Heat transfer simulation of unsteady swirling flow in a vortex tube

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Abstract. Effectiveness of not-adiabatic vortex tube application in the cooling systems of gas turbine blades depends on characteristics of swirling flows formed in the energy separation chamber. An analysis of the flow structure in the vortex tube channels has shown a presence of a complex three-dimensional spiral vortex, formed under relatively high turbulence intensity and vortex core precession. This indicates the presence of a significant unsteady flow in the energy separation chamber of the vortex tube that has a great influence on convective heat transfer of the swirling flow to the inner surface of tube. The paper contains the results of investigation of gas dynamics and heat transfer in the vortex tube taking into account the flow unsteadiness.

1. Introduction

Application of swirling flows in technology (flow rotary motion by means of various swirling devices) leads to a large-scale effect on flow parameters and, consequently, on the heat transfer [1]. Three-dimensionality of the velocity field and proportionality of tangential and axial velocity components (that is specific for swirling flows) determine a formation of three-dimensional pressure field with values of radial gradient comparable to longitudinal gradient. A presence of transverse velocity components (tangential and axial) enhances the convective transport of momentum, energy and mass allowing change in the swirling flow structure. It defines some specific properties of swirling flows in the context of technical application and their ability to intensify heat and mass transfer processes, to align the local temperature inhomogeneities due to convective mixing, to inhibit or to enhance the random perturbations, to stabilize the flow in a complex heat transfer with chemical reactions and combustion, to provide recirculating flow in the combustion chambers with high efficiency of fuel burn-out, and etc [1].

The necessity of studying the heat transfer of swirling flows in the axisymmetric channels of vortex energy separator is connected with requirements to improve the cooling systems of turbine blades [2]. Swirling flow application allows intensifying the heat transfer and leads to an increase of heat transfer coefficient across the channel length. Energy separation allows increasing the cooling efficiency of the most heat-stressed areas of the blade [2, 3].

2. Problem Statement

The analysis of flow structure in the vortex energy separator and the estimation of heat transfer intensity have been performed using the method of 3D numerical simulation. The research object was the vortex tube with a diameter of the energy separation chamber equal to d = 10 mm. An untwist plate
was set at the “hot” end of the tube. The area of the throttle disclosure was chosen to obtain the required value of the relative proportion of cooled stream μ. The flow in the channels of the vortex energy separator could be described by the system of differential equations of continuity, momentum, energy and state, and the heat transfer in solid body could be described by Fourier equation. There were specified conditions of continuity of temperature and heat flow equation for conjugation at the boundary “gas – solid body”. The 3D numerical simulation was performed for the steady, viscous, turbulent flow, taking into account compressibility, nonisothermality, and absence of chemical reactions and phase transformations. The described system of equations was closed by the two-parameter turbulence model k-ω SST.

Figure 1. Vortex tube geometry

3. Numerical modeling of heat transfer under stationary conditions

The conjugate problem of gas dynamics and heat transfer in the vortex tube under stationary conditions was numerically simulated to estimate the heat transfer intensity on the energy separation chamber. The calculations were performed for air and superheated water steam flows. The results have shown that the heat transfer coefficient increases with the growth of expansion ratio in a vortex tube and decreases along the length of the energy separation chamber. Such dependences of α are fair for all the studied regimes for air and water steam.

Properties of steam as a cooler are noticeably better than those of air. It could be explained by higher heat capacity of steam. Graphical dependences are shown in fig. 2. It can be seen that these dependences are equidistant with the aspect ratio \( \alpha_{\text{c}}/\alpha_{\text{air}} = 1.65 \).

The influence of swirling on the interaction between the flow and the channel walls may be specified by the critical angle of flow swirling on the channel surface that equals:

\[
\tan \varepsilon_{\phi} = \frac{\tau_{\phi\omega}}{\tau_{x\omega}}
\]

\( \tau_{\phi\omega}, \tau_{x\omega} \) – are the projections of surface friction stress on the coordinate axes. The swirling angle in the wall region changes little along the radius of the channel. This is why:

\[
\tan \varepsilon_{\phi} = \frac{\omega}{u}
\]

where \( u, \omega \) – are the flow velocity components (axial and peripheral) in the wall region.

The value of \( \tan \varepsilon_{\phi} \) characterizes the degree of deviation of the limit streamline from the axial direction, i.e. the curvature of the streamline in the wall region.

The degree of flow swirling is gradually reduced along the energy separation chamber, from the swirling device to the middle of the tube. There is some increase of the degree of flow swirling in the region of the unswirling device that is caused by significant reduction of axial velocity component. Formation of recirculation zone and near-axial reverse flow are shown in fig. 3.

