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Effect of cavity-injector/radial-strut relative position on performance of a trapped vortex combustor

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A B S T R A C T

Previous works have put forward the key role of radial strut in a trapped vortex combustor (TVC), however, few researches focusing on radial strut can be found in the existing literature so far. The present study is carried out to investigate the effect of the cavity-injector/radial-strut relative position on the performance of a trapped vortex combustor. This effect is directly explored by TVC combustion experiments that are run at atmospheric pressure using RP-3 liquid aircraft fuel. The specific positions include: the inline arrangement, the intermediate arrangement and the staggered arrangement. The staggered arrangement shows remarkable advantages in terms of ignition, lean blow out (LBO) and combustor temperature rise, whereas the inline arrangement performs rather poorly. Numerical simulations with validated methodology of non-reacting flows are then conducted for the purpose to explain the experimental results. The good performance of the staggered arrangement is mainly attributed to the counter-rotating streamwise vortex pair, the high turbulent kinetic energy and turbulent dissipation rate.

1. Introduction

Flame stabilization, which is one of the fundamental issues for aero-engine combustors, is usually achieved through the creation of a toroidal flow reversal that entrains and recirculates a portion of the hot combustion gases to provide continuous ignition to the incoming air and fuel [16]. In conventional combustors, swirlers are ubiquitously used in primary zones to establish recirculation zones for flame stabilization, at higher inlet velocities, however, these zones become less stable. In contrast to conventional combustors, trapped vortex combustor (TVC) provides an alternative concept in flame stabilization. In a typical TVC, cavities are used for flame stabilization. If the geometry of cavity is carefully designed and the cavity air is introduced in a proper manner, vortex would be trapped in cavity and is least vulnerable to changes of flow condition, which provides potential of flame stabilization under high velocity conditions.

There are two crucial issues in TVC design. One is the establishment of desired vortex flow pattern in cavity which acts as the continuous ignition source. The other issue involves transporting and mixing the heat and burnt gases from cavity into the mainstream flow. The latter issue is often addressed with the help of radial struts or radial rods.

The concept of TVC was initially proposed by Hsu in 1995 and his configuration has been extensively studied [8,9,13–15,23,24]. The US Air Force Research Laboratory (AFRL) has developed four generations of TVCs. The primary improvement of the second generation TVC over the first generation is the set of two radial struts immersed in the mainstream, it is demonstrated that, by mixing hot products from the cavity with the main fuel and air, the radial struts are effective in the rapid ignition of the mainstream and uniform temperature distribution. Due to the improvements in combustor performance, the radial struts are applied in the following two generation TVCs [3,6,7,18,19]. Fig. 1 shows a schematic of the AFRL third generation TVC, in which typical position of cavity and radial strut can be seen. However, individual performance of radial struts is not investigated or discussed in detail. Merlin, Domingo et al. investigated a TVC by Large Eddy Simulation (LES), the test rig consists of a main annular lean flow, a cavity located toward the axis of symmetric of the combustor and a set of rods located right upstream of cavity, the rods act similarly as radial struts [17]. The effects of the main flow rate, the length of the cavity, injecting secondary air and adding a swirling motion were examined, here again, the rods were not of certain concern. Jin, He et al. developed a TVC which has dimensions similar to that of combustors in service, still, no special attention was paid to radial struts [11,12]. More recently, Singhal, Agarwal, Ravikrishna et al. developed a compact TVC, they proposed a passive strategy of utilizing inclined struts along with a flow guide vane for mixing enhancement [1,2,21,22]. The benefits of the struts were analyzed by CFD insight into

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Nomenclature

TVC	trapped vortex combustor
AFRL	Air Force Research Laboratory
LES	large eddy simulation
CFD	computational fluid dynamics
T_3	inlet temperature
M_a	inlet Mach number
FAR	fuel/air ratio
LBO	lean blow out
RANS	Reynolds-averaged Navier–Stokes
k	turbulent kinetic energy
ε	turbulent kinetic energy dissipation rate
PIV	particle image velocimetry
x	axial coordinate
y	radial coordinate
z	spanwise coordinate

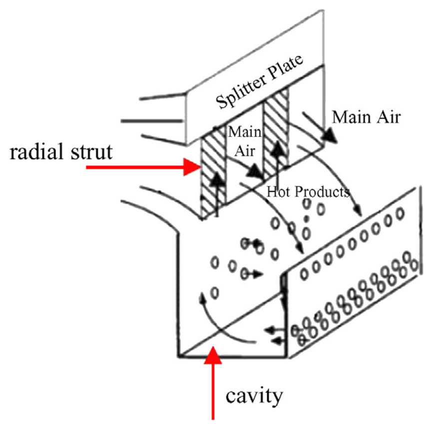

Fig. 1. A generic TVC geometry: AFRL third generation configuration [3].

the flow field. It is observed that the cavity products travel along the struts complete up to the combustor top wall, which is the precursor to improved mixing, the flow between the struts is normally. The interlock nature of the different flow structures in the spanwise direction is thought to lead to enhanced mixing. Furthermore, a comparison between the four-strut case and the six-strut case was made, the better performance of the four-strut case was mainly ascribed to the wider stagnation zone formed behind the struts, which helps to achieve a high volume flux and momentum for individual hot product streams issuing from cavity.

