower MFRs. And the flame stabilization mechanism (see Fig. 24(c) and (d)) is different from that of syngas. The methane and syngas combustion in the TVC with the flow guide vane are found to be different in terms of the flow structure, flame location and fuel-air mixing patterns. However, these phenomena are shown to be dominated by the MFR and the local cavity equivalence ratio.

In addition to the premixed and non-premixed combustion modes as discuss above, TVC can also be operated in the rich-burn,

Fig. 22. (a) Schematic of the inclined struts with the flow guide vane in TVC, (b)–(e) experimental flame images for four TVC cases with inclined struts (30% main area blockage) and the flow guide vane. Flow conditions are maintained same for all cases at $V_{ma} = 20$ m/s, $V_{ca} = 0.0$, $\Phi_{main} = 0.3$ and $\Phi_{overall} = 0.45$. (b) 4 struts, $L/D = 1$, (c) 6 struts $L/D = 1$, (d) 4 struts, $L/D = 0.8$ and (e) 4 struts, $L/D = 1.2$. Reprinted from [32] with permission of Taylor & Francis.

Fig. 23. (a) Trapped vortex combustor and fuel and air injection system, (b)–(d) OH contours at the fuel composition are varied. Reprinted from [112] with permission of Elsevier.

quick-mix, lean-burn (RQL) combustion mode or some hybrid approach between premixed, diffusion and RQL. This enables TVC being more fuel-flexible such as natural gas [58] and minimum NOx generation from fuel-bound nitrogen.

3.4. Aeroacoustics characteristics

When air stream flows over cavities, intense self-sustained acoustic oscillations may occur under certain conditions [101]. If the oscillations are coupled with the resonance of the engine structure, this may result in a catastrophic failure [115]. Cavity is assumed to be open, when reattachment occurs near the cavity's trailing edge. However, when the reattachment point is located on the cavity's bottom, it is considered to be closed. For the closed cavities, acoustic fluctuations are associated with a broadband frequency spectrum. However, open cavities selectively amplify a number of acoustic tones, as typically found in cavity combustors. Those acoustic tones may be generated as normal resonance phenomena or an acoustic feedback loop. Normal resonance occurs, when the free stream Mach number is below 0.2 [116]. The open- or closed-cavity flow characteristics were shown to be altered by imposing micro-jet air flow [117].

When high Mach number air flows over a cavity, the acoustic feedback mechanism [118] is schematically illustrated in Fig. 25. The faster grazing flow passing over the slower recirculation in the cavity gives rise to Kelvin-Helmholtz oscillations in the shear layer. The shear layer then leads to vortices. Instability is created by the interaction of the shear layer and unsteadiness in the cavity [119]. The phishing shear layer is pulsed arrives at the trailing edge of the cavity. This implies the development of a region of high pressure next to another low pressure, which leads to an acoustic dipole. The radiated acoustic waves propagating upstream disturb the shear layer at the leading edge of the cavity. This in turn causes additional vortex shedding. The feedback loop resulting from vortex-acoustics interaction may selectively amplify a dominant frequency [118].

A formula to predict the acoustic resonant frequency was proposed about 50 years ago [120]. The empirical constants involved in the formula need to be modified, if an influence of an opposing wall is considered. Recently, unsteady RANS simulations were conducted [119] to improve the formula proposed in Ref. [120]. This was done by replacing the empirical constant (vortex velocity to the free stream velocity) by vortex velocities extracted from numerical results. The equation provides reasonable estimates of the acoustic resonant frequencies, which agree well with the experimental

Fig. 24. (a)–(b) OH (ppm) contours for syngas cases M1P–M6P, (c)–(d) OH (ppm) contours for methane cases. (a) and (c) without premixing, (b) and (d) with premixing. Reprinted from [113] with permission of Taylor & Francis.

Fig. 25. Features of cavity flow instability, instantaneous vorticity contours for wake mode at 3 different times. Adapted from [118] with permission of Dr. B.F. Kutlu, B. H. Saracoglu, G. Paniagua and J. Kapat.

measurements, especially at high Mach numbers [30]. To study unsteady reacting cavity flow in a TVC, KIVA-3 V [65], a numerical tool was applied. Unsteady Reynolds-averaged Navier–Stokes equations were solved with k - ϵ turbulence model and a modified eddy dissipation concept. It was found [65] that the cavity depth mode acoustic resonances are predominant over the shear layer resonances [120] in the expected combustor-operating range. This implies that resonant frequencies do not depend on the flow velocity or cavity length, but depend on the cavity depth. The cavity air and fuel injection seems to have no effect on the resonant frequencies. This further confirms the depth-mode resonance. Acoustic power is found to increase with the cavity injection. An extended literature review [121] was performed to summarize some recent advances in simulations, modeling, and control of flow/acoustics resonances in

flows over open cavities. Flow-excited acoustic resonance in deep cavity was analytically modeled [122]. Experimentally measured values were used for the vortex convection velocity and phase to calculate the amplitude of the oscillation and frequency ratio. It was concluded that the model provides good predictions. Flow-excited acoustic resonance in a shallow cavity was also studied [123]. It was demonstrated that there was a significant change in the acoustic feedback mechanism and amplification of the induced fluctuations by the pressure of the closed cavity.

Aeroacoustics signature of a combustor/reacting TVC was experimentally measured [124], as shown in Fig. 26. The measurements as shown in Fig. 26(a) and (b) indicate that the OASPL (overall sound pressure level) is increased with the primary air velocity and cavity equivalence ratio (Φ_c).

Fig. 26. Variation of overall sound pressure level with (a) primary air flow velocity, (b) momentum flux ratio (MFR) at 3 different Reynolds numbers. Reprinted from [124] with permission of Elsevier.

4. Derived concepts of trapped vortex combustor

Next-generation gas turbine engines [125–127] are expected to perform better than conventional engines [85,102] in many aspects. For example, advanced/future combustors are much shorter and utilize non-metallic materials to meet the demand of required thrust-to-weight ratio. The compact combustors are associated with a higher temperature gradient [39], a shorter residence time [23], which is beneficial in reducing the NO_x emissions. However, unburned hydrogen-carbon (UHC) and CO emissions may increase due to inadequate reaction time. In addition, the partially-reacted fuel could escape the shorter combustion chamber. And the mixture may continue to burn in the turbine stages, which could pose a series of rotating component challenges such as not rotating vane and blade durability, and increased pressure loss. To meet the conflicting challenges and requirements, trapped vortex combustion concept can be modified and applied.

4.1. Ultra-compact cavity combustor

One configuration of a more aggressive trapped vortex combustor designs is known as ultra-compact combustor (UCC) [128,129]. This novel design of UCC is to meet the challenges of improved engine durability, higher peak temperatures, higher compression ratio, and reduced weight with lower emissions. Intensive research and development on UCC are underway [130,131]. There are two main objectives: (1) how to achieve effective stabilization of the primary reaction zone in the circumferential cavity, (2) how to effectively migrate the primary zone products back into the core to present flow to the high-pressure turbine consistent with traditional combustor design. To achieve those objectives, two different configurations of ultra-compact combustors have proposed as shown Fig. 27(a) and (b) respectively.

The first configuration is TVC-based UCC design (see Fig. 27(a)). It is axisymmetric and involves sustaining cavity rotation in the same plane as the core flow. The cavity vortex is stabilized in the presence of opposing jets of air and fuel [133,134]. Its size is such that migration from the cavity occurs smoothly in the absence of additional entrainments from the upstream core. The second configuration is also known as high-g combustor, as shown in Fig. 27(b). Air is injected into the circumferential cavity with a tangential component. Thus a second regime of bulk fluid movement is induced around the engine centerline. The exhaust emissions and temperature from such high-g combustor at varying operating conditions are quantified and measured [135]. Experimental study of a high g-loaded combustion system has been successfully conducted in Ref. [130]. The experimental results confirm that this type of high-g

loaded system has great potential to be used as an ultra-compact combustor for a main burner, or as an inter-turbine burner (ITB) [136,137].

