

Mathematical Numerical and Analytical Solutions to the Problem of Longitudinal Velocity Distribution in a Single Row System of Impact Plane Parallel Jets Flowing on a Plane Surface with Allowance for Losses in Nozzles and Friction

Lobanov Igor Evgenjevich*

Doctor of Technical Sciences, Moscow Aviation Institute, Moscow, Russia

***Corresponding Author:** Lobanov Igor Evgenjevich, Doctor of Technical Sciences, Moscow Aviation Institute, Moscow, Russia.

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Abstract

Analytical and numerical solutions are obtained for the problem of the longitudinal velocity distribution in a single-row system of impacting plane-parallel jets impinging on a flat surface, based on a second-order nonlinear differential equation. The solutions differ from the existing ones by taking into account a larger number of determining factors, take into account the nonlinearity of losses on a flat surface. The available solutions can be characterized as a special case of those obtained in this work. The results can be used to determine the local coefficients of mass transfer and heat transfer.

Key words: *Mathematical; Numerical; Analytical; Method; Speed; Impact; Jet; longitudinal; Single row; System; Plane-parallel; Surface; Flat; Resistance; losses; Nozzle*

Introduction

Jet blowing of surfaces is one of the most effective ways to increase the intensity of heat transfer when air flows around bodies. Under optimal conditions, it provides an increase in the intensity of heat transfer three to five times compared to longitudinal flow. The main advantages of jet blowing in comparison with other methods of intensifying heat transfer in gases: high intensity with relatively low power consumption for its implementation, combined with simplicity and flexibility of process control with the possibility of achieving heat transfer intensification only in certain areas of the surface. These advantages have led to a fairly widespread use in various fields of technology. Subsonic jet blowing of surfaces is used in aviation and rocket and space technology, power

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In power engineering, jet blowing is used in air cooling systems for gas turbine parts: blades, disks. Intensification of drying and heat treatment processes in the production of roll materials by the jet method is one of the main ways increasing the efficiency of their production. The jet supply of the heat carrier in the rolling production is used in installations for heat treatment of steel and non-ferrous sheets. In heat exchangers with impact jet systems, one of the

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heat carriers is supplied to the heat exchange surface in the form of a jet system, and the other side is heated (cooled) by another heat carrier. Local cooling of fuel rods and blocks of electronic equipment is provided by jet systems.

In systems for the protection of aircraft from icing, for cleaning the runways from snow and ice, there are devices for blasting the surface with hot air.

A fairly complete analysis of theoretical and experimental work on fluid dynamics and heat transfer in a jet flow around bodies is given in [1].

The relevance of the study lies in the fact that the intensity of supply and removal of heat from the surface is a factor that to a greater extent determine the efficiency and reliability of machines and devices of modern technology, as well as the productivity of many technological processes and the quality of the final product. This circumstance is especially important in those machines and apparatus in which gaseous heat carriers are used. The most accessible coolant is air, but it is inferior to liquid coolants in terms of the intensity of heat transfer from the surface. Consequently, studies on the intensification of heat transfer processes when air flows around bodies and surfaces are becoming more and more relevant.

In a considerable number of cases in the study for impact jets, empirical dependences are used, obtained on the basis of the method of similarity theory and thermal modeling; therefore, the development of theoretical methods seems to be very important.

In practice, systems of plane-parallel slotted jets are often formed using a nozzle box with a system of flat nozzles (or milled slots) (Figure 1).

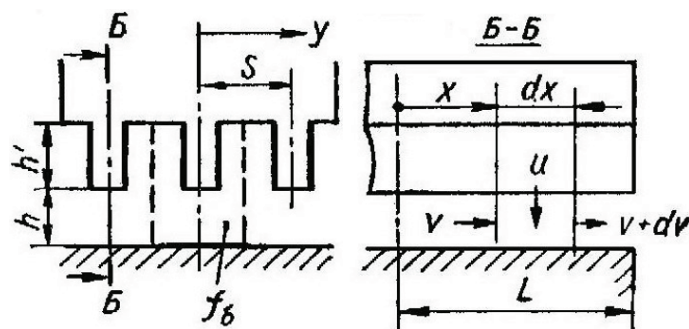


Figure 1: Computational model of a two-row system of impact plane-parallel jets flowing onto a flat surface.

Such a design of the device provides a symmetric outlet to both lateral edges of the heat exchange surface (in the direction) of all the exhaust air from the nozzle, which has the greater effect on the flow field and, consequently, on the heat and mass transfer coefficients, the smaller the ratio of the cross section of the waste flow to the area of the outlet section of the flat nozzle equal to (- the width of the outlet section of a flat nozzle or slot; - the length of the heat exchange surface in the direction of the exhaust air outlet; - the pitch of the jets in the system), which is called the relative cross-sectional area of the exhaust stream. $\frac{xf_b}{bL} = \frac{f_b}{bL}$

