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FURTHER DEVELOPMENT OF HIGH-SPEED TRAIN DRAG REDUCTION TECHNOLOGY, BASED ON NON-UNIFORM MICROBLOWING

Introduction

High speed train is an intensively developing kind of modern transport. Due to importance of its efficiency improvement, the research area in this field is very wide (from magneto-levitation principles application to pantograph optimization), but the most actual subject of study is high-speed train aerodynamics. Turbulent Flow Control (TFC) is one of the most perspective directions of modern Fluid Dynamics. For typical wheel trains with the cruising speed of 300 km/h, the aerodynamic drag is about 85% [1] and its friction component is about 30% of the total train's drag [2], so the problem of friction drag reduction is one of the most actual for such kind of vehicles. Its **theoretical and practical actuality** can be demonstrated by the fact that due to typical sizes and speeds of modern vehicles (aircrafts, ships, cars and, in particular, trains) the most of their surface is streamlined by turbulent flow mode and turbulence is one of the most complicated physical phenomena. It causes the additional generating of a wide range spectra of vortical structures and initiates the process of strong energetic interaction between them, turbulent flow mode is characterized by substantial increment of energy loss and, as a result, additional friction. That is why any efforts, directed to a purposeful modification of turbulent exchange mechanism can not only reduce the friction drag, but, as a result, minimize the fuel consumption and harmful pollution into atmosphere. There are several effective methods in order to reduce the friction component of drag modifying air flows, namely: suction, blowing, surface riffling, application of very special tools like Large Eddy BreakUp devices or even exotic enough plasma actuators [3]. The microblowing (injecting a small amount of air through the streamlined surface into the boundary layer) seems to be the most effective, reasonable and practically applicable to high-speed trains (Fig. 1) and its mathematical modelling and further efficiency analysis is the **goal** of the presented research.

1. Principal structure of the decomposed mathematical model of flow around high-speed train with microblowing

Decomposition principles. The conducted research was based on a unified and simplified high-speed train geometry and working conditions, namely: 8 carriages 25 m×3.4 m×3.8 m (length × width × height) train with total length 25×8=200m (Fig. 1), 100 m/s (360 km/h) cruising speed and symmetrical flow around it. The most important problem is to get the aerodynamic characteristics of a long (200 m) high-speed (about 100-125 m/s and more) train with presence of small value of locally distributed blowing velocity (about 0.1 m/s). This problem has been solved by its effective decomposition into two following conjugate parts: (1) Modeling of the flow around 3D high-speed train without considering the blowing effect in a big domain, covering the whole train body; (2) Independent modelling the turbulent boundary layer in small enough domain, localized in the vicinity of train external surface. Such decomposition is possible because of two reasons: (1) Blowing effect, due to its localization near streamlined surface, affects effectively only on the skin friction coefficient, which under non-separation conditions can't change the parameters of pressure distribution over train body. So, pressure distribution can be calculated only once for the case of blowing absence; (2) The boundary layer parameters can be determined independently for different kinds of blowing influence on the base of known pressure distribution, when blowing is absent.

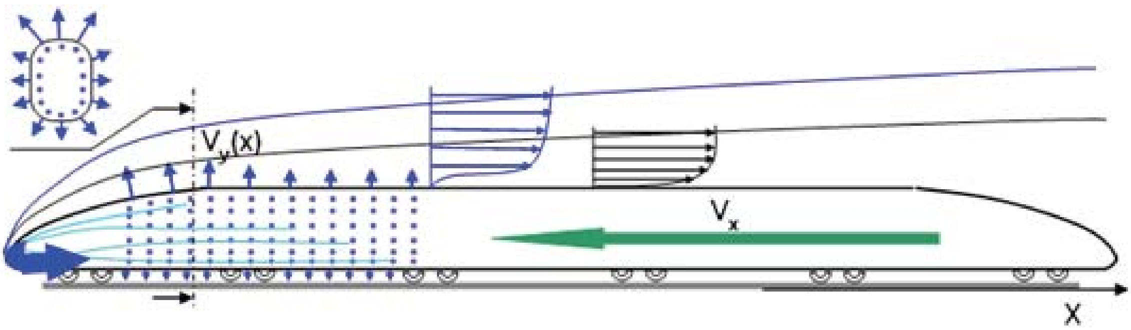

Fig. 1. The principal idea: to realize microblowing through the streamline surface (or its part) of high-speed train

