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Analyzing the Influence of Design and Operating Conditions on Combustion and Emissions in Premixed Turbulent Flames: A Comprehensive Review

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Abstract: **Recently, premixed combustion has dominated the field of combustion research worldwide. The current work is a review that addresses the effects of design and operating regimes on the combustion and emission characteristics of premixed turbulent flames. The study accounts for recent developments aimed at overcoming combustor operability issues that influence emissions and flame stability. Various experimental setups have been utilized in investigations, with results pertaining to performance and emissions concerning premixed turbulent flames. Thus, the objective of this paper is to provide a comprehensive review of the effects of swirl vane angles and equivalence fuel-air ratios for tests conducted both with and without secondary air, aiming to improve combustion performance and reduce emissions. This review extensively analyzes published studies to provide and discuss different strategies for controlling premixed turbulent combustion techniques within a wide range of swirl vane angles and equivalence air-fuel ratios.**

Keywords**: Premixed Turbulent Flame; Swirl vane angle; Equivalence fuel-air ratio; Design and Operating Regimes on Combustion; Burner emissions; Turbulence Models**

I. INTRODUCTION

Industrial furnaces serve as external combustion system utilized for power generation and aircraft propulsion. Numerous research efforts have been undertaken to fulfill the design criteria of combustors, encompassing flame stability, high combustion efficiency, and low emissions [1-6]. Flame stability is locally considered when the flame speed equals the local mean velocity, preventing flame stagnation and flashback [7-12]. Control over flame stability and combustion intensity can be achieved through the implementation of swirl mechanisms. Swirl generation necessitates the use of vane swirlers, either mechanically through rotation or aerodynamically via tangential injection into a flow stream [13-18]. The swirl flow is characterized by the swirl number (SN), denoting the ratio of the axial flux of angular momentum to the axial flux of axial momentum [19-24]. The flow field of a confined high-swirl burner comprises six primary fluid mechanic features as identified by Chterev et al.[25]. Typically, the SN of low-swirl burners (LSBs) can be determined based on three main geometrical parameters as studied by Therkelsen, P. L. et al. [26]. D.T. Yegian and R.K. Cheng [27] demonstrated the development of a simple vane-swirler capable of replacing the air-swirler employed in prior versions of the Weak-Swirl Burner, facilitating the production of a diverging flow field essential for stabilizing a lean premixed flame above the burner tube exit. Colorado, A. [28] conducted an experimental and numerical investigation into pollutant emissions and stability of gaseous-fueled reactions stabilized with two premixed-fuel-flexible and ultra-low NOx burner technologies. Therkelsen, P. [29], conducted a comparison of the aerodynamics between confined high-swirl burners (HSBs) and LSBs. Johnson et al. [30] compared a high-swirl burner (HSB) (SN=0.73) with the same burner modified for operation as a low-swirl burner (LSB) (SN = 0.5). Flow field measurements were conducted under both atmospheric conditions and gas turbine-relevant conditions of elevated temperature and pressure using particle image velocimetry (PIV). Littlejohn et al. [31] conducted laboratory experiments to examine the effects of fuel on turbulent premixed flames produced by a gas turbine LSB. Analysis of normalized velocity statistics revealed similar features in both non-reacting and reacting flow fields of the LSB. Legrand et al. [32] conducted stereoscopic PIV measurements for both conventional HSBs and LSBs.

II. GEOMETRY OF LOW SWIRL BURNER

The following section outlines some of the design constraints of Low Swirl Burners (LSBs) as observed in previous studies, accompanied by a concise overview of their configurations [33-37]. Therkelsen et al. [26] conducted a parametric study on various geometrical configurations of LSBs for methane combustion in open atmospheric conditions to ascertain design constraints. The results indicated that the swirl number (SN) should fall

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within the range of 0.4 to 0.55. The swirler can feature straight or curved vanes with angles (α) ranging from 37° to 45°. Optimal center channel to burner radius ratios (R) were observed to range from 0.5 to 0.8. Additionally, the exit length (L) can vary from 2 to 3 times the burner radius. Table 1 summarizes the design parameters of LSBs utilized in previous studies cited in the literature.

