Mathematical modeling of swirled flows in industrial applications

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Abstract. Swirled flows are widely used in technological devices. Swirling flows are characterized by a wide range of flow regimes. 3D mathematical modeling of flows is widely used in research and design. For correct mathematical modeling of such a flow, it is necessary to use turbulence models, which take into account important features of the flow. Based on the experience of computational modeling of a wide class of problems with swirling flows, recommendations on the use of turbulence models for calculating the applied problems are proposed.

Swirled flows are widely used in technological devices such as pumps, hydraulic turbines, cyclone units, separators, burners and furnace devices, chemical reactors, etc. At the same time, the flow regimes essentially depend on the way the swirl is organized, the intensity of the swirl, the fluid properties and the process conditions (single and multiphase flows, heat exchange, chemical reaction, mass forces, etc.). Swirling flows are characterized by a wide range of flow regimes such as a quasi-solid rotation with a maximum tangential velocity at the periphery of the rotation region; vortex flows with central recirculation zones; a rotation with one or several concentrated vortices; a flow with bubble or spiral vortex breakdown; a reconnection of the vortex filaments and the formation of vortex rings etc.

In recent years, 3D mathematical modeling of flows is widely used in research and design. However, the lack of validity of the models can lead to unreliable numerical results and errors in the devices design. For correct mathematical modeling of such a flow, it is necessary to use turbulence models, which take into account important features of the flow. In this case, widely used RANS models of eddy viscosity ($k$-$\varepsilon$, $k$-$\omega$ SST, $k$-$\varepsilon-\zeta$-f) usually do not allow obtaining correct results. Methods of Direct Numerical Simulation (DNS) and Large Eddy Simulation (LES) with a resolution of the near wall layer are still rarely used to solve the applied problems due to enormous computational costs.

The aim of the paper is to generalize the experience of the modeling of the turbulent quasi-stationary and transient swirling flows. In-house CFD code SigmaFlow based on the finite volume method and SIMPLE-like procedure for solving the Navier-Stokes equations used for numerical simulations.

Simulation of laminar swirling flows in a cylindrical container with a rotating lid (figure 1) shows that, using the second-order discretization schemes and a sufficient mesh resolution, calculations can reproduce such a structure observed experimentally in the swirling flow [1, 2] as multiple bubble vortex breakdown [3].
For turbulent flows with a weak swirl, a comparison of computational results with the experimental data for a swirling flow in a pipe (figure 2) [4] and a flow in a model tangential combustion chamber (figure 3) shows that it is quite acceptable to use eddy viscosity models.

**Figure 1.** Flow in a container with the rotating lid: (a) the geometry; (b) the flow in the central cross-section; (c, d) velocity components along the vertical line ($H/R = 1.0$, $Re = 1800$, numerical grid contains 0.8 million cells); (e, f) $H/R = 3.25$, $Re = 2752$, the grid contains 10 million cells ((e) is the experiment, and (f) is the zero isoline of the vertical velocity component in the calculation).  

**Figure 2.** Swirling flow in the pipe ($S = 0.17$, $Re = 3.103$): (a) axial velocity; (b) tangential velocity.
Figure 3. The flow in the model tangential combustion chamber of the IT SB RAS: (a) the chamber scheme, (b) tangential velocity, (c) axial velocity.

When there are concentrated vortices in the flow, the eddy viscosity models lead to large errors (figure 4) due to certain limitations of the Boussinesq approximation associated with misrepresentation of the turbulent anisotropy. For this class of flows, Reynolds stress models, based on the differential equations for the Reynolds stresses (RSM), are the most optimal turbulent models.

Figure 4. Swirling flow in a pipe with a concentrated vortex ($S = 0.17$, $Re = 5 \times 10^4$): (a) axial velocity; (b) tangential velocity.

In some cases, an increase in the swirl number leads to the formation of unsteady precessing vortices in the swirling flow. For such flows, the URANS models with isotropic eddy viscosity do not describe the flow even qualitatively, as it can be seen from the results of the calculation for the flows in the model vortex burner (figure 5) and for the flow downstream the runner of the hydraulic turbine (figure 6, 7). URANS RSM models with acceptable computational costs give correct results comparable in accuracy with eddy-resolving LES and hybrid LES/RANS models [5, 6].
Figure 5. Swirling flow in a vortex burner: (a) axial velocity, (b) tangential velocity, (c) pulsations of the axial velocity, (d) pulsations of the tangential velocity.
Figure 6. Vortex structures behind the runner of a hydraulic turbine. Turbulence models: (a) EVM ($\zeta$–$\phi$), (b) RSM, (c) hybrid LES/RANS.

Figure 7. Power spectrum density of pressure signals at the cone wall.

It is interesting to use the so-called URANS models of the second generation, in particular, the model of partially averaged Navier-Stokes equations (PANS), proposed in [7]. Within the approach, the width of the averaging filter controlled by a given ratio of modelled turbulence energy to the total kinetic turbulence energy $f_k$. Depending on the value of $f_k$, seamless transition from RANS at $f_k = 1$ to DNS at $f_k = 0$ is realized. The physical resolution of the flow structures is independent of the mesh spacing. In case of sufficient mesh resolution, the PANS can resolve the most important energy-containing vortex structures (figure 8). However, the PANS method needs both additional development and comprehensive testing, especially for near-wall flows.

Preliminary calculations by means of URANS RSM should be used to determine the flow nature and to justify the selection of the turbulence model, such as RANS, URANS or LES, which will be used for the massive simulations in the engineering design process. An eddy-resolving turbulence model, that can accurately resolve all the energy-containing scales of the flow, is preferable if there are sufficient computational resources.
Figure 8. Vortex structures downstream the runner of the hydraulic turbine visualized by the $\lambda_2$ criterion. Turbulence models: (a) PANS RSM, $f_k = 0.6$, (b) hybrid LES/RANS.

**Conclusion**

Based on the experience of computational modeling of a wide class of problems with swirling flows, recommendations on the use of turbulence models for calculating of applied problems has been proposed.

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