

Influence of swirl number on semi-confined flames

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Abstract: Stoichiometric methane air swirling flame has been modelled using RANS equations and a simplified mechanisms of reaction. The reaction zone is strongly affected by the swirl intensity. The higher the swirl number is, the narrower the reaction zone is. The thermodynamic state of reaction products matches well that of equilibrium state at constant pressure.

Keywords: CFD, RANS, Swirl, Flame, Methane.

1. Introduction

This research develops in the frame work of combustion of lean mixture fractions of natural gas. The effects are lower atmospheric emissions, reduction of fuel consumption and prevention of unburned methane that is one of the green house gases. It is commonly known that swirling flows promote the stable combustion of lean mixtures. This research is focus on swirling flames of lean mixture.

There is a wide range of numerical models applied on combustion and turbulent flows [1, 2]. The treatment ranges from a reduced mechanism of chemical reactions using LES [3], statistic treatment of tabulated experimental data in RANS [4] or reaction rate controlled by turbulent mixing in RANS [5].

This paper is devoted to the numerical analysis of swirling flames in a confined burned. Swirling has important influence in mixing [6-7]. Besides, coupling turbulence and combustion is a challenging issue because of the wide range of characteristic times to deal with.

There are different definitions for the Swirl number. In this work, it is assumed the ratio of azimuthal versus axial momentum.

The computational domain and the numerical modelling are presented in Section 2. In Section 3, results are discussed and the conclusions are summarised in the final section.

2. Numerical Model

The numerical domain consists of two coaxial nozzles: the central one supplies fuel and; the annular one supplies the air flow. Both nozzles discharged into a combustion chamber of 122 mm diameter. Dimensions and operating conditions correspond with the Roback and Johnson burner [8]. Swirl is induced by fix blades located in the annular nozzles, see figure 1. Different swirl numbers are obtained when the trailing angle of the blades is changed.

Navier Stokes equations for three-dimensional, steady, turbulent and reactive flows have been solved. Table 1 summarizes the main geometrical details of the burner and the operating conditions.

The transport coefficients are evaluated using a mixing law based

on local composition and temperature. Operating condition is at ambient pressure of 1 atmosphere.

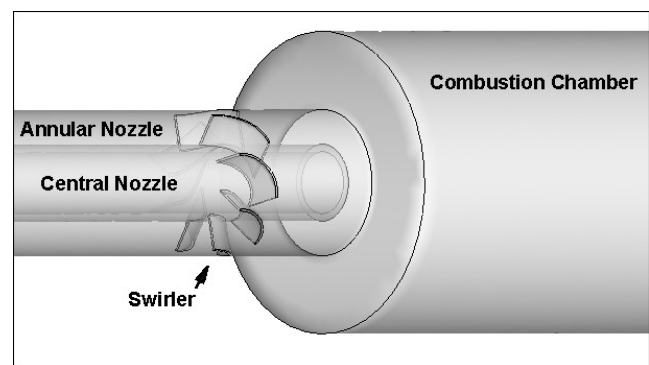


Figure 1. Scheme of the swirling burner.

Table 1. Operating conditions of the burner.

Variable	Fuel	Air
Injection	Central Nozzle	Annular Nozzle
Diameter (mm)	0-25	31-59
Composition (Mass Fraction)	14% CH ₄ + 86% N ₂	22% O ₂ + 78% N ₂
Temperature (K)	300	1200
Axial Velocity (m/s)	0.66	1.54
Turbulence Intensity (%)	12	7.5
Specific Heat (J/kg/K)	Polynomial function of temperature	
Viscosity (kg/m/s)	1.087 10 ⁻⁵	1.7894 10 ⁻⁵
Thermal Conductivity (W/m/K)	0.00332	0.0242

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3. Influence of Swirl Number

This section is devoted to the analysis of profiles and contours of stoichiometric flames when changing the swirl numbers.

Three swirl numbers have been tested. $S = 0.2$ represents a weak swirling intensity. In this case, the central jet has a minimum mixing with the annular one. $S = 0.7$ represents the limit between low and high swirling injectors.

$S = 1.2$ represents a strong swirling intensity. In the last case, central jet has more efficient mixing. The radial distribution of pressures promotes a shear layer that expands in the radial direction.

3.1. Profiles of Mass Fractions and Temperature

This subsection let identify the mixing and consequent combustion of the jets.

Figures 1 and 2 show radial and axial profiles of methane mass fraction and temperature respectively. The axial axis is the Z one. $Z = 0$ corresponds with the discharge of the nozzles.

Different radial profiles located at 5, 50, 100, 200 and 300 mm from the discharge of the nozzle are depicted. The last graph is the axial evolution of the variables along the axis.

