T-RANS based analysis of turbulent swirling flows

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Abstract

Confined incompressible turbulent swirling flows exhibiting vortex breakdown have been computationally investigated. Transient Reynolds averaged numerical simulations (T-RANS) have been performed employing a differential Reynolds stress model (RSM) to address turbulence. It has been shown that much better agreement with experimental data can be achieved utilizing this approach in comparison to a steady-state procedure. This reveals the importance of the coherent transient motion in combination with the non-isotropic turbulence structure in swirling flows. The predictability of the vortex core transition and the influence of downstream conditions on the upstream flow, depending on whether the flow is sub- or super-critical, has also been investigated.

Keywords: Turbulent swirling flows; Turbulence modelling; T-RANS; RSM; CFD

1. Introduction

Swirling flows are observed in nature, for example tornadoes and typhoons, and have been widely used in technical applications, such as aeronautics, heat exchange, spray drying, separation, combustion etc. It is the application in gas turbine combustors that is of particular interest to the current work. In combustion systems, at a sufficient degree of swirl, an internal recirculation zone (IRZ) is generated, which allows a high rate of mixing and thus heat release, as well as providing a zone for flame stabilization. The creation of an IRZ can be interpreted as a result of a transition from super-critical to sub-critical flow; the so-called vortex breakdown.

Many previous numerical studies of turbulent swirling flows have been based upon steady state solutions of the Reynolds averaged Navier–Stokes (RANS) equations [1]. It is known [2,3,4] that turbulent swirling flows exhibit a strong interaction between certain Reynolds stress components and the pressure gradient structure, which needs to be addressed by the turbulence model. For this reason, the more sophisticated and more expensive Reynolds stress models (RSM) [5] of turbulence are generally preferred to the turbulence viscosity based models, such as the k-ε model [6]. However, as demonstrated in our recent work [7,8] the RSM may not provide an improved accuracy compared to the simpler, two-equation k-ε model, within the framework of RANS.

In the present work, we extend our analysis to transient Reynolds averaged numerical simulations (T-RANS), for investigating the role of coherent transient structures, employing RSM as the turbulence model. As the experimental database, the LDA measurements of Escudier et al. [9] have been utilized, which were obtained for a constant density turbulent swirling flow exhibiting vortex breakdown.

2. Modelling

The analysis has been based on the general-purpose CFD code CFX5 [10], treating the continuity and momentum equations by a coupled solver, applying a finite element based finite volume discretization in conjunction with a collocated unstructured grid. In Reynolds Averaged Numerical Simulations (RANS) of turbulent flows, a time averaging [1] is applied to variables. This gives rise to a steady-state formulation. In the so-called transient Reynolds averaged numerical simulations (T-RANS), an ensemble averaging is employed [1]. Thus, the time dependent term in the

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governing equations is retained, which resolves the organized transient motion, whereas the random part of the transience is to be modelled by a statistical turbulence model. In the present work, we apply a T-RANS formulation using RSM as turbulence model, where the quadratic SSG correlation [11] has been used for the isotropisation of production term, in modelling the pressure-strain tensor.

At the inlet, spatially varying profiles of dependent variables have been prescribed. At walls, the no-slip boundary conditions hold, modelling the near-wall turbulence via a wall-functions approach. At the outlet, zero-gradient conditions have been applied. For avoiding a contradiction of this condition with a sub-critical swirling flow, which can occur downstream, not an axial, but rather a radial outlet boundary has been defined (ring-shaped radial outlet).

The advection terms have been discretized by the so-called high resolution scheme [10], which achieves maximum possible accuracy between first and second order, without loosing the boundedness.

For discretizing the transient term, a second-order backward Euler scheme [10] has been used. For determining the time step size, two criteria have been simultaneously applied. On the one hand, it has been required that cell Courant numbers do not exceed unity. On the other hand, it has been required that the time step size is an order of magnitude smaller than the eddy turnover time, for ensuring a sufficient temporal resolution of the motion of large structures.

