TEKA. COMMISSION OF MOTORIZATION AND ENERGETICS IN AGRICULTURE – 2016, Vol. 16, No.3, 57-62

Use of detached-eddy simulation method (DES) in calculations of the swirled flows in vortex apparatuses

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Received September 08.2016: accepted September 12.2016

Summary. On the basis of mathematical modeling of fluid flow in vortex devices verification of use of detached-eddy simulation method in the swirling flows in vortex chamber superchargers is made. Research of a flow with use of different turbulence models was made for vortex chamber supercharger in two working points of the characteristic: with the open exit channel and closed. Verification has been spent on integrated parameters, and also on kinematic, by comparison of static pressure value of on the top end cover of the device. It is received that the hybrid turbulence model DES does not allow, as well as model SST precisely to predict value of vacuum on an axis of the vortex chamber. The error makes an order of 20 %. However, DES predicts almost correct, on 20 % big, than model SST, values of vacuum on an axis in a throat axial diffuser on an input in the vortex chamber. Besides, by means of DES it is possible to describe more adequately unsteady structures near to an axis of the vortex chamber, and also vortex core precession that does not allow to make SST turbulence model. By optimization of vortex devices, and vortex chamber superchargers in particular, simulation time essentially is better to use SST turbulence model with rotation-curvature correction.
Key words: vortex chamber supercharger, verification, DES, numerical calculation, turbulence model, vortex valve.

INTRODUCTION

The swirled flows are one of the most spreading kinds of fluid and gas flows in the nature and the technics. In the nature they meet in the form of a tornado and cyclones. In the technics the mankind has learnt to use properties of the swirled flows in devices with various purpose: separators, valves, swirl tubes, cyclones, mixers [1]. For all these devices presence of the swirl chamber, and also presence of the hydrodynamic effects caused by rotating of fluid flows, such as vacuum formation on a chamber and excessive pressure on periphery is communal [2].

Today, on account of complication of the analytical processes description in vortex chambers, there were many attempts to describe the swirled flows on the basis of the simplified hydrodynamic approaches and physical experiments that has led to a finding of a bulk semiempirical dependences of flows data and design procedures of vortex apparatus [1, 3, 4].

Vortex apparatuses were widely spreading in the industry specially in extreme or special service conditions where big values get positive properties of jet devices, and vortex in particular, such as reliability and durability, contrary to lacks of such devices [5, 6].

In this article vortex chamber superchargers [2] and control units by flows fluid – vortex valves are reviewed, which one being elements of fluidics are capable to throttle fluid flows driving through them, up to a shutoff. They do not contain movable mechanical parts and consequently possess high reliability and the durability many times over surpassing mechanical devices of similar function [5, 7].

THE ANALYSIS OF RECENT RESEARCHES AND PUBLICATIONS

Vortex chamber superchargers and vortex valves united hydrodynamic features of a fluid flow through them and similarity of pressure distribution along radius of the vortex chamber, and also presence of an essential pressure gradient along radius [2, 8].

The last some decades a wide spreading have received methods of the numerical solution of the Reynolds averaged Navier-Stockes equations, and visualization of fluid flow in various hydraulic and pneumatic units, including vortex devices [9]. The given methods except conclusive advantages of studying difficult hydrodynamic effects and flows possess such lacks as the considerable time necessary for calculation and the big errors, in case of incorrect use and selection of turbulence models [10]. Besides, use of those or other commercial and free software products narrows a choice of turbulence models and approaches to the simulations, that set of models which are built in packages for calculations. The writing of own software products demands even more considerable time expenses and resources that forces to use packages for calculation and turbulence model from among built in products. Thus, essential value gets correctness of a choice turbulence and mathematical models for calculation for the purpose of adequate results reception [10, 11]. Especially it concerns the swirling flows in vortex devices where along with small errors in integrated parameters, considerable divergences in kinematic, for example, in pressure size in axial zone are observed [10, 12].