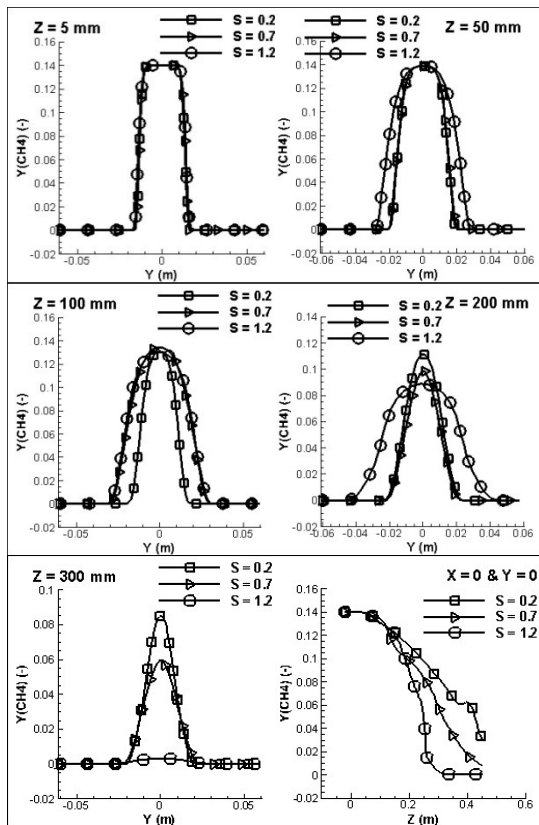


Figure 2. Radial and axial profiles of methane mass fractions.

$Z = 5$ mm let identify the central jet of methane and the annular jet of heated air. Assuming the flame front as the maximum temperature gradient, it is clear it is located in the shear layer that is in the zone of mixture between both jets.

In sections $Z = 200$ mm, the strongest swirl evidences better methane mixing and higher flames temperatures. Also the flame front of $S = 1.2$ is more expanded in the radial direction than the other flames.

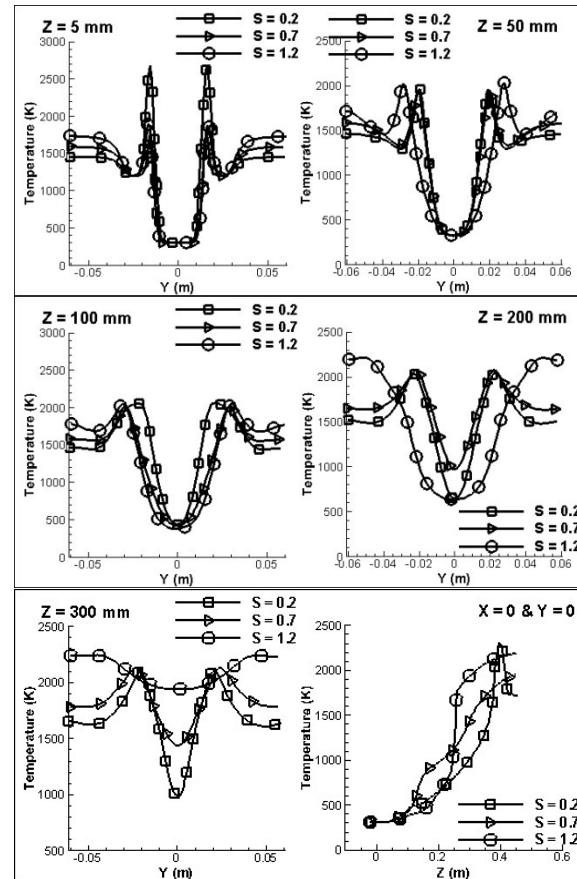


Figure 3. Radial and axial profiles of temperature at different sections.

In section $Z = 400$ mm there is no reaction zone for $S = 1.2$ since the temperature is uniform. As for the axial profile, it is evident the complete consumption of methane in $Z = 250$ mm for the highest swirl number.

It is evident that the strong swirl produces more efficient mixing and therefore, the flame front is located near the discharge of the nozzles.

3.2. Contours of Mass Fractions and Temperature

In this section, contours in a longitudinal slice are presented. Temperature is depicted in figure 4 whereas the major products of reaction are depicted in figures 5 and 6. Every contour has the same scale of colours to help to contrast the effect of different swirl numbers.

The flame is confined but the burner is open to the ambient. In order to have a reference of the expected composition and temperature values, the equilibrium state at constant pressure combustion [9] have been calculated using the CEA code developed by the NASA [10], see Table 2. The products of reaction evidence similar level of temperature and major species than those of equilibrium at constant pressure.

