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Evaluation of the performance of two turbulence models in the prediction of swirling turbulent flow

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Abstract: The performance of two different turbulence closure models in the prediction of turbulent swirling flow is presented .The models evaluated are the Reynolds stress transport model (**RSM_SSG**) and the Kω_SST model . This study is a direct comparison between numerical simulation and measurements of the overall flow variables mean and kinetic turbulent of a swirled turbulent flow with different sections. The comparison of the calculation results with measurements confirmed the inadequacy of two models.This handicap is related to the complexity of the structure of the flow (unsteady, three-dimensional, various turbulence scales...)

Key words: Swirl, Turbulence, Simulation.

1. Introduction

Turbulent flows are largely used in engineering in particular within the turbojets and of the systems of combustion [1-2]. They make it possible to increase the output of combustion by a better mixture of fuel with the air, to reinforce the stability of the flame and to reduce its length by the presence of the zone of central recirculation induced by the swirl In this area the flow is strongly non stationary with curved threads of current and presents a strong anisotropic turbulence [3].To optimize the design (design) and to improve the performances of the burners, the properties of the swirling turbulent flows must be predicted perfectly. For that, several investigations based on a variety of methods were carried out [4-5].

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2. Mathematical Formulations

The turbulent flow of an incompressible fluid is described by the realized equations of Navier Stocks expressed in a stationary regime by:

$$\frac{\partial U_l}{\partial x_l} = 0 \qquad (1)$$

$$\frac{\partial U_i U_l}{\partial x_l} = -\frac{1}{\rho}\frac{\partial P}{\partial x_i} + \nu \frac{\partial^2 U_i}{\partial x_l \partial x_l} - \frac{\partial \overline{u'_i u'_l}}{\partial x_l} \qquad (2)$$

Where: U_i and u'_i are the components average and fluctuating speed in the direction x_i , P is the pressure, ν is kinematic viscosity and ρ is the density of the fluid. Additional equations must be derived for the terms from constraints of Reynolds $\overline{u'_i u'_j}$.

2.1. Model of turbulence:

In the model with constraints of Reynolds (RSM), the terms $\overline{u'_i u'_j}$ are calculated starting from their own transport equations written in the general form:

$$\frac{\partial \overline{u'_i u'_j} U_l}{\partial x_l} = \frac{\partial}{\partial x_l}\left[\left(\nu + \frac{\nu_t}{\sigma_k}\right)\frac{\partial \overline{u_i u_j}}{\partial x_l}\right] + \left(-\overline{u'_i u'_l}\frac{\partial U_j}{\partial x_l} - \overline{u'_j u'_l}\frac{\partial U_i}{\partial x_l}\right) + \phi_{ij} - \frac{2}{3}\varepsilon\delta_{ij} \quad (3)$$

In its version SSG [8], the term of correlation between the fluctuations in pressure and the deformation of the fluctuations speed $\phi_{i,j}$ are expressed by:

$$\phi_{ij} = -(C_1\varepsilon + C_1^* P_k)b_{ij} + C_2\varepsilon(b_{ik}b_{kj} - \frac{1}{3}b_{mn}b_{mn}\delta_{ij}) + (C_3 - C_3^*\sqrt{\Pi_{ij}})kS_{ij} + C_4 k(b_{ik}S_{jk} + b_{jk}S_{ik} - \frac{2}{3}b_{mn}S_{mn}\delta_{ij}) + C_5 k(b_{ik}\Omega_{jk} + b_{jk}\Omega_{ik})$$

(4)

Where $S_{ij} = \frac{1}{2}\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right)$ is the tensor of the rate of average shearing. $\Omega_{ij} = \frac{1}{2}\left(\frac{\partial U_i}{\partial x_j} - \frac{\partial U_j}{\partial x_i}\right)$ Is the average tensor of vorticity, $b_{ij} = \frac{\overline{u'_i u'_j}}{2k} - \frac{1}{3}\delta_{ij}$ is the tensor of anisotropy and $\Pi_{ij} = b_{ij}b_{ij}$ its invariant. The turbulent kinetic energy is evaluated starting from its definition $k = \overline{u'_l u'_l}/2$, turbulent viscosity by its modeling in the model $\nu_t = 0.09k^2/\varepsilon$ and the scalar ε is obtained by its transport equation of the model $k - \varepsilon$.

