Chapter 1

Introductory Chapter: Swirling Flows and Flames

Toufik Boushaki

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/intechopen.86495

1. Introduction

Swirling flows are used in a very wide range of industrial applications. In non-reacting cases, examples of applications include vortex amplifiers and reactors, heat exchangers, jet pumps, cyclone separators, whirlpools, tornadoes, etc. In reacting cases, swirlers are widely used in combustion systems, such as gas turbines, industrial furnaces, boilers, gasoline and diesel engines and many other practical heating devices. Effects of using swirl on flow and combustion are significant and various and concern, for example, aerodynamics, mixing, flame stability, intensity of combustion and pollutant emissions. In this chapter, we are interested in the use of swirling flows in combustion systems.

In industrial plants, the geometric methods of flame stabilization are based on increasing the residence time of reactive gases either by the wake effect *bluff-body burner*, by the flow rotation of reactants *swirl burner* or by a combination of these two mechanisms.

Burners with helical flows generally referred to as the swirl burner have very wide applications in the industrial field. In the literature, many examples of uses of swirling jets are found as a means of controlling combustion [1–4]. Other studies focused on the swirl effect on the characteristics of lifted flames [5], stabilization and blow-out phenomenon [6–8] and pollutant emissions [9–13].

2. Swirl generation techniques

There are several ways to generate the rotation of a flow. They can be classified into three main categories:

- Use of fins or adjustable propellers tangentially deflecting the axial flow. Because of its simplicity, this device is generally used in industrial systems, in particular in gas turbines. However, this type of device introduces significant head losses, and the intensity of swirl is limited (design of fins) [14].
- Rotating mechanical devices which generate a rotational movement to the fluid passing between them [10].
- Tangential injection of part or all fluid quantity into a main duct. The intensity of the swirl is then determined by the ratio between the flow injected tangentially and that injected axially [15, 16].

3. Swirl number

The swirl number (S_n) is a dimensionless number that characterizes the rotating flows. It is defined as (Beér and Chigier [1])

$$S_n = \frac{G_\varphi}{RG_x^{'}} \tag{1}$$

where G_φ is the axial flux of the tangential momentum, $G_x^{'}$ is the axial flux of axial momentum and R is the exit radius of the burner nozzle. This number determines the intensity of swirl; the more this number is higher, the more the swirl effect is strong. The fluxes G_φ and G_x are given by the following expressions:

$$G_\varphi = \int_0^R (Wr)\ \rho U\ 2\ \pi\ r\ dr \tag{2}$$

$$G_x = \int_0^R U\rho\ U\ 2\pi\ r\ dr + \int_0^R p\ 2\pi\ r\ dr \tag{3}$$

U and W are the axial and tangential components of the velocity, respectively; p is the static pressure of the flow.

The introduction of this swirl number is based on G_φ and G_x measurements along the axis the flow. To experimentally evaluate S_n, it is necessary to have access to the velocity and pressure distributions on cross sections of the rotating flow. The swirl number can be calculated geometrically with the dimensions of the swirler and burner, as in [17, 18].

4. Swirl effects on flames

According to some studies as Beér and Chigier [1], for flows with a low swirl number ($S_n = 0.6$), there is no recirculation of the flow (**Figure 1**). The swirl induces an increase in the

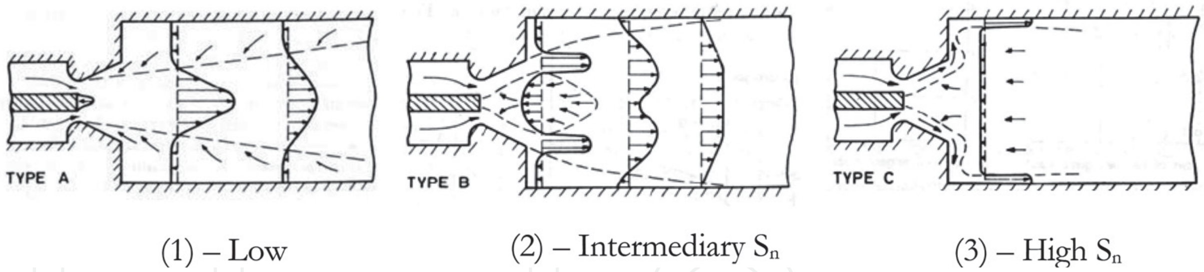

Figure 1. Swirl effect on flames [1]. (1) Low S_n, (2) intermediary S_n and (3) high S_n.

