METHOD OF CALCULATING THE SEPARATION FLOW WITH DUST PARTICLES AT THE ENTRANCE TO ROUND SUCTION PIPE IN CONDITIONS OF THE APPROACH FLOW

A. K. LOGACHEV*, O. A. AVERKOVA*, E. I. TOLMACHEVA*

* Belgorod State Technological University named after V.G. Shukhov
(BSTU named after V.G. Shukhov), 308012 Belgorod, Russia
e-mail: kilogachev@mail.ru, web page: http://www.bstu.ru

Key words: discrete vortex method, separated flows, flows in suction channels, local exhaust ventilation.

Abstract. Modeling the separation flows at the entrance to suction ducts is necessary to determine the efficient intake area, jet contraction coefficient and the velocity fields in their radius of action. The simplest and the most thoroughly researched one is the separation flow at the entrance to the round thin-walled suction pipe, which is a part of many process facilities; simulation of flows in its range of action is considered in many scientific works. For the numerical modeling of such flows the boundary element method [1], the numerical solution of Navier-Stokes equations for viscous incompressible fluid [2] and the discrete vortex method were used. In the paper [3] there was developed a method of mathematical modeling of flow separation at the entrance to suction ducts with the use of stationary discrete vortexes. On the free surface of the flow the free vortexes circulation was set, after which the average velocity in the suction duct and the velocity field were approximately determined. The approach flow should be taken into account only if its velocity is lower than the intake velocity in the pipe. Modernization of this method seems to be of interest, as it would allow calculating the separation flow characteristics for both high-velocity and low-velocity approach flows. This can be obviously achieved if the intake velocity in the pipe is set, and the circulation on the free vortex sheet is determined in the process of the problem solution.
The purpose of this work is developing the method of mathematical modeling of separation flow at the entrance to round thin-walled suction pipe at the presence of an approach flow using stationary discrete vortexes, as well as its verification.
The developed method of mathematical modeling of separation flow at the entrance to suction pipe at the presence of an approach flow allows building the appropriate velocity field of an air flow, the limit trajectories of dust particles and determining the aspiration coefficient.

1 INTRODUCTION

The modeling of separation flows at the entrance to suction ducts is necessary for determining the efficient suction area, the jet constriction coefficient and velocity fields in their range of action. The simplest and the best researched is the separation flow at the entrance to round thin-walled suction pipe, which is a part of many technological facilities; a lot of scientific research works are devoted to modeling flows in its range of action. For the numerical modeling of such flows the boundary-element method [4], the numerical solution of Navier-Stokes equations for viscous incompressible liquid [2,4] and discrete vortex method [5-7] were used. In this paper [7] there was developed a method of mathematical modeling of flow breakdown at the entrance to suction ducts with the use of stationary discrete vortexes. The free vortexes circulation was set on the free stream surface, after which the average velocity at the suction pipe and the velocity field were calculated approximately. The approach flow is taken into account only if its velocity is lower than the suction velocity in the pipe. Modernization of this method is of great interest, which would allow calculating the properties of separation flow, both for the low-velocity and the high-velocity approach flow. This can be obviously done, if we define the suction velocity in the pipe, and the circulation on the free vortex sheet is determined in the process of numerical calculation.

The purpose of this work is to develop a method of mathematical modeling of the separation flow at the entrance to round thin-walled suction pipe in conditions of the approach flow with the use of stationary discrete vortexes, and its verification.

2 THE MAIN CALCULATION RATIOS AND THE COMPUTING ALGORITHM CONSTRUCTION

The discrete mathematical model (fig.1) is built in the following way. At the flow boundary there are infinitely thin vortex rings (black circles in fig.1) and control points (crosses in fig.1) – the arbitrary points on the circle, embracing the pipe, or on the suction section. Let us point out, that in the suction section on the symmetry axis the zero radius vortex is located, so it's not taken into account. The number of discrete vortex rings is equal to the number of control points. In the control points on the pipe walls the impermeability condition is performed – the velocity along the normal direction amounts to zero. In the suction section the velocity along the outward normal direction is similar and amounts to v_0. The division to discrete vortex rings and control points is uniform, the control points are in the centre among the vortex rings. The distance between two neighbouring vortex rings is equal to discrete pitch size r_h. The free stream surface consists of free vortex rings (hollow circles in fig.1) and is formed on the sharp edge A of the pipe. It is determined by iterational method, as further described. Parallely to the pipe axis the flow approaches with the velocity v_∞.

Let us define N – the number of the attached vortex rings; N_s - the number of free vortex rings; x^p - control point, $p = 1,2,\ldots,N$.

The velocity in the arbitrary point x along the $\vec{n}$ direction is calculated by the formula:

$$v_n(x) = \sum_{q=1}^{N} \Gamma(\xi^q) G(x,\xi^q) + \gamma \sum_{q=1}^{N_s} G(x,\zeta^q) + n_1 v_\infty, \tag{1}$$

where ξ^q - the location point of the q-th attached vortex ring with circulation $\Gamma(\xi^q)$, $\gamma = \mathrm{const}$ - circulation of a free vortex ring, ζ^q - the location point of the q-th free vortex ring.

