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Research Paper

Prediction of swirling cold flow in a solid-fuel ramjet engine with a modified rotation/curvature correction SST turbulence model

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HIGHLIGHTS

- We propose a new and simple rotation–curvature correction factor of SST-CC model.
- We develop an in-house code to simulate the swirling flow in a research solid-fuel ramjet.
- We investigate the swirling non-reacting turbulent flows in a research solid-fuel ramjet.
- The impact of the rotation–curvature correction on predicting swirling flow is demonstrated.
- The swirl has a significant effect on the solid-fuel ramjet flow field.

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ABSTRACT

In this paper, numerical investigation of swirling non-reacting turbulent flows in a research solid-fuel ramjet has been conducted. An in-house code has been developed in order to solve axisymmetric Reynolds-averaged Navier–Stokes equations of the turbulent swirling compressible flowfield. A new and simple rotation–curvature correction factor of curvature correction Menter's shear stress transport turbulence model (SST-CC) is presented. The modified model (SST-CCM) is verified using two-dimensional flow in a U-turn channel and then used to study the effect of rotation–curvature correction on swirling flow in the solid-fuel ramjet. The predicted results show that the modified model (SST-CCM) can estimate the rotation–curvature effects as efficiently as the original SST-CC and requires lower computational effort. For the solid-fuel ramjet, the predicted results showed satisfactory agreement with the experimental data. This analysis also showed the importance of the swirling flow with simultaneous influence in the combustor and aft mixing chamber.

1. Introduction

The solid-fuel ramjet (SFRJ) is a simple air-breathing propulsion system. SFRJ consists of dump type combustor, an air exhaust nozzle, and an air intake system. The SFRJ combustor is a hollow cylindrical solid-fuel grain. A sudden dump inlet is used for flame stabilization and to enhance the mixing and burning of all the available fuel that is in a gas phase. The low fuel regression rate is the main disadvantage of the SFRJ. The combustion efficiency is strongly affected by the mixing degree of the fuel that in a gas phase with the air. The mixing degree of the reactants depends on the reactant residence time and level of turbulence. The residence time should be long enough to burn all of the reactants until a certain point where the combustion is no longer possible. This point is called the flammability limit of the combustor [1]. Therefore, combustion efficiency will increase with increasing the residence time (enhance mixing and reacting the reactants). Many researchers have examined the parameters affecting on the combustion efficiency, flammability limit and regression rate. These parameters are the composition of the reactants, the mass flow rate, the flow turbulence, the size and geometry, the pressure, the initial temperature of the reactants and providing the combustor with swirling flow [2–7].

Swirl flows are widely used as a tool to increase the mixing of fuel in a gas phase with the air to increase the efficiency of the chemical reactions and stabilization processes in the high intensity combustion chamber. Lilley and Rhode [8] have made numerical studies on a two-dimensional (2-D) axisymmetric turbulent swirling reacting and non-reacting flows on ramjet combustors. They used K-Epsilon turbulence model and finite difference formulation with two different combustor configurations. Pein

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and Vinnemeier [9] have experimentally investigated the effect of swirling flows on the efficiency of the chemical reactions, combustion products, and specific thrust. They found that the combustion efficiency and specific thrust are strongly increased in swirling flow. Duesterhaus and Hogl [5] have conducted a series of experiments with and without swirl on a solid fuel ramjet combustor to measure the influence of air mass flow density and inlet temperature on the efficiency of the chemical reactions and fuel regression. Nejad and Vanka [10] have experimentally and numerically obtained the detailed mean and turbulence data for flows with and without swirl at the inlet for a cold flow dump combustor model. They showed that for the 2-D axisymmetric, the K-Epsilon turbulence model is inadequate in capturing the complex turbulent structure of confined swirling flows and requires further modifications and improvements. Ahmed and Nejad [11] have made an experimental study on a coaxial dump combustor with the isothermal swirling flow. They observed that the swirl has significantly influenced on the flow behavior inside the combustor by offering a new flame-anchoring tool.

Recently, AbdelGayed and Abdelghaffar [12] have used ANSYS-fluent DES (Detached Eddy Simulation) and realizable K-Epsilon turbulence model with Dellenback [13] experimental data to predict characteristics of swirling flow on lean premixed combustor. Elizaveta and Berthold [14] have numerically predicted jet flows with and without swirl in a model combustor with both RANS (Reynolds-Averaged Navier Stokes) and LES (Large Eddy Simulation) models. They reported that, LES is more accurate than RANS but it is still computationally too extensive. Furthermore, modifications and improvements of RANS models are needed. Spalart and Shur [15] have proposed a rotation–curvature correction as an improvement for RANS models to deal with the system rotation and stream line curvature. Particularly, Smirnov and Menter [16] have used Spalart's approach to improve the Menter's shear stress transport (SST) turbulence model, but their method increases the programing complexity and the computational cost. This motivates us to modify Smirnov's approach to be simple with lower computational cost.

In the present work, the swirl effect on non-reacting, turbulent flow within a laboratory solid-fuel ramjet (SFRJ) has been predicted and analyzed numerically using an in-house code. The aims of this article are as follows:

- To modify the Menter's shear stress transport with rotation–curvature correction (SST-CC) turbulence model with a new and simple rotation–curvature correction factor.
- To investigate the non-reacting swirling turbulent flow characteristics inside a laboratory solid-fuel ramjet.
- To demonstrate the impact of the rotation–curvature correction of the Menter's shear stress transport model in both of the rotation–curvature SST (SST-RC), and the modified SST-CC (SST-CCM) turbulence models for capturing the details of the swirling flow in SFRJ.