Table 2. Thermodynamic Equilibrium Combustion.

	Initial state	Equilibrium values
Pressure (atm)	1	1
Temperature (K)	300 (fuel) 1200 (air)	2243.97
Composition (Mass Fraction)	14% CH ₄ (fuel) 22% O ₂ (air)	8% CO ₂ 7% H ₂ O

The increase of swirl number is a precursor of shorter reaction zones and quick. The simulations were carried out under the hypothesis of thermal isolated walls. This is the reason of the isothermal lines to cut in perpendicular the wall boundaries of the domain.

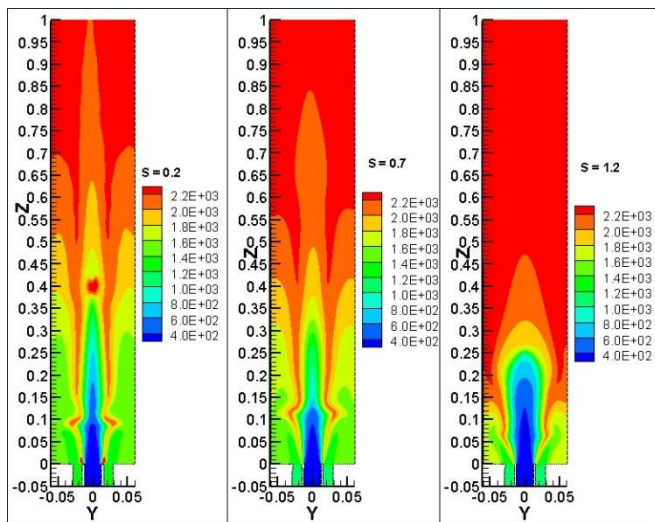


Figure 4. Contours of temperature in a symmetry slice.

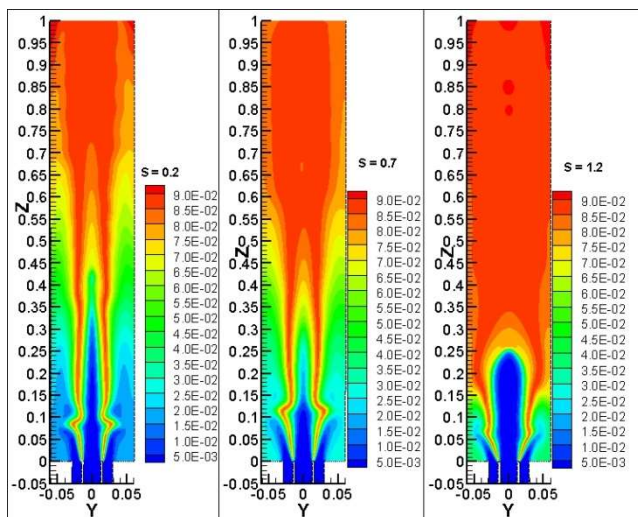


Figure 5. Contours of H₂O mass fraction in a symmetry slice.

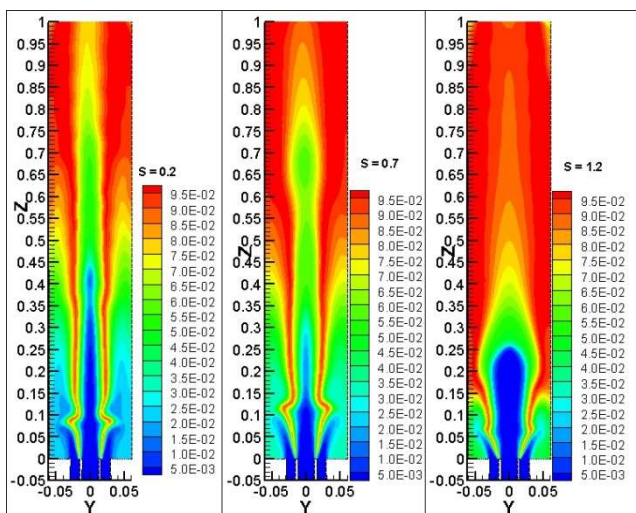


Figure 6. Contours of CO₂ mass fraction in a symmetry slice.

4. Conclusion

Numerical simulation of three dimensional turbulent and reactive flows has been carried out to study the effect of swirling in the flame. Turbulence model was the standard k-epsilon. A simplified mechanism of reaction was used to predict major species. The thermodynamic state of the product of reaction is near this of equilibrium at constant pressure.

Strong swirl has an important influence on the radial expansion of the shear layer and a better mixing. In the case of reaction, strong swirl is a precursor of shorter reaction zones and narrower flames fronts.

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