$$\frac{\partial \varepsilon}{\partial t} + U_l\frac{\partial \varepsilon}{\partial x_l} = \frac{\partial}{\partial x_l}\left\{(\nu + \nu_t)\frac{\partial \varepsilon}{\partial x_l}\right\} + \frac{\varepsilon}{k}\left(-1.44\overline{u_i u_j}\frac{\partial U_i}{\partial x_j} - 1.83\varepsilon\right) \quad (5)$$

The constants of the model are presented in table 1.

C_1	C_1^*	C_2	C_3	C_3^*	C_4	C_5
3.4	*1.8*	*4.2*	*0.8*	*1.3*	*1.25*	*0.4*

Table1. Constants of RSM _SSG model

The model K _ω SST is based on the general model K_ω [11] whose transported variables are the turbulent kinetic energy K and the turbulent frequency ω.Its equations are as follows [6]:

$$\frac{\partial k}{\partial t} + U_l\frac{\partial k}{\partial x_l} = \frac{\partial}{\partial x_l}\left[(\nu + \sigma_k\nu_t)\frac{\partial k}{\partial x_l}\right] + \tilde{P}_k - \beta^* k\omega \quad (6)$$

$$\frac{\partial \omega}{\partial t} + U_l\frac{\partial \omega}{\partial x_l} = \frac{\partial}{\partial x_l}\left[(\nu + \sigma_\omega\nu_t)\frac{\partial \omega}{\partial x_l}\right] + \alpha_2\frac{\omega}{k}P_k - \beta_2\omega^2 + 2(1-F_1)\frac{\sigma_{\omega,2}}{\omega}\frac{\partial k}{\partial x_l}\frac{\partial \omega}{\partial x_l} \quad (7)$$

Where the function of F1 mixture (equal to the unit in close wall and null in the remote area) is defined by:

$$F_1 = \tanh\left\{\left(\min\left[\max\left(\frac{\sqrt{k}}{\beta^*\omega y}, \frac{500\nu}{y^2\omega}\right), \frac{4\sigma_{\omega,2}k}{CD_{k\omega}y^2}\right]\right)^4\right\} \quad (8)$$

Where is there the normal distance to the wall nearest and the term $CD_{k\omega}$ equivalent to the positive portion to the term of cross diffusion of the equation (9). $CD_{k\omega}$ have a lower limit in order to avoid a division by 0 in the equation of F_1 and is defined by:

$$CD_{k\omega} = \max\left(2\sigma_{\omega,2}\frac{1}{\omega}\frac{\partial k}{\partial x_j}\frac{\partial \omega}{\partial x_j}, 10^{-10}\right) \quad (9)$$

The transition enters the two formulations, $K\ \omega$ and $K\varepsilon$, is done through the function F_1 .Thus, when F_1 is 0 far from the walls, the formulation k-ε is activated turbulent kinematic viscosity is given by:

$$\nu_t = \frac{\alpha_1 k}{\max(\alpha_1\omega, SF_2)} \quad (10)$$

Where $S = \sqrt{S_{ij}S_{ij}}$ and *F2* is related second to mixture defined by:

$$F_2 = \tanh\left\{\left[\max\left(\frac{2\sqrt{k}}{\beta^*\omega y}, \frac{500\nu}{y^2\omega}\right)\right]^2\right\} \quad (11)$$

The Model SST contains also a limiting device in order to avoid the artificial construction of turbulence in the areas of stagnation:

$$P_k = \nu_t\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right)\frac{\partial U_i}{\partial x_j} \to \tilde{P}_k = \min\left(P_k, 10\beta^* k\omega\right) \quad (12)$$

2.2. Geometrical Configuration**:**

The mass flow rates of air where adjusted to 64 kg / h selected at a constant preheat temperature of 50 °C.

