Development of models and algorithms of aerodynamic drag of a high-speed train and calculations of particle entrainment

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Abstract. The work is a study of the patterns of jet-cavitation air flows when flowing around a high-speed passenger train. On the basis of theoretical studies, the forces of resistance (frontal and near-wall) of the external environment to the movement of the train, the influence of cavitation currents on the near-wall layer, the current flows generated during the movement of the rolling stock, the resistance of the external environment of the rolling stock, both as a whole and on each car of the train, are determined, the influence of cavitation flow from solid particles lying on the underlying surface, critical velocities that reduce the entrainment of solid particles, establishing the regularity of the movement of entrained solid particles. The work also includes a theoretical determination of the aerodynamic drag coefficient and hydrodynamic pressure forces, normal and shear stresses on the surface of the wall of a train consisting of n cars, a study of the effect of gaps between cars and on the speed characteristics of the train, leading to a change in the acceleration of cars.

1 Introduction

When moving rolling stock, there are resistances that prevent the movement of rolling stock in an open area. Along with the main resistance forces, there are places of resistance of the local environment (in the open air). The main of the six elements of the main resistance is the resistance of the air environment and energy dissipation in the environment. With an increase in the speed of movement of the rolling stock, the influence of the external environment on the resistance significantly affects the movement of the train, which will lose energy to overcome these resistances. At a speed of 10-20 km per hour, the resistance of the external environment is 19% of the main resistance energy dissipation in the environment. At 60 km per hour and above, these resistance indicators increase sharply and amount to 46-61%. In addition, with an increase in the speed of the train, the loss of energy in the section of oncoming trains will increase, in the presence of air wind, the formation of return jets both around the train and under the train, which forms erosion of the track

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surface, giving entrainment of solid particles, the trajectory of which sometimes pose a danger both to the environment and to the train itself. This is also explained by the fact that, as a consequence of the increase in the speed of trains, the configuration of the train, the distance between the trains, the height of the bottom of the train plays a significant role. Cavitation is formed and cavitation erosion occurs (stagnant zones, turbulence zones), and there is also a non-standard flow of the environment (air), both drag and tangential forces of surface trains increase, resulting in variable velocity field, voltage over time and movement of rolling stock can switch to oscillatory mode, which leads to instability of movement, where local resistance becomes dangerous, that is, reduces the safety of movement of the train. The entrained particles from the underlying surface spread into the surroundings, and also threaten the surface of the wagons.

Depending on the speed of the train, the length, the distance between the trains and other technical characteristics, both in the whole composition of the rolling stock, and between and around the trains, cavitation effects occur, which will significantly change the resistance forces, lifting forces and the speed of the environment (air).

2 Problem statements

In order to determine the velocity field in the vicinity of a rolling high-speed train, the problem of jet flow around the rolling stock, which is generally spatial, is considered below in the vertical plane, taking into account different possible configurations of a high-speed train. At the same time, taking into account the smallness of the kinematic viscosity of air at a temperature of 10° -20 °C, $\nu = 0{,}134 \cdot 10^{-4} \frac{m^2}{\sec}$ these tasks are divided into two parts:

- the boundary layer above the surface of the rolling stock of the train, where the influence of the friction force is taken into account, the thickness, which is small and the jet flow around the rolling stock of the train is ideal incompressible at $M \le 0{,}25$, where M is the Mach number;

- at $0{,}25 < M < 1$, we consider the flow of an ideal compressible fluid (air). If there is a strong wind in the atmosphere, the air flow will be a mixture of suspended particles. In this case, the above-mentioned jet problems will be considered in the model of interacting interpenetrating media [1]. In [2-4], in some cases, solution methods for ideal liquids are given.

The flow of viscous air is considered directly above the surface of the rolling stock of the train, and the determination of the velocity field makes it possible to determine the resistance forces due to friction. The influence of the high-speed train movement on the atmosphere, as well as the surrounding region, mainly extends to the final width of the atmosphere. In practice, we will have a two-layer air movement over the surface of the rolling stock with a thickness of $\delta(x)$ and the lower layer (the region is the boundary layer) of the solution determined in the process, the flow of an ideal liquid G_Z (Fig. 1).

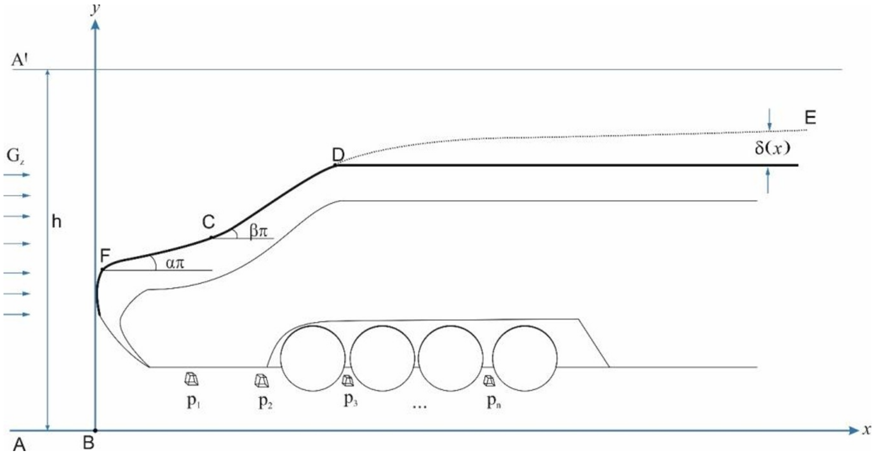

Fig. 1. Aerodynamic shape of a high-speed train and solid particles near it.

