Vietnam Journal of Mechanics, NCST of Vietnam Vol. **22**, 2000, No 1 (29 - 38)

NUMERICAL AND EXPERIMENTAL MODELING OF INTERACTION BETWEEN A TURBULENT JET FLOW AND AN INLET

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ABSTRACT. In ventilation devices to get rid of harmful substances out of working places, we use sucking devices. The local sources of pollution are evacuated by them. A basic element when creating the model of sucking device is: the source of harmful substances is discussed as a rising convective flow, which is ejected out of sucking spectrum, created by a sucking apparatus. In the present work, the flow is a whole one with variable quantity of motion and kinetic energy along it's length. The change in those two parameters is caused by and is in dependent function of the inlet spectrum. There has been discussed a two-component flow of air and gas in ventilation devices. A two-velocity scheme of flow is used to realise the numerical method. An integral method of investigation is used, based on the conditions of conservation of mass contents, quantity of motion and kinetic energy. It's been accepted that quantity of motion and energy change in function of inlet action. A comparison of numerical results and natural experiment are made for two conditions: full suck and not full suck. Conclusion is that the present model is precise and can be unset for engineering calculations.

Notation

Q_c - capacity in initial section

Q_i - capacity in inlet

L - distance between outgoing section of jet and inlet

r_0 - initial radius of jet

r_i - initial radius of inlet

u_g - velocity of air (carrier phase)

u_{po} - initial velocity of admixture

u_{go} - initial velocity of air

R_u - dynamic boundary layer

R_p - diffusion boundary layer

ρ_p - density of admixture

u_p - velocity of admixture (smoke)

u_{gn} - maximum velocity of air

u_{pm} - maximum velocity of admixture

Re_p - Reynold's number

χ - concentration of admixture

χ_0 - initial concentration of admixture

F_x - inter-phase forces

ν_{tp} - turbulent viscosity of admixture

ν_{tg} - turbulent viscosity of air

Sc_t - schmidt's turbulent number

S_{ij} - complexes of constants

ρ_g - density of air (carrier phase)

ρ_{po} - initial density of admixture

ρ_{go} - initial density of air

G - Specific weight	G_1 - initial specific weight
I - quantity of motion	I_1 - initial quantity of motion
E - flow energy	E_1 - initial flow energy
	A_{ij} - values of integrals

1. Introduction

The applications of some methods of calculating such devices are given in [1] and others. Some well-known works about this problem [1, 2, 3] etc., when developing a numerical model of the flow, discuss it often by method summing up the flows (superposition). Allthrough the last given satisfying results, by a theoretical point of view it's not very precise. It has been presumed summing up a real turbulent jet flow to a potential one, created by an inlet (Sucking) Spectrum. in order to avoid this moment, in the present work, the flow is a whole one with variable quantity of motion and kinetic energy along its length. The change in those two parameters is caused by and is in dependent function of the inlet spectrum. This shown in experimental studies [4, 5, 8]. In the present model, the unreliable summing up of the flows is avoided and has given a solution of complex interaction of jet and inlet spectrum, using the usual methods in the dynamics of real fluids.

2. Basic of the numerical model

There has been discussed a two-component flow of air-smoke gases. To realise the numerical model a two-velocity scheme of the flow is used and it has been accepted that velocities of two components do not coincide [6, 7].

The system equation of motion for axis-symmetrical two-phase turbulent jets can be received by development of theory of turbulent jet of Abramovich and in cartesian-coordinate has a form:

$$\frac{\partial u_g}{\partial x} + \frac{1}{y}\frac{\partial(\nu_g y)}{\partial y} = 0, \tag{2.1}$$

$$\frac{\partial u_p}{\partial x} + \frac{1}{y}\frac{\partial(\nu_p y)}{\partial y} = 0, \tag{2.2}$$

$$u_g\frac{\partial u_g}{\partial x} + \nu_g\frac{\partial u_g}{\partial y} = -\frac{1}{\rho_g}\frac{\partial}{\partial y}\left(y\rho_g\overline{u'_g\nu'_g}\right) - \frac{\overline{u'_g\nu'_g}}{y} - \frac{F_x}{\rho_g}, \tag{2.3}$$

