Energy Proceedings
Vol 54, 2025
ISSN 2004-2965

Numerical study of the effect of flow/mixture stratification on the combustion of a dual swirl oxymethane flames for gas turbine model

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ABSTRACT

In the current work, a numerical works for oxy-methane ($CH_4/CO_2/O_2$) partially premixed flames were conducted to investigate the complex interactions between different flame features and operational factors by exploring a premixed oxymethane flame within a dual annular counter-rotating swirl (DACRS). The numerical model is validated against experimental temperature along the burner axis. The effect of equivalence ratio, oxygen fractions, and flow/flame interactions on the temperature distribution and flame structure were studied. The burner is divided internally into two annular tubes. The secondary gas stream is routed via the gap between the inner and outer tubes, while the primary gas stream is contained within the inner (pilot) tube. The velocity ratio of 3.0 is consistently maintained by the primary and secondary streams. The secondary stream's velocity is fixed at 1.667 m/s, while the primary stream's velocity is set at 5 m/s. Using this configuration, the relationships between flow and flame dynamics are investigated for a variety of equivalency ratios between different combinations of primary and secondary oxygen fractions (primary being 25%, and secondary being 39%). While the secondary equivalency ratio (φ_s) fluctuates, the primary equivalency ratio (φ_p) stays constant at 0.9. The results show that equivalence ratio changes have a significant impact on flame shape, reactivity, stability, and burner operability, whereas oxygen fraction changes have a significant impact on flame dynamics, recirculation zone formation, and temperature distribution.

Keywords: Oxy-combustion, lean premixed, dual annular counter-rotating swirl (DACRS), stratified flames.

NONMENCLATURE

Abbreviations	
DACRS	Dual annular counter-rotating swirl
OF_p	Primary oxygen fraction
OF_s	Secondary oxygen fraction
V_p	Primary velocity
V_r	Velocity ratio
V_s	Secondary velocity
Symbols	
n	Year
φ_p	Primary equivalence ratio
φ_s	Secondary equivalence ratio

1. INTRODUCTION

Gas turbines are an important alternative in an era when clean and dependable energy is required. They deliver steady electricity while having less economic and environmental consequences, both of which are critical to tackling climate change and meeting the world's expanding energy demands. Compared to coal plants, gas turbines provide better flexibility and shorter start-up times, making them an efficient energy source for a wide range of sectors throughout the world. Their low emissions assist to mitigate the effects of climate change, particularly in combined cycle facilities in conjunction with other hydrocarbon power plants.

There have been various initiatives in the realm of technology to comply with norms and regulations governing pollution emissions [1]. In accordance with broader environmental goals, these efforts employ technological breakthroughs to lessen the environmental impact of emissions. Industry strives to decrease its environmental effect via innovation and adaptability, paving the path for a more sustainable and clean future. One of these technologies is the use of clean fuels to minimize pollutants. Natural gas has received a lot of interest in this field since its principal

This is a paper for the 16th International Conference on Applied Energy (ICAE2024), Sep. 1-5, 2024, Niigata, Japan.

component, methane, is not a perfectly clean fuel but emits very little CO2 owing to high temperature combustion [2].

One approach that shows promise for reducing emissions and fuel consumption and promoting environmental sustainability is ultra lean combustion [3]. This approach is recommended because it reduces NOx, which is a commonly used way for lowering NOx in a range of applications, and it may lower the combustion temperatures as low as feasible [4-6]. A burner with a twin cone design was utilized by A. Toffolo et al. [7] to produce fuel air cross flow and airflow swirl. With this design, the fuel and air are blended to form a homogeneous mixture. This arrangement increases flame stability, bringing it close to extinction even in lean conditions, while aiming for low NOx emissions. Numerous devices, including boilers [8], gas turbines [2], internal combustion engines [9], and industrial furnaces [10].

