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Modified shear stress transport model with curvature correction for the prediction of swirling flow in a cyclone separator

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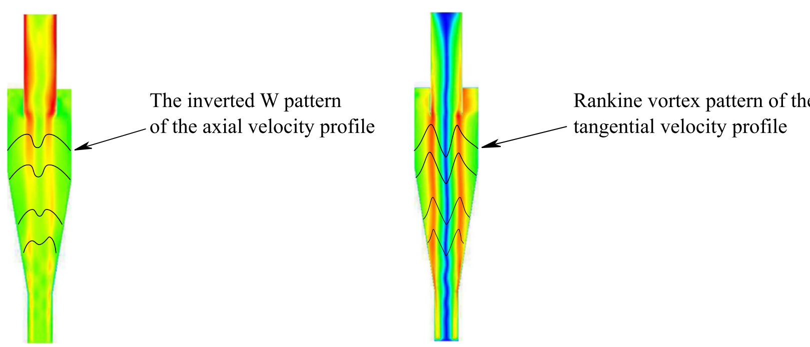
HIGHLIGHTS

- A sensitized Eddy Viscosity Model to rotation curvature effects is proposed.
- The proposed turbulence model is validated and compared with other models.
- The model is successfully applied to the simulation of high swirling flow.
- The complex features of the swirling flow are reproduced in cyclone simulations.
- The robustness of the model is confirmed in the cyclone performance calculations.

GRAPHICAL ABSTRACT



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ABSTRACT

The paper investigates the confined swirling flow in a cyclone. The numerical simulations are performed using a proposed eddy viscosity turbulence model, which accounts for the effects of the streamline curvature and rotation. This distinguishes the current model from the conventional Eddy Viscosity Models (EVMs) that are known to fail to predict the Rankine vortex in swirling flows. Although computationally more expensive approaches, the Reynolds Stress Model (RSM) and Large Eddy Simulation (LES), have demonstrated a high capability of dealing with such flows, these techniques are often unsuited for use in complex design studies where computational speed and robustness are key factors. In the present approach, the Shear Stress Transport with Curvature Correction (SSTCC) turbulence model is modified by the introduction of the Richardson number to account for the rotation and curvature effects. The numerical predictions were validated using experimental results and also compared to the data obtained using the RSM model and various EVMs without the proposed modifications. The investigations started with a benchmark case of a flow through a channel duct with a U-turn, after which more challenging simulations of a high swirling flow within a cyclone separator device were performed. The results show that the proposed model is competitive in terms of accuracy when compared to RSM and proves to be superior to the RSM model in terms of computational cost. Furthermore, it is found that the proposed model preserves the ability to represent the Rankine vortex profile at different longitudinal levels of the cyclone. It is also more efficient in terms of the computational cost than the SSTCC model without the introduced modifications.

1. Introduction

Vortex and swirling flows occur in a wide range of different mechanical apparatus, for instance, in dust collection devices,

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spray dryers, vortex tubes and combustion chambers. In addition, vortices and swirling flows are commonly encountered in nature in atmospheric phenomena, such as tornadoes and dust devils. A superb prologue to the swirling flows found in nature and in technology is given by Lugt (1983).

A cyclone separator is a fixed and stationary mechanical device that separates dispersed solid particles from a carrier gas stream by employing a centrifugal force. The tangential inlet at the top of the device plays an important role in the mechanism and working principle of the cyclone. The dimensions of the inlet and the vortex finder cause the flow to descend in a spiral motion. This creates a centrifugal force that deposits the solid particles onto the cyclone body wall, after which the particles spiral down with the descending flow. At the end of the conical part of the cyclone, the solid particles are trapped at the hopper section or are discharged via an apex exit (see Fig. 1). The gas phase reverses and ascends axially in a spiral motion at the core of the cyclone and exits through the upper exit pipe.

Cyclones are common in many (heavy or light) industrial applications and they are designed as classifiers or separators. Their widespread presence is due to several factors, among which the complete absence of moving parts, the low maintenance cost, the low running cost and the simple geometry are considered as crucial.

A large number of numerical and experimental studies have been conducted to investigate the flow within the cyclone. The majority of the numerical simulations were performed by using either the turbulent resolving approaches (Large Eddy Simulation (LES) or Detached Eddy Simulation (DES)) or the Reynolds Stress Model (RSM) (Elsayed and Lacor, 2013). It should be noted that the flow within the cyclone is characterized as a strong swirling flow with a strong streamline curvature. In this scenario, the conventional Eddy Viscosity Models (EVMs) fail to predict the effects of strong streamline curvatures. This is unfortunate, as the robustness and computational cost of the EVMs are superior to RSM Smirnov and Menter (2009) and Hreiz et al. (2011).

