Prediction of flow through swirl generator and validation by measured data

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Abstract. It is a well-recognized fact that reliable predictions of turbulent swirling nonpremixed flames are very difficult, especially for practical cases where application of LES methods is not feasible. It is also clear that detailed measured data of inlet velocity profiles for swirling combustion air are unavailable in practical applications. Therefore there is a need for validation of industry-standard codes for the prediction of flow through swirl generators. In this work are predictions validated by published experimental data for a swirler with guide vanes, which is similar to a typical flame holder in a staged-gas low-NOx burner. Computations are done in ANSYS Fluent v12 code using a range of frequently used moment-closure turbulence models. Impact of grid type and quality is investigated. Discussion of the results is confronted with previously published observations on this topic. The aim is to critically evaluate the applicability of computations to determine inlet boundary conditions for swirling air in industrial combustors.

1. Introduction

Swirler (swirl generator, flame holder) is a key burner design element that significantly influences the flow pattern in combustion chambers. The purpose of a swirler is to convert part of axial momentum of the flow to a tangential momentum. This type of flow is required in many burners and also in other applications, including e.g. separation of particulate emissions in cyclones. In burners, swirling flow is important for flame stabilization and as a primary measure to decrease NOx emissions. Swirler generates a low pressure zone in the flame core, which for confined flames leads to two recirculation zones that dilute reacting fuel and air by inert combustion products (flue gas). This desirable process can in cases with increased tangential momentum lead to unstable oscillations called precessing vortex core (PVC). The phenomenon may cause undesirable acoustic emissions and in extreme cases it may even destabilize the combustion process. Swirling flows and PVC are both the subject of a significant research activity as documented e.g. by (Nicholas Syred 2006), (Ranga Dinesh & Kirkpatrick 2009)).

For the quantitative description of the relative strength of tangential momentum is used a nondimensional swirl number (S), which is defined as the ratio of axial flux of tangential momentum over axial flux of axial momentum (Gupta, D. G. Lilley, et al. 1984). In most cases published works provide values of swirl number calculated on the basis of swirl generator geometry as proposed by (Claypole & N. Syred 1981). The geometric swirl number must however be used thoughtfully, as it is suitable only for specific swirler geometries, e.g. when guide vanes cover the whole cross-section of air flow tube and there are no short-cut currents. In spite of this, number of authors provides geometry-based swirl number as the only information about swirl intensity, e.g. (Cortés & Gil 2007), (Fernandes et al. 2006). Swirl number calculated from measured velocity profiles is encountered less frequently in the literature, e.g. in (Khezzar 1998) or (Coghe et al. 2004), but it is essential in the case of this work, as measured data are necessary for the validation of predictions.

There are two basic types of swirling flow – low swirl flows typically with swirl number lower than 0.6 and strongly swirling flows with higher value of swirl number. Precessing vortex core is encountered mainly in the case of strong swirl flows, with the exception of flow through sudden expansion (which is the case also in most burners), where PVC has been observed even with lower swirl numbers (Ranga Dinesh & Kirkpatrick 2009).

Lately, research in the area of swirling combustion has concentrated mainly on the flame itself with much activity centered around two specific burners, namely the TECFLAM burner (Schmittel et al. Published under licence by IOP Publishing Ltd
2000), (Landenfeld et al. 1998), (Meier et al. 2000) and the Sydney burner (Kalt et al. 2002), (Al-
Abdeli et al. 2006). In research works, the prevailing practice is to use measured velocity profiles at
the inlet of a combustion chamber, i.e. on a plane after the swirler. The simulation then develops from
the measured velocity inlet conditions, e.g. in (Escue & Cui 2010). Some authors in the past even used
guessed velocity profiles at the inlet (flat, parabolic, etc.) like in (Dong & David G. Lilley 1994).
However, as pointed out in (Roux et al. 2005) or (Sadiki et al. 2006) the practice of using measured
velocity profiles may not be always suitable for computational predictions and in practical applications
where measured data are not available it is simply infeasible.

This is why recent efforts aim to replace the measurement of inlet velocity profiles by modeling
flow through the swirler (Selle et al. 2004; Moureau et al. 2007; Sadiki et al. 2006). Such approach
leads to increased computational requirements, which is however becoming acceptable. In the case of
Large Eddy Simulations (LES) which have increased demands on the quality of data for inlet
boundary conditions, such treatment is almost a necessity.

