Numerical Study of Stratified Flames Using Reynolds Averaged Navier Stokes Modeling

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ABSTRACT: Reynolds averaged Navier Stokes technique was used to develop a validated numerical model for stratified flames. The validation was carried out with the experimental data of the non-swirl flames of the Cambridge dual annulus swirl burner. The RNG $k-\varepsilon$ turbulence model along with the SG-35 skeletal chemical mechanism was found to give a good prediction of scalar and vector quantities while resulting in the reduction of computational time by 99.75% in comparison with that required for large eddy simulation techniques used in the literature. The effect of stratification at a constant input power, global equivalence ratio, and Reynolds number was examined. At stratification ratios (SRs = $\phi_{in}/\phi_{out}$) 1 and 2, intense burning, marked by the higher OH concentration, was observed close to the bluff body. Beyond SR = 2, the region of intense burning shifts downstream away from the bluff body. This is a result of the high equivalence ratio in the inner annulus, which is beyond the rich flammability limit of methane−air flames, and as a result, the primary flame region is shifted downstream after the mixtures from inner and outer annulus have mixed properly to produce a mixture with the equivalence ratio in the flammability limit. The maximum temperature was found to increase by 24.1% when the SR is increased from 1 to 2 and the combustion efficiency was found to significantly improve by 267%. The highest maximum temperature of 2249 K is observed for the mildly stratified flame at SR = 2. Beyond SR = 2, the maximum temperature decreases, while the combustion efficiency increases slightly.

1. INTRODUCTION

The introduction of compositional inhomogeneity in the reaction zones due to inlets with different compositions leads to “stratified flames”. Stratified flames are considered to be special cases of partially premixed flames wherein the fluid streams are within flammable limits such that the reaction front propagates over a range of equivalence ratios. Studies involving laminar stratified flames1–5 have shown improvement of flammability limits and a higher rate of reaction in comparison to premixed flames. The improvement is attributed to the back-supported burning, wherein the radicals and heat from the reaction zone propagate toward the mixture ahead of the flame front similar to the case of burning happening from stoichiometric to lean mixtures. Kang and Kyritsis6 reported significant improvement in flame speed prediction by taking into account the history of stratified flame propagation apart from local equivalence ratio values and its spatial gradient. Pasquier et al.7 made similar observations while experimentally examining flame propagation through a lean, turbulent, and stratified mixture of propane and air. The flame propagation in the turbulent flame was found to improve with stratification. Furthermore, in the turbulent flame, the local burning velocity can vary depending upon the local composition of the mixture and the distribution of mixture composition along the flame front.

Several laboratory scale burners have been designed and experimentally examined to study the flame propagation and behavior through stratified mixtures. Some of the prominent burners that have been extensively studied experimentally and numerically are the Oracle burner,8 Cambridge slot burner,9 Darmstadt burner,10 Cambridge Swirl burner,11 Sydney inhomogeneous piloted burner,12 and the BASIS burner.13 Sweeney et al.9,14 experimentally studied the structure of stratified flames with low turbulence. In comparison with premixed flames, the stratified flames were found to have higher surface density and scalar dissipation. However, in another burner at a higher turbulence level, the surface density, curvature and scalar dissipation were found to show negligible dependence on stratification.15 Stratification was found to elevate the $H_2$ and CO levels in the flame in comparison with premixed cases.11 Swirl was found to affect the extent of preferential transport and enhance the mean stratification
gradient. Thus, stratification can significantly impact the flame structure and behavior, necessitating further studies.