We accept the current as flat, potential, stationary. In the problem of determining the distribution of velocities, pressures and densities in the surrounding region, as well as the coefficient of resistance to the movement of the train, we take as formed due to perturbation during the movement of the train in an unlimited air environment. It is assumed that the resulting perturbed air movement is potential, stationary, since the motion of the high-speed train is subsonic, and therefore it is assumed to take into account the compressibility of the air. It is also assumed that at a distance h (figure 1.) from the side wall of the train, the speed of air particles will be much less than the speed of the train.

It is also considered that during the movement of the composition in the surrounding region, there are solid particles (p_1, p_2, p_3 ,..., p_n is meant as crushed stone figure 1) of different shapes and masses on the Earth's surface. Under the influence of the movement of the composition formed by the air flow, the problem of the distribution of velocities in the air under the composition or in the vicinity of the wagons of the composition and the impact force on each particle (crushed stone) is solved. As a result, there is a separation of particles on the Earth's surface (fine gravel or sand) and their entrainment in the surrounding region, taking into account the force of the flow in a linear pattern of resistance.

3 Theoretical basis

The plane problem of rolling stock flow in the vertical plane of an ideal incompressible fluid (air flow) is considered. It is assumed that the rails are located on a vertical surface. Imagine that we will have the origin of coordinates on the front of the train in moving coordinates, assuming that the train is moving at a constant time velocity V_n (Fig. 2).

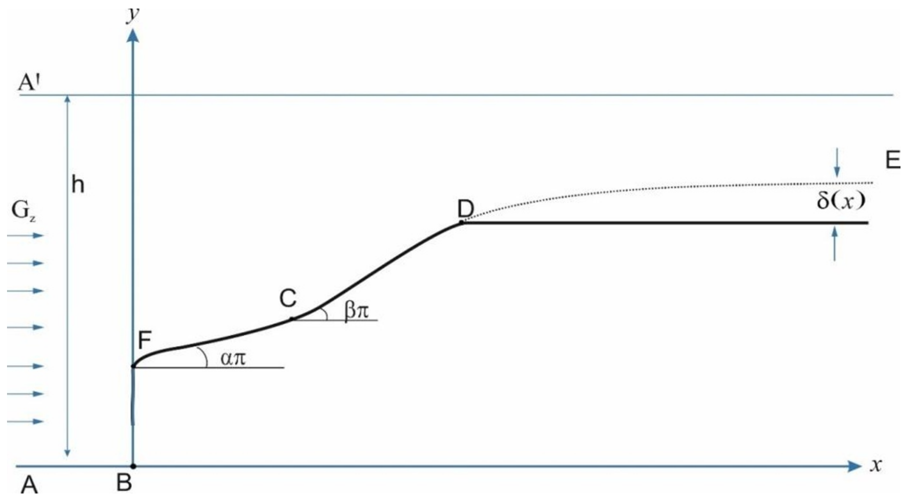

Fig. 2. The vertical plane of flow around a moving high-speed train in an ideal incompressible fluid is considered

Here the boundaries *BF*, *FC* and *CD* with the horizon have angles $\frac{\pi}{2}$, $\alpha\pi$ and $\beta\pi$ respectively. Then the velocity of the air particles away from the train at point *A* will be $V_A = V_n$ directed along the *x*-axis $A\vec{B}$. The area of the air flow will be the area of the curve passing through the points *ABFCDE* and back EA', the free surface DE. The flow is flat, stationary (liquid), the air is incompressible, can be an ideal liquid, and since the kinematic viscosity of the air is determined by the equality $\nu = 0{,}134 \cdot 10^{-4} \frac{m^2}{\sec}$.

Suppose that the appearing motion of air particles is potential, then the velocity of air particles is determined by the equality

$$\vec{V} = grad\varphi \tag{1}$$

where $\varphi(x, y)$ is the velocity potential.

The continuity equation has the form:

$$\frac{\partial \rho u}{\partial x} + \frac{\partial \rho v}{\partial y} = 0 \tag{2}$$

where u, v are the components of the velocity vector of air particles.

We introduce the stream function $\Psi(x, y)$ in the form

$$u = \frac{1}{\rho}\frac{\partial \Psi}{\partial y}, \quad v = -\frac{1}{\rho}\frac{\partial \Psi}{\partial x} \tag{3}$$

where $\rho = \begin{cases} const & when \quad M < 0{,}3 \\ \text{variable} & when \quad M \geq 0{,}3 \end{cases}$ and *M* – Mach number.