Post-processing of the calculation results allowed obtaining an equation of swirling flow damping in the initial section of the energy separation chamber of the vortex tube for air:

\[
\varepsilon_{\phi} = 1.184 \bar{L}^{-0.014};
\]
for water steam:

$$
\varepsilon_p = 1.272 L^{-0.024}.
$$

(4)

Post-processing of the calculation results allowed to get a criteria equation of heat transfer:

$$
Nu_{d,fl} = 0.419 \cdot Re_{d,fl}^{0.646} \cdot \varepsilon_p^{10}.
$$

(5)

These dependences allow determining the distribution of heat transfer coefficients along the energy separation chamber, taking into account the flow swirling, and may be applied for calculating the regime and geometrical parameters of non-adiabatic vortex tubes.

4. Numerical modeling of heat transfer under stationary conditions

An unsteady calculation of heat transfer allowed revealing sight mass flow oscillations through the vortex energy separator. Oscillation frequency is 660 Hz. The results of calculation were fixed in three points in time: for maximal mass flow \( t=t_0 \), for minimal mass flow \( t=1/2t_0 \) and for medium mass flow value \( t=3/4t_0 \). The results of calculation are shown in figures 4-6.
Temperature distributions in the channel (fig. 4) have revealed the energy separation effect; there is a difference of average temperatures of peripheral and axial flows (fig. 6).

The centrifugal forces act on the swirling gas flow and forming of a radial static pressure gradient (fig. 5). The radial pressure gradient decreases along the tube from nozzle to throttle because of dissipation. Besides, it causes setting pressure gradient in the axial region energy of the separation chamber. This pressure gradient is directed from throttle to diaphragm and forms the reverse flow shown in fig. 5. It is shown that the size of the axial region of this reverse flow constantly changes over time.

Figure 4. Streamlines (a color matches the total temperature): a) $t=1/2t_0$; b) $t=3/4t_0$; c) $t= t_0$

Figure 5. Streamlines in axial section (a color matches the total pressure of the flow): a) $t=1/2t_0$; b) $t=3/4t_0$; c) $t= t_0$
The temperature distribution (fig. 4) and form of the streamlines (fig. 6) allow revealing the presence of unsteady interaction of gas flows, rotating at different distances from the axis. There is an influence of large and small scale turbulence that defines a formation of secondary vortex structures and precessing vortex core of the flow.

Vortex precession is clearly visible in the main flow sections (fig. 6) that are located at 0.01 m from the center of the tangential nozzle. The core of the stable swirling flow is displaced from the axis of the channel starting from the third section, and, as a result, the flow becomes a pulsating precessing vortex flow. It is obvious that mass flow oscillations at the channel outlet are the result of these pulsations.

Flow swirling intensifies heat transfer from the walls of the channel. Heat transfer coefficient significantly increases in the region of tangential nozzle and reaches value $\alpha=1380 \text{ W/(m}^2\text{K)}$, and then it decreases along the channel by 40%. The region of the most effective regimes (for air) relative to energy separation efficiency and heat transfer coefficients is in ranges $\mu=0.5 \div 0.7$ and $\pi=2 \div 3.3$.

5. Conclusion

Numerical modeling of conjugate gas dynamics and heat transfer allowed analyzing the flow structure in the energy separation chamber of the vortex tube for steady and unsteady regimes. The modeling of the flow structure that forms in the vortex tube channels has shown the presence of the complex three-dimension vortex system under the conditions of significant flow unsteadiness. Forms of the streamlines are determinant for the fact that unsteady interaction of flows rotating at different distances from the axis with the influence of significant large and small scale turbulence leads to the formation of secondary vortex structures and precessing vortex core of the flow.

The results of numerical calculation allowed defining the heat transfer coefficient at the inner surface of blade cooling channel $\alpha=1380 \text{ W/(m}^2\text{K)}$. This agrees well with the experimental data obtained earlier. Unsteady calculation of heat transfer allowed revealing mass flow oscillations with frequency 660 Hz.

The research of heat transfer in the vortex tube channels has been carried out using air and water steam as coolers. There effect of damping swirling flow on the heat transfer rate has been estimated.

The flow swirling degree gradually decreases along the energy separation chamber from swirling device to the middle of the tube. Significant decrease of axial velocity component in the region of
unswirling plate causes small growth of the swirling degree. Post-processing of the calculation results allowed obtaining the equation of swirling flow damping in the initial section of the energy separation chamber of the vortex tube. Post-processing of the calculation results allowed obtaining the equations to define the distribution of heat transfer coefficients along the energy separation chamber for calculating the regime and geometrical parameters of non-adiabatic vortex tubes. The results obtained are not exhaustive in the context of heat transfer from swirling flows in the channels. This serves a basis for the research continue.

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7. References
[1] Biruk V V, Veretennikov S V, Guryanov A I and Piralishvili Sh A 2014 Vortex effect. Technical applications Vol. 2 Part 2 (Moscow: Nauchtechlitizdat)
[2] Piralishvili Sh A and Zhornik I V 1988 Proc. of Scientific and Technical Conference «Vortex effect and its technical application» (Kuibyshev: KuAI Press) 87-91
[3] Piralishvili Sh A and Veretennikov S V 2011 Journal of Samara State Aerospace University (Samara: SGAU Press) vol 3 241-247