Proceedings of the International Conference on Heat Transfer and Fluid Flow
Prague, Czech Republic, August 11-12, 2014
Paper No. 86

Heat Transfer Enhancement in Swirling Flows

Teresa Parra, Ruben Perez, Miguel A. Rodriguez, Francisco Castro
University of Valladolid, Department of Energy and Fluid Mechanics
Paseo del Cauce 59, 47011 Valladolid, Spain
terpar@eii.uva.es; jrubenpd@gmail.com; miguel@eii.uva.es; castro@eii.uva.es

Artur Gutkowski
Lodz University of Technology, Institute of Turbomachinery
219/223 Wolczańska, 90-924 Łódz, Poland
artur.gutkowski@p.lodz.pl

Robert Z. Szasz
Lund University, Energy Division, Lund, Sweden
robert-zoltan.szasz@energy.lth.se

Abstract **-** In this paper, the influence of swirl number on mixing of two confined coaxial jets is analysed. The swirlers are designed using fixed vanes with different trailing edge angles in the annular nozzle resulting swirl numbers ranging from 0.14 to 0.95. Numerical model is validated using non reactive benchmarks. Low, intermediate and large swirling injectors are simulated to contrast the flow pattern. The presence of Inner Recirculation Zone associated to intermediate and high swirl numbers plays an important role in the heat and mass transfer since promote high gradients with minimum head loss. Low swirl injectors show large mixing regions in absence of the central vortex structure.

Keywords**:** Swirl number, CFD, Mixing, Recirculation zone.

1. Introduction

Swirling flows in burners are common because of the stabilization of lean flames with minimum head losses, ultra low emissions and fuel saving. This issue has important environment implications since the fuel slip due to incomplete combustion is a harmful greenhouse gas.

Firstly, the simulation requests the generation of a mesh that is a discretization of a continuous geometry into a computational domain. The geometry of the burner is composed by two coaxial nozzles, a swirl generator (a number of fixed vanes on the annular nozzle) and the combustion chamber. Configuration corresponds to the experimental characterization performed by Roback and Johnson (1983) being the only difference the swirl injector, such as is depicted in figure 1.

Despite the simple geometrical set-up of the benchmark, the flow pattern shows complex aerodynamic behaviour. The case considers two coaxial jets: one axial and another annular swirling jet. An expansion ratio of 4 in area produces the Outer Recirculation Zone (ORZ) when annular jet enters in the chamber. This kind of configuration has been analyzed by Palm (2006) for swirl numbers 0, 0.6 and 1.2.

Main difference in flow pattern between low and large swirling injectors is the presence of an expansion or a recirculation in the centre of the chamber. If swirl number is over 0.6, the flow turns back into the centre and then vortex break down phenomenon appears to form an Inner Recirculation Zone (IRZ). The region between both recirculation zones with high shear is where mixture occurs. Whereas, if swirl number is lower, there is an Inner Divergence Zone.

The selection of numerical methods is a prerequisite to perform accurate numerical simulations to better predict the performance of the swirling flow burner.

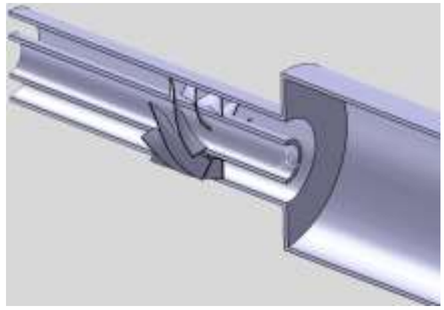
Fig. 1. Scheme of the swirling burner of Roback and Johnson (1983) with swirler angle 64º

2. Numerical Model

The conservative equations for 3D, steady, turbulent and incompressible flow are solved with a second order scheme looking for better accuracy even if the convergence is worst. Table 1 summarizes the boundary conditions for the nozzle inlets. Main uncertainty is the transitional flow regime. The 3D mesh has 1.5 million hexahedral cells.