It can be concluded that radial struts are of paramount importance to trapped vortex combustors, however, little effort has been made so far to conduct systematic investigations. A similarity between the works mentioned above is that the configurations behave with two-dimensionality in terms of both air flow and fuel injection, to a certain extent. In particular, the fourth generation TVC of the AFRL uses a large number of fuel injectors to realize good distribution and mixing of the fuel and air. In realistic aero-engine combustors, however, the amount of fuel injectors is limited, the air flow and fuel distribution are of strong three-dimensional properties. Under these conditions, we believe that the cavity-injector/radial-strut relative position in the spanwise direction would be an important issue for a TVC, which has motivated the present work.

2. Combustor model and experimental setup

2.1. Combustor model

Fig. 2 shows a two-dimensional schematic and a photo of the combustor model. The model is generally a 180 mm-wide rectangular trapped vortex combustor, it is composed of a dump diffuser, cowls, a central bluff body, radial struts, cavities, liners and casings. The dump diffuser comprises of a straight walled pre-diffuser, of area ratio 1.472, which projects into a step region where the flow is divided into three streams. The cavity has a length of 50 mm and a depth of 43 mm, resulting in a cavity length to depth ratio of $50/(2*43) = 0.581$. This value is expected to provide both low-pressure drop and good flame stability as it is very close to

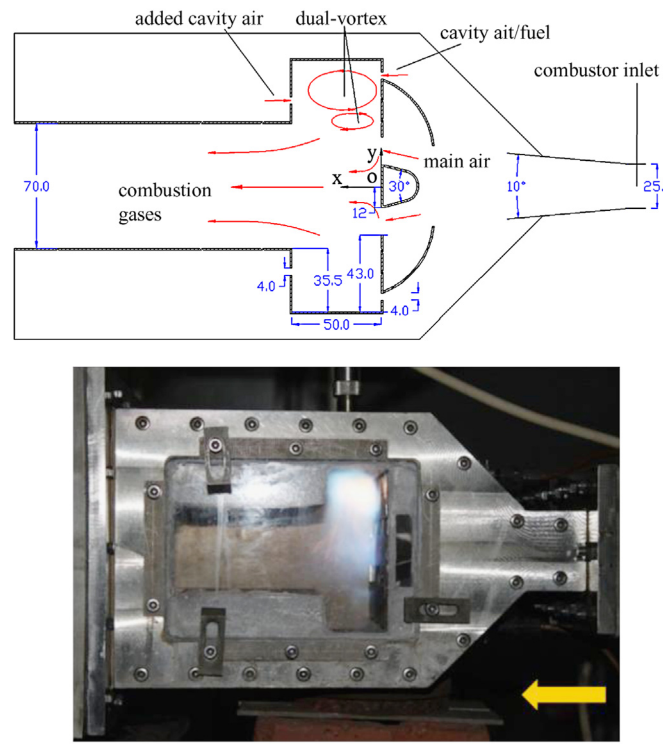

Fig. 2. 2-D schematic and a photo of the combustor model (flow from right to left). All dimensions in mm.

the optimal value 0.59, which was determined by Hsu [8,9]. This Cavity air is introduced through four 4 mm-wide slots which are located in the cavity fore walls and the cavity after walls, respectively. The dome of the mainstream is comprised of a bluff body and radial struts and is designed to be flush with the cavity fore walls. The mainstream is introduced through the square passages formed by the bluff body and radial struts. Fuel is delivered to the combustor through six pressure-swirl injectors (3 for each cavity) that are located in the cavity fore wall slots. A spark plug mounted to be flush with the bottom wall of the outer cavity is used as the ignition source. The liner of the combustor is made entirely of high temperature Nimonic alloy GH3044 to provide durability to stand up to the severe test conditions, while the casing is made of 310S stainless steel. The cavities and the liner walls downstream of cavities are both film cooled, in particular, the cooling air in cavities are introduced in a manner to reinforce the vortical flow within cavities. As compared with the AFRL rig, the present rig utilizes two rows of 10 mm-diameter dilution holes to improve the quality of the temperature distribution. On one of the lateral sides of the combustor, a 15 mm-thick silica glass of size 187 mm × 134 mm is installed to allow optical access. Also shown in Fig. 2 are the x, y axes with the origin located in the downstream surface of the bluff body. The direction of the z axis, which can be determined by the right-handed screw rule, is perpendicular to the paper-plane.