$$u_p\frac{\partial u_p}{\partial x} + \nu_p\frac{\partial u_p}{\partial y} = -\frac{1}{\rho_p}\frac{\partial}{\partial y}\left(y\rho_p\overline{u'_p\nu'_p}\right) - \frac{\overline{u'_p\nu'_p}}{y} + \frac{\overline{\nu'_p\chi'}}{\rho_p} + \frac{F_x}{\rho_p}, \tag{2.4}$$

$$u_p\frac{\partial \chi}{\partial x} + \nu_p\frac{\partial \chi}{\partial y} = -\frac{1}{\rho_g}\frac{\partial}{\partial y}\left(\rho_g\overline{\nu'_p\chi'}\right) - \frac{\overline{\nu'_p\chi'}}{y}, \tag{2.5}$$

where $\chi = \frac{\rho_p}{\rho_g}$, F_x - inter-phase forces [9]:

$$F_x = k_x \rho_p (u_g - u_p)^2.$$

The coefficient k_x is contrary to [10], that's function of Reynold's number, formed by experimental formula as follows:

$$k_x = B(1 + b_1 Re_p^{0.5} + b_2 Re_p)$$

where $B = 0.01 \div 0.03$; $b_1 = 0.179$; $b_2 = 0.013$; $Re_p = \frac{(u_g - u_p) D_p}{\nu_p}$.
It's necessary to give the boundary conditions ($y = 0$; $y = R_u$), when solving over system of equations.

In the equations of movement, the double correlation of velocity, concentration $\overline{u'_g \nu'_g}$, $\overline{u'_p \nu'_p}$, $\overline{\nu'_p \chi'}$, we can define these correlations, using turbulent viscosity and the field of mean parameters:

$$\overline{u'_g \nu'_g} = -\nu_{tg} \frac{\partial u_g}{\partial y}; \quad \overline{u'_p \nu'_p} = -\nu_{tp} \frac{\partial u_p}{\partial y}; \quad \overline{\nu'_p \chi'} = -\frac{\nu_{tp}}{Sc_t} \frac{\partial \chi}{\partial y}.$$

An integral method of investigation is used, based on the conditions of conservation of mass contents, for total quantity of motion, for kinetic energy of two-phases, conditions from higher rank of concentration and additional relations between parameters. It has been accepted that quantity of motion and energy change in function of inlet action [8].

The numerical model is developed on the basis of following integral conditions [5]:

$$\int_0^\infty \rho_g u_p y dy = G_1, \tag{2.6}$$

$$\int_0^\infty \rho_g u_g^2 y dy + \int_0^\infty \rho_p u_p^2 y dy = I(x), \tag{2.7}$$

$$\frac{\partial}{\partial x} \int_0^\infty \rho_g u_g^3 y dy = -2 \int_0^\infty \rho_g \nu_{tg} \left(\frac{\partial u_g}{\partial y}\right)^2 y dy - 2 \int_0^\infty u_g F_x y dy + E(x), \tag{2.8}$$

$$\frac{\partial}{\partial x} \int_0^\infty \rho_p u_p^3 y dy = -2 \int_0^\infty \rho_p \nu_{tp} \left(\frac{\partial u_p}{\partial y}\right)^2 y dy + 2 \int_0^\infty u_p F_x y dy + E(x), \tag{2.9}$$

$$\frac{\partial}{\partial x}\int_0^\infty u_p\chi^2 y dy = -2\int_0^\infty \rho_g u_g \frac{\nu_{tp}}{Sc_t}\left(\frac{\partial \chi}{\partial y}\right) y dy, \tag{2.10}$$

$$R_u = Sc_t R_p. \tag{2.11}$$

In our equations above a model of turbulence analogies to schetz's model is suggested [7] as follow:

$$\nu_{tg} = k_x R_u u_{gm},$$
$$\nu_{tp} = k_x R_u u_{pm}.$$

On the right side of equations (2.7), (2.8) and (2.9) standing the quantity of motion and flow energy are variables along the stream. According to experimental studies [4], [5], [8]. They can be presented in the following:

$$I(x) = I_1(1 + k_1\overline{x}^n), \tag{2.12}$$
$$E(x) = E_1(1 + k_2\overline{x}^n). \tag{2.13}$$

The equations (2.12), (2.13) are numerically investigated when inputting suitable for the solution values of k_1, k_2, n and m for the corresponding regime [4], [5].