The Reynolds number ccalculated as the product of the axial average air velocity at the nozzle exit and the throat diameter of the diffuser divided by the kinematic viscosity of the air at 50 °C and approximately 60000.

Where the air was injected in annular space of 50mm radius in cylindrical chamber has a 420mm a length.

The intensity of the rotational movement of the flow is characterized by the value of the swirl number given by:

$$S_0 = \frac{\int_0^\infty UWr^2 dr}{R_o \int_0^\infty U^2 r dr} \qquad (13)$$

Where U and W is average axial and speed tangential average speed.

2.3**.** Solving method:

The resolution of the equations is carried numerically in a configuration of 3D Fig.1.A grid of 1.8 million cells of the hexahedral type was employed.

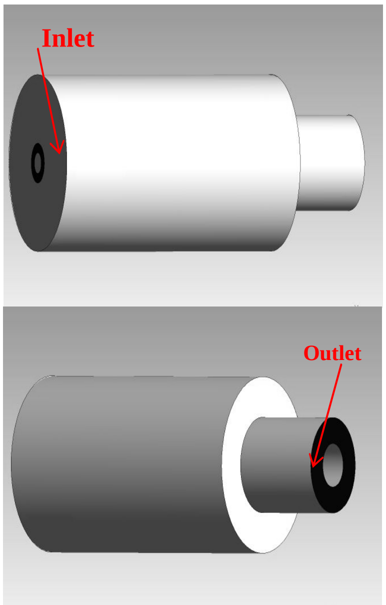

Fig.1. Global View of chamber

The Navier –Stokes equation with the above-mentioned turbulence closure were discretized and solved .Because variable values are stored at the cell volume centers, the cell face values must be interpolated .To avoid numerical diffusion the QUICK scheme was used in discretization of the momentum equations . The second order scheme was used for the ε and Reynolds stress equation. PRESTO was used for the pressure interpolation and SimpleC was used for the pressure –velocity coupling.

Tree types boundary conditions are needed to close the system. At the inlet of the jet, all variables are real (measurement), except for the dissipation of turbulent kinetic energy which is calculated by the equation:

$$\varepsilon = C_\mu^{0.75} \frac{k^{1.5}}{0.7D} \qquad (14)$$

Adiabatic walls were used for all in the model. An outflow was imposed for the exhaust of the model.

3. Results

3.1. Turbulent Quantities

The turbulent kinetic energy profiles for each model RSM_SG and k-ω_SST are given in Fig.2. We have seen that the turbulent kinetic energy is correctly predicted by the turbulence models. It is seen that near the inlet region the comparison between the prediction calculated and experimental data is satisfactory, again approaching the exit of the domain of calculation comparison is not good agreement for the co and counter swirl, like in measurements , where the flow is may to established.

3.2. Mean Velocities

The calculation results obtained are compared to actual measurements on the same configuration (geometry and inlet conditions) using a multiple probe hot wire anemometer Fig.5, shows for the tow statistical models, the radial profiles of mean velocity components for different stations. The first point is that two models qualitatively corroborate the measurements and the detections of the central recirculation zone defined by a negative axial velocity in the center. Fig.3.