The function $G(x,\xi)$ expresses the influence on point $x(x_1,x_2)$ of the vortex ring with singular circulation, located in point $\xi(\xi_1,\xi_2)$.

$$G(x,\xi)=\frac{4(A_1b+A_2a)E(t)}{b(a-b)\sqrt{a+b}}-\frac{4A_2F(t)}{b\sqrt{a+b}} \text{ at } b\neq 0,\ G(x,\xi)=\frac{\xi_2^2 n_1}{2a\sqrt{a}} \text{ at } b=0,\ 2x_2\xi_2=b>0,$$

$$a=(x_1-\xi_1)^2+\xi_2^{\,2}+x_2^{\,2}>0,\ A_1=\frac{\xi_2^{\,2}n_1}{4\pi},\ A_2=\frac{\xi_2}{4\pi}\left[(x_1-\xi_1)n_2-x_2n_1\right],\ F(t)=\int_0^{\pi/2}\frac{d\theta}{\sqrt{1-t^2\sin^2\theta}},\ t=2b/(a+b)$$

$$E(t)=\int_0^{\pi/2}\sqrt{1-t^2\sin^2\theta}\,d\theta;\ F(t)=\sum_{i=0}^{4}c_i(1-t)^i+\sum_{i=0}^{4}d_i(1-t)^i\ln\frac{1}{1-t};\ E(t)=1+\sum_{i=1}^{4}c_i(1-t)^i+\sum_{i=1}^{4}d_i(1-t)^i\ln\frac{1}{1-t};$$

c_i, d_i are taken from tables [8].

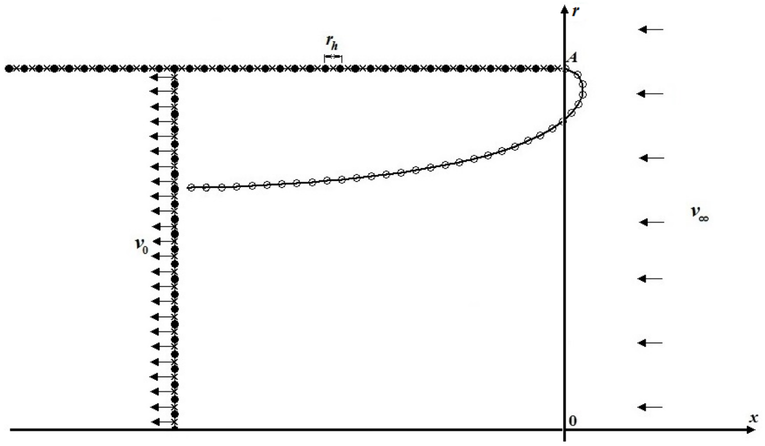


Figure 1: The discrete mathematical model of separation flow at the entrance to round suction duct (pipe) in meridional plane

If the distance from point x to point ξ is smaller than the discrete pitch size r_h, this function is calculated according to formula: $G(x,\xi)=\left((x_1-\xi_1)n_2-(x_2-\xi_2)n_1\right)/(2\pi r_h^2)$. In the case of $x=\xi$ the function is $G(x,\xi)=0$.

The computing algorithm is constructed in the following way. After defining the location points of attached vortexes and the control points a two-dimensional array is formed $G^{pq}=G(x^p,\xi^k);\ p=1,2,\ldots,N;\ q=1,2,\ldots,N$. The initial coefficients at the first unknown vortex circulation on the sharp edge A: $G(x^p,\xi^1)=P(x^p),\quad p=\overline{1,N}$. The vortexes are numbered from this point. Then the iteration procedure starts.

1. A one-dimension array of absolute terms is formed

$$v^p=-n_1v_\infty-\sum_{q=1}^{N}G(x^p,\xi^q),\ p=1,2,\ldots,N.$$

2. The initial coefficients are altered:

$$G(x^p,\xi^1)=P(x^p)+\sum_{k=1}^{N_s}G(x^p,\zeta^k),\quad p=\overline{1,N}.$$

At the first iteration $N_s = 0$ and coefficients $G(x^p,1)$ don't alter.

3. A system of linear algebraic equations in the unknowns $\Gamma(\xi^q)$ is solved:

$$\sum_{q=1}^{N} \Gamma(\xi^q) G(x^p, \xi^q) = v(x^p),\ p = 1,2,3,\ldots N$$

The vortex ring circulation on the sharp edge is memorized: $\gamma = \Gamma^1$.

4. The free stream surface, beginning from the sharp edge *A,* is constructed.

Using the formula (1), at $\vec{n} = \{1,0\}$ the velocity component v_x, is calculated at $\vec{n} = \{0,1\}$ - velocity component v_r. The following point (x', r') is determined from the previous one (x,r) using the formulas: $x' = x + \Delta t v_x / \sqrt{v_x^2 + v_r^2}$, $r' = r + \Delta t v_r / \sqrt{v_x^2 + v_r^2}$, where Δt - is a pitch, which is chosen to be rather small. The free stream surface will consist of free vortex rings, located a discrete pitch size away from each other r_h. So, in the process of calculation, the distance to the previous free vortex ring is checked at each stage. As soon as this distance becomes equal, within the accuracy of insignificant error, to discrete pitch size at a certain point, the next vortex ring is placed into this point. This construction goes on to the exhaust section, after which the iteration procedure begins from 1 and continues, until the absolute difference between the old circulation value γ on the free stream surface and the new one is higher than the given accuracy ε.

