Applied Energy 225 (2018) 940–954

Contents lists available at ScienceDirect

Applied Energy

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

Combustion and stability characteristics of ultra-compact combustor using cavity for gas turbines

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HIGHLIGHTS

- An asymmetric ultra-compact combustor was designed based on trapped-vortex combustion technology.
- The compactness and fuel–air mixing rate are important factors affecting combustion and emission characteristics.
- The relationships between flow characteristics and performance, including combustion, emission, and stability, were analysed.
- The combustor had good adaptability to the fuel type, and the emission indexes of NO_x were less than 1.5 g/(kg fuel).

ARTICLE INFO

Keywords:
Ultra-compact combustor
Trapped-vortex combustor
Cavity
Methane
Combustion characteristics
Stability

ABSTRACT

Engine efficiency, emission characteristics, and structural dimensions are important considerations for gas turbines that are used in transportation applications. Ultra-compact combustion technologies are attracting attention for use in the development of gas turbines due to their low emissions and low cost. This paper studies ultra-compact combustors for gas turbines through experimentation. Furthermore, an asymmetric combustor (fuelled with methane) is designed based on trapped-vortex combustion technology. In addition, four structural configurations of mainstream flame holders and three sizes of combustion zones are considered. The combustion, emission, and stability characteristics of seven combustors are experimentally studied in detail using a gas component analyser, particle image velocimetry, a dynamic pressure system, and a data acquisition system. The fuel adaptability of the combustor is analysed numerically. Under typical experimental conditions, the combustion efficiencies were higher than 94% and the emission indexes of unburned hydrocarbon and nitrogen oxide were in the range of 3–7 and 0.5–1.5 g/(kg fuel), respectively. Additionally, no combustion instability was observed for any experimental conditions. The inlet injection velocity of the mainstream zone (and the combustion power of the combustion zone) significantly influenced the emissions of carbon monoxide and unburned hydrocarbons, the combustion efficiency, and the dynamic pressure characteristics. The volume of the combustion zone, air injection velocity of the combustion zone, structural type, and blockage ratio of the mainstream flame holder all influenced the combustion and stability characteristics to different degrees.

1. Introduction

Structural dimensions, combustion performance, and emission characteristics are important aspects to consider in the design of combustors for gas turbines used in transportation engineering. Moreover, as the technology has developed, the inlet velocity, inlet temperature, and equivalence ratio of advanced combustors have gradually increased, improving the thrust-weight ratio of gas turbines [1,2]. This trend has made it difficult to further reduce pollutant emissions, widen the stable combustion range, or extend the service life of combustors.

With regard to the problem of pollutant emissions, various kinds of low-emission combustors have been developed for gas turbine engines, such as flameless combustion technology [3], lean premixed prevaporized (LPP) [4], rich-burn, quick-mix, lean-burn (RQL) [5], twin annular premixing swirler (TAPS) [6], variable-geometry combustors (VGCs) [7], and trapped-vortex combustors (TVCs) [8,9]. With regard to the problem of the stable combustion range, stable combustion can only be achieved by adopting the bluff-body flame holder [10] or cavity flame holder [11] under high-velocity conditions.

The vortex combustor has three main advantages. First, the trapped vortex formed in the combustion zone can be reinforced using suitable air and fuel injection [12–14], meaning that the stable combustion

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https://doi.org/10.1016/j.apenergy.2018.05.084
Received 3 February 2018; Received in revised form 10 May 2018; Accepted 20 May 2018

Nomenclature

Standard

B	volume (m^3)
c_0	acoustic velocity (m/s)
D	height of zone (mm)
d_0	diameter of pressure transfer tube (m)
EI	emission index (g/kg fuel)
H	height of inlet channel (mm)
$\|H(j\omega)\|$	amplitude characteristics
H	height of mainstream holder (mm)
J	velocity gradient tensor
L	length of pilot combustion zone (mm)
L_0	length of pressure transfer tube (m)
P	pressure (Pa)
Q	flow rate (kg/h)
R	anti-symmetric part of velocity gradient tensor
Re	Reynolds number
S	symmetric part of velocity gradient tensor
T	temperature (K)
U	velocity
V	velocity (m/s)
Λ	eigen value
Δ	total pressure loss coefficient
Z	damping rate
Y	kinematic viscosity (m^2/s)
ψ(ω)	phase frequency characteristics
Ω	frequency (Hz)
[·]	molar
C, M, a, m, n, x, y	constant