LES is already quite widely used, but application to more complex geometries is still very difficult.
The reason due to which LES of most practically relevant swirling nonpremixed flames is not feasible,
is the excessive number of computational cells in a discretized model. This is caused by the great span
of scales inherent to practical fired heaters, where gas nozzles are few millimeters in diameter, while
combustion chambers have dimensions in meters or tens of meters. Due to the necessity to use
uniform mesh cell size for the whole computational model in LES, such applications currently may be
simulated only by moment closure turbulence models or by hybrid approach which combines RANS
models at the walls with LES in the rest of the flow.

It could seem that RANS models are in decline due to the rising popularity of more advanced
methods (LES, DES) but they still dominate in practical industrial applications ((Pallarés et al. 2009),
(Stefanidis et al. 2006)). In the area of swirling nonpremixed combustion, several turbulence models
are used that have been validated with relative success by measured velocity profiles. Specifically, it
has been shown that the RNG k-ε turbulence model is acceptable for the prediction of low-swirl flows
(up to 0.6), where it performs even better than the RSM model (Escue & Cui 2010). For the modeling
of higher-swirl flows, it has been shown that solving the anisotropic Reynolds stresses directly by
RSM is a more fitting option. The work (Wegner et al. 2004) even shows that unsteady RANS model
based on RSM is applicable for the description of the precessing vortex core. The authors also report,
that for a high-quality prediction it is necessary to include swirler in the simulated domain, otherwise
velocity profiles may be deformed.

In validation studies of computational codes, authors often use their own measured data that are not
provided in sufficient detail for others to use. It is also often necessary to communicate with the
experimenters, as detailed geometry of the swirler is usually not included in publications. Typically,
schematic drawing of the experimental setup and main dimensions of the combustor are just
complemented by the value of swirl number in the text. After a longer period of time it becomes
increasingly difficult to find all necessary specifications even for the authors of those experimental
studies.

Below in a table is a summary of publications concerned with the measurements of swirling flows
in combustors. The specifications for each case include type of the swirler, measurement method, as
well as indication of whether the experiment was done in isothermal flow or reacting flow. The list
covers only a selection of the most important works concerned with swirling flow in combustion
chambers, with focus on recent publications.

| Table 1. Summary of experiments on confined swirling flows |
|----------------------------------------------------------|
| Expansion ratio | Re       | S – swirl number | Experimental technique | Swirl generation | Confined / reacting |
| (Yadav & Kushari 2010) | 3 | 4095-8189 | 0-1.48 | Hot wire | Axial guide vanes | y | Isothermal |
| (Raj & Ganesan 2009) | 2.33 | 146 000 | 8 guide vanes, angle 30° | y |Isothermal |
| (Mak & Balabani 2007) | 2.5 | 10000 | 0-0.65 | PIV |Axial guide vanes | y |Isothermal |
| (Fudihara et al. 2007) | oblique | 0.2-3.2 | PIV, LDV | TANGENTIAL AIR INLET | y | NG/air |
| Reference | Swirler Type | Operating Conditions | Measurement Techniques | Additional Details |
|-----------|--------------|----------------------|------------------------|--------------------|
| Meier, Weigand, et al. (2007) | Radial swirler | 35000, 0.6 | OH chemiluminescence, LDV, Raman scattering | CH4/air |
| Weigand, Meier, et al. (2006) | Radial swirler – 8 for the central nozzle, 12 for the annular nozzle. | 15000-58000, 0.55-0.9 | LDV, PLIF, Laser Raman Scattering | CH4/air |
| Fernandes et al. (2006) | Swirler with variable blade angles | 81000, 1.05 | LDV, microphone, CCD camera for flow visualisation | Isothermal |
| Pollard et al. (2005) | Axial swirler with 8 vanes | 71000, 0.89 | LDV | Isothermal |
| Roux et al. (2005) | 12 vanes tangential entry | 10000-20000, 0-0.43 | LDV | CH4/air |
| Wang et al. (2004) | Tangential air inlet | 1.94 | LDV | Isothermal |
| Coghe et al. (2004) | Tangential air inlet into the main flow | 20700 – air jet, 5600 – fuel jet, 0.82 | LDV, thermocouple; emission spectrosopy in visible range | NG/air |
| Grinstein et al. n.d. | TARS - axial and radial swirler | >70000, 0.25-0.75 | PIV, LDV, PDPA | Isothermal |
| Widmann et al. (2000) | Vane-cascade | 8,0 | Pitot tube | Isothermal |
| Schmittel et al. (2000) | Movable-Block | 8,3 | LDV, thermocouple | NG/air |
| (A.R. Masri et al. 2000) | Tangential air inlet + bluff body at the outlet | unconfined, 12800, 0-1.6 | LDV | NG/air |
| Zhou et al. (2000) | Tangential air inlet into the main flow | 2, 47600, 1 – 2.1 | PDPA | Isothermal |
| Landenfeld et al. (1998) | Movable-Block | Regas=8000 ; Reair=42900, 0.95; 2 | LDV, LIF, Rayleigh scattering | CH4/air |
| Khezzar (1998) | Radial swirler | 1.82 | LDA | Isothermal |
| Ballester et al. (1997) | Axial swirler | 7.2 | Pitot tube, thermocouples | NG/air |
| Dellenback et al. (1988) | Tangential air inlet | 1.94 | LDA | Isothermal |
| Escudier & Keller (1985) | Radial guide vanes | 2, 7000, 0-1.23 | LDA | Isothermal |
| Rhode et al. (1983) | Guide vanes | | Pitot tube | Isothermal |