3 VERIFICATION OF MATHEMATICAL MODELING METHOD

The calculation was carried out at $\varepsilon = 10^{-8}$, $r_h = 0{,}000625$ m, the pipe radius *R* = 0,1m, the suction velocity $v_0 = 1$ m/s; the distance from exhaust section to the pipe entrance 6*R*; the pipe wall length 11*R*, the pitch of stream-line construction $5 \cdot 10^{-7}$ m. The calculation results are presented in nondimensional form. The length scale -*R*, the velocity scale - v_0.

The results of building a stagnation stream-line at the velocity v_∞ of the approach flow of the greater suction velocity are shown v_0 in fig.2. The following notations are introduced here: I – calculations at $\overline{v} = v_\infty / v_0 = 2$; II – at $\overline{v} = 10$; III – at $\overline{v} = 50$; line 1 – calculations by A.K. Gilfanov, Sh.H. Zaripov [4] in a potential model by the boundary-element method, line 2 – calculations by discrete vortex method without accounting the flow breakdown according to the algorithms, designed in this work; line 3 – calculation in the model of viscous incompressible liquid (numerical solution of Navier-Stokes equations) [4]; line 4 - calculations according to the designed method; 5 – free stream surfaces, constructed by the designed algorithms. The comparison of the calculation data demonstrates that the computation of the stagnation stream-line is correct, and the calculations within the framework of this paper are close to calculations with the account of viscosity.

The comparison of the calculated flow patterns at $\overline{v} = 50$ is shown in fig.3. The stagnation stream-line is denoted with a dashed line. The stream-lines are identical except for the separation area. In the model of viscous incompressible medium the separation area size is smaller.

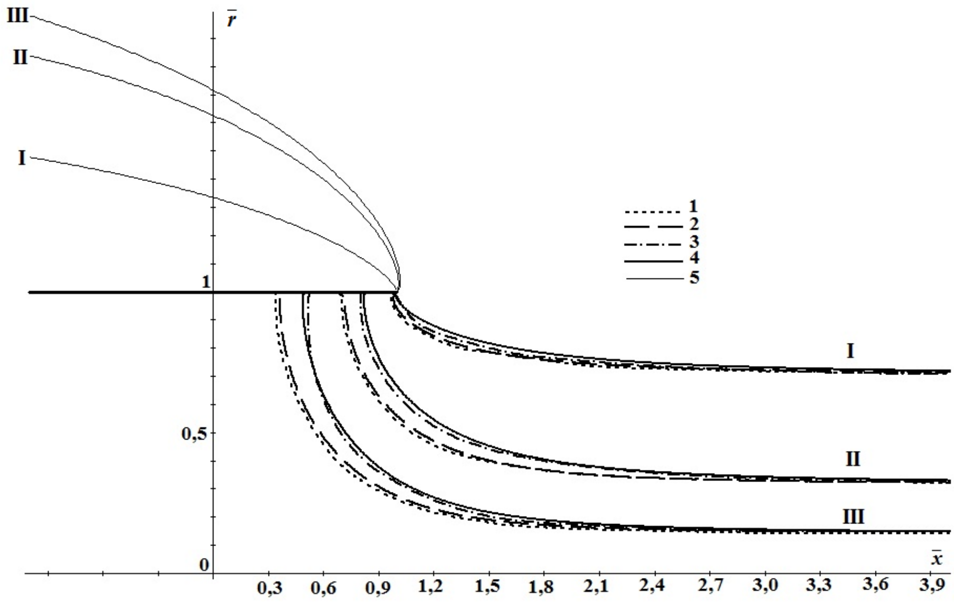


Figure 2: Stagnation and free stream-lines at the entrance to round thin-walled suction duct

The calculations at $\bar{v} = 0,02$ are virtually identical, too (fig.4). A slight deviation is observed at the separation area boundary. In the model of viscous incompressible liquid it shrinks at the removal in the suction duct, unlike the calculations within the framework of this paper.

Fig. 5 shows the flow patterns at the entrance to a slot-like and round suction ducts, constructed within the framework of potential flow model with the use of conformal mapping [9], viscous incompressible liquid with the use of Navier-Stokes equations' numerical solution [9] and the model, presented in this work. The calculations were carried out at various velocities of the approach flow, but not higher than the suction velocity. The stagnation stream-line is shown with a dashed line. Though the flow patterns are similar enough, at the entrance to the a slot-like suction duct the separation area, constructed with conformal mapping method, is narrower than the separation area, constructed with the designed calculation procedure. In the viscous incompressible liquid model the calculated width of separation area is considerably wider, but of the finite length, as compared to calculations within the framework of other models.

Among the aspiration objectives there is studying the dust particle dynamics in the round thin-walled duct's range of action, determining the extreme trajectories of dust particles and the aspiration coefficient.

So, in this work the extreme trajectories of dust particles were constructed, with the use of differential equations system of their movement:

$$\frac{dv_x}{dt} = \frac{u_x - v_x}{\tau}, \frac{dx}{dt} = v_x, \frac{dv_r}{dt} = \frac{u_r - v_r}{\tau}, \frac{dr}{dt} = v_r,$$

where $\tau = 2R \cdot \mathrm{St}/v_\infty$ - relaxation time, St - Stokes number; u_x, u_r - medium velocity components; v_x, v_r - particles velocity components, t – time.

