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**Applied Mathematics and Mechanics (English Edition)**

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## A numerical investigation of CO<sub>2</sub> dilution on the thermochemical characteristics of a swirl stabilized diffusion flame \*

Shidvash Vakili<sup>1,2,†</sup>, Yasaman Tohidi<sup>1</sup>, Jafar Al-Zaili<sup>3</sup>, Rouzbeh Riazi<sup>1</sup>

1. Faculty of New Sciences and Technologies, University of Tehran, North Kargar Street, Tehran, Iran;
2. Department of Mechanical Engineering, University of Manitoba, Winnipeg, MB R3T 5V6, Canada;
3. Department of Mechanical Engineering & Aeronautics, Northampton Square, London, EC1V 0HB

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The turbulent combustion flow modeling are performed to study the impacts of CO<sub>2</sub> addition to the fuel and oxidizer streams on the thermochemical characteristics of a swirl stabilized diffusion flame SM1. A flamelet approach along with three well-known turbulence models are utilized to model the turbulent combustion flow field. The  $k-\omega$  SST shows the best agreement with the experimental fields compared to other methods. Then, the  $k-\omega$  SST is employed to study the effects of CO<sub>2</sub> dilution on the flame structure and strength, temperature distribution, and CO concentration. To determine the chemical effects of CO<sub>2</sub> dilution, a fictitious species is replaced with the regular CO<sub>2</sub> in both fuel and oxidizer streams. The results indicate that the flame temperature is decreased when CO<sub>2</sub> is added to either fuel or oxidizer streams. The flame length reduction is observed at all levels of CO<sub>2</sub> dilution. The H radical concentration indicating the flame strength decreases following by the thermochemical effects of CO<sub>2</sub> dilution processes. In comparison with fictitious species dilution, chemical effects of CO<sub>2</sub> addition enhance CO mass fraction. The numerical simulations show that by increasing the

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† Corresponding author, E-mail: vakili<sup>1</sup>@ut.ac.ir

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8 level of dilution the rate of flame length reduction is more significant at low swirl  
9 numbers.

11 **Key words** Swirl stabilized flame, CO<sub>2</sub> dilution, Methane-Air chemical effects,  
13 turbulent flame structure, steady flamelet model

## 18 1 Introduction

21 The ongoing depletion of fossil fuels, along with the global warming issue has become a sig-  
22 nificant concern in recent years. In this regard, two basic strategies are increasingly recognized  
23 to control this issue. Firstly, alternative fuels such as biogas and syngas, composed of up to  
24 40% of diluents, are considered to replace the fossil fuels. Secondly, different new technologies  
25 have been proposed to control emission levels; e.g. oxy-fuel combustion technology for CO<sub>2</sub>  
26 Capture and Storage (CCS) [1], flameless combustion regimes [2], and Exhaust Gas Recircu-  
27 lation (EGR) [3]. The principle of both strategies is the dilution of reactants using different  
28 methodologies. Therefore, it is necessary to perform a precise study on the effects of diluent  
29 addition to fuel and oxidizer streams. To achieve this aim, the injection of CO<sub>2</sub> into either the  
30 fuel or oxidizer stream has been taken into consideration by several researchers. Since CO<sub>2</sub> is a  
31 combustion product, it can be easily extracted from the exhaust gas by condensing water vapor  
32 exists in the combustion products. Using CO<sub>2</sub> as a diluent has significant impacts on the flame  
33 structure, flammability limits, and pollutant emissions. Several researchers have investigated  
34 the effects of CO<sub>2</sub> dilution on the characteristics of different flames.

44 Liu et al. [4] depicted that the CO<sub>2</sub> addition to the fuel and oxidizer streams influences  
45 the flame structure through thermal and chemical effects in a laminar diffusion flame. They  
46 reported that the reaction  $\text{OH} + \text{CO} = \text{H} + \text{CO}_2$  is mainly responsible for the chemical effects  
47 of CO<sub>2</sub> dilution. Erete et al. [5] experimentally considered the effects of CO<sub>2</sub> addition on the  
48 structure and pollutant emissions of turbulent diffusion flames. They found that with the higher  
49 diluent concentration in the fuel stream, visible flame length and flame temperature are reduced.  
50 Park et al. [6] performed a numerical simulation to study the impacts of CO<sub>2</sub> addition to the fuel  
51 and oxidizer streams on the flame structure of counter-flow diffusion flames. They had shown  
52 that the amount of radicals like H and OH is limited by addition of CO<sub>2</sub> to both reactant sides.  
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Mameri et al. [7] showed that the increase of CO<sub>2</sub> in biogas composition induces a decrease in the temperature, OH and H mass fractions. They also found that the chemical effects of CO<sub>2</sub> addition lead to the increase of CO and NO. Chen and Ghoniem [8] investigated the chemical effects of CO<sub>2</sub> dilution on CO formation for an oxy-fuel swirling flow diffusion flame. They depicted that CO mass fraction increases in high levels of CO<sub>2</sub> dilution. Glaborg and Bentzen [9] showed that in an oxy-fuel combustion system, the concentration of CO increases in the near burner regions. Hoerlle et al. [10] evaluated the effects of CO<sub>2</sub> addition to the fuel stream for a co-flow flame configuration. Their results depicted that a decrease in flame length, temperature, and CO mass fraction increases the volume rate of the diluent. The effect of CO<sub>2</sub> addition on the flame structure has been considered by some researchers. Cao et al. [11] studied the impacts of pressure and dilution of fuel side on co-flow diffusion flames. Both numerical and experiment results depicted that the flame length decreases by addition of diluent to the fuel stream in atmospheric pressure. Wilson and Lyons [12] investigated the effects of fuel stream dilution on the structure of turbulent diffusion flames. They argued that as the concentration of diluent increases, the flame shape becomes more cylindrical. Cao et al. [13] demonstrated that flame length is proportional to the mass flow rate of reactants in co-flow diffusion flames. Watanabe et al. [14] found out that the overall average length of oxy-flames is considerably shorter than that of air-flames in a swirl stabilized combustor. Furthermore, other researchers concluded that CO<sub>2</sub> dilution is an effective way to decrease pollutant emissions such as soot and NO<sub>x</sub> [15, 16].

Other researchers compared the impacts of different diluents added to fuel or oxidizer streams. Park et al. [17] investigated the effects of different diluents in methane-air diffusion flames and showed that thermal effects of CO<sub>2</sub> addition lead to a reduction in flame temperature and NO<sub>x</sub> emission. Zhuo et al. [18] conducted a numerical study on the impact of N<sub>2</sub>, CO<sub>2</sub> and H<sub>2</sub>O addition to fuel streams on combustion characteristics of syngas turbulent non-premixed jet flames. Their results demonstrated that the CO<sub>2</sub> diluted flame has the highest reduction in flame temperature amongst the other diluted flames. They had also shown that the CO<sub>2</sub> addition shortens flame size and provides the lowest extinction and re-ignition temperatures. Wang et al. [19] performed a numerical investigation on the physical and chemical impacts of CO<sub>2</sub> and H<sub>2</sub>O dilution in the diffusion flames. They showed that the flame temperature is reduced due to thermal and chemical effects of CO<sub>2</sub> dilution. Also, The chemical effects of

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8 CO<sub>2</sub> dilution increase the emission index of CO (EICO) while the thermal and dilution effects  
9 slightly reduce it. Min et al. [20] studied the effects of Ar, N<sub>2</sub> and CO<sub>2</sub> addition to the oxidizer  
10 stream on the flame length and lifting behavior of diffusion flames. They concluded that the  
11 pure dilution effect is a primary factor that affects the behavior of flame length. Xu et al. [21]  
12 investigated the effects of H<sub>2</sub>O and CO<sub>2</sub> addition to the oxidizer stream and the characteristics  
13 of co-flow diffusion flames. They found that the chemical effects of CO<sub>2</sub> replacement of N<sub>2</sub> in  
14 the air stream, decrease OH and temperature followed by thermal effects.  
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19 Although the effects of CO<sub>2</sub> dilution have been considered on several research fronts, few  
20 studies have been done to investigate the effects of air swirl on the characteristics of CO<sub>2</sub> di-  
21 luted flames. Swirling flames are commonly used in a wide range of engineering applications  
22 such as gas turbines and internal combustion engines [22]. These kinds of flames have several  
23 merits that justify their use. The fundamental significance of swirling flames is their role in  
24 increasing the degree of mixing between fuel and oxidizer, decreasing the flame length, im-  
25 proving flame stability, resulting in pollutant emission reduction [22, 23, 24, 25, 26]. A wide  
26 range of research has been conducted in the study of combustion characteristics of turbulent  
27 premixed [27, 28, 29], non-premixed [30, 31, 32, 33, 34] and partially premixed [35, 36] swirling  
28 flames. Beer and Chigier [37] proposed a non-dimensional swirl number to characterize the  
29 intensity of swirl in a swirling flow. It is defined as the ratio of the axial flux of angular momen-  
30 tum to the axial flux of axial momentum, but in this study a geometric swirl number  $s_g$ , which  
31 is the ratio of circumferential velocity to axial velocity is utilized to indicate the swirl intensity.  
32 The swirl number can be enhanced by the increasing of circumferential component of the ve-  
33 locity. The swirling flow is capable of generating turbulent recirculation zones complicating the  
34 flame structure. Generally the recirculation zone is established for swirl numbers greater than  
35 0.5 [38]. In this situation, induced centrifugal forces create an adverse pressure gradient in the  
36 flow direction leading to the decrease of axial velocity, and finally, the flow direction becomes  
37 reversed. This causes the creation of a recirculation zone downstream of the burner [39]. The  
38 presence of a recirculation zone increases the residence time of reactants in the combustor which  
39 leads to a better mixing and a perfect reaction.  
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54 It is noteworthy to mention that the selection of an appropriate turbulence model plays a  
55 major role in the simulation of swirling flames. Some researchers focus on the numerical methods  
56 with reasonable calculation time and cost that are able to capture the main characteristics of  
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flow fields along with the distribution of major and minor species [40, 41, 42, 43, 44, 45]. In this regard, Reynolds-averaged Navier-Stokes (RANS) turbulence models have shown acceptable levels of accuracy in the prediction of main flow features, and their results for mean values are comparable with more complicated turbulence models like Large Eddy Simulation (LES) [46]. In the current study three different turbulence models including standard  $k-\varepsilon$ ,  $k-\varepsilon$  RNG (Re-Normalisation Group), and  $k-\omega$  SST (shear stress transport) are utilized to study the effects of turbulence on the characteristics of Sydney swirl flame (SM1).  $k-\varepsilon$  RNG is recognized as a model which shows reasonable behavior for swirling flows which presents more accurate results compared to standard  $k-\varepsilon$  [47].  $k-\omega$  SST provides good accuracy in adverse pressure gradients [48], and gives satisfactory results in the simulation of swirling flows [49, 50, 51].