The problem of the influence of the processed flow on the heat transfer along the axis when blowing the slotted nozzles is reduced to the following (Figure 1). First, the mass balance is recorded over the elementary volume of a pipeline with a cross section at a constant density of the coolant: $xf_b dx f_b \rho = \text{const}$

$$vf_b + ub dx = (v + dv) f_b = vf_b + f_b dv \dots (1)$$

The dependence of the transverse velocity along the axis obviously follows from expression (1): ux

$$u(x) = \frac{f_b}{b} \frac{dv}{dx} \dots (2)$$

With a continuous supply of air to the pipeline along its entire length the flow is accelerated in the direction, so the velocity at the exit from the channel is equal to: $\frac{dv}{dx} \times f_b$

$$v_2 = \frac{b}{fb} \int_0^L u(x) dx = \frac{bL}{fb} \dots (3)$$

where is the average transverse speed. u_{cp}

The momentum equation for an elementary volume:

$$f_b (p + \rho v^2) = f_b (p + dp + \rho(v + dv)^2) + dF_{Tp} \dots (4)$$

where is the friction force. F_{Tp}

Opening the brackets and dividing both sides of equation (4) by, we determine the pressure gradient: $dx \left(-\frac{dp}{dx} \right)$

$$\left(-\frac{dp}{dx} \right) = \frac{d}{dx} \left(\frac{F_{Tp}}{f_b} \right) + 2\rho v \frac{dv}{dx} \dots (5)$$

It is further postulated that the part of the pressure gradient caused by the friction force F_{mp} , is directly proportional to the square of the local speed of the waste stream:

$$\frac{d}{dx} \left(\frac{F_{tp}}{f_b} \right) = \xi_{tp} \frac{L}{d_r} \frac{\rho v^2}{2} dx, \quad (6)$$

Where is the coefficient of friction resistance; - hydraulic diameter of the through channel. $\xi_{tp} d_r$

Therefore, the pressure gradient is:

$$\left(-\frac{dp}{dx} \right) = 2\rho v \frac{dv}{dx} + \xi_{tp} \frac{L}{d_r} \frac{\rho v^2}{2} \dots \quad (7)$$

Energy balance over the nozzle volume between the cross-section in front of the nozzle in the supply receiver $s dx$ and the outlet section of the nozzle: $b dx$

$$p_p + \frac{\rho u_p^2}{2} = p + \frac{\rho u^2}{2} + \zeta_c \frac{\rho u^2}{2}, \quad (8)$$

Where is the pressure in the receiver; - speed in the receiver; - the value that takes into account the pressure loss in the nozzle (coefficient; high values - for holes with sharp edges, smaller - for holes with abraded edges, zero - for profiled nozzles). $p_p u_p (u_p = u_p) \zeta_c \zeta_c = 0 \div 1,69$

Thus, we have 3 equations - (2), (7), (8) - with three unknowns: $u(x)$, $v(x)$, $p(x)$...

Let us write equation (8) in the following form $\left(\bar{f} = \frac{b}{s} \right)$:

$$p_p - p = \left(1 + \zeta_c - \bar{f}^2 \right) \frac{\rho u^2}{2} \dots \quad (9)$$

Differentiating equation (9) with respect to we get:

$$\left(-\frac{dp}{dx} \right) = \left(1 + \zeta_c - \bar{f}^2 \right) \rho u \frac{du}{dx} \dots \quad (10)$$

Let us rewrite equation (2) in the following form:

$$u(x) = \bar{f}_b \frac{dv}{d\bar{x}}, \quad (11)$$

Where. $\zeta_c = \xi_{mp} \frac{L}{d_r}$, $\bar{x} = \frac{x}{L}$

The left-hand sides of equations (7) and (10) are equal to the pressure gradient, therefore, their right-hand sides can also be equated; after being cut by 2ρ , we get:

$$v \frac{dv}{d\bar{x}} + \frac{\zeta_c}{4} v^2 = \frac{1 - \bar{f}^2 + \zeta_c}{2} u \frac{du}{d\bar{x}} \dots \quad (12)$$

Next, we find the derivative $\frac{du}{d\bar{x}}$ from equation (11), after which

from equation (12) we obtain the basic nonlinear differential equation for the longitudinal velocity: $v(x)$

$$\frac{1 - \bar{f}^2 + \zeta_c}{2} \bar{f}_b^2 \frac{d^2 v}{d\bar{x}^2} \frac{dv}{d\bar{x}} - v \frac{dv}{d\bar{x}} - \frac{\zeta_c}{4} v^2 = 0 \dots \quad (13)$$

In [4], the last basic equation is significantly simplified by accepting that friction is negligible compared to flow acceleration (i.e.) as well. After the introduction of the following designations: $\zeta_c \approx 0$, $f^2 \ll 1$

$$\eta x \stackrel{\text{def}}{=} A \bar{x}, \quad (14)$$

$$\text{where, } A \stackrel{\text{def}}{=} \frac{1}{\bar{f}_b} \sqrt{\frac{2}{\zeta_c + 1}}$$

we obtain the following differential equation for the average longitudinal velocity in the section: v_x

$$v'' = v \dots \quad (15)$$

This circumstance significantly reduces the theoretical value of the obtained solutions of equation (15), especially for the cases of heat exchange surfaces of great length.