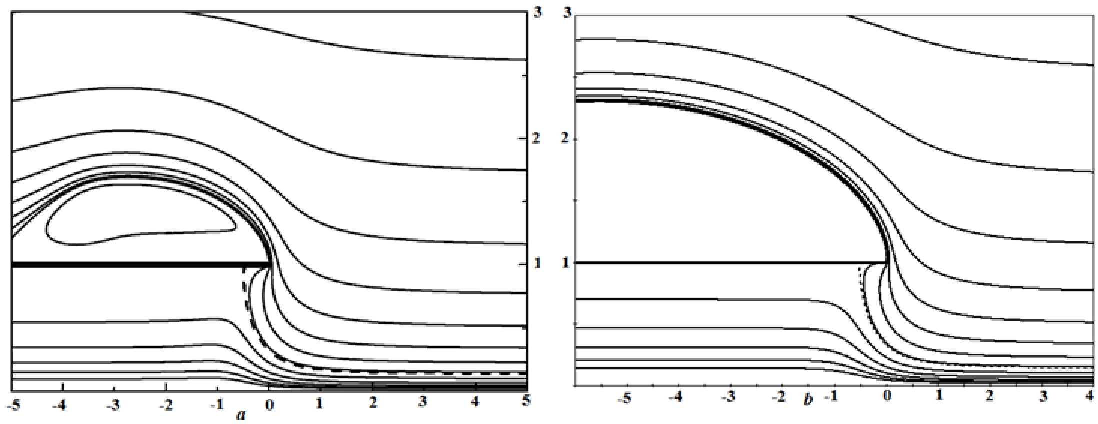


Figure 3: Stream-lines at $\overline{v} = 50$: *a* – calculations in the model of viscous incompressible liquid [4], *b* – calculations according to the designed computational procedure

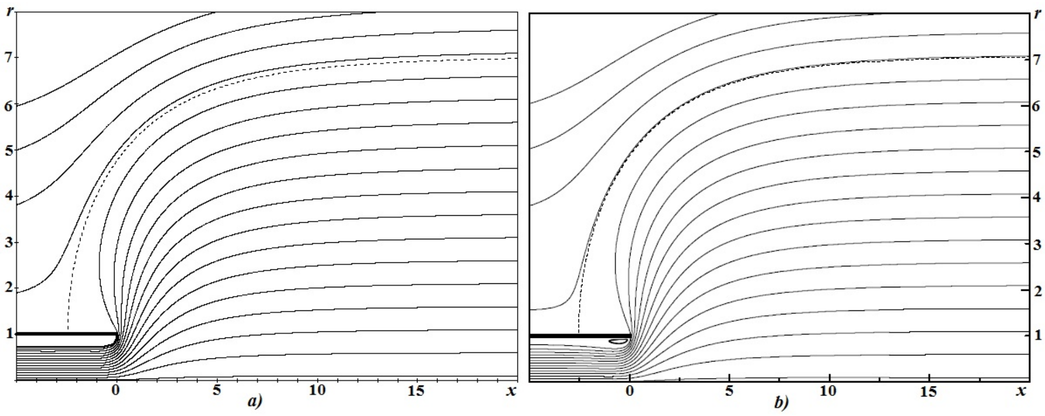


Figure 4: Stream-lines at $\overline{v} = 0.02$: *a* – calculations according to the designed method; *b* – calculations in the model of viscous incompressible liquid [4]

The extreme trajectory was determined by means of bisection method. The Stokes number and the initial position of a dust particle were denoted, the relaxation time was determined. The initial velocities were assumed as equal to the approach flow velocity. To the variable U_l the ordinate of a particle, caught by the pipe, was placed, and in the variable U_p - the ordinate of a deposited particle. In the initial approximation there was set $U_l = R$, $U_p = 40R$. The variable $S_r = (U_p + U_l)/2$. Then a cycle was organized, which performed until the condition $|U_p - U_l| > 0{,}00000001$. In the internal cycle the particles' trajectories were built. At the exit from the internal cycle the particle's getting into the pipe was checked. If yes, then the variable is $U_l = S_r$, otherwise $U_p = S_r$, the particle escape coordinates assumed the value $(100R, Sr)$.

The aspiration coefficient was determined from the formula: $A = (R_c / R)^2 \overline{v}$, where R_c - the initial distance to the symmetry axis of the found extreme trajectory of the dust particle. The withdrawal from the entrance to the suction duct was equal to 100*R*.