entrainment of the ambient fluid and a decrease in the axial velocity of the flow. Axial velocity radial profiles remain a Gaussian form as long as the swirl remains below 0.5. Velocity maximum deviate from the axis when approaching S_n = 0.6. Thus the degree of jet opening and the entrained mass flow then increase continuously with the swirl number. From a swirl intensity of about 0.6, a recirculation zone appeared in the main flow. The size and position of this recirculation zone varies with the intensity of swirl [1, 17]. This zone is an essential element for the stabilization of flames because it contains preheated fresh gases and allows a better combustion.

The swirl is commonly used in combustion because it has a stabilizing role for the flame [1, 8]. Indeed, if the swirl intensity is strong enough, a recirculation zone will appear. The latter is a region in which fresh gases and flue gases are well mixed. In addition, swirl improves the entrainment of gases and greatly increases flame-blow limits [3, 7]. Beer and Chigier [1] show the effect of the swirl intensity on the behaviour of the flame as shown in **Figure 1**.

- Case (1): The intensity of swirl is low; the flame behaviour is similar to that encountered without swirl. The flame is detached from the burner.
- Case (2): The intensity of swirl is intermediary; the flame is stabilized closer to the burner, in the recirculation zone rich in fresh gas. Turbulence levels are high and combustion is intense.
- Case (3): The intensity of swirl is high; the interaction of flame/walls is intense; this is in generally an undesirable case, except in certain industrial furnaces to obtain an intense and uniform radiation.

Many advantages of swirling reacting flows are now well-known and studied, as the flame stabilization improvement through the vortex breakdown phenomenon, due to the central recirculation zone (CRZ) occurrence [3, 7, 19, 20] and enhancement in turbulent mixing of reactants by means of the precessing vortex core (PVC). Authors [21–25] studied the flow characteristics and mixing properties of the swirling double concentric jets at low Reynolds numbers with control discs. Jourdaine et al. [26], investigated premixed swirling flames of CO_2–CH_4–O_2 and CH_4-air using different optical diagnostics. Benim et al. [27] studied numerically turbulent swirling flames in a model gas turbine combustor, using OpenFOAM code through the LES approach. Elbaz and Robert [16] investigated non-premixed methane swirling flames and particularly the quarl geometry effect on the flame structure. They were interested in the measurements of the turbulent flow field, concentrations of species and temperature distribution. Khalil Ahmed and Gupta [28] studied the colourless distributed combustion (CDC) combustor. CDC was examined with both swirling and non-swirling cases using different injection of velocity to improve distributed combustion. Orbay et al. [29] reported experiments and numerical simulations of swirling turbulent flows in non-reactive and reactive cases in an academic gas turbine combustor. They conducted PIV-LDV measurements and LES calculations focusing on the characterization of the flow structures, the effect of inflow swirl and the heat release in a premixed natural gas-air combustor. Candel et al. [30] performed a review of some recent progresses on swirling flame dynamics, particularly with the presence of acoustic perturbations. They found that the presence of acoustic perturbations in swirling flows induces a vorticity wave which is convected by the flow. They showed that the response of flame is characterized by a combination of heat release rate fluctuations generated by the incoming acoustic and convective perturbations. Von Lavante and Yao [31] studied numerically different types of axisymmetric internal configurations to examine the development of turbulent swirling and non-swirling flows along the flow. A numerical algorithm for solving the three-dimensional axisymmetric internal turbulent flows was developed. Good agreement of the calculation and theoretical results of the velocity profiles and pressure distributions was obtained. Iyogun et al. [14] presented an experimental investigation on the stability of swirling non-premixed CH_4 flames in a coaxial burner. Measurements were conducted for both reacting and non-reacting swirling flows. Cozzi and Coghe et al. [32] investigated by stereo-particle image velocimetry (S-PIV) technique the initial region of a swirling gas jet on a model burner in isothermal swirling air jets. Their study was interested to identify the presence of vortex breakdown, the central recirculation zone (CRZ) and the precessing vortex core (PVC). Boushaki et al. [13] investigated turbulent flames on a swirl burner with a radial injection of fuel (**Figure 2**). The burner consists of two concentric tubes with a swirler placed in an annular part supplying the air. Eight vanes are made to induce a swirl intensity variation. The central pipe delivers a fuel radially through eight holes symmetrically distributed on the periphery of the tube near the exit burner.

