БЪЛГАРСКА АКАДЕМИЯ НА НАУКИТЕ • BULGARIAN ACADEMY OF SCIENCES

ПРОБЛЕМИ НА ТЕХНИЧЕСКАТА КИБЕРНЕТИКА И РОБОТИКАТА, **58**
PROBLEMS OF ENGINEERING CYBERNETICS AND ROBOTICS, **58**

София • 2007 • Sofia

A Theoretic-Experimental Model of Sensors with Opposite Confronting Streams*

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1. Introduction

From a constructive viewpoint one of the simplest pneumatic sensors of object presence are those, constructed on the aerodynamic principle "interaction of opposite confronting streams". This principle has got one major advantage with respect to the others, used for signalizers design, and it is expressed in the fact that the contamination of the receiving channel is practically reduced to zero, which ensures reliable and continuous work of the device. Some investigations have been done [1-4], but no theoretic or semi-empirical method is proposed for the design of sensors from this type with apriori given operating features.

The purpose of the present study is to propose a model for the creating of pneumatic sensors with opposite confronting streams and to realize a laboratory sample of such a sensor on the basis of some theoretic-experimental relations of the influence of the functional geometric and pneumatic parameters on the outflow and colliding of opposite streams.

2. Theoretic-experimental model

2.1. Selection of the principal functional scheme

Fig. 1 shows the accepted principal functional scheme of a sensor with opposite confronting streams. It is a miniature pneumatic system, consisting of an emitter nozzle 1, a collector nozzle 2, a connecting pneumatic line 3 and an output 4.

* This study is in compliance with Project No 010074 "Investigations of the Information Processes in Fluidic Media", IIT-BAS.

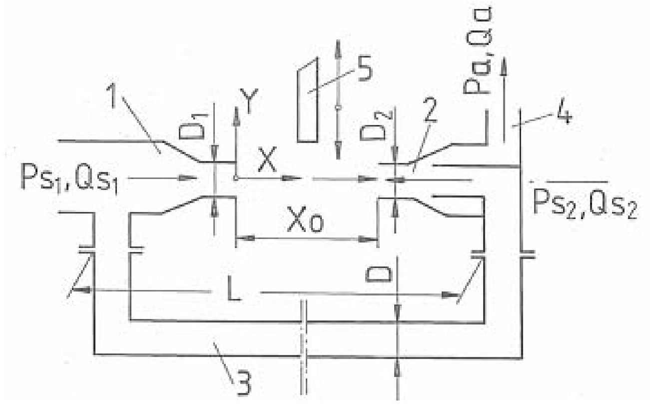

Fig. 1. Principal functional scheme of a sensor with opposite confronting flows

The flow parameters Q_{S_1} and P_{S_1} in the emitter nozzle 1 and the flow parameters Q_{S_2} and P_{S_2} in the collector nozzle 2, the geometric parameters D_1 and D_2 of these nozzles and of their connecting pneumatic line L and D are thus selected, that the interaction (the confronting) of the two streams occurs in the input section of the collector nozzle or close to it, inside the nozzle. The parameters of the information output signal are the pressure P_0 and the flow rate Q_0.

2.2. Experimental equipment and methodology of the investigations

The experiments, accompanying the design, are accomplished with the help of the experimental equipment, presented in Fig. 2, which includes longitudinal supports with micrometric screws 5, 9 and 17. The first two move axially the two nozzles – one with respect to the other, and the third one moves transversely the object considered along the main flow.

