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Ignition characteristics of a novel mixed-flow trapped vortex combustor for turboshaft engine

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ABSTRACT

This paper describes an experimental investigation of the effect of flow conditions on the ignition performance of a conceptual combustor. This novel combustor is the first time designed and evaluated for turboshaft engine, known as the mixed-flow trapped vortex combustor (TVC) that utilizes a single cavity to provide flame stabilization. The single cavity is located obliquely on the right side of the combustor. Liquid RP-3 kerosene is directly injected into the cavity. The basic ignition process and the sound theoretical foundation for relating ignition characteristics to all the relevant operating variables were examined experimentally for the first time of the TVC. Simultaneous imagines of flame structure by high-speed camera were obtained to study the basic ignition process in the combustor. The key factors of the success of each ignition process were analyzed. The ignition process of the TVC consists of three stage: 1) the formation of a flame kernel, 2) the subsequent propagation from this flame kernel to all parts of the primary zone, and 3) the spread of flame from a lighted dome to an adjacent unlighted dome. Ignition was made easier by increasing in pressure, temperature, and was impaired by increasing in velocity. Stable flame was achieved in the mixed-flow TVC for a wide range of flow conditions. As the temperature increased, the range of ignition was broadened and the ignition fuel to air ratio (FAR) was reduced. The successful completion of this testing verified that this novel mixed-flow TVC has reasonable structural design and good ignition performance.

1. Introduction

As an important device for energy conversion and power generation, turboshaft engines consume billions barrels of liquid kerosene every year. Liquid kerosene is a non-renewable fossil fuel. The overuse of fossil fuel has a negative impact on air pollution, global warming, and climate change. Pollutant emissions from energy processes have become of great public concern due to their impact on health and environment [1]. Today, aircraft must fly farther, faster, and with ever-increasing payloads and mission capability. Modern turboshaft engines are developing towards high thrust-to-weight ratios, low fuel consumption, high reliability, and low life-cycle costs [2]. However, a dilemma appears in conventional turboshaft engine combustors. At high power (e.g. during take-off), thermal oxides of nitrogen (NOx) is enhanced whereas carbon monoxide (CO) and unburned hydrocarbons (UHC) are dominant at low power (e.g. during idle) [3]. Aeroengine manufacturers are constantly improving energy processes in turboshaft engines to improve energy conversion efficiency and meet emission regulations for NOx, CO, and UHC. With the increasingly stringent regulation of fuel consumption and pollutant emission, modern turboshaft engines is therefore required to explore efficient and cleaner combustion technology.

In recent years, trapped vortex combustion (TVC) technology [4] as a novel combustion technology, has gained more and more attention and may become the next-generation combustion technology [5]. The TVC is an innovative combustor concept that departs from the traditional swirl stabilized designs used in gas turbine engine combustors for the past 60 years. The performance improvement obtained from the previous studies: 1) 40% expansion of the operating envelope of effective combustion efficiency above 99%; 2) 50% reduction in engine blowout limits; 3) 50% improvement in relight if blowout occurs; 4) 55% reduction in NOx for the advanced commercial engine cycle as compared to the 1996 International Civil Aviation Organization (ICAO) standard; 5) 50% reduction in combustion lengths [6–19]. Because of these characteristics, TVC has obvious advantages in improving energy conversion and conservation efficiency. For the past 25 years, TVCs are

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Nomenclature

f_{ig}	fuel to air ratio at ignition
FAR	fuel to air ratio
OFAR	overall fuel to air ratio
P	air pressure, Pa
P_3	inlet total pressure, kPa
Q_e	vortex flowmeter data, m^3/h
R_g	gas constant of air, J/(kg·k)
T	air temperature, K
T_3	inlet air temperature, K
TVC	trapped vortex combustion
U_a	inlet air velocity, m/s
W_{a3}	air mass flow rate, kg/s
W_f	fuel mass flow rate, kg/s
x_n	independent measured parameter
Y	measured parameter
ρ	air density, kg/m^3
$\varepsilon_{f_{ig}}$	uncertainty of ignition FAR
ε_P	uncertainty of precision pressure
ε_{Q_e}	uncertainty of vortex flowmeter
ε_T	uncertainty of thermocouple
$\varepsilon_{W_{a3}}$	uncertainty of air mass flow rate
ε_{W_f}	uncertainty of fuel mass flow rate
ε_{x_n}	uncertainty of dependent parameter
ε_Y	uncertainty in the measurement

widely applied to large-scale gas turbines, waste incinerators, ramjets, scramjets, ultra-compact and high-g combustors, inter-turbine burners, in-situ and flameless reheat combustors [20] as a promising combustion technology for energy conversion and conservation. To our knowledge, there is no publicly published literature showing that the trapped vortex combustion technology has been used on small turboshaft engines and no one has investigated this idea of stabilizing a flame on turboshaft engine combustors. One of the goals of this paper is to fill this gap.