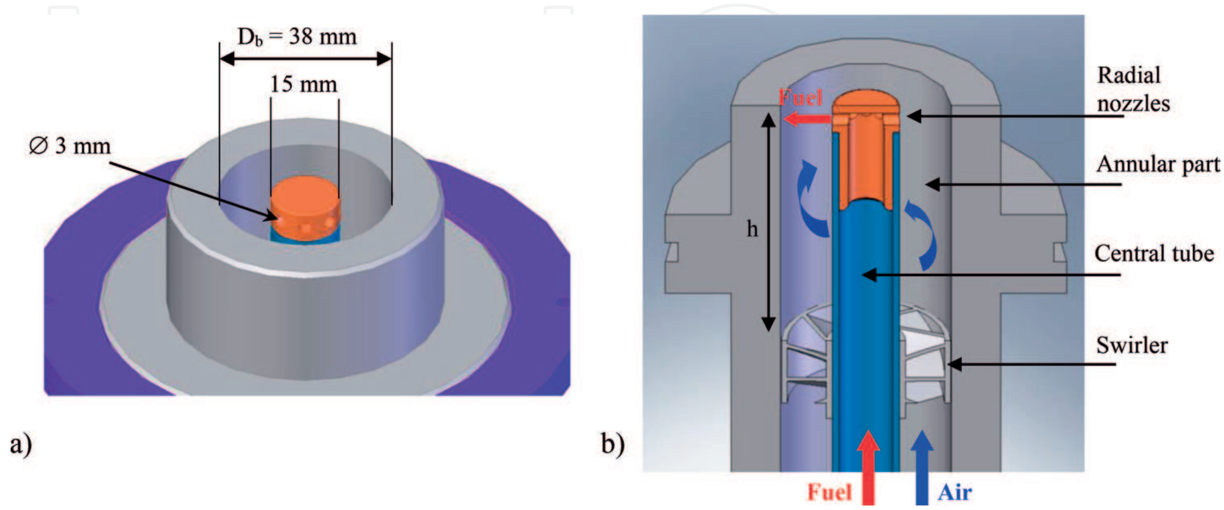

Figure 2. Diagram of the coaxial swirl burner, (a) 3D view of the top part and (b) vertical cross section.