To better understand the complex relationships between several operational factors and flame characteristics in oxy-methane premixed flames in a dual annular counter-rotating swirl (DACRS) burner, our present computational work aims to analyze these relationships. The study specifically attempts to clarify the impacts on temperature distribution, product creation rates, combustion progress factors, and flame structure that arise from the equivalency ratio, oxygen fractions, and flow/flame interactions. The study looks at how important oxygen fractions and equivalency ratios are for emissions profiles, operability improvement, and flame stabilization.

1. EXPERMETAL SETUP

As shown in Figure 1, a dual annular counter-rotating swirl burner (DACRS) is used for testing in the current investigation, as reported by our research group [11, 12]. The burner is made up of two annular tubes, the inner tube of which has a throat diameter of 5 mm being the conduit for the main gas. The main gas stream splits out at a 45-degree angle and 1.0 mm in height via an inner shroud. With internal and exterior diameters of 7 mm and 29 mm, respectively, the secondary gas stream passes through the annular gap between the inner and outer tubes. Prior to entering the combustor, the secondary gas likewise diverges at a 45^o angle over a 5.0 mm. To increase flame stability, counter-rotating inner and outer swirlers with 45° vane angles are fitted at the ends of the tubes. There are eight vanes in the inner swirler and twelve 2.0 mm thick vanes in the outside swirler.

The flame starts and continues at the end of the inner shroud within a particular-sized quartz tube that measures 12 inches in length, 3 inches in inner diameter, and 6 mm in thickness. Its design puts a strong emphasis on a shorter tube length to minimize exposure to ambient air, which should minimize fluctuations and noise during combustion. This purposeful arrangement inhibits the efficient exchange of heat and pressure between the release zones, enabling a concentrated analysis of the static instability and flame emissions alone. For a thorough investigation of combustion dynamics that minimizes outside impacts on the observed events, these components must be included.

The bottom portions of the inner and outer tubes were equipped with distinct lines for CH_4, CO_2, and O_2. This is to ensure that, before to entering the whirling zones, the gases were well mixed. Thermal mass flow controllers (Aalborg Inc.) with an accuracy of ±0.5% were used to regulate the mass flow rates of these gases. The velocity ratio (Vr) was kept at 3, and the equivalency ratio (φ_p) was held at 0.9 in the mainstream. 5 m/s was chosen as the principal stream input velocity (V_p). The oxygen fractions (OF_P and OF_S) of the primary and secondary streams were varied while keeping constants for other parameters.

Temperature was measured using an R-type thermocouple with a 1-mm junction (PtRh-13%/Pt). The thermocouple was attached to a LabVIEW data collection system that was configured to capture and average three hundred temperature readings after it had stabilized.

2. THE NUMERICAL MODEL

Formulas describe the time-averaged behaviors of turbulent reactive flows in steady state and incompressible situations were used and solved. These relations describe the average characteristics of the flow and provide information about the underlying dynamics of turbulent reactive processes. The process of developing and using mathematical formulas to forecast turbulence effects to get the temperature, pressure, and time-averaged velocity fields needed for computational fluid dynamics (CFD) analysis is known as the turbulence model. This element is necessary to improve the understanding of the results. There are several turbulent viscosity-based turbulence models, but no one model that works for all simulations. A transient standard k-ε turbulence model is used in this work. Additionally, the

Discrete Ordinate (DO) model, a computational technique that partitions angular space into finite directions, was used to do radiation modelling.