To compare the UCC design as shown in Fig. 28(b), a segment of a conventional annular combustor is illustrated in Fig. 28(a). Air enters the combustion chamber through dome swirlers and liner holes. The air is used for mixing and cooling. In the conventional design, the residence time in the combustor depends on its axial length. Thus the engine should be long enough to achieve complete combustion. The fuel-air mixture is burned, and then exits the combustor. The hot combustion product is then convected to turbine inlet guide vanes. The vanes redirect the flow at the correct angle at the high pressure turbine rotor. In a typical engine system, the air exiting the compressor is decelerated and de-swirled, before entering the combustion system plenum. The air is then locally re-swirled in the combustor to improve mixing and flame stabilization. Then the flow is turned once again and accelerated before entering the turbine. Each of these processes takes place in the engine axial direction. However, in the UCC design/concept, a cavity runs around the outer circumference of the extended turbine inlet guide vanes [138–140], as shown in Fig. 28(b).

Fuel is injected into this UCC cavity. Beside the cavity, there is a radial cavity that extends to the inner platform on each vane. The main objective is to burn rich in the circumferential cavity. This provides much of the required combustion residence time to take place in the circumferential direction of the engine, rather than axial as is designed conventionally. The flow within this cavity is swirled to produce high-g loading and to enhance fuel-air mixing. Flame stabilization is achieved as hot combustion products are recirculated inside the cavity. The intermediate combustion products are transported via wakes into the radial cavities in the vane surfaces. Here combustion continues at a reduced equivalence ratio, since the mainstream air is entrained into the wakes. Finally there may be a minimum blockage flame, where combustion products are entrained and distributed into the main flow.

The main findings obtained from the previous studies [138–141] on the UCC are summarized as:

- 1) Excellent lean-blow out (LBO) performance.
- 2) Higher combustion efficiencies over a wide operating range.
- 3) Higher heat release rate in comparison with conventional combustors by up to 200%.
- 4) Stable, efficient operation at 200–300% higher loading than for conventional combustors.
- 5) The radial-vane cavity effectively transports the mixture from the cavity to the main flow.

Fig. 27. Illustration of conceptual differences between trapped vortex UCC and high-g designs. Adapted from [132] with permission of the American Institute of Aeronautics and Astronautics (AIAA) Inc.

Fig. 28. (a) Conventional combustion system and (b) ultra-compact Combustor (UCC) concept [140]. Courtesy of Dr. J. Zelina.

- 6) Short combustion lengths in comparison with conventional combustors operating at similar conditions.
- 7) Pressure effects enable the combustion efficiency being improved for a given configuration. However, it has little impact on the lean-blowout (LBO) performance.
- 8) The unreacted mixture transport into the main airflow is a strong function of air injection and cavity g-loading. Increased g-loads create a centrifugal effect in the cavity, keeping the unreacted mixture toward the cavity outside diameter. However, a limit is reached where flame extinction occurs in the cavity, due to high velocities that are unable to sustain the flame. Therefore a window of optimal g-loading seems to be 500–3500 g.

A further development of the UCC concept is denoted by the cavity-inside-cavity (CIC) design [37]. Its main idea is to introduce a second cavity, channeled inside the primary one. All fuel needed is injected through the secondary cavity. Additional air is also injected

in the CIC to increase fuel-air mixing and to create a stable vortex inside the cavity. This is the basic concept of such CIC burner.

4.2. High-g cavity combustor

High-g combustors [142,143] are proposed and designed as an alternative configuration of UCC due to the potential benefits of combustion at high-g loading. The flame speeds were found [144] to increase across a range of g-load from 500 to 3500 g. And the combustion efficiency was increased, as shown in Fig. 29(a). To explain this behavior, a 'bubble transport hypotheses' was developed and validated [144]. It stated that buoyant bubbles of reacting mixture were accelerated beyond the local flame front by the increased density gradients induced by the g-load. The bubble S_b (burning velocity) was further shown to be related to the g-load on the fluid by $S_b = 1.25g^{0.5}$. Observed flame propagation then progressed at the greater of either the turbulent flame speed or the bubble velocity. Recent numerical simulation [145] showed that good agreement

Fig. 29. (a) Variation of combustion efficiency with cavity g-loading, (b) variation of lean blowout OFAR with cavity g-loading [140]. Courtesy of Dr. J. Zelina.

Fig. 30. UCC (ultra-compact combustor) designed in Air Force Institute of Technology with common-source diffuser, side cutway (top) and front detail with diffuser outer and middle pieces removed (bottom). Reprinted from [132] with permission of the American Society of Mechanical Engineers (ASME).

was obtained. The propagation mechanism was shown to be primarily Rayleigh-Taylor instability with turbulent flame speed and thermal expansion.

The high-g combustor as shown in Fig. 30 is designed by using high swirl in a circumferential cavity to enhance reaction rates via high cavity g-loading on the order of 3000 g's [126,140]. Increase in reaction rates indicates that the combustor volume can be dramatically reduced. Experimental results have shown promise of high-g combustor for future engine applications. Lean blowout (LBO) fuel-air limits at 25–50% the value of current systems were demonstrated as shown in Fig. 29(b). Combustion efficiency was measured over a wide range of high-g combustor operating conditions as shown in Fig. 29(a). The results confirmed the attractive features of high-g cavity combustion.

The previous and on-going researches on high-g cavity-based combustion systems reveal:

- 1) Shorter combustion lengths approximately at 50% of conventional combustors operating at similar conditions.
- 2) Excellent LBO performance. The high-g combustor is about 200–400% that of conventional combustors while still maintaining the same or lower LBO levels. For some configurations, LBO does not depend on combustor loading parameter.
- 3) A trade exists between the cavity extraction via radial vane cavities which affect temperature distribution, LBO and combustion efficiency.
- 4) Unreacted mixture transport into the main airflow depends strongly on air injection and cavity g-loading.
- 5) Increased g-loads create a centrifugal effect in the cavity, keeping un-reacted mixture toward the cavity OD (outer diameter). However, a limit is reached where flame extinction occurs in the cavity due to high velocities which are unable to sustain the

flame. Therefore a window of optimal g-loading appears to be 500–3500 g's.

- 6) Higher g-loads result in efficiency degradation.
- 7) Pressure has little effect on the LBO performance but improves the combustion efficiency for a given configuration.
- 8) Future research is needed to better understand proper film-cooling [146] hole geometry and placement of coolant on the hybrid vane of a high-g combustor. A number of film-geometries are investigated by Johnson et al [140] such as fan-shaped holes, laid-back holes, trenches, and ramps.

In general, understanding and developing TVC-based ultra-compact [139,141] and high-g combustors are critical for turbine-burner research and development in that they provide insights about flame-holding and combustion in high accelerating (radial) flows.

4.3. Inter-turbine burner (ITB)

With cavity flame-holding capacity, the continuous-turbine-burner (CTB) concept was proposed as an augmentative combustor at UC Irvine [147]. In such burners, combustion continues in the stator and rotor. Thermodynamic analysis [148] showed that applying CTB in ground-based engines and aircraft turbojet engines gives rise to improvement on power/weight and combustion efficiencies. To avoid complications with burning in a stator or rotor stage, the inter-turbine-burner (ITB) concept is proposed [148]. CTB can be assumed to consist of N -stage ITB, as N is infinitely large. There are various options to choose the combustion chamber. One option is to take advantage of the transition duct between the low- and high-pressure turbine stages. Another option is to utilize the turbine stator (nozzle) passages. However, this option is associated with the challenge of significant acceleration of the flow in the presence of mixing and reacting. Another option is to use both the transition duct and the first stator (turbine nozzle) in the low-pressure turbine. This enables the combustion processes beginning in the transition duct but extending into the stators. All these options require combustors to be more compact, i.e. a smaller size, with decreased residence time.

