Applied Energy 216 (2018) 286–295

Contents lists available at ScienceDirect

Applied Energy

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

# Performance enhancement of a trapped-vortex combustor for gas turbine engines using a novel hybrid-atomizer

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

[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] Key Laboratory of Aero-engine Thermal Environment and Structure, Ministry of Industry and Information Technology, PR China

## HIGHLIGHTS

- A workable TVC fueled by two different atomizers is designed and investigated.
- A novel hybrid-atomizer is designed and adopted for cavity fueling.
- Comparison experiments are conducted on the TVC fed by two different atomizers.
- More excellent performance is achieved by the TVC fueled by novel hybrid atomizer.

## ARTICLE INFO

*Keywords:*
Trapped vortex combustor
Combustion efficiency
Ignition
Lean blowout
Atomizer

## ABSTRACT

A novel hybrid-atomizer, combining the spray characteristics of pressure-swirl, airblast and fan atomizers, was designed and adopted for cavity fueling in a trapped vortex combustor (TVC). Furthermore, comparison experiments were conducted under atmospheric pressure to investigate the combustion characteristics of the combustor fueled using the novel hybrid atomizer and a simplex pressure-swirl atomizer. The discrepancies were directly explored in terms of ignition, lean blowout (LBO) limit, and combustion efficiency. The results indicate that the novel hybrid atomizer achieves significant advantages in terms of the combustion characteristics when compared to the simplex pressure-swirl atomizer. The outer-cavity ignition FAR achieved by the novel hybrid atomizer is 50% lower than pressure-swirl atomizer at Mach 0.25 and 0.29, with an inlet temperature of 373 K. In addition, the LBO limits acquired by the novel hybrid atomizer are lower than those of the pressure-swirl atomizer within the full range of operating conditions. Furthermore, a higher combustion efficiency is achieved by the novel hybrid atomizer compared to the pressure-swirl atomizer under most operating regimes.

## 1. Introduction

Modern gas turbine engines have been increasingly designed to achieve a continuous reduction in fuel consumption, a significant part of which is acquired though improvements in the energy conversion efficiency. As an important component in a gas turbine engine, the combustor plays a key role in the energy conversion process. Therefore, a number of studies have been carried out on the use of a combustor. However, achieving an excellent performance of an advanced gas turbine combustor, which demands high combustion efficiency and excellent stability over a wide range of operating conditions, particularly for high power engines, is a significant challenge. To achieve an excellent performance, great effort has been paid to the performance enhancement of a conventional combustor. Therefore, the dome and fuel atomizers in a conventional combustor are becoming increasingly complex. Researchers have also focused on alternative combustion concepts. As an example, the trapped vortex combustor (TVC) has received significant attentions owing to its excellent performance, which can achieve both high combustion efficiency and excellent stability over a wide range of operating conditions [1,2]. Differing from a conventional combustor, a TVC uses a cavity to create recirculation zones for flame stabilization. If the cavity is properly designed and the cavity air is supplied in an appropriate manner, vortex will be generated and trapped inside the cavity over a wide range of operating. In addition, studies have shown that a TVC achieves excellent advantages in terms of ignition, emissions, and pressure loss when compared to a

* 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, China.
*E-mail address:* hxmnuaa@outlook.com (X. He).

https://doi.org/10.1016/j.apenergy.2018.02.111
Received 12 December 2017; Received in revised form 28 January 2018; Accepted 16 February 2018

**Nomenclature**

| | |
|---|---|
| AFR | air to fuel ratio |
| $CH_4$ | methane |
| CO | carbon monoxide |
| $CO_2$ | carbon dioxide |
| FAR | fuel to air ratio |
| FID | flame ionization detection |
| H | strut height, mm |
| HC | hydrocarbons |
| L | strut axial length, mm |
| LBO | lean blowout |
| Ma | inlet Mach number |
| $O_2$ | oxygen |
| PDPA | phase Doppler particle analyzer |
| PIV | particle image velocimetry |
| PMF | modified pneumatic multi-point fueling |
| TVC | trapped vortex combustor |
| W | strut width, mm |
| X | axial coordinate |
| Y | radial coordinate |
| Z | spanwise coordinate |

conventional gas turbine combustor [3–7].