PISO was the algorithm for pressure-velocity coupling since the option provides faster convergence. Multigrid options provide a substantial reduction of the computational time. It consists on solving equations on a coarse mesh to get initial solution to iterate on a finer mesh. However, multigrid is not suitable for reactive cases because the averaging on temperature field is a precursor of the lack of accuracy on the reaction rate. Parallel processing is important to afford resolution of meshes with adequate spatial resolution. The domain decomposition process was established to minimize the processor boundaries and therefore, saving information transfer time.

Table. 1. Boundary conditions of nozzles.

	Radio (inner-outer) (m)	Velocit y (m/s)	Temperature (K)	Turbulent Intensity (%)	Length scale (m)	Passive scalar
Annular inlet	0.0128-0.0295	1.54	900	7.5	0.017	0
Central inlet	0-0.0125	0.66	600	12	0.025	1

As for the turbulence model, among RANS models of 1, 2 or 4 equations, the most accurate was the k-ε RNG model dominated by the swirl. It is recommended by Ferziger (2002) to deal with the non-isotropic turbulence associated with the swirling. Bearing in mind the flow pattern is dominated by recirculation zones and fluid separation of the boundaries, the turbulence wall treatment was that of non equilibrium, hence it is not necessary to control the y+ range of variation.

Table. 2. Details of different set up of swirl injectors.

Design	Flat plate	Curved blade	Flat plate
Chord	50 mm	50 mm	25 mm
Swirler Angle	22º	54º	64º
Swirl number	0.14	0.74	0.95

Swirl generator is characterized by eight- fixed vanes in the annular nozzle with a fix angle in the trailing edge, Parra (2014). The definition assumed for the swirl number is the relation between the flow-averaged-azimuthal velocity and the corresponding axial velocity, see equation 1. Hence different swirl numbers request different orientation for the vanes. Previous studies have verified the lack of influence of the swirler's chord on the swirl number as well as the weak influence of the design (flat plates or curved blades) on the final flow pattern. Table 2 shows the different swirler configurations presented in this paper to provide different swirl numbers.

$$S = \frac{\int \rho v_\theta v_z 2\pi r dr}{\int \rho v_z^2 2\pi r dr} \quad (1)$$

3. Influence of Swirl Number

This section is devoted to the analysis of the flow pattern associated to low and high swirl numbers. Figure 2 shows, for non-reactive case and swirl numbers of 0.14, 0.74 and 0.95, the contours of temperature in a longitudinal plane and the volumes of iso-value null for axial velocity. Annular jet has a temperature of 900 K whereas central jet has 300 K; hence temperature gradient suggests the mixing. Besides, the zero axial velocity surfaces identify the position, shape and size of recirculation zones. Bearing in mind the ORZ that is formed due to the sudden expansion in the discharge of the annular nozzle it has a diminishing in size while increasing the swirl number. Swirl number 0.74 shows an incipient IRZ while Swirl number 0.95 shows a larger IRZ. The IRZ forces the mixing; hence temperature is homogenized very close to the nozzle's discharge. This means that temperature is homogenized in more remote sections of the nozzle's discharge in the cases with low azimuthal velocity. Furthermore, the shape of the IRZ in the upstream stagnation point is convex for swirl number 0.74 and concave for swirl number 0.95 increasing significant effect on heat transfer for larger swirls.