The solution to this differential equation (15) for changing the speeds $v_x = f(\eta x)$ and under the system of slotted jets, which can be represented as follows [4]: $u_x = f(\eta x)$

$$\frac{v(x)}{u_{cp}} = \frac{1}{\bar{f}_b} \frac{\text{sh}(A \bar{x})}{\text{sh} A}; \quad (16)$$

$$\frac{u(x)}{u_{cp}} = A \frac{\text{ch}(A \bar{x})}{\text{sh} A} \dots \quad (17)$$

Naturally, total neglect of friction leads to tangible errors, therefore, to take it into account, one has to resort to empirical dependencies (including the same authors [5]) for local coefficients mass transfer, the change of which in the direction corresponds to the velocity distribution [4-5]: $\beta_i \equiv \text{m} \cdot \text{c}^{-1} \cdot \text{xu}(x)$

$$\frac{\beta_i(x)}{\beta_i(L)} = \left[\operatorname{ch} \eta_x + \frac{\left(\frac{\eta_x^3}{6} - \frac{\eta_x^5}{120} \right)}{2A} \zeta_k \right]^{-\frac{2}{3}} \dots \quad (18)$$

Similar solutions can be obtained by researching fluid dynamics of suction collectors [2]. In this case, a more complex differential equation is solved that connects the average longitudinal velocity in the section and the longitudinal coordinate: v_x

$$[\bar{V}_x']^2 - A^2 \bar{V}_x'^2 - [\bar{V}_0']^2 = 0, \quad (19)$$

where is the volumetric flow rate; ; ; ; the index means the outlet section of the channel; ; ; - slot width; - the length of the heat exchange surface in the direction of the exhaust air outlet; - the angle of inclination of the platform to the abscissa axis; - universal characteristics of the collector; - constant coefficient of local resistance of the collector; - consumption coefficient [2].

$$V_x V_x' = \frac{dV_x}{dx} u_x$$

$$= V_x' \left(\frac{\cos \varphi}{\delta} \right) V_0' = \frac{dV_x}{dx} \Big|_{x=0} \bar{V}_x = V_x / V_b \text{ "b" } f_x / f_b \equiv 1$$

$$f = \frac{\delta L}{\cos \varphi} \delta L \varphi \delta \Delta x A = \mu_1 \frac{f_0}{f_b} \sqrt{\zeta_k + 1} \zeta_k \mu_1$$

The solutions of this differential equation lead to the following expressions for the longitudinal and transverse velocities, respectively ($\bar{x} = x/L$) [2]:

$$\bar{v}_x = \frac{v_x}{v_b} = \frac{\operatorname{sh}(A\bar{x})}{\operatorname{sh} A}; \quad (20)$$

$$\bar{u}_x = \frac{u_x}{u_{cp}} = A \frac{\operatorname{ch}(A\bar{x})}{\operatorname{sh} A} \dots \quad (21)$$

More detailed theoretical studies of this problem are given in [3], where modeling of the movement of a coolant with a variable flow rate along the path and for a pipeline of variable cross section is considered, which is beyond the scope of this study.

Differential equation (19) is somewhat more complicated than (15), but simpler than (13), since the term characterizing friction losses is taken constant, and in the main differential equation (13) it is variable and proportional to the square of the speed.

Analytical and numerical solutions of the problem of longitudinal velocity distribution in a single row system of impact plane parallel jets flowing on a plane surface. Analysis of the obtained calculation data

The foregoing stipulates that the basic differential equation (13) has an indisputable advantage over the existing ones (15), (19), since much fewer assumptions were made in its derivation, but it allows one to determine the desired flow rates with a much higher accuracy when taking into account a larger number of determining parameters ...

General a nontrivial formal analytical solution to the Cauchy problem of the main differential equation (13) has the following form:

$$v(x) = e^{\int \left\{ x \ni \left\{ x+2 \int \frac{\bar{f}_b^2 (1-\bar{f}^2 + \zeta_c) x}{\zeta_k - 2 \bar{f}_b^2 (1-\bar{f}^2 + \zeta_c) x^3 + 4x} dx + C_1 = 0 \right\} \right\} dx + C_2} \quad (22)$$

A nontrivial formal analytical solution to the Cauchy problem of the main differential equation (13) has the following form: ($v(0) = v_0$; $v'(0) = v'_0$)

$$v(x) = e^{\int_0^x \left\{ x \ni \left\{ x+2 \int \left(\frac{v'_0}{v_0} \right) \frac{\bar{f}_b^2 (1-\bar{f}^2 + \zeta_c) x}{\zeta_k - 2 \bar{f}_b^2 (1-\bar{f}^2 + \zeta_c) x^3 + 4x} dx = 0 \right\} \right\} dx + \ln v_0} \quad (23)$$

The exact analytical solution of the boundary value problem for the main differential equation (13), as can be seen from (23), cannot be obtained due to significant nonlinearity; therefore, it should be solved by a numerical method.

Solutions (22) and (23) of the basic differential equation (13) are much more complicated than the previously obtained solutions (16) and (20), which indicates the indisputable advantage of the former over the latter.