Table 1: Review on the values of the swirler design variables

Ref	Number of vanes	Vane angle α	$R = \frac{D_{hub}}{D_{SW}}$	Blockage ratio	Swirl number	Results
Therkelsen et al. [26]	16	32, 37 and 42	0.52, 0.67 and 0.8	-	From 0.4 to 0.55	1- Reduce pressure drop across the LSI. 2- Ten LSI share a common feature in that 70% to 80% of the premixture flows through the vane annulus.
Johnson et al. [30]	16	45	0.63	58%	0.5	Flow fields of the lower swirl injector are devoid of a large dominant recirculation zone.
Cheng et al. [38]	16	40	0.63	58%	0.51	1- Outer recirculation zone generated at the corner of the dump plane promotes the formation of attached flames. 2- Enclosure effects on the LSI are strongly coupled to the fuel type and dump plane geometry but are less dependent on the enclosure size
Littlejohn et al. [39]	8	37	0.776	71%	0.4	1- PRNG improves flame stability at $\phi = 0.7$ and FGR > 0.2. 2- PRNG was found to have no effect on NOx but CO was reduced significantly at $\phi = 0.8$. 3-LSB was satisfactory for predicting prompt NOx at lean and highly dilutes conditions.
Cheng et al. [40]	16	40	0.66	-	9.5	LSI exhibits the same overall behaviors at STP and at gas turbine conditions.
Day et al. [41]	8	37	0.76	78%	9.55	Lean CH4 and C3H8 flames exhibited local heat release characteristics that were similar to those of the corresponding steady unstrained 1D idealized flames.

Cheng et al. [38] conducted a study investigating the impact of combustor geometry on flame and flow field properties of a Low Swirl Burner (LSB) configured for burning hydrocarbon and hydrogen fuels in gas turbines. They varied the diameter of the confined tube attached at the burner's exit plane [42-46]. Flow recirculation was induced by low static pressure in the central core of the combustor downstream of the swirler. Swirl burners where distinct recirculation zones are formed are termed high swirl burners (HSB), characterized by intense swirl flow and the presence of a central cylindrical solid body, along with the corresponding swirl number [39].

A review of the literature indicates a limited number of studies investigating emissions using LSBs. Among the available research, Johnson et al. [30] conducted a comparison of emissions generated by HSBs (SN=0.73) and LSBs (SN=0.5).

III. LOW SWIRLBURNER EMISSION

The pursuit of premixed combustion technologies has emerged as an effective approach to mitigate undesirable emissions in industrial burners. Najib Aminu Ismail et al. [47] presented a critical review focusing on an asymmetric swirling combustor capable of operating in a flameless mode, offering excellent uniform temperature fields and lower pollutant emissions, both crucial aspects in combustion processes [48-53]. The uniform temperature field is attributed to the absence of a flame signature, enabling a broader combustion zone.

MD Azazul Haque et al.[54] delved into various combustion concepts, including lean premixed air-combustion and oxy-combustion, discussing various gas turbine burner technologies extensively. These include dry low NOx, enhanced-vortex, perforated-plate, and micromixer burners, exploring their operating principles,

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fuel flexibility, and potential for superior performance under oxy-combustion conditions [53, 55].

Sujeet Yadav et al. [56] offered a comprehensive understanding of coal combustion to mitigate emissions from coal-fired furnaces. The authors delved into thermodynamic aspects of the combustion process, while also investigating the effects of various submodels such as devolatilization, char combustion, radiation, and turbulent models on the process of pulverized coal combustion [57-59]. V N Shtern [60] reviewed counter flows, double counter flows, and circulation cells in swirling flows, arguing that these phenomena can be attributed to a common swirl decay mechanism (SDM).

Sherif S. Rashwan et al. [61] addressed the stability, approaches, and emission control of premixed flames in various applications, investigating the effects of oxidizer and fuel flexibility using oxy-fuel combustion and hydrogen enrichment on combustion efficiency and flame stability. They also discussed the impacts of operating and combustor design conditions on flame characteristics.

M.M. Noor et al. [62] provided a review and discussion of recent research and developments in Moderate or Intense Low-oxygen Dilution (MILD) combustion, examining its successful application in closed furnaces and the potential for open furnace MILD combustion. Sébastien Candel et al. [63] reviewed aeroengine combustors and gas turbines where aerodynamic injectors create a rotating component to the flow, forming a central recirculation zone that anchors the flame. They discussed how the swirl response to acoustic perturbations generates vorticity waves, influencing flame behavior.

Elkelawy et al. [64-71] highlighted the potential improvement in combustion and emissions behaviors when using alternative fuels such as biodiesel in conventional diesel engines. Additionally, they proposed co-firing solid fuel as a new method to address industrial burner combustion challenges [64, 72-74].

