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Swirling distributed combustion for clean energy conversion in gas turbine applications

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A R T I C L E I N F O

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A B S T R A C T

Distributed combustion provides significant performance improvement of gas turbine combustors. Key features of distributed combustion includes uniform thermal field in the entire combustion chamber, thus avoiding hot-spot regions that promote NO_x emissions (from thermal NO_x) and significantly improved pattern factor. Rapid mixing between the injected fuel and hot oxidizer has been carefully explored for spontaneous ignition of the mixture to achieve distributed combustion reactions. Distributed reactions can be achieved in premixed, partially premixed or non-premixed modes of combustor operation with sufficient entrainment of hot and active species present in the flame and their rapid turbulent mixing with the reactants. Distributed combustion with swirl is investigated here for our quest to explore the beneficial aspects of such flows on clean combustion in simulated gas turbine combustion conditions. The goal is to develop high intensity combustor with ultra low emissions of NO and CO, and much improved pattern factor. Experimental results are reported from a cylindrical geometry combustor with different modes of fuel injection and gas exit stream location in the combustor. In all the configurations, air was injected tangentially to impart swirl to the flow inside the combustor. Ultra-low NO_x emissions were found for both the premixed and non-premixed combustion modes for the geometries investigated here. Swirling flow configuration, wherein the product gas exits axially resulted in characteristics closest to premixed combustion mode. Change in fuel injection location resulted in changing the combustion characteristics from traditional diffusion mode to distributed combustion regime. Results showed very low levels of NO (~3 PPM) and CO (~70 PPM) emissions even at rather high equivalence ratio of 0.7 at a high heat release intensity of 36 MW/m^3-atm with non-premixed mode of combustion. Results are also reported on lean stability limit and OH^* chemiluminescence under both premixed and non-premixed conditions for determining the extent of distribution combustion conditions.

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1. Introduction

Regulations concerning emissions, along with concern for cleaner environment have motivated combustion engineers to develop novel combustion techniques for achieving ultra low levels of pollutants emission (such as, NO_x, CO, unburned hydrocarbons and soot) from gas turbine combustors. Recently, colorless distributed combustion (CDC), which shares similar principles of high temperature air combustion (HiTAC) [1], has emerged as a novel promising option to achieve near zero emissions of NO_x and CO in addition to significantly improved pattern factor, stable combustion and low noise emission for gas turbine combustion application. The name colorless is due to negligible visible signatures from the flames as compared to conventional flames in gas turbine combustors.

In conventional gas turbine combustors, swirlers are commonly used so that the flow entering the combustor has not only axial component of velocity but also tangential and radial velocity. Swirl provides hot gas recirculation zone at entrance to the combustor for better mixing of the reactants and enhanced flame stability. A recirculation zone is created downstream of the swirler, wherein the flow reversal results in mixing of hot product gases with the incoming fresh stream of reactants. This provides high and uniform temperatures in the combustion zone in the form of a well stirred reactor. The hot mixture provides the ignition energy for the fuel to ignite and stabilize the flame. In premixed condition, the reaction zone is stabilized in a region where hot product gases and the fresh stream meet, and is present as a very thin reaction zone. However, in non-premixed condition, fuel is injected in the shear region formed near to the zero stream line boundaries and the recirculation region which provides the low velocity region for flame stabilization with the evolution of high temperatures from the flame. For flames operating in diffusion mode, the reaction zone is stabilized to result in large temperature gradients and hot-spot regions that result in high NO_x levels [2].

In previous studies on furnace flames using high temperature air combustion (HiTAC), avoidance of thin concentrated reaction

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front in the flame has been achieved by controlled recirculation and mixing of large amount of combustion gases with the fuel and air streams prior to ignition of the mixture to provide distributed reaction zone. Preheating of air stream has been employed to provide spontaneous ignition of the fuel with volume distributed combustion and achieve stable flame without any flame holding device. HiTAC also provides low pressure drop as compared to traditional methods of flame stabilization and provides significant fuel energy savings. However, it is to be noted that preheating of the combustion air or the fuel is neither necessary nor required to achieve distributed reactions. The concept has been successfully demonstrated to achieve low NO_x and CO emissions, stable combustion, low noise and simultaneously achieve significant energy savings using range of gas, liquid and solid fuels for furnace applications [1,3–6]. Therefore, much work has been reported under normal pressure furnaces flames of low thermal intensity (~0.1–1 MW/m^3-atm). However, for gas turbine application the combustion intensity is much higher (~20 MW/m^3-atm). In furnace flames demonstrated energy savings in industrial scale furnaces have resulted in some 30% energy saving, over 50% pollution reduction, uniform thermal field (better than 25 K) in the entire combustion chamber, compact combustion furnace size (25% reduction in furnace size), and low noise. Such simultaneous benefits have never been achieved in practical industrial furnaces. The objective here is to further develop the HiTAC technology for high intensity gas turbine combustion applications. The high temperature combustion work has been known by different names, such as, high temperature air combustion (HiTAC) [1,3], excess air combustion, and flameless oxidation (FLOX) [4].