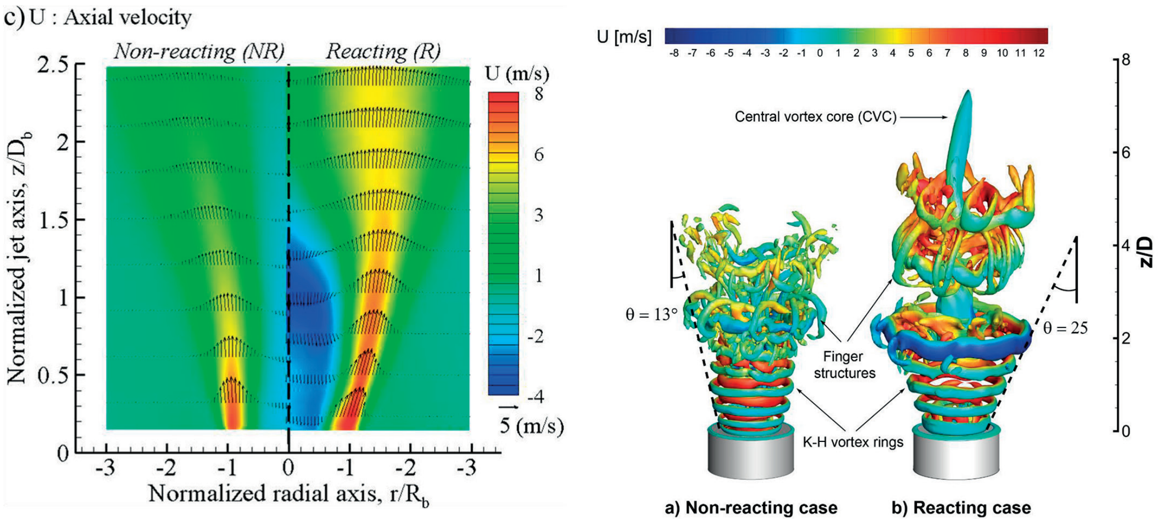

Figure 3. On the left: fields of axial velocity (U) under non-reacting and reacting conditions ($S_n = 0.8$ and $\Phi = 0.8$) [13]. On the right: snapshot of iso-surfaces of Q-criterion for the non-reacting (a) and reacting (b) cases [33].

Experimental and numerical investigations have been performed on this burner configuration as shown in **Figure 3**. On the left of **Figure 3** [13], it shows contours of axial (U) velocity up to 2.5D downstream of the flow in non-reacting and reacting cases with the condition of a swirl number $S_n = 0.8$ and a global equivalence ratio $\Phi = 0.8$. The velocity field is symmetrical about the dashed line $x = 0$. Note that only the left part of the field (x/R_b: from 0 to −3) is plotted in **Figure 3**. Velocity fields highlight the higher axial expansion induced by the combustion in the reacting flow. As expected, with high swirl intensity, an internal recirculation zone (IRZ) appeared for non-reacting and reacting conditions. The IRZ becomes larger by the combustion due to the change in fluid density and more intense for the reacting case compared to the non-reacting case.

On the right of **Figure 3**, the 3D coherent structures are identified using Q-criterion iso-surface for both non-reacting and reacting flows [33]. The iso-surfaces are coloured by the instantaneous axial velocity. The Q-criterion identifies vortices of an incompressible flow as connected fluid regions with a positive second invariant of the velocity gradient tensor [34]. The 3D coherent structures can reveal in a discernible manner the swirling flow instabilities. Two similar structures are present in the isothermal and the reacting flows, which are the vortex rings and the finger structures. In the near field at the burner exit, each jet is composed of two shear layers (ISL and OSL) owing to the annular geometry of the burner. More details about these works can be found in the previous paper of the authors [35–37].

5. Swirl effects on pollutant emissions

Schmittel et al. [10] showed that the use of swirl in non-premixed combustion can lead to the reduction of pollutant emissions, particularly that of nitrogen oxides. Indeed, under the swirl effect and thus the mixing improvement of reactants, the flame temperature decreases and leads to the decrease of NOx production. In addition, when the intensity of the swirl is sufficient, increasing the swirl number induces a reduction of residence time in hot areas. This also has the effect of limiting NOx formation. However, it is necessary to find a swirl intensity that achieves a compromise between on the one hand the reduction of pollutant emission and, on the other hand, the distance flame burner to prevent the flashback. The study of Coghe et al. [11] on a lean natural gas burner (ϕ = 0.69) showed that NOx reduction can reach 30% for a swirl number between 0.7 and 0.82. Pesenti and Lybaert [38] tested in a 300 kW furnace with a swirl burner and an air co-flow by comparing three ratios of tangential airflow to total flow (air + natural gas) 0, 0.5 and 1. The authors showed that the optimum in terms of NOx emission is obtained when 50% of tangential air is injected. Burguette and Costa [39] evaluated the influence of the swirl intensity on NOx through the angle of the blades constituting the swirler. They found that at 45° the NOx rate is the most important; however, at 45° lower or higher, NOx emissions decrease. The authors explain these results by the fact that at 45° the recirculation zone starts, and therefore the residence time increases close to the burner, thus increasing the intensity of combustion and consequently the temperature and NOx formation. Cozzi and Coghe [12] studied NOx emissions on a coaxial swirled natural gas flame. They reported that the swirl intensity has a strong effect on non-premixed flames in which very low levels of NOx can be obtained at higher swirl.