Experimental techniques while incredibly valuable and insightful can only offer limited understanding of the flow and reaction phenomenon. Numerical simulation can provide additional insights into flame behavior broadening the understanding. The large eddy simulation (LES) model can predict flame characteristics that are similar to the experimental observations. LES models the large eddies using the Navier Stokes equation by filtering the eddies of the smallest length scale. In order to model the small eddies that are smaller than the grid size, sub grid scale (SGS) models are used. The choice of the sub-grid size, SGS model, and the combustion model could affect the result of the simulation.\textsuperscript{16}

The numerical modeling of stratified flames has been carried out by many researchers using different LES and combustion models.\textsuperscript{17−19} Brauner et al.\textsuperscript{20} solved the LES/PDF-based transport equation by utilizing the Eulerian stochastic field method with reduced chemistry. Turkeri et al.\textsuperscript{21} conducted a similar study using a hybrid LES/PDF approach where the Eulerian approach discretized using finite volume method was used for solving mass and momentum equations, while the Lagrangian Monte Carlo framework was used for modeling the transport equations for the joint PDF of compositions. They compared and found better agreement with experimental results than Brauner et al.\textsuperscript{20} LES simulation of stratified flames in the Darmstadt burner has also been carried out by Ni\textsuperscript{22} Wen et al.\textsuperscript{23,24} and other researchers.\textsuperscript{25}

While the LES models can provide excellent agreement with experimental data, they are still computationally expensive requiring anywhere between 11,000 and 360,000 core hours.\textsuperscript{25} Most of the LES based modeling are carried out for small lab scale combustors. The use of computationally expensive LES in design of large-scale burners would limit the design parameters that can be studied. In order to examine the dynamics and emissions of such burners Reynolds averaged Navier Stokes (RANS)-based numerical models are used. RANS can significantly decrease the computational requirement at the expense of accuracy enabling the study of significantly large number of design parameters, contributing to the design of efficient burners. However, similar to LES models, the RANS models also need to be validated with experimental results to ensure reasonable accuracy while requiring least possible computational effort.

Ghadimi et al.\textsuperscript{26} used the RANS approach to model stratified flames. Two PDF models were used for the reaction progress variable and the mixture fraction: the β-PDF and flamelet PDF PDF approach, which were coupled with a premixed FGM chemistry model. The flamelet PDF approach was found to give better prediction than the β-PDF approach. Salehjamei et al.\textsuperscript{27} used the unsteady RANS technique to validate mildly swirling stratified flames and further carry out a study on a modified swirl burner to study the effect of angular and radial stratification. While significant efforts have been made to develop and validate numerical models for stratified combustion, these efforts have been primarily focused on LES. Furthermore, studies isolating the effect of stratification ratio (SR) without changing the input power and equivalence ratio and Reynolds number have not been discussed, in the literature, for the Cambridge burner. The experimental studies carried out by Sweeney et al.\textsuperscript{15} had different input powers for each of the stratified cases discussed. Most of the numerical studies focused on the development of numerical models for the stratified cases while analyzing the same flames as the ones reported by Sweeney et al.\textsuperscript{15}

In the present work, a comprehensive validation of a numerical model developed using the steady RANS technique for stratified combustion in a dual annular burner is presented. The validation is carried out using experimental data as well as LES results available in the literature. Furthermore, the effects of stratification at constant power input, global equivalence ratio, and Reynolds number are studied.

2. EXPERIMENTAL CONDITIONS USED FOR VALIDATION

The schematic diagram of the dual annular burner developed at Cambridge University\textsuperscript{15} is depicted in Figure 1. Each of the two annuli is supplied with a premixed mixture of fuel and air that are at different equivalence ratios. \( U_o = 8.31 \text{ m/s} \) is the velocity magnitude of the flow in the inner annulus, \( U_{co} = 18.7 \text{ m/s} \) is the velocity magnitude in the outer annulus, while \( U_{co} = 0.4 \text{ m/s} \) is the velocity magnitude of air in the co-flow region. The flames that have been used for validation are shown in Table 1. These flames correspond to cases without swirl but with varying degrees of stratification. Here, SR is defined as, SR = \( \phi_{in}/\phi_{out} \).

