
The flow and turbulence in an IC engine cylinder were studied using the SSG variant of the Reynolds stress turbulence closure model. In-cylinder turbulence is characterized by strong turbulence anisotropy and flow rotation, which aid in air-fuel mixing. It is argued that solving the differential transport equations for each turbulent stress tensor component, as implied by second-moment closures, can better reproduce stress anisotropy and effects of rotation, than with eddy-viscosity models. Therefore, a Reynolds stress model that can meet the demands of in-cylinder flows was incorporated into an engine flow solver. The solver and SSG turbulence model were first successfully tested with two different validation cases. Finally, simulations were applied to IC-engine like geometries. The results showed that the Reynolds stress model predicted additional flow structures and yielded less diffusive profiles than those predicted by an eddy-viscosity model.

1 Part of this research was undertaken while the lead author took sabbatical leave at Delft University of Technology, The Netherlands.

The Re-Stress Turbulence Model

In this section, the description of the modeling equations used in this research is given first. Numerical implementation of these equations in the KIVA code follows.

The performance, efficiency, and exhaust emissions of reciprocating engines are highly dependent on the air-fuel mixing process inside the combustion cylinder. For direct-injection (DI) engines, the complexity of the combustion process is further augmented due to the heterogeneous distribution of the liquid fuel inside the combustion chamber. Therefore, to increase the performance efficiency and to reduce the pollutant emissions, the air-fuel mixing process becomes essential to the design of DI engines. One standard practice is to increase the fluid turbulence, such as geometry-induced turbulence using bowl-in-piston, to enhance the air-fuel mixing. Accordingly, a better understanding of the turbulent flow structure inside the engine cylinder is essential for a better design.

The turbulent flow inside the reciprocating engine has several characteristics which cannot be described by any conventional eddy-viscosity turbulence model (EVTM), such as the two-equation k-ε and k-ω models. First, due to complex geometry, wall effects, and flow rotation, the turbulence is highly anisotropic. Because different stress components respond differently to these effects and, in particular, to a rapid compression and expansion, exhibiting different degrees of hysteresis, a proper reproduction of the mixing process requires an accurate modeling of the space and time evolution of the stress anisotropy tensor. The anisotropy of turbulence cannot be accounted for by any currently available conventional EVTMs.

Without modifications, these EVTM also cannot properly account for flow rotation, which includes swirling and tumbling effects. Swirling flow is an important design feature for improving combustion and mixing. In addition, the influence of the cylinder wall and the flow characteristics of secondary fluid motions and streamline curvature are all important and need to be resolved by any turbulence model to correctly reproduce flow physics inside the engine cylinder.

Therefore, to better understand the physics of turbulent flow and to improve the engine design, a higher level turbulence modeling is the Reynolds-stress turbulence flow inside the cylinder of piston engine like geometries will be given. One major advantage of using the SSG model is that no wall distance parameter is needed as with the LRR model. This feature is especially desirable and important for the piston engine flow simulation, due to the movement of the piston over time.

To validate the SSG model using KIVA-3, solutions of fully developed channel and pipe flows will be given first. These results were compared with the available experimental and DNS data. Afterwards, two engine like flows will be studied. The first case is an axisymmetric direct-injected stratified charge (DISC) engine with a bowl in the piston, which is used to study the effect of bowl-in-piston on the in-cylinder flow structure. A teapot geometry for a two-stroke engine with side ports is included as the second case. These are the baseline cases given for the KIVA-3 code. Finally, a flametube combustor flow case rounds out the application study. Details of fluid and flow properties, such as velocity, temperature, Reynolds-stresses, turbulence kinetic energy, etc. will also be given along with the comparison of the results among RSTM, k-ε model, and experimental data.