In the section that follows, the computational domain is described, and then the combustion model and numerical procedure will be explained. In section 3, the results of numerical simulations are discussed. The numerical simulations are validated against the experimental data using three different turbulence models. Velocity profile, mixture fraction, temperature, and CO mass fraction are compared with the experimental results. In subsection 3.2, the thermal and chemical effects of CO<sub>2</sub> addition to either fuel or oxidizer stream on the flame structure, temperature distribution and CO concentration of Sydney swirl stabilized diffusion flame [30] are investigated. Furthermore, the study has been extended to consider the influence of swirl intensity (number) on the flame structure of fuel-diluted flames. The paper will be closed by a summery and conclusion in Section 4.

## 2 The numerical modeling

### 2.1 The computational domain and flow modeling

In the present study, the fuel, swirl air, and co-flow air streams are supposed to be provided by Sydney swirl burner placed inside a wind tunnel [30]. The wind tunnel drives a co-flow unswirled air stream through a surrounding duct with the square cross-section. Figure 1 illustrates schematic of last 50 mm of swirl burner, its surrounded air stream duct, and established reacting flow zone above burner exit plane. In this figure,  $U_j$ ,  $U_s$ ,  $W_s$ , and  $U_e$  are the fuel jet, swirl axial, swirl tangential, and the co-flow air stream velocities, respectively. As shown in Figure 1, a 60 mm diameter annulus provides the swirling pure air and encompasses the stream of a fuel jet

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**Table 1** Flow characteristics of Sydney swirl burner.

Case	Fuel	Oxidizer	$U_j(m/s)$	$U_s(m/s)$	$W_s(m/s)$	$U_e(m/s)$	Temperature (K)	Pressure (kPa)
SM1	Methane	air	32.7	38.2	19.1	20.0	300	1013

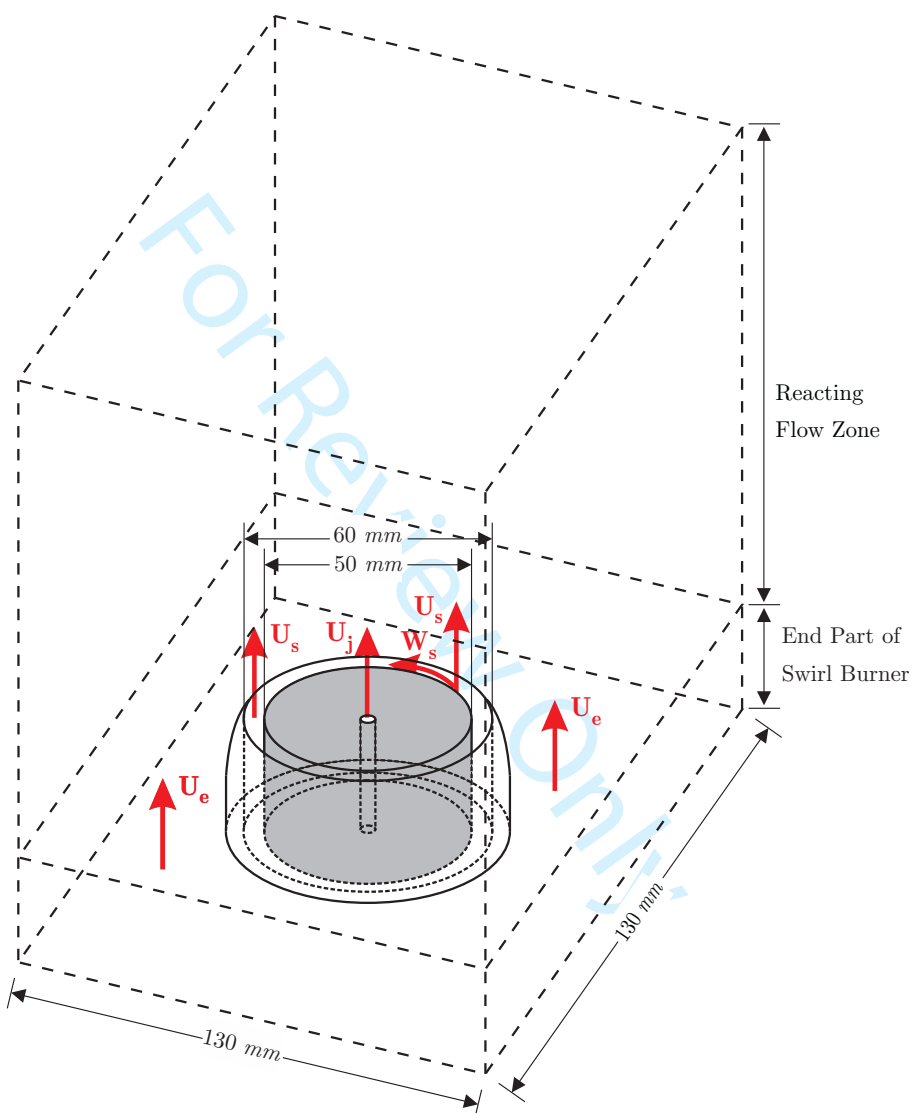
and a ceramic bluff-body face. In other words, fuel and oxidizer are separated by a bluff-body which generates recirculation zones in the flow field [52]. The diameter of fuel jet stream and bluff-body surface is  $d=3.6\text{ mm}$  and  $D=50\text{ mm}$ , respectively.

Table 1 denotes SM1 case flow specifications injected into the reacting flow field by swirl burner and wind tunnel. Regarding the magnitudes of swirl flow components, the swirl number of case SM1 is  $W_s/U_s=0.5$  which is categorized as a medium swirl number, and RANS turbulence models are capable to capture its main flow characteristics. Also, the Reynolds number of fuel jet, swirl air flow, and co-flow air streams are 7200 and 75900, and 46000 respectively.

In present numerical investigation, the flow field depicted in Figure 1 is modeled by a two-dimensional wedge-type configuration and shown in Figure 2. To achieve a fully developed flow condition, the inlet flow streams are extended  $D=50\text{ mm}$  upstream of the burner exit plane. As demonstrated in Figure 2, the computational domain of reacting zone has been extended 350 mm from the burner exit plane along the  $x$  axis. The fuel, swirling air, and co-flow air inflows are numerically modeled implementing inlet velocity condition at a section beyond burner exit plane shown as inlet section. The turbulence intensity of fuel jet, swirl air flow, and co-flow air streams is being recognized to be 5%, 4%, and 2% sequentially. At outlet and side sections, Dirichlet condition is applied to maintain a uniform fixed pressure at those boundaries during flow and combustion computations. Temperature is set to the constant value of 300 Kelvin in all inlet boundaries. The no-slip velocity, zero normal gradient temperature, and zero normal gradient pressure conditions are imposed on solid walls. For the near wall region, a wall treatment is utilized. The inlet, sides, and outlet planes of the computational domain are discretized by structured quadrilateral control volumes clustered near the burner exit plane.

## 2.2 Combustion model

From the combustion modeling perspective, different models have been used to validate the swirl flames. One of the promising models which are able to capture turbulence-chemistry interaction with an acceptable accuracy is the laminar flamelet model which has been utilized



**Fig. 1** The end part of Sydney swirl burner; fuel, swirl air, and coflow velocity directions and the dimensions of bluff-body and swirl air exit plane.



where  $\rho$ ,  $T$ , and  $c_p$  denote density, temperature, and specific isobaric heat capacity, respectively. Density is characterized by ideal gas system. Also a polynomial parameterization is used to express the heat capacity as a fourth-order polynomial using two temperature ranges.  $Y_k$ ,  $h_k$ , and  $\dot{\omega}_k$  represent mass fraction, specific enthalpy, source term of chemical species  $k$ , respectively. A chemical reaction mechanism is used to calculate the chemical species source term  $\dot{\omega}_k$ . In steady laminar flamelet model, the mixture fraction along with the scalar dissipation rate at stoichiometric mixture fraction ( $\chi_{st}$ ) is utilized to define the flame structure. In the present study, the flamelets are computed via the open-source chemistry software Cantera [56]. Then the Favre presumed Probability Density Function (PDF) approach are used to estimate the mean species mass fraction and temperature.

$$\tilde{Y}_k = \int_0^\infty \int_0^1 Y_k(Z, \chi_{st}) P(Z, \chi_{st}) dZ d\chi_{st} \quad (3)$$

$$\tilde{T} = \int_0^\infty \int_0^1 T(Z, \chi_{st}) P(Z, \chi_{st}) dZ d\chi_{st} \quad (4)$$

Statistical independent assumption is utilized to decompose the joint PDF  $P(Z, \chi_{st})$ .

$$P(Z, \chi_{st}) = P(Z) P(\chi_{st}) \quad (5)$$

The statistical independence separates the effects of large scale flow motions such as mixing (measured by mixture fraction  $Z$ ) from small scale characteristics of flame such as local diffusion zone thickness (measured by scalar dissipation rate  $\chi_{st}$ ) [52]. A  $\beta$ -shape PDF and a simple Dirac function are employed for the mixture fraction distribution and the scalar dissipation rate, sequentially. Besides the flow motion and turbulence model equations, two other Favre averaged transport equations are discretized for the mixture fraction and its variance.

$$\frac{\partial \bar{\rho} \tilde{Z}}{\partial t} + \frac{\partial \bar{\rho} \tilde{u}_i \tilde{Z}}{\partial x_i} = \frac{\partial}{\partial x_i} \left( \mu_{eff} \frac{\partial \tilde{Z}}{\partial x_i} \right) \quad (6)$$

$$\frac{\partial \bar{\rho} \tilde{Z}''^2}{\partial t} + \frac{\partial \bar{\rho} \tilde{u}_i \tilde{Z}''^2}{\partial x_i} = \frac{\partial}{\partial x_i} \left( \mu_{eff} \frac{\partial \tilde{Z}''^2}{\partial x_i} \right) + 2\mu_{eff} \left( \frac{\partial \tilde{Z}}{\partial x_i} \right)^2 - \bar{\rho} \tilde{\chi} \quad (7)$$

Here,  $u_i = (U, U_r)$  is the velocity component in the Cylindrical direction  $x_i = (x, r)$ ,  $\bar{\rho}$  is the time averaged density, and the effective viscosity  $\mu_{eff}$  is the summation of molecular and eddy

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viscosities, i.e.  $\mu_{eff} = \mu + \mu_t$ , where  $\mu_t$  is calculated using a turbulence model. In Equation 7, the mean scalar dissipation rate  $\tilde{\chi}$  is given by:

$$\tilde{\chi} = C_\chi \frac{\varepsilon}{k} \widetilde{Z''^2} \quad (8)$$

where  $C_\chi = 2$  [57] and  $k$  and  $\varepsilon$  are the turbulent kinetic energy and dissipation rate, sequentially. In current SLFM, the chemical reaction mechanism applied for  $\text{CH}_4$  combustion is GRI 2.11 with 49 species and 277 reactions [58]. Radiation heat transfer is also omitted.

