Aerospace Science and Technology 74 (2018) 81–92

Contents lists available at ScienceDirect

Aerospace Science and Technology

www.elsevier.com/locate/aescte

Numerical study of non-reacting flowfields of a swirling trapped vortex ramjet combustor

Song Chen [a,c], Dan Zhao [b,*]

[a] Department of Mechanics, KTH Royal Institute of Technology, SE-100 44 Stockholm, Sweden
[b] Department of Mechanical Engineering, College of Engineering, University of Canterbury, Private Bag 4800, Christchurch 8140, New Zealand
[c] School of Mechanical and Aerospace Engineering, College of Engineering, Nanyang Technological University, 50 Nanyang Avenue, 639798, Singapore

ARTICLE INFO

Article history:
Received 28 April 2017
Received in revised form 12 September 2017
Accepted 3 January 2018
Available online 3 February 2018

ABSTRACT

In this work, 3D numerical investigations of a trapped vortex combustor operated in different swirling flow conditions are performed by solving Reynolds-averaged Navier–Stokes equations with Reynolds-stress model. Emphasis is placed on the non-reacting flowfield characteristics and the stability of the locked vortex. Validation is performed first by comparing the present results with experimental data available. It shows that the Reynolds-stress model can provide good predictions for flows with a swirl number up to 0.98. It is also found that the cavity vortex can be trapped well in flows with different swirl numbers. To further study the "locked" vortices, flow disturbances are introduced to the trapped vortex combustor via suddenly increasing swirl number from 0.6 to 0.98. The transient simulation results reveal that the cavity vortex is highly resistant to the flow disturbances and is still well trapped in the cavity, while vortex shedding of the conventional breakdown vortex is observed in the presence of the flow disturbances. Turbulence intensity and kinetic energy are found to be significantly increased by approximately 300%, which indicates that the fuel–air mixing can be dramatically improved. This study shows that the swirling trapped vortex combustor is an alternative promising robust and efficient combustor concept.

1. Introduction

Flame holding is one of the most important issues needed to be addressed in designing a combustor operated in high speed flows. In supersonic combustors (i.e. scramjet combustors), cavities have already been found to be an effective flame holding device with a simple configuration [1]. The main idea of the cavity flame holder is to create a stable recirculation zone inside the cavity with relatively low flow speeds and a hot pool of radicals, which can extend the flow residence time and act as a continuous ignition source [2–4]. Trapped Vortex Combustor (TVC) [5] is a promising combustion concept for the next generation energy-efficient, low-emission, and high performance subsonic combustors. In the concept of TVC, a large vortex is formed inside a well-designed cavity, rotating smoothly and not shedding out the cavity. This cavity vortex is therefore named a "trapped" vortex [5] or "locked" vortex [6]. Fuels and air can either be injected upstream for early mixing [7,8] or be directly injected into the cavity for mixing and combustion [5]. Because the vortex locked in the cavity is quite stable due to the protection of the cavity, the recirculation zone with hot chemical reaction products inside the cavity behaves just like an "igniter". It is a reliable, continuous, and energetic ignition source. It can significantly improve the combustor performance. Previous experimental tests [5,9] confirmed that TVC has many attractive features, such as: (1) extremely lower lean blowout limits compared with the conventional bluff-body [10] and swirl-stabilized combustors, (2) very low pressure drop/loss over the cavity, (3) a wider operating range with a higher combustion efficiency at or above 99%, and (4) a significant reduction in NO_x emissions.

Compared with TVC, combustors in the presence of swirling flows have been studied for a long time [11] to generate recirculation zones for flame stabilization. Swirling flows are usually introduced into combustors via the use of swirl vanes or direct tangential flow injection through slots. The degree of swirl is commonly characterized by a non-dimensional swirl number S. It is defined as the ratio of axial flux of angular momentum to R times the axial flux of the axial momentum [11] as given as:

$$S = \frac{1}{R}\frac{\iint_A r\bar{u}_\theta \bar{u}_x \, dA}{\iint_A \bar{u}_x^2 \, dA} \tag{1}$$

---

[*] Corresponding author.
E-mail address: dan.zhao@canterbury.ac.nz (D. Zhao).

https://doi.org/10.1016/j.ast.2018.01.006
1270-9638/

Nomenclature

A	cross section area
A^*	normalized pressure fluctuation amplitude
D	upstream combustor diameter, 0.05 m
H	cavity height
I	turbulence intensity
k	turbulent kinetic energy
L	cavity length
L_P	cold total pressure loss
$\bar{p}$	mean static pressure
p^*	normalized pressure, divided by the dynamic pressure $1/2\rho U^2$
P_{ref}	reference total pressure, 1 atm
ΔP	total pressure drop between the combustor inlet and outlet
r, θ, z	cylindrical coordinates (radial, tangential, and axial directions, respectively)
R	radius
Re	Reynolds number
S	swirl number
S_{ij}	mean strain-rate tensor
t	time
t^*	normalized time, divided by D/U
T	cavity after-body disk thickness
$\bar{u}_i$	mean velocity in x_i direction
U	maximum mean axial flow velocity at the inlet
x, y, z	Cartesian coordinates
α	fluctuation amplitude decay rate
ε	turbulence dissipation
ω	turbulence specific dissipation
ρ	density
μ	dynamic viscosity