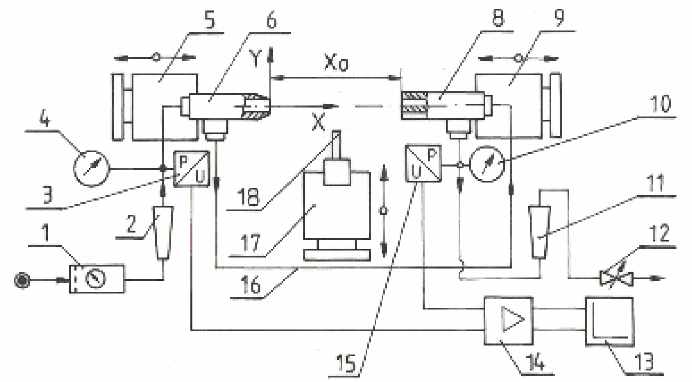

Fig. 2. Experimental equipment

The accuracy of the displacements measuring is 0.01 mm. The parameters of the supply air, the pressure and flow rate are determined and kept at constant values with the help of the preparing pneumatic group 1. The flow rates and pressures of the air in the pneumatic lines of the system are measured by rotametric flow measuring devices 2 and 11, precise manometers 4 and 10 and inductive pressure sensors 3 and 15. The alterations of the pressures in the pneumatic lines are registered with the help of a recording device 13 with the help of an amplifier 14. The emitter nozzle 6, the collector nozzle 8 and the pneumatic line, connecting them, are changeable.

In order to carry out the experimental research, the following sequence is used:

a) The emitter nozzle 6 and the collector nozzle 8 are co-axially mounted on the supports with the help of a device. They are connected by a flexible plastic tube with an inner diameter *D* and length *L*.

b) The input of the collector nozzle 8 is closed with the help of a rubber gasket and the pressure P_a and the flow rate Q_a are measured at the output of the sensor.

c) The gasket is removed from the input of the collector nozzle and the pressure P_a and the flow rate Q_a are measured once again at the output of the sensor.

d) Collector 8 is shifted with the help of support 9 forward or backward depending on that, whether the values of the output variables P_a and Q_a at opened input of the collector nozzle are larger or smaller than these values at closed input of the collector nozzle. The displacement continues up to the moment, when the indications become equal in the two cases. Under this circumstance the confronting of the opposite flows occurs in the input section of the collector nozzle, which ensures a maximal output signal without contamination of the collector nozzle.

e) Baffling 18 is placed perpendicularly to the main stream, flowing out. The baffling itself is a sufficiently large plate. The measuring of the output parameters continues.

f) At alteration of any of the system parameters the order of locating the collector nozzle with respect to the emitter one is repeated.

g) The apriori prepared plastic tubes of different length and section are easily changed, without the necessity to destroy the system.

h) The influence of the object (baffling) position in relation to the working axis (the common axis of the emitter and the collector nozzle) on the values of the sensor output signals is defined, measuring the values of the sensor output signal at each shift of 0.5 mm of the baffling.

2.3. Theoretic-experimental determination of the sensor parameters

The basic construction features of sensors of this type are reduced basically to some requirements towards the dimensions and the shape of the two nozzles and of the pneumatic line, connecting them.

The practical task in the design of a sensor with opposite confronting streams, implemented on the basis of the scheme in Fig. 1, is the determination of the optimal (with respect to the output signals pressure P_a and flow rate Q_a) geometric parameters X_0, D_1, D_2, L and D at defined and constantly maintained parameters of the supply air (pressure P_{s_1} and flow rate Q_{s_1}). The investigations have indicated that this can be done only in a combined analytic-experimental way.

The determination of the sensor parameters at the design stage requires apriori knowledge of the basic parameters of the flow between the two nozzles. It can be assumed with acceptable accuracy, that the flow run from the emitter nozzle to the input section of the collector nozzle (Fig. 3) has the nature of a free axial-symmetrical turbulent flow. Hence, the main parameters of this flow can be determined on the basis of the familiar hydrodynamic relations for a free turbulent flow.

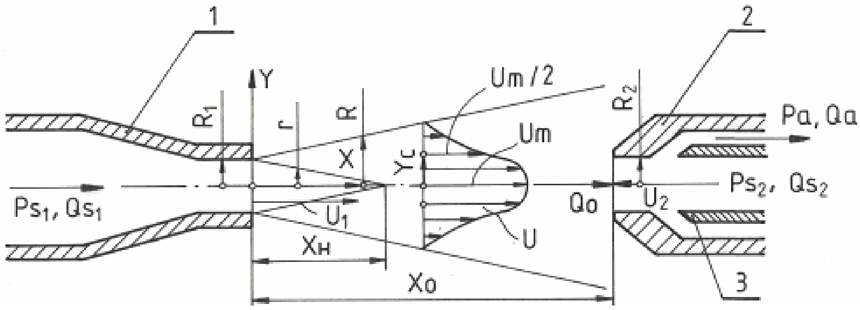

Fig. 3. Basic parameters of the flow between the emitter and the collector nozzles

The dimensionless transverse rate profile of the flow outside its core at $X>X_н$ can be described with the help of the well known semi-empirical relation of Shlichting or by the equation [5].