If the train is moving at a maximum speed of $350-400km/h$, the air density is variable, and at *M<0.3*, the air density is constant, since ρ can change by a small amount, that is, $\rho=\rho_0+\Delta\rho$, where $\frac{\Delta\rho}{\rho_0}<<1$. Equality (3) satisfies the continuity equation (2).
We introduce a complex potential $w(z)=\varphi(x,y)+i\psi(x,y)$, where $z=x+iy$. Then from the equalities (1), (3) we have that the introduced complex function of the velocity potential will be *p*-an analytical function.

$$u=\frac{\partial\varphi}{\partial x}=\frac{1}{\rho}\frac{\partial\psi}{\partial y},\quad v=\frac{\partial\varphi}{\partial y}=-\frac{1}{\rho}\frac{\partial\psi}{\partial x} \tag{4}$$

When a train is moving at subsonic speed, for the case $M<1$ at $\rho=const$, $u=\frac{\partial\varphi}{\partial x}=\frac{1}{\rho}\frac{\partial\psi}{\partial y}$, $v=\frac{\partial\varphi}{\partial y}=-\frac{1}{\rho}\frac{\partial\psi}{\partial x}$, a method is proposed for solving jet problems of a compressible fluid by first solving the problem for an incompressible fluid (then $\Delta\rho=0$).
In the case of an incompressible fluid $\rho=const$ and then the introduced function will be an analytical function in the flow region G_z (Figure 2).
The flow region G_z has, along with solid boundaries, a free surface DE, detached at point *D*, from the surface of the train, along which we assume the pressure constant. In this regard, we will display the flow region G_z to the region G_0 - the upper half-plane, the real axis of which is in the region G_0 corresponds to the boundary of the region in the figure 3.

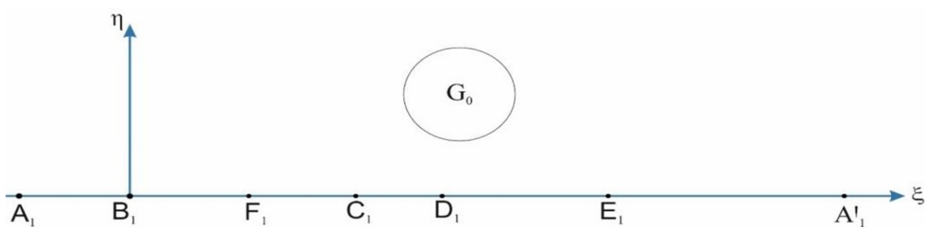

Fig. 3. Is a mapping of the flow region G_z to region G_0

Is a mapping of the flow region G_z to region G_0 – the upper half-plane, the real axis of which in region G_0 corresponds to the boundary of the region in figure 3. Then the introduced functions of the velocity potential $\phi(x,y)$ and the current function $\psi(x,y)$ satisfy the Laplace equation, and the complex potential $w(z)=\varphi(x,y)+i\psi(x,y)$ will be an analytical function both in the flow domain G_z $(z=x+iy)$ and in the canonical region G_0, where $\zeta=\xi+i\eta$, $\xi-$ in the real, $\eta-$ in the imaginary region (Fig. 2).
The segment *AB* of the region G_z corresponds to the segment A_1B_1 in the region G_0, where $\eta=0,\ -\infty<\xi<0$.
The segment *BF* corresponds to the segment B_1F_1, where $\eta=0,\quad 0<\xi<f$.

The segment *FC* corresponds to the segment F_1C_1, where $\eta = 0, \quad f < \xi < c.$ (5)
The segment *CD* corresponds to the segment C_1D_1, where $\eta = 0, \quad c < \xi < 1.$
The free surface *DE* corresponds to the segment D_1E_1, where $\eta = 0, \quad 1 < \xi < e.$

The boundary of the flow region EA' corresponds to the segment E_1A_1',
where $\eta = 0, \quad e < \xi < \infty$ in the region G_0.

From the equalities (1.4) for $\rho = const$ we have that the introduced, complex potential $w(z) = \varphi(x, y) + i\psi(x, y)$ is an analytical function in the region G_0. Using the principle of matching boundaries and introducing the Jankowski function in the form

$$\omega(\zeta) = \ln\frac{V_0}{\overline{V}(\zeta)} = \ln\frac{V_0}{V(\zeta)} + i\theta \tag{6}$$

where $\vec{V} = u - \vec{i}v$ conjugate complex velocity; u, v components of the velocity vector $\vec{V} = u\vec{i} + v\vec{j}$; θ - the angle of inclination of the velocity vector, air particles to the horizon. To determine the Jankowski function $\omega(\zeta)$ in the region G_0, we have the following boundary conditions:

Along the segment $A_1B_1 : \eta = 0, -\infty < \xi < 0 \quad \mathrm{Im}\,\omega = \theta(\xi) = 0$

