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Full Length Article

# Towards colorless distributed combustion regime

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## HIGHLIGHTS

- Investigated the flowfield under swirl and distributed combustion conditions.
- PIV diagnostics assisted between air dilution and modeled lower $O_2$% entrainment.
- Integral length scale was calculated at flame boundary using OH-PLIF.
- Calculated Reynolds and Damkohler numbers identified the CDC combustion regime.
- CDC major controllers include flame thickness, velocity and controlled low $O_2$ conc.

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## ABSTRACT

Colorless distributed combustion (CDC) is a novel method for efficient and environmentally benign cleaner energy conversion of fossil and biofuels. CDC has been investigated in different configurations and geometries, with support to seek near zero emissions, uniform thermal field, energy savings, low pressure drop, and reduced combustion noise. In this paper, distributed combustion is investigated with focus on the flame-flowfield interaction and the different quantities that affect distributed combustion. The velocity field was obtained using particle image velocimetry (PIV) with focus on mean and fluctuating quantities. The flowfield information helped differentiate between the impact of increasing Reynolds number (through air dilution) and the impact of lowering oxygen concentration (through modeled entrainment). The flowfield information was further processed to give the integral length scale at the flame boundaries. The integral length scale along with the fluctuating velocity is critical to determine turbulence Reynolds number and Damköhler number. Together these numbers identify the combustion regime at which the combustor is operating. This information clearly distinguishes between traditional swirl flames and distributed combustion and helps explain the significant benefits of distributed combustion as it operates in a well-stirred reactor regime. The results revealed that major controllers of the reaction regime are flame thickness and laminar flame speed; both are significantly impacted by lowering oxygen concentration through entrainment of hot reactive species from within the combustor, which is important in distributed combustion. Understanding the controlling factors of CDC is critical for the development and deployment of this novel method for near zero emissions from high intensity combustors and energy savings using fossil and of biofuels for sustainable energy conversion.



## 1. Introduction

The quest for cleaner energy sources have motivated combustion researchers to develop novel technologies that can deliver high combustion efficiency with favorable environmental performance using available traditional and derived fuels, such as biofuels. To that end, colorless distributed combustion (CDC) offers most promise for near zero emission to conform to the increasingly stringent pollutants emission regulation. The performance of CDC has been the focus of investigations for the last decade over a wide variety of geometries, heat release intensities, and fuels [1–4], with the goals of near zero pollutants emission and overall enhanced performance. Laboratory scale experiments on CDC revealed fuel flexibility for both liquid and gaseous fuels including biofuels [4,5]. The use of biofuel without the need to change any of the combustor components as a "drop-in" fuel is critical to increase the deployment of biofuels in current and future high intensity stationary gas turbine engines. Laboratory scale experiments have revealed that different biofuels can be used directly as a "drop-in" fuel with no change to the fuel injectors/combustor geometry. These experiments have also shown that biofuels (Butyl Nonanoate

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and Hydrogenated Renewable Jet Fuel) can have lower pollutants emission compared to fossil liquid fuels (kerosene, JP-8) [5]. The results on much reduced emission is an addition to the benefits of biofuels in reducing the life cycle greenhouse gas emissions by some 60–80% (Switchgrass Fischer-Tropsch fuel [6] and Camelina hydrogenated renewable jet fuel [6,7]). Other researchers have also focused on tackling these issues concerning combustion and emissions with more focus on furnaces than gas turbine applications [8–12].

The CDC technology shares some of the basic principles on which high temperature air combustion (HiTAC) was built [13]. HiTAC has demonstrated ultra-low emissions, uniform thermal field, and significant energy gains for near atmospheric pressure furnace applications. In HiTAC, low oxygen concentration air, preheated to high temperatures along with reactive gas species are used for combustion. This method resulted in combustion gases temperature that is some 50–100 °C higher than that of the preheated low oxygen concentration fuel–air mixture just prior to ignition. The low oxygen concentration in the reactants (2–5% by volume) is achieved through the internal/external entrainment of combustion gases, which also increases the air temperature [13].

On the other hand, in CDC, decrease in oxygen concentration and increase in temperature of the fresh mixture stream is achieved through internal entrainment of hot reactive species from within the combustor. This entrainment and the subsequent adequate mixing prior to ignition are critical components in distributed combustion that results in volume-distributed reaction over the entire volume of the combustor. The volume distributed combustion is much different than normal combustion that possess a thin concentrated reaction zone characterized by high reaction rates and presence of local hot spots. It is noteworthy that the same amount of fuel is consumed but with a lower temperature rise in the combustor. This low reaction rate is achieved through increased dilution with hot reactive species that also lowers the oxygen concentration in the reactants, and simultaneously increase temperature of the reactants. The term colorless stems from the lack of visible emission from the flame under normal conditions.