![Figure 1. Schematic diagram of the dual annular Cambridge open swirl burner, reproduced with permission from Sweeney et al.\textsuperscript{15} (all dimensions in millimeters).](374x475 to 497x573)

3. NUMERICAL MODELING

The numerical modeling of combustion is done using the ANSYS FLUENT commercial code. The generalized form of governing equations for the conservation of mass, momentum, species, and energy for a time-invariant flow is given as\textsuperscript{28}

\[
\frac{\partial}{\partial x_j} \left( \rho \overline{u_j} \right) + \frac{\partial}{\partial x_j} \left( \rho \overline{u_i u_j} \right) = \frac{\partial}{\partial x_j} \left( \nabla \cdot \Phi \right) + \nabla \cdot \mathbf{S} \quad i = 1, 2, 3, \ldots, n \quad j = 1, 2, 3, \ldots, n
\]

3.1. Governing Equations. The continuity equation for a time-invariant flow is written as

\[
\frac{\partial}{\partial x_j} \left( \rho u_j \right) = 0
\]
The Reynolds averaged momentum conservation equation for a time-invariant turbulent flow is written as

\[
\frac{\partial(\rho u_i u_j)}{\partial x_j} = -\frac{\partial P}{\partial x_i} + \frac{\partial(\tau_{ij})}{\partial x_j} + \frac{\partial(-\rho u_i u_j)}{\partial x_j} + \rho g
\]

(3)

where the viscous stress tensor, \(\tau_{ij}\), is given by

\[
\tau_{ij} = \mu \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3} \frac{\partial u_k}{\partial x_k} \delta_{ij} \right)
\]

(4)

Here, \(\delta_{ij} = 1\) if \(i = j\), \(\delta_{ij} = 0\) if \(i \neq j\), and \(\rho u_i u_j\) is the Reynolds stress term in a turbulent flow.

### 3.2. Energy and Radiation Equation

The energy equation considering transfer of heat due to conduction, viscous dissipation, diffusion of species, and source terms can be written as

\[
\frac{\partial \rho u_i Y_j}{\partial x_i} = \frac{\partial}{\partial x_i} \left( \kappa_{ij} \frac{\partial T}{\partial x_i} \right) + \sum_j \frac{\partial}{\partial x_i} \left( \rho D_{ij,m} \frac{\partial Y_j}{\partial x_i} \right) + S_i
\]

(5)

Inclusion of radiation from gases is important to accurately model the combustion flows. The combustion gases comprising non-luminous radiation sources such as \(\text{H}_2\text{O}\) and \(\text{CO}_2\) make the inclusion of radiation from gases important to accurately model the temperature of the combustion gases. Radiative transfer equation (RTE) is generally used in CFD to model the radiation from gases. RTE is derived based on energy balance on an elementary volume taken along the direction of a pencil of rays and confined within an elementary solid angle.\(^{29}\)

The RTE is\(^{30}\)

\[
\frac{dl(r,s)}{ds} + (\alpha + \sigma_t) l(r,s) = \frac{\kappa_0^2 \sigma T^4}{\pi} + \frac{\sigma_t}{4\pi} \int_0^{\pi} l(r,s) \Phi(\theta') \sin \theta' \, d\Omega'
\]

(6)

The discrete ordinate method has been used for modeling the RTE.\(^{31}\) The absorption coefficients (\(\kappa\)) for the flue gases are determined using the weighted sum of gray gas model developed by Smith et al.\(^{32}\)

### 3.3. Transport of Chemical Species and Chemical Mechanism

The transport of any \(j\)th species inside the combustor can be modeled using the following equation\(^{33}\)

\[
\frac{\partial \rho u_i Y_j}{\partial x_i} = \frac{\partial}{\partial x_i} \left( \rho D_{ij,m} \frac{\partial Y_j}{\partial x_i} \right) + \frac{D_{ij}}{T} \frac{\partial T}{\partial x_i} + R_i
\]

(7)

The reaction mechanism given by Smooke and Giovangigli,\(^{34}\) referred to as SG35, has been used to model the chemical reactions occurring in the combustion zone. The reaction mechanism contains 16 species and 35 elementary reactions, 10 of which are backward reactions with modified Arrhenius rate coefficients. The SG35 reaction kinetic mechanism was developed for laminar flames but has been used for numerical modeling of turbulent flames by many researchers.\(^{34,35}\) Arrhenius equation is used to calculate the kinetic rate of each reaction.\(^{36}\) The present work utilizes the eddy dissipation concept (EDC) that was proposed by Magnussen\(^{37}\) for turbulence-chemistry interaction. The EDC assumes that the reaction occurs in small turbulent structures. Mixed is burned approach is utilized in the EDC model while also enabling the use of different rate of turbulent reactions for a multi-step chemical mechanism. To accelerate the integration of the chemical kinetics, the in situ adaptive tabulation technique was used.