Along the segment $B_1F_1 : \eta = 0, \quad 0 < \xi < f \quad \mathrm{Im}\,\omega = \theta(\xi) = \dfrac{\pi}{2}$

Along the segment $F_1C_1 : \eta = 0, \quad f < \xi < c \quad \mathrm{Im}\,\omega = \theta(\xi) = \alpha\pi$

Along the segment $C_1D_1 : \eta = 0, \quad c < \xi < 1 \quad \mathrm{Im}\,\omega = \theta(\xi) = \beta\pi$ (we assume that $\beta < \alpha$)

Along the segment $D_1E_1 : \eta = 0, \quad 1 < \xi < e \quad \mathrm{Re}\,\omega = 0$

Along the segment $E_1A_1' : \eta = 0, \quad e < \xi < \infty \quad \mathrm{Im}\,\omega = 0$

Introduce the function $\omega_1(\zeta)$ in the form

$$\omega(\zeta) = \sqrt{\zeta - 1}\sqrt{\zeta - e}\,\omega_1(\zeta) \tag{7}$$

Then for the introduced function $\omega_1(\zeta)$ - analytic in the flow region G_0, we have the following conditions:

Along the segment $A_1B_1 : \eta = 0, -\infty < \xi < 0 \quad \mathrm{Im}\,\omega_1 = 0$.

Along the segment $B_1F_1 : \eta = 0, \quad 0 < \xi < f \quad \mathrm{Im}\,\omega_1 = \dfrac{\pi}{2}\dfrac{1}{\sqrt{e - \xi}\sqrt{1 - \xi}}$

Along the segment $F_1C_1 : \eta = 0, \quad f < \xi < c \quad \mathrm{Im}\,\omega_1 = \dfrac{\alpha\pi}{\sqrt{e - \xi}\sqrt{1 - \xi}}$ (8)

Along the segment $C_1D_1 : \eta = 0, \quad c < \xi < 1 \quad \mathrm{Im}\,\omega_1 = \dfrac{\beta\pi}{\sqrt{e - \xi}\sqrt{1 - \xi}}$

Along the segment $D_1E_1: \eta=0, \quad 1<\xi<e \quad \operatorname{Re}\omega_1=0$

Along the segment $E_1A_1': \eta=0, \quad e<\xi<\infty \quad \operatorname{Im}\omega_1=0$

Using the Schwarz integral formula, we define the desired function $\omega_1(\zeta)$ in the form $\omega_1(\xi)=\frac{1}{\pi}\int_{-\infty}^{\infty}\frac{\operatorname{Im}\omega_1(t)\,dt}{t-\xi}$. Then, using the boundary conditions for $\operatorname{Im}\omega_1$ (8), we obtain the following equality for the desired function $\omega_1(\zeta)$:

$$\omega_1(\zeta)=\frac{1}{\pi}\left\{\int_0^f\frac{\frac{\pi}{2}dt}{\sqrt{1-t}\sqrt{e-t}(t-\zeta)}+\int_f^c\frac{\alpha\pi dt}{\sqrt{1-t}\sqrt{e-t}(t-\zeta)}+\int_c^1\frac{\beta\pi dt}{\sqrt{1-t}\sqrt{e-t}(t-\zeta)}\right\}$$

Having calculated the integrals, we obtain an analytical expression for the desired function $\omega_1(\zeta)$ in the region G_0

$$\omega_1(\zeta)=-\frac{2}{\sqrt{\zeta-e}\sqrt{\zeta-1}}\left\{\ln F(0,\zeta)\left[F(f,\zeta)\right]^{1-2\alpha}\left[F(c,\zeta)\right]^{2(\beta-\alpha)}\right\} \tag{9}$$

$$F(0,\zeta)=\frac{\sqrt{\zeta}\sqrt{e-1}}{\sqrt{e}\sqrt{\zeta-1}+\sqrt{\zeta-e}};$$

$$\text{where } F(f,\zeta)=\frac{\sqrt{\zeta-f}\sqrt{e-1}}{\sqrt{\zeta-1}\sqrt{e-f}+\sqrt{\zeta-e}\sqrt{1-f}}; \qquad (10).$$

$$F(c,\zeta)=\frac{\sqrt{c-\zeta}\sqrt{e-1}}{\sqrt{\zeta-1}\sqrt{e-c}+\sqrt{1-c}\sqrt{\zeta-e}}.$$

Given the equalities (7) and (10), we obtain expressions for the Jankowski function $\omega_1(\zeta)=-\ln\mathrm{F}(\zeta)$ (11),

$$\text{where } \mathrm{F}(\zeta)=F(0,\zeta)\left[F(f,\zeta)\right]^{1-2\alpha}\left[F(c,\zeta)\right]^{2(\beta-\alpha)} \qquad (12).$$

Given the equalities (1.11), (1.6) we obtain expressions for the distribution of the conjugate complex velocity in the region G_0

$$u-iv=\overline{V}(\zeta)=V_0\mathrm{F}(\zeta) \tag{13}$$

where $\zeta=\xi+i\eta$.