To improve part-power performance of turbine engines, the US Department of Defense (DOD) supported 3 projects, aimed to develop and demonstrate ITB technology on gas turbine engines [147,148]. One project conducted by Creare, Inc. is to perform cycle analyses to examine the potential benefit of ITB. Another project conducted by Spytek Aerospace Corporation is to implement an ITB to existing engines. Emphasis is placed on how to provide air into the primary combustion zone of the ITB and to successfully entrain the combustion products into the main flow. The final project is to provide detailed ITB designs and their integration into small turbine engines. This research is conducted jointly by Honeywell Aircraft Engines and Advanced Products Research, Inc., which has prior experience with trapped vortex combustors. Preliminary results showed that implementing ITB can lead to part-power fuel efficiency being increased by 7 to 17%. These projects demonstrate the growing feasibility of employing ITB to achieve the design of more compact and efficient engines. However, detailed information of these studies were not fully documented due to the commercial nature.

4.3.1. T -s cycle analysis of ITB

Temperature-entropy cycle analysis is conducted to gain insight on the ITB and CTB performances. Fig. 31 shows the concept for ITB (inter-turbine burner). There may be 1, 2, or N such ITB as shown in Fig. 31(a) and (b). Clearly, as N goes to infinity, the N -ITB cycle approaches the CTB cycle [148]. In the ideal application of ITB, combustion occurs in both the stator and rotor regimes of each stage. Temperature remains constant through all stages, while additional thermal energy balances the rates for energy conversion to kinetic

Fig. 31. T-s (temperature-entropy) cycle analysis: (a) 1-ITB, (b) N-ITB. Adapted from [148] with permission of Dr. F Liu and WA Sirignano.

energy and mechanical work. One application of ITB in practice is that combustion is present between consecutive turbine stages. Fuel injection and burning between stages leads to a monotonically increasing temperature in that portion, immediately followed by a sharp temperature decrease through the turbine stage. The sharp temperature drop occurs at constant or near constant entropy. This enables thermal energy being converted to mechanical work in the turbine stage (nozzle or rotor). Another application of ITB is that the combustion can occur within the nozzle. Thermal energy is increased, and part of it is converted to kinetic energy. The temperature is then decreased dramatically in the downstream region of the stator and the rotor. Here, thermal energy is again converted to kinetic one. And the kinetic energy is finally converted to mechanical work. Any application of ITBs will lead to a more compact engine with a smaller size and less weight.

The performance improvement by implementing ITB in comparison with conventional gas turbine engines is clearly confirmed in Fig. 32. The results are obtained by conducting temperature-entropy (T-s) cycle analysis [148]. The specific thrust and TSFC (thrust specific fuel consumption) are dramatically increased.

In spite of the attractive features of ITBs, there are many challenges that need to address the combustion within the turbine stage and the stator passage. For example (1) how to ignite in a high-acceleration flow; (2) how to achieve effective flame-holding in a high-acceleration flow; (3) how to completely vaporize liquid fuel for complete mixing and combustion within a short residence time; (4)

how to achieve hydrodynamic stability of a stratified flow with a large turning acceleration; (5) how to meet the increased demands for rotors and stators cooling; and (6) how to maintain an acceptable loading of aerodynamic forces on the rotor blades.

4.3.2. ITB in a turning or converging channel

These challenges associated with the development and application of ITB in subsonic and supersonic engine systems intrigues intensive experiment and numerical research. For example, experiments were conducted at UC Irvine [147,148] in a high-speed subsonic combustion rig with optical windows for laser diagnostic measurement. The photos of the cavity combustion are shown in Fig. 33(a)–(c).

The qualitative behaviors for liquid-fuel combustion as shown in Fig. 33(d) were found to be quite similar to those of gaseous fuel, as the experimental setup reached thermal equilibrium. The combustion was more vigorous. However, as fuel flow rate is increased dramatically, combustion can not be sustained. However, for most of the conditions described in the operational map, liquid-fuel combustion was achieved. The temperature profile across the cavity is shown in Fig. 33(e). Details measurements including non-reacting flow and reacting cases (combustion test) with gaseous and liquid fuels supplied are available in Refs [140,149]. It is found that (1) there are two distinct combustion zones; the shear layer and the cavity. (2) The cavity behaves like a stirred reactor and the shear layer behaves like a diffusion flame. (3) The mixing time scales

Fig. 32. Performances of turbofan engines as a function of fan bypass ratio: (a) specific thrust, (b) thrust specific fuel consumption. Reprinted from [148] with permission of Dr. F. Liu and W. A. Sirignano.

Fig. 33. (a)–(c) Three regimes of cavity-stabilized (trapped vortex) combustion, (d) liquid-fuel combustion at $Re = 40,000$, (e) temperature profile across the cavity. Reprinted from [148] with permission of Dr. F. Liu and W. A. Sirignano.

determine the division of overall combustion between the cavity and the shear layer. (4) The temperature pattern at the exit shows that the mixing of burned gases and the main air flow is more efficient in the shallow-cavity case in comparison with the deep-cavity case. These findings are confirmed with the numerical studies of cavity-driven reacting flows.

The effect of curvature on flame-anchoring as expected in ITB is experimentally studied [148,149], as shown in Fig. 33(a). Two test sections are designed. Both tested sections share the same channel curvature and contraction characteristics. The cavity dimensions and axial locations are exactly the same. The only difference of these two sections was the radial location of the cavity. One test rig had the cavity on the channel's inner wall of, while the other test rig had the cavity on the channel's outer wall. The cavity depth is variable to create deep (5 cm) or shallow (2 cm) cavity. For each setup, two cavity aspect ratios ($L/D = 1$ and 2.5) were studied. The fuel such as propane and liquid n-heptane in liquid and gaseous was injected at different places to find the optimum injection location. The injection location was found to affect the absolute values of temperatures and burning efficiency, but the qualitative behavior of the flame-holding was not affected. Flame blowout investigations [150] were also conducted, as the fuel and air flow rates were varied over a wide range. This is achieved by keeping the fuel flow rate constant and the air-flow rate increased from zero to blowout. The blowout tests showed that the cavity combustion went through 3 distinct regimes as shown in Fig 33(a)–(c). This behavior was found to occur in both test sections with both shallow and deep-cavity configuration for gaseous fuels.

To analyze flame-anchoring mechanisms, CH^* chemiluminescence investigation was by conducted via using a charge-coupled-device sensor on a camera with a narrowband filter 431 ± 10 nm. In

addition, a high-speed camera was applied to capture flame images. The bright areas in Fig. 34 denote the areas of combustion. It can be seen that combustion takes place in both the shear layer and the cavity. It is also found that the flame in the shear layer is anchored at the cavity's upstream edge. And the shear layer is linearly expanding. However, the cavity where the combustion occurs is almost uniform.

The series of experimental studies [147,148] reveal that:

- 1) The combustion is associate with a diffusion flame at low Reynolds numbers, when it was confined to the shear layer.
- 2) In the presence of a combustion inside the cavity, the measured temperature profile inside the cavity is almost uniform, except near the walls. This mimics a well-stirred reactor.
- 3) If the equivalence ratio of the fuel-air mixture was within the flammability limit, combustion occurred. It was initiated by the strong heat transferred from the shear layer via convection and radiation.
- 4) When Reynolds numbers is large, the percentage of combustion in the shear layer is decreased, while the percentage of cavity combustion is increased. This is confirmed by the change in relative intensities of the cavity combustion and the shear layer as shown in the narrowband-filtered images.