### 2.3 Numerical procedure

Here, the flow and combustion computations are conducted utilizing Open source Field Operation And Manipulation (OpenFOAM) toolbox [59]. It is an open source CFD software package written by object-oriented C++ programming language and has been developed by OpenCFD Ltd at ESI Group and distributed by the OpenFOAM Foundation. Favre averaged Navier-Stokes and continuity equations are solved using Pressure-Implicit with Splitting of Operators (PISO) [60] algorithm to couple the pressure and velocity fields as well as Equation 6 and Equation 7 for mixture fraction and its variance, respectively. In the next step,  $\tilde{\chi}$  is evaluated from  $\widetilde{Z''^2}$ ,  $k$ , and  $\varepsilon$ . The mean temperature is determined by using probability density functions. Finally, density is calculated from temperature and pressure fields and utilized for flow computations in the next iteration. The convection and diffusion terms are discretised using central schemes with the second order of accuracy. The Courant number is set to the constant value of 0.3, and as a result, the time steps are small (about  $2\text{e-}6$  s). For achieving the solution convergence, two criteria were monitored. Firstly, the residuals of all variables drop below  $10\text{e-}5$ . Secondly all the variables become stabilized and do not show any changes with iteration.

## 3 The results and discussion

In Figure 2, the axisymmetric two-dimensional computational domain were discretized using quadrilateral cells for current numerical experiments. To study the grid dependence of numerical solutions, the three different grid resolutions are adapted to perform flow field computations. The grid resolution is changed by varying its radial and the axial number of divisions. Table 2 denotes grid specifications utilized for grid independence numerical experiments.  $N_r$  and  $N_x$

**Table 2** The grid specifications generated for the grid study work of SM1 flame numerical simulation.

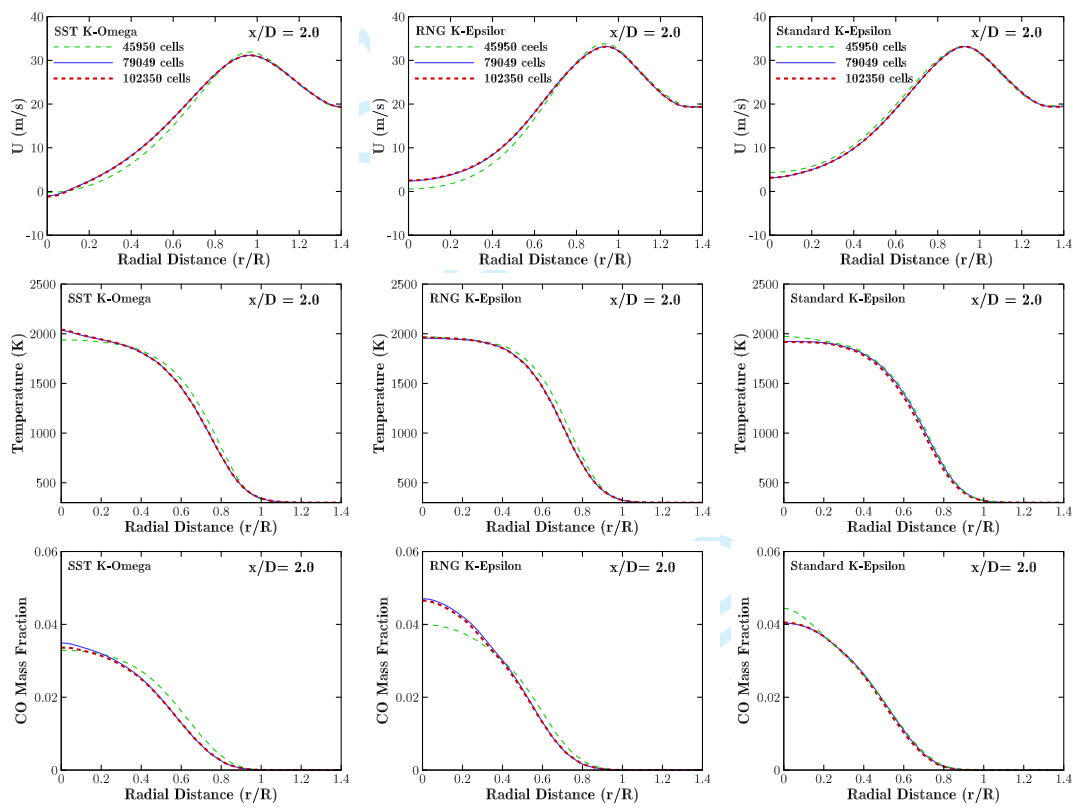
Grid	$N_r$	$N_x$	$N_{cell}$	$N_{point}$
Case 1	176	250	45950	92623
Case 2	251	299	79049	159060
Case 3	281	350	102330	205773

indicate the number of divisions in radial and axial directions, respectively. Figure 3 shows the profile of axial velocity for three grid resolutions in  $x=0.1m$ , which is a critical region due to the presence of secondary recirculation zone. As shown in this figure, the numerical results obtained from flow calculations on the grid with 79049 cells show a similar level of accuracy concerning those obtained on the grid with 102350 for all three turbulence models. Therefore, the grid with 79049 cells is employed to perform flow and combustion computations throughout the present study. The radial fuel inlet section, bluff-body surface, and swirl air plane are uniformly divided into partitions with  $\Delta r = 0.06, 0.21, \text{ and } 0.25 \text{ mm}$ , respectively. The wind tunnel coflow air section was non-uniformly discretized by 80 quadrilaterals clustered near the swirl air inlet section. In axial direction, the grid is spaced with  $\Delta x = 0.64 \text{ mm}$  at the nozzle exit plane.

### 3.1 Validation

The numerical results obtained by present simulations are validated using experimental data provided by Al-Abdeli and Masri [30], Kalt et al. [32], and Masri et al. [34]. Figure 4 compares the calculated  $U$  velocity along the radial axis using three turbulence models with those of measurement at different  $x$  coordinates.

As shown in this figure, the numerical simulations follow the trend of experiment results. The negative values of  $U$  velocity at axial locations of  $x/D=0.136$  and  $0.4$  indicate the reverse flow pattern due to the presence of bluff-body surface which are captured well by all three turbulence models. The value of  $U$  velocity is over predicted around the center line At  $x/D=0.4$ . It is because of the limited capability of Reynolds-averaged Navier-Stokes (RANS) models in shear flow computations which is mainly responsible for imprecise prediction of strong deceleration in the central jet flow. The downstream central recalculation zone which is due to the occurrence of vortex breakdown produces negative values on the center line at  $x=1.4$ . Although standard  $k-\varepsilon$  is not able to capture the downstream recirculation zone, both  $k-\omega$  SST and  $k-\varepsilon$  RNG



**Fig. 3** Grid sensitivity study of the predicted axial velocity, temperature, and CO mass fraction for three distinct turbulence models.

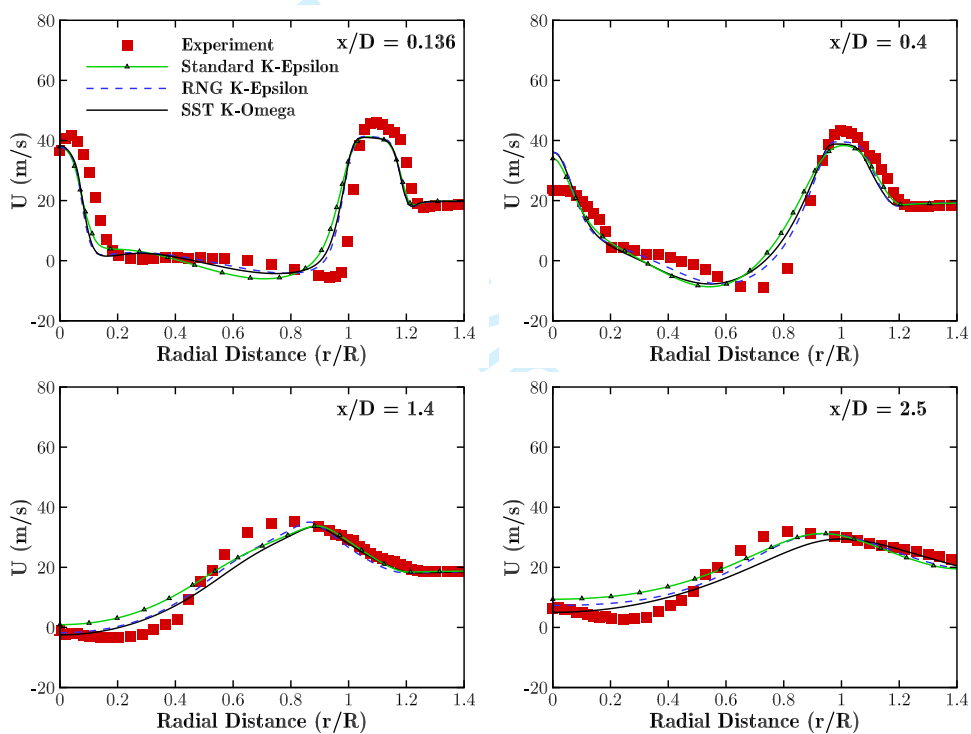


Fig. 4 Radial profile of the predicted axial velocity component compared with measurements at different axial locations.

models predict the rotating flow in this region with the acceptable accuracy.