Despite growth of use hybrid methods of turbulent flows simulations, the application the Reynolds averaged Navier-Stockes simulations (RANS) is more simple, steady and economic, in the computing plan, in comparison with hybrid, and LES (Large Eddy

Simulation) approaches, and DNS (direct numerical simulation) [13-15].

However, semiempirical turbulence models lead to some regular defects which can be corrected introduction in model of corresponding corrections, in particular corrections on streamline curvature and system rotation, which in the vortex core should provide suppression of turbulent viscosity, and in stationary shift flows the correction does not become more active [16, 17].

Verification of mathematical models is necessary for a substantiation of correction applicability, including with use of the described correction, on the basis of comparison with experimental features of fluid flows in vortex chamber superchargers (VCS) and vortex valves. Rotation-curvature correction use is described in many sources for the various swirled flows in cyclones, vortex pipes and flows with turns [12, 16, 17], however experience of its use for calculation of fluid flows in vortex valves and vortex chamber superchargers is absent. Besides, there are no also results of fluid flow simulation in vortex chamber superchargers by means of hybrid models and their comparison with less computational power models RANS and URANS (Unsteady Reynolds averaged Navier-Stockes simulations).

OBJECTIVES

The work purpose is verification of mathematical simulation of fluid flows in vortex chamber superchargers and vortex valves.

THE MAIN RESULTS OF THE RESEARCH

Experimental researches of the vortex device (fig. 1) have been made for verification of numerical simulations, which can be used in as vortex chamber supercharger and as the vortex valve. Installation for physical research included the vortex device, blower, receiver and measuring equipment. Pressure in channels was measured by manometers, ambient temperature - mercury thermometers, the fluid flow rate in channels - flowmeters. For experimentation the transparent model with diameter of the vortex chamber 60 mm (fig. 1,) with and without radial diffuser in the axial drainage channel has been made. Numerical experiment was passed in object-oriented library for Computational Continuum Mechanics OpenFoam [18].

Today there is enough considerable quantity of computer programs for CFD simulation including a considerable quantity of various turbulence models, however authors of publications [10-12, 16, 17] come to a conclusion that one of the best on computing expenses and calculation errors of turbulence models is modified two-layer «$k-\omega$» shear stress transport model (SST) [19]. It was considering features of a fluid flows about solid walls and in an external stream. At the same time, application of DNS and LES, and also hybrid models can lead to more exact solutions [20], however is interfaced to difficultly surmountable computing expenses now and in immediate prospects [21].

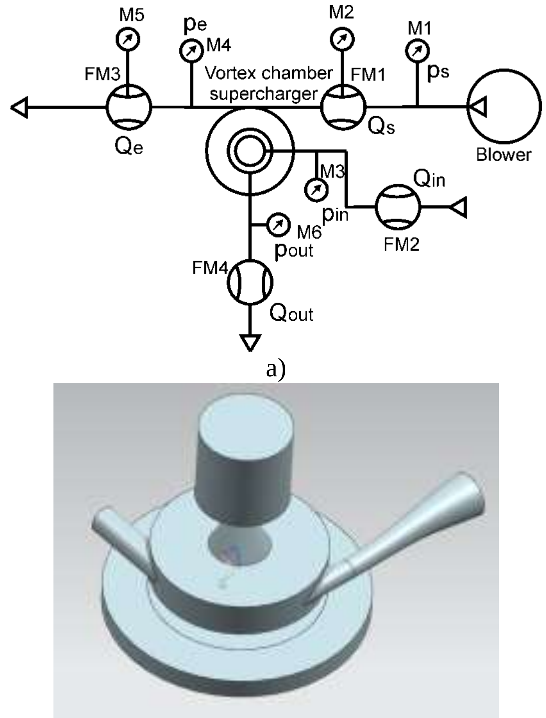

Fig.1. Layout of the experimental stand (a) and three-dimensional model of vortex chamber supercharger, used in simulation (FM – flowmeter, M- manometer)

