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# Swirling Flow Prediction in Model Combustor with Axial Guide Vane Swirler

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Swirling air flow is a key feature in many types of combustors. Tangential flow component is generated in an aerodynamic element called swirler (swirl generator, flame holder), which is often designed in the form of axial guide vanes. Such design is typical in low-NOx diffusion burners with staged gas and/or air supply. The swirler is a key burner design component that significantly influences the flow pattern in combustion chambers. Current industrial practice in the CFD modelling of swirling flow combustors tends to include swirler into the computational domain since detailed measured data of inlet velocity profiles for swirling combustion air are generally unavailable. However, including swirler into computational domain has not been verified or deeply discussed for standard turbulence models. Therefore there is a need for validation of RANS-based industry-standard codes in the prediction of flow through swirl generators. This work compares predicted velocity profiles and swirl numbers to the measured data. Measurement was carried out at the water tunnel facility with guide vane swirler placed before a sudden expansion chamber. Several drawbacks of standard turbulence models are revealed. Results show problematic predictions near the axis of water tunnel and near the wall.

## 1. Introduction

Swirl-stabilised non-premixed flames are frequently used in industrial burners, but they represent one of the most difficult problems to predict computationally. Only with the advances in large eddy simulations (LES), successful predictions of in-flame properties were reported (Fureby et al. 2007; Sadiki et al. 2006; James, Zhu, and Anand 2007). The LES approach is unfortunately still too computationally expensive for the simulation of large-scale fired heaters due to their huge dimensions (on the order of 10 m) and the need to resolve fine features like gas nozzles with diameters on the order of 1 mm. The only viable alternative for practical predictions in the present as well as for a number of years to come thus consists of models based on first or second-order turbulence closures. Modeling of the combustion chemistry via simple eddy dissipation model, which utilizes the strategy mixed-is-burned, relies on the accurate turbulence prediction more than any other chemistry model. The reason is that turbulence is the driving factor for mixing and therefore also for chemistry and heat release. The importance of the turbulence modeling is therefore amplified.

Recent focus in literature was on swirl and turbulence propagation inside a combustion chamber (Fernandes, Heitor, and Shtork 2006; Tinney et al. 2006). The key problem was sudden expansion and its effect on velocity and pressure field in a chamber. A little attention is paid to the flow-field just behind the axial swirl generator.

The key question in predicting swirling diffusion flames is, whether the prediction of swirl using geometry of swirl generator is dependable. In the literature, only scarce instances may be found of

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measurements suitable for the validation of such swirl generation predictions (Mak and Balabani 2007; Fernandes, Heitor, and Shtork 2006). In most cases of advanced predictions of swirling flows including those mentioned above, boundary conditions on the inlet are typically specified using measured velocities and velocity fluctuations. Occasionally, swirl is even specified by geometric swirl number, i.e. by inclination of swirl generator vanes (helixes)(So, Ahmed, and Mongia 1985). Neither of these approaches is however suitable for most cases of practical predictions of swirl-stabilised gas and liquid fuel burners, due to the large variety of swirl generator designs used by burner vendors and due to the unavailability of detailed measurements.

Measured data on flow through axial swirlers are unfortunately rare. Recent experimental work that has been selected as the basis for this study uses a model combustor with isothermal water flow (Mak and Balabani 2007). The swirler used in this work is similar to a typical flame holder in a staged-gas low-NOx burner.

Several research works dealing with the flow prediction in axial swirlers may be found (e.g. (Wang et al. 2004), but they mainly focused on the downstream of the sudden expansion within a combustion chamber. This work is aimed at the flow field just after the axial guide vane generator. Several Reynolds-averaged turbulence closures (RANS) are applied and compared. Unsteady formulation is found to be necessary due to large fluctuations (U-RANS).

For the quantitative description of the relative strength of tangential momentum a nondimensional swirl number (S) is used, which is defined as the ratio of axial flux of tangential momentum over axial flux of axial momentum (Gupta, Lilley, and Syred 1984). In most cases published works provide values of swirl number calculated on the basis of swirl generator geometry as proposed by (Claypole and 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. (Fernandes, Heitor, and Shtork 2006; Cortés and Gil 2007). Swirl number calculated from measured velocity profiles is encountered less frequently in the literature, e.g. in (Khezzar 1998; Coghe, Solero, and Scribano 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 and Kirkpatrick 2009).

## 2. Experimental data for validation of CFD simulation

Since we were aware of the importance of the swirling generation and propagation on the combustion process the investigation was initiated to find capabilities of the utilized software ANSYS Fluent®. Published experiment with the axial guide vane swirler was sought. Similar concept was adopted in many works, e.g. (Mak and Balabani 2007; Fernandes, Heitor, and Shtork 2006; Ahmed and Nejad 1992; Wang et al. 2004). In the first stage we focused on the flow field prediction just behind the swirler and before a sudden expansion. Our aim is to see ability of the solver to predict flow through guide vanes.