Domain and mesh. The domain for the pressure distribution and drag without blowing in order to minimize the computing resources was built only for a half of train body, located on one side of symmetry plane, so the geometrical sizes for the 200m train's domain are: length 300 m, width 50 m, and height 41 m. For first part of the computational problem (flow around 3D high-speed train without blowing) the unstructured tetrahedron mesh with wall inflation procedure was built in this domain, consisting of 1868372 mesh nodes. The boundary layer region simulation (the 2-nd part of the computational problem) was determined on the base of suggestion of developed turbulent boundary layer: $h_y = 1.2\delta$, $\delta = 0.37L/\mathrm{Re}_L^{0.2}$, $Re_L = V_\infty L/\nu$, δ - thickness of turbulent boundary layer, developing along flat plate without pressure gradient. This correlates well with the conditions for the longest section of high-speed train body, between the end of its head cabin and the beginning of the tail cabin (will be discussed in details later), $V_\infty = V$ – free stream flow velocity. The results of mesh verification, built for boundary layer modelling, have shown that the number of points of domain separation in *x*- and *y*- directions can be taken as $N_{x\,\max}$=500 and $N_{y\,\max}$=1500 respectively. The mesh was orthogonal and nonuniform in both *x*- and *y*- directions, so that: $x_{i+1} = 1.01x_i$, $y_{j+1} = 1.01y_j$.

2. Computational method – part 1

To simulate the 3D flow around high-speed train without blowing effect influence, the following system of Reynolds-Averaged Navier-Stokes (RANS) governing equations has been solved under the assumption of stationary incompressible turbulent flow. The order of accuracy of the finite-volume discretization was chosen as second and due to slightly convergent iteration process the residuals for all variables were taken as $\varepsilon = 5\times10^{-5}$.

Boundary conditions. The boundary conditions were established with taking into account the motion of ground surface relatively train body as follows: **Inlet face:** Velocity-inlet; **Lateral face, remote from the train:** Velocity-inlet; **Lateral face coinciding with the symmetry plane of the train**: Symmetry; **Top side:** Velocity-inlet; **Bottom face – ground surface:** Moving Wall; **Outlet face:** Pressure-outlet; **External surface of train:** Wall (no-slip).

Turbulence model. The turbulent flow properties have been modelled according to RANS approach on the base of one-equation Spalart-Allmaras model of turbulent viscosity ν_t.

3. Computational method – part 2

Governing equations. The second part of computations is associated with necessity to simulate the micro-blowing effect, that has been made on the base of own hand-made code of integrating the 2D system of stationary incompressible boundary layer equations. This system has been approximated by the implicit finite-difference scheme, having the second order accuracy, and solved by the marching method in the prevailing flow direction.

Boundary conditions. The boundary conditions were determined in a traditional boundary layer flow modeling way: **Input section** ($x = x_{in}$), $p = p_\infty; V_x = V_\infty (y/\delta_{in})^{1/7}$, where δ_{in} - turbulent boundary layer thickness at $x = x_{in}$. **Wall:** $V_x = 0; V_y = V_{blow}$, where V_{blow} - the given blowing velocity. **Outer domain boundary** - free stream conditions: $V_x = V_\infty; p = p_\infty$. Here V_x, V_y - velocity components in the *x*- and *y*- directions, p - pressure.