Numerical solutions of the basic nonlinear differential equation (13) with respect to the longitudinal velocity $v(\bar{x})$ It is most convenient to represent in the form, for which the basic equation should be divided into. Within the framework of this study, numerical calculations with acceptable accuracy were carried out using the Runge – Kutta – Felberg method of 4-5 orders. $v(\bar{x}) v_b^2$

For convenience, we represent the numerical computational solutions of the main differential equation (13) for the Cauchy problem in the following form: we compare them with approximate numerical solutions for: $\bar{v}(0)=0$; $\bar{v}'(0) = 1$

The governing parameters in the main differential equation (13) vary in the following ranges [1-5], values take values from zero for heat exchange surfaces of small length to units or even tens for very long heat exchange surfaces, the length of heat exchange surfaces can be meters or even tens of meters (for formal solutions, solutions are possible for). $\bar{f} = 0 \div 0,212$ $\bar{f}_b = 0,28 \div 3,5$ $\zeta_c = 0 \div 1,69$ $\zeta_k = 10^2 \vee 10^3$

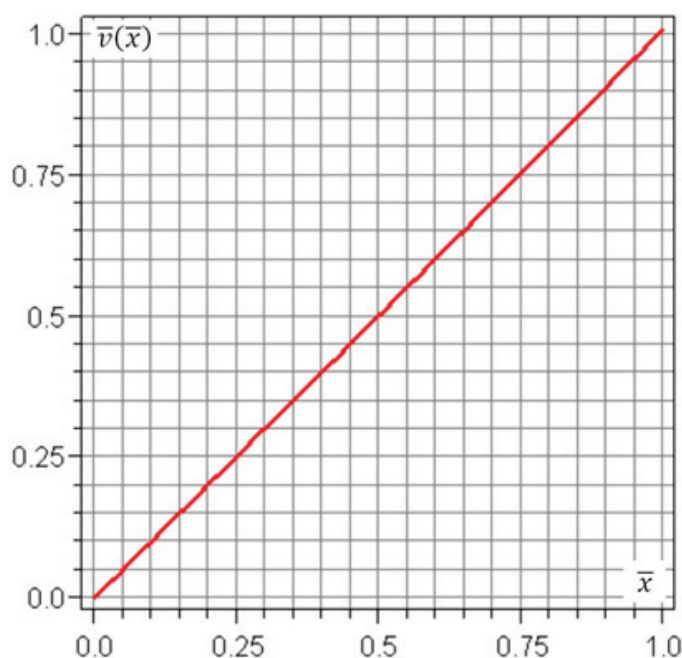
The main interest is the influence on the solution of the basic differential equation (13) of the parameters $\bar{f}$ and ζ_k

The performed numerical calculations showed that for $\zeta_k = 0$ the behavior of the dependence for the above conditions of the Cauchy problem are between a straight line (Figure. 2) at; to a concave curve (Figure. 3) at; ... It should be noted here that. $\bar{v}(\bar{x}) \bar{f} = 0$ $\bar{f}_b = 3,5$ $\zeta_c = 1,69$ $\bar{f} = 0,212$ $\bar{f}_b = 0,28$ $\zeta_c = 0$ $\lim_{\bar{f}_b \rightarrow \infty} \bar{v}(1) = 1$

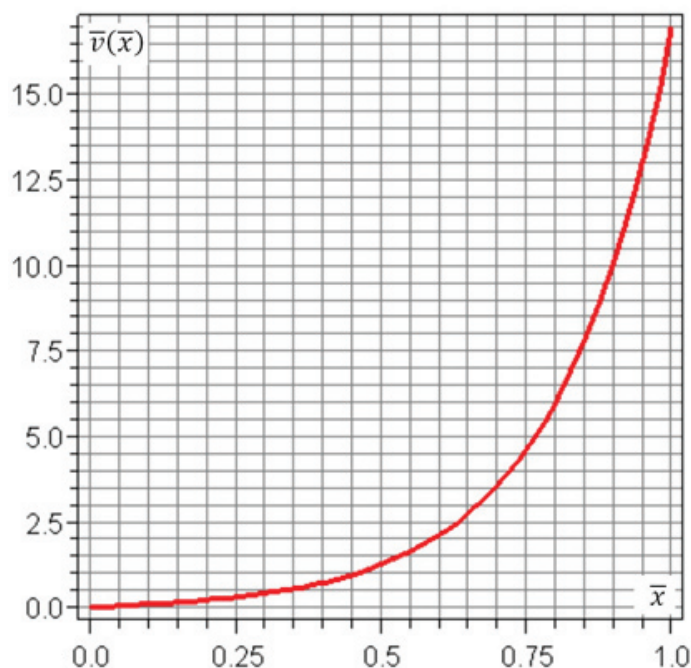
The influence of the parameter, which was neglected when obtaining the existing solutions, on the value is about 5%. $\bar{f} \bar{v}(\bar{x})$

In figure. 4 shows a calculated dependence similar to Figure. 1, but at $\zeta_k=100$, from which it can be seen that the effect of frictional resistance is rather insignificant even with a significant increase in the coefficient of frictional resistance. Similar results are shown in Figure. 5 and 6, but for typical Figures. 3. $\bar{v}(\bar{x}) \zeta_k$ $\bar{f}$, $\bar{f}_b$ ζ_c