After a literature survey the most proper source of measured validation data with the geometry description was found in a work of (Mak and Balabani 2007). They utilized axial guide vane swirler. The geometry of experimental setup was further clarified in personal communications with one of the authors (Balabani 2010). This is common problem among many published articles with experimental data. Nearly none of them provide complete geometry specification, which would allow to create reliable model for CFD computation.

The measurements were performed for a vane swirl generator by optical method (particle image velocimetry, PIV). Geometry of the computational domain including the swirl generator is displayed in Figure 1. Inclination of the guide vanes in the present case is 45°. The experimental work was focused on analyzing flow features in a sudden expansion and its deeper analysis by proper orthogonal decomposition (POD), but they measured also velocity components above the expansion ($x/D = -0.44$)

in order to determine accurately the amount of swirl in the expanding flow. These velocity measurements above the expansion were used in the present work to validate computational predictions. Working medium was water.

*Figure 1: Sudden expansion chamber with swirler (Mak & S. Balabani 2007)*

### 3. Swirl number

Intensity of swirl in a confined space is characterized by swirl number. It is defined as a ratio of axial flux of tangential momentum to the axial flux of axial momentum defined as:

$$S = \frac{1}{R}\frac{\int_0^R(\rho U W r^2 dr)}{\int_0^R \rho U^2 r dr}$$

Swirl number evaluation in CFD needs different integration than with radius. The integral over area was adopted according:

$$S = \frac{1}{R}\frac{\int_A \rho U W r dA}{\int_A \rho U^2 dA}$$

Calculated swirl number based on experimentally measured data in the plane x/D = -0.44 was 0.65. It corresponds to the inclination angle of guide vanes 45°.

### 4. Model and computational setup

In order to perform grid independence study, three grids were created. Low-density grid had 900 000 grid cells, mid-density grid had 1 700 000 cells and high-density grid consisted of 2 700 000 cells. All meshes consisted of polyhedral elements.

Commercial solver ANSYS Fluent v12.1 was used for simulations and post-processing. Four different turbulence models were utilized, namely the SST k-ω (Menter 1994), realizable k-ε (Shih et al. 1995), RNG k-ε and RSM (Launder, Reece, and Rodi 1975). Second order upwind discretization scheme was used for all the equations, but the pressure which employs PRESTO!. Transient simulation was run to be able to capture unsteady flow effects such as precessing vortex core. Since we wanted to compare predicted data with the validation data from the study of (Mak and Balabani 2007) it was necessary to make the same control plane at the x/D = -0.05. At this plane the line was created and data from the line were exported. All the results are averaged values over several seconds of physical time.

In the case of swirl number analysis, the seven planes were created. First plane (x/D=-2) located right behind the swirler and the last plane (x/D=0.68) located downstream of sudden expansion. Swirl number is evaluated on those planes and results are shown in the next chapter.

### 5. Results

Three turbulence models were tested for ability to predict flow field in three-dimensional domain. Figure 2 shows comparison of results from the three turbulence models. For axial velocity profiles the decrease was predicted in the center by all the models however only SST k-ω and RNG k-ε turbulence model on a rough mesh predicted reversed flow. Since the results were not confirmed on a finer meshes it might be rejected as unreliable results.

Problem in predictions of axial velocity is caused on one hand by radial momentum transport from the swirl effect and on the other hand in contrary by jet penetration downstream from the short-circuit through the center of guide vane swirler.
Other effect is caused by guide vanes which generates vortex shedding. Those vortices are then pushed toward the wall by radial transport of momentum, travel downstream and influence near wall velocity profile.