Marco Osvaldo Vigueras-Zúñiga et al. [75] conducted a study on flame behavior, finding that employing a high swirl number swirler in premixed flames burners promoted biogas fuel combustion in combustion chambers, resulting in reduced pollutant emissions and prevention of non-combustion zones.

Elkelawy et al. [76-79] experimentally investigated the effect of different biogas components mixed with commercial diesel fuel on combustion and emissions behaviors. Their findings indicated changes in NOx and CO emissions and flame temperature with varying biogas proportions in the combustion process [80-84].

Ziyu Wang [85] performed an experimental investigation evaluating combustion performance and flame behavior using various fuels. The study concluded that flame instability is influenced by factors such as equivalence ratio, flame radius, temperature, pressure, and diluent type and mole fraction.

X. Zhao, W. Peng, et al. [86] experimentally investigated swirl and counter-swirl configurations, finding that the counter-swirl outperformed the co-swirler in terms of producing higher flame temperatures and lower emissions concentrations. Expanding the internal point of the swirling stream contributed to the improvement of the combustion system[87, 88].

IV. MAIN ZONES IN COMBUSTOR

The basic design of combustor is generally comprises three zones, primary, secondary and dilution [89-91]. The secondary air holes are of smaller diameters and their number is large, while the swirl in the primary zone is weaker. The combustion efficiency at the end of the primary zone is always less than that at the end of the combustion processes

A. COMBUSTION IN THE PRIMARY ZONE

Within In the primary zone of real combustors, conditions are exceedingly complex, with multiple processes occurring simultaneously, including droplet evaporation, gaseous diffusion, and chemical reactions. Zakaria Mansouri et al. [92] conducted a numerical investigation of an atmospheric lean-premixed swirl-stabilized burner. The results revealed the presence of an outer recirculation zone (ORZ) in the inlet burner corner, regardless of the swirl number. Upon reaching a critical value (SN = 0.75), an inner recirculation zone (IRZ) emerged at the center of the burner inlet due to vortex-breakdown. Further increasing the swirl number to an excessive value resulted in the upstream propagation of the IRZ into the combustion chamber, leading to flame flashback.

D. Butz et al. [93-95] conducted an experimental investigation focusing on the overall flame structure by examining radial profiles of temperature and mixture fraction, along with scatter plots of temperature, CH4, and CO versus mixture fraction. They extended the gradient-free regime identification (GFRI) approach to automate the classification of local reaction zone structures. Classification criteria were established based on the ratio of local heat release rate peaks associated with premixed and non-premixed reaction zones located in close spatial proximity. An automated process was implemented to classify 1D Raman/Rayleigh sample lines into premixed, dominantly premixed, multi-regime, dominantly non-premixed, or non-premixed flame zones [96-101].

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Suresh Nambully et al.[93] introduced a method utilizing flamelet tabulated detailed chemistry, initially applied to simulate laminar flames (1D and 2D) across various grids for validation. Subsequently, the method was employed to simulate a turbulent burner studied experimentally by Suresh Nambully et al. [102].

B. DROPLET EVAPORATION

Several studies have investigated various factors influencing droplet evaporation. Gulcan Ozel-Erol et al. [103] conducted an analysis on the impact of water droplet injection on the propagation rate of statistically planar stoichiometric n-heptane-air flames using three-dimensional carrier phase Direct Numerical Simulations (DNS). Their findings revealed that most water droplets do not fully evaporate within the flame due to their high latent heat of evaporation under the considered conditions. Consequently, the cooling effect resulting from latent heat extraction during droplet evaporation predominates over reactant concentration dilution, leading to a reduced reaction rate of the progress variable and thicker flame front compared to premixed turbulent flames without droplets.

Riccardo Concetti et al. [104] investigated the effects of water droplets on combustion mode, noting a dependency on their relative position within the spray flame. This resulted in a partial shift from non-premixed to premixed mode. Additionally, spray combustion occurred under relatively fuel-richer conditions with water injection, consistent across laminar and turbulent flows. Evaporation was assumed to occur at the stoichiometric flame temperature found in the wake flame. It's worth noting that larger droplets may evaporate quickly due to their size and experience secondary atomization at critical Weber numbers[105, 106].

