Modern fluid motion physics: on the jet streams induced by a body form in the unrestricted uniform flow of real fluid. Parts 2 and 3: circular cylinder and ball

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Solution of problems on interaction of the unrestricted uniform flow of real fluid – air – with circular cylinder and ball is produced. In the main in essence new idea – on origin of the jet streams in the unrestricted flow of real fluid running against obstacle – is a basis of the solution. Common approach and method allowed physically adequate and mathematically correctly describing the flow field around a body and determining forces of the flow action on the body. Combination of new theoretical approach to dynamics of the jet streams with the boundary layer theory clears the way to a passage from empirical coefficients of drag, lift and others to valuable theoretical calculation in problems of aero- and hydrodynamics.

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Introduction

Physically adequate solution of problems on the interaction dynamics of a liquid free jet – water – with a body, stated in one of previous articles [1] of the author, has allowed to suppose that interaction of the unrestricted uniform flow of real fluid with a solid obstacle is accompanied by origin of the jet streams – before the obstacle and near its lateral surface. Quantity of velocity and, accordingly, the velocity head of the jet streams is considerably greater of these parameters of the unrestricted flow (in contrast to the jet streams of the liquid free jet, which ones have a quantity of these parameters equal practically to its of initial jet). The jet streams interact by its internal boundary with the body surface and then with the flow part behind it, and by its external boundary – with the unrestricted flow, moving at each side of the body. These jet streams determine the flow field structure of real fluid around the body.
Physically adequate solution of a problem on the interaction dynamics of the unrestricted flow of real fluid with the thin flat plate of the unrestricted span at any angle of attack [2], achieved by the same way as it was earlier made, i.e. by graphic-analytical method, but by means of curves from assemblage of conical sections (in contrast to the circumference arches, used in solution of problems on interaction of the liquid free jet with a body), allowed reproducing the flow field structure and distribution of pressure onto the plate in full accordance to the experimental research results, adduced in [3, fig. 83].
Thus thesis on origin – inducing – of the jet streams and its influence onto structure and intensity of the flow and pressure fields depending on the body form and its spatial orientation is took by the author – in combination with the boundary layer theory – as a basis for passage from experimental determination of empirical coefficients of a body form resistance to valuable theoretical reproducing kinematics and dynamics of interaction of a body with the unrestricted flow of real fluid.
An object of the given article is to show effectiveness of the method, stated in previous article [2], by examples of interaction of the unrestricted flow of real fluid – mainly air – with circular cylinder as a 3-D analogue of thin flat plate and also with a ball and its 2-D analogue in the kind of a disk.

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Approach

In its basis, the approach to the raised in Introduction problems corresponds quite to that, stated in article [2], and one represent by itself development of thesis on the determining influence of the jet streams onto the flow field kinematics and dynamics of interaction of a body and the unrestricted flow.

Solution: part 2

This is a problem on interaction of the unrestricted uniform flow of real fluid – air – with the immovable circular cylinder of infinite span, oriented strictly across the flow. Preliminary analysis of a flow field around the cylinder allows, as it was done before [2], to distinguish the following parts of the flow:
- one part – in the limits of the cylinder diameter as its middle section, running against front side of the cylinder, - is a part of the flow before the obstacle;
- two parts, passing by the cylinder cross-section at both sides of it;
- one part – in limits of the cylinder diameter, adjoining its back side, - is a part of the flow behind obstacle.

The first of the enumerated flow parts branches into two identical streams, and every of its turns about before the cylinder in order to pass by this obstacle. In that way, the flow part transmutes into two jet streams, which ones form between itself and the cylinder front side a braking zone with surplus pressure in it. A profile of distribution of the surplus – dynamical – pressure in this zone corresponds to curvature of effective internal boundary of the jet streams and the cylinder contour. Two parts of the flow, moving at both sides of the cylinder section, exert lateral resistance to progressive motion of the jet streams. Such external action leads to pressing the jet streams to the cylinder surface, to a decrease of thickness of the jet streams and, correspondingly, to an increase of its velocity and velocity head. As a result, the jet streams overcome lateral resistance of surrounding its flow and pass by the cylinder section, pushing away the flow external parts. Just the jet streams determine, in the main, realization of the local and general continuity condition of the flow while the unrestricted flow passes by obstacle. Moving with acceleration and carrying along together itself the flow external parts, the jet streams, owing to accumulated by its inertia of progressive motion, separate with immovable and invariable, i.e. hydrodynamically not adapted, surface of the cylinder immediately before its middle section. After separation, the jet streams surround the flow part behind the cylinder and exert upon it ejecting action, accompanying by rarefaction in a flow zone, adjoining back side of the cylinder section.

An origin of the jet streams is bound up with transition of real fluid flow from only viscous – creeping – motion to its hydrodynamic motion at $20 < Re < 40$, when the inertia forces exceed action of the viscosity forces on the order. In this period, the jet streams, although ones adjoin lateral and, partially, back part of the cylinder section, at the same time they already form a small closed zone of separation, containing a symmetrical pair-vortex structure correspondingly to symmetrical pair of the jet streams. The closed pair-vortex structure near back side of the cylinder section forms with it single streamlined body; a drag coefficient of the such body is decreased as a length of the structure is increased under action of the jet streams when the unrestricted flow velocity is increased.

Gradual increase of the flow velocity leads to an outstripping increase of velocity and velocity head of the jet streams. The separation point of the jet streams corresponding to such intensification is successively displaced along back part of the cylinder section in direction its middle; the jet streams increase gradually dimensions – length along the flow axis and diameter – of the closed pair-vortex structure and also intensity of its rotation. As a result, gradual increase of the separation zone area behind the cylinder leads to a pace deceleration of lowering of the drag coefficient curve in comparison with only viscous flow according to Stokes (1851).

Basic forces, applied to the cylinder, are the followings:
- surplus pressure – onto a part of front side of its section;
- rarefaction along the lateral sides of its section;
- rarefaction at back side of its section.

All these forces are excited by action of the jet streams as a result of interaction of the cylinder with the unrestricted uniform flow of real fluid. Really, quantity and distribution of surplus pressure onto front part of the cylinder section are determined by projection of a velocity head, applied along internal boundary of the jet stream, with taking into account of an increase its velocity, onto a normal to the cylinder section contour in the limits of $0 \leq \theta \leq 35^0$; therefore the surplus pressure reaches its maximum quantity in frontal point of the cylinder section, and the pressure is decreased up to zero in a point of smooth connection of internal boundary of the jet stream with the cylinder section contour in a distance approximately 35^0 from its frontal point. An accelerated circular motion of the jet stream along lateral part of the cylinder section contour, $35^0 \leq \theta \leq (70^0 or 85^0)$, increases action of centrifugal forces, determined by average – in its thickness – velocity of progressive motion, and in that way excites an increase of rarefaction along the lateral part of the cylinder. After separation – immediately before the cylinder middle – the jet streams have the greatest magnitude of velocity and a velocity head of its progressive motion; an action of every jet stream onto a vortex of the closed pair-vortex structure behind the cylinder is reduced to a pair of forces, rotating the vortex, and to a force, applied to the vortex mass center and directed down-flow. Thus rarefaction behind the cylinder corresponds and is equaled by number to the greatest velocity head of the jet stream.

An increase of the unrestricted flow velocity up to quantities corresponding to Re > 150 leads to situation, when a velocity head of every of the jet streams becomes sufficient for self-depending involving the whole of the fluid mass, adjoined back side of the cylinder section, into rotatory movement. Now the symmetrical pair-vortex structure gives place to formation and throwing out down-flow of vortexes by every jet stream in turn. Such structure of a wake behind the cylinder is quite similar to structure, formed behind a thin flat plate and described in previous article [2] of the author.

According to the results of O. Flachsbart (1932) experimental research [4], an interaction of every of the jet streams with a formed and thrown out by its vortex has a double character. At $150 < Re \leq 1.86 \cdot 10^5$ and M << 0.6, the greatest rarefaction behind the cylinder equal in number to a velocity head of the jet stream, and at $Re = 6.7 \cdot 10^5$ rarefaction behind the cylinder is sharply decreased up to ~ 8 percent of a velocity head of the jet streams.

According to the results of A. Ferri (1942) experimental research, phenomenon in the kind of the sharp decrease of rarefaction, detected by Flachsbart, is not appearing at $0.6 \leq M \leq 0.8$, and magnitude of rarefaction behind the cylinder equal in number to a velocity head of the jet streams.

Explanation of phenomenon, detected by Flachsbart, is, probably, in that duration of interaction of the jet stream with the formed by its vortex at M << 0.6 is essentially greater than at $0.6 < M \leq 0.8$ according to Strouhal number; therefore an increase of Reynolds number to $6.7 \cdot 10^5$ ensures sufficiently long-term intensive interaction of the jet stream with vortex. In one's turn, the vortex – before its throwing out away from the cylinder – has a time to draw additional fluid mass in space between itself and the cylinder back side and thereby to increase pressure behind the cylinder; as a result, a drag coefficient of the cylinder is decreased.

Other explanation of a cause of sharp decrease of rarefaction behind the cylinder is in that a laminar interaction of the jet stream with fluid, adjoined the cylinder back side, accompanied by in turn formation and by throwing out large-scale vortexes, is supplemented by formation of succession of small vortexes in immediate proximity to a point of separation of the jet stream and the cylinder surface. Great number of these small vortexes fills with surplus a space between the cylinder back side and large-scale vortexes. An uninterrupted replenishment of so called vortical foam stipulates surplus pressure in it, which one compensates to a marked degree a rarefaction, stipulated by throwing out of large-scale vortexes.

The above-stated description of qualitative aspect of interaction of the real fluid flow with circular cylinder, corresponding to the well-known results [4, 6] of experiments, adduced in fig. 1, is a description of general conceptual model of phenomenon as necessary condition for transition to solution of the following problems – on kinematics of the flow field around the cylinder and on dynamics of its interaction

In the beginning, the author supposes it expedient to elucidate a question on kinematics and dynamics of interaction of the liquid free flat jet with circular cylinder similarly to that as it is made in previous article [1, fig. 8a].

Fig. 2a shows a possibility in application of grapho-analytical method, stated in mentioned article, for construction of kinematics of the liquid free flat jet, directed eccentrically onto the cylinder, when the jet thickness not exceeds or, in the given case, is equal to the cylinder radius.