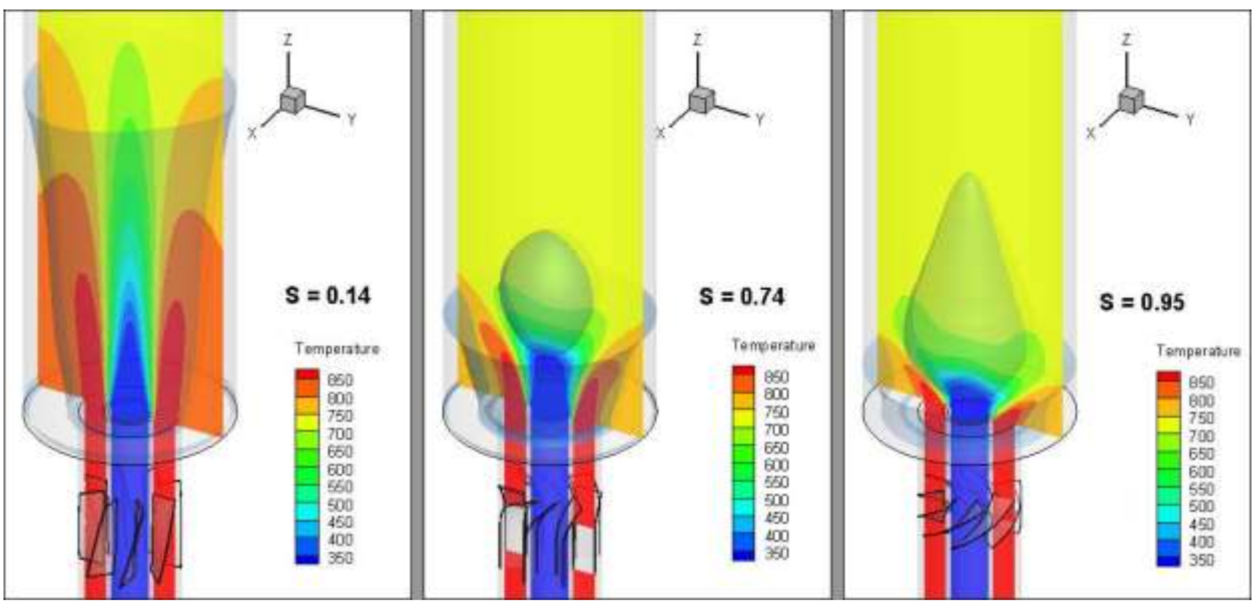

Fig. 2. Contours of temperature in the plane x = 0 and iso-surfaces of null axial velocity to locate recirculation zones. Left) Swirl no. 0.14, Center) Swirl no. 0.74 and Right) Swirl no. 0.95.

IRZ plays an essential role in homogenizing temperature. Because of the IRZ, the shear layer is deflected. The bigger the IRZ is, the thinner the shear layer is. Hence higher gradient appears. Another aspect is that the upwind stagnation point of the IRZ is approaching the discharge of the central nozzle while increasing the swirl number; hence the mixing region is small.

