Results of Numerical Modeling of Combustion Processes in a Vortex Chamber

Artem V. Badernikov^{1,*}, Shota A. Piralishvily², and Alexander I. Guryanov²

¹UEC-Saturn, Rybinsk

²Rybinsk State Aviation Technical University

Abstract. The results of numerical modelling of combustion in a vortex chamber are presented. The calculations are performed using $k-\varepsilon$ and $k-\varepsilon$ with curvature correction of streamlines turbulence models. Upon combustion calculation of the well mixed mixture the Burning Velocity Model (BVM) was applied. The usage of the streamlines curvature correction allows to increase the accuracy of the prediction of the circumferential velocity component and the temperature field in the vortex chamber.

1 Introduction

Investigations of the oppositely directed swirling jets interaction confirm the presence of shear mixing layers that generate high-intensity turbulence, large-scale eddies and three-dimensional vortex structures. The observed effects are used to organize intensive mixing of fuel and air components, followed by firing augmentation of the prepared fuel-air mixture with high intensity in a limited volume. The mentioned concept has developed in the designs of various reverse-flow burner units, the basis of which is the modified design of the vortex tube [1].

The purpose of this paper is to investigate the usage possibility of the correction model for the streamlines curvature in calculation of highly swirling counter-directed flows, and also to determinate the main modelling factors which influence the solution.

2 Experimental part

The investigation of spatial distribution of mean tangential velocity, mean temperature and mean axial velocity profiles inside and at the outlet of the vortex chamber, was made in the paper [2]. The vortex chamber with the diameter $D_{ch} = 152.5$ mm and relative dimensions ($\bar{F}_{inlet} = 0.12$, $\bar{R}_{outlet} = 0.511$, $\bar{L}_{ch} = 2$) is equipped with a quartz glass window for laser-optical measurements of the flow velocity and holes for platinum-rhodium thermocouples. The premixed mixture of air and natural gas was used as a fuel. Simplicity of configuration and a sufficiently large amount of experimental data in the paper [2] make it possible to use it as a model task for adjusting the physical and mathematical model that correctly reflects

* Corresponding author: badartem@mail.ru

the characteristic features inherent in the swirling flow in a vortex reverse-flow burner module, taking into account the combustion reactions.

3 Calculation model

Geometry for the 3D CFD simulation and calculation model of the vortex chamber is shown in Fig 1 and Fig. 2 respectively. For calculation purposes, the initial geometric model of the vortex chamber was simplified. Also to save the computer resources, the full-scale model was replaced by sector 1/8, on the lateral boundaries of which the boundary conditions of periodicity were set. To increase the stability of the calculation, a volume simulating the atmosphere condition was added to the exit from the vortex chamber. The rest of the geometry was modelled without any simplification.

Fig. 1 – Geometry of the vortex chamber

Fig. 2 - Vortex chamber calculation model

The boundary conditions simulated the vortex chamber testing mode: Premixed mixture of fuel and air with an excess air factor $\alpha = 1.1$ and flow rate $G = 2.19$ g/s (per sector 1/8) was applied to the tangentially located ports. The Reynolds number $Re = V_{in} \cdot R_{ch} / \nu$ was $Re = 34400$; output pressure was $P = 101325$ Pa. To ensure the stability of the calculation, the boundary condition of the inlet with airflow velocity of 1 m/s was established from the front side of the free volume. On the external surface of the vortex chamber, the boundary conditions of the heat flux were set, which model the heat exchange with the ambient environment: the convective part of the heat flux was calculated according to the formula $q_{conv} = \alpha (T_{wall} - T_{air})$, where $\alpha = 5$ W/m²K; the heat flux from the radiation was calculated using the formula $q_{rad} = \sigma \cdot \epsilon \cdot [(T_{wall})^4 - (T_{air})^4]$, where $\sigma = 5,67E-8$ – the Stefan-Boltzmann constant, $\epsilon = 0,8$ – emissivity of the wall.

The calculations of the reacting flow were made using both the original turbulence k- ϵ model, and k- ϵ with streamlines curvature correction (k- ϵ CC) [3]. For the calculations, the Burning Velocity Model (BVM) was used [4], the chemical reaction kinetics was modelled by detailed kinetic mechanism containing 28 substances and 100 reactions.