Figure 5 shows predicted mixture fraction alongside those of experimental data at axial locations of  $x/D = 0.2, 1.1, 1.5,$  and  $3$ . In this figure,  $k-\varepsilon$  RNG model overestimates the mixture fraction around the fuel jet centerline at axial flame locations from  $x = 0.2$  to  $1.5$ . This theme emerges that the turbulence flow calculations using  $k-\varepsilon$  RNG model within the high shear region around fuel jet core leads to an estimation of longer distance for fuel jet flow diffusion. On the other hand, the result of  $k-\omega$  SST matches well with experiment results at the aforementioned axial locations. All three turbulence models predict the amount of mixture fraction less than measurements in regions near the bluff-body surface, i.e., at  $x/D=0.2$  and for radial distances more than  $r/R=0.06$ . This is because the turbulence models cannot capture precession of central jet and show a straight flow movement which causes a redistribution of fuel from the jet to upstream recirculation zone. This trend has been also observed in LES simulation of swirling flames [39]. The underestimation of mixture fraction makes its profile to be close to its stoichiometric values. The stoichiometric mixture fraction is an indicator of the flame front where the computed flame temperature reaches its maximum value. Therefore, it is anticipated that the temperature distribution would be over-predicted in regions near the bluff-body surface. However, the results related to  $k-\omega$  SST in this region show the higher level of accuracy compared with two other turbulence models.

Figure 6 shows comparisons for the radial profiles of the temperature field at different axial locations. All turbulence models show a discrepancy in the region near to burner exit plane ( $x/D = 0.2$ ) which is due to the underestimation of mixing field. In other axial locations the results are comparable with the results of LES reported by Malalasekera et al. [53]. Since the temperature distributions at downstream locations are closely related to the mixture fraction predictions,  $k-\omega$  SST shows the best prediction of temperature field in all axial locations.

The comparison of CO mass fraction with experiment results at different axial locations are shown in Figure 7. CO profiles are congruent with temperature results with similar trends and peaks. There is a significant under prediction of CO in the region near the bluff-body surface for  $k-\varepsilon$  RNG method. This is because the mixture fraction distribution is close to the lean flammability limit of the mixture for this model, so a considerable effect on the CO profile is observed in this region. CO concentration is well predicted at downstream axial locations by all three methods.

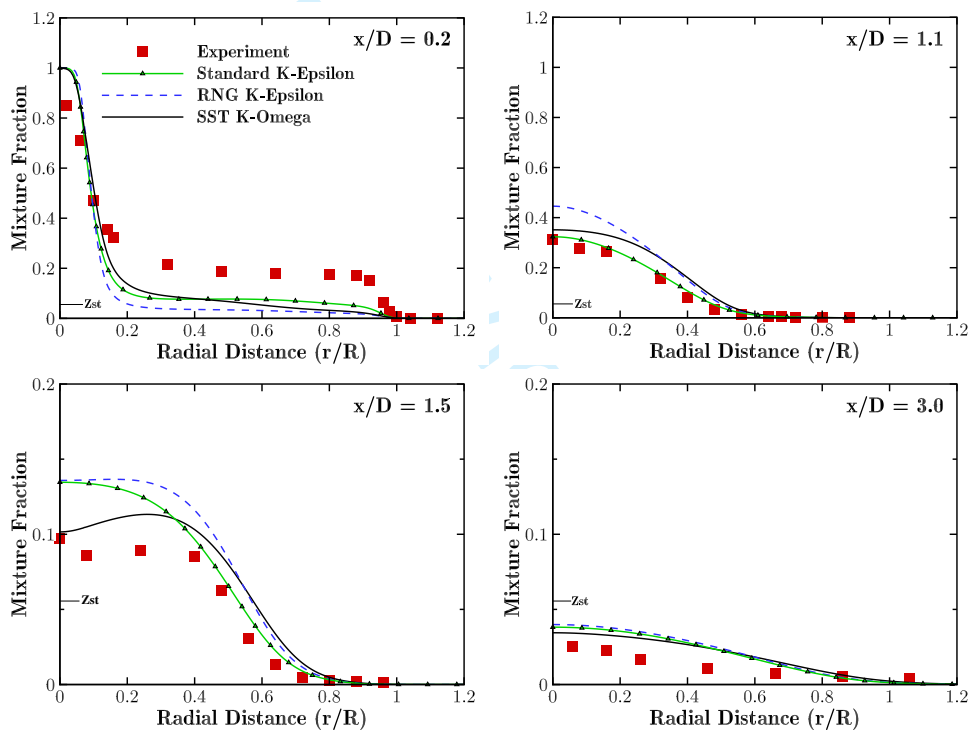
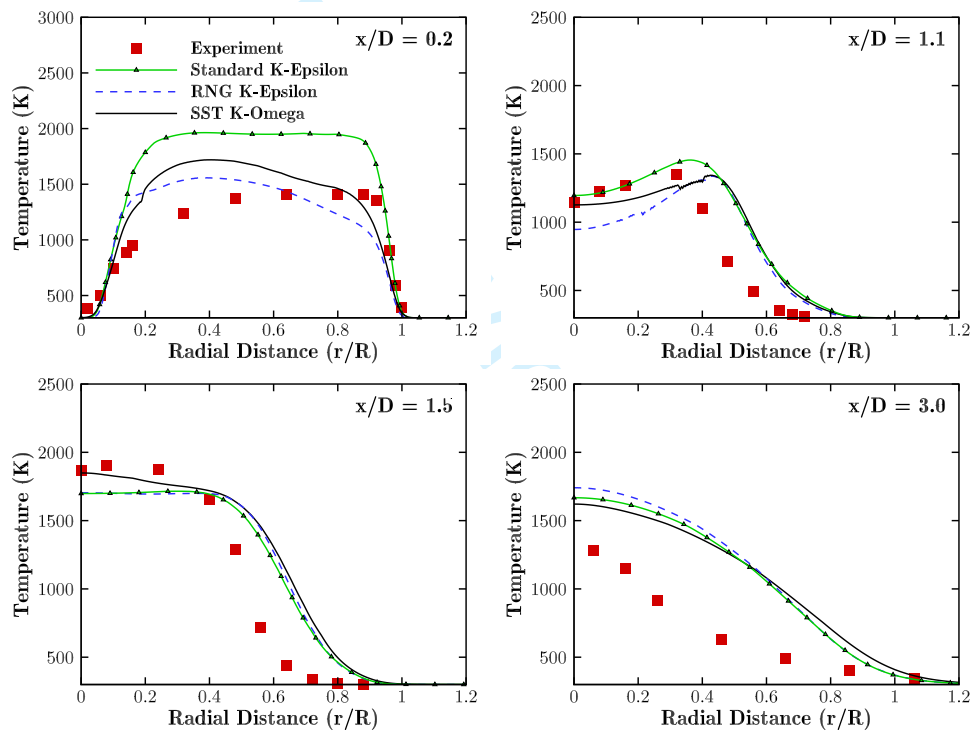


Fig. 5 Radial profile of predicted mixture fraction compared with measurements at different axial locations.



**Fig. 6** Radial profile of predicted temperature distribution compared with measurements at different axial locations.

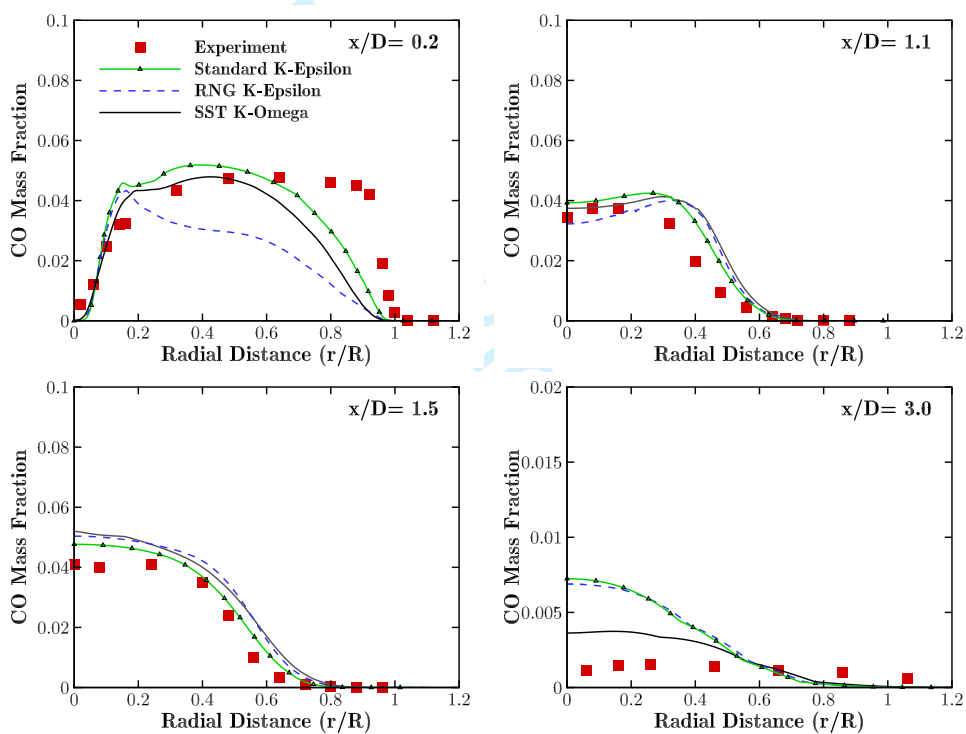
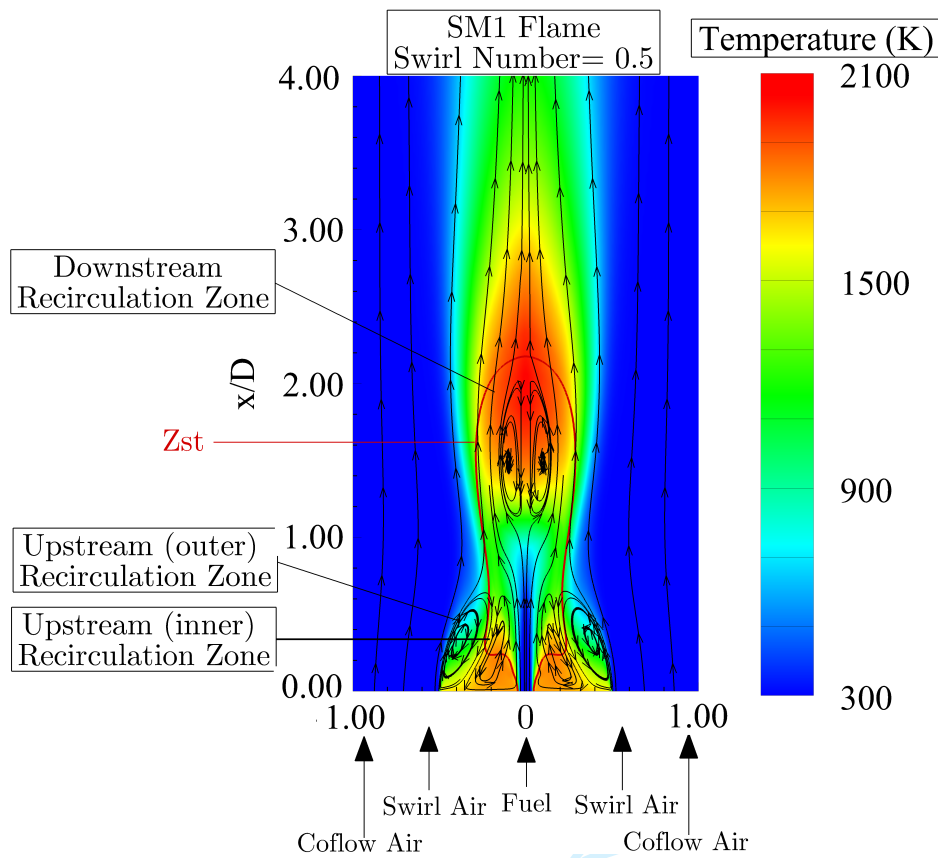