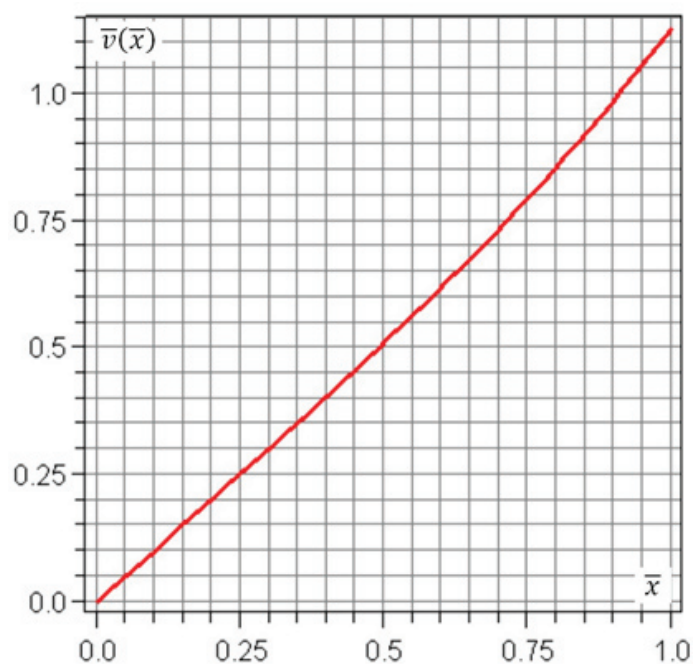
Figure. 3-6 it is clearly seen that neglect or incomplete (approximate) consideration of friction resistance generally leads to significant discrepancies with the exact solution of the basic differential equation (13), which especially affects extended heat exchange surfaces.



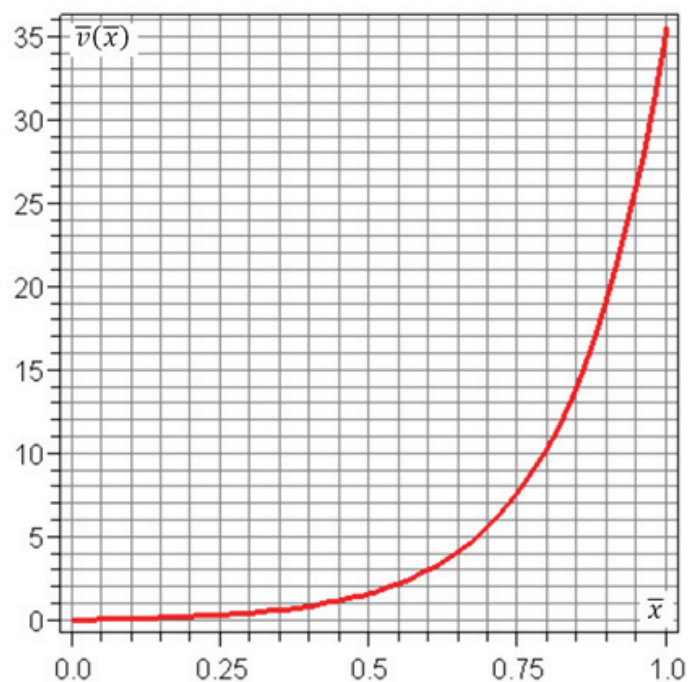
Picture 2: Solution of the Cauchy problem for at for parameters; $\bar{v}(\bar{x}) \bar{v}(0)=0$; $\bar{v}'(0)=1$ $\bar{f}=0$ $\bar{f}_b = 3,5$ $\zeta_c = 1,69$ $\zeta_k = 0$



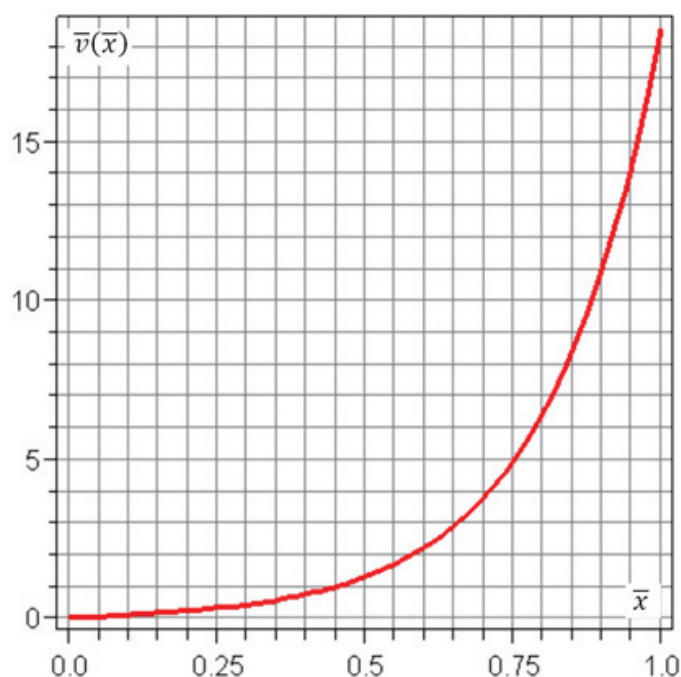
Picture 3: Solution of the Cauchy problem for at for parameters; $\bar{v}(\bar{x}) \bar{v}(0)=0$; $\bar{v}'(0)=1$ $\bar{f}=0,212$ $\bar{f}_b = 0,28$ $\zeta_c = 0$ $\zeta_k = 0$