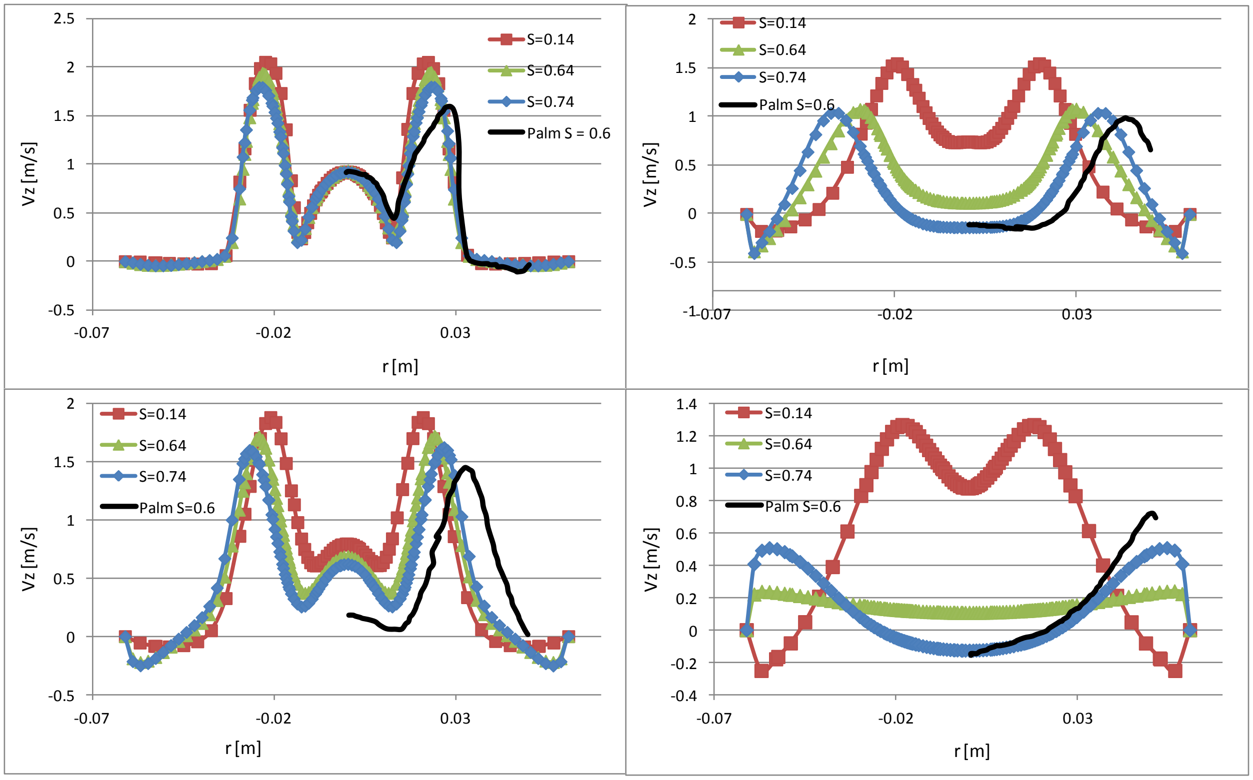

Fig. 3. Radial profiles of axial velocities con different sections. Upper Left) Z = 5mm, Lower Left) Z = 25mm, Upper Right) Z = 50 mm and Lower Right) Z = 100 mm Experimental values of Palm (2006).

Figure 3 shows the radial profiles of axial velocity for Swirl numbers 0.14, 0.64 and 0.74 in different cross sections located at Z = 5, 25, 50 and 100 mm from the discharge of the nozzles as well as the experimental results from Palm (2006). Every section evidences the increase of momentum mixing while increasing the swirl. The sections Z = 5 mm, 25 and 50 mm show that the numerical results are less dissipative than experimental results but section Z = 100 mm section shows a good agreement with the experimental results. Negative values of the axial velocity evidence the existence of recirculation zones. It is clear the presence of ORZ in sections 25 and 50 mm for any swirl. As for the IRZ, it only appears for Swirl 0.74.

Figure 4 shows the radial profiles of temperature for Swirl numbers 0.14 and 0.74 in different cross sections located at Z = 5, 50, 100 and 300 mm from the discharge of the nozzles. Every section affected by the IRZ, Z > 5 mm and Swirl > 0.6, evidences the increase of heat transfer while increasing the swirl. Mass fraction shows similar results in the same sections. It is clear the homogenization role played by the IRZ for high swirl numbers.

Figure 5 show longitudinal contours of the passive scalar, turbulent kinetic energy and axial vorticity. The first one let identify mass mixing. Steam lines let identify the IRZ concluding the important role played in homogenizing species. Turbulent kinetic energy show maximum values on the shear layer but there is not relevant production of energy inside the IRZ. Finally, the axial vorticity is located on the annular jet because of the swirler and in the IRZ, where fluid spin as a rigid solid, with minimum deformation.