Now we determine the velocity of particles on a free surface from the conditions $V_n=V_0\lim_{\xi\to\infty}F(\xi,0)$.

Using equality (12) and assuming $\eta=0$ and calculating the limit of $\xi\to\infty$, we obtain equality $V_n=V_0\Phi_0(f,c,e)$; where

$$\Phi_0(f,c,e)=\sqrt{e-1}\left[\left(\frac{\sqrt{e-1}}{\sqrt{e-f}+\sqrt{1-f}}\right)^{1-2\alpha}\left(\frac{\sqrt{e-1}}{\sqrt{e-c}+\sqrt{1-c}}\right)^{2(\beta-\alpha)}\right] \tag{14}$$

So equality (1.13) will be written as:

$$\overline{V}(\zeta)=\frac{V_n}{\Phi_0}\mathrm{F}_0(\zeta) \tag{15}$$

In the flow region G_z, the source with the flow rate q $(q=V_n h)$ is point $A(x\to\infty)$, the drain is point E with the same flow rate q. The complex potential whose area of change is a band of width q and then for the complex potential, using the Kristoffer integral formula, which gives a mapping of the area of change of the function $w(\zeta)$ to the region G_0 :

$$\frac{dw(\zeta)}{d\zeta}=\frac{q}{\pi}\frac{1}{(e-\zeta)} \tag{16}$$

Now we define the velocity field of air particles in the flow region G_z in parametric form; to do this, we find the mapping function of the region G_z and G_0, which gives the correspondence of the points of the regions, G_z and G_0, the dependence between the variables z and ζ, in the regions G_z and G_0 as follows $dz=\frac{dz}{dw}\frac{dw}{d\zeta}d\zeta=\frac{q}{\pi(e-\zeta)}\frac{\Phi_0}{V_n\mathrm{F}(\zeta)}$ or using the equalities (14), (15).

$z(\zeta)=\frac{h\Phi_0}{\pi}\int_0^{\zeta}\frac{d\xi}{(e-\xi)\mathrm{F}(\xi)}$; or

$$\hat{z}(\zeta)=\frac{z(\zeta)}{h}=\frac{\Phi_0}{\pi}\int_0^{\zeta}\frac{d\xi}{(e-\xi)\mathrm{F}(\xi)}; \tag{17}$$

The equalities (1.15) and (1.17) give the distributions of the velocity field $u\left[\hat{x}(\xi,\eta),\hat{y}(\xi,\eta)\right]$ and $v\left[\hat{x}(\xi,\eta),\hat{y}(\xi,\eta)\right]$,

where $\hat{x}(\xi,\eta)=\mathrm{Re}\left[\frac{\Phi_0}{\pi}\int_0^{\zeta}\frac{d\tau}{(e-\tau)\mathrm{F}(\tau)}\right]$; $\hat{y}(\xi,\eta)=\mathrm{Im}\left[\frac{\Phi_0}{\pi}\int_0^{\zeta}\frac{d\tau}{(e-\tau)\mathrm{F}(\tau)}\right]$ (18).

Now let's start determining the mapping parameters *f*, *c* and *e* from the conditions of correspondence of the boundaries of the regions G_z and G_0 (because at $\eta=0$, the segments of the region G_0 correspond to the solid boundaries of the flow region G_z) we have, since the lengths of the segments *BF*, *FC* and *CD* are given, l_{BF}, l_{FC}, l_{CD} respectively

$$\hat{l}_{BF}=\frac{\Phi_0}{\pi}\int_0^f\frac{d\xi}{(e-\xi)|\mathrm{F}(\xi)|};\ \hat{l}_{FC}=\frac{\Phi_0}{\pi}\int_f^c\frac{d\xi}{(e-\xi)|\mathrm{F}(\xi)|};\ \hat{l}_{CD}=\frac{\Phi_0}{\pi}\int_c^1\frac{d\xi}{(e-\xi)|\mathrm{F}(\xi)|};\qquad(19)$$

where $\hat{l}_{BF}=\frac{l_{BF}}{h};\ \hat{l}_{FC}=\frac{l_{FC}}{h};\ \hat{l}_{CD}=\frac{l_{CD}}{h}$.

At high train speeds of more than 280 km/h and above, the compressibility of the air should be taken into account. Using the developed approximate method for determining the velocity field and other parameters, we will find them. Then for a compressible fluid, when the process is polytropic, the pressure and density are determined by the equalities

$$p=p_0\left(1-\frac{V^2}{V_0^2}\tau_0\right)^{\gamma+1},\ \rho=\rho_0\left(1-\frac{V^2}{V_0^2}\tau_0\right)^{\gamma},\ \tau=\tau_0\left(1-\frac{V^2}{V_0^2}\tau_0\right)^{\gamma}\qquad(20)$$

where $\gamma=\frac{1}{n-1}$, $\tau_0=\frac{V^2}{V_{\max}^2}=\frac{n-1}{n+1}M_0^2$, $M_0=\frac{V_0}{a}$ - the Mach number along the free surface, *a* is the velocity of sound propagation in the atmosphere, *n* is an indicator of polytropy.