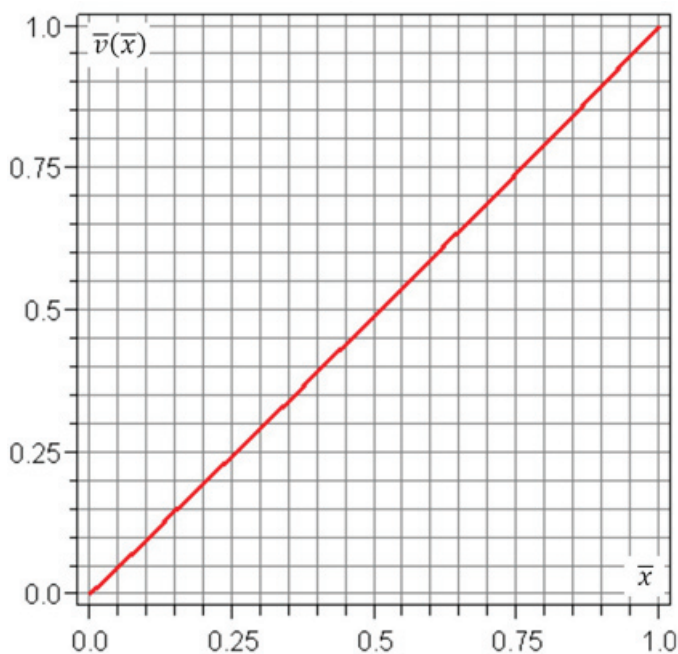
Picture 4: Solution of the Cauchy problem for at for parameters;
 $\dots \bar{v}(\bar{x}) \quad \bar{v}(0)=0; \quad \bar{v}'(0)=1 \quad \bar{f}=0 \quad \bar{f}_b=3,5 \quad \bar{\zeta}_c=1,69 \quad \bar{\zeta}_\kappa=100$



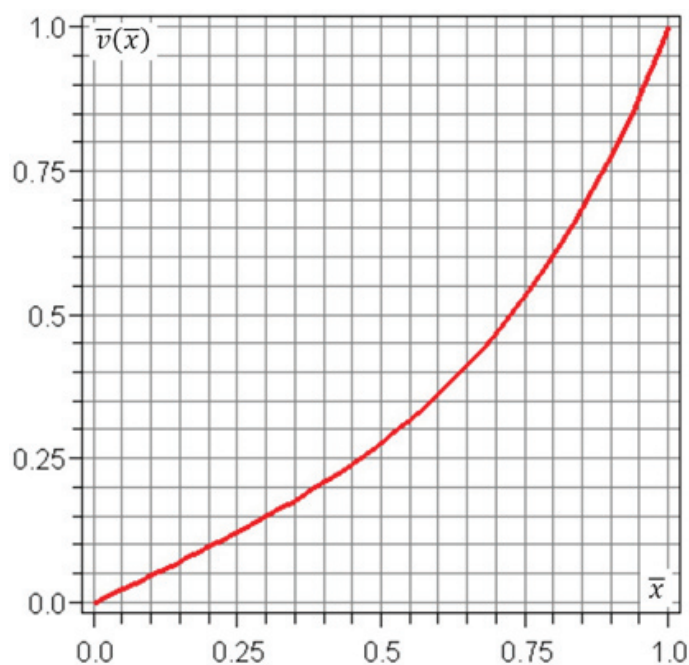
Picture 6: Solution of the Cauchy problem for parameters; $\dots \bar{v}(\bar{x}) \quad \bar{v}(0)=0; \quad \bar{v}'(0)=1 \quad \bar{f}=0,212 \quad \bar{f}_b=0,28 \quad \bar{\zeta}_c=0 \quad \bar{\zeta}_\kappa=10$



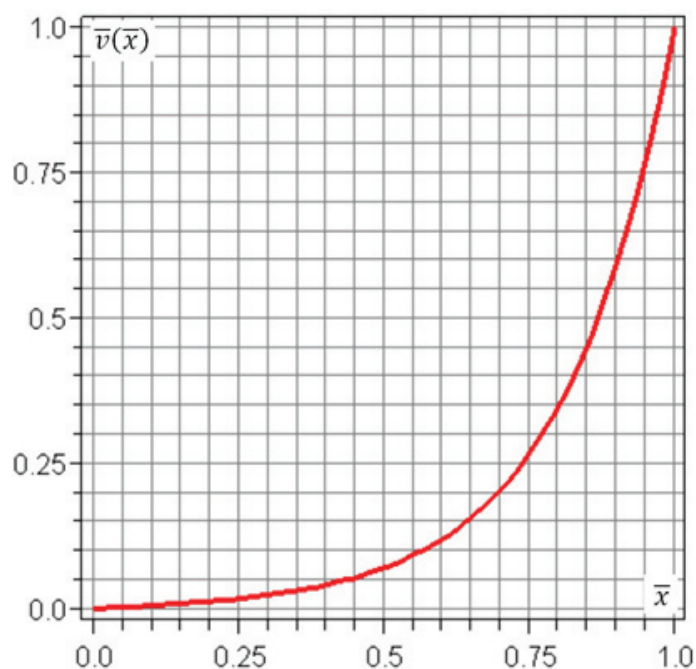
Picture 5: Solution of the Cauchy problem for parameters; $\dots \bar{v}(\bar{x}) \quad \bar{v}(0)=0; \quad \bar{v}'(0)=1 \quad \bar{f}=0,212 \quad \bar{f}_b=0,28 \quad \bar{\zeta}_c=0 \quad \bar{\zeta}_\kappa=1$