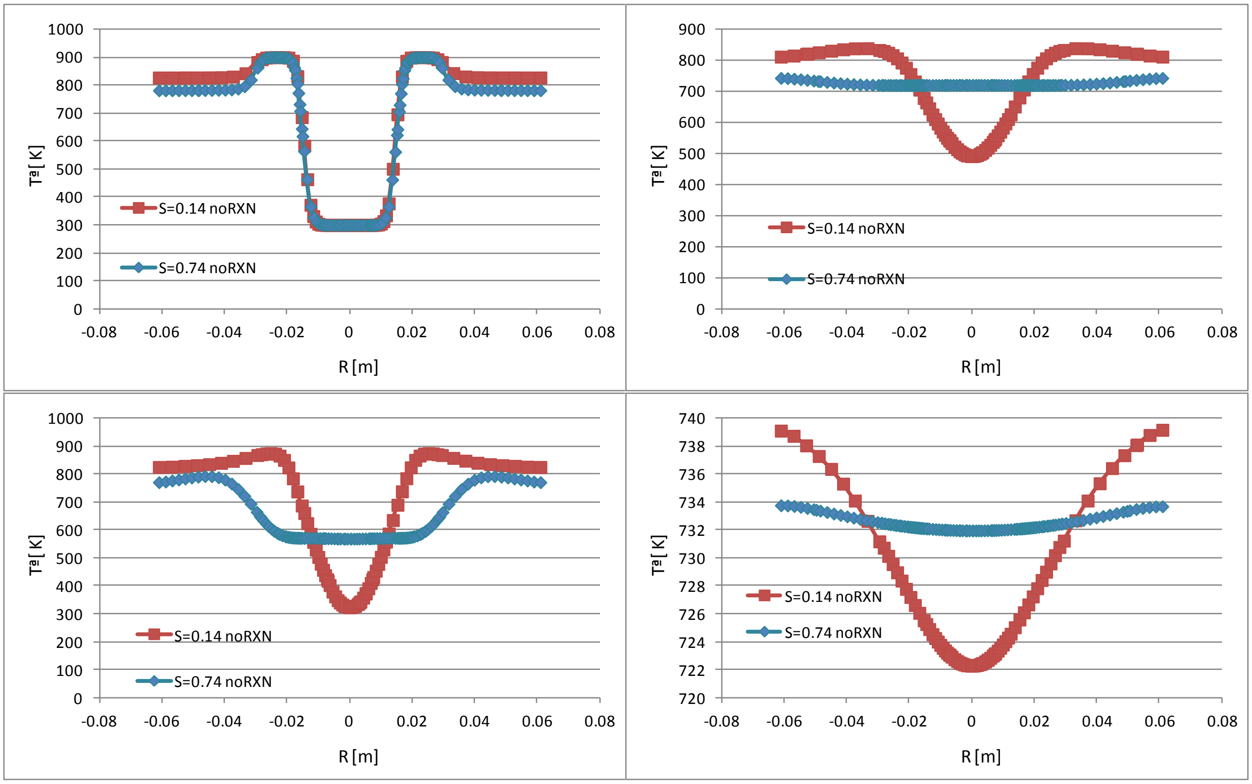

Fig. 4. Radial profiles of axial velocities con different sections. Upper Left) Z = 5mm, Lower Left) Z = 50mm, Upper Right) Z = 100 mm and Lower Right) Z = 300 mm.