Using equation (2.11) we get the connection between diffusion boundary layer R_p, dynamic boundary layer R_u and Schmidt's turbulent number Sc_t

$$Sc_t = Sc_g\big(1 + \sqrt{1 + \xi_0}\big)$$

$Sc_g = 0.75$ (in the investigation of Abramovich), ξ_0 is an adjusted initial particle concentration which is expressed by the following ratio:

$$\xi_0 = \frac{\chi_0}{1 + \chi_0}.$$

In the system of equation (2.6) $\div$ (2.10) the marked integrals are done using the similarity of cross velocity and concentration distribution of the kind:

$$\frac{u_g}{u_{gm}} = \frac{u_p}{u_{pm}} = \exp(-K_u\eta^2),$$
$$\frac{\chi}{\chi_m} = \exp(-K_\chi\eta^2),$$

where $\eta = \dfrac{y}{x}$, $K_u = 92$ [6], $K_\chi = Sc_t K_u$.

Having done the integrals after some revision and normalization, we obtain the following system of algebraical-differential equations:

$$A_{11}\chi_m\overline{u}_{pm}\overline{x}^2 = G_1, \tag{2.14}$$

$$A_{21}\overline{u}_{gm}^2\overline{x}^2 + A_{22}\chi_m\overline{u}_{pm}^2\overline{x}^2 = I_1(1+k_1\overline{x}^n), \tag{2.15}$$

$$\frac{\partial}{\partial x}\left[A_{31}\overline{u}_{gm}^3\overline{x}^2\right] = -A_{32}\overline{u}_{gm}^3\overline{R}_u - A_{33}\overline{u}_{gm}\left(\overline{u}_{gm}-\overline{u}_{pm}\right)^2\overline{x}^2 + E_1(1+k_2\overline{x}^m), \tag{2.16}$$

$$\frac{\partial}{\partial x}\left[A_{41}\chi_m\overline{u}_{gm}^3\overline{x}^2\right] = -A_{42}\chi_m\overline{u}_{pm}^3\overline{R}_u + A_{43}\overline{u}_{pm}\left(\overline{u}_{gm}-\overline{u}_{pm}\right)^2\overline{x}^2 + E_1(1+k_2\overline{x}^m), \tag{2.17}$$

$$\frac{\partial}{\partial x}\left[A_{51}\chi_m^2\overline{u}_{pm}\overline{x}^2\right] = -A_{52}\chi_m^2\overline{u}_{pm}\overline{R}_u, \tag{2.18}$$

where

$$\overline{x} = \frac{x}{y}, \quad \overline{u}_{pm} = \frac{u_{pm}}{u_{go}}, \quad \overline{u}_{gm} = \frac{u_{gm}}{u_{go}}, \quad \overline{R}_u = \frac{R_u}{y}, \quad \overline{R}_p = \frac{R_p}{y}.$$

In which the values of A_{ij} integrals given in Table 1. Normalisation is done with the initial parameters of the flow. The system of equations (2.14) ÷ (2.18) is solved numerically using a suitable algorithm. The joint solution of (2.14) ÷ (2.18) comes to an equation regarding u_{gm} of the kind:

$$S_{38}\overline{u}_{gm}^9 + S_{37}\overline{u}_{gm}^8 + S_{36}\overline{u}_{gm}^7 + S_{35}\overline{u}_{gm}^6 + S_{34}\overline{u}_{gm}^5 + S_{33}\overline{u}_{gm}^4 + S_{32}\overline{u}_{gm}^3 + S_{31}\overline{u}_{gm}^2 + S_{30}\overline{u}_{gm} + S_{29} = 0, \tag{2.19}$$

where S_{ij} is complex of constants, which given in Table 2.

Table 1

A_{11}	$\int_0^\infty \left(\frac{\chi}{\chi_m}\right)\left(\frac{u_p}{u_{pm}}\right)\eta d\eta$	$\frac{1}{2(K_\chi+K_u)}$
A_{21}	$\int_0^\infty \left(\frac{u_g}{u_{gm}}\right)^2\eta d\eta$	$\frac{1}{4K_u}$
A_{22}	$\int_0^\infty \left(\frac{\chi}{\chi_m}\right)\left(\frac{u_p}{u_{pm}}\right)^2\eta d\eta$	$\frac{1}{2(K_\chi+2K_u)}$
A_{31}	$\int_0^\infty \left(\frac{u_g}{u_{gm}}\right)^3\eta d\eta$	$\frac{1}{6K_u}$