### 3.4. Numerical Scheme and Boundary Conditions

A numerical model developed on ANSYS Fluent 20R2 was used for the numerical study. Figure 2 shows the different domain dimensions that have been used to compare the different numerical domains that can be used for the study and further justify the choice of the 2D numerical domain used for most of the study in the present work.

The length of the numerical domains was 250 mm, while the radius was 110 mm. The flow at the inlet of the numerical domains was supplied at a temperature of 300 K. For the inner and outer annuli, a preliminary study was conducted to study and compare the use of plug flow inlet boundary condition and an inlet condition with velocity profile. The velocity profile was calculated by simulating a 3D domain for the upstream of the

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**Figure 2.** Schematic diagram of the different numerical domains that has been examined along with the imposed boundary conditions (BCs).
burner (i.e., flow in concentric tubes). A pressure outlet boundary condition was applied to the side and top of the domains where the gases exit the computational domain. The quarter 3D domain had an additional periodic boundary condition applied while the axisymmetric boundary condition was used for the 2D domain to account for their symmetry in the radial direction. At the bluff-body and the top of the tube walls, a no-slip boundary condition was used along with the adiabatic thermal boundary condition.

The RNG $k−\varepsilon$ turbulence model has been in the present study to model turbulence as it has been used by many researchers, previously, to model flows in combustion systems. The coupled algorithm was used to solve the momentum and continuity equations together. The pressure equation was discretized using second-order scheme, while the second-order upwind scheme was used to discretize other equations. When the maximum residuals of the mass, momentum, energy, and species equations were less than $10^{-4}$, the solution was said to be converged.

4. RESULTS AND DISCUSSION

This section first discusses the reasoning for the selection of inlet boundary conditions, computational domain type, and mesh size. Following this, a comprehensive validation study on the stratified flames along with a numerical study using the validated model is presented.

4.1. Effect of Inlet Conditions. The computational domain, for all the studied cases, starts from the plane of the bluff body, as such the effect of the flow inlet boundary condition was assessed. The boundary condition for the inlet can be specified as a plug flow where the flow enters the domain as a uniform flow or with a fully developed flow profile. The flow profile to be used at the inlet boundary condition was assessed. The boundary condition for the inlet was adopted for the rest of the cases. Further studies have been carried out using the 2D numerical domain.

Figure 4. Comparison of velocities along the radius at different heights from the bluff body plane using different computational domains for cold case (cSwb1) with velocity profiles as inlet conditions for inner and outer annulus. Experimental results from Sweeney et al.15

Figure 3. Comparison of the effect of using plug flow and a velocity profile derived from 3D numerical simulation for cold case (cSwb1). Experimental results from Sweeney et al.15

velocity profiles are much well developed for the 2D profile resulting in better agreement with the experimentally measured axial velocity. As a result, the use of fully developed profiles as inlet boundary condition was adopted for the rest of the cases in the present work.

