"INTERNAL" COLLISIONS OF GAS JETS

A. B. Bartman, É. T. Bruk-Levinson, and A. I. Zhidovich

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The inverse problem of the theory of opposing-jet collision with a central body (deflector) is considered; this problem has engineering applications. Simple relations describing the form of the deflector and the diffuser–confuser attachment are obtained.

In considering internal problems of hydroaerodynamics [1, 2], the difficulties which arise are intensified on attempting a rigorous study of flow with induced stratification of the velocity field. At the same time, such problems may be successfully overcome in external problems [3-5]. In practice, for example, a certain number of models of jet hydroaerodynamics have been successfully introduced [3].

The applicability of one such model to a new class of problems of the internal collision of jets and flow rotation is shown below; these problems are important in engineering applications.

The model of the collision of gas flows at subsonic velocities is based on the description of the potential core of the flow of two colliding jets. In the axisymmetric case, in order to determine the basic kinematic characteristics, it is sufficient to consider the plane problem of collision in steady conditions. A significant deficiency of this simplification is the inadequacy of the real problem in the collision zone [3]. Chalpygin's classical idea allows the traditional scheme with a point of stagnancy (Fig. 1a) to be replaced by the concept of a central stagnant zone (Fig. 1b), at the boundary of which the gas velocity has some relatively small value v_c.

The characteristics of the stagnant zone and the whole flow are determined on specifying the pressure, which may be larger than the pressure in the incoming flow, i.e., if v_c is the minimum flow velocity [1].

In real flows with frontal collision of jets in the central zone (the zone of strong deceleration and rotation of the jets) there arises a region of dissipative effects. It is convenient to use the idea of a "stagnant zone" for the kinematic demarcation of this region and the potential core of the flow. However, the dissipative region, generally speaking, is unstable and serves as a source of turbulent inhomogeneities for the adjacent regions of turbulent flow.

The required stability of the potential core may be attained if there is a configurationally equivalent solid body at the site of the stagnant zone. The kinematic similarity of the problems of jet flow around such a body and the stagnant zone is obvious. From a dynamics perspective, it is appropriate to speak of flow around a central body (deflector) with a thin boundary layer, at the external boundary of which velocity v_c is reached.

It is of fundamental importance, however, that in problems of flow around a stagnant zone (i.e., deflector), the configuration of the stagnant zone itself is not assumed to be specified, but is determined in the course of solving the problem, as a function of the velocity v_c and other kinematic properties of the flow.

Thus, in the present case, it is necessary to solve an inverse flow problem: to calculate the form of the deflector around which jet flow is consistent with potential conditions of the flow as a whole. The formal solution of the following problem is known: coaxially symmetric collision of two identical jets issuing from two identical channels (of width 2H) in opposite directions and flowing into two other identical channels (of width 2d) which are perpendicular to the first (Fig. 2) [6].

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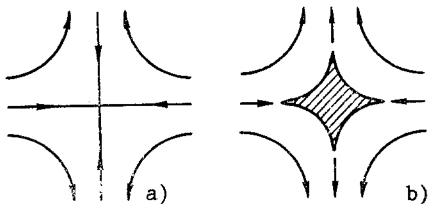

Fig. 1

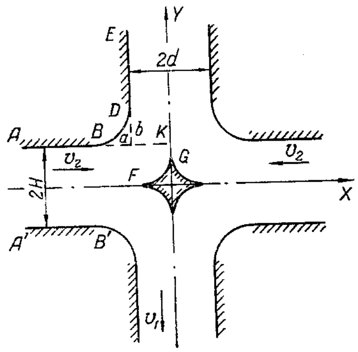

Fig. 2

Fig. 1. Motion of two colliding jets with a point of stagnancy (a) and a stagnant zone (b).

Fig. 2. Motion of two colliding jets in the presence of a deflector at the site of the stagnant zone: AB, DE, rectilinear sections of horizontal and vertical channels, respectively; BD, free streamline of jet; a, b, characteristic dimensions of free jet boundary; v_2, ρ_2, velocity and density of medium in colliding jets; v_1, ρ_1, velocity and density in vertical channel; v_c, gas velocity at boundary of stagnant zone FG (minimal flow velocity); H, d, halfwidths of horizontal and vertical channels; l = BK, distance from inlet cross section of horizontal channel to vertical axis of symmetry; v_0, gas velocity at free streamline (maximum flow velocity); ρ_0, density of retarded flow.