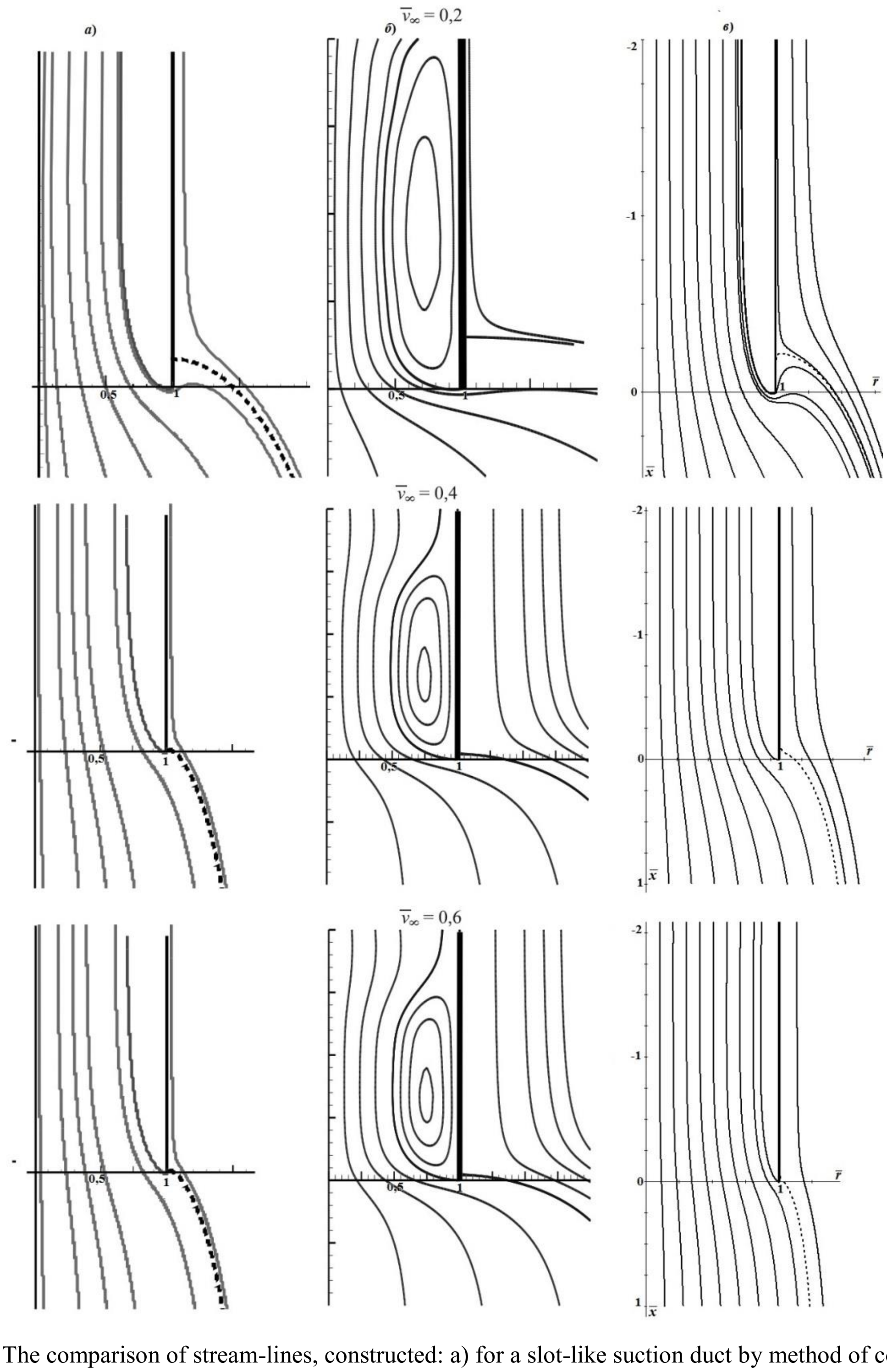


Figure 5: The comparison of stream-lines, constructed: a) for a slot-like suction duct by method of conformal mapping [9]; b) for a slot-like suction duct in the viscous liquid model [9]; в) for a round pipe according to the designed method

The comparison of the aspiration coefficient alteration depending on the dimensionless velocity of the approach flow and various Stokes numbers is presented in Fig.6, where there is a good congruence of calculations with the use of the designed computation procedure and the calculations, performed in [4], in the viscous incompressible liquid model. The maximum difference is observed at St=0,1 and $\bar{v} = 0,02$, but it doesn't exceed 7%.

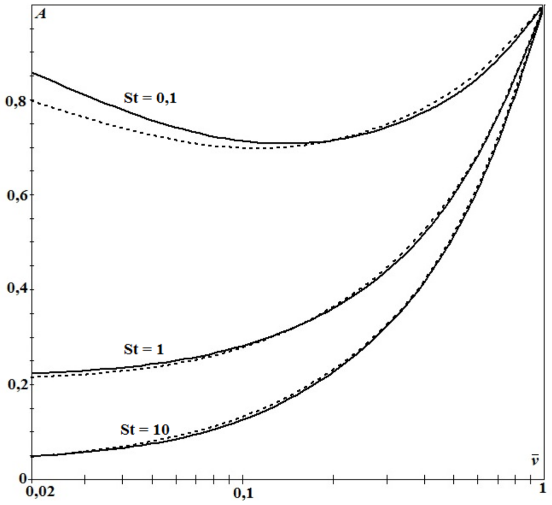
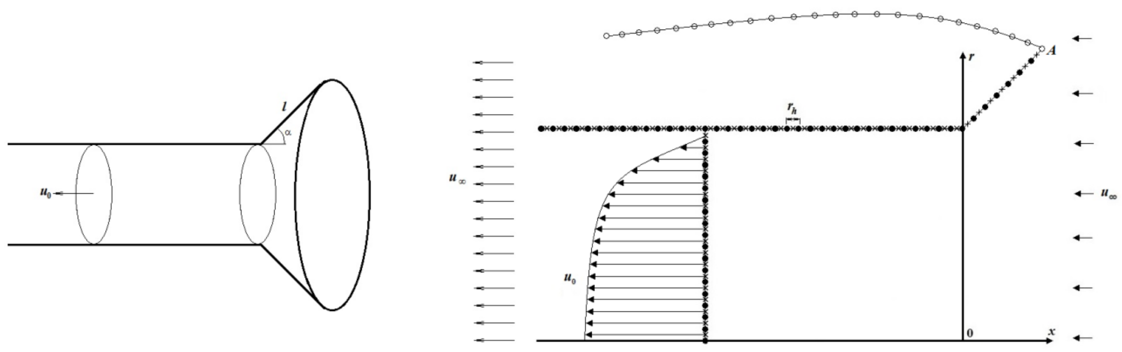