The combustor would face serious technical challenges and requirements in the development. One of the primary requirements of the turboshaft engine combustor is to achieve easy and reliable lightup during ground starting [1,21,22].This is very important especially for the turboshaft engine in China, which has a vast territory and complex meteorological conditions. The operating conditions of the combustor vary greatly with the change of altitude in the plateau. It must sometimes operate at low temperatures and pressures, and at FAR encountered in flight that lie well outside the normal limits of flammability for hydrocarbon/air mixtures. Increasing the complexity of aircraft tasks and variations in the operating conditions, an additional requirement of rapid relighting of the combustor after a flameout in flight under transit conditions at high altitude is more prominent [23]. Since the TVC concept was proposed by AFRL (Air Force Research Laboratory) in 1990s or late 1980s [4,24,25], the TVC extensive research has already been conducted to shed lights on the fundamental physics and mechanisms of cavity-based flame concepts, the development and evolution history of TVCs, the cavity flow/aerodynamics, fuel-air injection and mixings, emissions and combustion performances, combustion of alternative fuels, and aero-acoustics characteristics [20]. Unfortunately, a complete set of the effects of flow parameters such as pressure, temperature and velocity on ignition performance characteristics are not available in the archival literature. It is believed that the ignition is a complex process including the evaporation and mixing of fuels [26,27]. If the ignition performance of a combustor is unsatisfactory, the first step is to find out in which stage the bottleneck should be arising in the ignition process. This information can be obtained quite readily by examining the position of the ignition loop in relation to the stability limits. While, the details of the processes occurring during the ignition of the TVC has not been systematically investigated and rarely reported by researchers.

The primary objective of this paper is to develop and evaluate the TVC concept for turboshaft engines, named mixed-flow TVC. The mixed-flow TVC being developed differs from conventional TVCs and uses axial staged combustion with a rich-quench-lean design approach. All of the liquid fuel is injected into the cavity. Mainstream airflow is used to trap the vortices in the cavity increasing the mixing time, and provide addition air to mix with the partially hot products to complete combustion and quench NOx formation. The mixed-flow TVC is designed as a combustor that combines the characteristics of the reverse-flow combustor and the through-flow combustor. Thus, the mixed-flow TVC is named. The main advantages of this layout are efficiently using the available radial space behind the centrifugal compressor and allowing close coupling between the compressor and turbine. A novel concept combustor can be obtained that provides a more compact unit, a short shaft length and low surface-to-volume ratio. The other objective of this paper is to conduct an in-depth study on the effect of flow parameters on the ignition performance of the mixed-flow TVC. The present study is different from previous work by paying a great attention to the ignition process of the mixed-flow TVC to obtain basic information about the chain of reasons for the superior ignition performance of TVC. Continuous shooting of flame images by a high-speed camera is an effective method to investigate the ignition process [28–30]. A better understanding of the ignition process trends and influence of flow parameters will provide a much-needed foundation for the design of a novel compact mixed-flow TVC for turboshaft engines.

2. Experimental details

2.1. mixed-flow TVC sector test rig

The mixed-flow TVC is mainly composed of diffuser, liner and casing. The high-pressure airflow out from the axial diffuser enters the liner is divided into two parts: one part is injected to the cavity for combustion, and the rest of air is for liner dilution and combustor cooling purpose. A cross-section of the basic geometry of the TVC illustrate some of the key features and flow patterns as shown in Fig. 1.

The combustion air flows into the cavity from a direction which is opposite to that when the air enters the combustion zone from the outer passage. This is similar to the reverse-flow combustor concept. Meanwhile, the dilution and cooling air flow in the liner from a

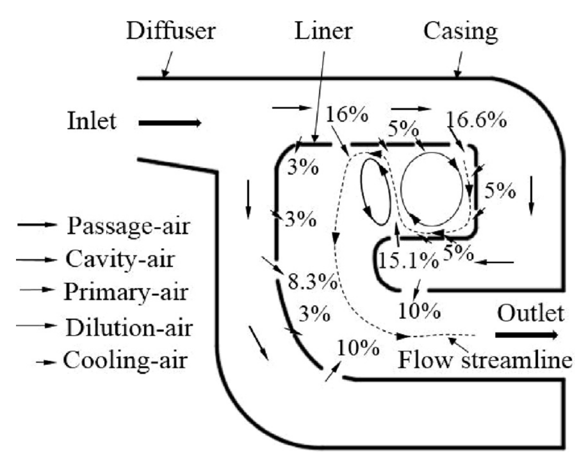

Fig. 1. Flow patterns and airflow distribution of the mixed-flow TVC.