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Effect of strut length on combustion performance of a trapped vortex combustor

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ABSTRACT

Experimental studies with four different strut setups are conducted to investigate the effect of strut length on combustion performance of a trapped vortex combustor (TVC). The experimental results indicate that ignition, lean blowout (LBO) and combustion efficiency depend to a great extent upon the length of the strut. The longer struts show prominent advantages in terms of ignition and LBO, whereas the shorter ones perform rather poorly. Interestingly, the combustion efficiency achieved by the shorter struts is higher than the longer ones. Furthermore, RANS based simulations are also performed to explain the experimental results. From the detailed numerical simulations, it can be inferred that the poor ignition performance and LBO limits of the shorter struts are mainly caused by the great amount of mainstream air entrained into the cavity. And the higher combustion efficiency achieved by the shorter struts is mainly attributed to much more wake regions formed behind the struts.

1. Introduction

Recirculation zones for flame stabilization in conventional combustor are usually generated by swirler or bluff-body. While the recirculation zones downstream of the swirler or bluff-body will become less stable at higher inlet velocities. In order to achieve flame stabilization over a wide flow conditions both in subsonic flow and supersonic flow engines, a new concept known as trapped vortex combustor (TVC) was proposed. In a TVC, cavity is designed to create recirculation zones for flame stabilization. In the previous studies, it has been demonstrated that excellent ignition performance and significant low LBO limits could be achieved by TVC. This is mainly attributed to the stable vortex trapped inside the cavity. Besides, the TVC also exhibits great potentials to diminish pollutant emissions and reduce pressure loss at high flow conditions [1–3].

Due to its excellent performance characteristics, a great many of efforts have been made by researchers in the TVC study. The previous works are mainly focused on two aspects of the TVC. One is the desired flow structure inside the cavity, meanwhile the other one is the mixing between cavity products and mainstream air. For subsonic flow engines, Katta and Roquemore [4,5] revealed the effect of mass injection on flow dynamics of TVC. They found that the mass injection can alter the flow dynamic characteristics both inside and around the cavity. Therefore, they proposed that a sufficient amount of fuel and air should be injected directly into the cavity to obtain good performance. Kumar and Mishra [6,7] revealed the effect of secondary air jet momentum on both reacting and non-reacting flow fields in the cavity. According to their studies of reacting flow, they found that the cavity flow structure depends highly upon the secondary air jet momentum. However, under non-reacting flow conditions, the cavity flow structure is less sensitive to the secondary air jet momentum. Merlin et al. [8] adopted large eddy simulation (LES) to investigate the effect of cavity air injection strategies on the cavity flow filed. Three different flow models inside the cavity were observed in their numerical studies. For supersonic flow engines, many attentions were paid on the cavity geometry, flow dynamics and fueling scheme [9]. Successful ignition is difficult to be achieved in the TVC for the short flow residence time. Thus, many efforts were made to enhance the ignition performance. Most recently, being different form the previous study, Denman et al. developed a "real" hypersonic engine running at Mach 7.3 to investigate the ignition and combustion performance. The results indicated that the cavity-based engine shows significant advantage in term of ignition as compared with the engine without cavity. In addition, successful ignition was achieved by the cavity-based engine at equivalence ratios ranging

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Nomenclature

Br	total blockage ratio ... %	LBO	lean blow out
CFD	computational fluid dynamics	ES	large eddy simulation
CH_4	methane	l	axial length of cavity ... mm
CO	carbon monoxide	O_2	oxygen
CO_2	carbon dioxide	PIV	particle image velocimetry
EDM	eddy dissipation model	TVC	trapped vortex combustor
FAR	fuel to air ratio	W	strut width ... mm
FID	flame ionization detection	x	axial coordinate
H	strut height ... mm	y	radial coordinate
HC	hydrocarbons	z	spanwise coordinate

from 0.60 to 0.70 as the gaseous ethylene was fed. However, successful ignition was not observed by the engine as the methane was supplied. In their ongoing study, the ignition and combustion of surrogate fuel mixture (64% ethylene and 36% methane by volume) were further examined with different fueling schemes. And the results suggested that it is a huge challenge to acquire successful ignition by the surrogate fuel without the hydrogen-pilot [10,11].