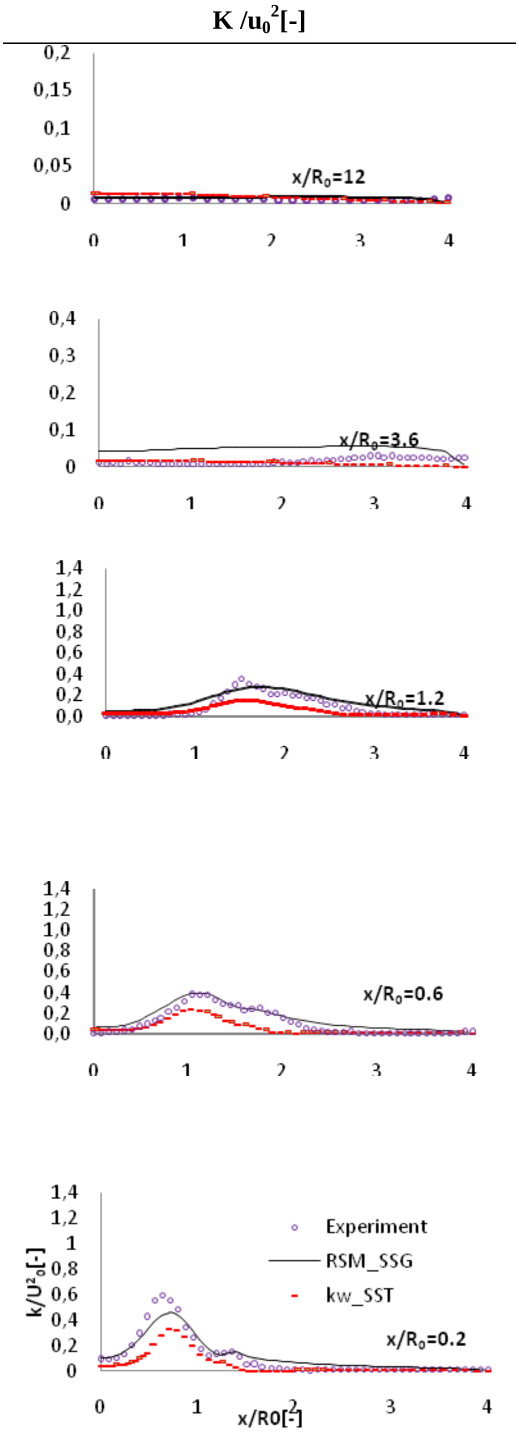

Fig.2. Comparison of kinetic turbulent energy profiles

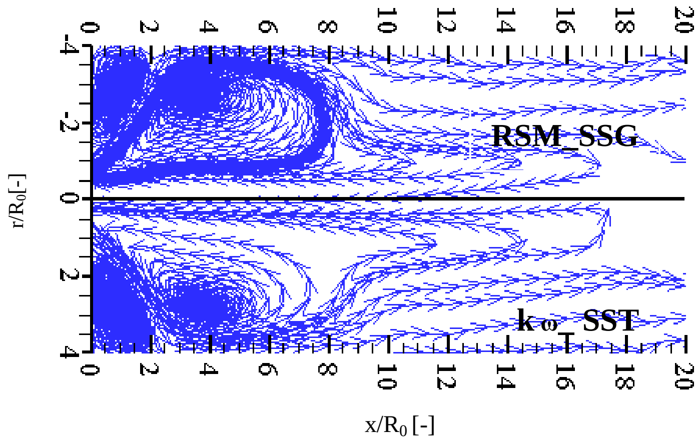

Fig.3.Stream function of RSM_SSG and k ω_SST

For $z < 3R_0$ the model k-ω _SST is able to predict the speed variables with an acceptable degree. In addition, all models of this position can not. It should also be noted that the value of the measured radial velocity is not zero on the axis beyond this station therefore the flow cannot be axisymmetric Fig.4.The model RSM_SSG applied has not improved the calculation results can be due to the low area of the mesh density.