A_{32}	$2K_x \int_0^\infty \left[\frac{\partial}{\partial\eta}\left(\frac{u_g}{u_{gm}}\right)\right]^2 \eta d\eta$	K_χ
A_{33}	$2K_x \int_0^\infty \left(\frac{u_g}{u_{gm}}\right)^2 \eta d\eta$	$\frac{K_\chi}{2K_u}$
A_{41}	$\int_0^\infty \left(\frac{\chi}{\chi_m}\right)\left(\frac{u_p}{u_{pm}}\right)^2 \eta d\eta$	$\frac{1}{2(K_\chi + 3K_u)}$
A_{42}	$2K_x \int_0^\infty \left(\frac{\chi}{\chi_m}\right)\left[\frac{\partial}{\partial\eta}\left(\frac{u_g}{u_{gm}}\right)\right]^2 \eta d\eta$	$\frac{4K_\chi K_u^2}{(K_\chi + 2K_u)^2}$
A_{43}	$2K_x \int_0^\infty \left(\frac{u_p}{u_{pm}}\right)^2 \eta d\eta$	$\frac{K_\chi}{3K_u}$
A_{51}	$\int_0^\infty \left(\frac{\chi}{\chi_m}\right)^2\left(\frac{u_p}{u_{pm}}\right) \eta d\eta$	$\frac{1}{2(2K_\chi + K_u)}$
A_{52}	$\frac{2K_x}{Sc_t} \int_0^\infty \left[\frac{\partial}{\partial\eta}\left(\frac{\chi}{\chi_m}\right)\right]^2 \eta d\eta$	$\frac{K_\chi}{Sc_t}$

Table 2

$S_1 = I_1(1 + k_1 x^n)$	$S_2 = E_1(1 + k_2 x^m)$
$S_3 = \frac{S_1 A_{11}}{G_1 A_{22}}$	$S_4 = \frac{A_{21} A_{11} x^2}{G_1 A_{22}}$
$S_5 = \frac{4A_{41} A_{51} x}{2A_{41} A_{52} + A_{42} A_{51}}$	$S_6 = \frac{A_{11} A_{43} A_{51} x^2}{G_1(2A_{41} A_{52} + A_{42} A_{51})}$
$S_7 = \frac{S_2 A_{11} A_{51} x^2}{G_1(2A_{41} A_{52} + A_{42} A_{51})}$	$S_8 = \frac{n I_1 k_1 x^{n-3}}{2A_{21}}$
$S_9 = -\frac{G_1 A_{22} A_{52}}{2A_{11} A_{21} A_{51} x^4}$	$S_{10} = \frac{2A_{22} G_1}{A_{11} A_{21} x^3}$

$$S_{11} = (A_{33}x - A_{31})x \qquad S_{12} = 3A_{31}S_8x^2$$

$$S_{13} = x^2A_{31}(S_5S_9 + S_{10}) \qquad S_{14} = 3A_{31}S_7S_9x^2$$

$$S_{15} = 3A_{31}S_6S_9x^2 + S_{11} + A_{32}S_5 \qquad S_{16} = -x^2(6A_{31}S_6S_9 + 2A_{33})$$

$$S_{17} = x^2(3A_{31}S_6S_9 + A_{33}) \qquad S_{18} = A_{32}S_7$$

$$S_{19} = A_{32}S_6 \qquad S_{20} = -2A_{32}S_6$$

$$S_{21} = A_{32}S_6 \qquad S_{22} = 2S_3^3S_4(1 + S_4)$$

$$S_{23} = 2S_3S_4S_{12} + S_3^2S_{15} + S_4S_{14} + S_{18} \qquad S_{24} = S_4^2S_{12} + 2S_3S_4S_{15} + S_3S_{19}$$

$$S_{25} = S_4(S_4S_{15} + S_{19}) \qquad S_{26} = S_3^2S_{20} - S_2S_4^2$$

$$S_{27} = x^2S_4(S_5 + x^2 - x - 1)k \qquad S_{28} = I_1(k_1x^n)\frac{A_{11}}{A_{22}G_1}$$

$$S_{29} = -S_2S_3^2 \qquad S_{30} = S_3^4S_{17} + S_3^2S_{13} + S_3^2S_{12}$$

$$S_{31} = S_3^2S_{16} - 2S_2S_3S_4 \qquad S_{32} = S_{17}S_{22} + S_3^2S_{21} + 3S_3^2S_4S_{13} + S_{23}$$