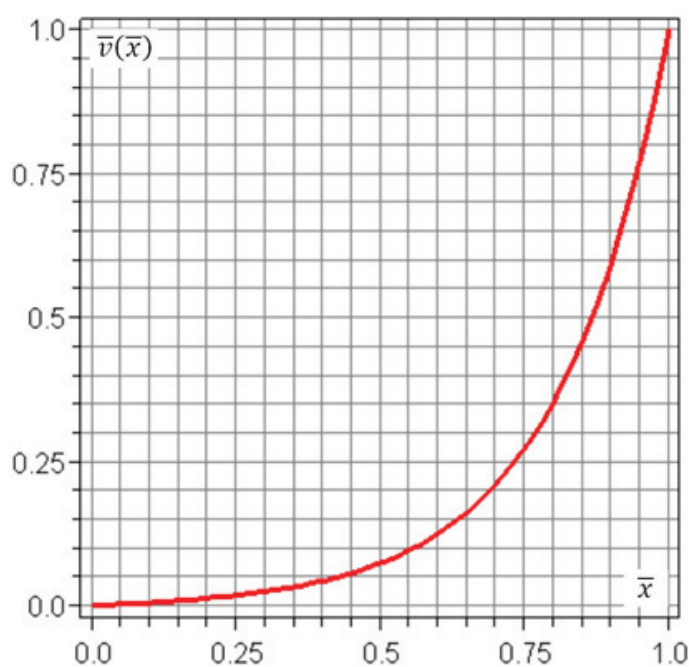
Picture 7: Solution of the boundary value problem for at for parameters; $\dots \bar{v}(\bar{x}) \quad \bar{v}(0)=0; \quad \bar{v}(1)=1 \quad \bar{f}=0 \quad \bar{f}_b=3,5 \quad \bar{\zeta}_c=1,69 \quad \bar{\zeta}_\kappa=0$



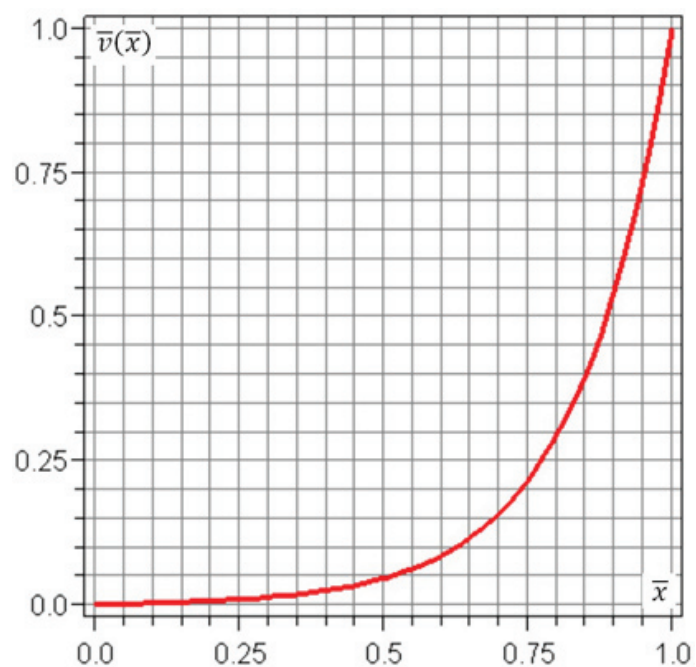
Picture 8: Solution of the boundary value problem for at for parameters; ... $\bar{v}(\bar{x})$ $\bar{v}(0) = 0$; $\bar{v}(1) = 1$ $f = 0$ $f_b = 3,5$ $\zeta_c = 1,69$ $\zeta_k = 1000$



