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Towards lower gas turbine emissions: Flameless distributed combustion

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ABSTRACT

We report on a number of attempts in which a flameless combustor design for gas turbine applications was proposed. Through the different experimental findings of other researchers, we attempt to develop a deeper understanding of the behavior of flameless combustion systems and the major parameters impacting their emission performance. Whenever possible, we shall extend the discussion on the reported experimental/analytical results and highlight what would be considered as an interesting finding. This survey shows how the flameless combustion regime delivered on the promise of ultra-low NO_x and CO emissions levels. At some operating conditions, both of NO_X and CO levels fall to the single digit range (< 10 ppm). The flameless phenomenon pushes the limits of flame stability to very lean fuel-air mixtures. It can be achieved with various fuels and blends and using both of the gaseous and liquid fuels, whether the combustion is in the premixed or non-premixed mode. It may be thought to offer enhanced combustion stability when compared to the lean premixed combustion systems.

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1. Introduction

The desire in energy security and the increasing demand for power, which can be associated with a rapid economic or population growth, may stimulate a serious atmospheric pollution [1,2]. Renewable energy sources can be thought to provide the power needed and to mitigate the environmental impact of conventional fossil fuels, which is caused by the greenhouse emissions emanating from combusting fossil fuels. Unfortunately, there are some issues regarding the development and adoption of the sophisticated and non-conventional energy sources, such as renewables. Such a sophisticated option requires both of the following; the availability of the advanced technology to support the development of renewable systems, and a strong economy to fund the cost of investment in renewables. Consequently, the first movers towards adopting renewable energy options would be just the well-developed and rich countries of the world [3]. Technical problems would rise into consideration when variable renewable energy sources are adopted (like the solar or wind power) for integration into electric power grid. Electrical power grids and generation plants require a balance to be maintained between the supplied power and the required power demand. This power balance keeps the electrical frequency constant, at a value of 50 or 60 Hz. If the power generated from such renewable sources is not controlled properly, this power balance will be hard to maintain. Power imbalance can cause mechanical failure in the power generation machinery, and such weather-dependent energy sources might be hard to manage [4]. Basically, such considerations would delay the global shift to renewables, until they mature towards greater technical and economic feasibility. Currently, we can appreciate any transitional solutions involving the adoption of cleaner fuels and the development of cleaner combustion systems, like using natural gas as a fuel instead of the more polluting crude oil products [3,5]. The environmental concerns on burning hydrocarbon (HC) fuels and the strict emissions performance standards for gas turbines (GTs), along with the strategic need for energy security, are the reasons that motivate researchers and manufacturers to explore novel combustion technologies. Such technologies would burn different fuels, maintain an efficient thermal energy conversion, and emit less of pollutants. This is part of the endeavor to build efficient energy conversion systems that would sustain a cleaner environment. Concerning GTs, the goal is to develop leaner combustion systems applicable for both stationary and aeronautical engines. These systems would handle high heat loads at higher thermal efficiency and provide higher temperature level at the inlet of turbine stages. Such would satisfy the current and future needs for GT power and propulsion systems. Furthermore, these systems must be eco-friendly; by offering lower fuel consumption and producing less NO_x and CO emissions to cope with the strict regulations. For example, depending on the type and load of a combustion system, the Environmental Protection Agency (EPA) of the USA would regulate the maximum NO_X emissions limit to 15 ppm (at 15% O_2) [6], and that of CO emission to 130 ppm (at 3% O_2) [7]. With a more strict futuristic projection for regulations, aircrafts are planned to produce 90% less NO_X by the year 2050 [8]. Since its introduction by Wünning [9], the flameless combustion mode has demonstrated low emission levels and it is seriously considered as an interesting option to implement in different applications.

Flameless distributed combustion is also known as the Flameless Combustion (FC), Colorless Distributed Combustion (CDC), Flameless Oxidation (FLOX®), High Temperature Air Combustion (HiTAC), and Moderate or Intense Low Oxygen Dilution (MILD). These are different names describing the same phenomena [10]. From this point forward, we shall use CDC or FC. The terms "Flameless/Colorless" are used to indicate that the flames of the oxidation regions do not provide significant visual signatures, compared to conventional flames. Such flames are almost invisible and the reaction region would be transparent. For example, the flames produced by an asymmetrical combustor operated in FC mode (we shall discuss this combustor design later) did not provide much of luminosity; these flames were seen only when the laboratory lights were switched off [11]. HiTAC commonly describes the regenerative industrial burners that preheat air beyond a temperature of 1000 °C. The term "Distributed" indicates that the reactions zone is widely distributed, such that the reactions are uniformly occurring over a large volume of the combustor. There is no single point of ignition in the fuel-air mixture and the reaction occurs throughout the whole volume, rather than occurring within an established and stable thin flame front. This distributed regime of combustion promotes a lower combustion temperature – for now the heat is released throughout a large volume – and a uniform temperature distribution across the combustor with leveled temperature gradients. Such uniformity mitigates the formation of hot-spots and lowers the global peek flame temperature, which reduces the production rate of thermal NOx. Achieving this thermal field uniformity of FC mitigates the formation of hot streaks near the combustor outlet and promotes a leveled radial profile of temperatures at the turbine inlet. This would prevent any thermo-mechanical damage to the turbine blades and the hot components downstream of the combustor. This would result in extending the service life of these high-value parts and a reduction in their maintenance costs. Extended life is an essential requirement with the continuous increase in turbine inlet temperatures (TIT) in GT engines [12]. In [13], it was reported that both the 1st and 2nd rows of turbine blades were damaged by the non-uniformity of TIT. Also, in [14,15], it was concluded that the over-heating of the hot turbine sections and the temperature variations along them (due to firing a fuel of a different composition from the standard one) would reduce the life of the most affected components by 20–43% of the standard life. It has been established that a high temperature of the turbine blades' metal necessitates a reduction in both the allowable stress applied on blades and their predicted creep life; this is quantified via the Larson–Miller parameter (LMP) [16]. For a typical high-pressure, high-temperature and internally cooled turbine stage, sensitivity analysis was conducted on the