Early TVC studies focused greatly on the flow dynamics to establish a desired flow structure inside a cavity. Kata and Roquemore found that the flow dynamic characteristics depend highly upon the mass injection strategy. They revealed that, not only does the mass injected into the cavity alter the dynamics of a flow inside a cavity, it also changes the flow characteristics around the cavity [8,9]. The role of the secondary air jet of a cavity was fully studied by Kumar and Mishra, who found that such a jet can alter the flow structure under both reacting and non-reacting flow conditions [10,11]. Moreover, different flow models inside a cavity were observed by Merlin et al. under different secondary air injection strategies [12]. To establish a stable vortex trapped inside a cavity, flow guide vanes within the mainstream path have also been adopted by researchers to direct a portion of the main flow into the cavity. Results suggest that this passive strategy can establish a desirable dual vortex structure in a cavity [13]. Pollutant reduction is also an important issue in TVC studies. A technology combining TVC with rich-burn, quick-mix, lean-burn (RQL) has been adopted by some researchers to reduce pollutant emissions [14–16]. Considering the advantages of flameless combustion technology [17–21] and a TVC in reducing such emissions, flameless combustion based on the use of a TVC has been applied to the pollutant emissions reduction [22]. Ghenai et al. [23] studied the pollutant emissions of a TVC using alternative fuels. Their results suggest that higher $NO_x$ emissions are observed when methane is replaced with a methane/hydrogen mixture with a 75% hydrogen fraction. In addition, lower $CO_2$ emissions were also found in their study. The emission performance of a TVC with a slight increase in temperature (100–200 K) was experimentally studied by Xing et al. [24], who aquired $NO_x$ emissions of less than 20 ppm (15% oxygen). Recently, significant attention has been given to the interaction and mixing between cavity products and mainstream air, and Agarwal et al. [25] proposed a passive strategy of using an inclined strut to enhance such mixing. Their results suggest that the hot products of the cavity successfully travel into the mainstream behind the strut, and greatly improving the mixing and increasing the flame coverage achieved. Zeng et al. [26] used a blunt body immerged in the mainstream for an enhance mixing. The results indicate that a more uniform combustor outlet temperature distribution can be acquired by adding a blunt body. In addition, after using a blunt body, higher combustion efficiency is achieved by the combustor. In addition, Jin et al. [27] developed a workable TVC and revealed that the weak regions behind the struts play a key role in the interaction between the cavity products and mainstream air. Wu et al. focused on the effects of the strut width on the performance of a TVC. In their study, they found that lower combustion efficiency occurs when using a slenderer strut under cavity-only fueling conditions. However, the overall combustion efficiency of a slenderer strut is higher than a wider strut when fueling the cavity and mainstream simultaneously [28]. Wu et al. also found that the strut wide has a large influence on the interaction between the cavity flow and mainstream. The interaction was further quantitatively estimated both in both a reacting flow and a non-reacting flow [29]. The effects of a high-spinning motion on the fuel/air mixing were investigated by Chen et al. [30], who found that improved fuel/air mixing can be achieved under a spinning motion. As a result, a more robust pilot flame can be formed inside the cavity. Most recently, Li et al. designed a workable TVC equipped with three different dome structures, and found that a dome structure has a large influence on the combustion efficiency, ignition, and lean blowout (LBO) of a TVC [31].

Previous studies have achieved significant progress in TVC applications. However, as an alternative combustor for a gas turbine engine, certain challenges still exist for a TVC. Taking the cavity fueling strategy as an example, although significant focus has been placed on this issue, most of the focus has been aimed at gas fuel [5,8,9,13,25,32]. For liquid fuel, however, the present atomizers for cavity fueling remain unsatisfactory. In early TVC studies [3,4], a simplex fuel injector bar was adopted for cavity fueling. However, the poor atomization acquired by a fuel injector bar is a major challenge for a TVC in terms of achieving satisfactory combustion efficiency, particularly for low-power operating conditions. In addition, the spray cone angle produced by the fuel injector bar usually lies between 5° and 15°. The cone angle is quite narrow, and more atomizers need to be added to the combustor. As a result, the weight of the combustor increases. A vaporizer atomizer has also been used by some researchers for cavity fueling, particularly for a single-cavity TVC [6,24]. Recently, Zhang et al. studied the performance of single-cavity TVC fueling with a vaporizer atomizer [33–35]. Although pre-evaporated fuel can be acquired by a vaporizer atomizer to achieve an excellent combustion performance with fairly low soot formation, the atomizer is more likely to be burned because it is immersed in the flame. In addition, the evaporation tube is too cold to sufficiently heat the fuel for ignition during the starting conditions. Considering the drawbacks of a fuel injector bar and vaporizer atomizer, a pressure-swirl atomizer has been widely adopted by researchers for use in cavity fueling [7,27–29,31,36,37]. Fig. 1 shows a schematic of a typical TVC cavity fueled by a pressure-swirl atomizer. It can be easily seen that if a pressure-swirl atomizer is used for cavity fueling, by which a normal circular pattern will be created, a portion of the droplets will directly impinge on the bottom wall of the cavity. This is unacceptable for the cooling of the bottom wall. The droplets injected

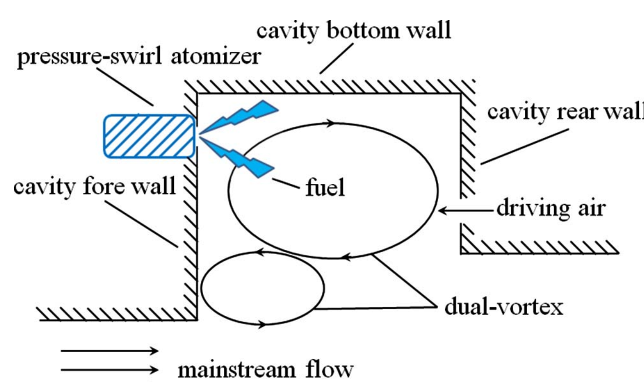


**Fig. 1.** Typical pressure-swirl atomizer for cavity fueling.