Fig. 7 Radial profile of predicted CO mass fraction compared with measurements at different axial locations.



**Fig. 8** The predicted structure of SM1 flame.

In summary,  $k-\omega$  SST shows more satisfactory results compared with the two other methods. In fact this model is recognized as a model which is capable to present acceptable predictions in regions with adverse pressure gradients. Therefore, in this study  $k-\omega$  SST is utilized for investigating the combustion characteristics of Sydney swirl flame (SM1).

The structure of swirl flames is too complicated; hence, the precise computation of flow field is a prominent factor in their numerical simulations. The computed flow streamlines patterns and temperature contours of SM1 are depicted in Figure 8. As is seen, two recirculation zones are resolved and emerged adjacent to bluff-body surface (upstream) and the one at downstream of the burner. The rotating gas zones resulting in a negative axial velocity lead to form a collar-like flow feature in the flame structure [30]. Moreover, the combustion products are trapped within the high-temperature zones predicted above the bluff-body and in the downstream recirculation region. In these zones, the hot gases provide a continual source of ignition for the

**Table 3** Non-dimensionalized flame length in different cases of fuel or oxidizer dilution.

Case	Fuel	Oxidizer	$Z_{st}$	L/D	Swirl Number
Case 1	CH <sub>4</sub>	79%N <sub>2</sub> +21%O <sub>2</sub>	0.055	2.18	0.5
Case 2	90%CH <sub>4</sub> +10%CO <sub>2</sub>	79%N <sub>2</sub> +21%O <sub>2</sub>	0.071	2.03	0.5
Case 4	80%CH <sub>4</sub> +20%CO <sub>2</sub>	79%N <sub>2</sub> +21%O <sub>2</sub>	0.089	1.93	0.5
Case 5	CH <sub>4</sub>	10%CO <sub>2</sub> +69%N <sub>2</sub> +21%O <sub>2</sub>	0.053	2.09	0.5
Case 7	CH <sub>4</sub>	20%CO <sub>2</sub> +59%N <sub>2</sub> +21%O <sub>2</sub>	0.050	2.02	0.5
Case 8	CH <sub>4</sub>	79%N <sub>2</sub> +21%O <sub>2</sub>	0.055	4.41	0.3
Case 8	90%CH <sub>4</sub> +10%CO <sub>2</sub>	79%N <sub>2</sub> +21%O <sub>2</sub>	0.071	3.80	0.3
Case 9	80%CH <sub>4</sub> +20%CO <sub>2</sub>	79%N <sub>2</sub> +21%O <sub>2</sub>	0.089	3.28	0.3
Case 10	CH <sub>4</sub>	79%N <sub>2</sub> +21%O <sub>2</sub>	0.055	2.80	0.6
Case 10	90%CH <sub>4</sub> +10%CO <sub>2</sub>	79%N <sub>2</sub> +21%O <sub>2</sub>	0.071	1.76	0.6
Case 11	80%CH <sub>4</sub> +20%CO <sub>2</sub>	79%N <sub>2</sub> +21%O <sub>2</sub>	0.089	1.68	0.6

incoming fuel and therefore, enhances the flame stability.

### 3.2 Dilution effects

The effects of CO<sub>2</sub> dilution on the combustion characteristics of the bluff-body swirl stabilized diffusion flame SM1 are studied by increasing the concentration of CO<sub>2</sub> in fuel and oxidizer streams up to 20%. Table 3 denotes the specifications of the cases considered to study the influences of CO<sub>2</sub> dilution. In case of dilution modeling, the molar fraction of O<sub>2</sub> in the air stream is constant whereas the composition of fuel and oxidizer varies by replacement of CH<sub>4</sub> and N<sub>2</sub> with CO<sub>2</sub>. L/D is the flame length (L) non-dimensionalized by bluff-body diameter (D). Flame length is one of the prominent parameters describing the structure of diffusion flames. There are different definitions for non-premixed turbulent flame length (L). In some instances, it is determined based on the visible flame length that has been proposed in experimental studies [5]. The other definition is that the flame length would be at the axial location of peak temperature on the centerline [21]. Another definition states that the flame length is considered as the axial distance on the centerline where the mixture fraction reaches its stoichiometric value. Since current studied flame structure has an hourglass shape in higher swirl numbers ( $s_g=0.6$ ), the furthestmost point of stoichiometric mixture fraction is not always on the centerline. In this regard, the flame length is defined as the highest axial distance between the fuel exit plane (bluff-body surface) and the place where the mixture fraction reaches to its stoichiometric ratio [41].

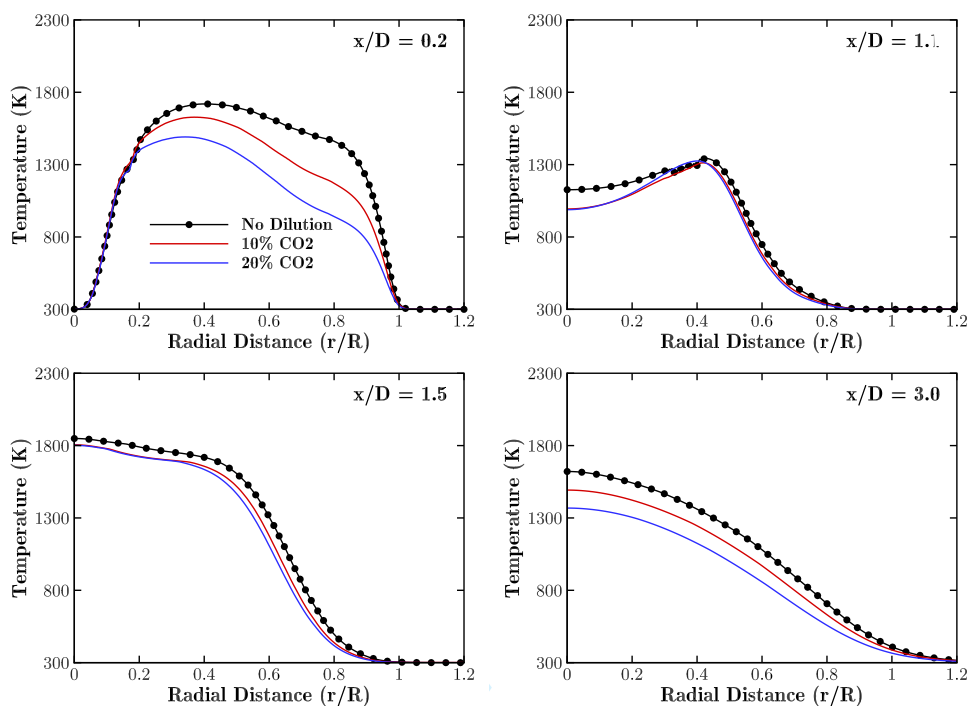
As denoted in Table 3, in a constant swirl number of 0.5, the non-dimensional flame length is

reduced gradually by addition of  $\text{CO}_2$  to the fuel stream. Compared to the no diluted case, the flame length decreases about 7% and 11.5% in the case of 10% and 20% dilution respectively. Considering the molar weight of  $\text{CO}_2$  and  $\text{CH}_4$ , the density of  $\text{CO}_2$  is higher than of  $\text{CH}_4$ . Since a fixed volumetric flow rate is set at inlet boundaries, the addition of  $\text{CO}_2$  to the fuel stream increases the mass flow rate of fuel jet, and therefore, an increment in flame length is expected. On the other hand, adding  $\text{CO}_2$  to the fuel stream decreases combustible components of fuel which leads to the reduction of mixing time and the time needed for combustion of the fuel, so the flame is formed in the region closer to the exit plane. The similar result is observed in different studies for methane-air diffusion flames diluted by  $\text{CO}_2$  [5, 18].