Fig. 2b shows a diagram of the interaction forces of initial jet and its jet streams with the cylinder. A product of a velocity head of initial jet and area of its unit on width of its cross-section is the unit (on its width) force of the jet. The initial jet is divided into two jet streams with its thickness determined by eccentricity of the jet relatively the cylinder. Zone of the initial jet bifurcation is restricted by the cylinder section contour and by internal boundaries of the jet streams up to a point of its smooth contact with the cylinder section contour. Distribution of pressure in this zone is determined by a projection its velocity head, acting on a tangent along the internal boundaries of the jet streams, onto a tangent to a circumference arch, passing on a normal to the cylinder section contour, with subsequent transfer of the projection along the mentioned arch up to the cylinder section contour, as it is showed in fig. 2b. In that way, the whole of forces of the constructed distribution of pressure are directed to the cylinder section center. A product of a velocity head of initial jet and the cross-section unit (on its width) area of every of two jet streams, determined by its thickness, is a unit (on the width) force of its progressive motion, i.e. inertial force. Motion of the jet streams along the cylinder section contour excites action of centrifugal forces onto it. Intensity of these centrifugal forces is determined by and equal in number to the unit force of progressive motion of every of two jet streams; in contrast to a unit force of progressive motion of the jet stream, the intensity is a unit force distributed along the arch of immediate contact of the jet stream with the cylinder section contour, i.e. between a point of initial contact of internal boundary of the jet stream with the cylinder section contour and a point of separation of the jet stream and the cylinder. Thus, the unit – on the initial jet width – forces can be produced by the following expressions

- the initial jet force

$$F_0 = (\rho\, v_0^2/2) \cdot b_0^2 \text{ , kgf;} \tag{1}$$

- the jet stream force

$$F_j = (\rho\, v_0^2/2) \cdot b_j^2 \text{ , kgf;} \tag{2}$$

- intensity of centrifugal forces of the jet stream

$$I_{jcf} = F_j\text{, kgf/m;} \tag{3}$$

- total quantity of centrifugal forces of the jet stream

$$F_{jcf} = (\rho\, v_0^2/2) \cdot b_j^2 \pi R_c \cdot \alpha/180^0\text{, kgf,} \tag{4}$$

where R_c is the cylinder radius, α is an angle of immediate contact of the jet stream with the cylinder section contour.
In that way, the more an arch length of action of centrifugal forces in comparison with the jet stream thickness the more a resultant of centrifugal forces in comparison with a force of a velocity head of the jet stream itself. The resultant of centrifugal forces coincides with a bisector of an angle α of immediate contact of the jet stream with the cylinder section contour and one is directed away from its center. Combination of action onto the cylinder of the surplus pressure, in zone of bifurcation of initial jet into the jet streams, and rarefaction, in zones its immediate contact with lateral parts of the cylinder section contour, leads – in dependence on a quantity of the initial jet velocity – to exact opposite results. When the initial jet velocity is sufficiently low, its jet streams wash large part of the cylinder section contour. In this case, predominance of total of centrifugal forces of the jet stream with its greater thickness excites a displacement of the cylinder in direction to coincidence of its section center with the initial jet axis. After such coincidence, its jet streams become equal to each other by its thickness, and, correspondingly to it, the total of both centrifugal forces acting in opposite directions become also equal by its quantity. Such state of stable equilibrium is a hydrodynamic self-centering of circular cylinder in the liquid free jet of real fluid (water, air). When the initial jet velocity is sufficiently high, its jet streams are separated from the cylinder surface immediately near a zone of the initial jet bifurcation. In this case, centrifugal forces are absent, and predominance of a force of surplus pressure of the jet stream with its larger thickness stipulates pushing out the cylinder away from the initial jet.
Fig. 3 shows the combined geometrical diagram of movement of the liquid free flat jet, directed strictly straight onto circular cylinder. The left side shows a bifurcation of the initial jet into two jet streams, when the initial jet thickness not exceeds or equal the cylinder radius. The right side represents geometrically possible construction of the jet stream of initial jet, when its thickness not exceeds or, in the given case, equals the cylinder diameter. In spite of geometrical possibility, such construction not allows achieving a compatibility with lateral passing flow. It is evident, the geometrical construction by means of the circumference arches is too simple and one cannot serve as a basis for graphical reproduction of kinematics of interaction of the unrestricted flow with the cylinder. At the same time, the separate parts in the kind of equilateral triangle with its side equal the cylinder diameter and rectangle, conjugated with it [1, fig. 8a] and contained the basic flatness line, BFL, (in fig. 2a), as before are the parts of general approach to the problem solution. Further solution of the problem envisages, as it was before, application of curves from assemblage of conical sections: ellipse, parabola, hyperbola and circumference with its evolvent.
Fig. 4, at its right side, represents construction of effective internal boundary of the jet stream in the kind of a hyperbola arch, showing a turn of the jet stream from the flow central line up to a point of smooth contact of the boundary with the cylinder section contour. A problem is that in the beginning to find the contact point and then to find a method of construction of the hyperbola arch between the flow central line before the cylinder and the contact point on the cylinder section contour. Succession of solution of this part of the problem is the following:
- the first asymptote of the hyperbola is a part of the flow central line before the cylinder with its beginning in frontal point of the cylinder section contour;
- the second asymptote is a straight line out of the beginning of the first asymptote at an angle 120^0 to it;
- the hyperbola axis is a straight line out of a point of intersection of asymptotes at 60^0 to its; the straight line intersects initial external boundary of a part of the unrestricted flow, running against immediately the cylinder (this is straight line parallel to the flow central line and touching the cylinder section contour); a point of intersection of these straight lines is one of apexes of equilateral triangle with its side half a side of basic triangle and with its orientation, coinciding with the latter; other apex of the small triangle is in the first asymptote of the hyperbola, and its third apex is in the second asymptote of the hyperbola; a beam out of the cylinder section center through the third apex of small triangle is deflected from the flow central line at an angle 35^0

and, in that way, one passes through a point of a contact of the hyperbola arch with the cylinder section contour.
Further solution is that a point of intersection of the beam 35^0 with the hyperbola axis is center of curvature in its apex, and a distance from the center to the point 35^0 on the cylinder section contour is radius of the hyperbola in its apex. Thus, real part of the hyperbola as internal effective boundary of the jet stream is placed between the flow central line (as the first asymptote) and the hyperbola axis and further – up to a point 35^0 in the cylinder section contour – follows the circumference arch, determining the hyperbola apex curvature. After smooth contact, internal boundary of the jet stream coincides with a part of the cylinder section contour up to a point of its separation immediately before the cylinder middle.
Other solution, very similar to the above-described solution, can be achieved by means of use of apex of small equilateral triangle, coinciding with the hyperbola axis, as center of curvature of the hyperbola apex and of use of a side of the triangle, placed opposite the apex, as a tangent to the hyperbola apex. Below, it will be showed that, in spite of geometrical possibility of such construction and proximity of the achieved result to the above-described, such construction not possessed necessary generality for graphical reproduction of the flow field at high subsonic velocities, M > 0.6, of the unrestricted flow.
Fig. 5, in its right side, represents construction of effective external boundary of the jet stream. This is boundary of a contact interaction of the jet stream with external passing flow. The boundary is, geometrically, combination of two curves: hyperbola and ellipse. A point of smooth conjugation of these curves is determined by the secant parabola (ellipse). Succession of construction of external boundary of the jet streams is the following:
- the first asymptote of the hyperbola coincides with initial boundary of a part of the unrestricted flow, running against immediately the cylinder, i.e. one is straight line parallel to the flow central line and touching the cylinder section contour;
- the second asymptote of the hyperbola is prolongation of the second asymptote, utilized at construction of internal boundary of the jet stream before the cylinder;
- a point of intersection of the hyperbola axis with prolongation of a side of basic equilateral triangle, placed perpendicular to the flow central line, is a curvature center in the hyperbola apex;
- a side of large equilateral triangle (at the right of basic triangle), placed opposite to its apex in center of curvature of the hyperbola apex, is a tangent to the hyperbola apex;
- real part of the hyperbola is restricted by secant parabola (ellipse); axis of the parabola is perpendicular to the flow central line and one passes through a point of intersection of the hyperbola asymptotes; real part of secant parabola touches the above-described radial beam 35^0 in a point of its intersection with the cylinder section contour; further, secant line intersects orthogonally the hyperbola as the jet stream external boundary and thereby restricts its real part;
- prolongation of external boundary of the jet stream – behind the secant line and orthogonal to it – has the kind of the ellipse arch with its major axis coinciding with the flow central line; at the same time internal boundary of the jet stream is placed equidistant to its external boundary after separation of the jet stream and the cylinder.
Such construction of effective boundaries of the jet stream stipulates smooth successive decrease in its thickness from its initial quantity equal the cylinder radius, R_c, to $0.90507R_c$, at $\theta = 35^0$ and then to $0.625R_c$ at $\theta = 70^0$; accomplishment of the continuity condition stipulates correspondingly smooth successive increase in its average velocity from initial quantity, v_0, to $v_{j35} = 1.10488v_0$ and then to $v_{j70} = 1.6v_0$. A thickness of the jet stream at $\theta = 35^0$ is determined by a length of the secant line arch in the limits of its effective boundaries. The number 0.90507 coincides with $\sqrt{\cos 35^0}$, and the number 1.10488 coincides, according to the continuity condition, with $1/\sqrt{\cos 35^0}$. Such "turning over" is bound with a change of a curvature sign of the jet stream boundaries before the cylinder and near lateral side of its section in a point $\theta = 35^0$.
Going on to a velocity head, it should be wrote

$$v_{j35}^2 = (1.10488v_0)^2 \equiv v_0^2/\cos 35^0 = 1.22v_0^2 \tag{5}$$

and, correspondingly,

$$p_{j35} = \rho v_{j35}^2/2 = 1.22\rho\, v_0^2/2 = 0.61\rho v_0^2\ . \tag{6}$$

Further motion of the jet stream along lateral part of the cylinder section contour is accompanied by intensive increase of its velocity and velocity head to maximum quantity

$$v_{j70}^2 = (1.6v_0)^2 = 2.56v_0^2 \tag{7}$$

and, correspondingly,

$$p_{j70} = \rho\, v_{j70}^2/2 = 2.56\rho\, v_0^2/2 = 1.28\rho v_0^2. \tag{8}$$

These quantities of a velocity head of the jet stream stipulate action of centrifugal forces onto lateral part of the cylinder section contour. A quantity of these forces, i.e. its intensity along a line of immediate contact of the jet stream with the cylinder section contour, is equal in number to a velocity head of the jet stream in the corresponding points of the contact. At the same time, pressure of a part of the unrestricted flow moving side by side the jet stream counteracts to these centrifugal forces. This counterpressure balances exactly at $\theta = 35^0$ action of centrifugal forces. Fig. 6 represents a diagram of the forces, acting at $\theta = 35^0$ of the cylinder section. Further, at $\theta = 70^0$, influence of the counterpressure becomes negligible, and lateral action of the jet stream onto the cylinder is determined, practically completely, by centrifugal forces, i.e.

$$p_{cf70} = -p_{j70} = -1.28\rho v_0^2 \tag{9}$$

The quantity corresponds quite to half-sum of quantities, taken in the well-known experimental researches [4, 6], adduced in fig. 1. Further motion of the jet stream between sections $\theta = 70^0$ and $\theta = 85^0$ is going on under action of the following factors:

- a maximum velocity head, achieved by the jet stream at its acceleration to section $\theta = 70^0$, promotes straighten trajectory of its motion, i.e. to its motion along a tangent to the cylinder section contour;
- a boundary layer of the jet stream at its external boundary is quite adapted to the passing part of the unrestricted flow and one promotes inertial progressive motion of the jet stream at section $\theta = 70^0$, i.e. its motion along a tangent to the cylinder section contour;
- a boundary layer of the jet stream at its internal boundary is in a contact with the inadaptable surface of the solid body, and curvature of surface of the body not promotes inertial progressive motion of the jet stream after section $\theta = 70^0$.