The distributed combustion regime avoids the formation of thin reaction zone and the hot spot zones in the flame. This significantly helps in mitigating thermal $NO_x$ formation and emission from the Zeldovich thermal mechanism [14]. The overall temperature of the flame is low so that there is less or no need to dilute the hot gases before introducing them to the turbine. This reduces power requirements of the gas turbine's compressor to directly enhance the gas turbine efficiency and simultaneously enhance both combustor and turbine lifetime.

The enhanced thermal field uniformity can also allow the combustor to fire at higher average temperature since there will be less temperature deviation from the average temperature and lower risk of burnout along with minimal or none air cooling requirements for turbine blades. Mitigation of the cooling air requirements will help increase the amount of gases available for work through the turbine or use of smaller size compressor. Alternatively, the increased work can be used to power the carbon capture and storage equipment. The deployment of carbon capture and storage technologies is critical for continued use of hydrocarbon fuels while minimizing the resultant carbon footprint and complying with the envisioned increase in pollutants emissions regulations. These potential benefits of deploying CDC add to the importance of investigating CDC in more details for wider deployment.

There is plenty of literature investigating distributed combustion in terms of pollutants emission demonstration [1–5], requirements to achieve distributed combustion for methane fuel [15] and other fuels as well [16], that offer much insight on the role of

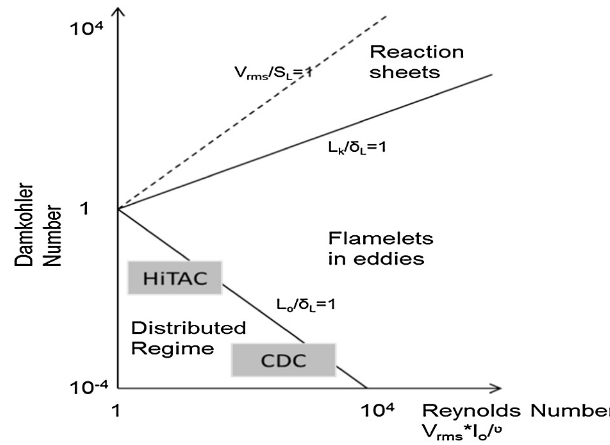


**Fig. 1.** Combustion regimes with respect to Da and Re'.

entrainment. However, critical questions still remain concerning the nature of distributed combustion and its regime with focus on flame interaction with the turbulence field. In a previous investigation, the velocity flowfield under swirl flames and distributed combustion conditions was investigated with focus to extract the difference in flowfield under the two conditions of swirl assisted combustion and distributed combustion. The information obtained from PIV was coupled with OH-PLIF to qualitatively outline the reaction behavior. It was concluded that under distributed combustion, the OH zone resided farther away from the entry jet and high turbulence region. This is much different than that found in swirl flame as previously shown by the authors [17]. In this paper, the interaction between flame characteristics and flow characteristics are compared with focus on turbulent quantities (integral length scale and turbulent Reynolds number) and reaction time scale quantities (flame speed and thickness), which have not performed before. This helps to identify and establish combustion regime for colorless distributed combustion.

Flame regimes are characterized by the reaction time scale and flow time scale. The distributed combustion regime is characterized by low Damköhler number, where the integral length scale is equal to or less than the flame thickness such that the combustion behavior is dictated by turbulent behavior rather than the molecular transport. High turbulence insures rapid mixing between entrained gases with the fresh stream, while high injection velocity prevents flame anchoring. Thus, the distributed combustion regime is different than traditional reaction sheets or flamelets in eddies regime. Fig. 1 shows the different regimes on adapted Borghi diagram [18–20], outlining the relative location of colorless distributed combustion along with the HiTAC and other flames.

Several researchers have combined different diagnostics to obtain the velocity field, and flame location and thickness for different flame configurations [21–28], resulting in useful insights for the different cases investigated in their respective investigations. However, limited data is available for distributed combustion simulating gas turbine conditions. A focus of this paper is to fill this gap.

## 2. Experimental facility

### 2.1. Experimental setup

The experiments were performed using a swirl burner under different configurations. Details of the swirl burner can be found elsewhere [29]. The experimental set-up, diagnostics, and flow