C. RATE OF CHEMICAL REACTION

Flame stabilization occurs through the continuous mixing of fresh mixture and recirculating combustion products, facilitated by recirculation in turbulent systems. Directional flame propagation is absent, with each element of fresh mixture undergoing three-dimensional processes of ignition and continuous reaction [107-109]. Flame speed becomes insignificant, serving only as an index of reaction rate when linked to a specific reaction zone volume and temperature level. Large-scale turbulence distorts the flame front, increasing surface area and consequently, burning velocity.

Convection turbulence and mixing patterns within combustors play independent roles, with changes in convection pattern, such as altering swirl angle, influencing turbulence intensity. At high swirl, convection mixing dominates, whereas at zero swirl, turbulent mixing prevails. Convection recirculation aids in controlling the composition of adjacent regions, reducing gradients by molecular diffusion, known as "micro-mixing," on a short timescale.

V. Pirouzpanah et al. [110] developed a mathematical model to investigate combustion characteristics in a dual-fuel (diesel-gas) engine at part loads, employing a quasi-dimensional multi-zone combustion model for diesel fuel combustion and a detailed chemical kinetics model for natural gas combustion. Rahmat Waluyo et al. [111] conducted large eddy simulations (LES) coupled with detailed chemical kinetic mechanisms to accurately predict temperature and species mass fraction in turbulent diffusion flames. Kapuruge Don Kunkuma Amila SOMARATHNE et al. [112] studied NH3/air swirl flames using large eddy simulation with detailed chemistry, revealing stabilized flames under stoichiometric and rich conditions. Di He et al.[113] performed accurate numerical simulations of methane-air combustion using the eddy dissipation concept for turbulence-chemistry interaction. Guessab Ahmed et al. [114] formulated a chemical kinetics mechanism using the Eddy-Dissipation Concept for RANS simulations of turbulent jet diffusion flames, applied to a natural gas/air flame.

D. COMBUSTION IN THE SECONDARY ZONE

All the theories outlined above can be applied to the secondary zone with varying flow characteristics. Combustion in the secondary zone holds significance for both combustion efficiency and pollutant reduction, particularly under conditions that may compromise primary zone efficiency. Practical units have measured primary zone combustion efficiencies as low as 40%. Approximately 30% of this inefficiency stems from unburned hydrocarbons, while the remainder is attributed to other gas compounds such as CO and H2. Therefore, optimizing combustion in the secondary zone is crucial for improving overall efficiency and reducing emissions in combustion systems.

V. AERODYNAMIC OF SWIRLING FLAMES IN COMBUSTION

Achieving high combustion efficiency and minimizing pollution formation are primary objectives for many designers. Both experimental and theoretical studies play complementary roles in enhancing the understanding of flow and mixing in furnaces and combustion chambers, thereby yielding improved results. Swirl burners are extensively employed in various industrial processes, including small package boilers, large power stations, and industrial furnaces [115-118].

N.V. Pilipenko [119] conducted numerical experiments on flame combustion of pulverized-coal fuel using three-dimensional modeling. The study focused on flow aerodynamics, temperature, and carbon oxides, exploring

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various pulverized-angle flame dispersities. Numerical simulation of heat and mass transfer processes is crucial for addressing modern scientific and technological challenges.

Sebastien Candel et al. [120] investigated the dynamics of swirling flames, highlighting the significance of the swirl number in defining flow structure and response to disturbances. Interaction between swirler response and incoming acoustic perturbations generates vorticity waves, influencing flame response through heat-release rate fluctuations.

M.T. Parra-Santos et al. [121] analyzed the interaction of confined non-reacting coaxial swirling jets using Large Eddy Simulation (LES). The study focused on low flow Reynolds numbers and transitional turbulent regimes, with swirl number around unity on the annular jet.

E. Gorelikov et al. [122] presented an experimental study on the aerodynamics and scalar characteristics of a premixed swirl-stabilized propane-butane/air flame. Optimal operating regimes of swirl-stabilized combustion were determined based on temperature distributions, velocity profiles, and visualization data.

Hesham Baej et al. [123] conducted numerical investigations using Computational Fluid Dynamics (CFD) to simulate a swirl premixed combustion system. Their study focused on flame stability, determining the critical recirculation zone size close to blow-off phenomenon, and correlating stability limits with total mass flow rate and equivalence ratios. They compared combustion of methane and carbon dioxide fuel blends with pure methane combustion.