(1) $$f = \frac{U}{U_m} = 1 - 0,75\eta_c^2 + 0,25\eta_c^3,$$

where U and U_m are the current and the maximal speed of the fluid particles in the boundary layer and along the flow axis; $\eta_c = Y/Y_c$; Y_c is the coordinate of the point, where $U = 0.5\ U_m$.

The fading of the flow maximal rate along its axis can be defined by the expression:

(2) $$U_m^* = U_m / U_1 = 9/X^*,$$

where $X^* = X/R_1$, and U_1 is the rate of the fluid particles at the beginning section of the flow, corresponding to the output section of the emitter nozzle 1 with radius R_1 (Fig. 3).

The geometric parameters of the flow are determined, applying the approximation theory of the boundary layer according to Shlichting. The width of the flow limit layer δ at a given section is determined in a dimensionless form by the expressions:

– for the main region of the flow ($X>X_н$)

(3) $$\delta^* = R^* = \frac{R}{R_1} = 1 + 0.16X^*.$$

– and for the beginning one ($X< X_н$)

(4) $$\delta^* = \frac{\delta}{R_1} = R^* - r^* = 0.27X^*.$$

The limits of the flow nucleus (Fig. 3), the radius r and the length $X_н$ are determined by the following equalities respectively:

(5) $$r^* = r/R_1 = 1 - 0.11\ X^*;$$

(6) $$X_н = 9R_1 \text{ or } X_н^* = 9.$$

Besides the relations, determined till now, it is very important to define the flow rate Q_0 of the main flow, going to the collector nozzle (Fig. 3). The value of this capacity will depend on the value of the supply flow rate Q_{S_1}, on the distance between the two nozzles X_0 and on the input resistance of the collector nozzle λ. It can be determined from the continuity equation:

(7) $$Q_0^{*} = \frac{Q_0}{Q_{S_1}} = U^{*}_{2av} R_2^{*2} \ ,$$

where $U^{*}_{2av} = U_{2av}/U_1$; U^{*}_{2av}, U_{2av} and U_2 are the dimensionless, the average and the current rate of the flow at the collector nozzle input; $R_2^{*} = R_2/R_1$ is the dimensionless radius of the collector nozzle (Fig. 3).

Applying for U^{*}_{2av} Bernoulli's equation for the flow in front of and after the input section of the collector nozzle, the equation given below is obtained:

(8) $$U^{*}_{2av} = \sqrt{\frac{1}{1+\lambda}\left(U^{*}_{2av}{}^{2} - \Delta P^{*}\right)} \ ,$$

where $U_{av}^{*} = U_{av}/U_1$ is the dimensionless average rate of the flow along the input section of the collector nozzle; $\Delta P^{*} = [2(P_2 - P)]/[\rho\ U_2^{2}]$ – dimensionless expression of the pressure drop after the input section of the collector nozzle; P and P_2 – static pressure of the flow in front of and after the input section of the collector nozzle respectively; λ – coefficient of the common resistance of the flow in the receiving channel (for this case $\lambda = 0.5$ [5]; ρ – density of the fluid in the receiving channel.

Because of the fact that the input section of the collector nozzle in the case considered is found in the main region of the flow, the average rate in front of it will be determined by the equality:

(9) $$U_{av} = \frac{2}{R_2^{*2}} \int_0^{R_2} U dU$$

or in a dimensionless form:

(10) $$U^{*}_{av} = \frac{2R^{*2}}{R_2^{*2}} U^{*}_{m} S.$$

Taking into account the values of R^{*} and $U_m{}^{*}$ from equations (2) and (3), equation (10) becomes:

(11) $$U^{*}_{av} = \frac{1.52 X_0{}^{*} S}{R_2^{*2}} \ ,$$

where the integral $S = \int_0^{R_2} U dU$ can be determined by the relation for rates distribution (1)

(12) $$S = 0.5\left(\frac{R_2}{R}\right)^2 - 0.75\left(\frac{R_2}{R}\right)^4 + 0.4\left(\frac{R_2}{R}\right)^5 ,$$

where $\frac{R_2}{R} = \frac{R_2^{*}}{1+0.16 X_0{}^{*}}$.