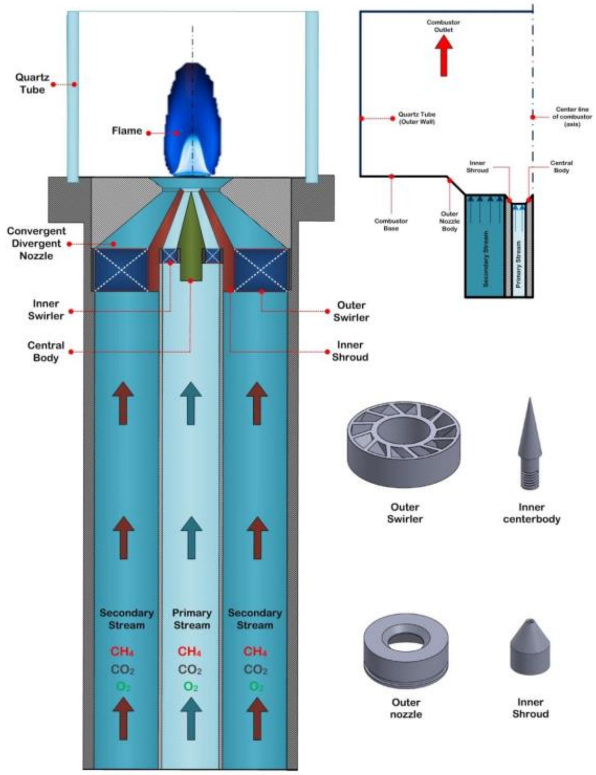

Fig. 1: Schematic of the dual annular counter-rotating swirl (DACRS) burner [11, 12].

Radiation intensity over the domain is computed by solving the radiative transfer equation (RTE) in these directions. It works well and is suggested for simulating various optical thicknesses in flames burning oxyfuel. This study used a partially premixed model as a component of the species modelling methodology. This model was adjusted for use in oxy methane simulations by adding fully premixed combustion.

3. Results and discussions

To examine the combustion characteristics of the DACRS flame, the computed data (using Ansys-Fluent 2022-R1) must be compared to experimental data. That stage is critical for verifying the computational model's trustworthiness and validating the numerical simulation. By contrasting the simulation and experimental results, the numerical representation's correctness is proven, adding validity to future study on DACRS flame combustion.

3.1 Model Validation.

Temperature is a key aspect in illustrating the features of flame combustion. An R-type thermocouple (PtRh-13%/Pt) with a 1-mm connector was utilized to assess temperature distribution in the DACRS flame. The post-processing stage included adjusting for heat radiation loss due to the thermocouple connection. For this correction, the convective heat transfer coefficient was calculated using Nusselt-Reynolds correlations [13-15]. Figure 5 depicts a comparison of the centerline temperature distributions in a DACRS flame obtained from numerical simulations and experimental measurements at an equivalence ratio of 0.9, V_p of 5 m/s, V_s of 1.67 m/s (V_r=3), primary oxygen fraction (OFP) of 34%, and secondary oxygen fraction (OF_s) of 30%. They have similar characteristics in terms of temperature distribution. Heat dissipation causes the temperature in the downstream and outer regions to progressively decrease, resulting in a little quantitative difference between the estimated and experimental values. Computed values are usually higher than observed flame temperatures. With a maximum deviation of roughly 12.9%, numerical forecasts and experimental outcomes are frequently in good agreement.

This discrepancy is attributed to potential thermocouple measurement errors, which can be caused by a variety of factors such as heat exchange and spatial variations. It is possible to rectify mistakes related to thermal radiation; however, accurately assessing these errors can be challenging for several reasons. These include the effect of inserting the thermocouple into the flame and the development of a soot layer that covers the thermocouple surface in the flame and causes mistakes in thermal resistance. Because of this, it might be challenging to determine the precise flame temperature by touch measurement because recorded temperatures usually appear lower than actual flame temperatures.

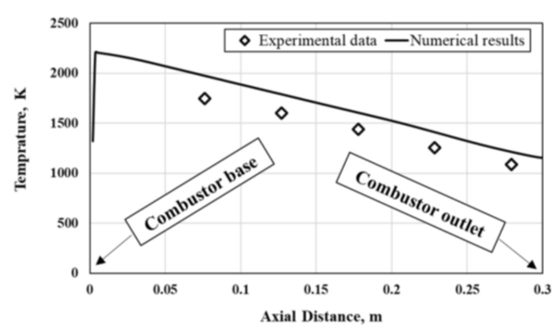

Figure 2: The predicted centerline temperature distribution compared to the equivalent experimental data at OFp=34% and OFs=30%Vp=5 m/s, Vs=1.67 m/s, φ_s= 0.8, φ_p= 0.9 and.