There are basically three types of swirlers (Gupta, D. G. Lilley, et al. 1984) – axial guide vane swirler, tangential inlet swirler and rotating pipe swirler. The rotating pipe swirler has not found wide application in practice and it is not used in combustion applications. The tangential inlet swirler is used relatively often especially thanks to its clearly defined swirl intensity and low pressure loss. It is also used in the two popular research projects, centered around the Sydney burner (Karpetis & R.S. Barlow 2002) and around the TECFLAM burner (Schmittel et al. 2000)) although with some modifications. Axial swirler, which is studied in this work, is popular in industrial burners mainly for its operational reliability and simple design.

2. Model validation

It is necessary to use data measured in a similar configuration to validate models that could provide prediction of swirling flow at a combustion chamber inlet. Published model validations (Fudihara et al. 2007; Widmann et al. 2000) were done for very specific swirl generator geometries, so in this work are used data published by (Mak & Balabani 2007) who used PIV method to analyze flow field in a model of combustor (see Fig. 1) with an axial guide vane swirler.

Simulations are in this work performed with moment closure turbulence models and a transient formulation (URANS). The tested turbulence models include mainly variants of the popular $k$-$\varepsilon$ model previously validated for different swirl generators e.g. in (Escue & Cui 2010; Fudihara et al. 2007; Widmann et al. 2000). The RNG $k$-$\varepsilon$ model has in those works displayed some superiority over the
standard k-ε model since it predicted more accurately recirculation zones in the combustors. Another model applied in this work is the shear stress transport (SST) k-ω model (Menter 1994), which removes the need for wall functions and was previously applied for isothermal flow in a vortex combustor simulation in (Ridluan et al. 2007). Reynolds stress model (RSM) was also included in the analysis, which is more computationally intensive but handles anisotropy of turbulence and has been reported to outperform two-equation eddy-viscosity models in highly swirling flows. Finally, the realizable variant of the k-ε model (Shih et al. 1995) was tested as well. All simulations were done with discretization of second order for momentum.

All the simulations were performed using a commercial code ANSYS Fluent v12 (ANSYS 2009). Reynolds number at the inlet (before swirl generator) was 10,000 and swirl number calculated from the measured velocity data was 0.64. Two meshes were created for the simulation. One used simplified geometry, taking advantage of the rotational periodicity of the flow domain, which covered 90° section of the whole domain. This simplified geometry was meshed with a high-quality all-hexahedral mesh with 1,138,000 cells. The second model included the whole flow domain and it was meshed by a more coarse mesh containing 621,000 polyhedral cells.

3. Conclusion

Results from the simulation are displayed in Fig. 2. The plots show averaged velocity over sufficient time period normalized with the average velocity magnitude. Position of the reporting cross-section lies downstream from the swirl generator but still upstream from the sudden expansion (see Fig. 1). The results of simulations display consistent local disagreements with measured data. While simulation suggests no reverse flow, the measurement contradicts it. The most consistent result among two grid sizes gives the RSM model. The biggest grid type sensitivity shows RNG k-ε. Generally the full model predicts lower axial velocity at the r = 0 m than the quarter model.
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