As a result, inertial progressive motion of the compact jet stream along a tangent to the cylinder section contour leads, in the beginning, $\theta = 35^0$, to a smooth decrease of centrifugal forces, and then, $\theta = 85^0$, to a separation of internal boundary of the jet stream and the inadaptable curvilinear surface of the cylinder. Now a force of the jet stream - as a product of area of its unit section and its velocity head - is, in the main, expended onto in turn formation and throwing out of vortexes away from back side of the cylinder. At the same time such expenditure of energy equalizes a velocity of the jet stream with a velocity of the unrestricted flow. Successively enumerated typical parts of the jet stream motion are indicated in fig. 6 and in three subsequent. Fig. 7 shows the rarefaction distribution at lateral and back sides of the cylinder section, corresponding to the above-stated description and the results of the well-known experimental research [4] at Re = $1.86 \cdot 10^5$ and M << 0.6.

Fig. 8 shows a change of external boundary of the jet stream correspondingly to the results of experiments [4, 6]: a thickness of the jet stream is decreased, and its velocity, accordingly to the continuity condition, is increased from $v_j = 1.6v_0$ at Re = 1.86· 10^5 to $v_j = 2.22v_0$ at Re = 6.7· 10^5. The most probable cause of such decrease of rarefaction behind the cylinder is described above in this text.
It should be noted, excessive increase of velocity of the jet streams from the moment of its origin and to its separation with the cylinder surface promotes stability of its laminar motion. Restriction by quantity $0.6v_0$ of an outstripping motion of the jet streams relatively the unrestricted passing flow promotes also conservation of laminar motion of the jet streams at its external boundary. Centrifugal forces, acting in a zone of immediate contact of the jet stream with the cylinder, $35^0 \leq \theta \leq 70^0$ *or* 85^0, promote continuous contact of the jet stream with the unrestricted passing flow, and at the same time these forces stipulate always potential possibility of separation of the jet stream and a body.
Fig. 9 shows the examples of construction of a pressure distribution of the liquid free jet on a front side of the cylinder section and flat surface. A difference of the first of its from analogous to it in the unrestricted flow is only that in the last case a velocity head of the jet stream is not constant and one is increased as the jet stream interacts with obstacle.
Fig. 10 shows a change of internal boundary of the jet stream and corresponding to it's a displacement of a point of initial contact with the cylinder section contour as Mach number is increased from M << 0.6 up to M = 0.6 and M = 0.8 accordingly to the results of Ferri experiments [5]. External boundary of the jet streams, in contrast to the results of Flachsbart experiments [4], remains invariable. The results of experiments at M = 1.85 [5] and the results of a visualization of air-flow at Mach numbers 0.9, 0.95, 0.98 and 2.5, adduced correspondingly in photo 222 and the unnumbered photo, placed before photo 1, in An album [7], is evidence of renewal of generation of vortical "foam" immediately behind the cylinder, but now with considerably lesser diameter of vortical bodies. Turbulization of a wake behind the cylinder is formed by throwing out the surplus vortexes in the kind of its clots. Rarefaction behind the cylinder is considerably decreased. A point of initial contact of internal boundary of the jet stream with the cylinder section contour is displaced to $\theta = 80^0$ (instead 35^0). A separation point is displaced to $\theta = 115^0$ at M = 2.5. These displacements are stipulated by influence of the shock waves onto the flow field kinematics.

Solution: part 3

A body of one of the simplest form in the kind of a thin flat round plate – disk is geometrical and hydrodynamic prototype of other simplest body but the 3-D form – a ball. At the same time both these bodies form the simplest spatial structure of a flow field – axisymmetric.
The results of experimental determination of the drag coefficient of the disk and ball, adduced in L. Prandtl book [8], testify to the following:
- in region of the creeping flows, $0 < Re \leq 10 \div 20$, when inertial forces are negligible, the drag coefficient of disk is some less that of ball; at the same time a dependence of the coefficient on Reynolds number both these bodies is graphically expressed by equidistant curves;
- in hydrodynamic region of the flows, $10 \div 20 < Re \leq 10^3$, the drag coefficient curve of disk passes smoothly to horizontal line in the level $C_x = 1.10 \div 1.12$ and one remains constant up to $Re = 10^6$ not far from "subcritical" curve of the cylinder drag coefficient. In contrast to the cylinder a curve of the disk drag coefficient has not sharp lowering at $Re = (2 \div 6) \cdot 10^5$ and M << 0.6. At the same time a curve of the ball drag coefficient is smoothly reduced to $C_x = 0.4$ at $Re = 4 \cdot 10^3$, then one is smoothly rose to $C_x = 0.5$ at $Re = 3 \cdot 10^4$ and – after its part not far from a horizontal at $Re = 1.6 \cdot 10^5$ – one is sharply reduced to $C_x = 0.1$ at $Re = 4 \cdot 10^5$. This curve for ball is now classical, and one is here described only for comparison with the curve for disk.

The results of visualization of the unrestricted flow around the ball, adduced in An album [7], testify to the following:
- in region of a creeping flows, $0 < Re \leq 0.1$, photo 9 (M. Coutanceau, 1968) [7] shows that a region of disturbance of still fluid (transparent silicon oil) is localized around the ball in the kind of sphere with its diameter equal approximately 2.2 diameter of the ball, i.e. a volume of zone of a disturbed fluid is ten times the ball volume. Tracks of the visualizing particles bring to light three zones of the fluid disturbance: a pushing on zone – before the ball, a suck in zone – behind the ball and a torus vortex zone, uniting two previous zones – around the ball middle section. The fluid is motionless outside the disturbance region. Photo 8 (M. Coutanceau, 1968) [7], made at the same Reynolds number, shows a fluid motion, flowing round the ball. Tracks of visualizing particles show zone of the flow braking and of a turn – near frontal point of the ball, zone of the flow acceleration – along the ball lateral surface up to its middle section and then a structure of tracks behind the ball symmetrical to that before the ball;
- in the flow region, $Re = 6.9 \div 9.8$, photo 25, 28 (M. Coutanceau) [7], both type of the ball motion – in motionless fluid and in the fluid flow – show asymmetry of a structure of the track lines. In motionless fluid, the suck in zone is increased; the torus vortex is displaced from the ball middle section to the ball back side. In the fluid flow, a zone behind the ball is increased, but the pair-vortex structure in it not appears yet;
- at Re > 50, photo 51 (M. Coutanceau,1974) [7], transition of a flow to hydrodynamic motion is completed: the torus vortex is displaced into a zone immediately behind the ball and one forms single hydrodynamic body with the ball, having the lesser drag.
The above-stated description of the results of quantitative estimation of the drag coefficient and visualization of a flow as Reynolds number is increased allows supposing the following:
- tenfold exceeding the disturbance zone of motionless real fluid around the ball at its motion, corresponding to the creeping flows, testifies to weak influence of a body form onto structure of a flow field and quantity of resistance to its motion; therefore it can be supposed that structure and dimensions of the disturbance zone of motionless fluid around the disk is very close by these parameters of the ball; two-dimensity of the disk stipulates, in the given case, some lesser resistance to its motion in comparison with the ball;
- divergence of the drag curves of the disk and the ball, as Reynolds number is increased at the developed hydrodynamic flow, is bound with features of interaction of the jet streams – induced by the obstacles in the unrestricted uniform flow – with a form of these bodies. In the case of the disk, the laminar jet stream in the kind of circular mantle goes off from its circular edge at constant angle ~ 45^0 (from the flow central line) and one envelops the torus vortex body. An increase of Reynolds number leads to an increase of the jet stream velocity and to a corresponding stretching the torus vortex body up to the utmost state, when a very long axisymmetric wake is formed behind the disk. The drag coefficient achieves its minimum quantity $1.10 \div 1.12$ and one remains invariable at further increase of a flow velocity. In the case of the ball, circular mantle of the laminar jet stream interacts in the beginning with its lateral surface in the limits$45^0 \leq \theta \leq \sim 85^0$, and then one envelops the torus vortex behind the ball. Separation of the jet mantle with the ball lateral surface at temperate Reynolds numbers is accompanied by its oscillations in the kind of periodic deflections in the limits$\sim 7.5^0 \mp 2.5^0$ from the flow central line, instead $\sim 45^0$ in the case of the disk. Because of the oscillations, the jet mantle compresses periodically the torus vortex in its diameter, stretches it flow down and therefore one stipulates more intensive lowering a curve of its drag coefficient in comparison with the disk. Some further increase of Reynolds number leads to formation of a long stationary wake behind the ball, just as it is described for the disk, and to stabilization of quantity of its drag coefficient. But, in contrast to the disk, laminar interaction of the jet mantle with a part of the unrestricted flow, adjoined back and lateral sides of the ball, is remained only at temperate – "subcritical" – Reynolds numbers. And then, at $Re = (3.5 \div 4) \cdot 10^5$, separation of the laminar jet mantle, moving at high velocity, from the ball surface is accompanied by that the boundary layer of the mantle near its internal boundary induces formation of vortexes in adjoined it layer

of the fluid, located near back side of the ball. In that way, the jet mantle becomes a circular generator of a stream of small vortexes, which ones destroy and oust the single torus vortex behind the ball, and ones fill and overfill with themselves this zone and form a cellular vortical structure – so called vortical "foam". Combination of centrifugal forces of multitude of small vortexes, replenishing continually the vortical foam under action of the jet mantle, leads to an increase of pressure behind the ball from rarefaction up to not great surplus quantity. Corresponding to it, a drag coefficient of the ball is approximately third. The results of visualization a flow around the ball, adduced in photos 56 and 58 (H. Werle, 1980) [7], corroborate rightness of the stated here description, according to which, formation of a single large-scale torus vortex or succession of small vortexes is going on just in a layer of stagnant fluid between the ball surface and internal boundary of the laminar jet mantle, induced by the ball front side. The single torus vortex is clearly seen in the first of the above-mentioned photos. In the second photo, the vortex is lack, and the zone is filled by chaotic moving particles. Photo 57, in the same series, shows a result of interaction of internal boundary of the jet mantle with the thin wire hoop, setting on the ball before its middle section:

- the jet mantle forms a returning vortex before the hoop along its perimeter, that is quite naturally for sharp obstacle, placed on smooth surface;
- an overcoming of the obstacle is accompanied by separation of internal boundary of the jet mantle and the ball surface on a length ~ 15 diameters of the hoop wire, i.e. near 95^0 from the ball frontal point, that is also naturally for zone of the ball middle section. In this section, the forces, pressing the jet mantle to the ball surface by the unrestricted passing flow, are negligible, while centrifugal forces, induced by the jet mantle itself, reach its maximum quantity;
- separation of the jet mantle and the ball surface is, naturally, accompanied by ejection, creating rarefaction in the separation zone, and by twisting portions of fluid in stagnation zone between the ball lateral surface and the jet mantle. In that way, the laminar jet mantle becomes generator of succession of small vortexes;
- further progressive motion of the small vortical bodies under condition of an increase of width of the separation zone is stimulated by its frictional connection with the jet mantle as source of linear momentum; diameter of the vortical bodies, following one after another, is increased as a width of the separation zone is increased. In one's turn, velocity of the jet mantle near its internal boundary is decreased because of emission of a part of kinetic energy of its progressive motion to a rotary and progressive motion of the vortical bodies; a thickness of the jet mantle near its internal boundary is correspondingly decreased, the boundary is displaced and thereby one some narrows a zone of separation. But at $\theta \cong 140^0$ the separation zone becomes similar to that of a body with its flat back part, and small vortical bodies fill a space behind the ball, forming so called vortical foam. Transfer of kinetic energy of the jet mantle to external layer of the vortical foam compensates rarefaction behind the ball and creates not great surplus pressure. In a result, the drag coefficient of the ball is took a third. In that way, the natural or artificially created wall turbulence between a 3-D body surface and the jet stream (mantle) as a result of interaction of the body form with the unrestricted flow of real fluid is a generator of the small-scaled vortical bodies, moving in the separation zone under coercion of the jet stream. Continual succession of the vortical bodies destroys the single large-scaled vortex and creates instead of it a vortical foam zone, which one increases pressure behind the body.