To simulate the experiments, numerical simulations are performed on high-speed, accelerating and turbulent turning flows of the ITB with and without cross-sectional-area change. This include (1) 2D non-reacting flow past a cavity, (2) 2D reacting flow past a cavity, (3) 3D reacting flow past a cavity, (4) 2D combustng flow past a cavity in a turning channel, (5) 2D combustng flow past a cavity in a converging channel, (6) 2D combustng flow past a cavity in a

Fig. 34. Averaged CH^* chemiluminescence: (a) deep cavity, (b) shallow cavity. Framing rate is 5000 fps. Reprinted from [148] with permission of Dr. W. A. Sirignano, D. Dunn-Rankin, F. Liu, B. Colcord and S. Puranam.

turning and converging channel [151,152]. The aim is to better understand the effects of turning flow, streamwise acceleration and a cavity on mixing, and the effects of fuel injection into the cavity on flame holding and fuel-air mixing. Fig. 35 shows the density and reaction-rate contours for the converging and turning cases.

High-reaction-rate is found to be much smaller in the turning/converging channel than the non-converging/turning channel. The high reaction rate region is downstream of the cavity. Finally, the less than 1% stagnation pressure losses confirm the merits of the ITB concept. The experimental and numerical results reveal that Kelvin-Helmholtz instability is always present in any channel-cavity flow. The centrifugal instability is related to Rayleigh's circulation criterion for stability: Rayleigh-Taylor instability is found to be present only in the curved channel configurations. Here gravitational forces

can be neglected. Since the combustion products are less dense but the fuel is denser than the flowing air in the channel, it is difficult to predict whether the Rayleigh-Taylor instability will be destabilizing or stabilizing. The density in the cavity is shown to be affected by the fuel injection configuration. As parallel injection is adopted, high-density fluid is injected at the cavity's upstream wall. And low-density combustion products fill most of the cavity. This makes the case with the cavity on the outside more susceptible to Rayleigh-Taylor instabilities.

4.4. In-Situ combustor

In order to achieve increased power output and cycle efficiency, with possibly reduced combustion emissions, a so-called in-situ

Fig. 35. (a) density contours for turning channels with disrupting injection, (b) density contours for turning channels with parallel injection, (c)-(d) reaction-rate contours for turning/converging channels. Reprinted from [139] with permission of Dr. F. Liu and W. A. Sirignano.

Fig. 36. Comparison of conventional (a) and in-situ reheat (b) combustor structures [153]. Courtesy of R. A. Newby.

reheat combustor (fuel injection via airfoil injection) was proposed and developed by Siemens Westinghouse Power Corporation [153]. The main objective is to develop a gas reheat concept applicable for gas turbines, in which fuel is added via one or more stages of blades and vanes. The fundamental idea is to inject enough fuel at the vane trailing edge to increase the temperature of the working medium. This kind of combustor has a similar application as ITB (inter-turbine burner). The ITB concept can be considered partly as a reheat strategy. However, an in-situ reheat burner is fully integrated into the flow configuration. The in-situ reheat process is similar to the sequential combustion reheat. In in-situ reheat combustor [154], fuel is injected through the high-pressure turbine stage airfoils instead of reheat combustor baskets, with reheat-combustion proceeding in the wakes of the airfoils. The reheat combustor basket applied with sequential combustion reheat is replaced by an ‘in-situ combustor’ representing the flow path between the blade and the vane. A schematic comparison of the turbine layouts with sequential combustion reheat and with in-situ reheat is shown in Fig. 36. It is conceptualized that the in-situ reheat combustor may be lower in cost, more compact and have a lower pressure drop than the sequential combustion reheat combustor. The in-situ combustors achieving low NO_x emissions have been conceived. However, they are still under development and tests. Numerical simulations were setup to estimate the performance of the in situ reheat cycles at turbine off-design conditions

4.5. Flameless TVC reheat combustor

As a valuable and promising candidate for a next-generation gas turbine engine combustion system, a flameless TVC Reheat Combustor (FTVCRC) [102,103] as shown in Fig. 37(a) and (b) is proposed and tested. FTVCRC combines the two recently developed combustion concepts: (1) the flameless combustion and (2) the trapped vortex combustion, as shown in Fig. 37(d)–(e). The former provides a promising combustion technology, flameless oxidation. Implementing the flameless combustion concept in furnaces indicates that it

has great potential to be applied in gas turbine engines for generating very low combustion noise, a uniform temperature distribution and negligibly small emission of NO_x and CO. The latter adopts the concept of stabilizing combustion in a small volume and at high flow rates. Thus FTVCRC can deliver multiple benefits, including environmental, economic and operational advantages. The main features of FTVCRC include higher efficiency, lower chemical and acoustic emissions, more reliable operation and extended life time of mechanical components [102,103].

Flameless combustion phenomenon was first observed in Ref. [155] from the experimental tests with a self-recuperative burner. It was shown that (1) the combustion was stable and very quiet; (2) no UV-signal, no UHC and NO could be detected; (3) CO emission was below 1 ppm; (4) no flame could be observed. These features characterize such flameless combustion, which is a new technology. It forms nearly invisible flames with a uniformly distributed combustion and temperature, producing very low combustion noise. It is also known as flameless oxidation [155], high temperature air combustion [156,157], moderate and intense low oxygen dilution (MILD) combustion [158,159] and heat recirculating combustion [156]. Following the previous study [155], extensive researches on flameless combustion were then conducted. To generate flameless combustion, low amount of fuel needs to react with a very high temperature oxidizer with intensified turbulence for rapid mixing. It is found that the high air temperature is effective on increasing the burning rate [157], thus allowing self-ignition. High temperature air combustion is found to reduce combustion noise, improve thermal field uniformity and flame stability, and generate lower peak temperature and smaller temperature gradients relative to air-diluted combustion.

Application of such a flameless combustion (FC) concept in industrial furnaces was attempted. The successful application encourages FC applications in other fields, such as land-based gas turbine engines for power generation. Flamme [160] worked on an EC funded project to develop FC burner technology, which can be operated under gas turbine conditions. It was found that at atmospheric conditions with a pressure loss less than 5%, both the acoustic and pollutant emissions levels from multiple FC burners are extremely low. Based on the previous numerical and experimental studies, it was proposed that there were 2 main requirements for generating flameless mode in gas turbine engines [102,103]. One is that the local turbulence should be intensified enough to achieve distributed reaction, i.e. the eddies are smaller than the reacting layer. The second is that after mixing with the exhaust gases, the mixture ignites before leaving the combustor, i.e. the ignition time delay of the mixture is shorter than residence time.

FTVRB involves the advantages of enhanced stability and reliability, low combustion noise, low emissions, uniform temperature distribution, improved pattern factor, and high efficiency. However, one of the main drawbacks of FTVRB is that it is found to be more susceptible to combustion instability. The experimental tests revealed that the cavity pilot flame was more susceptible to the onset of combustion-driven oscillations [3, 9–11] in pressure and heat release at certain operating conditions, as shown in Fig. 38. For a swirl ratio with high oscillation amplitudes, modal analysis confirmed that the combustion system is linearly unstable. To suppress such combustion instability, a phase-shift controller can be applied [102,103].

5. Various industry applications

In recent years, cavity flame holders as an integrated fuel injection/flame-holding approach have been proposed as a promising concept for flame-holding and stabilization in various industries such as power generation and waste incineration and aerospace.

Fig. 37. (a) cross-sectional sketch of the FTVRB combustor cavity, (b) view from upstream into the cavity with center body, star body and flaps, (c) radial view into cavity: no direct air injection into the cavity. Main flow in upward direction, (d) upstream view: no direct air injection into the cavity, (e) radial view into cavity: Tangential air = 30 kg/h, $\Phi_{\text{cavity}} = 0.83$. Main flow in upward direction. (f) Upstream view: Tangential air = 30 kg/h, $\Phi_{\text{cavity}} = 0.83$. Reprinted from [102] with permission of Dr. E. Gutmark.