Similarly, the flame length is reduced with the addition of  $\text{CO}_2$  to the oxidizer stream but, with a lower rate in comparison with the fuel stream dilution case. Compared to the no diluted case, the flame length decreases about 4% and 7.5% in the case of 10% and 20% dilution respectively. In the case of oxidizer stream dilution (i.e., replacement of  $\text{N}_2$  by  $\text{CO}_2$ ), the density of the oxidizer and consequently, its stream momentum increases. An increase in the momentum of the oxidizer flow results in the generation of stronger recirculation zones within the flow field which increases the level of fuel-oxidizer mixing. As a result, the flame length decreases due to increment of fuel-oxidizer mixing.

The effects of  $\text{CO}_2$  dilution, imposed to either fuel or oxidizer stream, on the flame characteristics can be investigated considering three perspectives. Firstly, the dilution process reduces the combustible components which affect the flame characteristics. Secondly, the high heat capacity of diluent results in thermal effects leading to flame characteristics changes. Thirdly, the participation of diluent in chemical reactions results in chemical effects on the combustion characteristics [6].

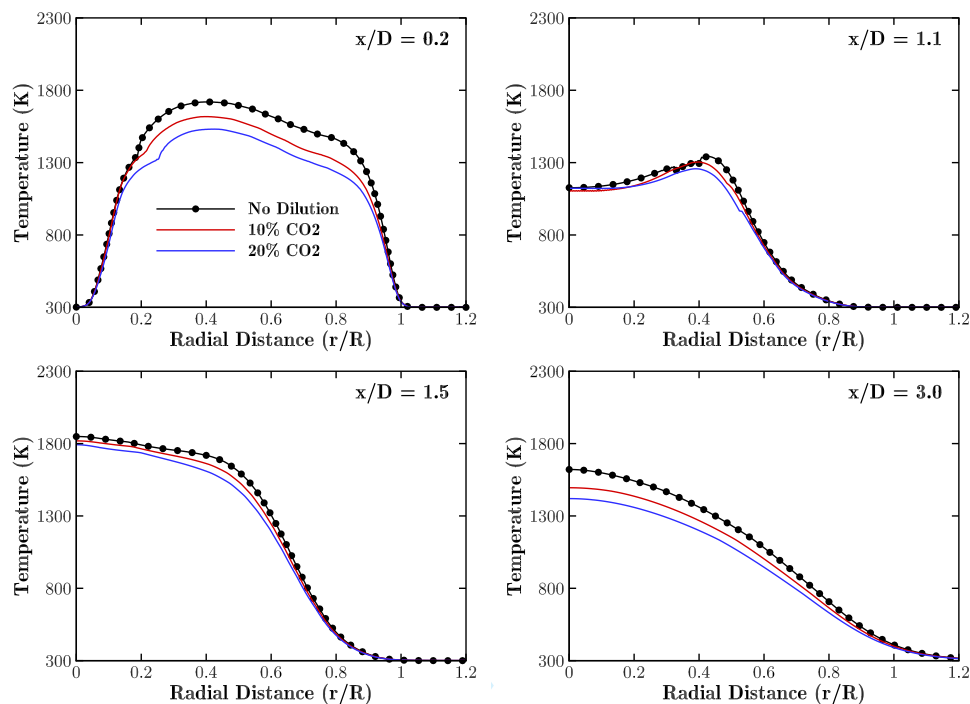
Figure 9 demonstrates the radial temperature profiles at axial locations of  $x/D = 0.2, 1.1, 1.5,$  and  $3.0$  in the case of  $\text{CO}_2$  addition to the fuel stream. It is observed that the increase of diluents molar concentration leads to the flame temperature reduction in all axial locations. With the higher concentration of  $\text{CH}_4$ , the increased breakage of exothermic bonds of carbon atoms in the hydrocarbon fuel leads to higher flame temperature. The lower amount of reactive species along with the high heat capacity of  $\text{CO}_2$  reduces the flame temperature. Additionally, chemical effects of  $\text{CO}_2$  dilution affect temperature distribution. The primary factor involved in the chemical effects of  $\text{CO}_2$  is the thermal dissociation of  $\text{CO}_2$  which is an endothermic



**Fig. 9** Radial profile of predicted Temperature in the case of no dilution, 10% dilution and 20% dilution of the fuel stream at different axial locations.

process, the high concentration of CO<sub>2</sub> leads to the flame temperature reduction. The largest temperature reduction is seen in the region near the bluff-body surface ( $x/D=0.2$ ) in which the temperature decreases about 498 K for 20% CO<sub>2</sub> diluted fuel case. As shown in Figure 9, by addition of CO<sub>2</sub> to the fuel stream, the maximum flame temperature moves toward the fuel-rich side. For instance, maximum flame temperature gets about 16% closer to the fuel rich side of the flame at the axial location of  $x/D=1.1$  when 20% CO<sub>2</sub> is added to the fuel stream. It can be explained by the position of stoichiometric mixture fraction (from 0.055 in no dilution to 0.089 in 20% CO<sub>2</sub> dilution case) which is an indicator for the flame front. The increment of CO<sub>2</sub> alters the flame stoichiometry and as a result, dislocates the profile of temperature in the direction of fuel side.

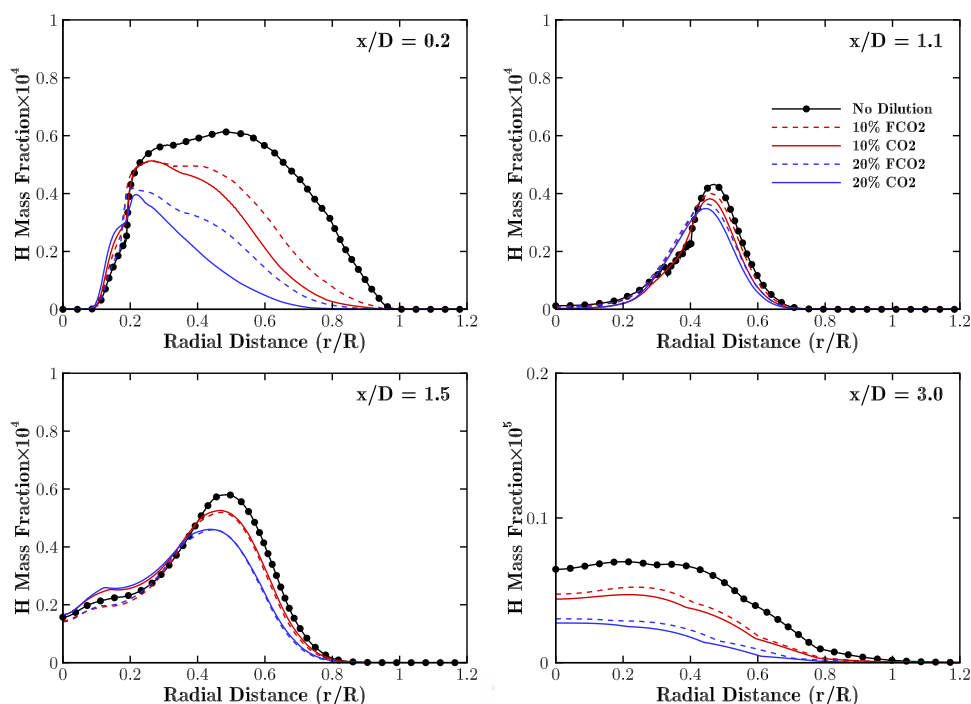
In Figure 10, the temperature profiles at axial locations of  $x/D=0.2$ , 1.1, 1.5, and 3.0 are shown for the case of CO<sub>2</sub> addition to the oxidizer stream (replacement of N<sub>2</sub> by CO<sub>2</sub>). Besides the higher heat capacity of CO<sub>2</sub> with respect to N<sub>2</sub>, the chemical effects of CO<sub>2</sub> addition lead to the reduction of flame temperature. The maximum temperature reduction near the bluff-body surface is about 276 K in the case of 20% CO<sub>2</sub> addition to the oxidizer stream compared



**Fig. 10** Radial profile of predicted Temperature in the case of no dilution, 10% dilution and 20% dilution of the oxidizer stream at different axial locations.

to non diluted case. As shown in Figure 9 and Figure 10, the flame temperature reduction is more noticeable when the diluent is added to the fuel stream. It can be related to the constant thermal power of combustion system in case of oxidizer dilution. The reduction in radial temperature distribution at  $x/D = 1.5$ , is less than other axial locations for both fuel and oxidizer stream dilutions. This is because in both dilution cases the zone with maximum temperature at downstream is predicted to be placed closer to the upstream recirculation zones. Moreover the dilution effects decrease the flame temperature in the flow field. Hence, in this axial location, which is the closest section to the downstream recirculation zone, the temperature changes is less noticeable. Maximum flame temperature reduction due to the addition of 20%  $\text{CO}_2$  is about 200 and 130 K for the fuel and oxidizer dilution cases respectively.