Formulas (18) will have the form:

$$\hat{x}(\xi,\eta)=\mathrm{Re}\left[\frac{\Phi_0}{\pi}\int_0^\zeta\frac{d\tau}{\left(1-\frac{V^2(\tau)}{V_0^2}\tau_0\right)^{\gamma}(e-\tau)\mathrm{F}(\tau)}\right]\qquad(21)$$

$$\hat{y}(\xi,\eta)=\mathrm{Im}\left[\frac{\Phi_0}{\pi}\int_0^\zeta\frac{d\tau}{\left(1-\frac{V^2(\tau)}{V_0^2}\tau_0\right)^{\gamma}(e-\tau)\mathrm{F}(\tau)}\right]\qquad(22)$$

For the mapping function we have (for a polytropic process in the air $p=p_0\left(\frac{\rho}{\rho_0}\right)^n$, where - p_0,ρ_0 is the pressure and density of the air during braking).

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$$\hat{x}(\xi,\eta)=\mathrm{Re}\left[\frac{\Phi_0}{\pi}\int_0^{\zeta}\frac{d\tau}{\left(1-\frac{V^2(\tau)}{V_0^2}\tau_0\right)^{\gamma}(e-\tau)\mathrm{F}(\tau)}\right];$$

$$\hat{y}(\xi,\eta)=\mathrm{Im}\left[\frac{\Phi_0}{\pi}\int_0^{\zeta}\frac{d\tau}{\left(1-\frac{V^2(\tau)}{V_0^2}\tau_0\right)^{\gamma}(e-\tau)\mathrm{F}(\tau)}\right];$$

n - the polytropy indicator, where $\gamma=\frac{1}{n-1}$.

Then, assuming $\eta=0$, the coefficients *f*, *c* and *e* are determined from the equalities:

$$\hat{l}_{BF}=\frac{\Phi_0}{\pi}\left|\int_0^{f}\frac{d\xi}{\left(1-\frac{V^2(\tau)}{V_0^2}\tau_0\right)^{\gamma}(e-\xi)\mathrm{F}(\xi)}\right|;$$

$$\hat{l}_{FC}=\frac{\Phi_0}{\pi}\left|\int_f^{c}\frac{d\xi}{\left(1-\frac{V^2(\tau)}{V_0^2}\tau_0\right)^{\gamma}(e-\xi)\mathrm{F}(\xi)}\right|;$$

$$\hat{l}_{CD}=\frac{\Phi_0}{\pi}\left|\int_c^{1}\frac{d\xi}{\left(1-\frac{V^2(\tau)}{V_0^2}\tau_0\right)^{\gamma}(e-\xi)\mathrm{F}(\xi)}\right| \qquad (23)$$

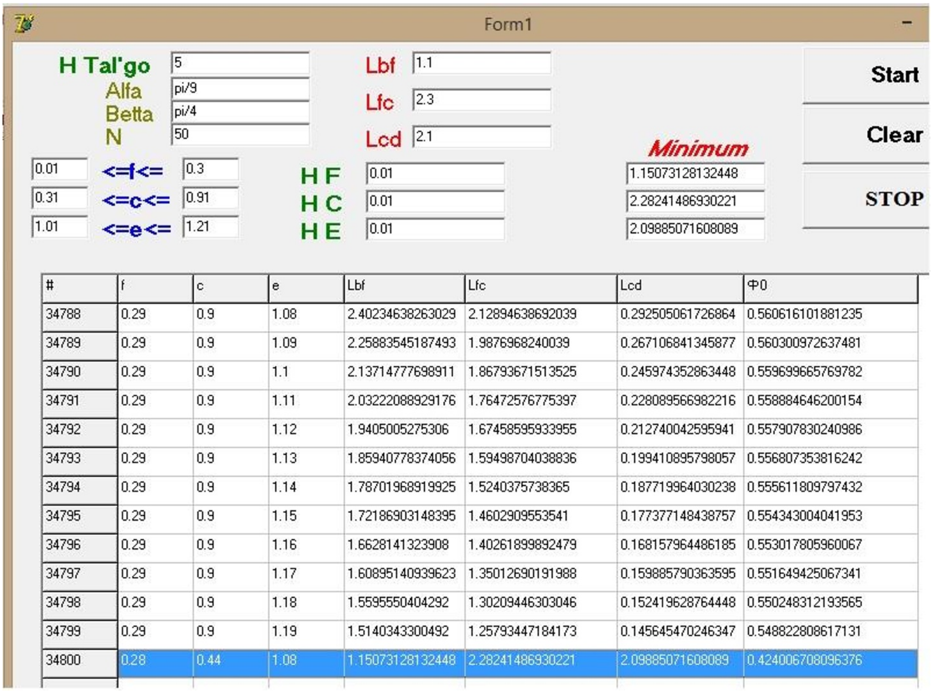
From these equalities, the length of the segments $\hat{l}_{BF}$, $\hat{l}_{FC}$, as well as the point of separation of the flow from the surface of the train $\hat{l}_{CD}$ are determined.