Boushaki et al. [15, 40] investigated reacting swirling flows on a burner with triple jets as shown in **Figure 4**. The burner is composed of three nozzles, one central of natural gas and two laterals of pure oxygen. Each nozzle is surrounded tangentially by four small jets around the main jets. These small jets generate a swirling motion of the flow; the swirl intensity is controlled by the flow rate in the actuators. The authors reported that the swirl intensity through the flow rate of actuators affects significantly the flow field and consequently the flame behaviour (stability, shape, pollutants). For example, **Figure 4b** illustrates NOx emissions as a function of the swirl intensity controlled by the flow rate ratio *r* (ratio of flow rate of jet actuators and total flow rate). The results show that the NOx emissions with swirl intensity decrease in the first part. In this part, the NOx reductions are about 22, 36 and 60%

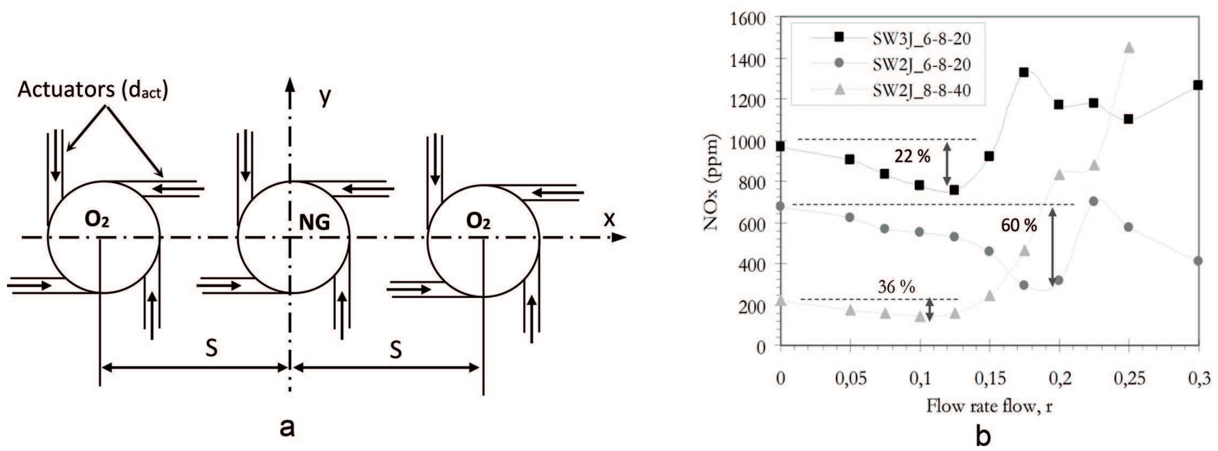

Figure 4. (a) Swirl burner with triple jets. (b) NOx emissions with the flow rate ratio for three burner configurations [15, 39].

depending to the burner configuration. From 0 to 15% of flow rate ratio, the swirling flow enhances mixing progressively and probably induces a reduction of NOx emission. Besides, the swirl by jet actuators enhances entrainment of combustion products, which decreases the flame temperature and NOx production. For the second part with higher swirl intensity, the increase of NOx production can be explained by the higher velocities of the small jet which disturb the main jets.

Boushaki et al. [13] and Nazim et al. [41] reported the effect of the swirl number on the NOx and CO emissions. They found that in the case of a swirl number of 1.4, the EICO rate is slightly lower than in the case of a swirl number of 0.8. The authors noted that the swirl intensity might tend to enhance the mixing and to increase the residence time inside the reaction zone, which promotes the CO conversion to CO_2. Concerning the NOx emissions, the authors found that increasing the swirl number tends to reduce the $EINO_x$ formation in particular for oxygen rate up to 27%. The authors explain this evolution by the decrease of flame temperature induced by the swirl through the Zeldovich mechanism. Some authors as [10, 42] by the experiments and computations demonstrated that NO_x emissions decrease when the swirl number increases, mainly because of the better mixing with combustion products in the inner recirculation zone created by high swirling flows.