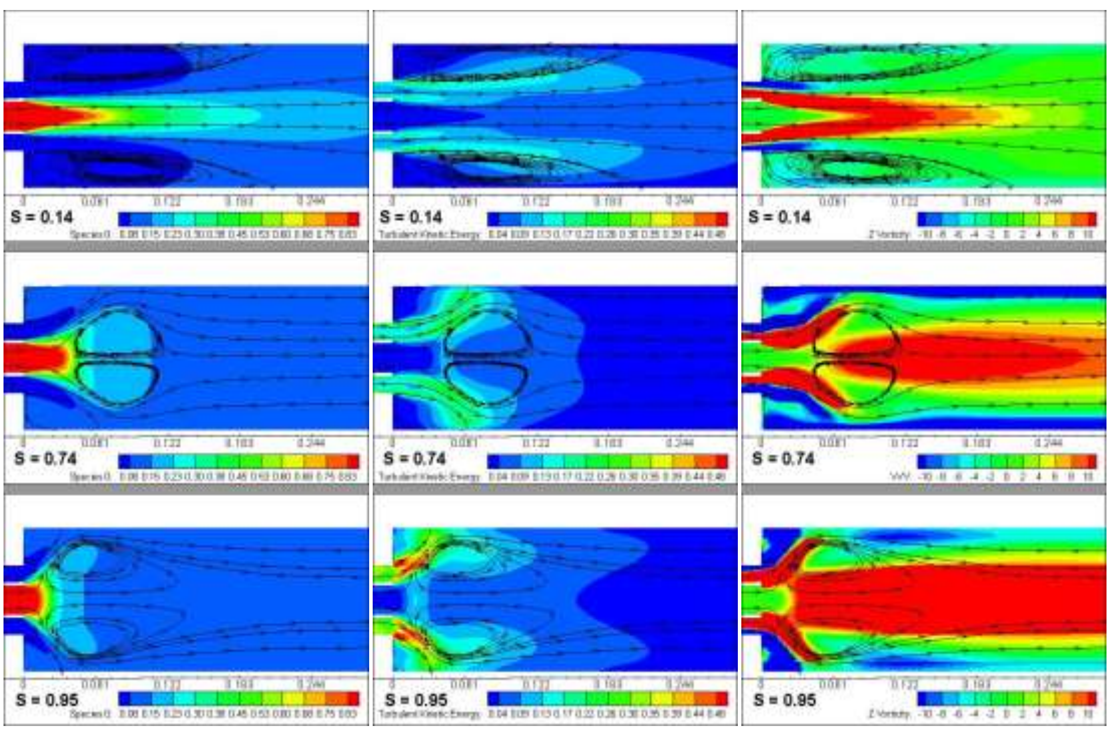

Fig. 5. Contours in the plane x = 0 and stream lines to locate recirculation zones. Left) Passive scalar, Centre) Turbulent Kinetic Energy and Right) Axial Vorticity for different Swirl numbers Upper) S = 0.14, Middle) S = 0.74, Lower) S = 0.95.

4. Conclusion

This paper studies the mixing of different swirling jets ranging from low to intermediate and high swirling numbers, validation was provided for high swirl number.

Low swirling injectors does not promote the fluid to turn over near the centre of the chamber, resulting larger mixing zones with weak gradients. Pressure distribution for intermediate and larger swirls promote the formation of a vortex bulb near the axis of the chamber, this inner recirculation zone is responsible of deflecting the shear layer and increases the gradients near the upstream of its lead stagnation point. As a result, mixing occurs at short distance of the nozzle's discharge. This justifies the common use of swirling to burn lean mixtures that would show instable behaviour without swirl.

Also the convex or concave shape of the recirculation point near this stagnation point is important on the mass and heat transfer. Future works involve the study of reactive cases.

Acknowledgements

The authors thankfully acknowledge the Spanish Ministry of Science and Innovation for the financial resources in the framework of the project reference ENE2011-25468.

We acknowledge PRACE for awarding us access to resource Curie-Genci based in France at CEA and MareNostrum based in Spain at BSC. Ref. 2010PA1766.

References

Ferziger J. H., Peric M., (2002) Computational Methods for Fluid Dynamics, 3rd edition, Springer

Palm R., Grundmann S., Weismuller M., Saric S., Jakirlic S., Tropea C. (2006) Experimental characterization and modelling of inflow conditions for a gas turbine swirl combustor International Journal of Heat and Fluid Flow 27 924–936

Parra T., Vuorinen V., Perez R., Szasz R. and Castro F. (2014). Aerodynamic characterization of isothermal swirling flows in combustors. International Journal of Energy and Environmental Engineering 5:85

Roback R., Johnson B.V. (1983) Mass and momentum turbulent transport experiments with confined swirling coaxial jets, NASA CR-168252