V_0 - the velocity on the free surface DE (Figure 2) is determined by the equality

$$V_0=\frac{V_n}{\Phi_0} \qquad (24)$$

4 Experimental results

The problem of the flow around the composition of a high-speed train, which reduces to an approximate calculation of the singular integral and gives the distributions of the velocity field, also setting the configurations of a real train and boundary conditions (18) in [5], a numerical solution satisfying equality (24) was performed and coefficients for a specific configuration of the composition *f, c, e* were found (figure 4).


Form1

H Tal'go	5	Lbf	1.1
Alfa	pi/9	Lfc	2.3
Betta	pi/4	Lcd	2.1
N	50		

					Minimum
0.01	<=f<=	0.3	H F	0.01	1.15073128132448
0.31	<=c<=	0.91	H C	0.01	2.28241486930221
1.01	<=e<=	1.21	H E	0.01	2.09885071608089

Start
Clear
STOP

#	f	c	e	Lbf	Lfc	Lcd	Φ0
34788	0.29	0.9	1.08	2.40234638263029	2.12894638692039	0.292505061726864	0.560616101881235
34789	0.29	0.9	1.09	2.25883545187493	1.9876968240039	0.267106841345877	0.560300972637481
34790	0.29	0.9	1.1	2.13714777698911	1.86793671513525	0.245974352863448	0.559699665769782
34791	0.29	0.9	1.11	2.03222088929176	1.76472576775397	0.228089566982216	0.558884646200154
34792	0.29	0.9	1.12	1.9405005275306	1.67458595933955	0.212740042595941	0.557907830240986
34793	0.29	0.9	1.13	1.85940778374056	1.59498704038836	0.199410895798057	0.556807353816242
34794	0.29	0.9	1.14	1.78701968919925	1.5240375738365	0.187719964030238	0.555611809797432
34795	0.29	0.9	1.15	1.72186903148395	1.4602909553541	0.177377148438757	0.554343004041953
34796	0.29	0.9	1.16	1.6628141323908	1.40261899892479	0.168157964486185	0.553017805960067
34797	0.29	0.9	1.17	1.60895140939623	1.35012690191988	0.159885790363595	0.551649425067341
34798	0.29	0.9	1.18	1.5595550404292	1.30209446303046	0.152419628764448	0.550248312193565
34799	0.29	0.9	1.19	1.5140343300492	1.25793447184173	0.145645470246347	0.548822808617131
34800	0.28	0.44	1.08	1.15073128132448	2.28241486930221	2.09885071608089	0.424006708096376

Fig. 4. Numerical solution satisfying equality (24) where coefficients are found for a specific configuration of a high-speed train (Afrasiab - Talgo 250) *f, c, e*

Having set all the values for ξ in a given interval from formula (1.8), the corresponding results of x and y are found, which are given in [5], and a graph of the function for variables x and y is constructed. Applying the results obtained, the velocity of air particles on the surface of trains, pressure, and particle velocity at a distance from the trains of a high-speed train are found in the tables below.

Table 1. Calculations of velocity, pressure and density were obtained on excel

$F(0,\zeta)$	$\omega(\xi)$	$\omega(\xi) = \sqrt{\xi-1}\sqrt{\xi - f\omega_1(\xi}$	$\omega_1(\xi)$	Φ_0	V_n	V_0	$\bar{V}$	$\bar{V}/V_n$
0.9398	0.06	0.06	0.73	0.55	50.0	90.1	84.7	1.69

Table 2. Speed distribution on the side surface of the train.

$\hat{x}$	$K_0(4\hat{x})$	$e^{(0,3\hat{x})}$	$K_0(4\hat{x})\cdot e^{(0,3\hat{x})}$	$V(\hat{x})=V_n\cdot K_0(4\hat{x})\cdot e^{(0,3\hat{x})}$
0.09	1.145	1.0273	1.176	81.684
0.1955	0.6222	1.0477	0.6519	45.268
0.2659	0.421	1.083	0.4559	31.6617
0.57	0.07914	1.1864	0.0938	6.5203

The velocity modulus on the free surface is also found $V_0=\frac{V_n}{\Phi_0}=1{,}178$, where $\Phi_0=\sqrt{1-f_0}=\sqrt{0{,}72}=0{,}8485$. On a free surface, the velocity is $V_0=1{,}178V_n$, V on the side wall of the train is determined by $V_b(\tau)=1{,}178V_n\sqrt{\frac{\xi}{\xi-f}}$, velocity of air particles on the surface of wagons.