Sub and superscripts

0	characteristic value
Cavity	cavity zone
Inlet	inlet of combustor
Jet	injection zone between two combustion zones
Main	mainstream zone
Pilot	combustion zone
Species	species of emissions, including CO, NO_x, and UHC

range can be very wide due to the adaption of the combustion zone [11,15]. Second, superior combustion performance can be achieved by preheating combustion by-products in the combustion zone [8]. Third, pollutant emissions can be reduced through the rational control of temperatures in the combustion zones, where temperatures should be kept below 1850 K to limit NO_x and smoke emissions [1]. Previous results demonstrated the low emissions of a combustor fuelled with methane or liquefied petroleum gas [5,16]. The trapped-vortex combustion mode has high potential for practical applications in gas turbine engines.

Several ultra-compact combustors based on trapped-vortex combustion technology have been designed and discussed. High combustion performance and low emissions were achieved [17–20]. Several types of trapped-vortex combustors have been proposed, and these research results have shown significant improvements in the combustion and emissions characteristics. Various factors that affect the performance of trapped-vortex combustion have been studied in detail, which has led to many performance improvements [21,22].

Ultra-compact combustion was initially studied for use in inter-turbine burners. Here, an inter-turbine burner is placed between the high- and low-pressure turbines of a gas turbine. Thus, large amounts of shaft power can be extracted from the low-pressure turbine by burning between the turbine sections. A conventional combustor cannot meet the required demands due to its large axial length. Ultra-compact combustors were explored both numerically and experimentally, and the axial flame lengths of ultra-compact combustors were extremely short compared with those of the conventional combustor [23].

A design method that prevents vortex shedding out of the cavity should be used to account for flow resistance. To improve the combustion efficiency, the efficiency of mass extraction from the cavity into the mainstream should be improved. Thus, the shape and dimensions of the vanes and the radial cavity were optimized, and the axial length and volume of the cavity were reduced. The high-acceleration and high-turbulence environment formed by the injection of fuel and air into the cavity helped to reduce the flame length. The results of the study demonstrated the possibility of applying ultra-compact combustion techniques to the inter-turbine burner [24]. There was a mass exchange between the circumferential and flow cavities, which affected the temperature distribution uniformity of the combustor exit. The OH distribution obtained by planar laser-induced fluorescence (PLIF) was used to analyse the mass exchange process. The effect of the cavity structure on the combustion temperature profile was analysed based on the OH distribution. The temperature distribution of the combustor exit was not sensitive to the fuel–air ratio, indicating that an ultra-compact combustor could be constructed with a simple fuel supply device [25]. All the above-mentioned studies on ultra-compact combustion were carried out with reference to the inter-turbine burner of a gas turbine. The design of the novel combustor (to be used as a major combustor)

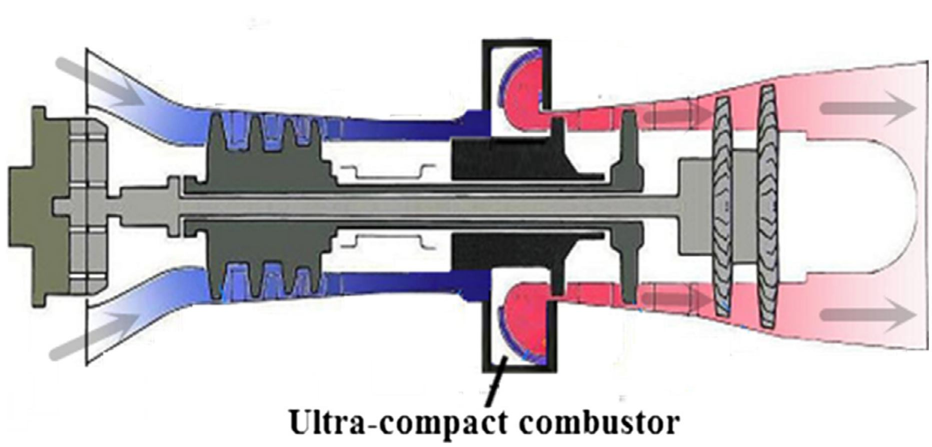

Fig. 1. Schematic diagram of a typical gas turbine using an ultra-compact combustor.