It is well known that a major drawback of the EVMs is their incapacity to capture the effects resulting from the rotating system. More specifically, if the flow exhibits a swirl motion, EVMs fail to represent the near wall region “free-loss vortex” part of the Rankine vortex. This is attributed to the use of the Boussinesq hypothesis that assumes that the eddy viscosity is an isotropic scalar which is untrue for more complex flows such as cyclones. In order to handle this weakness, many modifications aimed at the sensitization of EVMs to rotation and curvature have been suggested (see Refs. Howard et al., 1980; Gooray et al., 1984; Park and Chung, 1989). These attempts are limited and not universal, especially when dealing with 3D flows. Moreover, these corrections are not Galilean-invariant. In 1997, Spalart and Shur (1997) proposed an empirical alteration to EVMs to account for the system of rotation and streamline curvature, which in a sense is close to an idea of Knight and Saffman (1978). The former is more efficient as it measures the extra influence of the invariant contributor to the turbulence. It is also relatively easy to apply to 3D flows and unifies the description of the curvature and rotation effects in the mathematical model. Also in 1997, Hellsten (1998) proposed some improvement to the well known $k-\omega$ SST turbulence model. The modification included the sensitization for the effects of system rotation and streamline curvature. Among several different definitions of Richardson number (Ri), Hellsten realization replaces the turbulent time scale appearing in the Khodak and Hirsch (1996) definition by the mean-flow time scale $1/S_{ij}$. This results in a new and simple definition of the Ri number which can be written as follows:

$$Ri = \frac{\Omega_{ij}}{S_{ij}}\left(\frac{\Omega_{ij}}{S_{ij}} - 1\right) \tag{1}$$

By 2009, Smirnov and Menter (2009) had adapted the rotation-curvature correction function proposed earlier in Spalart and Shur (1997) to the shear stress transport $k-\omega$ model (SST $k-\omega$). The correction function was applied to the production term in both the k and ω transport equations. As a result, the corrected model, denoted as the SSTCC, becomes more accurate, computationally efficient and robust than its predecessor. In 2013, a new simpler rotation and curvature correction method for the SA model was proposed by Zhang and Yang (2013). These modifications avoid the calculations of the components of the Lagrangian derivatives of the strain rate tensor (DS_{ij}/Dt) by implementing Ri number. The model is denoted as SARCM, where the M stands for modified.

In this work, the definition of Ri number suggested by Hellsten is used to avoid the need to calculate the complex term (DS_{ij}/Dt), that appears in the non-dimensional argument $\tilde{r}$. This leads to a simpler version of the SSTCC, which is realized by implementing the Ri number. As a result, the obtained numerical code requires less computational time and is also competitive in terms of accuracy when compared to the RSM model. The new formula for $\tilde{r}$ is applied into the rotation function developed in Smirnov and Menter (2009). The proposed model is denoted as SSTCCM. Then, the two altered models, namely (SARCM and SSTCCM) and the conventional $k-\omega$ SST model, are implemented to study the flow within the cyclone. The swirl velocity components characterized by the tangential and axial velocity profile are compared with RSM and experimental data.

The paper is organized as follows. Section 2 provides a brief introduction to the swirling flow inside cyclones. The physical and analytical description of the vortex pattern is revisited. Section 3 describes the governing equations and turbulence modelling, which is followed by an explanation of the numerical implementation of the proposed approach. The results of the computational work are presented in Section 5. First, a U-duct problem is utilized for verification and validation studies. Then, a Stairmand cyclone model is numerically investigated to demonstrate the capabilities of the proposed formulation in a swirling flow regime. The conclusion is presented in Section 6.

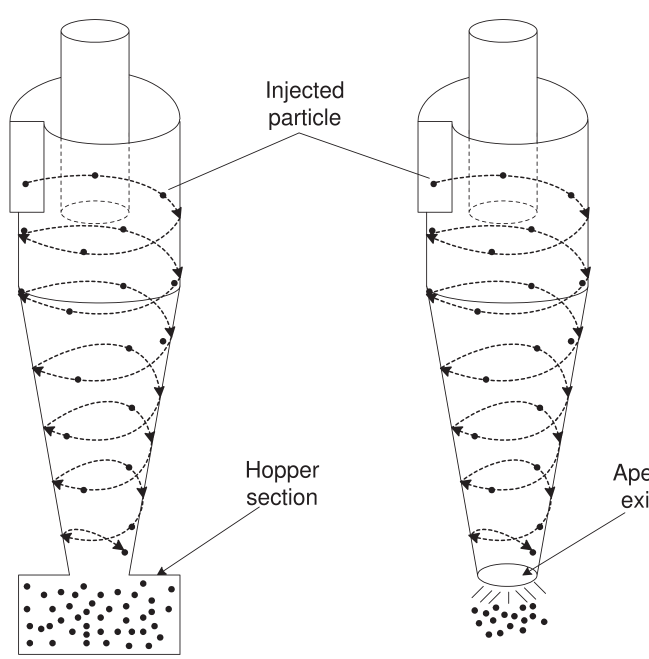

Fig. 1. Motion of collected particles inside cyclone separator.