The calculations were made by ANSYS CFX. For the calculation purposes, a block-structured hexahedral mesh with 300412 elements was built. The quantity of elements in the axial, radial and circumferential directions was chosen according to the basis of the previous study of the mesh convergence for the problem of air flow in a cyclone chamber, and was 150x45x30, respectively.

3.1 Model of streamlines curvature correction for two-parameter turbulence models

The two-parameters turbulence $k-\epsilon$ model is used for modelling a wide range of tasks, it's strengths are simplicity, good convergence of calculation, universality, while maintaining good accuracy. The known shortcomings of this model are manifested in not quite accurate modelling: Points of flow separation from smooth surfaces, flows in the boundary layer, strongly swirling flows, and very curved streamlines.

Some of the drawbacks of vortex viscosity models is that they are insensitive to curvature of flow lines and the rotation of the system. To take these effects into account, in the paper published by Spalart and Schur [3], the modification of the turbulent pulsations generation term is suggested, which increases the two-parameter models sensitivity to these effects.

The effect of the streamlines curvature correction leads to vortex viscosity decrease, which, in case of highly curved flows, makes it possible to realize the flow motion according to the free vortex law and to obtain the results which are adequate to the experiment. It should be noted that in case of the hydrocyclone calculation, the SST-CC model with the streamlines curvature correction shows the results close to the RSM Reynolds stress model, taking into account turbulence anisotropy, while it is much more saving in terms of the computing resources [5].

4 Results

The position of the flame front recorded experimentally is shown in Fig. 3, and the isolines of the temperature field obtained from the experiment is shown in Fig. 4.

Fig. 3. – Schematic picture of the flame front position (experimental data [2])

Fig. 4.- Isolines of the temperature field (experimental data [2])

4.1 Influence of a nonadiabatic wall

To determinate the extent of how much the heat transfer of combustion products influence the walls of the vortex chamber, the calculations were made by using two scenarios:

Assuming that the walls are adiabatic (no heat exchange with environment) in one case, and non-adiabatic walls of the vortex chamber (convective and radiation heat flux was taken into account) in the other. The calculation results are shown in Fig. 5 and 6.

Fig. 5. - Temperature field. Calculation with adiabatic walls

Fig. 6. - Temperature field. Calculation with non-adiabatic walls and k-ε CC

Fig. 7. - Temperature field. Results of calculations using the model k-ε without modifications.

Fig. 8. - Circumferential velocity component in the cross section $x/D_c = -3$.

As you can see in the figures, taking into account the non-adiabaticity of the vortex chamber walls plays the significant role in the formation of the temperature field in the rear part of the vortex chamber and the near-axis zone. Due to the vortex flow, the combustion products stay in the vortex chamber for a long time, and give off the heat to the walls, while the flow is directed from the periphery to the axis. This forms the region of the cooled combustion products in the near-axis zone, which was noted in the experiment.

Thus, for qualitative modelling of the temperature field in the vortex chamber, it is necessary to take into account the heat exchange with the walls, so further calculations are made with non-adiabatic walls.

4.2 The effect of the curvature correction of the streamlines

It is interesting to compare the results obtained using the classical turbulence k- ϵ model without modifications and with modification which takes into account the curvature of the flow lines. The calculation results which were made using the k- ϵ model without modifications are shown in Fig. 7; with streamlines curvature correction - in Fig. 6. Fig. 8 shows the graphs of the circumferential velocity component.

According to the Fig. 8 and 6 the usage of the streamlines curvature correction allows to increase the accuracy of the prediction of the circumferential velocity component and the temperature field in the vortex chamber.

The analysis of the figures 7 and 6 shows that the variant of the calculation in which the turbulence k- ϵ model is used without modifications, the combustion products are more intensively mixed in the vortex chamber area vs. the variant with the curvature correction. Temperature in the near-axial region of the vortex chamber is thus increased vs. the experiment.

5 Conclusions

1) For qualitative modelling of the temperature field in the vortex chamber, it is necessary to take into account the heat exchange with the walls.

2) The usage of the streamlines curvature correction allows to increase the accuracy of the prediction of the circumferential velocity component and the temperature field in the vortex chamber.

For further calculations of the vortex counter-flow burner modules, it is expedient to use the turbulence k- ϵ model in conjunction with the streamlines curvature correction model and the BVM combustion model. For qualitative modelling of the temperature field in the vortex chamber, it is necessary to take into account the heat exchange with the walls.

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7 References

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