The steady-state computations carried out for this study have been conducted using an in-house CFD code, and from part of an on-going study aimed at the characterization of time-mean and turbulence quantities in swirling reacting flows within a laboratory solid-fuel ramjet. The code is structured, density-based, finite-volume, cell-centered flow solver that solves the 2-D axisymmetric, compressible Reynolds-Averaged Navier–Stokes equations.

In the present study, the SFRJ geometry is kept the same, as only the swirl intensity is varied. Therefore, only the inlet swirl intensity affects the numerical predictions for three flow cases. The adopted three inlet swirl intensities are thought to be representative of the weak, medium, and strong swirling flow characteristics, two of them mentioned in [10] and the third in [13].

2. Numerical solution method

2.1. Governing equations

The Reynolds-averaged Navier–Stokes equations for 2-D axisymmetric compressible flow in cylindrical coordinate system (x, y, θ) in integral form over a control volume Ω can be written as follows:

$$\frac{\partial}{\partial t}\iiint_{\Omega}\boldsymbol{U}d\Omega + \iint_{S}(\boldsymbol{F}\cdot n_x + \boldsymbol{G}\cdot n_y)dS - \iint_{S}(\boldsymbol{F_v}\cdot n_x + \boldsymbol{G_v}\cdot n_y)dS = \iiint_{\Omega}(\boldsymbol{H}+\boldsymbol{H}_v)\cdot \varepsilon d\Omega \quad (1)$$

where $\boldsymbol{n} = n_x\boldsymbol{i} + n_y\boldsymbol{j}$ is the unit normal vector in outward direction of the boundary surface S, t is the time, $\varepsilon = 0$ for two-dimensional plane flow, and $\varepsilon = 1$ for axisymmetric flow. The conservative vector $\boldsymbol{U}$, convective flux vector $\boldsymbol{F}$, $\boldsymbol{G}$, viscous flux vector $\boldsymbol{F_v}$, $\boldsymbol{G_v}$ and axisymmetric source terms $\boldsymbol{H}$, $\boldsymbol{H}_v$ are given by

$$\boldsymbol{U} = \begin{bmatrix}\rho\\ \rho u\\ \rho v\\ \rho w\\ E\end{bmatrix}\quad \boldsymbol{F} = \begin{bmatrix}\rho u\\ \rho u^2+p\\ \rho uv\\ \rho uw\\ (E+p)u\end{bmatrix}\quad \boldsymbol{G} = \begin{bmatrix}\rho v\\ \rho vu\\ \rho v^2+p\\ \rho vw\\ (E+p)v\end{bmatrix}$$

$$\boldsymbol{F}_v = \begin{bmatrix}0\\ \tau_{xx}\\ \tau_{xy}\\ \tau_{x\theta}\\ u\tau_{xx}+v\tau_{xy}+w\tau_{x\theta}+q_x\end{bmatrix}\quad \boldsymbol{G}_v = \begin{bmatrix}0\\ \tau_{yx}\\ \tau_{yy}\\ \tau_{y\theta}\\ u\tau_{yx}+v\tau_{yy}+w\tau_{y\theta}+q_y\end{bmatrix}$$

$$\boldsymbol{H} = \frac{1}{y}\begin{bmatrix}\rho v\\ \rho vu\\ \rho(v^2-w^2)\\ 2\rho vw\\ (E+p)v\end{bmatrix}\quad \boldsymbol{H}_v = \frac{1}{y}\begin{bmatrix}0\\ \tau_{yx}\\ \tau_{yy}-\tau_{\theta\theta}\\ 2\tau_{y\theta}\\ u\tau_{yx}+v\tau_{yy}+w\tau_{y\theta}+q_y\end{bmatrix}$$

and

$$\tau_{xx} = \frac{2}{3}\mu\left(2\frac{\partial u}{\partial x}-\frac{\partial v}{\partial y}-\frac{v}{y}\right),\quad \tau_{yy} = \frac{2}{3}\mu\left(2\frac{\partial v}{\partial y}-\frac{\partial u}{\partial x}-\frac{v}{y}\right),$$

$$\tau_{xy} = \tau_{yx} = \mu\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right),\quad \tau_{yy}-\tau_{\theta\theta} = 2\mu\left(\frac{\partial v}{\partial y}-\frac{v}{y}\right)$$

$$\tau_{x\theta} = \mu\left(\frac{\partial w}{\partial x}\right),\quad \tau_{y\theta} = \mu\left(\frac{\partial w}{\partial y}-\frac{w}{y}\right),\quad q_x = k_f\frac{\partial T}{\partial x},\quad q_y = k_f\frac{\partial T}{\partial y},$$

$$E = \frac{p}{\gamma-1}+\frac{1}{2}\rho(u^2+v^2+w^2)$$

where u, v, w, T, p, ρ, and E represent the, axial, radial, tangential velocities, temperature, pressure, density, and total energy, respectively. The variable τ is the shear stress, γ is the ratio of specific heats, k_f is the thermal conductivity coefficient of the fluid, and μ is the total effective viscosity which equals to the summation of laminar and turbulent viscosities.

2.2. Turbulence modeling

In this study for turbulence closure three turbulence models have been adopted: the SST, SST-RC, and SST-CCM models. The last model is modified and discussed by the authors.

2.2.1. SST model

The Menter's shear stress transport (SST) turbulence model [17] uses a K-Omega model by Wilcox [18], which makes the

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