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Experimental study of lean ignition and lean blowout performance improvement using an evaporation flameholder

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ABSTRACT

The hyperburner of a turbine-based combined cycle (TBCC) works at a relatively low temperature and high local velocity flow conditions compared with an afterburner or a ramjet combustor. Therefore, wider lean ignition and blowout limits are required in a TBCC. Both a circular and crescent-shaped evaporation tube flameholders were designed and numerically simulated. Moreover, experiments were performed to measure the lean ignition and blowout performance for the two flameholder types under conditions of T = 450–650 K and Ma = 0.1–0.4. The results indicate that a crescent-shaped evaporation tube provides steady high temperature wake flow, thereby increasing the fuel evaporation rate, and that a crescent-shaped evaporation tube flameholder is superior to a circular evaporation tube flameholder; this is because the wake flow of a crescent-shaped evaporation tube is not affected by the Mach number of the flow. This is beneficial for both reliable lean ignition and wide lean blowout limits. For flows with high Mach numbers, when compared with a circular evaporation tube flameholder, the lean ignition and blowout performance is strongly enhanced for a crescent-shaped evaporation tube flameholder. The experimental results show that a crescent-shaped evaporation tube flameholder exhibits much better performance under flow conditions where T = 450 K and Ma = 0.4. The lean ignition and lean blowout equivalence ratios of a crescent-shaped evaporation tube flameholder were only 31% and 47% that of a circular evaporation tube flameholder, respectively.

1. Introduction

Turbine-based combined cycles (TBCCs) are a promising choice for next generation hypersonic flight propulsion systems. A tandem combined cycle engine employs a tandem arrangement of a turbo-core engine and ram combustor. A new augmentor called hyperburner is used in this engine. The engine thrust and air flow rate require stable acceleration to reach a hypersonic cruising speed, and a large range of flow conditions occur in the combustion chamber. The most critical challenge is to ignite and maintain stable combustion to enable transition from a low-velocity to a high-speed propulsion system [1–3]. General Electric and NASA have previously conducted the Revolutionary Turbine Accelerator (RTA) project. In this combined cycle engine, some of the salient features of the F110 engine augmentor, such as advanced integrated fuel injector flame holder struts and a trapped vortex liner, were included [4]. Partial-scale component rig experiments and design analysis showed that the hyperburner has wide stability limits and high chemical combustion efficiencies. Computational fluid dynamics (CFD) simulation results show the swirling vortical flow created inside the trapped vortex cavity and its interaction with struts located in the main core region. The predictions showed that the swirling flow from the trapped vortex region ingested into the low pressure regions created aft of the struts. The flow burner concept is capable of meeting the high performance goals of the RTA engine [5,6].

Successful combustion organization and combustion chamber design on an aircraft engine afterburner are important references for flame stability design of a TBCC hyperburner [7,8]. With the development of LDV/OH PLIF/PIV and high-speed photography, research on the ignition and extinction chemical kinetics and mechanisms of bluff body stabilizing flames have progressed further. Kiel revealed that vortex dynamics and not geometry is the dominant mechanism behind bluff body flame extinction. By summarizing many previous conclusions about bluff body lean extinction, they concluded that blowout is largely determined by the Damköhler number, rather than other dimensionless parameters. This dimensionless parameter correlates to the fluid dynamic time scale of the bluff body and the pressure and temperature that determines the chemical time scale. Moreover, his work concludes that flame holder size, and not shape, is the driving parameter

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Notation

κ	turbulent kinetic energy	Da	Damköhler number
ε	turbulent dissipation rate	mm	millimeter
SIMPLE	semi-implicit method for pressure linked equations	τ_{chem}	chemical reaction time scale
k	chemical reaction rate	τ_{flow}	mixture residence time scale
K	Kelvin temperature	L_{ref}	length of the recirculation region
T	flow temperature	Φ	equivalence ratio
U	flow velocity	E	fuel activation energy
Ma	Mach number		