In solving the problem, the following velocity relations are assumed: $v_0 > v_1 > v_2 > v_c$. The solution in [6] was obtained in the modified hodograph plane (σ, θ), where θ is the angle of the velocity in the physical flow plane with a positive direction of the x axis, and σ is a variable of generalized-velocity type for the given problem

$$\sigma = \int\limits_{v^2/v_0^2}^{1} (\rho/\rho_0)\, dv^2/v^2, \tag{1}$$

i.e., σ = 0 for a free surface, for example. For the characteristic flow velocities, the following sequence of values of σ is obtained: $0 < \sigma_1 < \sigma_2 < \sigma_c$.

In [6], parametric representations of the basic geometric elements of the flow were given:

1) equation of the stagnant-zone boundary FG

$$x = -(H/\pi)\, \rho_2 v_2/(\rho_0 v_c) \sum_{n=1}^{\infty} \{1/[n\zeta_{2n}(\sigma_c)]\}\, N_{2n} I_{2n}(\theta), \tag{2}$$

$$y = -(H/\pi)\, \rho_2 v_2/(\rho_0 v_c) \sum_{n=1}^{\infty} \{1/[n\zeta_{2n}(\sigma_c)]\}\, N_{2n} H_{2n}^{*}(\theta); \tag{3}$$

2) equation of free boundary

$$x = -d - (H/\pi)\, \rho_2 v_2/(\rho_0 v_0) \sum_{n=1}^{\infty} n^{-1}\{[Z_{2n}(\sigma_c)/\zeta_{2n}(\sigma_c)]\, N_{2n} - M_{2n}\}\, I_{2n}(\theta), \tag{4}$$

$$y = H\,[1 - (1/\pi)\, \rho_2 v_2/(\rho_0 v_0) \sum_{n=1}^{\infty} \{[Z_{2n}(\sigma_c)/\zeta_{2n}(\sigma_c)]\, N_{2n} - M_{2n}\}\, H_{2n}^{*}(\theta)], \tag{5}$$

$$M_{2n} = Z'_{2n}(\sigma_2) + (-1)^{n-1} Z'_{2n}(\sigma_1), \tag{6}$$

$$N_{2n} = \zeta'_{2n}(\sigma_2) + (-1)^{n-1} \zeta'_{2n}(\sigma_1), \tag{7}$$

$$I_\nu(\theta) = [\cos(\nu+1)\theta]/(\nu+1) + [\cos(\nu-1)\theta]/(\nu-1), \tag{8}$$

$$H^*_\nu(\theta) = [\sin(\nu+1)\theta]/(\nu+1) - [\sin(\nu-1)\theta]/(\nu-1). \tag{9}$$

Here $Z_\nu(\sigma)$ and $\zeta_\nu(\sigma)$ are linearly independent solutions of the ordinary second-order linear differential equation arising in separating variables of the Chaplygin equation in the plane (σ, θ); ν^2 is the separation parameter. In this form, in which the angle θ is the parametric variable (for the left-hand square in Fig. 2, the region of variation of this variable is $0 \leqslant \theta \leqslant \pi/2$), the dependence on external kinematic parameters takes on a special role. The following five parameters are taken as the unknowns: a, b, d, v_1, and v_c. From the conditions of the problem and the given form of the free surface, four relations are valid for these parameters

$$\alpha = H\rho_2 v_2/(\rho_1 v_1), \tag{10}$$

$$l = a + d, \tag{11}$$

$$a = (4H/\pi)\,\rho_2 v_2/(\rho_0 v_0) \sum_{n=1}^{\infty} (4n^2-1)^{-1} \{[Z_{2n}(\sigma_c)/\zeta_{2n}(\sigma_c)]\, N_{2n} - M_{2n}\}, \tag{12}$$

$$b = (4H/\pi)\,\rho_2 v_2/(\rho_0 v_0) \sum_{n=1}^{\infty} (-1)^{n-1} (4n^2-1)^{-1} \{[Z_{2n}(\sigma_c)/\zeta_{2n}(\sigma_c)]\, N_{2n} - M_{2n}\}. \tag{13}$$

Thus, the solution from [6] is parametrically undetermined. In itself, this is because "already-formed steady motion is considered, taking no account of the initial conditions which lead to the given steady motion" [7]. The information may sometimes be made definite by symmetrization of the flow or degeneracy of its geometric characteristics (for example, degeneration of the "stagnant zone" to a stagnant point), i.e., essentially by some preliminary treatment of the flow. However, in the general case which is of interest here, these methods are impermissible, and the formal solution in [6] does not allow the deflector to be uniquely determined.