In the produced operation comparison of most often applied model of turbulence SST with hybrid model DES has been compared. According to many studies [11, 12, 17] SST turbulence model possesses an optimum proportion of calculation accuracy to output of the computing system, but accuracy of calculation for the swirled flows of this model is not high. Therefore in vortex apparatuses it is necessary to apply SST turbulence model to reduction of inaccuracy CFD calculation adjusted curvature correction that practically does not influence calculation time, but improved of prediction pattern fluid flows. On the other hand, hybrid model DES, gives the chance to receive more exact result [22], but is more exacting to amount of the grid applied to calculation. To value rationality of application hybrid models DES for fluid flows in vortex apparatuses, in the given article comparison of simulation results described above turbulence models is effected.

Set of equations SST model looks as follows [19]:

$$\frac{\partial(\rho k)}{\partial t}+\frac{\partial}{\partial x_j}\left(\rho u_j k\right)=\frac{\partial}{\partial x_j}\left(\mu_{ef}\frac{\partial k}{\partial x_j}\right)+P_k-\beta^*\rho k\omega; \quad (1)$$

$$\frac{\partial(\rho\omega)}{\partial t}+\frac{\partial}{\partial x_j}\left(\rho u_j \omega\right)=\frac{\partial}{\partial x_j}\left(\mu_{ef}\frac{\partial \omega}{\partial x_j}\right)-\rho\beta\omega^2+$$

$$+Cd_\omega+\alpha\frac{\rho}{\mu_t}P_k, \quad (2)$$

where: ρ – density; k – kinetic energy of turbulent pulsation; x_j – Cartesian coordinates; u_j – components of the mean velocity vector; $\mu_{ef}=\mu+\mu_t$ – effective viscosity; μ_t – turbulent viscosity; μ – molecular viscosity; ω – turbulence eddy frequency; P_k – production of turbulence kinetic energy; Cd_ω – cross-diffusion term in SST model. Constants and the specification statement of the equations (1) - (2) can be found in [17].

Rotation-curvature correction in SST-model is realised by multiplication of production of turbulence kinetic energy in the equations (1) - (2) on function [17]:

$$f_{r_1} = \max\left\{\min\left(f_{rotation}, 1.25\right), 0.0\right\}, \quad (3)$$

where:

$$f_{rotation} = \left(1 + c_{r1}\right)\frac{2r^*}{1+r^*}\left[1 - c_{r3}\tan^{-1}\left(c_{r2}\tilde{r}\right)\right] - c_{r1}. \quad (4)$$

The constants c_{r1}, c_{r2}, c_{r3} are equal 1.0, 2.0 and 1.0 respectively [17]. Terms r^* and $\tilde{r}$ are calculated as follows:

$$r^* = \frac{S}{\Omega},$$

$$\tilde{r} = 2\Omega_{ik}S_{ik}\left[\frac{DS_{ij}}{Dt} + \left(\varepsilon_{imn}S_{jn} + \varepsilon_{jmn}S_{in}\right)\Omega_m^{rot}\right]\frac{1}{\Omega D^3}. \quad (5)$$

Components of the mean strain tensor:

$$S_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right).$$

Components of the vorticity tensor – $\Omega_{ij} = \frac{1}{2}\left(\left(\frac{\partial u_i}{\partial x_j} - \frac{\partial u_j}{\partial x_i}\right) + 2\varepsilon_{mji}\Omega_m^{rot}\right)$, where ε_{mji} – tensor of Levi-Civita.

$$S^2 = 2S_{ij}S_{ij}; \quad \Omega^2 = 2\Omega_{ij}\Omega_{ij}; \quad D^2 = \max\left(S^2, 0.09\omega^2\right).$$