Turbulence model. Here the algebraic Cebeci-Smith turbulence model, adopted by authors for taking into account the wall blowing effect, was applied:

$$\nu_t = \begin{cases} \nu_{t\,in} & \text{if} \quad y \le y_*; \\ \nu_{t\,out} & \text{if} \quad y > y_*, \end{cases} \tag{1}$$

where y_* is the coordinate of the point, that corresponds to the smallest distance y from the wall, for which $\nu_{t\,in} = \nu_{t\,out}$; $\nu_{t\,in} = l^2 \frac{\partial V_x}{\partial y}$ - inner representation of ν_t; $l = 0.4y(1 - \exp(-y^+ / A^+))$ - mixing length parameter; $y^+ = y\upsilon_* / \nu$ - dimensionless y coordinate according to wall law length scale; $\upsilon_* = \sqrt{\tau_w / \rho}$ - friction velocity; τ_w - wall shear stress; ρ - air density; $A^+ = f(V_y^+)$ - wall damping factor; $V_y^+ = V_y / \upsilon_*$ - dimensionless blowing velocity V_y according to wall law velocity scale; $\nu_{t\,out} = 0.0168 V_{out} \delta^* \gamma$ - outer representation of ν_t; V_{out} - value of V_x velocity component at the outer boundary of the boundary layer, in the case of flow without pressure gradient $V_{out} = V_\infty$; $\delta^* = \int_0^\delta (1 - V(x)/V_{out}) dy$ - the displacement thickness; $\gamma = 1/\left[1 + 5.5(y/\delta)^6\right]$ - intermittency factor. These computations (part 1 and part 2) have been made for the formulated above working conditions and with their parametrization, the obtained results are presented below.

4. Mathematical model verification

Pressure distribution analysis. The calculated pressure coefficient distribution $C_p = 2(p - p_\infty)/(\rho V_\infty^2)$ allowed to establish the fact of uniform and very close to zero distribution of pressure for the most of streamlined surface (about 85%) excluding head and tail parts of the high-speed train body. This allows to consider flow over the streamlined surface in this zone of high-speed train as close enough to 2D boundary layer over a flat plate.

Skin friction distribution analysis. The developed turbulent flow over a flat plate with perforated section ($C_b = V_y / V_\infty = 0.00277$, $x_{por} = [1.17;1.58]$), experimentally studied by Kornilov, Boiko [4], has been simulated numerically by the authors of this paper (Fig. 2a) and applied for determining the wall damping function in the form:

$$A^+ = \begin{cases} 764.1 V_y^+ + 26 & \text{if} \quad V_y^+ \le 0.01; \\ 36.5 / (8.5 V_y^+ + 1) & \text{if} \quad V_y^+ > 0.01. \end{cases} \tag{2}$$

The developed two-stage flow model, based on the proposed model of turbulence (1, 2), has been verified by its application to the case of non-uniform microblowing (Fig. 2b) through the set of three penetrable sections ($C_b = 0.00344$, $x_{1por} = [1.17;1.292]$, $x_{2por} = [1.313;1.413]$,

$x_{3\,por} = [1.434;1.534]$, $x_{4\,por} = [1.555;1.58]$). The obtained numerical results of local skin friction coefficient $C_f = 2\tau_w/(\rho V_\infty^2)$ demonstrate quite satisfying for practical needs level of correspondence to the experimental data, excepting the zone of flow relaxation behind the last porous section in the case of non-uniform microblowing. The applicability of this kind of non-uniform blowing has been tested for the high-speed train in the form of a set of transversal penetrable sections with $\Delta x_{por} = 10\,\text{m}$, intermitted by impenetrable sections, with the same width Δx (Fig. 3). The obtained distributions of $C_f(x)$ are illustrated by Fig. 4 (C_b=0.0025).