The following approximate scheme is physically sound and leads to a unique result. The above equations for the boundary of the stagnant zone and the free surface are expanded in generalized Fourier series in view of the trigonometric character of the functions I_ν, H^*_ν. Retaining only the first terms of these expansions, the contribution of the first (and basic, according to perturbation-theory conventions) eigenfunction of the Chaplygin equation will be correctly taken into account. In the hodograph plane, homogeneous boundary conditions will be rigorously observed on the "zero" sections of the boundary, and some "renormalization" of the inhomogeneous conditions is assumed. This leads to the following approximate form of the solution:

1) the equation of the stagnant-zone boundary FG

$$\begin{cases} x = -\alpha\,[(\cos 3\theta)/3 + \cos\theta], \\ y = -\alpha\,[(\sin 3\theta)/3 - \sin\theta], \end{cases} \quad 0 \leqslant \theta \leqslant \pi/2; \tag{14}$$

2) the equation of the free boundary

$$\begin{cases} x = -\alpha - \beta\,[(\cos 3\theta)/3 + \cos\theta], \\ y = H - \beta\,[(\sin 3\theta)/3 - \sin\theta], \end{cases} \quad 0 \leqslant \theta \leqslant \pi/2; \tag{15}$$

3) parametric relations

$$a = b = 4\beta/3, \tag{16}$$
$$a + d = l, \tag{17}$$
$$d = H\rho_2 v_2/(\rho_1 v_1). \tag{18}$$

If this approximation is compared with the first terms of the series from [6], then in formal terms this means

$$\alpha = [(H/\pi)\,\rho_2 v_2/(\rho_0 v_c)]\,N_2/\zeta_2(\sigma_c), \tag{19}$$
$$\beta = (H/\pi)\,\rho_2 v_2/(\rho_0 v_c)\,\{[Z_2(\sigma_c)/\zeta_2(\sigma_c)]\,N_2 - M_2\}. \tag{20}$$

If α and β are regarded as more general ("renormalized") coefficients including the perturbed influence of the next terms of the expansions from [6], α will be characterized only by a dependence on the velocity v_c, i.e., $\alpha = \alpha(v_c)$. At the same time, this dependence may be considered inversely: the required value of α is chosen and the velocity v_c is chosen as a function of this. In other words, the flow is tuned according to α, specified in the approximate form of the stagnant zone.

It is readily evident that the same discussion applies in the case of a dependence $\beta = \beta(v_0)$. The value of β is specified (as becomes clear below, from kinematic considerations), and the flow takes a velocity v_0 close to the free surface corresponding to the specified value of β. With this form of the solution, the parameter α (the effective deflector dimension) may be sufficiently freely used, and the parameter β is determined by the simple relation: $\beta = 3(l - d)/4$. It is obvious here that the equation of the free boundary (now regarded as a diffuser–confuser attachment) is obtained by a simple affine transformation of the deflector equation: first extension and then displacement by a vector corresponding to the output cross section of the channel.

Thus, the geometric elements of the structure controlling the flow have been completely determined, as follows.

1. Using the simple geometric relations

$$\cos\theta + (\cos 3\theta)/3 = (4/3)\cos^3\theta, \quad \sin\theta - (\sin 3\theta)/3 = (4/3)\sin^3\theta \tag{21}$$

Eq. (14), describing the form of the deflector, may be reduced to the form

$$x^{2/3} + y^{2/3} = (4\alpha/3)^{2/3}, \tag{22}$$

i.e., the equation of a classical curve of hypocycloidal type, an astroid. Thus, the deflector takes the form of an astroid, all the geometric properties of which are well known [8]. Examples of the appearance of astroids as the forms of wavefront caustics that are well known in acoustics and optics may be noted in this connection. Astroids represent the first and schematically simplest rearrangement of a wavefront, which may be compared with the rearrangement of flow due to the boundaries.