After the replacement of (11) in (8) and replacing the expression obtained in (7), the following relation is obtained for the flow rate Q_0 across the input section of the collector nozzle:

(13) $$Q_0^* = \sqrt{\frac{1}{1+\lambda}\left(\left(1.52SX_0^*\right)^2 - R_2^{*4}\Delta P^*\right)}\ .$$

This expression enables the determining of one of the parameters in it, in case the rest are either set or experimentally defined. Practically it is most appropriate to set the distance X_0 (due to operating considerations) and the flow rate Q_0 (following the requirement for an output signal, optimal with respect to its use), while the coefficient of the resistance and the pressure drop to be experimentally determined.

In order to give an optimal value to the flow rate of the supply air Q_{s_1}, it is necessary to optimize the relation of the values of the emitter nozzle D_1 (Fig. 3) and the static pressure P_{s_1} in it. The flow rate of the air supply flowing through the nozzle is:

(14) $$Q_{s_1} = \mu\frac{\pi D_1^2}{4}\sqrt{\frac{2}{\rho_1}P_{s_1}}\ ,$$

where μ is the coefficient of the nozzle capacity and ρ_1 is the air density in the output section of the nozzle.

Having in mind that in the absence of a load (Q_a = 0) $P_{a\ max} = P_{s_1}$ and after replacing in (14), a simplified expression is obtained for Q_{s_1}:

(15) $$Q_{s_1} = CD_1^2\ ,$$

where $C = \mu\frac{\pi}{4}\sqrt{\frac{2}{\rho_1}P_a}$.

If the value of the output pressure P_a of the sensor with confronting streams, necessary for the switching of a pneumatic-electrical transducer for example, is given, it follows from equation (15) that in order to reduce the supply flow Q_{s_1}, it is necessary to reduce D_1 respectively, increasing P_{s_1}.

The semi-empirical relations above obtained are not sufficient for determination of the sensor geometric parameters. It is also necessary to know the relations between the external parameters of the sensor, which practically is possible just in an experimental way on the basis of some generalized laboratory investigations. The basic results from the study with this purpose are given herein in a dimensionless form.

Figs. 4 up to 6 give in a dimensionless form the dependence of the optimal distance X_0^* between the emitter and collector nozzles, i.e., this distance, at which the confronting of the two streams occurs in the input section of the collector nozzle (Fig. 3), on the supply pressure P_{s_1}, the diameter of the collector nozzle D_2^* and the diameter D^* of the pneumatic line, connecting the nozzles.

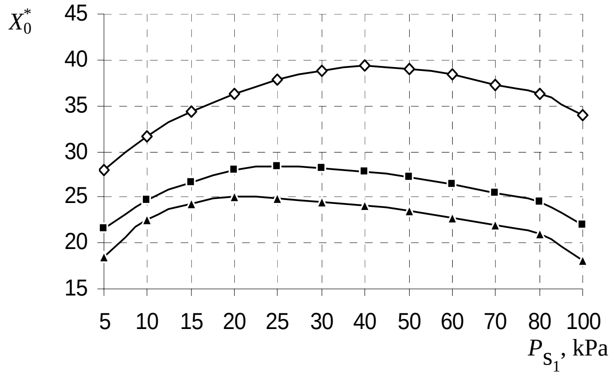

Fig. 4. Dependence of the distance $X_0^* = f(P_{S_1})$, between the nozzles on the supply pressure and the diameter of the connecting tube $D_2^* = 1$, $L^* = 100$ (—◇— D^*=1; —■— D^*=1.5; —▲— D^*=2)

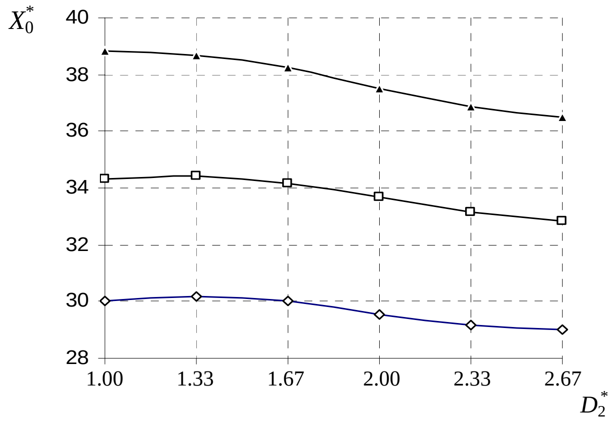

Fig. 5. Dependence of the distance $X_0^* = f(D_2^*)$ between the nozzles on the diameter of the collector nozzle and the supply pressure, D^*=1, L^*=100 (—◇—10 kPa; —□— 30 kPa; —▲— 50 kPa)