3.2 Effects of oxygen fraction on flame stability and macrostructure.

For the current cases 1, 2, 3, and 4, the primary equivalency ratio of 0.9 in the primary stream was maintained while the secondary equivalency ratio was changed by adjusting the equivalency ratio of the secondary stream, as shown in Figure 2. The results show that the flame gets stronger and more extended when the equivalency ratio in secondary streams increases. This indicates that the pilot flame, which has an equivalency ratio of about 0.9, supplies radicals and partially oxidized fuels, such as hydrogen and carbon monoxide, in addition to hot gases, to sustain the main flame. under case 4 with a secondary equivalency ratio (φs) of 0.55, these fuels and radicals help the fuel/air combination of the main flame burn more thoroughly, especially under highly fuel-lean situations. The effect of equivalency ratio on temperature distribution is seen in Figure 3. The maximum temperature distribution of the DACRS flame is significantly impacted by the equivalency ratio. Initially, the whole flame displays rather high maximum temperatures due to a high equivalency ratio in the secondary premixed gas. A rise in the equivalency ratio (ϕ) is associated with higher reaction rates and temperatures inside the combustor, which causes the volume of combusted gases to expand and the velocity inside the combustor to increase.

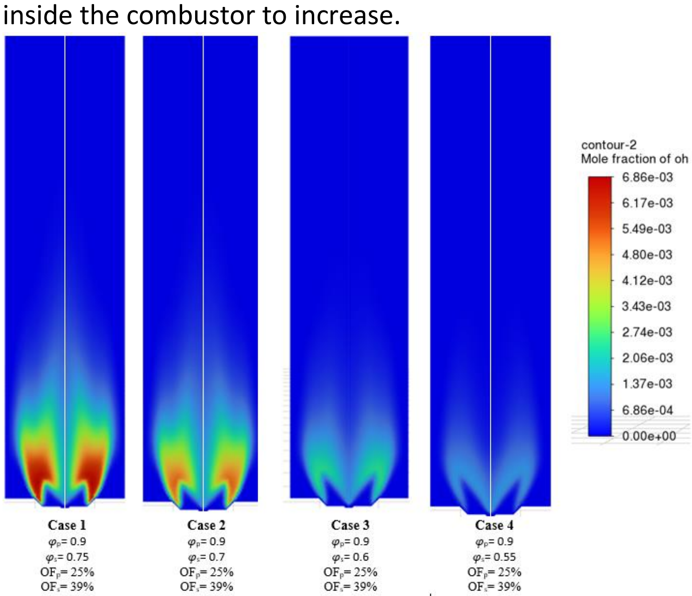

Fig. 2: profiles of OH radical concentrations at constant primary equivalency ratio of 0.9 and secondary equivalency ratios of 0.75, 0.7, 0.6 and 0.55.

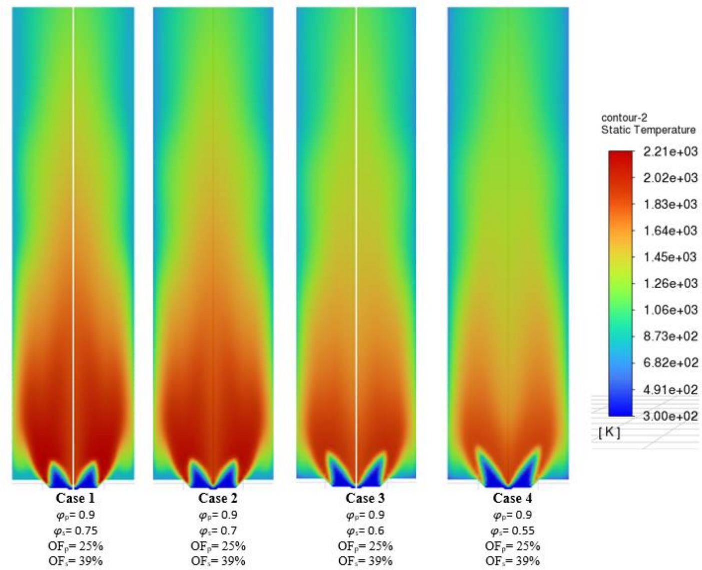

Fig.3: The effect of changing the equivalency ratio at a constant velocity ratio (Vr) of three on the temperature field at constant primary equivalency ratio of 0.9 and secondary equivalency ratios of 0.75, 0.7, 0.6 and 0.55.