Model DES combines approaches RANS and LES (a model in which large eddy turbulent vortex are resolved). In flow region where the size of a computing grid Δ is sufficient for the permission of power vortex, i.e. at $\Delta < L_{SST}^{RANS} = k^{3/2}/(\beta^*\omega)$ model LES is applied, and in other region - RANS is applied. In the given work the method of modelling DES on the basis of SST turbulence models was considered. The mathematical model of a method is based on the equation of carrying over of turbulence kinetic energy with use of turbulence linear scale in a following kind [22, 23]:

$$\rho\frac{\partial k}{\partial t} + \rho\frac{\partial}{\partial x_j}\left(u_j k\right) = \frac{\partial}{\partial x_j}\left(\mu_{ef}\frac{\partial k}{\partial x_j}\right) + P_k - \rho k^{3/2}/l_{DES}^{SST}; \quad (6)$$

$$\rho\frac{\partial \omega}{\partial t} + \rho\frac{\partial}{\partial x_j}\left(u_j \omega\right) = \frac{\partial}{\partial x_j}\left(\mu_{ef}\frac{\partial \omega}{\partial x_j}\right) - \rho\beta\omega^2 + Cd_\omega + \alpha\frac{\rho}{\mu_t}P_k; \quad (7)$$

$$l_{DES}^{SST} = \min\left\{l_{RANS}^{SST}, C_{DES}^{SST}\Delta\right\}; \quad (8)$$

$$l_{RANS}^{SST} = k^{1/2}/(\beta^*\omega); \quad (9)$$

$$C_{DES}^{SST} = 0{,}78F_1 + 0{,}61(1-F_1). \quad (10)$$

Constants and the specification statement of the equations (6) - (10) can be found in [22, 23].

The grid consisted of 22 million elements for simulation vortex apparatus with radial diffuser and 9 million elements for vortex apparatus without radial diffuser, and has been constructed so that to provide parameter Y+<2. The greater number of elements for the device with diffuser is caused by reduction of the elements size in diffuser owing to small width of the channel.

At flow simulation in the device as a working environment air was accepted. In many problems of transportation of fluid flows, gases and granulated solids by means of jet macrotechnics working pressure and velocities are that with sufficient accuracy, in them it is possible to consider flows incompressible [24]. Besides, on the basis of the previous works it has been received that use of compressed liquid model is not rational, owing to absence greater accuracy in calculations, but increases of calculation duration [25].

Following boundary conditions have been accepted: on all boundary faces "hard" boundary conditions are accepted: on a solid wall - the condition of a liquid sticking $\bar{V}\big|_b = 0$, in entrance cross-section of the channel of a supply was set value of a stagnation pressure $p\big|_b = p_s$, in exit channels – equality to pressure zero $p\big|_b = 0$.

At the task of boundary conditions of axial exits and vortex chamber entries that in the swirled flows pressure is distributed on stream radius was considered. Therefore the rated operating conditions has been increased and exit boundary conditions on new boundary face where pressure is almost equal to zero are set and does not change on radius [25].

The fluid flow research with use of different turbulence models was made for vortex chamber supercharger in two working points of the characteristic: with the open exit channel and closed. If the exit channel is closed, the fluid flow rate on an exit from the device is equal to zero that leads to a working point the fluid flow in which is accompanied by the greatest swirl of flow in the vortex chamber. A working point without a flow on an exit from the device it is possible to name idling vortex chamber supercharger. Presence or absence of a flow in the tangential channel of an exit from the device, and different degrees swirling of a flow in the chamber, linked with it, can lead to that on major portion of characteristic VCS it is better to use one turbulence model, and in other part of the characteristic – another. It carrying out of numerical simulations for two characteristic flowfield in the device depending on swirling degree of a flow.