Chemical effects of dilution also have a significant impact on the species mass fraction. In order to study the chemical effects of  $\text{CO}_2$  addition, a fictitious species  $\text{FCO}_2$  is introduced [4] with the same thermal and transport properties of  $\text{CO}_2$ . On the other hand,  $\text{FCO}_2$  does not participate in chemical reactions. According to this methodology,  $\text{FCO}_2$ , as an inert species, is added to fuel or oxidizer stream rather than regular  $\text{CO}_2$ . The differences between the results

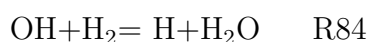


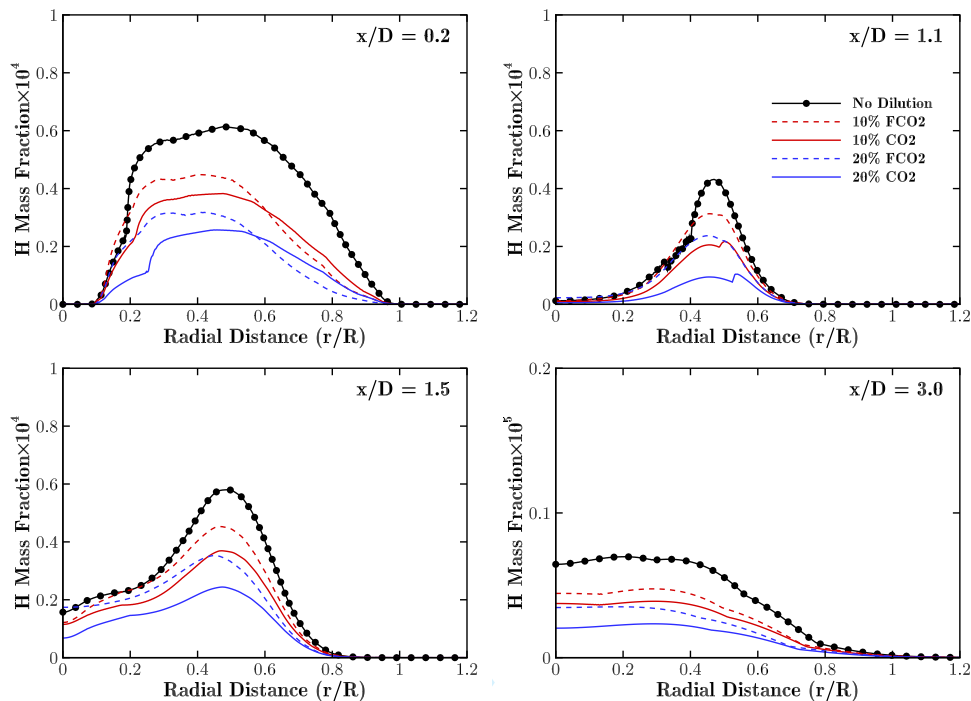
**Fig. 11** Radial profile of calculated H radical mass fraction in the case of no dilution, 10% dilution and 20% dilution of fuel stream at selected axial locations.

of CO<sub>2</sub> and FCO<sub>2</sub> dilution can determine the chemical effects of CO<sub>2</sub>.

Figure 11 and Figure 12 depict the profiles of computed H mass fraction at selected axial locations ( $x/D = 0.2, 1.1, 1.5,$  and  $3.0$ ) in the case of CO<sub>2</sub> and FCO<sub>2</sub> addition to the fuel and oxidizer streams, respectively.

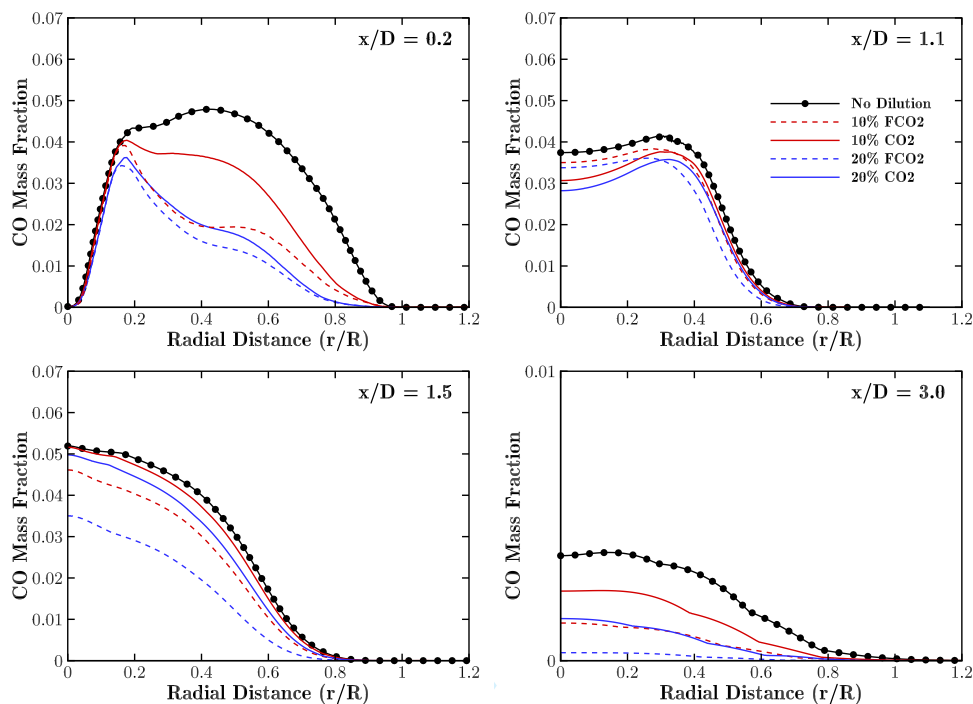
The flame strength can be assessed by the concentration of radicals such as H and OH [6] which their amount is expected to be more at higher temperatures. The comparison between FCO<sub>2</sub> and CO<sub>2</sub> dilution reveals that both thermal and chemical effects of diluent addition decrease H mass fraction in all axial locations. In methane combustion system, four reactions have the most impacts on the flame characteristics because of their high rates [10]. The reaction





**Fig. 12** Radial profile of calculated H radical mass fraction in the case of no dilution, 10% dilution and 20% dilution of the oxidizer stream at selected axial locations.

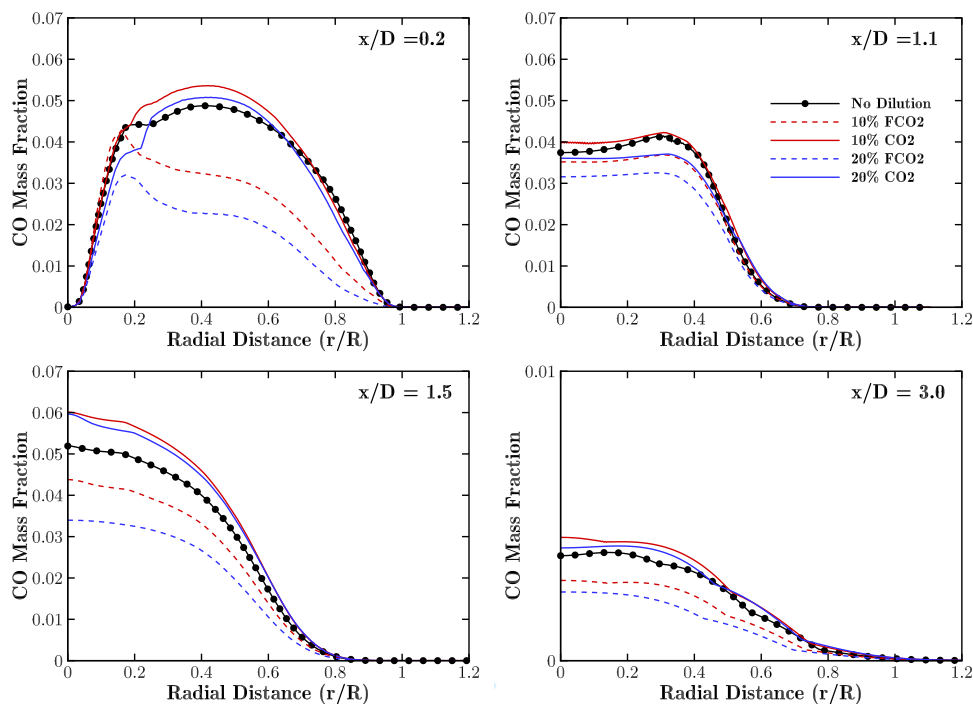
numbers are similar to the sequence in GRI-Mech 2.11. The reaction R99 is introduced as the main reaction responsible for the chemical effects of  $\text{CO}_2$  dilution by several authors [4, 6, 8, 10]. As the fuel is diluted by  $\text{CO}_2$  species, reaction R99 starts to consume H atoms. On the other hand, the reaction R38 and R53 are competing for the H atoms in the oxidizer and fuel sides, respectively. These reactions reduce their rates and consequently diminish the  $\text{H}_2$  and OH production. As a result, the reaction R84 is affected, and it leads to a further decrease of the H radicals. OH concentration is also reduced by addition of  $\text{CO}_2$  to the fuel and oxidizer streams. It is the direct result of H atoms consumption in reaction R99 which suppress reaction R38. As depicted in Figure 11 and Figure 12, comparing the results of  $\text{CO}_2$  dilution with  $\text{FCO}_2$  dilution reveals that the chemical effects of  $\text{CO}_2$  dilution are more noticeable when  $\text{CO}_2$  is added to the oxidizer stream. For instance, the maximum reduction of H radicals due to the chemical effects of  $\text{CO}_2$  addition is about 10% for both 10% and 20% fuel dilution cases at the axial location of  $x/D = 0.2$ . However, the chemical effects decrease maximum H radical concentration about 17% and 33% at the same axial location in the case of 10% and 20% oxidizer dilution respectively. This is because in higher flame temperature (see Figure 9 and



**Fig. 13** Radial profile of predicted CO mass fraction in the case of no dilution, 10% dilution and 20% dilution of fuel stream at selected axial locations.

Figure 10), the thermal dissociation of CO<sub>2</sub> is much easier. Since the flame length varies in different cases, it is difficult to compare the fuel and oxidizer dilution effects at an axial location far from the exit plane.

Figure 13 depicts the profiles of computed CO mass fraction for the fuel CO<sub>2</sub> and FCO<sub>2</sub> dilutions in radial direction at  $x/D = 0.2, 1.1, 1.5,$  and  $3.0$ . As can be seen in this figure, CO mass fraction decreases when CO<sub>2</sub> is added to the fuel stream in all axial locations. The difference between CO<sub>2</sub> and FCO<sub>2</sub> dilution cases confirms that the chemical effects of diluent addition to the fuel stream lead to the increase of CO mass fraction. It is important to mention that the produced CO mass fraction depends highly on the CO<sub>2</sub> mass fraction, H mass fraction and, flame temperature distribution [6]. As previously noted, in the case of fuel stream dilution, the temperature is much lower compared with the oxidizer stream dilution case. It is worth mentioning that the production of CO originates from CO<sub>2</sub> breaking down by thermal dissociation process. In this regard, even though the CO<sub>2</sub> concentration increases in the fuel stream, the produced CO mass fraction is low due to low flame temperature. On the other hand, the production of CO is limited by the reduction of H radical concentration. The rate of



**Fig. 14** Radial profile of predicted CO mass fraction in the the case of no dilution, 10% dilution and 20% dilution of oxidizer stream at selected axial locations.

reduction is minimum at the axial location of  $x/D = 1.5$  because the high temperature ( about 1850 K) and the high amount of H radical increase the production of CO compared to other axial locations. Maximum reduction rate of CO is about 6% and 14% for 10% and 20% fuel dilution cases respectively at  $x/D = 1.5$ . Also the chemical effects of  $\text{CO}_2$  addition increase CO concentration about 13% and 40% for 10% and 20% diluted fuel respectively at the same location.