At a distance H from the side wall of the wagon, where $V(\tau)=V_n\sqrt{\frac{\xi}{\xi-0{,}28}}$. Also, an experiment was conducted on the fly away of particles (crushed stone) on the high-speed train line in the city of Jizzakh, Dashtobod checkpoint, a new line, where the speed of a high-speed train reaches *230 km/h*. Before the passage of the high-speed train, the particles are shown in Figure 5, after the passage in Fig. 6.

Fig. 5. shows the particles before the train passes

Fig. 6. shows the particles after the train passed

And according to the results of the experiment, it was revealed that the calculations performed coincide with the experiment carried out due to the fact that the selected crushed stone was quite heavy and some were slightly displaced, some remained in their places at all.

5 Results discussion

Previously, the problems of entrainment of air flow particles formed during the movement of a high-speed train were considered [5, 6, 7], but the cases were not considered when the train (high-speed train) is moving simultaneously with solid particles (crushed stone) located in the vicinity of the train (Figure 1), in various areas along which the high-speed train passes, forming an air flow at high speed that can tear particles from the earth's surface and carry away in a certain direction, but the train continues to move next to possible carried away particles up to a certain point. Given that the train is moving at high speed uniformly in one direction, we believe that the motion of the entrained particles will mainly move in the direction of movement of the train with a slight deviation. When the train is moving, we take the air as incompressible (because the speed of movement of the train is $V_n \leq 250km/h$, the Mach number is $M < 0,32$). So it is possible to introduce the velocity potential and current functions satisfying the continuity equation $u(x,y) = \dfrac{\partial\varphi}{\partial x} = \dfrac{\partial\psi}{\partial y}$, then the complex potential in the flow region G_z, $z = x + iy$ is analytical functions, where $0 < x < \infty$, $0 < y < \infty$, which are also found in [5].

In [8, 9], the problem of the removal of individual solid particles from the Earth's surface is considered. In reality, there may be *n* - pieces of solid particles located randomly on the earth's surface. A model of entrainment of solid particles lying in the vicinity on the Earth's surface with various configurations formed by the movement of air flows of a high-speed train is considered. In [9] considered, the problem of a single solid particle with a diameter d, with a density $\rho_ч$, whose motion was saltational, and in the model of quadratic resistance to the movement of particles from the Earth's surface, the separation velocity was not assumed. The problem of carrying away *n* pieces of solid particles is also considered, the direction of separation, which occurs in the vertical direction, is found [7]. To study the issues of entrainment of solid particles from the Earth's surface, we use the equation of motion of solid particles as a continuous medium during separation, and moves as a whole. Then the model of saltational motion gives the field the opportunity to determine the trajectory and patterns of particles. In the case when the distance between the particles was much greater than the height, then the method of individual particles was applied, where it was found that the separation of each particle was weakly influenced by neighboring particles. With a uniform length distance between the particles, the model of a single particle is also applicable. We also obtained the air velocity acting on each solid particle located at the corresponding coordinates.

6 Conclusions

A sufficient number of materials have been studied [1, 8, 10-20] in this field. The collecated materials have been analyzed. The task was set to form models and algorithms for the flow of an ideal incompressible fluid around the composition and to calculate the entrainment of particles located in the vicinity of the composition. We can say that the goal of the ball set for us has been fulfilled. Calculations were performed to determine and distribute speeds in the vicinity of a high-speed train. The problem of determining the pressures during acceleration at the boundary of the layer according to the composition of a high-speed train is solved. Numerical calculations have been performed and a model has been compiled. Using this model, it is possible to calculate pressures at the boundary of the layer, as well as at different distances from a high-speed train. The speed and pressures at the boundary of a high-speed train were determined by numerical methods. The formulation and analytical solution of the problem of acceleration on the boundary layer of a high-speed train is given. The problem of tangential stresses is solved, the resistance of the air flow to the movement of a high-speed train is determined.

A numerical solution of the problem for determining the air flow resistance near and in the vicinity of a high-speed train is given. An experiment was carried out on the removal of small stones (impurities) located on the Earth's surface near and in the vicinity of trains by the air flow formed by the movement of a high-speed train. The analysis and research on the obtained results of the experiment "On the removal of small stones (impurities) located on the Earth's surface near and in the vicinity of trains, by the flow of air formed by the movement of a high-speed train" is made. The problem of the flow of small impurities of different sizes and masses by the air flow formed during the movement of high-speed trains has been analytically solved. Numerical calculation and analysis of the considered problem is carried out. The trajectories and laws of motion of impurities (of different configurations and masses) carried away from the Earth's surface are determined. Numerical calculations were carried out according to these formulas and the corresponding results were obtained.

The saltation movement of impurities (of different configurations and masses) carried away from the Earth's surface by an air flow generated during the movement of high-speed and high-speed trains are determined and calculated. Numerical calculations were carried out according to these formulas and the results were obtained. The calculations carried out have already found their application in the organization of the movement of the high-speed train "Afrasiab" (Talgo). The results of the research work will continue to be used (implemented) to ensure the safety of high-speed trains, as well as the environment.

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