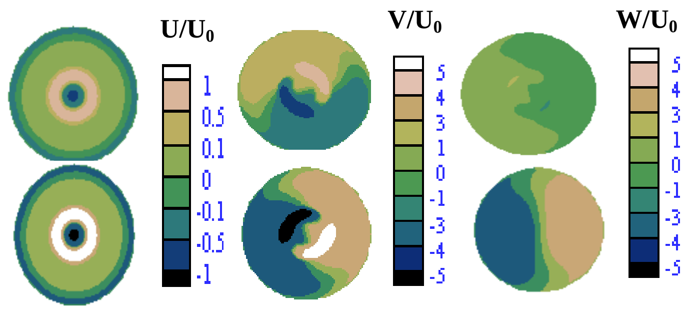

Fig.4. Mean velocities contours of RSM_SSG and k-ω _SST model

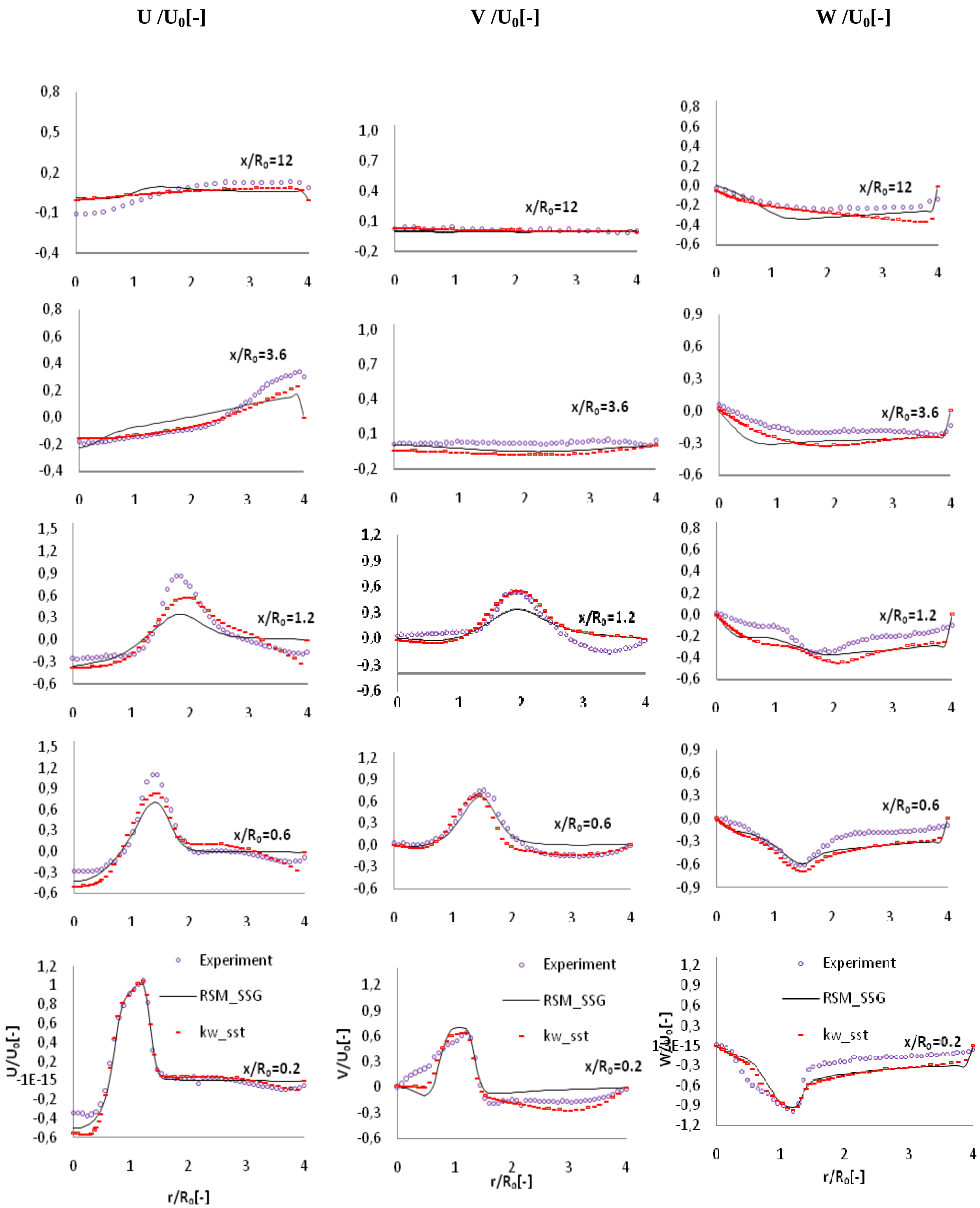

Fig.5. Comparison of different velocity profiles (axial, radial and tangential)

4. Conclusion

The performance of two turbulence models in simulation of low flow (air) in confine vortex is investigated numerically.

The calculation results obtained were worn on the average values of the flow confrontation .Theirs with actual measurements confirmed the failure of the two models.

This is due to the unsteady structure, three dimensional with a broad spectrum of turbulence scales, confirmed by an extension of investigation by the method of calculation of large scales (DDES).

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