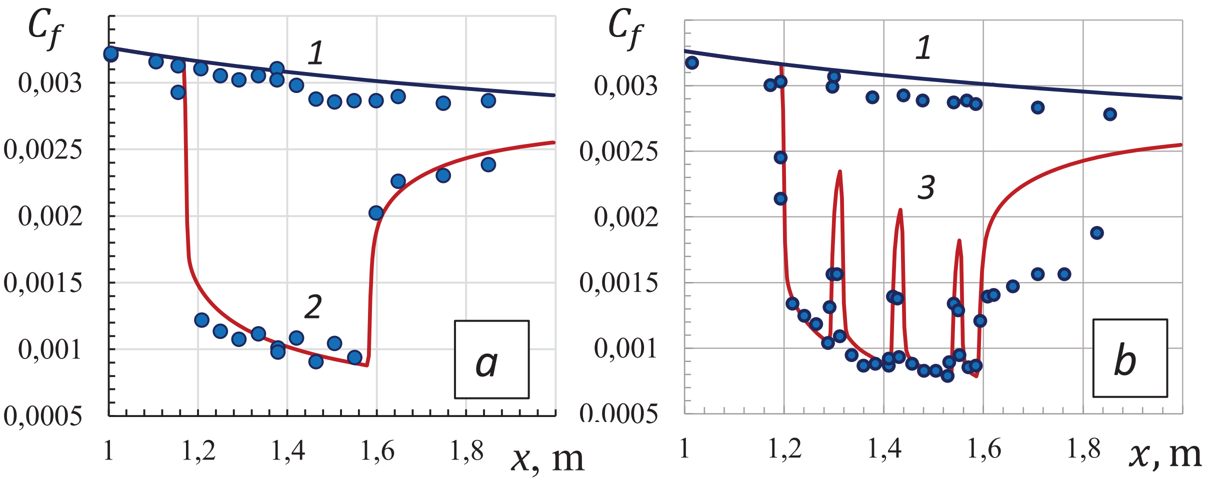

Fig. 2. Local skin friction coefficient distribution $C_f(x)$ along the flat plate with different kinds of penetrable sections: lines – Shkvar's numerical prediction of without blowing (line 1), with uniform blowing, C_b=0.00277 (line 2) and non-uniform blowing, C_b=0.00344 (line 3). Circles – corresponding experimental data, obtained by Kornilov, Boiko [4]

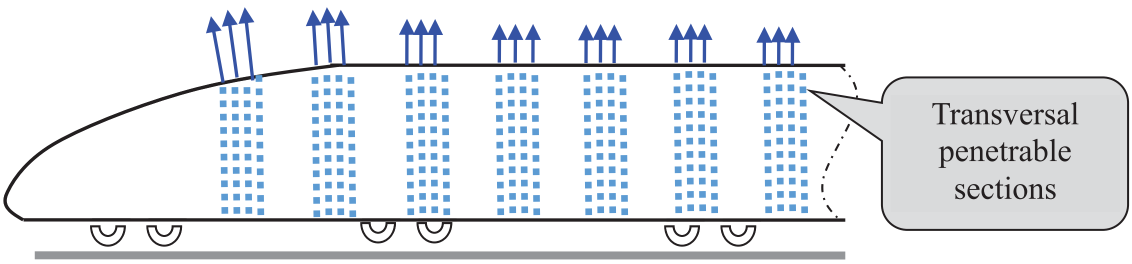

Fig. 3. One of possible realizations of non-uniform blowing through the array of periodic transverse porous sections

