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Experimental studies on injection nozzle flame stability for gas turbines using in-situ combustion applications

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Abstract

This paper presents the experimental results of the test conducted on 3 different geometries for injection nozzles. The objective of these experimental studies was to determine the optimal configuration with respect to flame stability in high velocity flows and aiming for an increase in temperature small enough to be comparable with the decrease in temperature due a subsequent expansion. These conditions are a consequence of the intended application, gas turbines using in-situ combustion. This uses a supplementary combustion in the turbine, intended to best approximate an isothermal expansion that would ensure a better efficiency for the gas turbine. Taking into account the drop in temperature is of approximately 100 degrees after a turbine stage, and the flow velocity is about 100 m/s at the exit of the turbine stage, a suitable solution was sought. The experimental results shown that none of the tested configurations matched the desired conditions, but one of the three geometries had a significantly better behaviour. At the same time, it was concluded that the number and dimension of the injection holes do not play a major role in flame stability in high velocity flows, but rather their shape. The injection nozzles with divergent holes proved to be the most stable and to provide the smallest increase in temperature for high velocity flows.

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Keywords: experimental; flame stability; gas turbine; in-situ combustion

Nomenclature

h	enthalpy
s	entropy
M	mass flow rate
T	temperature
V	velocity
ϕ	equivalence ratio

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1. Introduction

A turbine using in-situ combustion is a turbine in which fuel is injected and combusted, operating on a thermodynamic cycle which is a hybrid between the Ericsson and Brayton cycles, as we can see in Sirignano and Liu (1999), Liu and Sirignano (2001). The main difference resides in the way the turbine expansion occurs: adiabatic in the Brayton cycle, and isothermal in the Ericsson cycle. By releasing combustion heat inside the turbine, the expansion process departs the adiabatic curve in the enthalpy-entropy plane, and approaches an isothermal, the degree of approximation being a direct function of the capability to burn small amounts of fuel at numerous axial positions along the turbine (Fig. 1).

Earlier studies demonstrated the benefits of using reheat in the turbine to increase specific power and thermal efficiency, particularly when the turbine is connected with a heat regenerator, Sirignano and Liu (1999). A thermodynamic analysis demonstrates performance gains for turbojet engines with turbine-burners and for turbofan engines with inter-stage reheat turbines, Liu and Sirignano (2001). A pioneer cycle study by Sirignano and Liu (1999) compares the performance of a jet engine using traditional compression together with isothermal expansion. For low flight speeds, it was shown that the turbine burner uses less fuel than an afterburner engine but more than a traditional jet engine. For high flight speeds (above Mach 2.2), the turbine burner shows the best fuel economy. The turbine burner also enables a reduction in the size and weight of the engine. Previous numerical simulations, Cizmas (2003) and Chambers et al. (2006), showed that the best location for fuel injection is at the trailing edge of the inlet guide vane. No reliable information exists on the pollutants emission for an aviation turbine-combustor engine model that is mainly due to the lack of a well suited the kinetic mechanism. There is, though, one research report that mentioned approximately 15 % reduction in NOx normalized emissions for an in-situ reheat ground-turbine, Bachovchin et al. (2004). However, the fact that the specific power increases even in the absence of heat regeneration may be turned around and used to reduce the fuel consumption for the same engine power. As a result, the maximum cycle temperature decreases, thus enabling an overall NOx and pollutant emission reduction. By distributing the fuel combustion throughout the turbine, as close as possible to isothermal expansion, such that the overall engine thrust remains unchanged, a smaller temperature variation throughout the combustion process is obtained along with a reduced cycle maximum temperature.

Due to the distributed fuel injection and combustion, both in the main combustor and in the turbine combustor, the amount of fuel to be burned at each location is smaller, thereby allowing a more complete and efficient combustion, decreasing the amount of Unburned Hydrocarbons (UHC) and also the emission of solid particles (e.g. soot), creating the premises for a greener aircraft engine. On the other hand, when comparing real cycles, for components having same efficiency and if only isothermal expansion is considered, without constant temperature compression, the efficiency of the cycle falls below the Brayton cycle efficiency, Popescu et al. (2015), and efforts for designing better, more thermodynamically efficient turbines must be made in order to compensate this effect. Better said, an increase in the efficiency of the turbine stages, at the same power output, will maintain the initial cycle efficiency.

Turbine combustion is a recent concept, and the amount of work in the field is presently quite limited. An extensive review of recent work carried out in the field is provided in Sirignano et al. (2009), with respect to four related areas: (i) thermodynamic cycle analysis, (ii) reacting mixing layers in accelerating flows, (iii) flame holding in high speed flows and (iv) compact combustors.

Thermodynamic cycle analysis has been carried out for both continuous combustion Elliot (1963), and for inter-stage combustion Liu and Sirignano (2001), using component efficiencies based on typical, real life, values, and demonstrating performance gains related to lower fuel consumption, higher specific thrust, and enhanced operational speed and compressor pressure ratios for both turbojet and turbofan engines. The results are clearly showing benefits of the technology. Unlike this situation, the three last research areas are facing known difficult problems and only recently developed investigation methods promise to be able to handle them. It explains the current lack of understanding when they are present simultaneously and quantifies the challenge of performing stable combustion in the turbine.

Considering each area separately, we start with combustion in accelerating flows. It has been mainly studied for low Mach number reacting mixing and boundary layers, mostly for laminar, Marble and Adamson Jr. (1954), Chang (1965), Emmons (1956), Sharma (1970), but also some turbulent flows, Patankar and Spalding (1970), Givi et al. (1985). High speed reacting layers, as is the case of the problem proposed here, are scarcer, but some results on high speed flow combustion have been published Buckmaster et al. (1994), Grosch and Jackson (1991), Jackson and Hus-