Figure 6: The dependence of aspiration coefficient A on the dimensionless velocity of the approach flow $\bar{v}$

4 THE BELL VENT IN CONDITIONS OF THE APPROACH FLOW

The air flow approaches a bell vent with velocity u_∞ (fig.7 a). In the suction section of the bell there is a parabolic distribution of velocity, which corresponds to the viscous flow in a round duct with the average velocity u_0: $v = 2u_0(1 - r^2 / R^2)$, where R – is the radius of a suction duct. There should be found the regularities of the aspiration coefficient's alteration depending on the slope angle α, the bell length l and the approach flow velocity u_∞- $A = (R_c / R)^2 \bar{v}$, where R_c - the initial distance to the symmetry axis of the found extreme trajectory of the dust particle, $\bar{v} = u_\infty / u_0$. Let us point out, that the gravitation acceleration is directed oppositely to the velocity in the vent u_0, i.e. the bell vent is located vertically, but for the convenience of presentation it is shown in the horizontal position.

The discrete mathematical model (fig.7b) is built in the following way At the flow boundary there are infinitely thin attached vortex rings (black circles in fig.7b) and control points between them (crosses in fig.7b) - on the circle, embracing the pipe, or on the suction section. Let us point out, that in the suction section on the symmetry axis the zero radius vortex is located, so it's not taken into account. The number of discrete vortex rings is equal to the number of control points. In the control points on the pipe walls the impermeability condition is performed – the velocity along the normal direction amounts to zero. In the suction section the velocity along the outward normal direction is similar and amounts to v_0. The division to discrete vortex rings and control points is uniform, the control points are in the centre among the vortex rings. The distance between two neighbouring vortex rings is equal to discrete pitch size r_h. The free stream surface consists of free vortex rings hollow circles in fig.7b) and is formed on the sharp edge A of the bell. It is determined by iterational method, as further described. Parallely to the pipe axis the flow approaches with the velocity v_∞, which can be directed oppositely to the axis Ox, or can coincide with it. It must be pointed out, that the free stream surface can also descend into the bell at the low velocities of the approach flow.



a) b)

Figure 7: The bell vent at the approach flow: a) general flow pattern; b) discrete mathematical model in meridional plane

The dust particles trajectories were built with the use of differential equation of its dynamics:

$$\frac{d\boldsymbol{v}_p}{dt} = \boldsymbol{g} - \frac{\bar{\psi}\chi u_\infty}{2\cdot \mathrm{St}\cdot R}(\boldsymbol{v}_p - \boldsymbol{v}_a), \tag{2}$$

which corresponds to a system of standard differential equations:

$$\frac{dv_{px}}{dt} = -\frac{\bar{\psi}\chi u_\infty}{2\cdot \mathrm{St}\cdot R}\left(v_{px} - v_{ax}\right),\quad \frac{dx}{dt} = v_{px},\quad \frac{dv_{py}}{dt} = -g - \frac{\bar{\psi}\chi u_\infty}{2\cdot \mathrm{St}\cdot R}\left(v_{pr} - v_{ar}\right),\quad \frac{dy}{dt} = v_{pr}, \tag{3}$$

where $\mathrm{Re} = \rho_a\left|\boldsymbol{v}_p - \boldsymbol{v}_a\right| d_e/\mu$, μ – air dynamic viscosity coefficient, $\mathrm{St} = \rho_p d_e^2 u_\infty/(36\mu R)$, $\boldsymbol{v}_a$ – air velocity; ρ_a – air density; $\boldsymbol{v}_p$ – particle velocity; ρ_p – particle density; d_e – equivalent diameter of a particle; $\boldsymbol{g}$ – free fall acceleration; $S_m = \pi d_e^2/4$ – middle section area of a particle; χ – dynamic mode coefficient of a particle;

$$\bar{\psi} = 1,\ \text{if}\ \ \mathrm{Re} < 1;\quad \bar{\psi} = \left(1 + 1/6\cdot \mathrm{Re}^{2/3}\right),\ \text{if}\ \ 1 \le \mathrm{Re} < 10^3;\quad \bar{\psi} = \left(1 + 0{,}065\,\mathrm{Re}^{2/3}\right)^{1.5},\ \text{if}\ \ \mathrm{Re} \ge 10^3.$$

The equation (2) is not dimensionless, but the Stokes criterion is singled out, on the base of which a number of computational experiments will be carried out.

Here are some results of calculating velocity in the vent $u_0 = 1$ m/s and the approach flow velocity $u_\infty = 0{,}6$ m/s. The following parameters were used in the calculations: discrete pitch size $r_h = 0{,}000625$ m; pipe radius $R = 0{,}1$ m; pipe length $20R$; the suction opening is located in the centre of the pipe; stream surface construction pitch 0,0000025m; differential equation integration pitch of dust particle dynamics 0,001 – 0,005; accuracy of free stream surface construction $\varepsilon = 10^{-6}$.