The above-stated description of qualitative aspect of interaction of the unrestricted flow with the ball and the disk, corresponding to the results of the well-known experimental research, adduced in [8] and in fig. 11, is description of general conceptual model of the phenomena as necessary condition for passing on to a solution of problem on kinematics of a flow field around the ball and on dynamics its interaction with the real fluid flow.

In the beginning, the author supposes it to be expedient to elucidate the question on kinematics of the flow field around the ball like to that as it is made in its previous article [1].

Geometrically possible diagram of a flow near the front side of the ball surface can be constructed by means of the circumference arches. For example, if a circular cross-section area of the liquid free jet is half the ball middle section area, i.e. $A_{j0}/A_{bm} = 1/2$, where $A_{j0} = \pi R_{j0}^2$ and $A_{bm} = \pi R_b^2$, then $R_{j0} = R_b/\sqrt{2} = 0.7071R_b$. Radius of external surface of the circular jet mantle in a flatness of the ball middle section is determined by the continuity condition $A_{jm} = A_{j0}$ at $v_{jm} = v_{j0}$, i.e. $\pi R_{jm}^2 - \pi R_b^2 = \pi R_{j0}^2$, from where, taking into account $\pi R_b^2/(\pi R_{j0}^2) = 2$, it is following $R_{jm} = R_{j0}\sqrt{3}$, and a thickness of the circular jet mantle in the same section is $b_{jm} = R_{jm} - R_b = \left(\sqrt{3/2} - 1\right) R_b = 0.225R_b$.

Fig. 12a, in its left side, shows a diagram of construction of a profile of internal and external boundaries of the circular jet mantle as a result of interaction of the liquid free jet with the ball surface. Initial stage of the construction contains two figures in the kind of basic equilateral triangle with its side equal the ball diameter and one of its apex in the ball center, as well as basic rectangle with one of its bases, coinciding with a side of basic triangle parallel to the ball middle flatness, and with its height equal the ball radius. A circumference arch with its radius equal the ball radius and with its curvature center in lateral apex of basic triangle determines internal boundary of the jet mantle from the flow central lime before the ball up to its smooth contact with the ball section contour in a point of its intersection with lateral side of basic triangle. After the point, internal boundary of the jet mantle coincides with the ball section contour. Thus, the stage of construction corresponds and coincides with that stage of interaction of the liquid free jet with cylinder, shown in fig. 3.

Construction of external boundary of the jet mantle is stipulated by axial symmetry of a flow around the ball, and one contains the following stages:

- draw straight lines as boundaries of initial free jet to intersection with the ball diameter in its middle section;
- draw a straight line out of the right end of the ball diameter in its middle section to intersection with a straight line prolonging the left side of basic triangle side parallel to the ball middle flatness; the straight line must pass through a point of intersection of the left lateral side of basic triangle with the lower base of basic rectangle as a focus point, F;
- the point in straight line, prolonging the basic triangle side, determines radius of a turn of a boundary of initial free jet in the limits of the straight line, passing through the focus point, F;
- a part of straight line between the point F and the right end of the ball diameter is radius, determining extension of external boundary of the jet mantle.

The adduced description and an example in fig. 12a allow constructing the flow field trajectories near front and lateral sides of the ball surface by means of consecutive increasing of the free jet section. Such construction ensures smooth degeneration of curvature of the flow field trajectories into straight lines as the section of the free jet is increased side by side with keeping the continuity condition. At the same time such kinematic structure, although one is geometrically possible, is formal and physically not adequate construction as every increasing of a section radius of initial free jet is bound with necessity of increasing of the ball diameter and every previous layer of fluid is thus much hard for sequent layer as the ball body.

In that way, solution of a problem on kinematics of the unrestricted flow around the ball is again bound with necessity to use curves from assemblage of conical sections. At the same time, some geometrical elements – basic equilateral triangle with its side equal the ball diameter and rectangle conjugated with the triangle and containing in itself the basic flatness line, BFL, - as before form a basis for construction of the jet stream in the kind of circular mantle, enveloping the ball and a part of a flow behind it.

Fig. 12b, in its fight side, shows a diagram of construction of a profile of effective boundaries – internal and external – of the circular jet mantle interacting with the ball and with the unrestricted flow of real fluid. The left side of fig. 12b contains a diagram of fictitious boundaries of the mantle, constructed in the left side of fig. 12a, when the section area of the jet stream before the ball equal area of the ball middle section; thus a thickness of the fictitious jet mantle in the ball middle section equal$(\sqrt{2} - 1)R_b = 0.4142R_b$; the quantity, answering the continuity condition is used as the initial for construction of effective external boundaries of the jet mantle at $Re = 1.6 \cdot 10^5$ and at $Re = 4.3 \cdot 10^5$ correspondingly to the results Flachsbart experimental research [4]. A profile of the fictitious boundary is symmetrically reflected also to the right side of fig. 12b for comparison with effective boundaries of the real jet mantle. Construction of internal effective boundary of the jet mantle correspond to that of the cylinder, including displacement of a point of a smooth initial contact of the boundary with the ball section contour as Reynolds number is increased; the displacement according to the results of Flachsbart [4] and Povch [9] experimental researches is $(45^0 \div 51^0) \geq \theta \geq (43^0 \div 45^0)$. The largest quantity of the displacement angle is determined by radial beam, passing out of the ball section center through apex of the lesser equilateral triangle, which one coincides with asymptote120^0; other apex of the triangle coincides with the flow central line and its third apex – with axis of hyperbola, forming internal effective boundary of the jet mantle before the ball. Succession of construction of external effective boundary of the jet mantle envisages construction of the secant parabola (ellipse) branch, contacting smoothly with the mentioned radial beam on a point of its intersection with the ball section contour. Axis of secant line is perpendicular to the flow central line and one passes through a point of intersection of the hyperbola asymptotes; the upper part of the hyperbola up to the secant line is the front part of external effective boundary of the jet mantle; a part of the external boundary behind the secant line is an ellipse with its major axis coinciding with the flow central line; the ellipse arch is orthogonal to the secant line and one is smoothly conjugated with the mentioned upper part of hyperbola as a front part of external boundary of the jet mantle, but with inverse sign of curvature; this second part of the external boundary determines its effective thickness in zone $70^0 < \theta < 85^0$, where average in section velocity and correspondingly a velocity head of the jet mantle reach its maximum quantity. It is naturally to suppose that effective thickness of the jet mantle is lesser its fictitious quantity owing to lateral pressure of the unrestricted flow onto it. A condition for determination of effective – real – thickness of the jet mantle is in that a quantity of centrifugal forces in zone of immediately before the ball middle section equal in number a velocity head of the jet mantle, i.e. in zone where action of lateral pressure of the unrestricted flow onto the jet mantle is negligible. Acceptance of such condition allows using the results of the well-known experimental researches in the kind $C_p = f(Re)$ diagram, adduced in fig. 11, for determination of average in section velocity of the jet mantle in the mentioned zone:

- at "subcritical" Reynolds numbers

$$C_p = -0.605\, p_j/(\rho\, v_0^2/2), \quad (10)$$

from where

$$-\rho\, v_j^2/2 = -\rho\, (1.21 v_0)^2/2 \quad (11)$$

and, accordingly,

$$v_j = 1.095 v_0; \quad (12)$$

the second condition – a continuity condition – determines real effective thickness of the jet mantle relatively to its fictitious quantity

$$b_{je} = b_{jf}/1.095 = 0.4142\, R_b/1.095 = 0.378 R_b; \quad (13)$$

- at "critical" Reynolds number analogically

$$C_p = -1.2\, p_j/(\rho\, v_0^2/2), \quad (14)$$

from where

$$-\rho\, v_j^2/2 = -\rho\, (2.4 v_0)^2/2 \quad (15)$$

and, accordingly,

$$v_j^* = 1.549 v_0 \quad (16)$$

and further

$$b_{je} = b_{jf}/1.549 = 0.4142\,R_b/1.549 = 0.267R_b. \tag{17}$$

The obtained quantities of effective thickness of the jet mantle determine a position and curvature of a part of its external boundaries in the kind of the ellipse arches relatively the ball section contour behind the secant line. At the same time, position of the ellipse arches - together with asymptotes, axis and a curvature radius in its apex – determines position of a hyperbola arch as external boundary of the jet mantle behind the secant line. Besides that, the obtained quantities of the maximum velocity of the jet mantle determine the maximum quantities of centrifugal forces near the ball lateral surface immediately before its middle section:

- at "subcritical" Reynolds numbers

$$p_{jcf} = -\rho\,(1.1v_0)^2/2 = -0.605\rho v_0^2; \tag{18}$$

- at "critical" Reynolds number

$$p_{jcf}^{*} = -\rho\,(1.55v_0)^2/2 = -1.2\rho v_0^2. \tag{19}$$

The greatest quantity of rarefaction behind the ball at "subcritical" Reynolds numbers is approximately 2/3 of the greatest quantity of a velocity head of the jet mantle

$$p_{j180} = -(2/3)\cdot 0.605\rho v_0^2 = -0.4\rho v_0^2, \tag{20}$$

and at "critical" Reynolds number, when the vortical "foam" has forced out the single torus vortex behind the ball, centrifugal forces of the foam, determined by a velocity head of the jet mantle, not only compensate rarefaction behind the ball, but ones create some surplus pressure

$$p_{j180}^{*} = 0.2\rho v_0^2. \tag{21}$$

Laminar motion of a main body of the jet mantle, enveloping a zone of vortical foam, together with the unrestricted passing flow, gathering round it, is accompanied by throwing out the surplus small vortical bodies, turbulizing a wake behind the ball.

The results of Ferri experiments [5] testify to that a phenomenon of sharp decrease of the drag coefficient of a ball at sufficiently high velocities of subsonic air-flow, M > 0.6, and at Reynolds numbers up to $7\cdot 10^6$ is absent. At the same time, the results of visualization of interaction of supersonic air-flow with a ball Mach numbers 1.53, 3.0 and 4.01, adduced correspondingly in photos 266, 271 and 269 in An album [7], testify again to an origin of a zone of vortical foam, but now with considerably lesser diameter of vortical bodies; in a result, rarefaction behind the ball is sharply decreased. Separation of the jet mantle and the ball surface is going on at103^0, 114^0 and 117^0 correspondingly to the above-indicated Mach numbers and one is stipulated by action of the shock waves.