3. Results

A schematic drawing of the plexiglas water test rig of Escudier et al. [9] is provided in Fig. 1. Swirl is imparted to inflowing water by an axisymmetric array of 32 guide vanes. The radial inflowing fluid is guided by an axial annular duct to the main test section. The Reynolds number based on the tube diameter and the mean axial velocity was about 7000. Measurements were provided for two swirl levels, corresponding to guide vane angles $\phi = 62^\circ$ and $\phi = 70^\circ$. In addition, different exit area contractions were considered for investigating the influence of downstream conditions onto the upstream flow, depending on the downstream flow being super- or sub-critical. The inlet boundary of the solution domain was placed at the location indicated in Fig. 1. The distributions of the variables to be used as inlet boundary conditions were obtained by means of a detailed three-dimensional analysis of the inlet section extending from the upstream of the swirler guide vanes to the combustor [7,8]. A detail view of the generated three-dimensional grid is also shown in Fig. 1, which was generated based on a grid-independency study performed within the framework of a RANS formulation.

The instantaneous contour of the isosurface of zero axial velocity is shown in Fig. 2 at two moments of time, for the case with $\phi = 62^\circ$ and no exit area contraction. One can observe in Fig. 2 that the central reverse flow experiences strong changes in time, indicating the importance of three-dimensional and transient effects for this flow.

Figure 3 compares the previously obtained [7,8] zero axial velocity iso-surface as a result of a RANS formulation (based on RSM, obtained by a 2D-axisymmetrical formulation), with the time averaged iso-surface obtained in the present study, applying 3D T-RANS analysis (based on RSM), for the case with $\phi = 62^\circ$ and no exit area contraction. It is interesting to observe that the results of the same turbulence model (RSM) can show such a great discrepancy, depending on

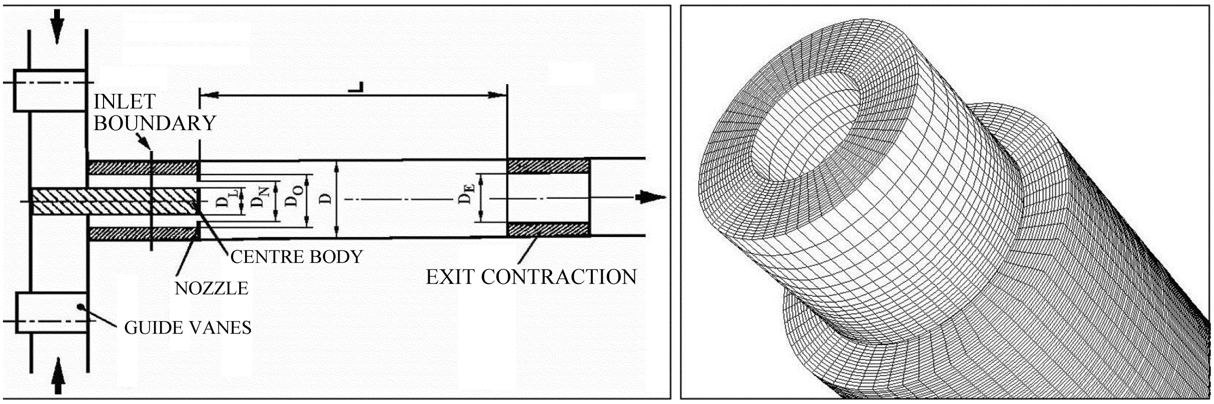

Fig. 1. Test rig [9] (left) and detail grid near inlet (right).