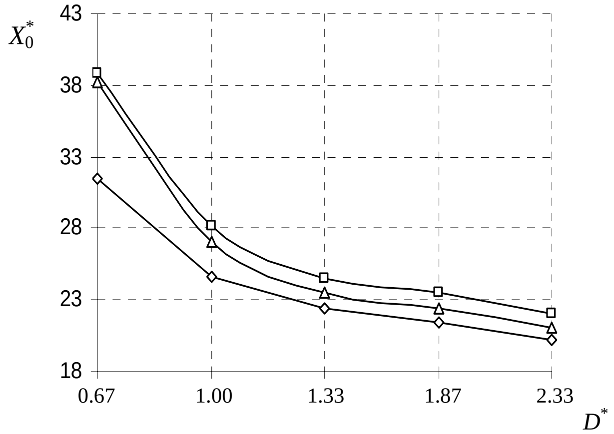

Fig. 6. Dependence of the optimal distance $X_0^* = f(D_2^*)$ between the nozzles on the diameter of the connecting tube and the output pressure, D^*=1, L^*=100 (—◇— 10; —□— 30; —△— 50)

The relation between the dimensionless output pressure P_a^* ($P_a^* = P_a / P_{S_1}$), the optimal distance between the nozzles X_0^*, the supply pressure P_{S_1} and the diameter D^* of the connecting pneumatic line is shown on Figs. 7 and 8.

The load characteristic, the dependence of the dimensionless output pressure P_a^* on the dimensionless output flow rate Q_a^* for the indicated relations of the geometric parameters towards the emitter nozzle diameter, is presented on Fig. 9.

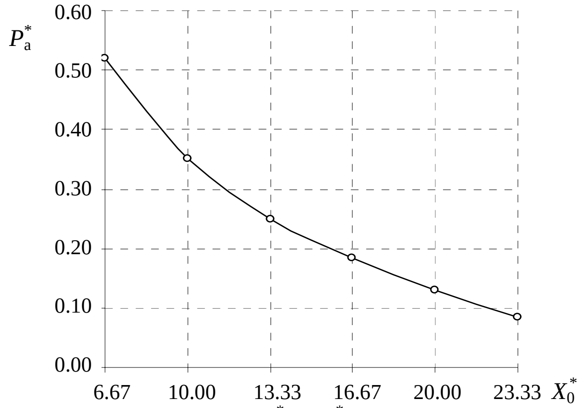

Fig. 7. Dependence of the output pressure $P_a^* = f(X_0^*)$ on the optimal distance between the nozzles ($D_2^*=1$, $D^*=1$, $L^*=100$)

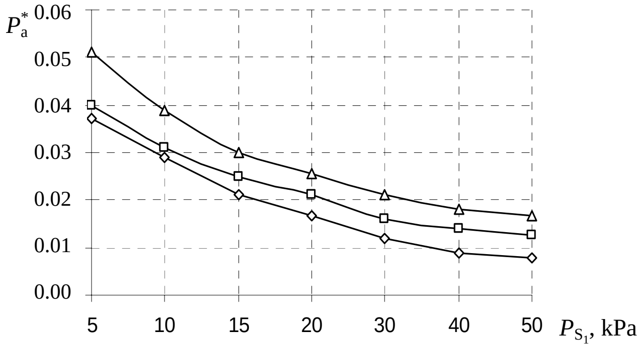

Fig. 8. Dependence of the output pressure $P_a^* = f(P_{S_1})$ on the supply pressure and the diameter of the connecting tube (—◇— $D^*=1$; —□— $D^*=1.5$; —△— $D^*=3$)