$$S_{33} = 3S_3^2S_4S_{16} + S_{26} \qquad S_{34} = 6S_3^2S_4^2S_{17} + 3S_3^2S_4S_{21} + 3S_3S_4^2S_{13} + S_{24}$$

$$S_{35} = S_3(3S_4^2 + 2S_4S_{20}) \qquad S_{36} = 4S_3S_4^3S_{17} + 3S_3S_4^2S_{21} + S_4^3S_{13} + S_{25}$$

$$S_{37} = S_4^3S_{16} + S_4^2S_{20} \qquad S_{38} = S_4^4S_{17} + S_4^3S_{21}$$

3. Results

Equation (2.19) is solved by the method of Newton. The determined u_{ij} is replaced consecutively in the rest equations and demanded quantities are given. With the initial conditions of flow: The initial concentration and velocities components, specific weight, quantity of motion and flow energy are used as input data:

$$X = 0,\ u_g = u_{go},\ u_p = u_{po},\ \chi = \chi_0,\ G = G_1,\ I = I_1,\ E = E_1$$
$$X = L,\ I = I_1(1 + k_1\overline{x}^n),\ E = E_1(1 + k_2\overline{x}^m).$$

The distance between outgoing section of jet and inlet is $\overline{L} = \dfrac{L}{r_0} = 20$ and the relation of capacities in initial section and in the inlet is:

$$\overline{Q}_c = \frac{Q_c}{Q_i}$$

where

$$Q_c = 2\pi \int_0^{r_0} u_p r dr, \qquad Q_i = 2\pi \int_0^{r_i} u_p r dr$$

with two cases: A case with full such ($\overline{Q}_c = 3.8$) and a case with not full such ($\overline{Q}_c = 1.6$), where I_1, E_1, k_1, n, k_2 and m are followed [4], [8].

$\overline{L}$	$\overline{Q}_c$	I_1	E_1	k_1	n	k_2	m
20	1.6	0.4447	0.4019	$6 \cdot 10^{-9}$	7.3300	$1.09 \cdot 10^{-13}$	11.4319
20	3.8	0.3113	0.2010	$9.11 \cdot 10^{-13}$	10.7720	$8.275 \cdot 10^{-19}$	16.0380

The following integral parameters of jet are results of solution: the change of maximum velocities components (u_{pm}, u_{gm}), concentration (χ) and borderlines of diffusion R_p and dynamic R_u jet boundary layers. Results of calculation about two conditions-full suck and not full suck given on Fig. 1 and Fig. 2, where there is comparison with experimental data [4]. In the experimental the second component as an admixture is a smoke gas. To determine the diffusion border of flow. We can make a comparison of numerical results and experimental results R_p.