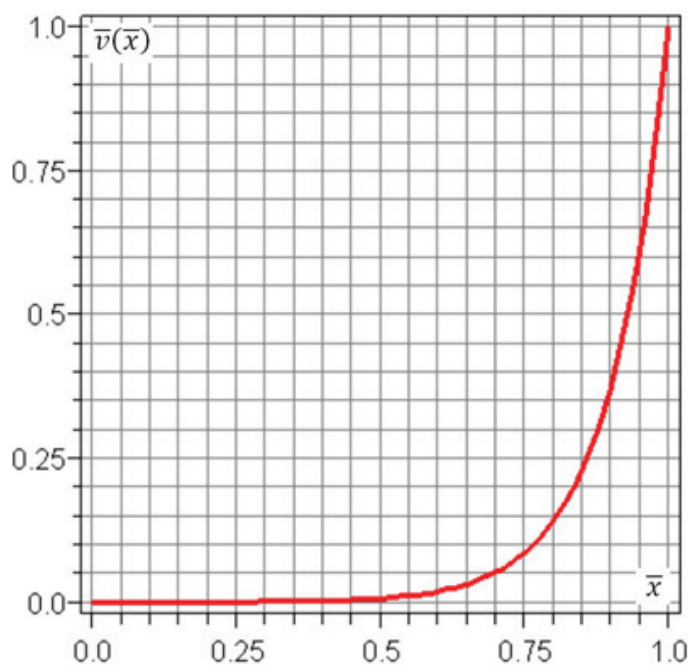
Picture 10: Solution of the boundary value problem for at for parameters; ... $\bar{v}(\bar{x})$ $\bar{v}(0) = 0$; $\bar{v}(1) = 1$ $f = 0,212$ $f_b = 0,28$ $\zeta_c = 0$ $\zeta_k = 1$



Picture 9: Solution of the boundary value problem for at for parameters; ... $\bar{v}(\bar{x})$ $\bar{v}(0) = 0$; $\bar{v}(1) = 1$ $f = 0,212$ $f_b = 0,28$ $\zeta_c = 0$ $\zeta_k = 0$



Picture 11: Solution of the boundary value problem for at for parameters; ... $\bar{v}(\bar{x})$ $\bar{v}(0) = 0$; $\bar{v}(1) = 1$ $f = 0,212$ $f_b = 0,28$ $\zeta_c = 0$ $\zeta_k = 10$



Picture 12: Solution of the boundary value problem for at for parameters; ... $\bar{v}(x)$ $\bar{v}(0) = 0$; $\bar{v}(1) = 1$ $f = 0,212$
 $f_b = 0,28$ $\zeta_c = 0$ $\zeta_k = 100$

After the numerical solution of the basic differential equation (13) for the Cauchy problem, we present the solution of the boundary value problem for this differential equation: $\bar{v}(0) = 0$; $\bar{v}(1) = 1$

For conditions similar to Figure. 2, when the solution for is a straight line (Figure 7). $\zeta_k = 0$ $\bar{v}(x)$

Deviations from straightness practically do not occur even with an increase from zero, not only to tens, but also to almost a hundred. A visible deviation from linearity occurs only if it becomes about 1000 (Figure. 8). ζ_k $\bar{v}(x)$ ζ_k

Therefore, for practical ranges of friction resistance coefficients at; the velocity profile practically does not differ from the linear one. $f = 0$ $f_b = 3,5$ $\zeta_c = 1,69$ $\bar{v}(x)$

Now we should turn to the solution of the above boundary value problem for the main differential equation (13) for conditions similar to Figure. 3. At, the solution for is a line whose growth is steadily increasing from zero to one (Figure. 9), which sharply differs from a straight line (compare with Figure. 7). $\zeta_k = 0$ $\bar{v}(x)$

With an increase in the drag coefficient, an increase in the velocity profile closer to zero decreases, and closer to unity, it increases, which is clearly seen in Figure. 10-12 respectively for: $\bar{v}(x)$ $\zeta_k = 1, 10, 100$

The latter indicates that at; the influence of the friction drag coefficient in the practical range of its variation on the velocity profile can be quite noticeable. $f = 0$ $f_b = 3,5$ $\zeta_c = 1,69$ $\bar{v}(x)$

Summarizing, we can say that the above results cover the solutions of the basic differential equation (13) for all practically used cases in a single-row system of impact plane-parallel jets flowing onto a flat surface [1-5] for the cases of the Cauchy problem and the boundary value problem, which made it possible to obtain solutions for longitudinal velocity distribution with lower $V(X)$ number of assumptions and get more accurate solutions than existing ones.

Main Conclusions

1. In the study, numerical solutions of a nonlinear differential equation were obtained for the distribution of longitudinal velocity in a single row system of impact plane-parallel jets impinging on a flat surface in a range of determining parameters of practical interest, more accurate than similar existing determinative equations.
2. The solutions obtained in the study made it possible to more accurately take into account the influence on the distribution of the longitudinal velocity of the parameters and in the entire range of determining parameters of practical interest. $\bar{v}(x)$ f ζ_k
3. The solutions obtained in the work showed that the influence on the distribution of the longitudinal velocity of the ratio of the width of the outlet section of the flat nozzle to the pitch of the jets in the system is no more than 5%. $\bar{v}(x)$ $f = b/s$
4. It has been proven that the influence of the friction resistance coefficient on the longitudinal velocity distribution can be very significant, especially for extended heat exchange surfaces. $V(X)$
5. The solutions obtained can be used to more accurately determine the heat transfer and mass transfer coefficients in a single-row system of impacting plane-parallel jets flowing onto a flat surface.

6. The developed theory and the obtained analytical and numerical solutions of the problem of the distribution of the longitudinal velocity in a single-row system of impacting plane-parallel jets impinging on a flat surface, based on a nonlinear differential equation of the second order, have been repeatedly tested at scientific conferences [6-9].

Main Conclusions

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