Applied Energy 208 (2017) 72–82

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Dome structure effects on combustion performance of a trapped vortex combustor

Mingyu Li[a], Xiaomin He[a,b,*], Yuling Zhao[a], Yi Jin[a,b], Zhenghao Ge[a], Yuan Sun[c]

[a] *Jiangsu Province Key Laboratory of Aerospace Power System, College of Energy and Power Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, PR China*
[b] *Co-Innovation Center for Advanced Aero-engine, Beijing 100191, PR China*
[c] *Eastern Airlines Technic Co., Ltd., Shanghai 200000, PR China*

HIGHLIGHTS

- A trapped vortex combustor with three different dome structures is investigated.
- A light-weight pneumatic multi-point fueling setup is designed for mainstream.
- The performance of the combustor depends highly upon the dome structure.
- The results are helpful to the design of the trapped vortex combustor.

ARTICLE INFO

Keywords:
Trapped vortex combustor
Dome structure
Combustion performance
Flow field

ABSTRACT

Experiments are carried out to investigate the effects of dome structure on the combustion performance of a trapped vortex combustor. The effects are directly explored in terms of combustion efficiency, ignition and lean blowout limits with three different dome structures. The experimental results indicate that the fairing-tube configuration exhibits excellent advantages in lean blowout limits and the outer-cavity ignition performance, whereas the fairing-plate configuration performs rather poorly. Interestingly, the fairing-plate configuration shows prominent superiority in the ignition performance of the inner-cavity. Additionally, the basic configuration performs moderately both in ignition and lean blowout limits. For the combustion efficiency, the fairing-plate configuration achieves the highest combustion efficiency when only cavity is fueled. Both expected and unexpected results are found when cavity and mainstream are fueled simultaneously. As anticipated, higher combustion efficiency are achieved by the basic configuration and fairing-plate configuration at low fuel/air ratio conditions. However, the highest combustion efficiency is obtained by the fairing-tube configuration at high fuel/air ratio conditions. Numerical simulations of non-reacting flows are then conducted to explain the experimental results. The great discrepancies in combustion characteristics may mainly attribute to the significant differences of the flow patterns both in cavity and mainstream.

1. Introduction

In a conventional gas turbine combustor, swirl is used to establish recirculation zones for flame stabilization. However, the recirculation zones would become less stable at higher inlet velocities. To achieve flame stabilization over a wide range of flow conditions, an alternative concept known as trapped vortex combustor (TVC) was proposed in 1995 [1]. In a TVC, an added cavity is designed to create the recirculation zones. If the cavity is carefully sized and the air is injected in a proper manner, vortexes would be generated and trapped inside the cavity over a wide operating range, which eventually increases the combustion stability [1–4]. Since the TVC concept was proposed, there are two major research areas in the TVC study. One is the theoretical work, the other one is the workable TVC study.

In the theoretical work, many efforts were put on the flow dynamics of TVC. To establish a desired flow structure for flame stabilization, special attentions were put on the injection strategy of the cavity. Studies showed that the mass injection can alter the dynamic characteristics of the flow inside and around the cavity [5,6]. Some work also found that the cavity flow structure depends highly upon the air jet

* Corresponding author at: Jiangsu Province Key Laboratory of Aerospace Power System, College of Energy and Power Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, PR China.
E-mail address: hxmnuaa@outlook.com (X. He).

http://dx.doi.org/10.1016/j.apenergy.2017.10.029
Received 27 June 2017; Received in revised form 23 September 2017; Accepted 5 October 2017
0306-2619/

Nomenclature

Br	total blockage ratio, %
CH_4	methane
CO	carbon monoxide
CO_2	carbon dioxide
e^{21}	approximate relative error
FAR	fuel to air ratio
FID	flame ionization detection
GCI	grid convergence index
H	strut height, mm
HC	hydrocarbons
L	strut axial length, mm
LBO	lean blowout
Ma	inlet Mach number
N	grid number for discretization error estimation
O_2	oxygen
p	average order
PIV	particle image velocimetry
PM	the plane between two radial struts
PMF	modified pneumatic multi-point fueling
PS	the plane along with a radial strut
PY	the x-z plane, which is of location y = 20 mm
r	grid refine order
TVC	trapped vortex combustor
W	strut width, mm
X	axial coordinate
Y	radial coordinate
y^+	dimensionless distance
Z	spanwise coordinate
Φ	the average axial velocity