The extreme trajectories of dust particles with numbers $\mathrm{St} = 0,01$ and $\mathrm{St} = 0,001$ almost overlap. The flow breakdown boundary is denoted with a continuous line (fig.8). With the increase of Stokes number St the aspiration area grows. The calculation was carried out at $u_0 = 1$ m/s.

The initial conditions for constructing the dust particles trajectories were set in the following way: $v_{px} = -u_\infty, v_{pr} = 0, x = 30R$. The extreme trajectory was determined with the use of bisection method. The Stokes number and the initial position of a dust particle were denoted, the relaxation time was determined. The initial velocities were assumed as equal to the approach flow velocity. To the variable U_l the ordinate of a particle, caught by the pipe, was placed, and in the variable U_p - the ordinate of a deposited particle. In the initial approximation there was set $U_l = R$, $U_p = 40R$. The variable $S_r = (U_p + U_l)/2$. The initial position of the particle's withdrawal from the axis $r = S_r$. Then a cycle was organized, which performed until the condition $|U_p - U_l| > 0,00000001$. In the internal cycle the particles' trajectories were built. At the exit from the internal cycle the particle's getting into the pipe was checked. If it was caught with a suction opening, then the variable is $U_l = S_r$, otherwise $U_p = S_r$.

In Fig.9 we can see that the extreme trajectories not necessarily finish at the bell boundary. It's explained by the presence of the branch point of dust particles, as shown in Fig.4, where there are presented dust particle's trajectories slightly lower and slightly higher than the extreme trajectory. The extreme trajectories of dust particles constrict to the bell's symmetry axis as compared to Fig.8.

The aspiration coefficient was determined from a formula: $A = (R_c / R)^2 \bar{v}$, where R_c - the initial distance to the symmetry axis of the found extreme trajectory of the dust particle, $\bar{u} = u_\infty / u_0$. The withdrawal from the entrance to the suction duct was equal to 30*R*. The dependence of aspiration coefficient on the length of the bell, located 90 degrees to the vent axis is shown in Fig.11. If the Stokes numbers tend to zero, the aspiration coefficient virtually doesn't change and tends to one at any bell length. Indeed, in the supposition of the uniformity of concentrations and velocities of dust particles in the air flow at the considerable distance from the suction duct, the aspiration coefficient is equal to the ratio of the cross-section area of dust particles extreme trajectories to the cross-section area of the aspirated air stream in the same section. If the Stokes number tends to zero, the extreme trajectories of dust particles coincide with stagnation stream-lines. So, the above mentioned areas coincide. To this case the Stokes number St = 0,001 corresponds. Here there is the right line $A \approx 1$. At the growth of the Stokes number, the aspiration coefficient decreases with the increase of the bell length. At the Stokes number St = 0.2 there is a sharp drop of aspiration coefficient in the range of bell length alteration from 0 to 1 calibre. It's interesting, that all the curves intersect in one point, which corresponds to the bell length equal to 0.5 of the caliber (caliber is the pipe radius *R*).

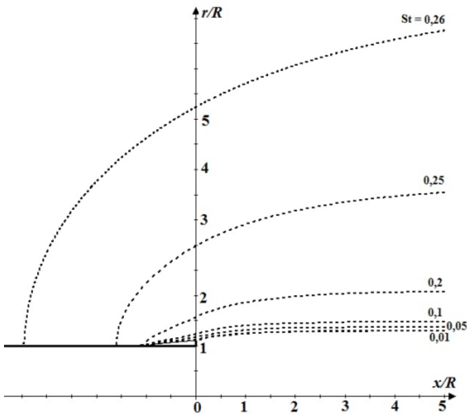


Figure 8: The extreme trajectories of dust particles at: $l/R = 0,1$ $\bar{u} = 0,6$.

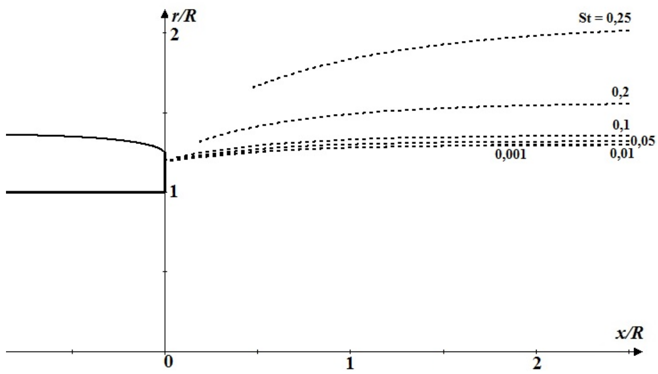


Figure 9: The extreme trajectories of dust particles at $l/R = 0,25$, $\bar{u} = 0,6$

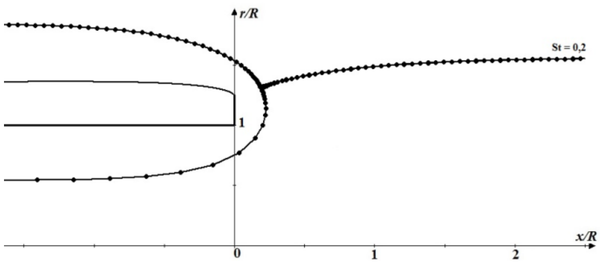


Figure 10: The trajectory of a dust particle at: St = 0.2, $l/R = 0,25$, $\bar{u} = 0,6$