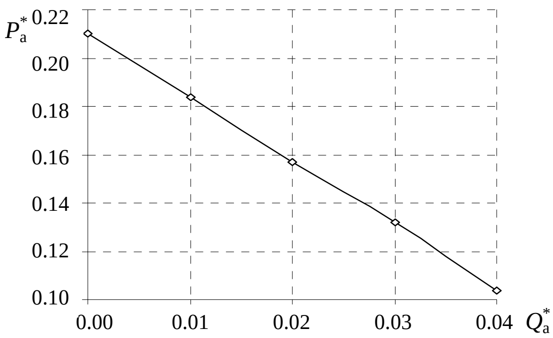

Fig. 9. Dependence of the output pressure $P_a^* = f(Q_a^*)$ on the dimensionless output flow rate ($X=X_0$, $D_2=1$, $D^*=1$, $L^*=100$)

The relations given on Figs. 8 and 10 determine the coefficients of restoring the pressure P_a^* and the flow rate Q_a^* ($Q_a^*=Q_a / Q_{S_1}$) respectively, at the indicated relations of the geometric parameters with respect to the diameter of the emitter nozzle D_1.

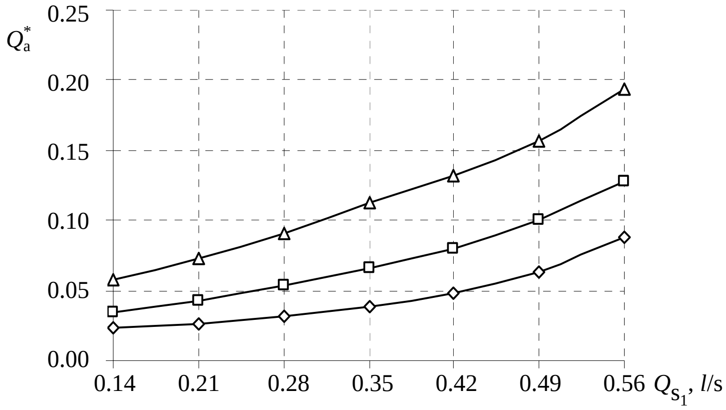

Fig. 10. Coefficients $Q_a^*= f(Q_{S_1})$ (D_2=1, L^*=100), (—◇— D^*=1; —□— D^*=1.5; —△— D^*=3)

Using the semi-empirical equations above derived and the experimental graphics obtained, the design of a sensor of an object presence based on the principle of opposite confronting streams can be realized. The necessary sequence is as follows:

1. The value of the output signal is accepted having in mind some functional considerations about the sensor (the output pressure P_a in the absence of output flow rate Q_a) and according to equation (15), the necessary supply flow rate Q_{S_1} is set at defined diameter D_1 of the emitter nozzle. The graphics on Figs. 9 and 10 are also used for that.
2. The supply pressure P_{S_1} is determined by equality (14), using Fig. 8 as well.
3. The values of the diameter D and the length L of the connecting pneumatic line are selected and Q_{S_2} is determined, which must be equalized to the flow, running through the input section of the collector nozzle, in order to ensure the streams confronting in the input section of the collector nozzle.
4. The values of R_2 and X_0 are defined from equation (13). At that the value of one of these parameters is accepted and serves to define the value of the other one, using the graphic relations, given on Figs. 4 up to 7.

3. Conclusion

On the basis of the results from the theoretic-experimental investigations accomplished, the following conclusions could be done:

– The scheme offered for the connection of a system of emitter and collector nozzles with the help of a flexible tube without throttle can be used to design pneumatic flow sensors with opposite confronting streams, working reliably under conditions of contaminated environment.

– The semi-empirical relations derived from the alteration of all the characteristic hydrodynamic and geometric parameters of the flow system with opposite confronting streams define with satisfying accuracy the fluid behaviour and can be used in the design of pneumatic sensors and shift measuring devices, using the effect of the opposite confronting of streams.

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Теоретико-экспериментальная модель сензоров с навстречными струями

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(Р е з ю м е)

Одним из самых простых сензоров наличия предмета является тот, построенный на основе принципа навстречных потоков. Цель настоящей работы предложить модель проектирования пневматических сензоров с навстречными потоками и создать лабораторный образец этого сензора. Используются теоретико-экпериментальные отношения зависимости функциональных геометрических и пневматических параметров потока и навстречных струй.