5.1. Aerospace application

One of the practical applications of trapped vortex combustion concept is to design a cavity flame holder to power a propulsion system in Aerospace industry. These propulsion systems include ramjets and scramjets and aero-engines.

5.1.1. Ramjets

Ramjets [78,84] are typically referred to a group of air-breathing jet engine that uses the engine's forward motion to compress incoming air without an axial compressor. They are different from supersonic combustion ramjets (scramjets). As the engines are moving forward, incoming air entering the engine inlet is compressed, then mixed with the fuel and burned in the combustor. Unlike conventional combustors implemented in gas turbine engines where a swirl stabilizer is applied to provide circulation zones by utilizing swirling flow, ramjets take advantage of flame holders such as bluff bodies [161] or sudden expansions, as shown in Fig. 39. These geometric structures can create recirculation zones with relatively low flow speeds for fuel-air mixing and flame stabilization [162].

The design of backward facing step or sudden expansion for flame stabilization is widely applied in solid fuel ramjets due to its simplicity for solid fuel grain assembly. The sudden change of cross-sectional area enables the recirculation zones being formed downstream the step, where the fuel-air mixing and stable combustion

could occur. Using bluff bodies for flame stabilization in ramjets was well reviewed in Ref. [162]. The effects of various parameters in the design of bluff bodies and flow conditions on stabilizing flame, such as the bluff body's configurations, pressure, temperature, and the fuel-air mixture composition were discussed. Experimental study was conducted to shed lights on the flame-stabilizing performance of applying baffles in high-speed flow streams [163]. The effects of the baffle shapes and diameters, the flow speed, pressure, and temperature were examined. It is shown that a higher inlet temperature helps widening the limit of burning. However, the inlet pressure has little effect on the stability range. It is also found that large bluff bodies applied in ramjet combustors are more effective on stabilizing the flame at high-speed flows. However, these larger flame holders have a larger blockage ratio and associated with larger drag and total pressure loss than the small bluff bodies. In 1980s, the barchan dune (BD) vortex flame holder was proposed [164]. Compared with conventional V-gutter flame holders, the BD-type ones can dramatically reduce drag and increase the flame stability limit. However, the main challenge in applying BD-type flame holder is how to maintain the complicated curve configurations in extremely hot temperature environments, since the performance of the flame holder depends strongly on its geometry.

Another design for effective flame-holding in ramjets is trapped vortex combustion. The main idea is to take advantage of well-designed cavity flame-holder to create a recirculation zone. In the

Fig. 38. Spectra of pressure and OH* chemiluminescence fluctuations for deactivated cavity air (a) and activated cavity air with an overall air injection of 40 kg/h (b). The cavity gas mass flow was 2.4 kg/h, the main air mass flow is 150 kg/h at an inlet temperature of 300 K. Reprinted from [102] with permission of Dr. E. Gutmark.

cavities, hot combustion products act as a continuous ignition source to achieve stable combustion. The use of such well-design cavities to stabilize and enhance combustion in mini-ramjets was studied for non-reacting and reacting flows [78,84] as shown schematically in Fig. 40.

Non-reacting flow simulations were conducted to gain insight on cold flow fuel-air mixing performance and identifying a proper propane (C_3H_8) injection strategy. Several different propane injection schemes were evaluated and compared. Four injection locations as summarized in Table 1 were tested. Except the last case the fuel is

added in the cavity's upstream, the other three fuel-injection schemes (Cases 1–3) are associated with the propane being injected into the cavity directly at different locations.

Simulation results of these 4 cases are shown in Fig. 41. It can be seen from Fig. 41(a) that the trapped cavity vortex is not enhanced but destroyed by the fuel injection, as indicated by the streamlines. Some propane mixes with the incoming air flow in a thin layer at the cavity opening and spills out. Part of the propane is transported to the cavity bottom. Fig. 41(b) shows that as the propane is added from the after-body's top (corresponding to Case 2), there is still a

Fig. 39. Schematic drawing of flame holders (a) a V-gutter; (b) a bluff body; (c) a sudden expansion [15]; (d) side and top view of Schematic of barchan dune (BD) vortex flame holder. Courtesy of Dr. S. Chen.

Fig. 40. Schematic of the proposed mini-ramjet engine. Reprinted from [85] with permission of Elsevier.

trapped vortex. However, it is compressed to be smaller by the propane stream. Fig. 41(c) shows the results of case 3, as the propane is added from the after-body's bottom. Since the fuel injection direction follows the trapped vortex's rotating direction, the strength of the cavity vortex is reinforced and enhanced. However, it can be seen that for the first three cases the equivalence ratio > 3.0 is present in the cavity and it is too rich to lead to combustion. Fig. 41(d) illustrates the simulation results, as the propane is added to the upstream main flow. It can be seen that the cavity vortex is still trapped in the cavity well. Furthermore, the equivalence ratios in the cavity are approximately 1.0 in comparison with 3.0 in the former cases.

Good fuel-air mixing performance is achieved as revealed in Fig. 41(d). This is due to the following facts. One fact is that the propane injection is "early" (further upstream). Another fact is that the contact surface area between the propane and air in the upstream injection is much greater than for the other 3 configurations. When the propane is added into the cavity directly, the contact surface of the air and propane is confined in the shear layer at the cavity opening. Thus, the propane can only slip out of the cavity via following the velocity tangential to the main air flow stream. However, the propane can penetrate into and interact with the main flow stream, and thus expands much more contact surface with the air, as it is added perpendicularly to the main air flow. This dramatically promotes the micro-mixing by manipulated macro-mixing. The final fact is that the flow structure of the propane jet is normal to the main air flow [165–167]. This also helps the fuel-air mixing process.

The counter-rotating vortex pair continuously rolls the surrounding air into the core of the propane jet. And the wake vortices and horseshoe vortex also increase the mixing rate. The best injection angle is found to be 90° , which is based on the optimum momentum flux. However, when the momentum flux ratio changes, the best angle needs to be further studied.

Angled fuel injection facilitates to enhance fuel-air mixing and decrease pressure loss. This injection scheme has been studied extensively in the scramjet community [48,94,98], as it generates a weaker shock, in comparison with normal fuel injections in supersonic flows. The injection angle effect was studied numerically [78] on the same miniature Ramjet as shown in Fig. 40 by choosing 3 injection angles (90° , 60° , and 30°), while maintaining the momentum flux ratio to be 1.09. Fig. 42(a) shows the combustion efficiency, as the injection angle is varied. It can be seen that injecting the propane at 90° leads to an increased combustion efficiency. However, there is a small difference at the combustor exit. As the injection angle is decreased, the fuel penetration depth is decreased so that the fuel stream is closer to the center-body. It is worth noting that since the analysis [78,84] is based on the optimum momentum flux of 1.09, the best injection angle of 90° is identified. However, this best angle may not be applicable to other TVC designs with a different fuel-air momentum flux ratio. For example, for a ramjet with a choked fuel nozzle, the optimum angle will not be 90° and needs to be optimized to provide best combustion performance. To shed lights on the effect of upstream injection location, 3

Table 1
Injection conditions at different locations. Courtesy of Dr. S. Chen.

Injecting location	Number of injectors	Injector diameter [mm]	Mass flow rate per injector [kg/s]	Injection velocity [m/s]	Momentum flux ratio
Case 1: fore-body $r = 0.03$ m	8	3.0	0.001513	78	~ 40
Case 2: after-body $r = 0.03$ m	8	3.0	0.001513	78	~ 40
Case 3: after-body $r = 0.008$ m	8	3.0	0.001513	78	~ 40
Case 4: upstream $z = -0.025$ m	8	2.8	0.001513	92	1.09

Fig. 41. Streamlines and equivalence ratio contours in the cavity for 4 different injection locations: (a) case 1, (b) case 2, (c) case 3, and (d) case 4. The arrow indicates the fuel injection location and direction [84]. Courtesy of Dr. S. Chen.

different injections with the same momentum flux ratio were examined as shown in Fig. 42(b) in terms of the combustion efficiency. If the propane is injected “early”, then it has more time to mix, burn and thus slightly higher combustion efficiency.