Author details

Toufik Boushaki

Address all correspondence to: toufik.boushaki@cnrs-orleans.fr

ICARE CNRS, University of Orléans, France

References

[1] Beér JM, Chigier NA, editors. Combustion Aerodynamics. Florida: Krieger, Malabar; 1972

[2] Syred N, Béer JM. Combustion in swirling flows: A review. Combustion and Flame. 1974;**23**:143-201

[3] Yuasa S. Effects of swirl on the stability of jet diffusion flames. Combustion and Flame. 1986;**66**:181-192

[4] Takahashi F, Schmoll WJ. Lifting criteria of jet diffusion flames. In: 23th Symposium (International) on Combustion; Orléans, France: The Combustion Institute; 1990; pp. 375-382

[5] Cha MS et al. Effect of swirl on lifted flame characteristics in nonpremixed jets. Combustion and Flame. 1999;**117**:636-645

[6] Poireault B. Mécanismes de combustion dans un brûleur méthane-air de type swirl (40kW): Influence de l'intensité de rotation. Thèse de l'université de Potiers. 1997

[7] Feikema D, Chen RH, Driscoll JF. Enhancement of flame blowout limits by the use of swirl. Combustion and Flame. 1990;**80**:183-195

[8] Masri AR, Kalt PAM, Barlow RS. The compositional structure of swirl-stabilised turbulent nonpremixed flames. Combustion and Flame. 2004;**137**:1-37

[9] Hatami R. Reduction of the NOx emission of a closed combustion chamber by changing to air flows with swirl. Applied Energy. 1981;**9**(2):159-164

[10] Schmittel P et al. Turbulent swirling flames: Experimental investigation of the flow field and formation of nitrogen oxide. In: 28th Symposium (International) on Combustion. The Combustion Institute. 2000. pp. 303-309

[11] Coghe A, Solero G, Scribano G. Recirculation phenomena in a natural gas swirl combustor. Experimental Thermal and Fluid Science. 2004;**28**:709-714

[12] Cozzi F, Coghe A. Effect of air staging on a coaxial swirled natural gas flame. Experimental Thermal and Fluid Science. 2012;**43**:32-39

[13] Boushaki T, Merlo N, Chauveau C, Gökalp I. Study of pollutant emissions and dynamics of non-premixed turbulent oxygen enriched flames from a swirl burner. Proceedings of the Combustion Institute. 2017;**36**:3959-3968

[14] Iyogun CO, Birouk M, Kozinski JA. Experimental investigation of the effect of fuel nozzle geometry on the stability of a swirling non-premixed methane flame. Fuel. 2011;**90**(4):1416-1423

[15] Boushaki T, Sautet JC, Labegorre B. Control of flames by radial jet actuators in oxy-fuel burners. Combustion and Flame. 2009;**156**:2043-2055

[16] Elbaz AM, Robert WL. Investigation of the effects of quarl and initial conditions on swirling non-premixed methane flames: Flow field, temperature, and species distributions. Fuel. 2016;**169**:120-134

[17] Sheen HJ, Chen WJ, Jeng SY, Huang TL. Correlation of swirl number for a radial-type swirl generator. Experimental Thermal and Fluid Science. 1996;**12**:444-451

[18] Gupta AK, Lilley DG, Syred N. Swirl Flows. United Kingdom: Abacus Press; 1984

[19] Ahmed SF, Balachandran R, Marchione T, Mastorakos E. Spark ignition of turbulent nonpremixed bluff-body flames. Combustion and Flame. 2007;**151**:366-385

[20] Mansouri Z, Aouissi M, Boushaki T. Detached eddy simulation of high turbulent swirling reacting flow in a premixed model burner. Combustion Science and Technology. 2016;**188**(11-12):1777-1798

[21] Galley D, Ducruix S, Lacas F, Veynante D. Mixing and stabilization study of a partially premixed swirling flame using laser induced fluorescence. Combustion and Flame. 2011;**158**:155-171

[22] Stöhr M, Arndt CM, Meier W. Transient effects of fuel-air mixing in a partially-premixed turbulent swirl flame. Proceedings of the Combustion Institute. 2015;**35**(3):3327-3335

[23] Steinberg AM, Arndt CM, Meier W. Parametric study of vortex structures and their dynamics in swirl-stabilized combustion. Proceedings of the Combustion Institute. 2013;**34**:3117-3125