H_2O and CO_2 are the main elements included in the exhaust streams that are created when oxymethane is burned. Burning releases poisonous carbon monoxide (CO) in addition to CO_2 and H_2O. In oxygen rich combustion, it is extremely crucial to monitor CO emissions because of their influence on the environment. Inadequate fuel conversion to CO_2 petrol is another indicator of increased CO emissions. The contour of the CO mole fraction along the combustor's centre plane is seen in Figure 4. By observing the changes in CO levels across the combustor's geographical distribution, one might potentially provide insight into the distribution and concentration of this combustion by product. Upon examining the full picture more closely, CO mole fractions drop as the secondary equivalency ratio decreases. One of the things causing this is the increased methane mole fraction in the secondary stream, which elevates CO levels. This rise in methane concentration causes an increase in carbon atoms since the ϕp is already high, which in turn affects the growth in CO production. This result can be explained by the fact that CO_2 dissociates more quickly at higher temperatures when it is created under larger ϕs. Consequently, the increased CO content in the combustor environment is increased by these high dissociation rates.

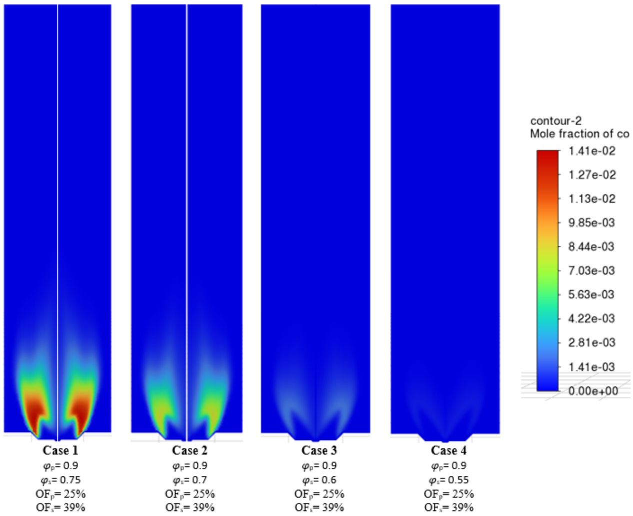

Fig.4: Contour plots depicting the distribution of CO at constant primary equivalency ratio of 0.9 and secondary equivalency ratios of 0.75, 0.7, 0.6 and 0.55.

4. CONCLUSIONS

In conclusion, a numerical study explored the interplay of flame characteristics and operational factors in partially premixed oxy-methane flames within a dual annular counter-rotating swirl (DACRS). Verification against experimental data along the burner axis revealed insights into temperature distribution, flame structure, and their dependencies on equivalency ratio, oxygen fractions, and flow interactions. The relevance of secondary stream equivalency ratios in affecting flame characteristics is clarified by the examination of the impacts of equivalence ratios on flame stability and macrostructure. In fuel-lean situations, higher secondary equivalency ratios promote more complete combustion by strengthening and extending the flame. Equivalency ratio's effect on temperature distribution highlights how important it is for increasing reaction speeds and increasing the volume of combusted gas. The complicated behavior of carbon monoxide emissions, a major environmental problem, is impacted by dissociation rates and methane concentrations. This highlights the need of monitoring and comprehending combustion byproducts in situations with high oxygen content. These results highlight the complex interactions between combustion factors and further our understanding of DACRS flame behavior.

ACKNOWLEDGEMENT

The authors wish to acknowledge the support established by King Fahd University of Petroleum & Minerals (KFUPM) done by the KFUPM Consortium for Hydrogen Future on project no. H2FC2309. The support received through the KFUPM Interdisciplinary Research Center for Hydrogen Technologies and Carbon Management (IRC-HTCM) on project no. INHT2409 is also appreciated.

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