However, the combustion efficiency difference at the combustor exit is almost negligible. In comparison with the combustor length, the small changes of the injector location has little impact on the overall combustor performance.

Fig. 42. Combustion efficiency η_c of injection schemes with (a) 3 different injection angles, (b) 3 different upstream injection locations [84]. Courtesy of Dr. S. Chen.

Fig. 43. Three dimensional fuel stream trajectories viewed in the relative reference frame: (a) 0 rpm combustor flow and (b) 30,000 rpm combustor flow [84]. Courtesy of Dr. S. Chen.

The effect of spinning motion [78,84] on the fuel injection effect and mixing characteristics was numerically studied in the miniature ramjet, as shown in Fig. 40. 3D stream trajectories when propane-burned combustion occurs are viewed in the rotating reference frame as plotted in Fig. 43. In the absence of spinning motion, the propane stream goes straightly through the combustion chamber (see Fig. 43(a)). However, the presence of spinning motion leads to the fuel stream being bent due to Coriolis force, $-2\vec{\Omega} \times \vec{u}_r$ (see Fig. 43(b)).

To shed insights on the effect of the spinning motion on fuel-air mixing, the distributions of the turbulent kinetic energy are illustrated in Fig. 44. When the TVC combustor is associated with spinning motion as shown in Fig. 44(b), the level of turbulent kinetic energy is dramatically increased to approximately 2500 J/kg due to

the effects of Coriolis force and eddy diffusivity, in comparison with 1000–1500 J/kg of the non-spinning combustor. The kinetic energy in the spinning cavity as shown in Fig. 44(b) is confined within the cavity opening. It is the primary vortex produced by the entrainment of the main air flow. However, the kinetic energy in the non-spinning combustor is transported to the cavity's bottom along the locked vortex.

The spinning motion effect on trapped vortex combustion temperature is shown in Fig. 45. It can be observed that there is a cavity pilot flame with a maximum temperature of 2400 K in both spinning and non-spinning combustion chambers. Furthermore, the maximum temperature zone in the spinning combustion chamber is slightly downstream, while it occurs in the non-spinning combustor just located behind the after-body.

Closer observation on the temperature contour of the non-spinning combustion chamber as shown in Fig. 45(a) reveals that the entire main combustion chamber is filled with hot combustion products, and even in the region close to the combustion chamber casing. However, in the spinning combustor as shown in Fig. 45(b), the hot flow region in the main combustion chamber is concentrated more to the axis. Furthermore, the temperature close to the spinning combustion chamber casing is not as high as the non-spinning one. This is due to the density change resulting from combustion. The density change in the spinning motion introduces another type of a secondary flow resulting from centrifugal forces. When a fluid element in the spinning flow is considered, its density is suddenly decreased because of heat release. The centrifugal force exerted on the fluid element is less than the radial pressure gradient as mathematically described as $\rho \frac{u_\theta^2}{r} < \frac{dp}{dr}$. Thus, the fluid element will be pushed to a new balanced position towards the combustor center line where the centrifugal force equals to the pressure gradient.

5.1.2. Scramjets

For supersonic air-breathing engines, the time available for fuel addition, fuel-air mixing and combustion are very short, of the order of 1 ms. Therefore flame stabilization [24,90] plays an important role in the development of scramjets. Conventionally, there are 3 techniques for flame-holding in supersonic flows: (1) creating a recirculation region where the fuel and air can be mixed partially at relatively low velocities, (2) interaction between partially or fully mixed fuel and oxidizer and a shock wave, and (3) forming coherent structures containing unmixed fuel and oxidizer, where a diffusion flame occurs, as the mixtures are convected downstream. These traditional techniques can be implemented in a supersonic combustor in 3 different configurations, as shown schematically in Fig. 46.

Fig. 44. Turbulent kinetic energy in the combustor flows: (a) 0 rpm and (b) 30,000 rpm [84]. Courtesy of Dr. S. Chen.

Fig. 45. Temperature contours of the combustion chamber: (a) non-spinning and (b) spinning [84]. Courtesy of Dr. S. Chen.

As an integrated fuel injection/flame-holding technique, trapped vortex combustion has been proposed as an alternative promising concept during the past few decades in Scramjet communities [168]. It is an alternative promising flame-holding scheme, due to the promising results obtained from flight tests and the feasibility demonstrations in lab-scale supersonic combustor. Currently, there are two main research directions: 1) trapping a vortex within the cavity and 2) cavity-actuated mixing enhancement for flame-holding and stabilization of supersonic combustion. The first application of cavity flame holders was a joint Russian/French dual-mode scramjet flight test (hydrogen fueled) [169]. The flame holder was designed by the Central Institution of Aviation Motors (CIAM) in Moscow. Further experimental tests [170,171] confirmed that using a cavity after the ramp injector can lead to significant improvement of the hydrocarbon combustion efficiency in a supersonic combustor. Similar flame stabilization schemes [23,48] have been applied on a solid-fuel

supersonic combustor. It was found that self-ignition and sustained combustion of PMMA (Plexiglas) under supersonic flow conditions were achievable.

Previous works on scramjet TVCs have confirmed the benefits of upstream fuel injection. The mixing and combustion characteristics of a supersonic combustor in scramjets were numerically studied [172], as the fuel is added upstream of a cavity flame-holder. It was shown that the interaction of the fuel jet with the shear layer at the cavity opening affects strongly the fuel-air mixing and flame-holding processes. As the fuel jet flows over the cavity, a “counter-rotating vortex pair” of the jet in cross-flow rolls up the shear layer. The mass exchange between the main stream and the cavity is then enhanced. If a stable flame is locked inside the cavity, the interaction also transports hot combustion products to the jet and the main stream to ignite the unburned fuel-oxidizer mixture. A number of previous investigations [173,174] have also shown that upstream fuel

Fig. 46. Three typical flow field schematics of traditional injection/flame-holding schemes for supersonic combustors. (a) under-expanded fuel injection normal to the cross-flow, (b) injection behind a sudden expansion produced by a step, (c) fuel injection at an angle. Reprinted from [23] with permission of Dr. A. Ben-Yakar and R. K. Hanson.

injection helped to dampen cavity oscillations. This fuel injection configuration helps to enhance the shear layer growth rate which in turn promotes to stabilize the cavity vortex [175]. Optimum design of a cavity flame holder corresponding to the most effective flame-holding capability with a minimum flow loss can be achieved from comprehensive studies of the flow-field and/or fuel-oxidizer mixing characteristics of reacting and non-reacting cavities. Intensive research efforts related to non-reacting cavities employed in low and high Mach number air flows are well reviewed and summarized in Refs. [23,48]. Open questions impacting the effectiveness of using such cavities as flame holders in supersonic combustion chambers are discussed in Sect. 3.

5.1.3. Aero-engines

The trapped vortex (TV) combustion concept is also exploited in the design of next-generation aero-engines to improve altitude relight, lean-blow-out, and durability while maintaining cost, weight and combustor exit temperature profile. A new TV annular combustor (TVC) was proposed and designed [25] as shown schematically in Fig. 47. It takes advantages of driven cavities incorporated into the combustor liners. The TV combustor being developed is different from the conventional one in that it uses a rich-quench-lean design approach. All fuel is introduced into the cavities. Here, the fuel is evaporated and mixed with a portion of the total air, partially burns and eventually leaves the cavities. Vortices are trapped in the cavities by using the main air chutes through the dome to increase the mixing time, and provide additional air to mix with the partially burned gases to achieve complete combustion and to quench NO_x formation prior to reaching the combustor exit.

