Improvement of Two-Equation Turbulence Model with Anisotropic Eddy-Viscosity for Hybrid Rocket Research

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Abstract: For a hybrid rocket engine, it has been proven by ground and flight experiments that the fuel regression rate can be accelerated by swirling injection of the oxidizer. It is know a swirling turbulent flow has anisotropic nature in its turbulent viscosity. In this study, the objective is to improve the applicability of existing treatment of isotropic turbulent model such as two-equation, eddy viscosity, model by introducing anisotropic eddy-viscosity coefficients that can adjust particular direction of these with substantial derivative of vorticity, in order to simulate swirling turbulent flows in hybrid rocket engines. Simulation results for some swirling turbulent flows with the existing model and with an improved model will be compared.

Keywords: Swirling Flow, Turbulence Modeling, RANS, Hybrid Rocket.

Extended Abstract

Hybrid rocket propulsion is one of space propulsion techniques for the next generation now researched actively. As shown in Figure 1, this type of rocket consists of solid fuel and liquid oxidizer. Typically, acrylic or wax is used as the solid fuel, and liquid oxygen is used as the oxidizer. Therefore, it has high safety because the fuel does not contain explosives as ingredients and low environmental load by exhaust than that of a solid rocket motor. In addition, the rocket shows good characteristics of capability that thrust modulation like a liquid rocket engine, and higher specific impulse than a solid rocket motor.

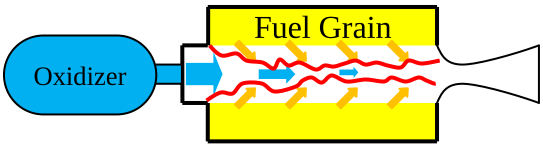


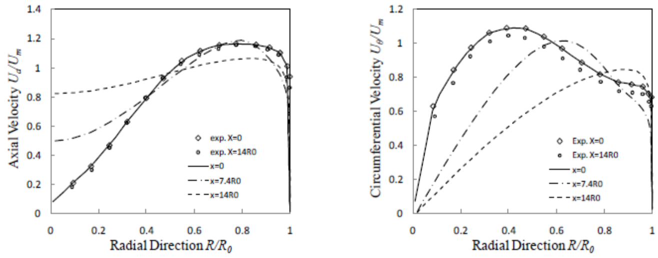
Figure1 Outline of a hybrid rocket engine

Though, in case a conventional fuel, such as, HTPB or PE, etc., a hybrid rocket engine has limitation that only low fuel regression rate can be obtained. As one of methods for enhancing fuel regression rate, a swirling-oxidizer-typed hybrid rocket engine that induces swirling flow in the chamber was invented. It has been clarified by experimental investigations that the regression rate can be improved by this method. Also, some numerical studies are reported.

In general, for the case that CFD is employed as a design tool of the combustion chamber, the Reynolds Averaged Navier-Stokes (RANS) equations have been used because of their reasonable computational costs compared to those of LES and DNS. On this occasion, a two-equation turbulence model, such as k-ε model, has been often selected in order to obtain turbulence stresses. However, as is well known, ordinary liner turbulence models based on the eddy-viscosity assumption cannot simulate flow field like swirling turbulence in pipe precisely. Because the turbulence transport in swirling flows is usually anisotropic which is small in selective directions, a turbulent model assuming isotropic turbulence transport cannot describe swirling flow in principle. Hence the Reynolds stress models (RSM) solving for each directional Reynolds stresses have been used for these swirling flow field. Though, because the variables of these models are increased by numbers of elements of Reynolds stresses, complexity of coding and calculation cost widely increase in comparison with standard two-equation turbulence models.

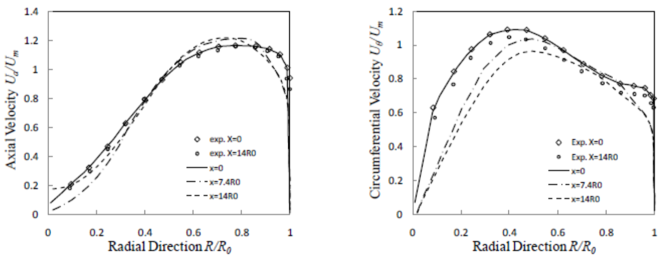
Recently, Yoshizawa, et al. have developed the improved two-equation turbulence model, which is usable for simulating swirling turbulence flow [1].This model is based on the standard k-ε model. An eddy-viscosity of this model is reduced by a coefficient constructed with substantial derivative of vorticity indicating swirling of mean flow. So, the turbulence stresses of all directions are reduced uniformly.

Authors simulated the experiment of low velocity swirling flow in a pipe by Murakami, et al. [2] as a prior case for evaluating applicability of the improved model to the swirling-oxidizer-typed hybrid rocket engine [3]. Figure 2 shows radial distributions of circumferential and axial velocity in that simulation. The points indicate experimental value and lines indicate result of simulations. In the figure, the improved model can well describe experimental values unlike standard model except central and near wall regions.



Axial velocity Circumferential velocity

Standard Model



Axial velocity Circumferential velocity

Improved Model

Figure: 2 Results of simulation of low velocity swirling flow

Because the treatment of Yoshizawa, et al. reduces an eddy-viscosity coefficient without any reference of directions of turbulent stresses, naturally, it cannot fully deal with the anisotropic turbulent transport. As such an example, we have found a case where this situation applies in other swirling flow simulation results.

In this study, the objective is to improve the applicability of existing treatment of isotropic turbulent model such as two-equation, eddy viscosity, model by introducing anisotropic eddy-viscosity coefficients that can adjust particular direction of these with substantial derivative of vorticity, in order to simulate swirling turbulent flows in hybrid rocket engines. Simulation results for some swirling turbulent flows with the existing model and with an improved model will be compared.

References

[1] Yoshizawa, A., “Turbulent-viscosity modeling applicable to swirling flows, based on a composite time scale with mean-flow helicity partially incorporated”, Journal of Turbulence.

[2] Murakami, M., et al., “An Experimental Study of Swirling Flow in Pipes”, Transactions of the Japan Society of Mechanical Engineers. B, vol.41, No.346, pp.1793-1801, 1975.

[3] Motoe, M, et al.,” Validation of Numerical Simulation of Swirling Turbulent Flow for Hybrid Rocket Research”, AIAA 2011-560