representing geometry [9–11]. Chandhuri's experimental work shows that near blowoff, local flame extinction first occurs along the shear layers. Following extinction, fresh reactants entrain and then react within the recirculation zone, with all other parts of the flame extinguished. This flame kernel within the recirculation zone may survive for time scales of approximately one hundred milliseconds, potentially re-igniting shear layers and causing the entire flame to be re-established for a short period of time. This shear layer extinction and re-ignition events can occur several times before final blowoff, which occurs when the flame kernel fails to re-ignite the shear layers before being extinguished, thus leading to global flame extinction [12–14]. The work by Steven reveals that coherent wake structures play a role not only in extinguishing the flame sheet but also in dissipating the hot products that are crucial to anchoring the flame at the bluff body edge. By comparing both high speed images and simultaneous OH PLIF/PIV between the vitiated and unvitiated conditions, it was observed that the Bénard-Von Kármán instability is much more coherent and that the blow-off process is much more abrupt in vitiated flows [15]. For engineering applications, the SPEY MK202 and AL31-F engine afterburners exhibited superior ignition and flame stability advantages with a particular evaporative flame stabilizer [16]. In the SPEY MK202 engine afterburner, a circular evaporation tube stabilizer with three circles was designed to obtain wider blowout limits and meet engine propulsion performance requirements. The AL31-F engine afterburner is equipped with a special V-shaped evaporation stabilizer, to which an evaporation tube is fitted on the non-air inlet of a small V-gutter stabilizer. The recirculation zone behind the small V-gutter stabilizer provides an advantageous ignition mixture.

Because of the large bypass ratio in a tandem combined cycle engine [17], low flow temperatures and high local velocities produce disadvantages for ignition and flame stability in a TBCC hyperburner. At present, the inlet temperature range of an afterburner is 650–1050 K, whereas for a TBCC hyperburner, the inlet temperature can be as low as 450 K. The boiling point of aviation kerosene is between 450 and 550 K, so the inlet temperature is lower than the boiling point of kerosene, which is adverse to fuel atomization. The inlet flow Mach number of an afterburner is generally not greater than 0.25, whereas the local Mach number of a TBCC hyperburner can be as high as 0.4 under ramjet mode. However, the question remains whether the afterburner evaporation stabilizer can meet the broader scope of ignition and stable boundary flow conditions when it is directly applied to a TBCC hyperburner.

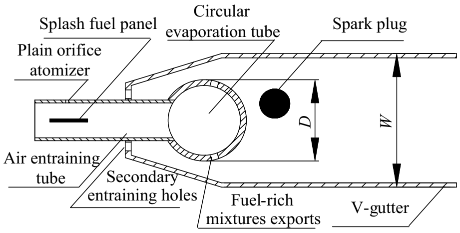
In this study, work was performed regarding the lean ignition and blowout limits of crescent-shaped and circular evaporation tube flameholders. The experimental and CFD simulation results show that a crescent-shaped evaporation tube flameholder greatly improved the lean ignition and extinction performance than a circular evaporation tube flameholder. This is because the wake vortex behind the evaporation tube not only provides suitable flow conditions but also improves the fuel evaporation rate in the evaporation tube. The lean ignition and blowout equivalence ratio was only 31% and 47% that of a circular evaporation tube flameholder, respectively, under inlet flow conditions of T = 450 K and Ma = 0.4.

2. Experimental system

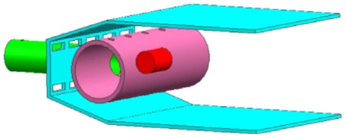
2.1. V-gutter flame-holder with pre-vaporization

The evaporation flameholder works as follows. Fuel is injected in an air entraining tube using plain orifice atomizers. It first spits on the splash fuel panel and atomizes it into uneven-sized droplets. Then, it enters in a circular evaporation tube. A rich fuel gas mixture is formed and spurts out of the vent hole after the evaporation of the fuel and its mixing with air in the tube. Then, the rich fuel gas mixture combines with secondary air coming from secondary air entrained holes on the head of the flameholder, which forms an appropriate mixture suitable for ignition and combustion. The reason that the flameholder is beneficial for ignition and flame stability is due to the small wake flows behind the evaporation tube and large-scale wake flows at the rear of a V-gutter flameholder. A spark plug is located in the small reflux zone behind the evaporation tube, where the flame is ignited and stabilized. Then, the flame spreads out to the large-scale wake flows at the rear of the V-gutter flameholder, and thus, ignition occurs in the entire burner. For a general V flameholder, the ignition zone fuel concentration is influenced by the mainstream fuel distribution, and the combustor pressure pulsates vigorously during the ignition period. However, for an evaporation tube flameholder, the ignition zone fuel concentration remains unaffected owing to the existence of a small reflux zone behind the evaporation tube. By adjusting the mass of fuel flowing in the plain orifice atomizer, we can control the ignition zone equivalence and achieve soft ignition.

The evaporation tube of a traditional evaporation flameholder is circular, as shown in Fig. 1. We present a crescent-shaped



(a) Structure diagram



(b) Schematic diagram

Fig. 1. Sketch of a circular evaporation tube flameholder.