5.2. Power generation

For power generation, a lean premixed TV combustor has been designed and tested in Ref. [17]. The trapped vortex combustor was fired on methane and tested, as shown in Fig. 48. For comparison, a simple bluff body combustor was also tested. All tests were

performed at elevated pressures and inlet temperature and at lean fuel-air ratios, which were representative of power generation gas turbine engines.

The experimental data obtained from the bluff body and TVC showed that combustion efficiency was above 99.5% as shown in Fig. 49(a). Furthermore, the TVC efficiency is much higher than that of the bluff body. Although the wall quenching effects which are relatively constant for both the bluff body and TVC configurations, the TVC design leads to the CO emissions being reduced by more than a factor of 10. The reduction in CO emissions results from the flame holding features involving increased interaction between the premixed methane and air flow and the hot products of the combustion in the TVC cavity. As shown in Fig. 49(b), the TVC has made dramatic improvements on the overall emissions characteristics. As reported in Ref. [17], less than 20 ppm of CO and NO_x @15% O_2 is achieved over a useful stoichiometric range, superior to the bluff body performance. Furthermore, the 10 ppm NO_x /10 ppm CO threshold is achieved. In summary, the performance evaluation confirms that the optimized design of TVC has the great potential for successful integration into a prototype power generation system because of its robustness and straightforward design.

To achieve low emissions over a wide range of fuel types for land-based stationary gas turbines, a spin-off trapped vortex combustion approach was proposed and evaluated [58]. It combines the potential advantages of trapped vortex combustion and a staged rich-burn quick-mix, lean-burn (RQL) [176] combustor. Experiments were conducted at an inlet-air temperature of 644 K and 10 atm (1013 kPa) pressure condition. The measured CO and NO_x levels are found to be quite low as expected. This finding is consistent with that obtained in Ref. [44], in which the TVC concept was evaluated on heavy-duty gas turbines. The premixed injection of natural gas into the TVC at heavy-duty gas turbine conditions was tested. As the cavity residence time is increased, NO_x emission is decreased. The emission performance was measured, as rich zone equivalence ratio is varied over a range of operating conditions as shown in Fig. 50.

Fig. 47. (a) schematic drawing of the cross-section, (b) proposed TVC combustor-diffuser-nozzle module, (c) TVC full annular rig with instrumentation [25]. Courtesy of Dr. K. Barlow.

Fig. 48. Schematic of tested combustor with a bluff-body and TVC hardware.

Fig. 49. (a) combustion efficiency versus Φ_{fe} for the bluff body combustor and TVC combustor, (b) CO vs NOx from TVC [17]. Reprinted from [17] with permission of the American Society of Mechanical Engineers (ASME).

Fig. 50. Comparison of experimental data of combustion emission versus PSR-mix-PFR model, (a) cavity residence time, (b) rich zone equivalence ratio. Reprinted from [58] with permission of the American Society of Mechanical Engineers (ASME).

The TVC has been confirmed with reduced emissions and high turn-down with liquid fuels. It could also overcome existing lean pre-mixed performance constraints.

Due to the attractive features of the TVCs, Ramjen Power Systems, Inc. is currently working on commercializing a lean-premixed methane-fired trapped-vortex combustion system [29]. This TVC is based on locking a vortex structure between the fore- and aft-bodies of the cavity. Strong interaction between the hot highly turbulent cavity gas and the cold channel flow is created by using flame stabilizing features designed and placed in the channel flow.

5.3. Waste incineration

Waste incinerator is simply a combustion system/device, which is used to burn waste materials [177–180]. The incinerator's performance depends on (1) its combustion stability and (2) how well the combustion air and waste material or fuel are mixed and maintained at high temperature for sufficient time. To achieve good performance, the main requirements for designing an effective incineration system include:

- 1) capability to handle varying waste compositions
- 2) compliance with increased regulatory/emission requirements
- 3) maximum possible combustion efficiency
- 4) capability to handle varying flows-waste may be produced continuously or in batches
- 5) efficient and effective pollution (air/water/land) control equipment
- 6) low maintenance costs
- 7) capability to maintain combustion performance over long timescales
- 8) reliable start-up essential for a standby incinerator
- 9) high availability- if the incinerator unit is unavailable, the process plant may require shutting down, thus incurring major costs.

The first trapped vortex incineration may be dated back to 1990s [178–180]. It is derived from a dump combustor with movable ceramic plugs implemented to create a combustion cavity to trap vortex, as shown schematically in Fig. 51(a). The combustion process was found to strongly depend on the aspect ratio of the combustor and the equivalence ratio. ‘Quiet’ [178] and high-frequency resonant modes were observed to be associated with vortex pairs locked in the cavity [179]. However, a low-frequency resonant mode (chugging) was also found in a cavity (see Fig. 51(b)) with a large aspect ratio and low equivalence ratio. This oscillation mode is not desirable to waste incineration, since the recirculation zone in the cavity is periodically pushed out, which will reduce the residence time.

The destruction and removal efficiency can be as low as 90% due to the periodic destruction of the recirculation zone. The high- and low-frequency modes result from self-sustained combustion instability [3,9]. This was confirmed by the 1D acoustic analysis of the combustion system [179,180]. The acoustically-excited vortex combustor [178,179] was design to destruct liquid and gaseous waste surrogates. In the incineration application, fluid waste/pyrolysis gas surrogates are injected into the recirculation zones of the device's combustion cavity [178,179]. Here the surrogates are trapped for relatively longer time under high temperature and/or high radical

concentration conditions. This enables the surrogates to be destroyed to a high degree.

6. Challenges for TVC designs and implementation

The main challenges revealed from the foregoing and ongoing studies of trapped vortex combustion in high- or low Mach number flows [181–183] can be summarized as:

- 1) Cavity and its stability: to achieve flame holding [184,185], cavities with the length-to-depth ratio $L/D < 7-10$ (also known as open cavities) are good candidates, since they are associated with reduced drag coefficients in comparison with closed cavities with $L/D > 10-13$. The dimensions of an open cavity need to be properly chosen for ignition and flame-holding [186,187]. For example, the cavity depth needs to be determined according to the required residence time to initiate ignition, while the cavity length needs to be designed to provide sufficient volume of radicals to sustain the combustion further downstream [188,189]. In addition, an unstable cavity can enhance mixing [190–192] and ignition as a result of strong cavity resonant oscillations. However, this cavity is unlikely to provide a continuous flame-holding region [193,194], as revealed in previous experimental studies. To sustain continuous and stable combustor, a stable cavity is preferred [194,195].
- 2) Fuel injection: fuel injection from a jet nozzle upstream or inside the cavity can dramatically change the characteristics of shear layer (for example, the thickness and stability of the shear layer). Thus the cavity flame-holding performance [190,191] is altered. Previous studies have confirmed that the interaction between fuel injection and a cavity leads to different oscillation frequencies [183]. One of the important research areas are fuel injection, especially in supersonic flow conditions. Typically, there are 2 types of injection concepts. One is steady, for example skewing and/or swirling the fuel jet. The other is unsteady, such as using small perturbations. One of the typical perturbations is pulsed

Fig. 51. (a) Schematic drawing of the trapped vortex combustor used in the incineration experiment, (b) schematic drawing the dominant hydrodynamic feature of the incineration combustor. Adapted from [178] with permission of Taylor & Francis.

jets [192]. Little previous work has been conducted on pulsed injection into supersonic flow.