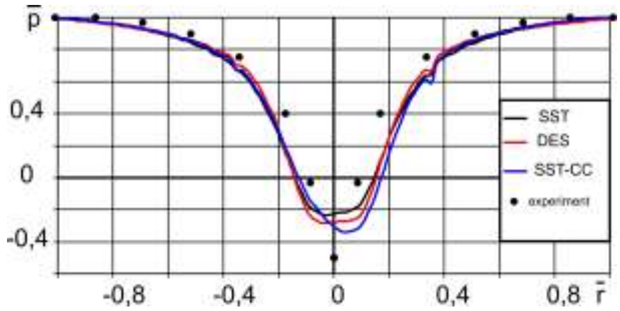

Fig. 2. Pressure distribution along radius of the vortex chamber in device with radial diffuser (SST – shear stress transport turbulence model, SST-CC – shear stress transport turbulence model with rotation-curvature correction)

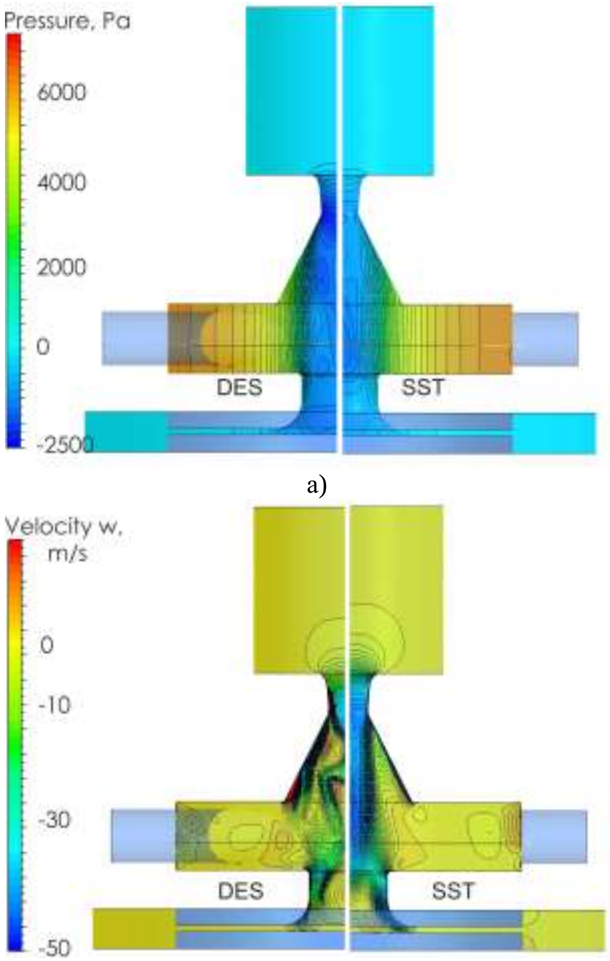

Fig. 3. Flowfield in vortex chamber supercharger with radial diffuser and with the closed exit tangential channel: a) field of pressure; b) field of axial velocity

Owing to essential nonstationarity flow and vortex core precession in the chamber, kinematic characteristics of a flow in the device change the values, therefore to measure them and to make verification on them difficult enough. Verification has been spent on integrated parameters, and also on kinematic, by comparison of static pressure value of on the top end cover of the device (fig. 2). On fig. 2 pressure and radius are related to pressure of a supply and radius of the vortex chamber accordingly. The present comparison is mainly based on the data of [26].

Analyzing pressure distributions on chamber radius it is possible to come to a conclusion that the hybrid model of turbulence DES does not allow as well as model SST precisely to predict value of vacuum on an axis of the vortex chamber. The error makes an order of 20 %. However, as appears from fig. 3,a DES predicts almost correct, on 20 % big, than model SST, values of vacuum on an axis in a throat axial diffuser on an input in the vortex chamber. Besides, apparently from fig. 3,b by means of DES it is possible to describe more adequately unsteady structures near to an axis of the vortex chamber, and also vortex core precession that does not allow to make SST turbulence model.