4.2. Effect of Computational Domain Dimensions. Most of the numerical studies carried out in the literature using LES necessitated the use of a full 3D computational domain to model the time-dependent fluctuating components in the three axes. The modeling domain can be simplified using the axisymmetric assumption that can enable the use of periodic boundary conditions when using a quarter of the 3D domain. Additionally, a 2D domain can also be used to further simplify the model and reduce the computational cost; however, the 2D domain cannot be used for LES. A preliminary study was carried out to study the effect of a full 3D domain (3D-F), a quarter 3D domain with periodic boundary condition (3D-Q), and a 2D domain with axisymmetric boundary condition, on the numerical results. Figure 4 shows the comparison of axial and radial velocity profiles at $Z = 10$ mm and $Z = 50$ mm for the cold case (cSwb1). It can be seen that almost the same results are obtained using either of the three geometries. This conclusion is further confirmed for the highly stratified flame case (Swb9), as shown in Figure 5. On a 2.3 GHz, 32 core Haswell processor (16 × 2) with 128 GB of DDR4 memory, the 3D-F case took 25 min per 1000 flow iterations, the 3D-Q case took 13 min per 1000 flow iterations, while the 2D case took 4 min/1000 iterations, on an average. The use of 2D cases resulted in an 84% reduction in computational time in comparison to the 3D-F case. Thus, the use of the 2D domain will not only provide similar results to the 3D domain but also significantly reduce the computational time. On the same computational system, the 2D case took approximately 2 h per case to deliver the final converged solution. Further studies have been carried out using the 2D numerical domain.

4.3. Mesh Independence Study. A mesh independence study was carried out for the 2D numerical domain to determine the optimum mesh size that results in lower computational time while providing good numerical results. A coarse mesh with 39,000 (39k) cells, a medium mesh with 78,000 (78k) cells, and a fine mesh with 145,000 (145k) cells
Figure 5. Comparison of velocities, temperature, and mass fraction of CH$_4$ at different heights from the bluff body plane using different computational domains for highly stratified flame case (Swb9) with velocity profiles as inlet conditions for inner and outer annulus.

Figure 6. Comparison of different mesh sizes showing OH mass fraction and temperature at $Z = 30$ mm from the bluff body plane.

Figure 7. Comparison of axial velocities obtained using the RNG $k$-$\varepsilon$ turbulence model to the data obtained experimentally (Sweeney et al.$^{15}$) and LES/PDF simulations (Turkeri et al.$^{21}$) at different axial and radial positions.

Figure 8. Comparison of temperature profile obtained using RNG $k$-$\varepsilon$ turbulence model to the data obtained experimentally (Sweeney et al.$^{15}$) and LES/PDF simulations (Turkeri et al.$^{21}$) at different axial and radial positions.
were compared. The OH and temperature distribution along the radial axis at $Z = 30$ mm for the highly stratified flame (Swb9) were compared. Figure 6 shows the comparison of the OH and radial temperature profile. It can be seen that the three meshes give very close results from each other with very marginal changes. Maximum difference was observed in the case of OH calculation, wherein a maximum difference of 8% was observed between mesh sizes of 145k and 39k, while a maximum difference of 3% was observed between mesh sizes of 145k and 78k. Therefore, the mesh with 78k cells was used for validation and further studies.

4.4. Validation with Experimental Data and LES Modeling. In this section, results obtained using the RNG $k$–$\varepsilon$ turbulence model are compared to those obtained using LES/PDF simulation by Turkeri et al.\textsuperscript{21} and the experimental study by Sweeney et al.\textsuperscript{15}

4.4.1. Axial Velocity. Figure 7 shows the comparison of axial and radial velocity profiles, respectively, for the three flames with different levels of stratification at different heights from the bluff body plane.

It can be seen that for the axial profiles, close to the center of the combustion domain, that is, $r < 0.01$ m the axial velocities are over predicted. Away from the center, the calculated axial velocities are in good agreement with the experimental and LES/PDF results. Furthermore, in most of the cases, the peak axial velocity predicted by the RNG $k$–$\varepsilon$ turbulence model is in better agreement than the LES/PDF model, with the exception occurring at $Z = 50$ mm where the peak of the predicted axial velocity is shifted toward the center of the domain.