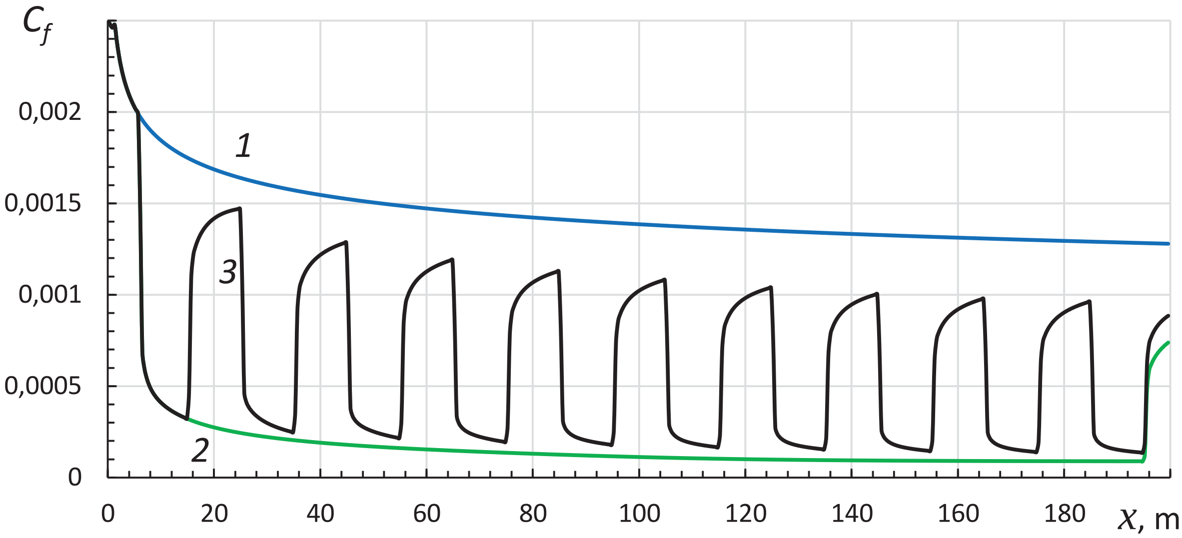

Fig. 4. Local skin friction coefficient as a function of the length of perforated section for:
1 – no blowing; 2 – uniform blowing, C_b=0.0025; 3 – non-uniform blowing, C_b=0.0025

The obtained distributions of C_f allow to get the total skin friction coefficient of train's body $C_F = \frac{S_{extern}}{S_{mid}} \frac{1}{L} \int_0^L C_f dx$, where $S_{extern} = 2420\,\mathrm{m}^2$ - area of external streamlined surface of a train, $S_{mid} = 12\,\mathrm{m}^2$ - area of its middle section, L=200 m – train length. For the flow without microblowing this coefficient is $C_{F0} = 0.2916$, for the uniform microblowing $C_{Fu} = 0.04351$ and in case of non-uniform microblowing $C_{Fn-u} = 0.1336$. Thus, uniform microblowing with C_b=0.0025 allows to reduce skin friction drag in $C_{F0} / C_{Fu} = 6.7$ times, but can't be realized practically due to high risk of flow separation. Nevertheless, non-uniform periodically intermitted microblowing with the same intensity C_b is not so dangerous and requires only a half of secondary air flux. Moreover, as it can be seen from Fig. 4, the distribution $C_f(x)$ for non-uniform blowing (line 3) is localized closer to line 2 that corresponds to uniform blowing than to line 1, which is related to no blowing case. According to the results of numerical predictions it allows to achieve the skin friction drag reduction in $C_{F0} / C_{Fn-u} = 2.18$ times. In real physical conditions the non-uniform microblowing expected to be even more effective due to lower relaxation rate over impermeable sections of streamlined surface than it was predicted on the base of the developed numerical model.

Conclusions

1. The methodological concept and corresponding mathematical model of turbulent flow development over the high-speed train with uniform and periodically intermitted non-uniform microblowing through its streamlined surface have been developed.

2. The obtained results show the efficiency of microblowing application to the high-speed train.

3. The conducted numerical predictions of turbulent boundary layers over flat plate with both uniform and non-uniform microblowing demonstrate quite good agreement to the corresponding experimental data, but in the non-uniform case the modelling approach requires improvement in the region behind the last penetrable section that will be the subject of further authors efforts applications. The numerically simulated periodically intermitted non-uniform microblowing through the streamlined surface of high-speed train have demonstrated its great potential that should be studied theoretically and experimentally.

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Afterword

This research is dedicated by its authors to the memory of two well-known Ukrainian scientists and educators in the area of mechanics of liquid and gas – Doctors of Phys.-Math.Sci., Prof. Movchan V.T. (5.10.1937-29.08.2017) from the National Aviation University and Prykhodko O.A. (14.04.1953-3.09.2018) from the Dnipro National University. R.I.P.