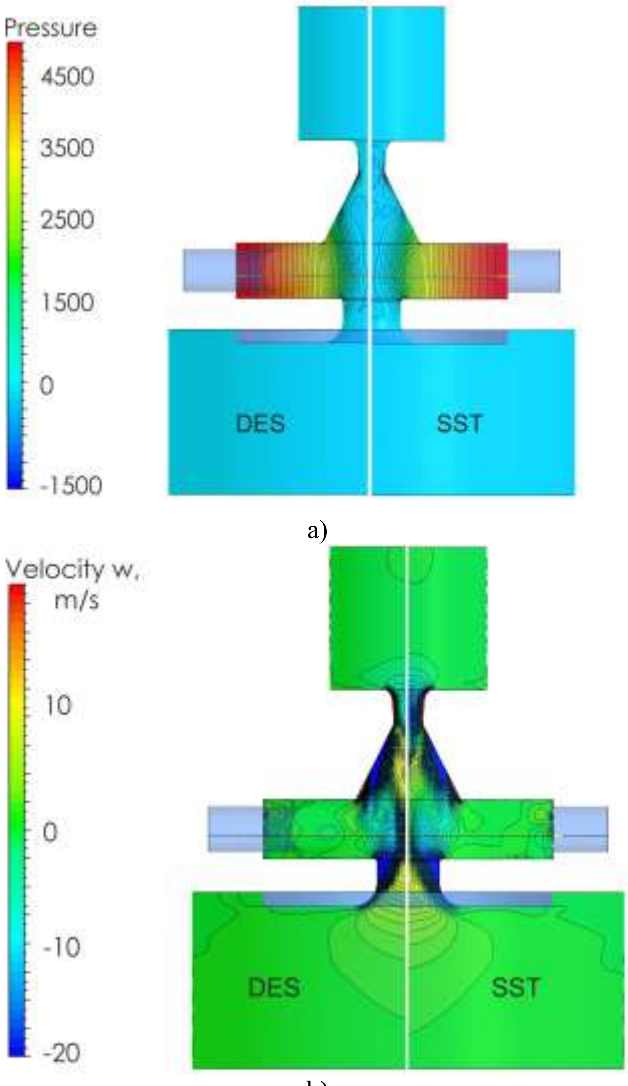

Fig. 4. Flowfield in vortex chamber supercharger without radial diffuser and with the opened exit tangential channel: a) field of pressure; b) field of axial velocity

On fig. 4 flowfield in vortex chamber supercharger are resulted at its normal operating mode with ingress of the pumped fluid in the exit tangential channel. Here a little smaller swirling degrees of a flow are observed, than at work with the closed exit channel.

Application DES changes a flowfield in the device a little. It is possible to see a major vacuum in a throat in axial diffuser at SST simulation with what it is linked a smaller error of calculation of the fluid flow rate which is sucked in the device (fig. 5). The difference in fluid flow rates arises owing to the different value of vacuum on an axis of the device. Qualitative coincidence of a predicted flow pattern in the device and flows in experimental model is observed. The secondary flow in the drainage channel will well be agreed with the data of vortex chambers experimental and theoretical researches of valves and superchargers [2, 5, 7, 26], besides, outcomes of calculation with use of hybrid model DES have the big affinity to flow experimental patterns.

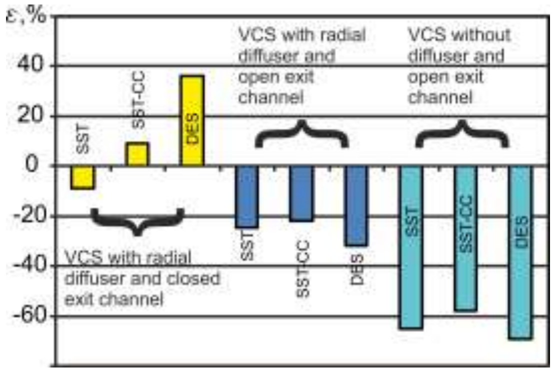

Fig. 5. Errors of calculation results of the volume flow rate which is sucked in the VCS

On the other hand, the better description of a flowfield in VCS by means of DES hybrid model has not led to reduction of calculation errors at comparison on flow integrated parameters (fig. 5).