4.4.2. Temperature. Figure 8 depicts the comparison of numerical and experimental temperature profiles for the three flames with different levels of stratification at different heights from the bluff body plane. The results from the RNG $k$–$\varepsilon$ turbulence model are in excellent agreement with the experimental data, with a maximum peak temperature difference of less than 5% for the case of Swb9. This difference in maximum temperature can also be noticed for the LES/PDF case. In most of the cases, the results from the RNG $k$–$\varepsilon$ turbulence model have the temperature profile shifted slightly toward the center of the flame resulting in the position of the temperature gradient shifted slightly toward the left of the experimental data, while with LES/PDF, the results are shifted slightly toward the right. The shift in the temperature profiles, of the present study, could be attributed to the shift in the peak of the axial velocities as seen in Figure 7.

4.4.3. Species. In this section, the prediction of major chemical species using the RNG $k$–$\varepsilon$ turbulence model and SG-35 kinetics model is validated with experimental data and LES/PDF. Figure 9 shows the comparison of methane mass fraction ($\text{CH}_4$) for the three flames with different levels of stratification at different heights from the bluff body plane. Despite the higher axial velocities at $Z = 10$ and 30 mm in comparison to experimental data, the mass fraction of methane predicted using the RNG $k$–$\varepsilon$ turbulence model is in excellent agreement for all three cases of flames. Furthermore, the RNG $k$–$\varepsilon$ turbulence model predicts methane fraction better than the LES/PDF model. For the case with $SR = 1$ (Swb1), the methane predicted is in good agreement at all the examined heights from the bluff body plane.

For the stratified cases at $Z = 50$ mm, the peak mass fraction of methane is over-predicted, while the peak mass fraction is also simultaneously shifted toward the center of the
combustion zone. The over-prediction could be because of the chemical mechanism in use that has not been optimized for use with stratified flames, while the shifted peak is due to the shift in the axial velocity toward the center. While from the LES/PDF simulation, the peak mass fraction is under-predicted while being shifted slightly away from the center. However, it should be noted that for both RNG $k-\varepsilon$ turbulence model and LES/PDF, the gradients or the shape of the profile matches that obtained from experimental measurements. Figure 10 shows the comparison of carbon dioxide mass fraction ($CO_2$), for the three flames with different levels of stratification at different heights from the bluff body plane. The predicted values from the RNG $k-\varepsilon$ turbulence model and SG-35 kinetic model show good agreement with the data obtained experimentally by Sweeney et al.\textsuperscript{15} However, at $Z = 30$ and 50 mm for the stratified cases (i.e., Swb9 and Swb5), the profiles are shifted slightly toward the center of the combustion zone. The validation results for $CH_4$ and $CO_2$ has been presented here; however, validation of oxygen and CO was also carried out. The RANS model with the SG-35 mechanism could predict all the major species with good accuracy.

Turkeri et al.\textsuperscript{21} reported requiring 25,536 core hours for completing a single case of simulation; however, the core type and core operating speed were not mentioned. In the present study, using the RNG $k-\varepsilon$ turbulence model along with SG-35 chemical mechanism 64 core hours were required to complete one case of numerical simulation, which is a reduction of 99.75%.

From the presented profiles of vector and scalar quantities, it can be concluded that given the significant decrease in computational cost relative to the LES/PDF, the RANS-based RNG $k-\varepsilon$ turbulence model performs well and can be used to study the time-averaged vector and scalar fields of the stratified flames with relatively small compromise on the accuracy of the predicted result. As evident from the shape of the vector and scalar profiles, RANS simulation can also provide a good estimate for comparative studies where the exact numerical value might be of less importance than the trend arising from the comparison of the cases.

### 4.5. Effect of Stratification

The experimental study carried out by Sweeney et al.\textsuperscript{15} for flames with different SRs has different power levels. In order to present a better comparison of the stratified flames at the same power level and global equivalence ratio, a numerical study is presented discussing the effect of change in the SR alone. Table 2 shows the characteristics of different flames that have been studied. The flames have the same global equivalence ratio and power level. The SR is varied between 1 and 4 in steps of 1. The inner and outer equivalence ratios are allowed to be varied so as to fix the global equivalence ratio and power level. The SR is varied between 1 and 4 in steps of 1. The inner and outer equivalence ratios are allowed to be varied so as to fix the global equivalence ratio and power level. The inner annulus velocity was set to 9 m/s, while the outer

| SR  | max. temperature (K) | combustion efficiency (%) |
|-----|----------------------|---------------------------|
| 1   | 1811                 | 6.07                      |
| 2   | 2249                 | 22.30                     |
| 3   | 2145                 | 30.52                     |
| 4   | 2110                 | 32.42                     |

**Figure 11.** Comparison of temperature contour at different SRs, input power = 20.73 kW, and $\phi_g = 0.68$ (all length dimensions in m).