In conclusion, returning to a problem on interaction of the liquid free jet with a ball, one cannot but take notice of that in spite of difference of a form of the jet streams – flat or circular, the diagrams in fig. 2 and description of the results of interaction is equally applied to these bodies.

Discussion of results

In connection with positive solution of a number of problems, stated in the given and previous articles [1, 2], the author supposes it to be advisable to note some features of the present situation in kinematics and dynamics of interaction of the real fluid flow with obstacle in the kind of the bodies of different form and its spatial orientation, which ones have engendered necessity of creation of a new in principle approach to overcoming of the given problem.

The first feature: "…*decisive success is reached not by means of piling up of experimental material and, on the contrary, by some few fundamental experiments in combination with theoretical considerations*" declared H. Schlichting in its compilation [4] with its size in more 700 pages. The book not contains a method of theoretical determination of a body drag, but in

the beginning of the second chapter, the author presents in fig. 2.2 diagrammatical image of a velocity profile in a boundary layer of low-viscous fluid, moving along the thin flat plate as if it corresponds to a photo of visualization of such real flow in previous fig.2.1. The photo shows clearly a deflection of tracks of the visualizing particles in both sides away from the plate before its front edge. It signifies that a viscous brake of the flow immediately near the plate surface coerces the flow to its accelerating action onto the brake layer up to going round it in order to answer the continuity condition. In spite of it, the mentioned diagrammatical image of the velocity profile not contains a layer of the accelerated motion of real fluid, superposed onto the brake layer. In his previous article [2], the author had considered and solved already a question on induction of the jet streams at longitudinal motion of real fluid flow along the thin flat plate and one had showed that the viscous resistance immediately near its surface is equivalent to a form resistance. Therefore, viscous resistance must also induce the jet streams, partially superposed and partially passing round such "soft" obstacle and by its heightened velocity one must ensure a carrying out the continuity condition. Prandtl and following him Schlichting was intending to show a boundary layer in its simplest shape, and, in the carried out experiment, they had saw not total picture of the flow, but only that what they want to see in it. They had not noticed a breach of the continuity condition in their diagrammatical image of a velocity profile. Disregard of the continuity condition signifies, in the given case, possibility of an unrestricted accumulation of a fluid near obstacle. Such predetermined interpretation of the specially organized experiment had closed during more than100 years a way to valuable development of mechanics of interaction of a real fluid flow with a body form as obstacle to its motion.
S. Goldstein may be unique, who as far back as 1938 had clearly stated: "The mathematical calculations by means of the boundary layer theory are based on the beforehand given distribution of pressure. Determination of the pressure distribution by means of the theory is impossible" [10]. The warning of the experienced specialist in a field of aero- and hydromechanics was, as usually, found to be vain.
The second feature. Development of theory of the ideal liquid jets, continued during more than 150 years with its often striking physical emptiness, compromises possibility of development of theory of the real fluid jets.
The third feature - is division of integral knowledge on the real fluid motion onto small fragments, not united, as a rule, between itself by logical connection.
Fig. 13 shows a graph in the kind of single curve, generalizing the results of numerous experimental researches of the ball drag coefficient in dependence on Reynolds numbers. The graph is accompanied by empirical expressions which ones reproduce successively its fragments [9]. Integral perception of the graph is broke by these empirical expressions.
Fig. 14 shows a part of equilateral hyperbola plotted on analogical well-known graph [4] as integral dependence in supposition of interaction of the unrestricted uniform flow of real fluid with a ball without separation of the flow and the ball surface.
Fig.15 shows a part of equilateral hyperbola plotted on analogical well-known graph of a drag coefficient of circular cylinder [4] in the same supposition on interaction without separation.
Fig. 16 shows graphical diagram, adduced in fig. 15 and supplemented by copy of equilateral hyperbola, displaced down to a half quantity of a drag coefficient of the cylinder. In that way, the lower hyperbola signifies a part of the cylinder drag, determined by its front side, and difference between experimental curve and the upper hyperbola is stipulated by exceeding real (with taking into account of separation of the flow and the cylinder) resistance of the cylinder back side in comparison with supposed interaction without separation.
The fourth feature is Prandtl experiment with the thin wire hoop mounted on a ball before its middle section. Interpretation by Prandtl of a cause of sharp lowering of the ball drag coefficient requires special consideration. The point is that the jet streams (mantle), induced by interaction of a body as obstacle to the unrestricted flow of real fluid, form a near flow field around the body. Features of kinematics and dynamics in the field are determined by the body form and its orientation to the flow direction. Property of the jet streams to be retained mainly laminar type of

its motion is stipulated by two basic factors: its accelerated motion before a body and along its lateral surfaces and also the unrestricted passing flow near its external boundaries. Owing to action of these factors, stability of laminar motion of the jet streams around a cylinder and ball is very close to stability of laminar flow along the thin flat plate as a limit case of the laminarizing influence of the external passing unrestricted flow onto motion of real fluid in the boundary layer. In contrast to it, stability of a fluid flow in a pipe is, as it generally known, the lowest because of negligible quantity of a flow section part near the flow axis, where the flow is more uniform then that close by the pipe wall. The determining influence onto laminarization of a motion of the jet streams in far wake belongs also to the unrestricted passing uniform flow, which one reduces disturbances, formed by throwing out of vortical bodies out of near wake behind a body. The laminar jet streams, formed by interaction of the liquid free jet with a surface of cylinder and ball, can be separated from a surface of these bodies immediately outside a zone of bifurcation of the initial jet, when a force of its progressive motion proves to be sufficient, as it is showed in figs. 2 and 12. This is an example of a straight correspondence of the phenomenon of hydromechanics to the first law of general mechanics. In addition, action of centrifugal forces of the jet streams outside a bifurcation zone of initial jet not promotes adjoining the jet streams to a surface of these bodies. The laminar jet streams, induced by interaction of the unrestricted uniform flow with the same bodies, can be also separated from its surface, remaining laminar owing to a presence of the unrestricted flow surrounding it.
Separation of the high velocity laminar jet stream from a body surface is also going on close by the cylinder and ball middle section as it is going on at sufficiently low velocities. Difference of the first of them is in that an interaction with the "dead fluid" at the side and behind a body is accompanied by rolling up the dead fluid layer, bordering to internal boundary of the jet stream, into a succession of vortical bodies. Diameter of these vortical bodies is inversely proportional to a velocity of the laminar jet stream, i.e. the more the jet stream velocity the lesser diameter, formed by it vortical bodies. Prandtl (1914) by means of the thin wire hoop, placed before the ball middle section, has provoked a formation of succession of small vortical bodies at low velocity of the jet mantle. An increase of diameter of the vortical bodies, as distance between the ball surface behind its middle section and internal boundary of the laminar jet mantle is increased, is bound with additional expense of energy of progressive motion of the jet mantle. Therefore a velocity of the jet mantle near its internal boundary is decreased, and its thickness, correspondingly to the continuity condition, is increased. In a result, internal boundary of the jet mantle is some displaced to the ball side. A decrease of a drag coefficient of the ball is, in this case, stipulated by centrifugal forces of the vortical bodies, moving in constrain conditions between the ball and the laminar jet mantle and forming the vortical foam behind the ball, but not by "displacement of a point of separation of a flow up to $110^0 \div 120^0$" [8]. If it was so as it had been explained by Prandtl, then centrifugal forces of vortical foam and of the jet mantle would balance each other.
Stated here and in previous articles of the author, published in "uk.arXiv.org" electronic edition during 2003 – 2008 years, examples of solution of problems within framework of the problem of interaction of the real fluid free jet and the unrestricted flow of real fluid with a body are practical demonstration of a new in essence method of approach to overcoming of the given problem. Created by the author, conceptual model of real phenomenon, corresponding to the results of well-known experimental researches is a basis of the method. The conceptual model is physically adequate description, which ensures its expression by graphical and analytical means and thereby ensures valuable theoretical reproduction of the real fluid kinematics and the interaction dynamics of the fluid flow with a body. According to the model, an interaction of the unrestricted uniform flow of real fluid with obstacles in the kind of a solid body and the viscous boundary layer near its surface as the braking factors is accompanied by inducing of the jet streams (mantles, layers). These streams interact with the braking factors and by its accelerated motion ensure not only flow round the obstacles but also realization the continuity condition.
The jet stream structure contains its flow kernel and viscous boundary layer near every of its

effective boundaries – internal and external. The unrestricted flow forms its viscous boundary layers near boundaries of the jet stream. Laminar interaction of the boundary layers of the unrestricted passing flow and the jet stream near its external boundary masks external boundary of the jet stream, therefore in the given article the boundary is called by effective. Just such conceptual model is the key to theoretical detection of this unknown earlier phenomenon. A notion on it and the examples of its application are evidence of creation of a new in essence physically adequate instrument for the rational theoretical reproduction of kinematics and dynamics of the near and far fields of a flow around obstacle in dependence on its form and spatial orientation. Ascertainment the fact of inducing the jet streams is also straight evidence of mechanical irreversibility of interaction of a body with the unrestricted flow of real fluid.

Final remarks

- Say it, please, and the separation problem, is still it?
- Separation, of what?
- Now, a flow, the stream, at last boundary layer…
- The problem is strongly closed down with the jet mantle.