- 3) Residence time and mixing: A number of researchers have confirmed the aerodynamic advantages of trapping vortices inside small aspect ratio cavities ($L/D < 1$) both as a means of reducing the drag penalties of cavities and obtaining stable flame holding in a low-speed combustor. A small aspect ratio cavity may be adapted to provide a stable and sustained combustion in supersonic flows [181,182]. However, the cavity flow residence time associated with high-speed flows will be smaller than for low-speed flows. The short residence time might eliminate its flame-holding capability [196–199]. Therefore, the residence time inside the cavity should be sufficient to initiate the ignition process, which can be characterized by Damkohler number (> 1). For example, to increase the residence time, fuel needs to be injected within the cavity flame holder to provide auto ignition and flame holding [200,201]. Otherwise, it was very challenging to achieve auto-ignition [201] from small dimension injectors in the Mach 6 flight condition and low combustor pressures of the design point.
- 4) Heat transfer effect of the cavity wall: As high temperature air is stagnating and locking in the cavity, excessive heat transfer [39] will occur to the cavity walls. To cool and protect the cavity surface, additional mass from a porous surface can be applied via transpiration/cooling technique [39–42]. This technique can reduce the pressure losses associated with the shock wave structure of the cavity. It also decreases the skin-friction losses on the cavity floor surface. Thus fuel mass bleeding inside the cavity pressure distribution. In this way, the intensity of the strong trailing-edge reattachment shock wave can be reduced. Therefore, an optimized cavity with transpiration/cooling technique applied needs to be designed to improve the pressure losses and to reduce the drag penalties.
- 5) Innovative materials: For most TVC applications, a primary combustion zone is established in the cavity with quench air introduced from the dome [202,203]. A strong recirculation zone with allied primary combustion in the cavity along with a high surface temperature in the transition region is created. The associated high thermal gradients causes high stress levels, even buckling and bending problems. This imposes a serious challenge to identify an optimal material for combustor cooling application, which needs to be meet the high thermo-mechanical requirements and survived in the hostile TVC environment. The material main properties and features should include but not limited to
 - a) Improved thermal resistance.
 - b) Increased corrosion resistance even in oxidizing environment.
 - c) Increased durability.
 - d) Increased stiffness, strength and decreased density (light-weighted).

Researches on applying SiC-SiC ceramic matrix composite (CMC) materials [40–43] on TVC are ongoing. Preliminary tests confirm that the CMC material provides dramatic improvement to the thermal capability. However, the stress and thermal gradients are not well controlled. Improvement on these materials needs to be achieved.

- 6) Shock wave-jet interaction: In supersonic flight conditions, shock waves can be generated from a cavity flame holder [181,182]. These waves enhance the mixing of fuel jets injected upstream of the cavity. As confirmed by the previous studies [181,182], the shock waves produced from a stable cavity can be used to enhance mixing, while an unstable cavity can be used to

actuate mixing. The jet will interact with the strong trailing-edge shock wave of the cavity, as it reaches to the back wall. The molecular mixing between supersonic air and gaseous fuel is enhanced by the oblique shock wave-jet interaction through the vorticity generated due to the baroclinic torque. This will significantly increase the spreading rate of the jet and mixing performance of the fuel/air, and so lead to increased combustion efficiency [196–200].

- 7) Flight conditions and total enthalpy of incoming air: During hypersonic flight conditions with a high Mach number ($M_a > 8$), both the inlet flow speed and the total enthalpy of air entering the combustor is quite high. In this hypersonic flight regime, the typical fuel for a cavity flame-holder is hydrogen, because of its reduced combustion characteristic times. Igniting the hydrogen-air mixing system by the cavity flame-holder can be achieved by the high-stagnation temperature radical runaway, even without appreciable heat release. As the flight Mach number is below Mach 8 but greater than 1 [181,182], applying an effective flame holder is crucial in the design of stable combustors. In this supersonic flight regime, a cavity flame holder needs to be designed to achieve longer flow residence times. This is due to the fact that the total enthalpies associated with hydrocarbon fuels (good candidate for supersonic flights) are relatively low but the ignition delay time is relatively longer. In general, properly designed cavities can be used in supersonic and hypersonic propulsion systems [181,182] over a wide range of flow/flight conditions.

7. Conclusions and future work

In this work, we have provided a review of trapped vortex combustors operated in subsonic, supersonic and hypersonic flows for flame holding in various engine systems, such as gas turbines, waste incinerator, ramjet, scramjet et al. Trapped vortex combustors are designed to produce a lock-in vortex, which is protected from the main stream flow. The vortex acts as a pilot flame. It also acts as a continuous ignition source for the main combustor. This is the fundamental working principle of trapped vortex combustors (TVCs). In a TVC, air and fuel injection should be strategically-placed in the forward and rear walls of the cavity to drive the vortex contained. As the fuel is injected into the cavities, it is quickly mixed and burned in the stable trapped-vortex flow structure. Here hot combustion gases are recirculated by the vortex. The characteristic flow field, aerodynamics, fuel-air mixing, combustion and acoustics features of the designed cavities are discussed.

To determine the optimum designs of the flame-holding cavity in subsonic and supersonic flow conditions, intensive experimental and numerical studies were performed to address industry concerns and to achieve ignition of both liquid and gaseous fuels and to minimize drag penalties. Insightful findings are obtained from both non-reacting and reacting tests and their interaction with fuel jets in terms of drag penalties for different cavity geometries, and flow residence time inside a cavity, which is crucial to initiate the ignition. The feasibility of applying TVC concept in industries has been demonstrated in practical gas turbine combustors operated with a realistic inlet temperature and pressure condition by burning different types and phases of fuel. Foregoing and ongoing studies on the TVC have confirmed that the TVCs offer significant improvements in LBO and altitude relight, in comparison with conventional swirl stabilized combustors. They can also offer a wider operating range as well as a great potential to operate efficiently with high inlet velocities. TVCs can be applied in a rich-burn, quick-quench, lean-burn (RQL) system to reduce NO_x emission, which involves burning low-cost fuels containing fuel-bound nitrogen. The TVCs can be operated in RQL mode as well as a staged, main/pilot mode. The following

concluding remarks on the combustion improvements by using TVC have been clearly confirmed and demonstrated at realistic conditions:

- 1) up to a 50% improvement in ignition, blow-out, and altitude re-light over conventional swirl-stabilized combustors
- 2) NO_x emissions reduction ranging from 40% to 60% of the 1996 ICAO standard;
- 3) an operating range that is 40% wider than conventional combustors
- 4) increased combustion efficiency at or above 99%.

Promising results have been obtained to date from both laboratories and real combustion tests. However, it is worth noting that the TVC technology is still in the stage of application and commercialization for subsonic engines and a stage of development for supersonic and hypersonic propulsion systems. The key challenges which need to be addressed for the development and application of flame-holding cavities for industrial combustors include

- 1) Optimizing the cavity dimensions and geometry such as different wall divergence angles to maximize the residence time, especially with a given inlet stagnation pressure and temperature at supersonic or hypersonic flight conditions.
- 2) Optimizing the fuel and air injection locations and distributions to achieve the optimum combustion dynamics and emission performance.
- 3) Identifying the light-weighted and durable cavity materials with excellent thermal-mechanical properties.
- 4) Developing a low-cost but effective cooling technologies with a low drag penalty.
- 5) Characterizing the combustion dynamics of ethylene, kerosene, biofuel or alternative fuels
- 6) Minimizing the acoustic signature of TVCs
- 7) Preventing the onset of combustion instability in TVCs.
- 8) Optimizing the hybrid operational combustion modes such as TVC/RQL and TVC/Flameless.

Commercial designs and practical issues associated with cost, weight, and life have not been addressed in any detail in this work. Follow-up programs are needed to further develop the capabilities of the TVC (trapped vortex combustion) and address these challenges and issues. The future research topics on TVC include but not limited to

- 1) Swirling (spinning) trapped vortex combustion.
- 2) Trapped vortex combustor with a guide vane.
- 3) Trapped vortex combustion system with dual or multiple cavities.
- 4) Pulse fuel injection.
- 5) Optimization study of fuel and air injection and distribution.
- 6) Geometric configuration optimization and reliability study of perforated orifices.
- 7) Innovative liner materials and heat transfer study of TVC.

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Supplementary materials

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