The distributed combustion investigated here is focused on high combustion intensity for stationary gas turbine combustion application. In some cases the flame signatures are extremely low so that there is no visible flame. This mode is called colorless distributed combustion (CDC). Previous investigations on colorless distributed combustion suggest significant improvement in pattern factor, low sound emission levels and ultra low emissions of NO_x and CO [7–11]. To achieve reactions closer to distributed regime and avoid thin reaction zone and hot-spot zones in the flames, controlled mixing between the combustion air and product gases is necessary so as to form hot and diluted oxidant stream with rapid mixing with the fuel. High recirculation of hot recirculated combustion gases and its fast mixing with the fuel leads to spontaneous ignition of the fuel with distributed reaction conditions. This result in avoidance of thin reaction zone and hot-spot regions in the flame to subsequently minimize or mitigate NO_x formation and emissions produced from the Zeldovich (thermal NO_x) mechanism [1,12].

In CDC, the reaction occurs in a distributed regime due to volume distributed mixture of the combustion gases, fuel and oxidizer in the entire combustion chamber. Depending on the ignition delay time and mixing time scales, reactions will be in a distributed regime as compared to thin reaction flame front in conventional flames. Such distributed combustion can be achieved by air injection at high velocities to avoid the stabilization with large thermal gradients in the flame. This is accomplished by appropriate separation of air and fuel jets and internal recirculation of large amount of hot and active species to aid spontaneous ignition of the mixture with the evolution of distributed reaction zone. The concept of separate injection of fuel and air at high velocity with desirable and controlled amounts of gas recirculation and mixing between the hot and active species present in the product gases and fresh reactants can be applied to combustors for operating at higher heat release intensities (5–50 MW/m^3-atm [13]) for gas turbine application. These requirements can be met with different configurations of fuel and air injection into the combustor using carefully tailored flow field in the combustor.

The importance of recirculation zone generation and good preparation of the air fuel mixture for ignition cannot be overstated. One common practice used to create recirculation and stabilize combustion is to utilize swirl flow that entrains and recirculates a portion of the hot combustion products back to the root of the flame. For such combustors swirl flow characteristics plays a major role in mixing and combustion [14,15].

Swirl flows have been widely investigated for several decades because of their extensive use in all kinds of practical combustion systems, including gas turbine combustion. Numerous experiments in swirl flows have been carried out extending from very fundamental isothermal flows and reacting flows to those formed in very complex swirl combustor geometries. This is provided in the extensive work of Gupta et al. [15] under low, moderate and strong swirl conditions. Experimental results have established the general characteristics of swirl flows that reveal the important effects of swirl on promoting flame stability, increasing combustion efficiency and controlling emission of pollutants from combustion [15]. Leuckel and Fricker [16] conducted a variety of measurements using a non-premixed single swirl burner consisting of an annular swirling air jet and a centrally located non-swirling fuel jet. Chen and Driscoll [17] have provided an understanding of the physical processes that occur within the non-premixed flames by examining the enhanced mixing characteristics in swirl flows that emanate from the formation of a central toroidal recirculation zone.

In this paper, air is injected tangentially into the combustion chamber at high air velocity to form swirling motion. This air jet entrains large amounts of product gases forming a recirculation zone. The amount of recirculation is controlled so that it increases the temperature of the air and product gas mixture above the auto-ignition temperature of the fuel. In the non-premixed condition fuel is injected some distance downstream to provide sufficient mixing (required mixing time is less than the ignition delay time). The uniformly mixed fuel/air/product gas will then spontaneously ignite to result in a distributed reaction regime, instead of a thin concentrated reaction flame front in normal flames. Hence, it may be noted that CDC cases discussed here differ from conventional gas turbine flames in that it does not require a flow reversal or low velocity region for flame stabilization. The product gases mixing with the fresh mixture increase the temperature of the mixture to high enough temperatures for spontaneous ignition of the mixture in the entire combustion zone as compared to only small region of the fresh mixture for flame stabilization in conventional flames. Swirl combustors with tangential air entry have shown to exhibit high swirl intensity, which helps reduce NO_x emission and enhance flame stability [18]. In this present paper, a cylindrical combustor incorporating tangential air injection has been investigated to evaluate the key features associated with introducing swirl on the combustor flow field. Focus here is on achieving colorless distributed combustion and enhance thermal and environmental performance of the combustor with ultra low emissions. Different exit arrangements have been examined along with various fuel injection scenarios for each exit arrangement. The resulting combustion zone will be investigated in detail with view to develop ultra-low combustor for gas turbine applications.

2. Geometry and configurations

Fig. 1 shows schematic diagrams of the CDC combustor examined here. In this work, the effect of combustor gas exit port location as well as fuel injection location is investigated with swirling air flow to the combustor created through tangential injection. A combustion intensity of 36 MW/m^3-atm at constant heat load of 6.25 kW is used to simulate gas turbine combustion conditions.