**Figure 12.** Temperature along the central axis of the flame at different SRs, input power = 20.73 kW, and $\phi_g = 0.68$. 

**Table 3. Effect of Stratification**

| SR  | max. temperature (K) | combustion efficiency (%) |
|-----|----------------------|---------------------------|
| 1   | 1811                 | 6.07                      |
| 2   | 2249                 | 22.30                     |
| 3   | 2145                 | 30.52                     |
| 4   | 2110                 | 32.42                     |
annulus velocity was set to 15 m/s, resulting in Reynolds numbers of around 6260 and 9017 for the inner and outer annulus, respectively. The slight change in Reynolds number seen in Table 2 is due to the changes in methane concentration with changes in equivalence ratios of the inner and the outer annulus.

Figure 11 shows the temperature contour of the open flame burner, while Figure 12 shows the temperature variation along the central axis at different SRs. At SR = 1, the flame temperature is significantly low with maximum temperature of 1811 K. Even with a small increase in SR the temperature significantly increases due to the increase in inner equivalence ratio. The maximum temperature increases to 2249 at SR = 2, which is an increase of 24%, beyond SR = 2 there is a small decrease in maximum flame temperature with an increase in
Table 3 shows the effect of stratification on maximum temperature and combustion efficiency.

The combustion efficiency is calculated as:

\[
\eta = \frac{\text{mass of carbon atoms out}}{\text{mass of carbon atoms in}} \times 100
\]

It can be seen in Table 3 that the combustion efficiency of the flame with SR = 1 is 73% lower than that of SR = 2 and 80% lower than SR = 3 and 4. Stratification significantly increases the maximum temperature and combustion efficiency in an open flame burner.

The significantly lower temperature of the flame with SR = 1 is attributed to the lower methane combustion in comparison to cases with higher SR. Figure 13 shows the contour plots of methane for different SRs. It is evident that for SR = 1, a large amount of methane remains unburnt and exits the computational domain, in comparison to flames with higher SR.

From Figures 11 and 12, it can also be seen that the temperature at the base of the flame, that is, close to the bluff body, between \(Z = 0\) and \(Z = 0.18\) m, is lower for the cases with SR = 3 and 4 in comparison to cases with SR = 2. Furthermore, the position of the maximum temperature for...
these cases with SR = 3 and 4 is shifted downstream close to Z = 0.22 m. This behavior of the flame can be explained by Figures 14 and 15, which show the contour plot of OH radical and the variation of OH radical along the central axis of the flame, respectively. For premixed turbulent combustion, the concentration of OH is used to signify the flame front.\(^{41,42}\) Therefore, Figures 14 and 15 suggest that for SRs 1 and 2, the primary flame front is located at the base of the flame, that is, near the bluff body, where most of the fuel-burning occurs. As the SR is increased, the primary flame front shifts downstream with less intense burning occurring at the base of the flame which could lead to lifted flames if the SR is increased further.