Acknowledgements

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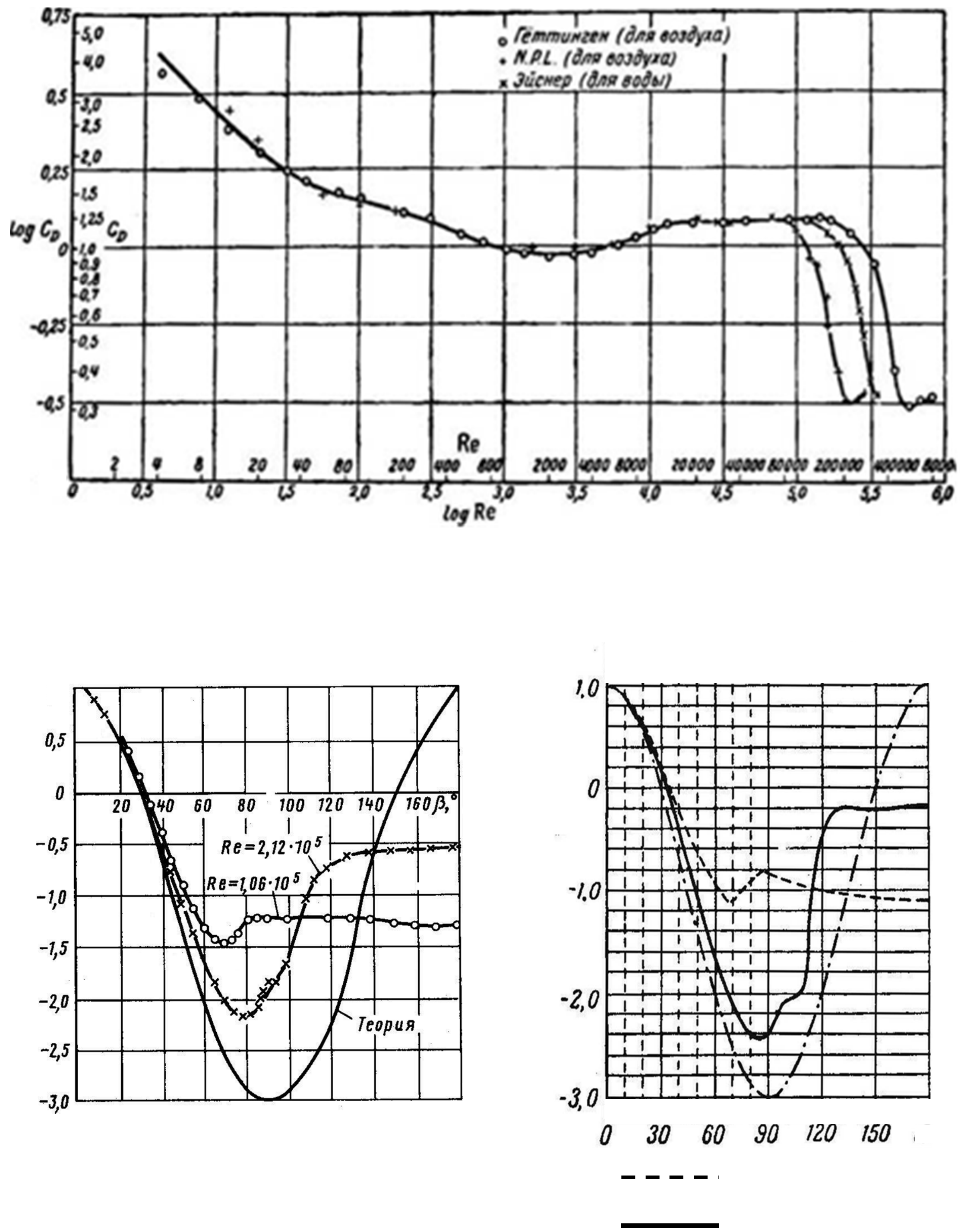


Fig. 1: a) a drag of a cylinder depending on Reynolds number at Mach number M << 0.6 [4]; b) the pressure distribution along the cylinder cross-section contour according to Jemtsev, M << 0.6 [6]; c) the same according to Flachsbart experiments [4]

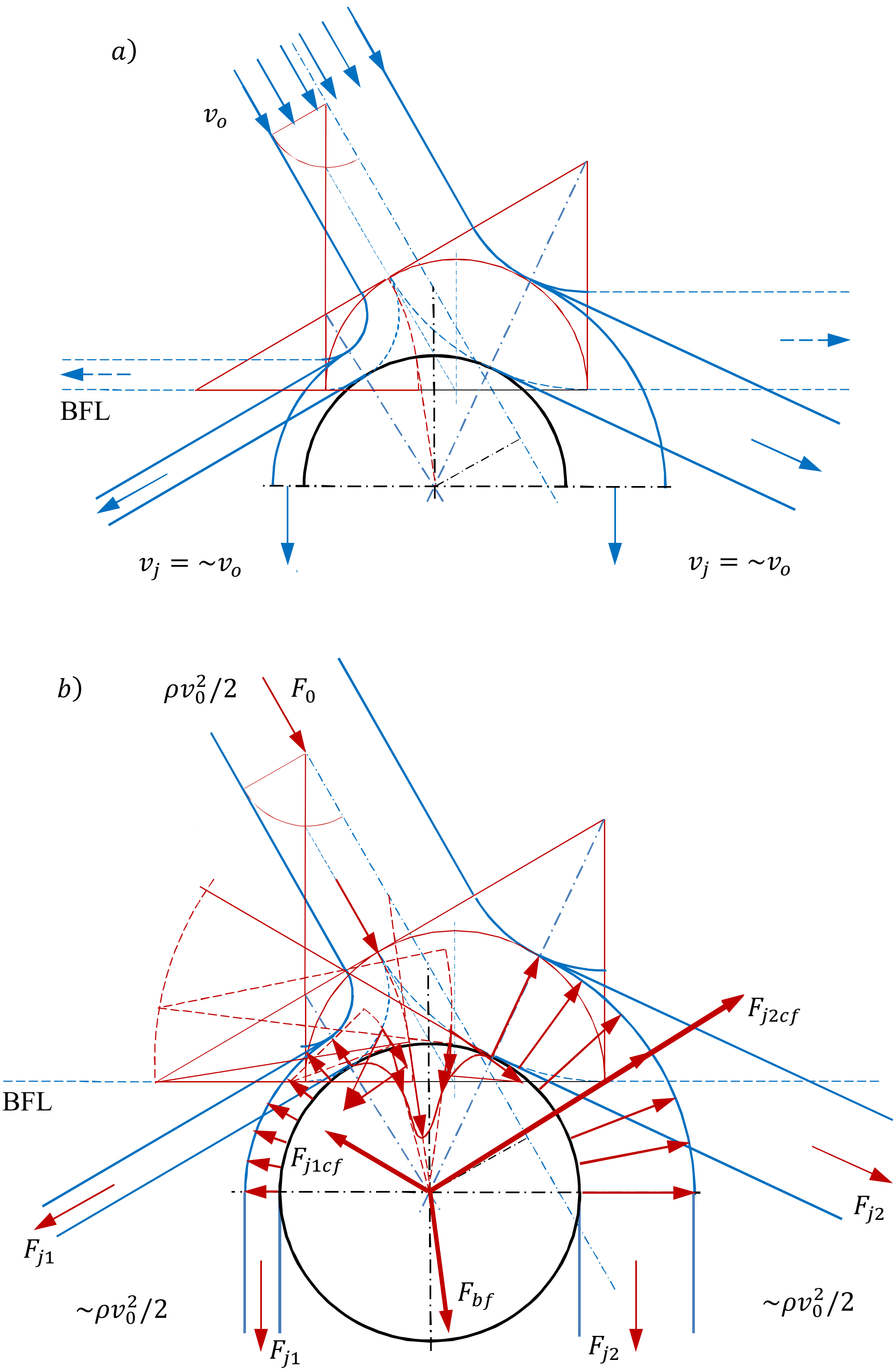


Fig. 2. The liquid flat free jet interacts with a cylinder: a) the eccentric jet with its thickness equal the cylinder radius; b) a diagram of forces, acting onto the cylinder

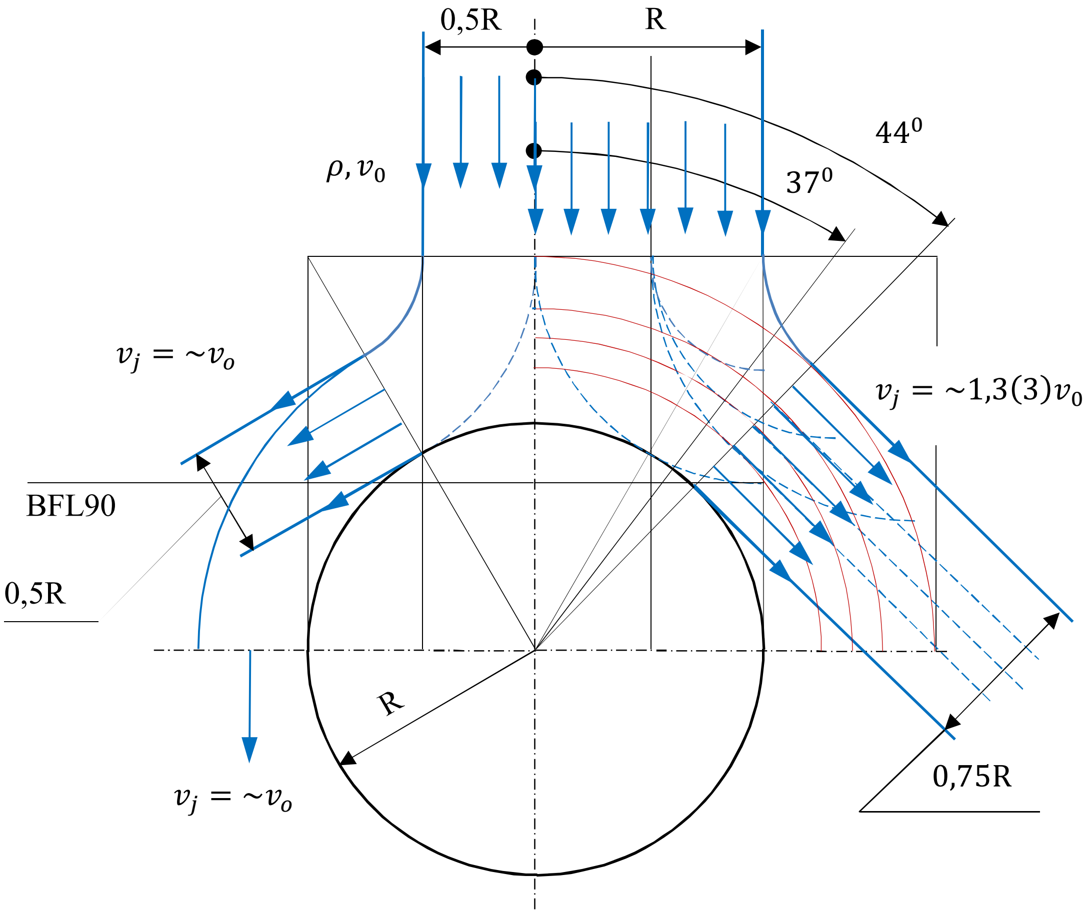


Fig. 3. Central flat free liquid jet with its width equal to the cylinder cross-section radius (the left side) and the jet with its width equal the cylinder cross-section diameter (the right side)