[24] Mansouri Z, Aouissi M, Boushaki T. Numerical computations of premixed propane flame in a swirl stabilized burner: Effects of hydrogen enrichment swirl number and equivalence ratio on flame characteristics. International Journal of Hydrogen Energy. 2016;**41**:9664-9678

[25] Huang RF, Duc LM, Hsu CM. Flow and mixing characteristics of swirling double-concentric jets influenced by a control disc at low central jet Reynolds numbers. International Journal of Heat and Fluid Flow. 2016;**00**:1-14

[26] Jourdaine P, Mirat C, Caudal J, Lo A, Schuller T. A comparison between the stabilization of premixed swirling CO_2-diluted methane oxy-flames and methane/air flames. Fuel. 2016

[27] Benim AC, Iqbal S, Meier W, Joos F, Wiedermann A. Numerical investigation of turbulent swirling flames with validation in a gas turbine model combustor. Applied Thermal Engineering. 2017;**110**:202-212

[28] Khalil Ahmed EE, Gupta KA. Towards distributed combustion for ultra low emission using swirling and non-swirling flowfields. Applied Energy. 2014;**121**:132-139

[29] Orbay RC, Nogenmyr KJ, Klingmann J, Bai XS. Swirling turbulent flows in a combustion chamber with and without heat release. Fuel. 2013;**104**:133-146

[30] Candel S, Durox D, Schuller T, Palies P, Bourgouin JF, Moeck J, et al. Progress and challenges in swirling flame dynamics. Comptes Rendus Mecanique. 2012;**340**:758-768

[31] Von Lavante E, Yao J. Numerical investigation of turbulent swirling flows in axisymmetric internal flow configurations. Flow Measurement and Instrumentation. 2012;**25**:63-68

[32] Cozzi F, Coghe A, Sharma R. Analysis of local entrainment rate in the initial region of isothermal free swirling jets by Stereo PIV. Experimental Thermal and Fluid Science. 2018;**94**:281-294

[33] Mansouri Z, Boushaki T. Experimental and numerical investigation of turbulent isothermal and reacting flows in a non-premixed swirl burner. International Journal of Heat and Fluid Flow. 2018;**72**:200-213

[34] Hunt JCR, Wray AA, Moin P. Eddies, streams, and convergence zones in turbulent flows. Report CTR-S88; Stanford: Stanford University, Center for Turbulence Research; 1988. pp. 193-208

[35] Merlo N, Boushaki T, Chauveau C, de Persis S, Pillier L, Sarh B, et al. Combustion characteristics of methane-oxygen enhanced air turbulent non-premixed swirling flames. Experimental Thermal and Fluid Science. 2014;**56**:53-60

[36] Boushaki T, Koched A, Mansouri Z, Lespinasse F. Volumetric velocity measurements (V3V) on turbulent swirling flows. Flow Measurement and Instrumentation. 2017;**54**:46-55

[37] Zaidaoui H, Boushaki T, Sautet JC, Chauveau C, Sarh B, Gökalp I. Effects of CO_2 dilution and O_2 enrichment on non-premixed turbulent CH_4-air flames in a swirl burner. Combustion Science and Technology. 2018;**190**(5):784-802

[38] Pesenti B, Lybaert P. Numerical and experimental investigation of a 300 kW swirl gas burner: Flame shape and NOx emissions. In: 2nd European Combustion Meeting; Louvain-la-Neuve, Belgium; 2005

[39] Burguette M, Costa M. NOx emissions from unconfined swirl flames. In: 7th European Conference on Industrial Furnaces and Boilers INFUB7, Porto. 2006

[40] Boushaki T, Sautet JC. PIV measurements on oxy-fuel burners. In: The Particle Image Velocimetry: Characteristics, Limits and Possible Applications. InTech; 2012. pp. 123-148. ISBN 978-953-51-0625-8

[41] Merlo N, Boushaki T, Chauveau C, de Persis S, Pillier L, Sarh B, et al. Experimental study of oxygen enrichment effects on turbulent nonpremixed swirling flames. Energy & Fuels. 2013;**27**:6191-6197

[42] Frassoldati A, Frigerio S, Colombo E, Inzoli F, Faravelli T. Chemical Engineering Science. 2005;**60**(11):2851-2869