To improve the combustion performance of TVC, struts are applied between cavity and mainstream [12–18]. Inclined struts were proposed by Agarwal et al. [19,20] as a passive strategy to enhance the mixing between cavity products and mainstream air. They found that the cavity hot products are entrained into the wake regions behind the inclined struts and improved mixing is achieved in mainstream. However, the detailed strut parameters were not of certain concern in their study. Jin et al. [21,22] found that there is an optimal relative position between cavity-injector and strut. Furthermore, they revealed that the wake regions behind the struts are beneficial for the interactions between cavity products and mainstream air. Here, the individual effect of the strut on the performance of TVC is still not discussed. Subsequently, a workable TVC was developed by Wu et al. [23] to investigate the effect of strut width on combustion efficiency and emissions. Two configurations with different strut widths were investigated in their study. The results showed that higher combustion efficiency, lower carbon monoxide (CO) and hydrocarbons (HC) emissions were achieved by wider struts. Struts are also commonly used in the TVC for supersonic or scramjet engines. Hsu et al. [24] designed a TVC with different fueling schemes to examine the interaction between the cavity and the strut-injected fuel. They found that the flame distribution depends slightly upon the cavity fueling scheme. However, fuel injected upstream along the strut face burned more effectively. In addition, different wake shapes behind the strut were observed as a result of the modification of the flow field around the cavity and strut regions. Here again, the effects of the strut on the combustion performance were not investigated in detail. More recently, a cone strut together with a cavity was used by Zhang et al. [25] in a TVC running at Mach 3.27. Three different flame holders were used in their study: sole cone-strut holder, sole cavity holder and combined cone-strut and cavity holder. The results exhibited that excellent operating envelop is achieved by using the combined cone-struts and cavity holder as compared to the other two strategies. As anticipated, few attentions were paid on the strut here.

It can be seen that significant progress has been achieved in the TVC study, especially in the flow dynamics inside and around the cavity. Moreover, it also can be concluded that the strut is a very important module to improve the mixing between cavity products and mainstream air. Unfortunately, few efforts have been made so far to conduct systematical study on the design of the strut, especially for the strut length. Based on these conditions, special attentions of the present work are paid on the influence of the strut length on the combustion performance of a TVC. Compared with the existing literature, the main contribution of the present work is to provide not only a more comprehensive understanding about the effect of the strut length on the performance of a TVC, but also some valuable design concepts to the TVC designers, especially those who are interested in improving the mixing between cavity products and mainstream air.

2. Combustor and experimental and numerical setups

2.1. Combustor model

A trapped vortex combustor with an interchangeable dome setup is designed to investigate the effect of strut length on combustion performance of a TVC. Fig. 1 shows a 2-D schematic, a simplified combustor model and a photo of the test rig. The model is a 180 mm wide rectangular trapped vortex combustor, which is composed of a dump diffuser, cowls, dome, cavities, liners, fuel injectors, a spark plug and casing. The cavity has a length of 50 mm, a fore wall and a rear wall with depth of 43 mm and 30.5 mm, respectively. The cavity air and the cavity driving air are introduced through two 3.5 mm width slots and two 4.5 mm width slots, which are located in the cavity fore walls and rear walls respectively. The cavities and the liner walls are both protected by cooling air from the hot gas. The cooling air is introduced by inclined holes, which are of 0.5 mm in diameter and 30 degrees. To improve the outlet temperature distribution of the combustor, two rows of dilution holes with 15 mm and 10 mm in diameter are designed downstream of the cavities. Six pressure swirl atomizers are employed for the two cavities. A spark plug with 12 J stored energy is mounted at the bottom wall of the outer cavity. An optical accessible silica glass is installed on one of the lateral sides of the casing for visualization.

As shown in Fig. 1(b), the dome of the mainstream consists of a central bluff-body, struts and splitters. The four dome configurations with different strut lengths (L) investigated in the present work are exhibited in Fig. 2. The detailed parameters of the four dome configurations are listed in Table 1.

2.2. Experimental setup

2.2.1. Experimental setup

In the present work, a maximal air flow rate of 1.0 kg/s could be supplied by two compressors. The air supplied to the combustor is preheated by an electrical heater, by which the air can be heated from ambient temperature up to 493 K. In addition, the inlet air temperature is measured by a K-type thermocouple, which is set 30 mm upstream of the test rig. The uncertainties of the K-type thermocouple is 2.5%. RP-3 liquid aircraft fuel is used for cavity fuel injection. The air and fuel flow rate are measured by an