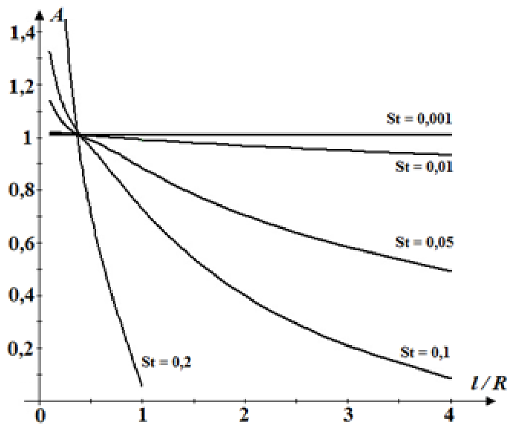


Figure 11: The dependence of aspiration coefficient on the bell length at $\alpha = 90^{\circ}$, $\bar{u} = 0,6$

At the twofold increase of the approach flow velocity the dependence of aspiration coefficient on the dimensionless bell length alters considerably (fig.12). At the Stokes numbers lower than 0.1 the aspiration coefficient tends to one in the whole range of bell length variations. The character of the aspiration coefficient alteration remains the same – it decreases at the bell length increase, but doesn't exceed 1. As the approach flow velocity has increased, it's possible to plot the graphs of the aspiration coefficients alteration at the increase of Stokes numbers to one. In the latter case, it was done in a narrow range of bell lengths alteration.

The determining of regulations in the dependence of aspiration coefficient on the slope angle of the bell to its axis at the fixed bell length is also of interest (fig.13).

As before, at the low Stokes numbers (less than 0.01) the aspiration coefficient tends to one. The graphs of variance are not steady; there is a low at the range of 45-60 degrees.

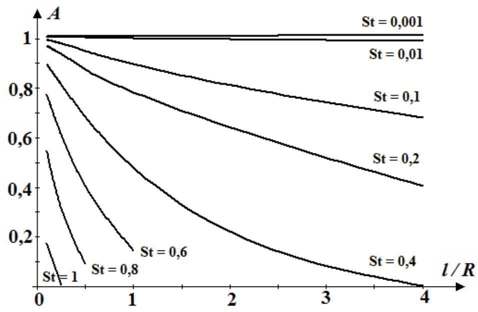


Figure 12: The dependence of aspiration coefficient on the bell length at $\alpha = 90^{\circ}$, $\bar{u} = 1,2$

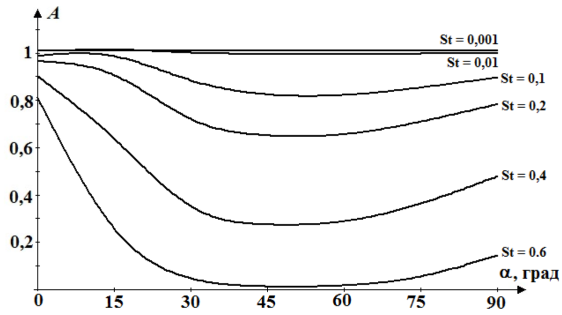


Figure 13: The dependence of aspiration coefficient on the bell length at $l/R = 1$, $\bar{u} = 1,2$ on the slope angle of the bell

CONCLUSIONS

- The developed method of mathematical modeling of the separation flow at the entrance to the suction pipe at the approach flow allows constructing an accurate velocity field of the air flow, extreme trajectories of dust particles and determining the aspiration coefficient.
- The work has been carried out with the financial support of the Grant Council of the President of the Russian Federation (project MD-95.2017.8).

REFERENCES

[1] Logachev, I.N., Logachev, K.I. and Averkova, O.A. *Local Exhaust Ventilation: Aerodynamic Processes and Calculations of Dust Emissions*, CRC Press, (2015).
[2] Gilfanov, A.K., Zaripov, Sh.Kh., and Maklakov, D.V. Calculation of Particle Concentration in the Problem of Aerosol Aspiration into a Thin-Walled Tube. *Fluid Dyn*., (2009) **44 (6)**, 873–881.
[3] O.A. Averkova, I. N. Logachev, K. I. Logachev and A. K. Logachev, The principles of separated flow at the inlet of the protruding duct with screens. *TsAGI Science Journal*, (2013) **44**, 219-243.
[4] Gilfanov, A.K., Zaripov, Sh.Kh. *Mathematical models of aerosols aspiration to thin-walled sample catchers*. Kazan: Kazan University, (2012).
[5] Khodakov, I.V. Modeling of Detached Flow at the Entry Polygonal Suction Hole. *Bulletin of BSTU named after V.G. Shukhov*, (2016) **2**, 11-15.
[6] Khodakov I.V. Numerical and Experimental Research of Detached Flow at the Inlet in the Suction Duct With Mechanical Screens. *Bulletin of BSTU named after V.G. Shukhov*, (2016) **3**, 6-12.
[7] O. A. Averkova, I. N. Logachev, and K. I. Logachev, Modeling of Flow Separation at the Inlet of a Suction Channel in Regions with Cuts, *Vychisl. Metody Programm* (2012) **13**, 298–306
[8] Abramovits, M. And Stigan, I. *Special functions reference book*. M.: Nauka, (1979).
[9] Varsegova, E.N. and Posohin, V.N. A Form of Separated Flow on an Entrance to Suction Slot-Hole Branch Pipe, *News of the Kazan State University of Architecture and Engineering*, (2015) **3**, 98-102.