where $\bar{u}_x$ and $\bar{u}_\theta$ are the local mean axial and tangential velocities, A is the cross section area, and R is the duct radius. When the degree of swirl is high (i.e. $S > \sim 0.6$), vortex breakdown [12,13] can be observed, which is characterized by the formation of an internal stagnation point on the vortex axis and reverse flows. Vortex breakdown has received much attention, since it was first observed by Peckham and Atkinson [14] over delta wings at large incidences. Sarpkaya [15] performed a series of experiments to study the vortex breakdown phenomenon and showed that the types and forms of vortex breakdown depend on swirl number and Reynolds number. Escudier and Zehndern [16] revealed a criterion for the occurrence of vortex breakdown through experiments and theoretical analysis. Lopez [17] used numerical simulations to investigate the axisymmetric vortex breakdown for confined swirling flows in a tube. Guo et al. [18] numerically studied the unsteady precessing vortex core in swirling flows by using the standard $k-\varepsilon$ turbulence model. Extensive numerical works have also been conducted to study the bubble-like vortex breakdown generated by swirling flows in combustion chambers. Yang et al. [19] numerically investigated a non-reacting gas turbine combustor with swirling flows using Reynolds-Stress Model (RSM). Schluter et al. [20] and Javadi et al. [21] conducted large eddy simulations (LES) to study turbulent swirling flows through a suddenly expanding circular pipe. Huang and Yang [22] numerically investigated the effects of swirling flow on combustion dynamics in a lean-premixed combustor by using LES.

The operation of conventional TVC may not involve with swirling flows. However, when TVC is installed in a spin-stabilized gun-launched projectile or a spinning-stabilized ramjet [23], the spinning motion of engine will introduce swirling flows in such combustor. Similar rotating flow over cavities could be found in rotating machineries. For example, in gas turbine engines where compressed air is commonly used for cooling, the cooling air flows over the cavities formed by turbine blade disks. This is one classical type of flows associated with swirling motion and cavities. Farthing et al. [24,25] experimentally studied the flow structure and heat transfer in these rotating cavities with axial cooling through-flows. It was found that non-axisymmetric and axisymmetric vortex breakdown occurred inside the cavity depending on the cavity length/depth ratio and the cavity spinning rate. Another example of similar swirling flow over cavities is the Ultra-Compact Combustor (UCC) [26] used in gas turbine engines. The UCC is essentially a cavity combustor operated in swirling flows, in order to improve the engine thrust-weight ratio. In this UCC concept, the swirling flow is generated by the compressor exit guide vanes, and passes over the cavity mounted circumferentially around the combustor. In our previous works [8,23], a small spinning ramjet TVC was investigated numerically. An interesting phenomenon that the single large cavity vortex is replaced by multiple vortices under the effect of Coriolis force has been found in a very high spinning rate of 30,000 rpm. However, our previous works mainly focused on the overall combustor performance instead of the details of the non-reacting flow characteristics and the cavity vortex dynamics. To the best knowledge of the authors, the swirling trapped vortex combustor (STVC) operated under swirling flow conditions has not received much attention. Therefore, the primary objective of the present investigation is to study the non-reacting flow and the vortex dynamics of the trapped vortex cavity under a number of well specified swirling flow conditions. Moreover, as it is known that conventional gas turbine combustors utilize swirling flows to establish recirculation zones for fuel–air mixing and flame stabilization, it would also be interesting to investigate whether it is possible to combine the benefits of conventional swirling flows and the cavity flows in combustor applications. These motivated the present work.

This paper begins with a description of the cavity combustor configuration and numerical models. They are presented in Sect. 2. Validation studies and numerical results of the STVC under different levels of swirling flows are then presented and discussed in Sect. 3. The key findings of the non-reacting flow characteristics and cavity vortex dynamics of STVC are summarized in Sect. 4.

2. Models and numerical method

2.1. Configuration of the TVC

A ramjet engine with a cavity flame holder on its annular casing is shown in Fig. 1(a). The axisymmetric combustor configuration consists of a sudden expansion and a cavity formed by a fore-body and an after-body disk downstream. For the current study, a simplified cylindrical cavity combustor as shown in Fig. 1(b) is adopted. In this combustor configuration, the cylindrical tube in the upstream of the expansion has a diameter D ($D = 0.05$ m) and a length of $0.5D$. The downstream tube has a diameter of $2D$. The cavity size is characterized by its length L and height H. In the previous works where the cavity is placed along the combustor axis [5], the optimum cavity size that is able to lock the vortex has been systematically studied. The same cavity size is used in the current combustor, which is $L/D = 0.6$ and $H/D = 0.38$. The ring-shape after-body disk has a thickness of T ($T/D = 0.1$). Although