momentum [7,8]. Besides, pollutant reduction is also an important issue in TVC study. The flameless combustion technology [9–13] and staged combustion technology [14] have been proved to be effective in the reduction of pollutant emission. So, combining flameless combustion and TVC was adopted by some researches to reduce the pollutant emission [15,16]. Additionally, a novel concept combining rich-burn, quick-mix, lean-burn (RQL) with TVC also could be found in literature to reduce pollutant emission of a gas turbine combustor [17]. In recent years, the mixing between cavity products and mainstream air has been found to be a key issue in TVC study. Agarwal et al. [18] proposed a passive strategy of using inclined struts to enhance the mixing between cavity products and mainstream air. The results suggest that the hot products of the cavity successfully travel into the mainstream behind the strut, which results in the great improved mixing and increased flame coverage in mainstream. Zeng et al. [19] used a blunt body immerged in the mainstream to enhance the mixing. Results showed that higher combustion efficiency is achieved by this strategy. Besides, Wu et al. [20] put their attentions on the effects of strut width on the performance of a TVC. They found that higher combustion efficiency would be achieved by the wider struts on cavity-only fueling conditions. However, the overall combustion efficiencies of the slenderer struts are higher than that of the wider struts on cavity-main fueling conditions. The effect of high-spinning motion on improving the fuel–air mixing was investigated by Chen et al. [21].

In the workable TVC study, special attentions of the researchers were put on the combustion performance. More recently, Jin et al. [22] developed a workable TVC. In their study, the combustion efficiency, flame characteristics and lean-blow-out (LBO) were fully investigated. Different from the models used in the previous studies, a dome composed of radial struts and bluff body was adopted in their model, while the design strategy of the dome structure was not mentioned in their study. Zhang et al. [23,24] designed and investigated a dual-vortex interstage turbine combustor. Almost all aspects of the combustion characteristics were evaluated in their study. Based on their experimental results, they believe that the dual-vortex interstage turbine combustor for gas turbine is technically feasible. A dome was also used in their combustor model. However, different from the dome structure designed by Jin et al., splitters were added in the dome in their study. Here, the design strategy of the dome structure was also not illustrated. The most famous workable TVC test rig was developed by Bucher and his colleagues [25]. The rig is a high pressure TVC sector, which is capable of operating at conditions of 20 atmospheres and 900 K inlet air temperature. Prominent altitude relight capability and LBO characteristics were achieved by the combustor. The combustion efficiency above 99% achieved by the combustor is of a 40% wider range than that obtained by conventional gas turbine combustor. Here again, a dome consisting of longer struts and splitters and bluff-body was also mounted on the test rig. As anticipated, the design strategy of the dome structure was still not discussed.

It can be seen that significant attentions have been paid to the TVC investigations. However, the underlying mechanisms are not well enough understood to date. Take the dome for example, as an imperative component of a gas turbine combustor, there were no dome setups could be found in most of the TVC studies. Additionally, although three different configurations of the dome structure were adopted in some of the previous work, the design strategies are not clear for lacking of comprehensive understanding of the dome. To our knowledge, the dome structure may have a great influence on the combustion performance of a TVC. However, little effort has been made so far to conduct systematic investigations on the dome. Under these conditions, the objective of this study is to get insights into the influence of the dome structure on a TVC. So, the present study differs from the previous work by paying a great attention to the dome structure of a TVC, using three different dome setups corresponding to those mentioned above. Compared to the existing literature, the main contribution of the present work is to not only provide a more comprehensive understanding of the dome effects on combustion performance of a TVC, but also provide some valuable design concepts to TVC designers, especially those who are interested in improving energy conversion efficiency and conservation of the liquid fuel energy.

2. Combustor and experimental and numerical setups

2.1. Combustor model

Figs. 1 and 2 show a photograph of the test rig and a 2-D schematic

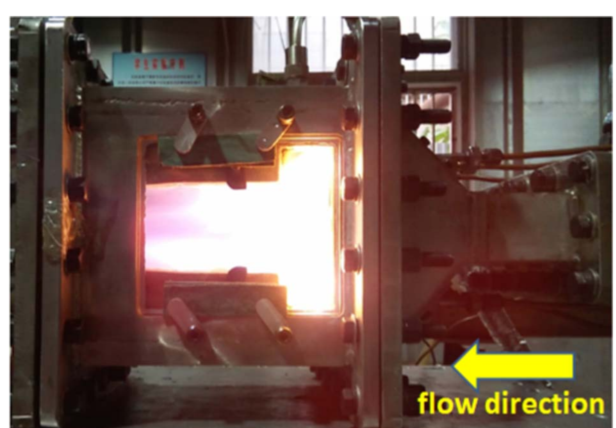

Fig. 1. A photograph of the combustion model combustor.