VI. METHODS OF SWIRL GENERATION

The generation of swirl has been achieved through various techniques. K. Khalil, F. El-Mahallawy [124] provided an overview of flow patterns such as swirl, tumble, and squish in internal combustion engines, highlighting their impacts on turbulence enhancement, combustion efficiency, and emission reduction. Different design approaches to generate these flows, including directed ports, helical ports, valve shrouding and masking, modifying piston surfaces, flow blockages, and vanes, were summarized. The review discussed how turbulence produced by swirl, tumble, and squish flows affects combustion parameters and exhaust emissions, emphasizing the importance of improving in-cylinder turbulence through recent investigations on these flows. Further experimental and numerical studies are needed to understand the impacts of organized flows on turbulence production, combustion behavior, and pollutant formation inside the cylinder.

The International Flame Research Foundation (IFRF) utilized tangential pipes and recently introduced movable radial blocks for swirl generation. Also, employed two co-axial jets to create swirl, while swirl vanes have been widely used in industrial furnaces. An axial tangential vane type burner has been designed, claiming to offer the most versatile performance in terms of swirl generation and combustion control.

VII. SWIRL MEASUREMENTS

Swirl measurements have been conducted by various researchers due to its significant impact. Among those who have investigated swirl. Ruoyang Yuan et al. [125] conducted measurements in swirling spray flames at blow-off, studying four different fuels with varying volatilities (ethanol, heptane, decane, and dodecane). Their work aimed to explore the influence of fuel properties on the behavior of swirling spray flames under stable and blow-off conditions, understand the role of local flame extinctions in global extinction of recirculating spray flames, and provide metrics for validating combustion models.

T. Plessing et al. [126] determined the turbulent burning velocity in planar turbulent premixed flames stabilized by low swirl. They investigated six lean methane/air flames, covering both flamelet and thin reaction zones regimes. Their methodology involved measuring the probability of finding the instantaneous flame front simultaneously with the velocity field, utilizing techniques such as OH-laser-induced predissociative fluorescence combined with Rayleigh thermometry or particle image velocimetry (PIV).

VIII. COMBUSTION MODELING AND SIMILARITY

Modeling and simulation heavily rely on ensuring similarity between the processes studied in the model and the prototype. Johnstone and Thring [127] distinguished five types of similarity for flow systems, including geometric similarity, dynamic similarity, and chemical similarity. These similarity criteria lead to dimensionless groups, typically established through dimensional analysis or from equations relating to the processes under study. It is essential that these groups are equal in both the model and the prototype.

Several efforts have been made to develop suitable treatments for modeling enclosed turbulent jet systems. Johnstone and Thring [127] suggested modeling for mixing, while Launder and Spalding [128] calculated eddy viscosity as a function of turbulence energy and its dissipation rate. The theoretical analysis by Manheimer, Segal, and Wolfshtein was based on the pun and Spalding method, incorporating the turbulence model of Launder. Experimental findings indicated that flammability limits

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increase with swirl, while they decrease with increasing air flow rate. Moreover, an increase in swirl degree reduces the stabilization flame distance by approximately one-third, leading to higher temperatures and improved combustion efficiency.

IX. EFFECT OF THE SECONDARY AIR INJECTION

Gad, H. M. et al. [129] conducted theoretical investigations on the arrangement of secondary air ports and their impact on the combustion characteristics of natural gas (NG) flames. Secondary air was introduced into the combustion chamber through its first half length, with nine different port arrangements discussed. These arrangements were categorized into three groups based on vertical heights.

Kapuruge Don Kunkuma Amila Somarathne et al. [130] aimed to understand the emission characteristics of turbulent premixed ammonia/air swirl flames in a gas turbine-like combustor under high pressure, with and without secondary air injection. The study observed a decrease in NO emissions with an increase in pressure, while unburnt NH_3 emissions in rich flame conditions also decreased with pressure increase. At an equivalence ratio of 1.2, NO and unburnt NH_3 emissions were minimized to around 200 ppm of mole fraction, with 6% volumetric exhaust flow of unburnt H_2 at an operating pressure of 0.5 MPa. Introducing a secondary air injection system resulted in significantly reduced emissions, achieving NO levels of around 100 ppm of mole fraction at 16% O_2 concentration, with zero NH_3 and H_2 emissions at a primary zone equivalence ratio of 1.2. Song Li et al.[131] conducted experiments and industrial-scale tests on a 300-MW low-volatile coal-fired boiler under deep air staging. They measured aerodynamic characteristics, gas temperatures and concentrations, furnace temperatures, and boiler efficiency for various secondary air mass flow rates. Under deep air staging, a steady central recirculation zone formed near the burner nozzle. Decreasing the flow rate led to reductions in swirl intensity and maximum axial, radial, and tangential velocities. Additionally, decreasing the secondary air-box damper opening resulted in lower gas temperatures and decreased rates of temperature increase, leading to ignition occurring farther from the burner.