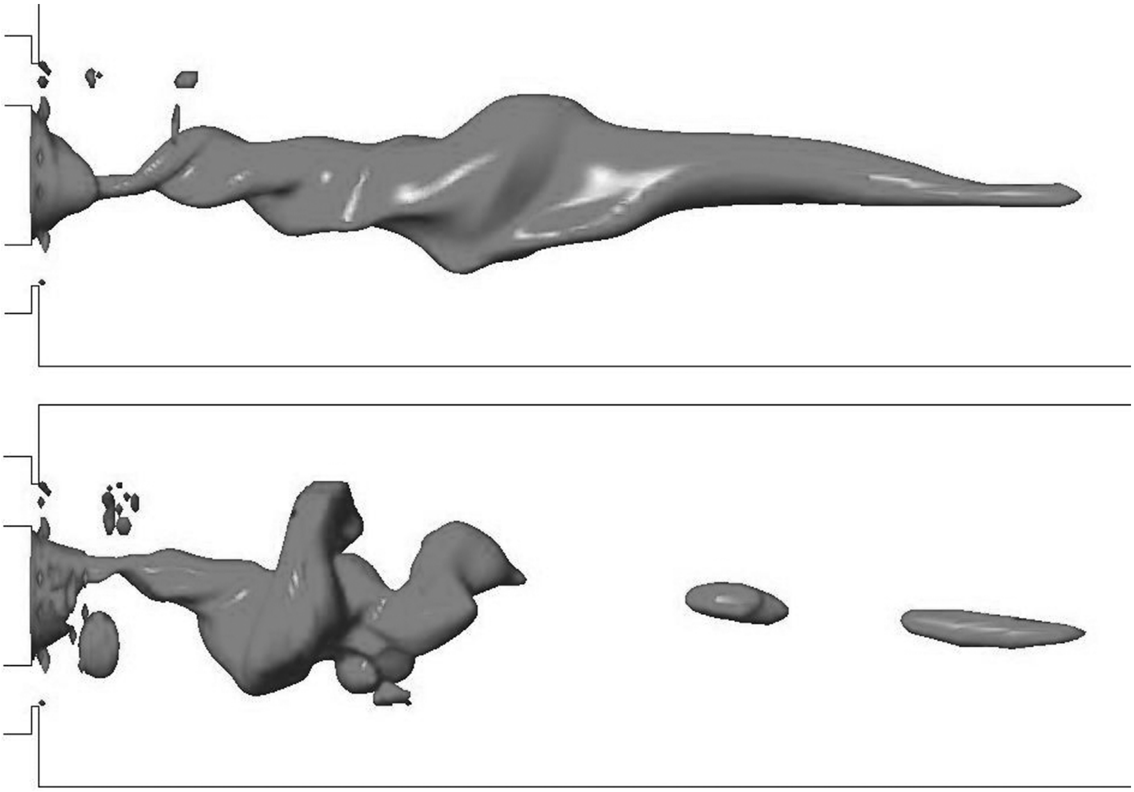

Fig. 2. Instantaneous iso-surface of zero axial velocity at two moments of time (ϕ = 62°, no exit area contraction).