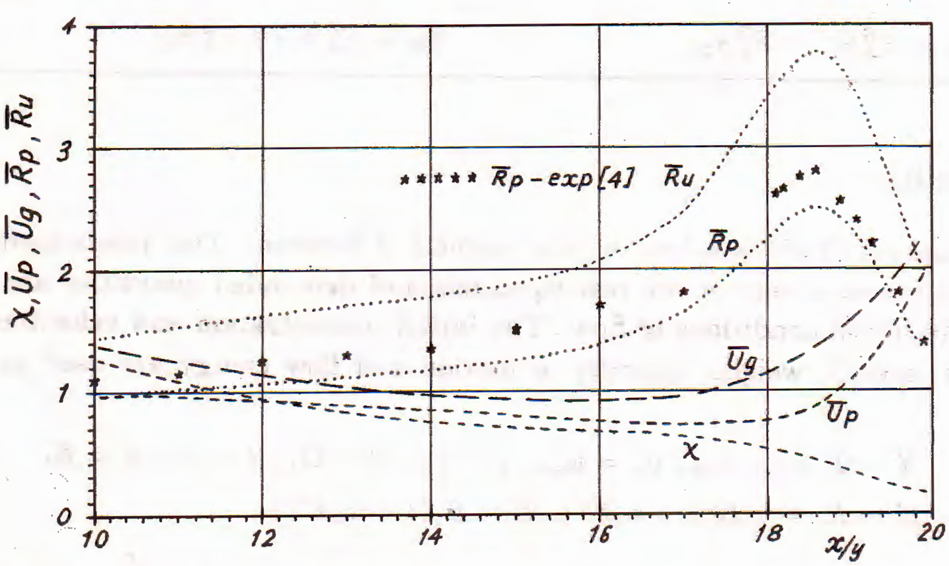

Fig. 1. A case with full suck

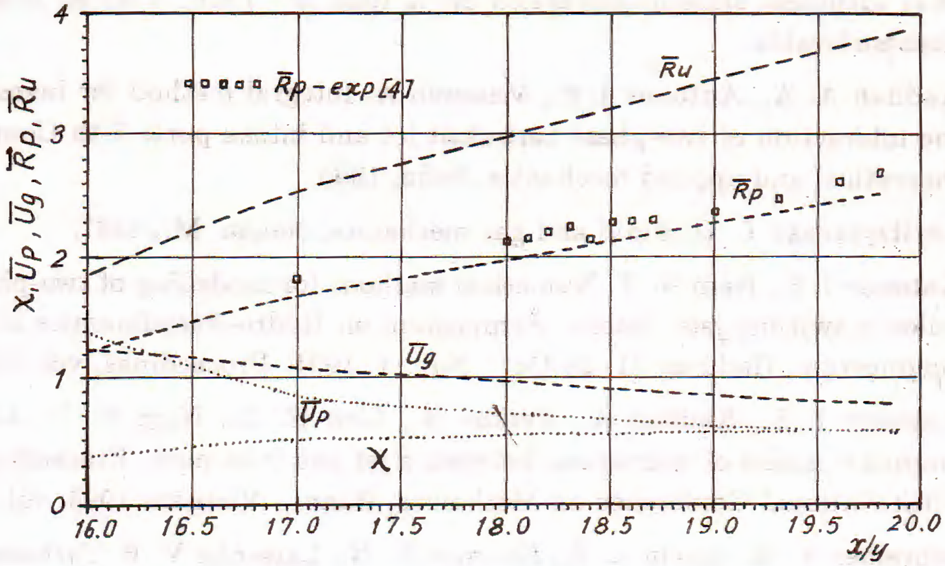

Fig. 2. A case with not full suck

Some conclusions are drawn by checking with the experimental data:

- the above model is more reliable and can be used for engineering calculations;

- the considerable contraction of diffusion boundary layer speaks about a great security in realising such devices. Being enveloped by a zone filled with air of environment, does no allow any harms to come out into the working places. This, of course, is possible when the sucking installation works in a condition of full suck or not full suck.

Acknowledgements

The authors would like to acknowledge the financial support and encouragement of Vietnam National Foundation for Basis Research on Natural Science.

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Received August 15, 1998

in revised form February 1, 2000

MÔ HÌNH SỐ VÀ THỰC NGHIỆM VỀ SỰ ẢNH HƯỞNG QUA LẠI GIỮA DÒNG PHUN RỐI VÀ MIỆNG HÚT

Trong các thiết bị thông gió để giải phóng các chất độc hại ở nơi làm việc, chúng ta sử dụng các thiết bị hút. Nguồn ô nhiễm cục bộ được lọc qua chúng. Các yếu tố cơ bản khi tạo mô hình thiết bị hút là: Các chất độc hại được xem như là dòng đối lưu bốc lên, được phun ra ngoài ống hút bởi những thiết bị hút. Trong công việc nghiên cứu hiện tại, dòng chảy được xem xét là một tổng thể với sự biến đổi động lượng và động năng dọc theo chiều dài của nó. Sự biến đổi của hai thông số này được chỉ ra bởi hàm số phụ thuộc của quá trình hút. Ở đây được đề cập đến những dòng chảy 2 thành phần: không khí và gas trong các thiết bị thông gió. Còn sơ đồ 2 vận tốc của dòng chảy được sử dụng để thực hiện phương pháp số. Phương pháp tích phân được áp dụng trên cơ sở bảo toàn khối lượng, động lượng và động năng. Nó được chấp nhận rằng động năng và động lượng biến đổi theo hàm của quá trình hút. Việc đối chứng các kết quả số với số liệu thực nghiệm được thực hiện trong 2 trường hợp: sự hút đầy và không đầy.

Tóm lại mô hình thực tại là đảm bảo độ chính xác và có thể được ứng dụng để tính toán trong kỹ thuật.