2. Analogously, the curvilinear sections of the diffuser–confuser attachment in Eq. (15) are formed by appropriately shifted arcs of astroids

$$x^{2/3} + y^{2/3} = (4\beta/3)^{2/3}. \tag{23}$$

3. The parametric relations are

$$\alpha = H\rho_2 v_2/(\rho_1 v_1), \quad \beta = 3(l - d)/4. \tag{24}$$

Thus, the basic approximate relations between the geometric dimensions of the deflector and the diffuser have been obtained. Note, in conclusion, that the possibility of flow stabilization by means of deflector surfaces has been confirmed experimentally [9].

LITERATURE CITED

1. L. I. Sedov, Plane Problems of Hydrodynamics and Aerodynamics [in Russian], Nauka, Moscow (1966).

2. Modern Hydrodynamics. Successes and Problems [Russian translation], Mir, Moscow (1984).
3. M. I. Gurevich, Theory of Jets of Ideal Liquid [in Russian], Nauka, Moscow (1979).
4. G. N. Abramovich, Theory of Turbulent Jets [in Russian], Fizmatgiz, Moscow (1960).
5. G. Birkhoff and E. H. Zarantonello, Jets, Wakes, and Cavities, Academic Press (1957).
6. E. D. Tomilov, Subsonic Plane Gas Jet Flows [in Russian], Nauka, Novosibirsk (1980).
7. L. M. Milne-Thomson, Theoretical Aerodynamics, Dover (1973).
8. A. A. Savelov, Plane Curves [in Russian], Nauka, Moscow (1960).
9. P. Chang, Control of Flow Separation, McGraw-Hill, New York (1976).

HEAT AND MASS TRANSPORT IN PETROLEUM-BEARING EARTHS

D. P. Volkov, G. N. Dul'nev,
B. L. Muratova, and A. B. Utkin

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A model for the structure of oil-bearing earth is offered together with a method for calculating its thermal conductivity with consideration of diffusion transport. Calculation resutls are presented as is an experimental determination of effective thermal conductivity of model materials and specimens of oil-bearing earths.

A major factor in increasing petroleum output is played by increasing the extractable fraction of geological reserves in oil fields. At the present time extraction methods involving thermal action on the oil stratum are being developed and put into use: heating of crack zones adjoining drillings by vapor, electrical heaters, and chemical reaction heat; forcing heating agents into the stratum — hot water, water vapor, hot gases; and creation of a moving combustion hearth within the stratum.

Study of the nonsteady-state temperature field permits determination of the size of the heated zone and the thermal utilization coefficient — the ratio of the heat accumulated in the stratum to that introduced into the stratum — and selection of a heat agent flowrate to produce desired heating conditions.

To calculate temperature fields within the plate, a knowledge of the thermophysical characteristics of oil-bearing soils is necessary. In the majority of cases measurements have been performed for concrete drillholes and locations, which allows use of such data under other conditions only with serious reservations. Oil-bearing earths are within the class of capillary porous bodies, the pores of which may contain liquid. Heat transport through moist bodies is normally accompanied by molecular transport of vapor and liquid, produced by the temperature gradient. Therefore, the majority of studies have used not true, but effective thermophysical properties, in particular, an effective thermal conductivity. The latter depends on many parameters, including the temperature gradient, pressure, relative direction of the gravitational force and thermal flux vectors, so that it is not as much a physical characteristic of the soil as a regime parameter.

Approximately 85% of oil-bearing locations contain petroleum in sedimentary deposits in the form of sands and sandstones, which consist of grains of quartz, feldspar, and mica, bound together primarily by a carbonate and clay cement. Figure 1 shows a schematic diagram of an oil-bearing soil. The grains and cement form a solid skeleton in the pores of which liquid and vapor are located. Depending on the volume of liquid within the material, the liquid either completely fills the pores (A), or a portion of the pores, spreading over the internal surface of the pore in the general case (B), while a portion of the pores remain dry (C). If we denote the total pore volume within the material by V_p, the dry pore volume by V_d, the liquid volume by V_l, and the gas volume in the pores the walls of which are wet by liquid by V_m (volume of moist pores), then

$$V_p = V_d + V_\ell + V_m. \tag{1}$$

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