Figure 14 depicts the profiles of CO mass fraction computed for the oxidizer  $\text{CO}_2$  and  $\text{FCO}_2$  dilution cases in radial direction at  $x/D = 0.2, 1.1, 1.5,$  and  $3.0$ . In the case of oxidizer dilution, higher flame temperature contributes to the thermal dissociation of  $\text{CO}_2$ , so in the locations with a high H mass fraction, the production of CO is considerably increased in the case of 10%  $\text{CO}_2$  addition at all axial locations (see Figure 14). The concentration of CO decreases slightly in the case of 20%  $\text{CO}_2$  dilution compared to 10%  $\text{CO}_2$  dilution because the low flame temperature limits the thermal dissociation of  $\text{CO}_2$ . The maximum increasing of CO concentration is seen at  $x/D = 1.5$  which is about 16% for both dilution cases. The chemical effects of  $\text{CO}_2$  addition is also more pronounced at  $x/D = 1.5$  compared to other axial locations (due to the higher

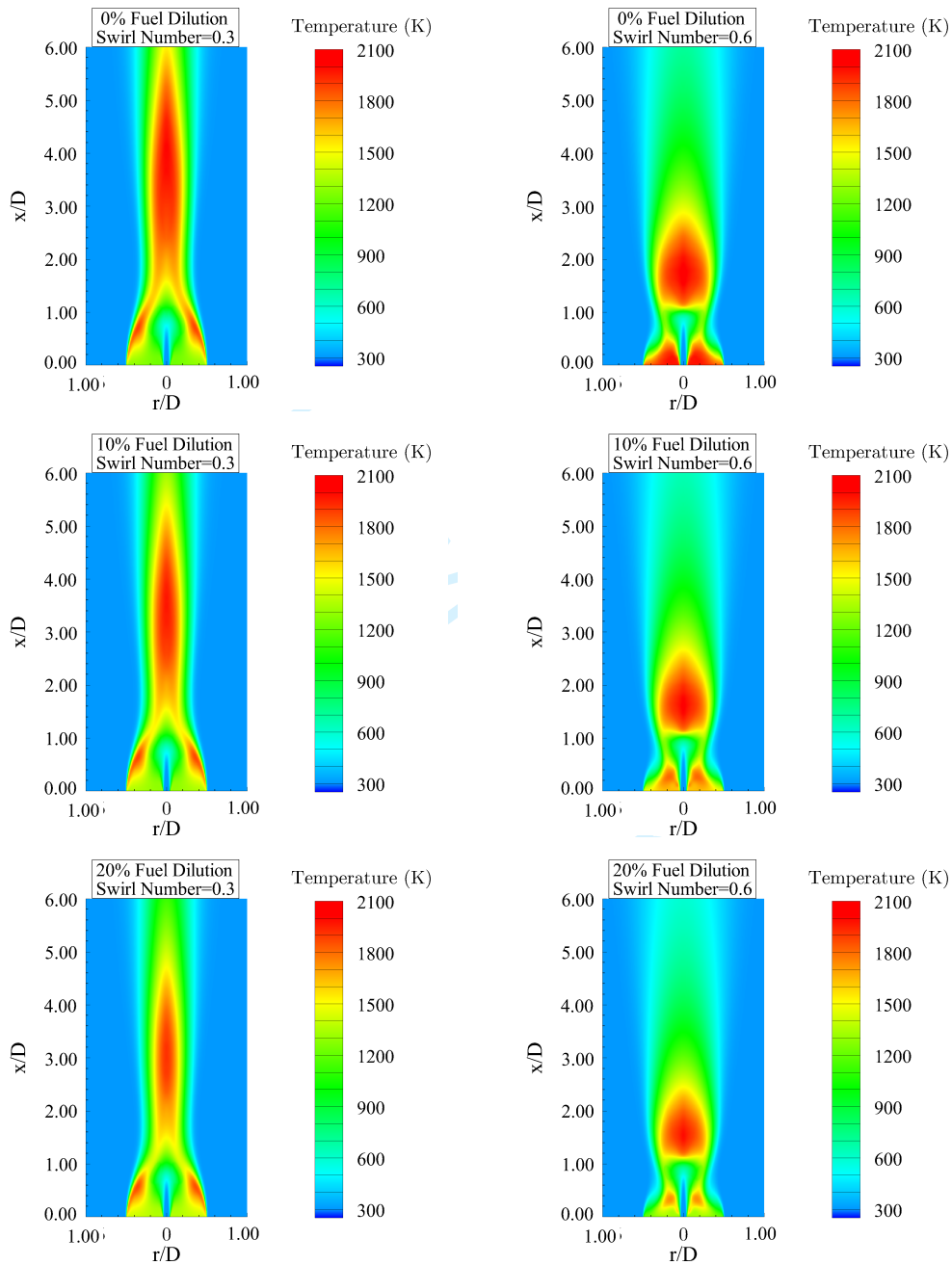
flame temperature), and it increases about 40% and 81% for the cases of 10% and 20% oxidizer dilution respectively.

To study the influence of fuel dilution and swirl intensity interactions on the flame structure, the CO<sub>2</sub> dilution of fuel stream with 10% and 20% CO<sub>2</sub> molar concentration is performed at the swirl number of 0.3 and 0.6. Figure 15 shows predicted temperature contours within the flow with 0%, 10% and 20% fuel dilution and at air swirl numbers of 0.3 and 0.6.

In swirl number of 0.3, a conical shape at the downstream position is formed in which the maximum flame temperature is located on the centerline of the nozzle. Correspondingly, at swirl number of 0.6, the flame has an hour-glass shape with sharp edges. In the undiluted case, the flame length is 36% longer at swirl number of 0.3 compared to swirl number of 0.6. Also the flame radius is smaller (about 10%) at the swirl number of 0.3. This is because, in low tangential velocities, the momentum of oxidizer decreases and the fuel stream penetrates more in the downstream. Conversely, in stronger swirl intensities (swirl number of 0.6), the adverse pressure gradient leads to flame length reduction. By the addition of CO<sub>2</sub> to the fuel stream, the length and radius of high temperature regions are reduced in both swirl numbers. This is because, in a lower concentration of CH<sub>4</sub>, the local heat release is significantly reduced due to the less breaking bonds of carbon atoms. The rate of flame length reduction is 14% and 25% at the swirl number of 0.3 for 10% and 20% dilution respectively, and is 37% and 40% at the swirl number of 0.6 in the case of 10% and 20% fuel dilution sequentially. When CO<sub>2</sub> is added to the fuel stream, the flame length decreases at all swirl numbers. It should be noted that by increasing the swirl number, the rate of flame length reduction (from 0% to 10% dilution) is more noticeable at the swirl number of 0.6 meaning that mixing time decreases significantly by both dilution and swirl effects. On the other hand, the rate of flame length reduction (from 10% to 20% dilution) is more significant at the swirl number of 0.3 showing that the effect of dilution on mixing time is dominant at lower swirl intensity.

#### 4 Conclusion

Currently, in the work being undertaken, the bluff-body swirl stabilized diffusion flame has been modeled using steady laminar flamelet model (SLFM) to investigate the effects of fuel and oxidizer CO<sub>2</sub> dilution on combustion characteristics.  $k-\omega$  SST turbulence model is utilized to close the Reynolds stresses. Considering the computational costs, 2D axisymmetric RANS



**Fig. 15** The temperature contours for the cases with 0%, 10% and 20% fuel dilution and swirl numbers of 0.3 (left) and 0.6 (right).

modeling is able to capture the important features of flow and combustion field, and the results are comparable with 3D URANS simulation; however, some details of flow features are missed in comparison with 3D LES simulation. In general, the results from computational methods are consistent with measurements, and follow the main trends of variables which are of interest in the current research. In the next stage, the effects of CO<sub>2</sub> dilution on the flame structure, temperature distribution, flame strength, and CO mass fraction is discussed. A fictitious species was replaced by the regular CO<sub>2</sub> in both fuel and oxidizer streams to determine chemical effects of CO<sub>2</sub> dilution. The fictitious species has the similar thermal and transport properties of CO<sub>2</sub> however, it does not participate in chemical reactions. The results show that the flame temperature had been reduced by addition of CO<sub>2</sub> to the fuel and oxidizer stream. The heat capacity and endothermic thermal dissociation process of CO<sub>2</sub> were responsible for the decrease of flame temperature. The chain carrier radical H, which is the indicator of flame strength, also decreased due to the thermal and chemical effects of CO<sub>2</sub> dilution. It is the result of H atoms consumption in reaction R99 which has been introduced as the primary reaction responsible for the chemical effects of CO<sub>2</sub> dilution. The flame length reduction is observed in all dilution cases. In the case of fuel dilution, it is mainly related to the decrease of the combustible component of fuel which decreased mixing time. Also in the case of oxidizer dilution, the flame length was reduced due to the increase in the momentum of oxidizer flow and generation of stronger recirculation zone. CO mass fraction is affected by the amount of CO<sub>2</sub> dilution, flame temperature and concentration of H atoms in the reaction zone. Since the production of CO originates from CO<sub>2</sub> breaking down by thermal dissociation process, CO mass fraction reduced in low-temperature regions where the CO<sub>2</sub> dissociation has been limited. Moreover, a study on the influence of fuel dilution and swirl intensity interactions on the flame structure has been conducted. The results depicted that the swirl number variation led to considerable changes in flame structure. At low swirl number, the flame had a conical configuration at the downstream position whereas, at higher swirl number, it showed an hour-glass shape. By the addition of CO<sub>2</sub> to the fuel stream, the length and radius of high-temperature regions have been reduced at all swirl numbers. This is because in a lower concentration of CH<sub>4</sub>, the breaking of carbon atom bonds decreased and it caused the reduction of local heat release. By increasing the level of dilution (from 10% to 20%) the rate of flame length reduction is more significant at low swirl number.

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