The active external heat and mass transfer multifunctional “one-wall” model with “nullified” friction resistance parietal boundary layer for the high-speed aircraft

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Abstract. In this paper, a new “single-wall” scheme of a high-speed wingless jet aircraft without compressor, which has the smallest, practically “zeroed” external friction and heat and mass transfer resistance with an active external near-wall boundary layer and tangential injection of the superheated steam from a cooling jacket SCC walls was proposed. Moreover, due to the limited flow rate of the combustible laminar sublayer vapor injection and the laminar “scaly” sublayer zeroed friction, the average Mach number of the vortex external near-wall boundary layer will be only 2% less than the Mach number of the flight speed. This circumstance allows not to merge the frontier layer of the hull (“fuselage”), as is done on the overwhelming majority of the aircrafts, but to use the energy and mass of the near-wall boundary layer as a normal incoming air flow.

1. Introduction

High-speed jet hybrid aircraft, which is, in fact, a hybrid combination of a wingless aircraft with a non-compressor jet engine, has its own history despite the youth of this new transport technical field [1-9].

In 1985, CIAM, together with NIMI, designed, manufactured and tested at the BMG stand a model of a six-chamber jet apparatus with a diameter of 152 mm with passive thermal protection zirconium dioxide plasma spraying of the entire model body except for the “bare” frontal cone of the model made of ordinary steel sprayed with household kerosene injected of six nasal openings with a diameter of 0.4 mm behind triangular deflectors of the same thickness against all six supersonic combustion chambers. As a result of bench blowing with an air flow Mach number that was twice large than usual and braking temperature $T_n*\geq 1700K$, the frontal cone of the active external kerosene cooling model was preserved, and the wedges of the internal compression pylons cones burned out under the shell (due to technological cracks in the heat-insulating coating) [4-6].

Kerosene vapors in the supersonic combustion chamber (SCC) at a rate of combustible-air flow velocity in its channels twice lower than initial velocity had ignited only when a self-igniting hydrogen was supplied. In the 90s, further tests in the Russian Federation did not last.
In the USA in 2005 this model was copied, but with fully heat-protective frontal cone twice lower than expansion half-angle ($V_{kn} = 70$), and brought to flight tests on the Terrier rocket. Further advancement of this “five-wall” scheme was not observed in the USA, apparently, due to the increased friction resistance and the associated losses [7–9].

Instead of this “five-walled” scheme, a new “double-walled” scheme that was called the “two-chamber” scheme (DCR: apparatus models with the rudimentary supersonic scramjet CC and “double-walled” SCC) was appeared in the USA.

2. The main results

In this paper, “single-wall” scheme of a high-speed wingless jet aircraft without compressor, which has the smallest, practically “zeroed” external friction and heat and mass transfer resistance with an active external near-wall boundary layer and tangential injection of the superheated steam from a cooling jacket SCC walls was proposed. Moreover, due to the limited flow rate of the combustible laminar sublayer vapor injection and the laminar “scaly” sublayer zeroed friction, the average Mach number of the vortex external near-wall boundary layer will be only at 2% less than the Mach number of the flight speed. This circumstance allows not to merge the frontier layer of the hull (“fuselage”), as is done on the overwhelming majority of the aircrafts, but to use the energy and mass of the near-wall boundary layer as a normal incoming air flow. Scheme of the near-wall boundary layer dotted tangential blowing of kerosene vapors is presented at the figure 1.

Knowledge of modern vortex mechanics of all boundary vortex flows, in contrast to mathematical empirical turbulence, allows this to be done [1-9]. Intermittent media vortex mechanic of large vortices had been evolving in Russia and the United States independently since the first experimental results were received in the 1950s [2-10]. These results were collected by Van Dyke in popular book for the beginning general reader [11]. All vortex mechanics analytical solutions of experimentally known natural boundary flows such as free boundary layer, near-wall boundary layer, jet, wake and etc. are described by well-known solutions of intermittent media vortex mechanics, including the declared external active near-wall boundary layer of "zeroed" friction resistance, given in this article, but are not yet verified experimentally.

According to the modern experimental data, the vortex mechanics of boundary flows deals with large vortices single-tier boundary layer between two wingtip vortices: an external incoming and an internal wingtip vortices flow of a “dotted” laminar sublayer, which has a physical parameter that is unique for each wingtip vortices flow. That parameter is the injection volume rate of its wingtip vortices flow [9, 10].
For a near-wall “turbulent”, or rather a vortex boundary layer, the first wingtip vortices flow is a dashed laminar near-wall sublayer, all parameters of which are also determined analytically, including all the necessary heat and mass transfer parameters and characteristics.

The main interest is provided by the active external parietal boundary layer of triple “zeroing”: friction, heating, and visibility — which could be received by using the tangential superheated steam “scaly blowing” of a high-speed aircraft mid-flight engine.