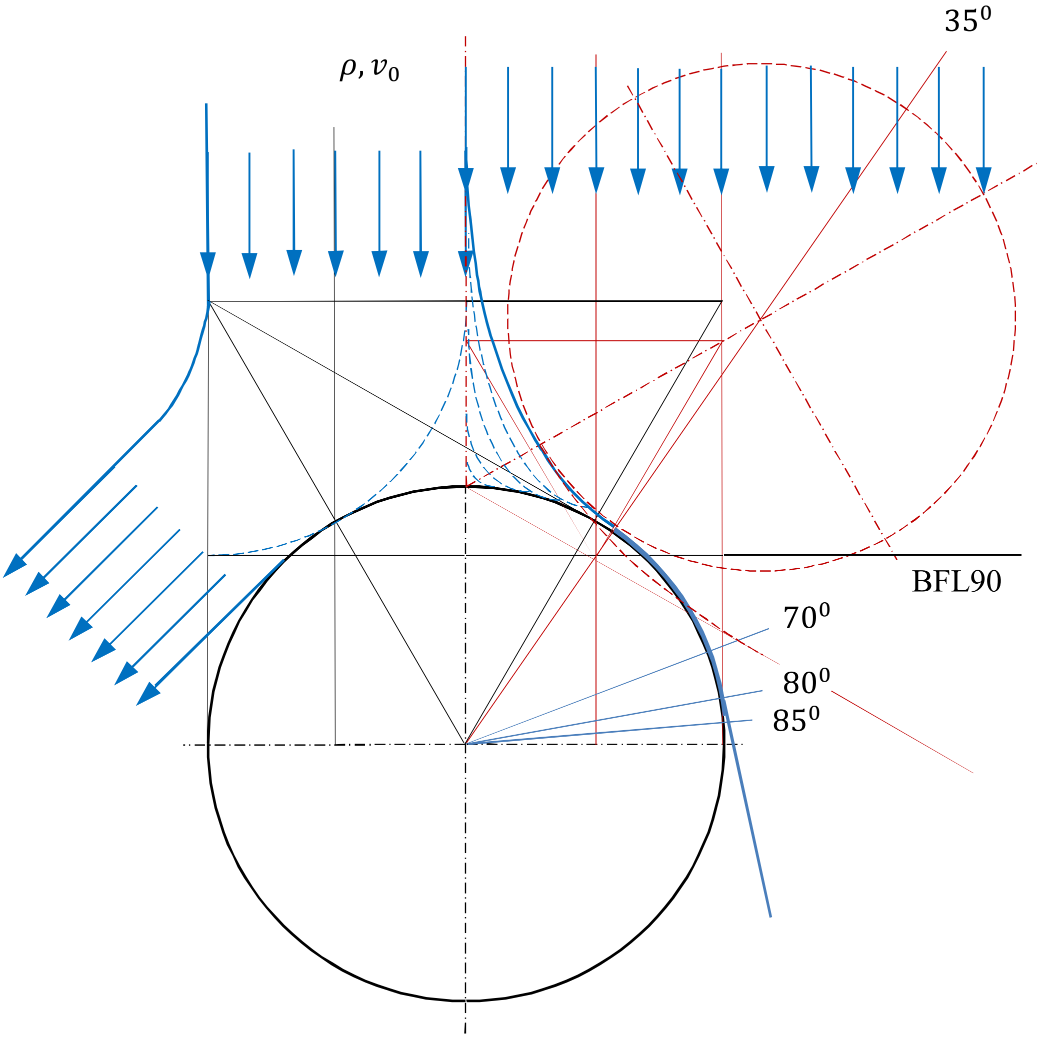


Fig. 4. Construction of effective internal boundary of the jet stream in the unrestricted uniform flow of real fluid (the right side) at “subcritical” Reynolds number and Mach number M << 0.6

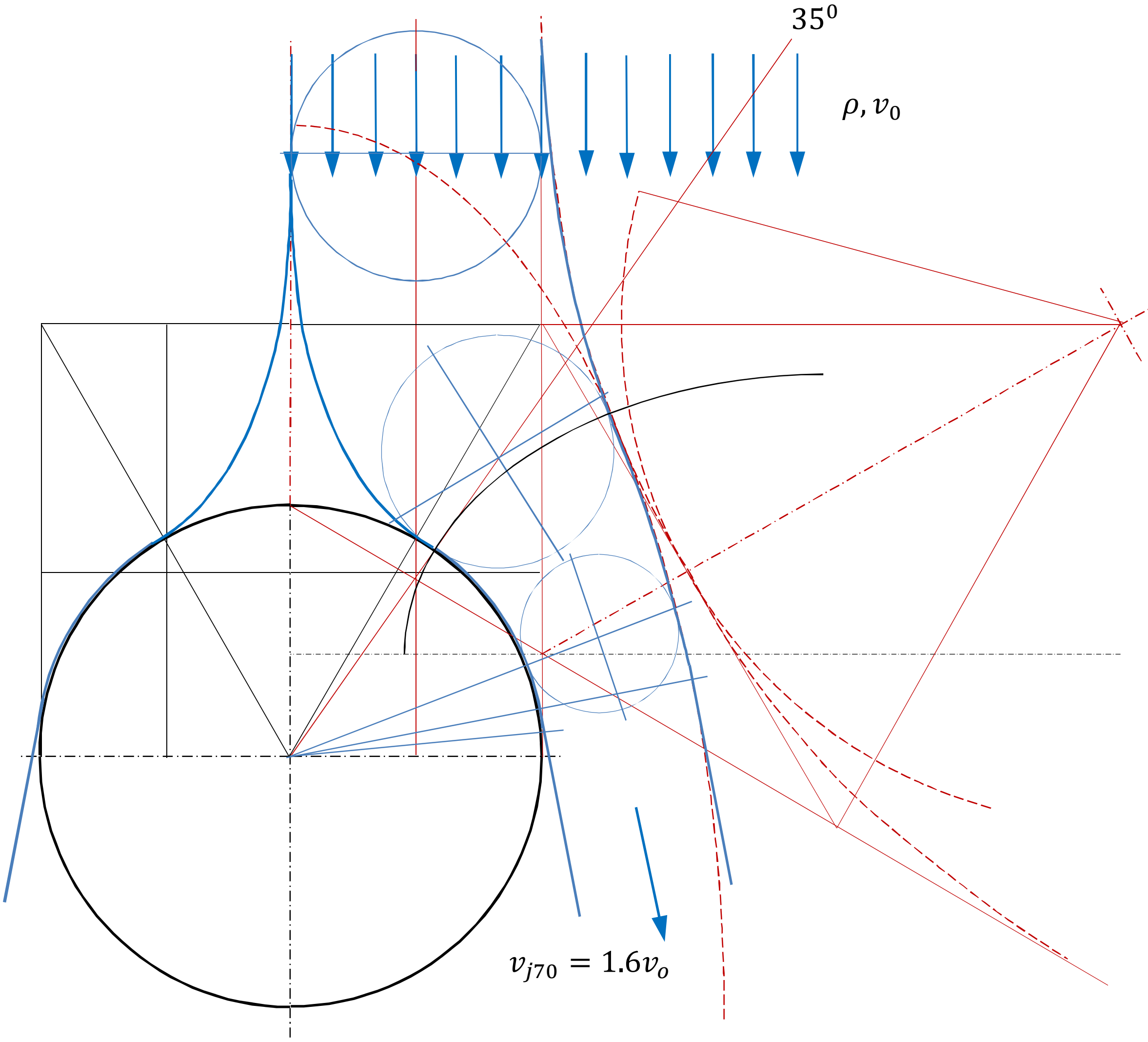


Fig.5. Construction of effective external boundary of the jet stream in the unrestricted uniform flow of real fluid (the right side) at “subcritical” Reynolds number and Mach number M << 0.6

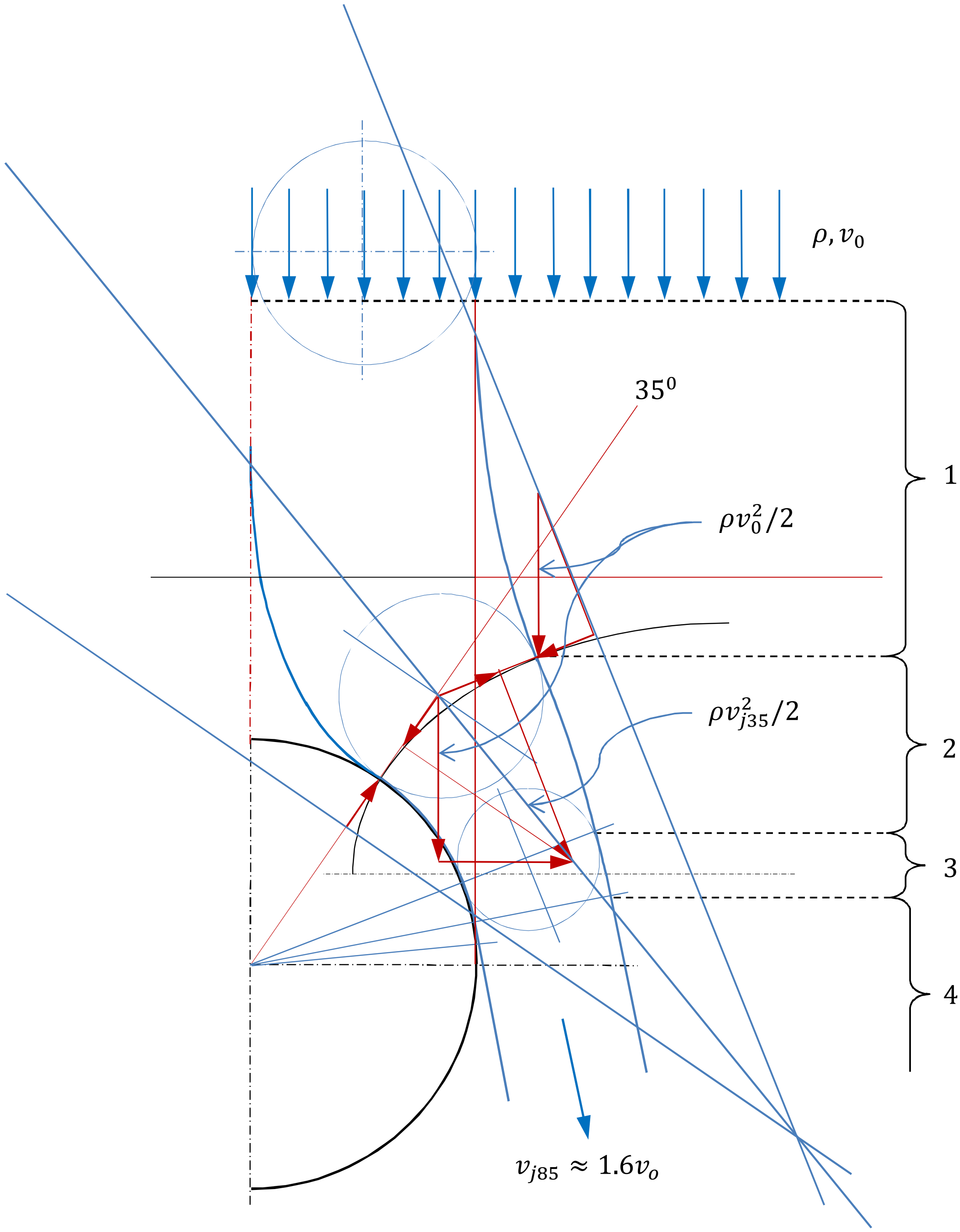


Fig. 6. Forces of interaction of the jet stream with the cylinder surface and with the unrestricted flow surrounding it in 35^0 point; stages of the jet stream motion: 1 – formation and initial acceleration, 2 – acceleration up to maximum velocity, 3 – inertial motion with separation from the cylinder surface, 4 – sucking off the fluid behind the cylinder and formation of a wake behind the obstacle