X. FINAL REMARKS

Turbulent combustion remains a dynamic field of research vital for the evolution of next-generation for combustion chambers. In conclusion, the following points are highlighted:

- Employment of New Combustion Technology: Innovative combustion technology offers solutions to address issues of incomplete combustion and short residence time.
- Importance of Combustor Optimization: Continual optimization of combustors remains crucial for enhancing flame stability and combustion efficiency. Novel materials with suitable thermal properties and innovative chamber designs, such as multi-inlets and combined burners, are proposed.
- Significance of Swirl Number: The swirl number serves as a key characteristic of swirling flows, with its determination best achieved through measurements of axial and tangential velocity profiles.
- Considerations for Experimental Trials: Previous trials conducted under high-temperature conditions predominantly utilized gaseous fuel to prevent probe clogging, while some using oil fuel faced challenges with geometry and failed to study the root section of the flame crucial for understanding flame aerodynamics.
- Caution Regarding Geometric Complexity: Experimental results from combustors or models with intricate geometries may lack generality, as geometric boundary conditions significantly influence flame dynamics.
- Challenges with Experimental Accuracy: Inaccuracies in experimental results can arise from the use of bare thermocouples, improper tapping point selection, and a lack of quantitative analysis between hot and cold tests, particularly under swirl conditions.
- Need for Further Investigation: More experiments are needed to explore flame behavior under high degrees of swirl, especially with oil-fired combustors.
- Limitations in Similarity Criteria: Distortions in model burner size and challenges in calculating average flame density limit the application of similarity criteria in modeling swirling flames.
- Understanding Combustion-Flow Interaction: The impact of combustion on turbulent flame flow patterns, particularly when swirl is introduced, remains a significant research challenge.
- Exploration of Equivalence Ratio and Reynolds Number Effects: Experimental and theoretical studies are required to investigate the effects of equivalence ratio and Reynolds number on combustion mechanisms, especially for commercial fuels.

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- Secondary Air Injection Angle: The influence of secondary air injection angle magnitude and model on combustor performance warrants further exploration.

- Addressing these points through rigorous research and experimentation will contribute to advancements in turbulent combustion understanding and technology.

XI. FUTURE WORKS

These proposed future works aim to deepen our understanding of swirling premixed turbulent flames through experimental and theoretical investigations. Here's a summary of the key points:

- Experimental Setup: Conduct experiments on an instrumented combustor with axial vane swirls of varying angles (20°, 30°, 45°, and 60°) to study the aerodynamic flow patterns of swirling premixed turbulent flames.

- Parameter Variation: Explore the influence of operating parameters such as equivalence fuel-air ratio (ϕ) and swirl vane angle (S) on temperature, emissions species concentrations, and velocity vectors under different conditions.

- Dual Air Systems: Investigate the effect of secondary air on premixed flame characteristics by employing a combustor with two air systems for primary and secondary air.

- Additional Parameters: Consider the impact of secondary air ratio (SAR) and the magnitude of secondary air injection angle on temperature, velocity, and species concentrations.

- Combustion Characteristics of Diesel Fuel: Analyze the combustion characteristics of diesel fuel ($C_{12}H_{26}$) under varying equivalence fuel-air ratios and swirl vane angles, both experimentally and theoretically.

- Validation and Theoretical Modeling: Validate experimental results with combustion simulations and develop theoretical methodologies to predict flame temperature distribution, emission characteristics, and velocity distributions along the flame length.

- Investigation of Flame Dynamics: Further investigate swirling flame dynamics, particularly in single- and multiple-injector configurations, considering interactions between swirling flames and potential coupling by azimuthal acoustic modes.

- Transient Regimes: Study transient regimes such as ignition and extinction in multiple-injector configurations, paying attention to interactions with swirling flows and observing phenomena like flapping modes near blow-off.

- Effect of Different Parameters on Flame Height: Investigate the impact of parameters like fuel-air ratio, equivalent burner diameter, and Reynolds number on flame height, highlighting their proportional relationships and significance.

These proposed future works represent a comprehensive approach to advancing our understanding of swirling premixed turbulent flames and addressing key challenges in combustion research.

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