The basis of this engine aeromechanics is the boundary layer vortex model which is the same for six known natural passive boundary flows such as free, near-wall, jet, trace, direct and etc. and the seventh “man-made” boundary layer of active “zeroed” friction with its “constant”, not semi-empirical analytical by the solutions of their integro-differential equations, giving analytical dependences of the classical Prandtl-Tollmienn turbulence constants on the main stream Mach number, on the wingtip vortices velocity shift and overheating of the inhibited vortex layer volumes, simultaneously defining such previously known only empirical dependencies of the friction and heat and mass transfer coefficients. The result of these solutions is the subject of the proposed work.

An analysis of the structural parameters of the vortex natural passive near-wall boundary layer and the boundary layer of active zeroed friction resistance shows the possibility of using it not only to solve three problems of zeroing (friction, kinetic heating, laser invisibility), but also to use it as a homogeneous mixture working stream in the coaxial feed tandem reactive engine of a high-speed aircraft what cannot be implemented for a passive parietal boundary layer with the Mach number of the middle boundary layer, which gives less pressure increase in the feed scramjet.

The classical differential equations of continuum mechanics have no solutions for vortex constant vorticity bicompound tangles with internal and external intermittency of the two different media curls from the two confluent flows injected streams and, moreover, have no solutions for the entire multistage vortex boundary layer. The applied part of the intermittent media vortex mechanics has that solutions. It considers the integro-differential gas-dynamic equations with known injection rates for the six characteristic sections of the boundary flow such as the frontal, the forward and the reverse cones of the aft pylon and bottom draft.

In addition to the gas-dynamic system, the complete system of equations of the multivariate vortex boundary layer also has a system of equations for the appearance of the probability of each cascade. The multifunctionality of the active “single-wall” layer is determined by the list of tasks performed by this layer.

In the system of vortex mechanics gas-dynamic integro-differential equations (flow rates, momenta, energy and moments of any boundary layer of six known types of the boundary vortex flows), the wingtip vortices injection velocity is the only analytically determined and determining physical parameter, which could be received as:

$$u_i = K_d \omega_i, \quad K_d = \left(\frac{\Delta_i}{\delta_i}\right)_m$$  \hspace{1cm} (1)$$

where $K_d$ is the maximum value of the Prandtl-Tollmienn “turbulence constant” determined by the intermittent media vortex mechanics, $\Delta_i$ — thickness of the curl of a large vortex captured by the $i$ satellite stream (for the near-boundary boundary layer of the main satellite stream and its “dotted” laminar sublayer), $\omega_i$ is the rotational (peripheral) velocity of a large vortex, $\delta_i$ is the vortex pitch of the vortex layer.

The model of a constant vorticity for each large vortex, and solutions based on the classical continuum mechanics equations determine the values and the dependence of this “constant” on the Mach number of the main wingtip vortices flow, the wingtip vortices flow parameter and overheating, which
are in good agreement with the experiment. In particular, the result for the submerged subsonic free boundary layer is $2K_\delta = \tan(15^\circ)$.

These intermittent media vortex mechanics equations determine the values of all the necessary boundary layer parameters such as layer thickness, layer thickness growth rate, translational and rotational (peripheral) velocities $u_\omega$ of large vortex and the entire boundary layer.

For the near-wall boundary layer, the steady condition determines the dependence between unknown turbulent friction coefficient and the average value of the known “turbulence constant” in a form:

$$c_\nu = 2K_\delta \left( \frac{u_\omega}{u_0} \right)^2, \quad K_\nu = \frac{\Delta}{\delta_\nu}$$

The equation (2) determines not only the coefficient of friction, but also the Stanton number for the vortex heat and mass transfer on the wall.

These relations, in particular, shows that the value of vortex exchange increases simultaneously with the value of friction coefficient and heat transfer on the wall. For example, for $u_\omega/u_0 = 1/6$ (for a gradientless boundary layer) and for $u_\omega/u_0 = 1/2$ (for a precarious vortex flow of a pseudo-jump) the turbulent friction coefficient and heat transfer in the pseudo-jump will be three times more.

3. Conclusion
For an artificial active external boundary layer with a “self-zeroing” laminar sublayer created by the tangential, partial injection of superheated fuel vapor, injection of the laminar sublayer is forcibly limited: for $\alpha = 2$ and $L_\omega = 15$, it should be 30 times less than the external flow injection rate.

At the same time the profile of the near-wall boundary layer longitudinal velocity fullness degree should increase in six times according to the assessment of the alternating media vortex mechanics, i.e. the denominator of the well-known classical power law speed profile formula that equates to $1/7$ should be $1/42$.

The average Mach number of near-wall boundary layer should increase twofold with a corresponding decrease in heat and mass transfer parameters.

Indirect estimates and comparisons of the available experimental values of the expansion velocities of the vortex layers of the supersonic boundary layer, near-wall boundary layer, and the track with zero injection on the axis of the track indicate the possibility of implementing a “single-wall” model of the active supersonic boundary layer with the “zeroed” friction heating and visibility for a high-speed aircraft.

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