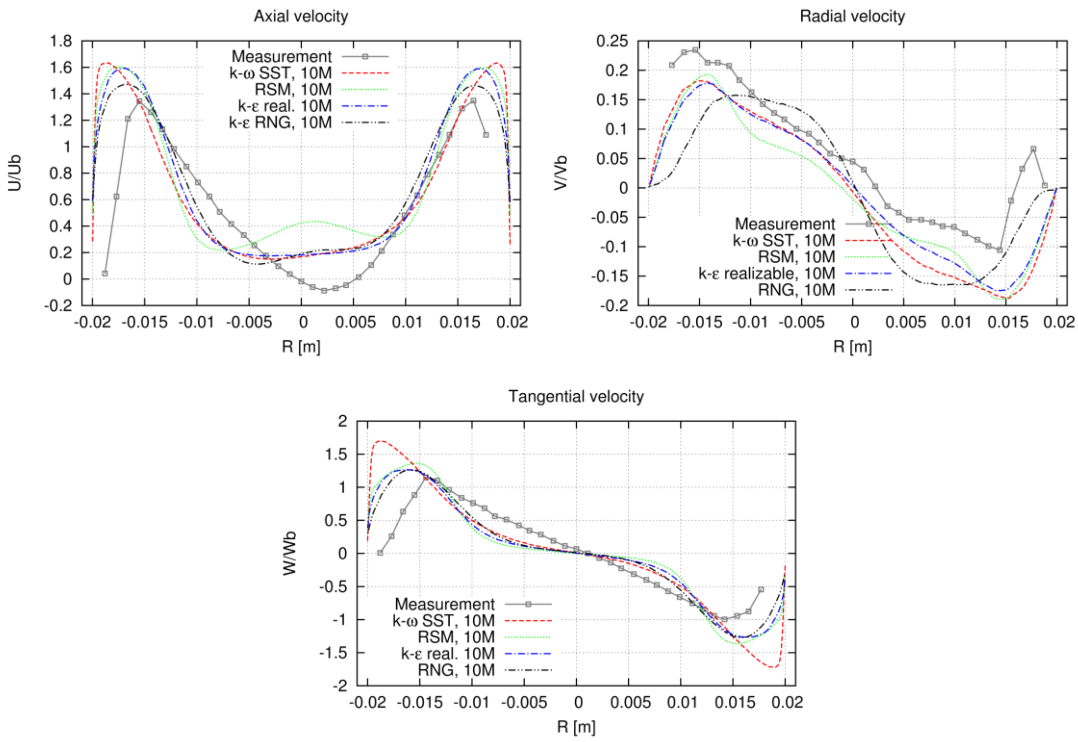


*Figure 2: Profiles of axial, radial and tangential velocity in the highest density mesh for four turbulence models*

Radial velocity profile near the axis is predicted well by all the models. However at the near-wall region strongly deviates from the measured data. It might be caused by vortex shedding mentioned earlier which affects flow field near wall and RANS turbulence models cannot describe it.
Near-axis tangential velocity and its gradient are in all cases underpredicted. While in the near wall region is tangential velocity significantly overpredicted. This leads us to hypothesis that swirling tangential momentum is pushed toward the wall while in the center of the stream dominates non-swirling jet, penetrating further downstream.
Swirl number was analyzed in seven planes downstream of swirl generator. Figure 3 shows comparison of three different grids and their effect on the swirl number predictions. The coarsest grid significantly affects predictions and should not be used. Other two grids give comparable results.
There is unphysical prediction of SST k-ω turbulence model. It shows increase of swirl number between plane x/D=-2 and x/d=-1 which cannot be achieved without artificial swirl generation. Other turbulence models have expectable profile. However, all of them overpredict swirl number at the plane x/D=-0.44 by approx. 17 %. RNG k-ε, realizable k-ε and RSM turbulence models predicts almost identical swirl number.

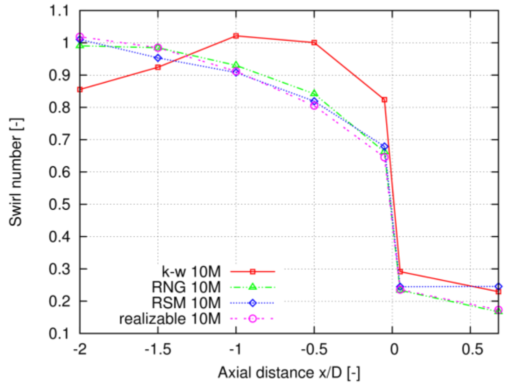


*Figure 4: Decay of axial flux of tangential momentum and growing relevance of axial flux*

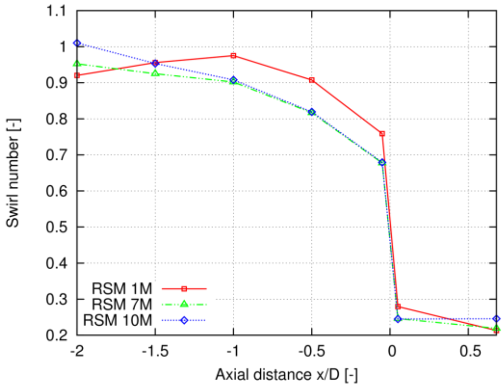


*Figure 3: Swirl number profile along the flow axis – grid independence study*

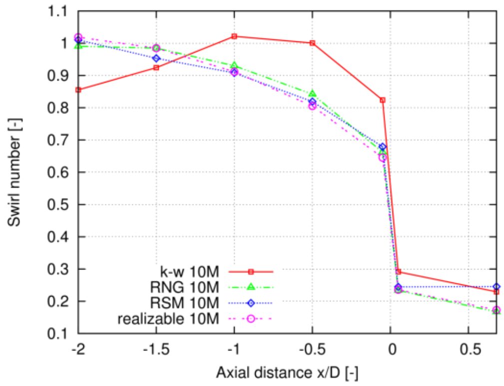


*Figure 4: Swirl number profile along the flow axis – turbulence model comparison*

Our data implies that none of the models is able to predict the solid body rotation of the core swirling flow, which is observed in the measured data. Moreover, the SST k-ω model shows an unexpected behavior in the tangential momentum transport behind the swirler, as monitored by the swirl number.

## 6. Conclusions

Results show that prediction of swirling flow in the given geometry is problematic. One key factor is combination of jet-like flow combined with the guide vane swirl generator influenced flow. Turbulence models fail to predict velocity flow fields in the near-wall region when interaction of these two flows is involved. Velocity predictions have significant deviation no matter what turbulence model is utilized from common set of commercially available turbulence models.

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