As the SR is increased, the mixture close to the bluff body gets richer due to an increase in the inner equivalence ratio (\(\phi_{in}\)). Figures 16 and 17 show the contour plot of the equivalence ratio and the variation of the equivalence ratio (\(\phi\)) along the central axis of the flame, respectively. These equivalence ratios have been calculated using the major species, utilizing the equation proposed by Sweeney et al.,\(^{15}\) which is given as

\[
\phi = \frac{X_{CO_2} + 2X_{CH_4} + X_{CO} + 0.5(X_{H_2O} + X_{H_2})}{X_{CO_2} + X_{CO} + 0.5(X_{H_2O} + X_{H_2})} \quad (9)
\]

It can be seen that as the SR increases the equivalence ratio close to the bluff body also increases. At SR = 4 the equivalence ratio near the bluff body is 1.23 due to which the intensity of burning is reduced. Van Maaren et al.\(^{15}\) and other researchers have shown that the laminar flame speed for the methane-air premixed flame is maximum at an equivalence ratio of 1.1, after which the flame speed starts to decrease as there is not sufficient oxygen to support the burning of fuel. Consequently, at SR = 3 and 4, the intensity of burning close to the bluff body is reduced and the primary flame front moves downstream at around 0.22 m along the central axis where the equivalence ratio is reduced below 1.1 due to the presence of more oxygen as evident from Figure 18, which shows the variation of oxygen along the central axis.

Figure 19 shows the axial velocity of the flames with different SRs along the central axis. The velocity profile along the axis is similar in all cases. For cases with SR = 1 and SR = 4, lower axial velocities can be observed in comparison to cases with SR = 2 and SR = 3. This behavior is attributed to the lower flame temperature with SR = 1 and SR = 4, as seen in Figure 12.

Figure 20 shows the velocity streamlines along with temperature contours near the bluff body. The size of the recirculation zone at the bluff body decreases with an increase in SR up till SR = 3, beyond which it again increases. This suggests the strength of the recirculation zone increase and then decrease, as a consequence mildly stratified flame seem to be more stable than the highly stratified flames.

5. CONCLUSIONS

LES modeling of stratified flames has been carried out by many researchers; however, they can be computationally very expensive limiting its use to small scale burners for research purposes only. In order to design industrial-scale combustors, RANS simulation should be used. RANS was used to develop and validate a numerical model for the combustion of stratified...
flames. RANS modeling with SG-35 chemical mechanism was used to study stratified flames with acceptable accuracy and a reduction of 99.75% in the computational time in comparison to LES/PDF simulation available in the literature. The major differences arise in the prediction of axial velocities near the center of the flame. However, the temperature and major species can be predicted with very good accuracy. To investigate the effect of stratification on the flame structure and combustion efficiency further simulations were carried out at a constant input power, global equivalence ratio and Reynolds number while varying the SR between 1 and 4. The temperature close to the bluff body was found to increase with an increase in SR to SR = 2. This is due to the increase in the inner equivalence ratio which promotes more intense burning. However, beyond SR = 2, the mixture near the bluff body becomes too rich, leading to less intense burning because of reduced oxygen concentration. This results in shifting of the primary flame region toward the downstream which could lead to lifted flames as the SR is further increased. Thus, mildly stratified flames may be more stable than the highly stratified flames at the same equivalence ratio, input power, and Reynolds number. Furthermore, stratification significantly increases the maximum temperature and combustion efficiency of the flames.

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**NOMENCLATURE**

- $D_{jm}$: mass diffusion coefficient for species $j$ in the mixture
- $D_{Tj}$: the thermal diffusion coefficient of the $j$th species
- $h$: acceleration due to gravity
- $I$: radiation intensity
- $k$: effective thermal conductivity
- $m_{CO_2,\text{out}}$: mass of CO$_2$ exiting the domain
- $m_{CH_4,\text{in}}$: mass of CH$_4$ entering the domain
- $n$: refractive index
- $P$: pressure
- $Re$: Reynolds number
- $R_i$: the net rate of production or consumption of species $j$ by chemical reaction
- $S$: energy source term including the reaction source term and radiation heat exchange
- $SR$: stratification ratio
- $T$: temperature
- $u$: velocity component
- $X$: mass fraction
- $Y_j$: mass fraction of species $j$
- $\kappa$: absorption coefficient
- $\Phi_i$: phase function
- $\phi$: equivalence ratio
- $\sigma$: Stefan Boltzmann constant = 5.669 × 10$^{-8}$ W/m$^2$ K
- $\Omega_i$: solid angle
- $\eta$: combustion efficiency

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