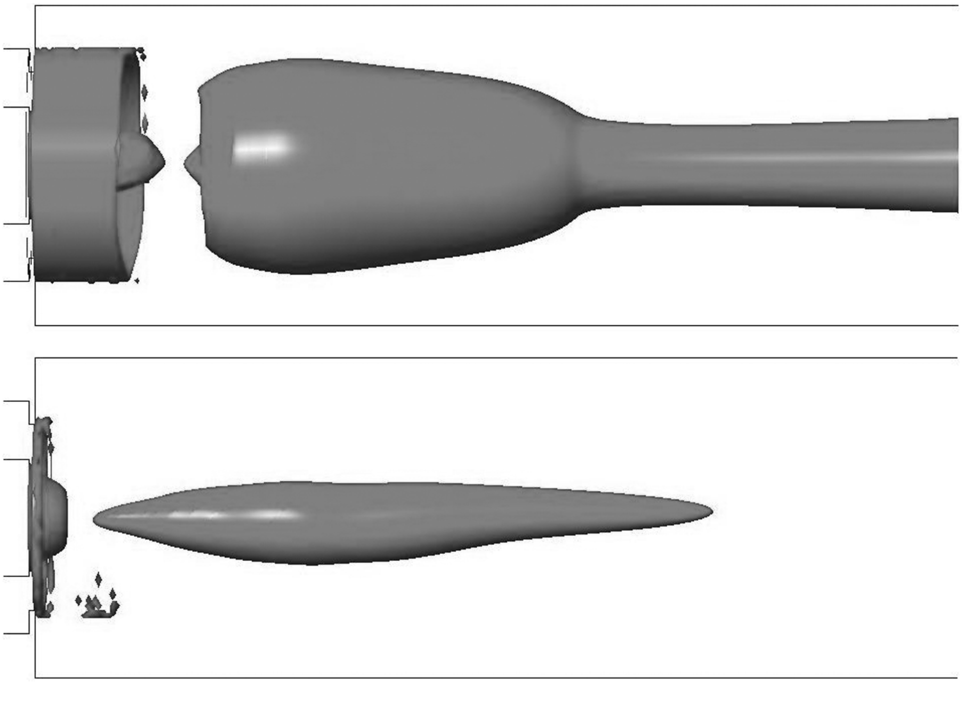

Fig. 3. Iso-surface of zero axial velocity: (top) RANS/RSM; (bottom) time-averaged T-RANS/RSM (ϕ = 62°, no exit area contraction).

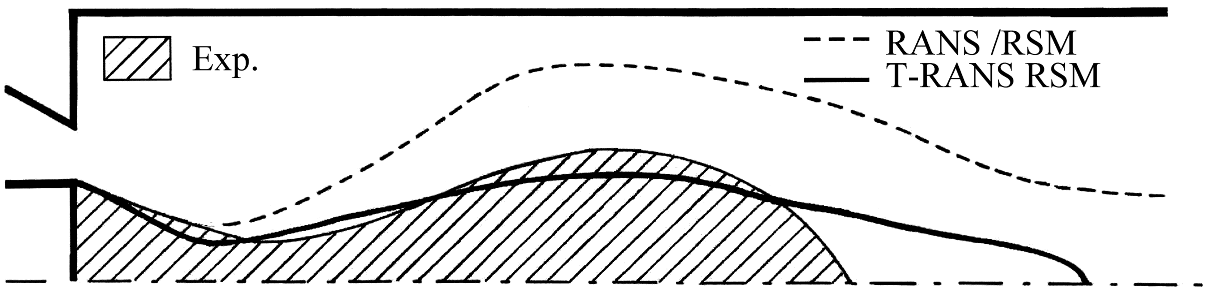

Fig. 4. Contours of IRZ (indicated by the zero streamline), comparison of predictions with experiments (ϕ = 62°, no exit area contraction).

if a RANS or T-RANS approach has been used. This demonstrates the importance of coherent transient structures in turbulent swirling flows.

A comparison of the results with the experiments are provided in Fig. 4, for the case with $\phi = 62°$ and no exit area contraction. In Fig. 4, one can observe that the conventional RANS/RSM approach strongly overestimates the radial extension of the IRZ. Furthermore, it predicts a non-closing IRZ, extending through the whole device. This does not agree qualitatively with the experiments, which exhibit a closed IRZ. On the other hand, the present T-RANS/RSM results show a pretty good agreement with the experimental contour, especially in the upstream region, quite well predicting the radial extension of the IRZ. Although some discrepancy behind the IRZ is observed, the present T-RANS/RSM computations predict a closing IRZ, in accordance with the experiments. It is obvious that the agreement of the present T-RANS/RSM results with the experiments is much better compared to the conventional RANS/RSM formulation (Fig. 4).

4. Conclusions

Confined turbulent swirling flows with vortex breakdown have been investigated by a 3D T-RANS/RSM formulation. By comparisons with experiments, it has been shown that the advocated approach leads to an improved predictive capability compared to the conventional RANS/RSM formulation, revealing the importance of three-dimensional coherent transient motion in such flows, in conjunction with a non-isotropic turbulence structure.

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