Comparison of simulation results with experimental researches has been made on following integrated parameters: the volume flow rate in the supply channel Q_s , the volume flow rate which is sucked in the device Q_{in} , static pressure in the exit channel p_e and for a normal operating mode of a supercharger - the fluid flow rate of an exit in the tangential channel Q_e .

In article results of comparison on the majority to integrated parameters since the divergence on them did not exceed 5 % are not resulted and did not depend on investigated turbulence models. Essential errors are observed only in definition of the volume flow rate which is sucked in the device, and these errors reach 70-80 % depending on turbulence model, flow swirling degrees and from flow setting of VCS. Apparently, from fig. 5, application of hybrid model has not allowed to reduce a calculation error, and it remains commensurable with a margin error other turbulence models, in particular SST.

Therefore, application of hybrid turbulence model DES allows to achieve the better description of a flowfield, vortical structures, but does not allow to reduce an error of integrated parameters calculation. By optimization of vortex devices, and vortex chamber superchargers in particular, simulation time essentially is better to use SST turbulence model with rotation-curvature correction since this model does not demand, unlike the hybrid models, essential degree of grid crushing, and, consequently, it is less, as well as it is less than requirement to computer system productivity.

CONCLUSIONS

1. On the basis of mathematical modeling of fluid flow in vortex devices verification of use of detached-eddy simulation method in the swirling flows in vortex chamber superchargers is made.
2. It is received on the basis of the analysis of pressure distribution on radius vortex chamber that the hybrid turbulence model DES does not allow, as well as model SST precisely to predict value of vacuum on an axis of the vortex chamber. The error makes an order of 20 %. However, DES predicts almost correct, on 20 % big, than model SST, values of vacuum on an axis in a throat axial diffuser on an input in the vortex chamber. Besides, by means of DES it is possible to describe more adequately unsteady structures near to an axis of the vortex chamber, and also vortex core precession that does not allow to make SST turbulence model.
3. By optimization of vortex devices, and vortex chamber superchargers in particular, simulation time essentially is better to use SST turbulence model with rotation-curvature correction since this model does not demand, unlike the hybrid models, essential degree of grid crushing, and, consequently, it is less, as well as it is less than requirement to computer system productivity.

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ПРИМЕНЕНИЕ МОДЕЛИРОВАНИЯ ОТСОЕДИНЕННЫХ ВИХРЕЙ (DES) В РАСЧЕТАХ ЗАКРУЧЕННЫХ ТЕЧЕНИЙ В ВИХРЕВЫХ АППАРАТАХ

А.С. Роговой

Аннотация. На основе математического моделирования течений жидкости в вихревых аппаратах произведена верификация применения метода моделирования отсоединенных вихрей (DES) в закрученных течениях вихрекамерных нагнетателей. Исследование течения с использованием разных моделей турбулентности производилось для вихрекамерного нагнетателя в двух рабочих точках характеристики: с открытым выходным каналом и закрытым. Верификация была проведена по интегральным параметрам, а также по кинематическим, путем сравнения с экспериментом величины статического давления на верхней торцевой крышке устройства. Получено, что гибридная модель турбулентности DES не позволяет, так же как и модель SST точно предсказать значение вакуума на оси вихревой камеры. Погрешность составляет порядка 20 %. Однако, DES модель предсказывает практически правильные, на 20 % большие, чем модель SST, значения вакуума на оси в горле осевого диффузора на входе в вихревую камеру. Кроме того, с помощью DES модели можно более адекватно описать вихревые структуры вблизи оси вихревой камеры, а также прецессию вихревого ядра, что не позволяет сделать SST модель турбулентности. При оптимизации вихревых устройств, и вихрекамерных нагнетателей в частности, лучше использовать SST модель турбулентности с поправкой на кривизну линий тока и вращение потока.

Ключевые слова: вихрекамерный нагнетатель, верификация, DES, численный расчет, модель турбулентности, вихревой клапан.