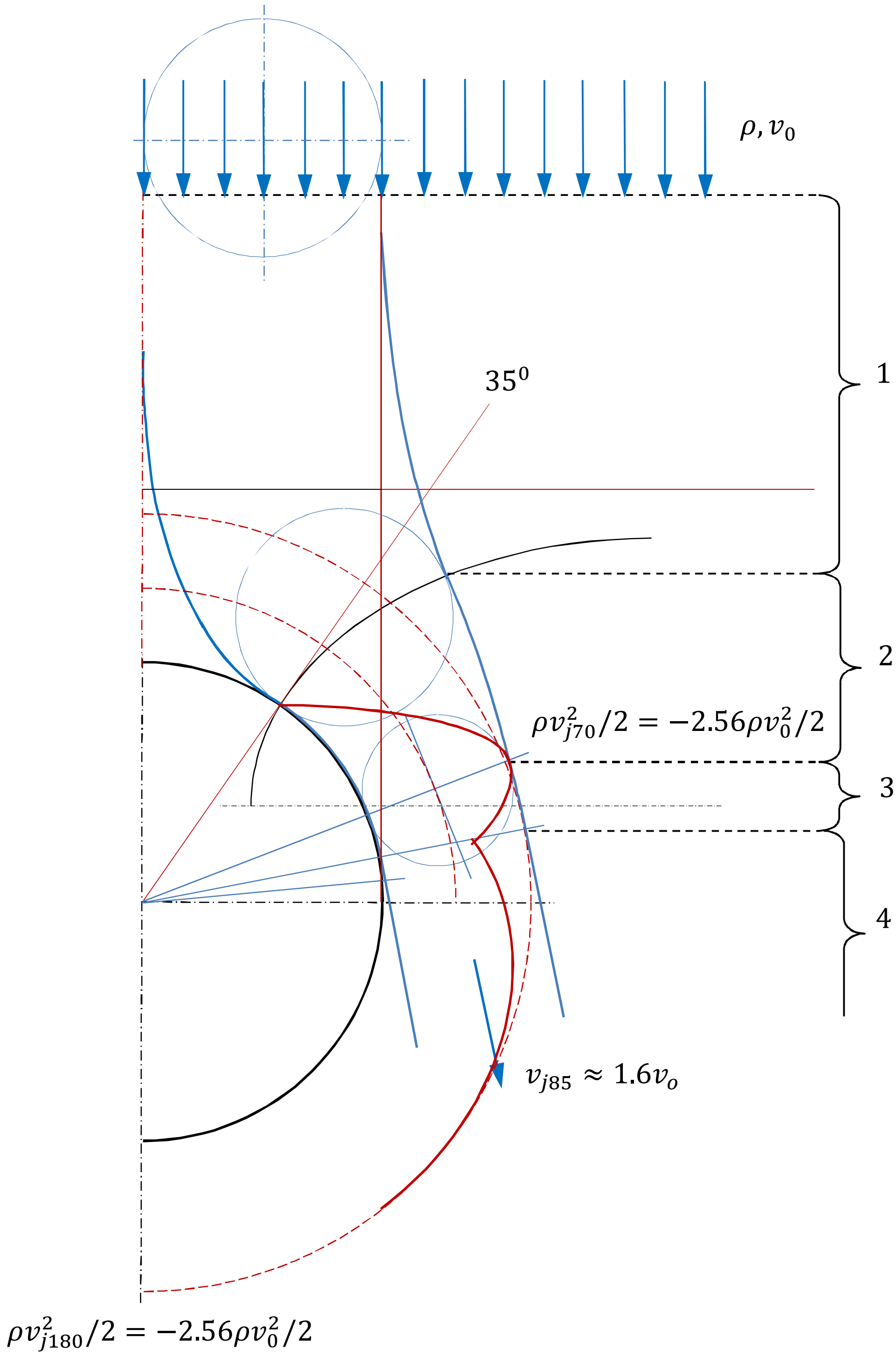


Fig. 7. Distribution of rarefaction along the lateral and back parts of the cylinder cross-section $35^0 \leq \theta \leq 180^0$ at "subcritical" Reynolds number and M << 0.6

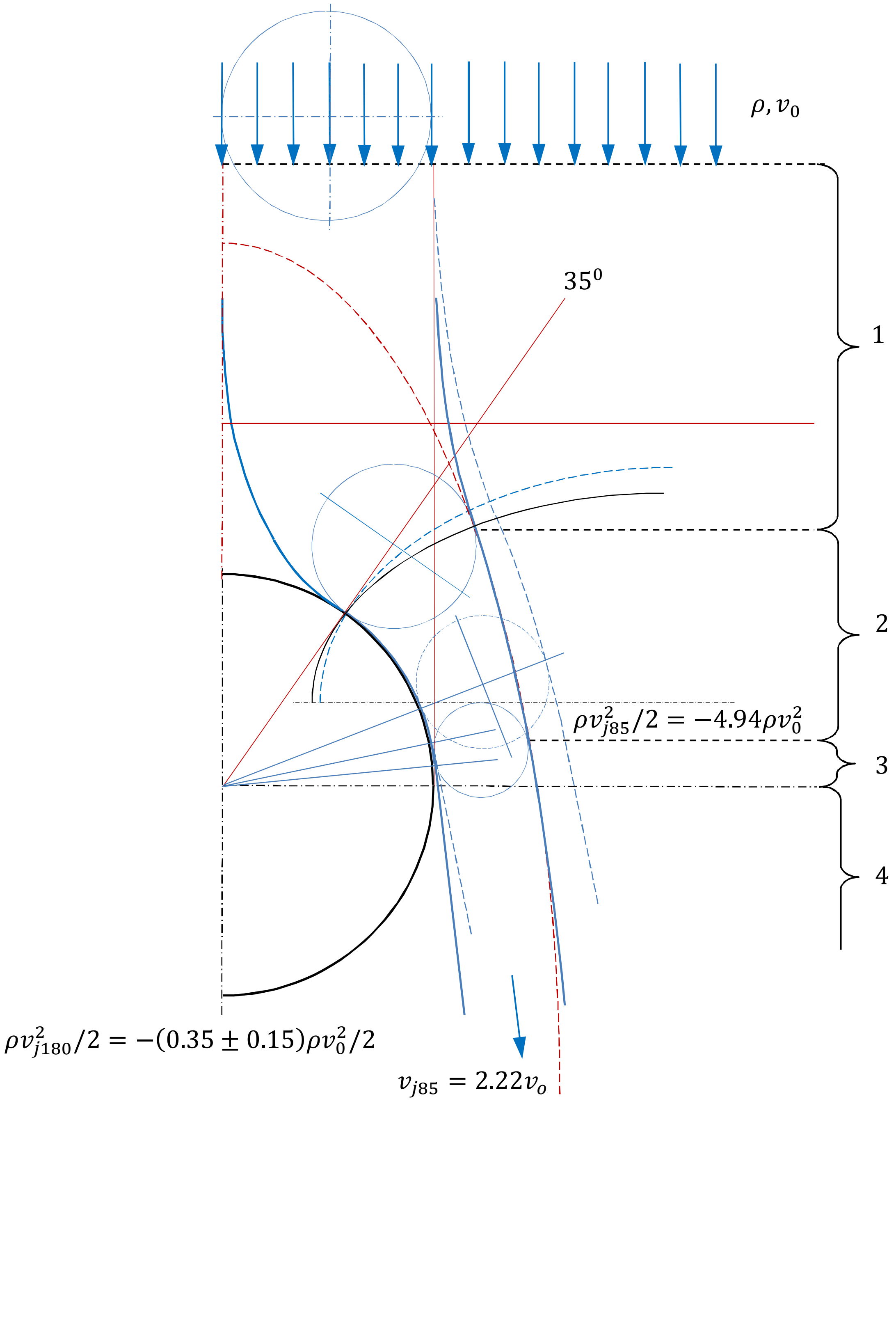


Fig. 8. Construction of effective external boundary of the jet stream in the unrestricted uniform flow of real fluid at “critical” Reynolds number and M << 0.6

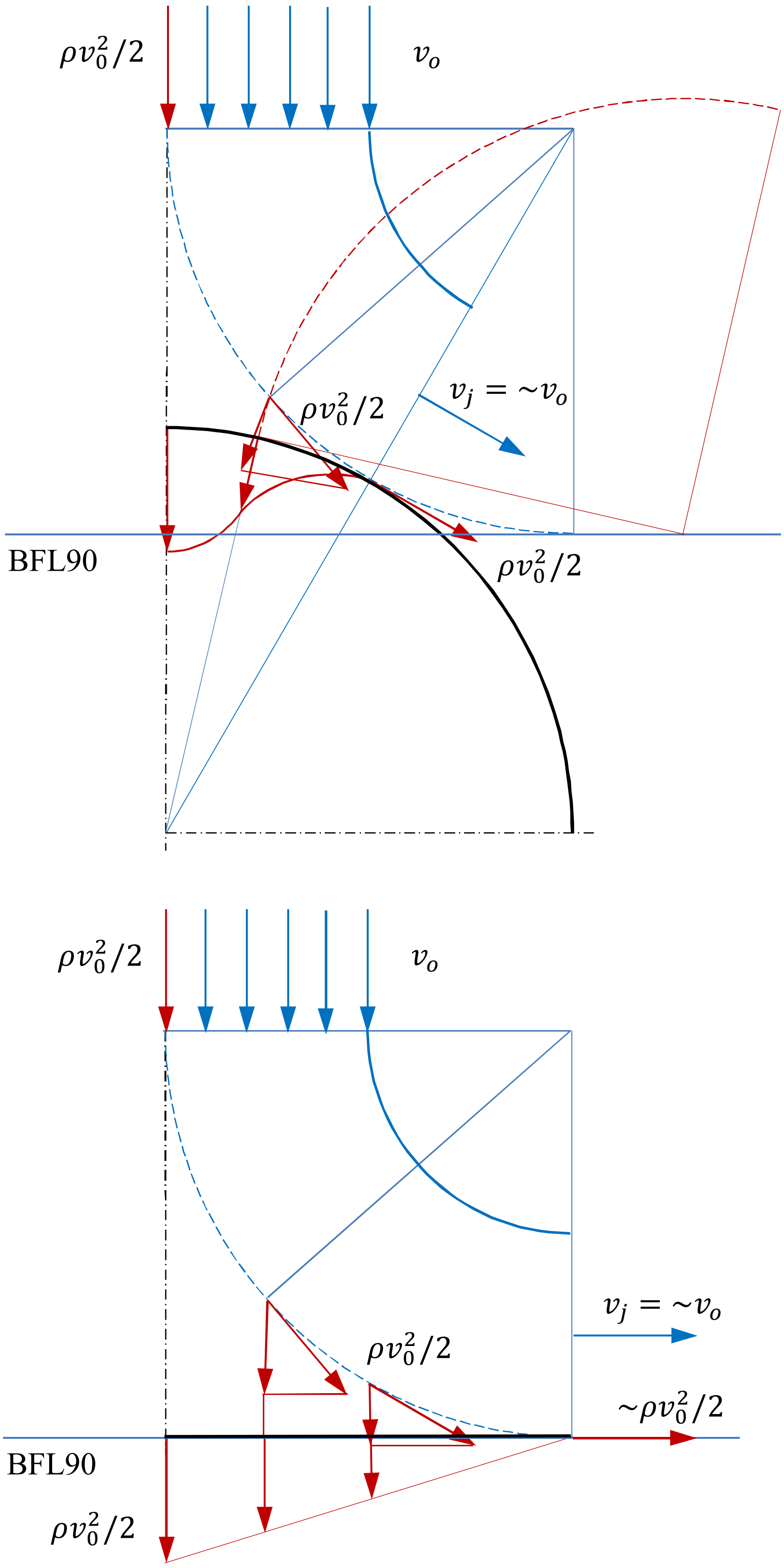


Fig.9. Examples of construction of the pressure distribution: a) on a fore part of the cylinder cross-section in coaxial interaction of the liquid flat free jet with the cylinder; b) in transversal interaction of the liquid flat free jet with a plane

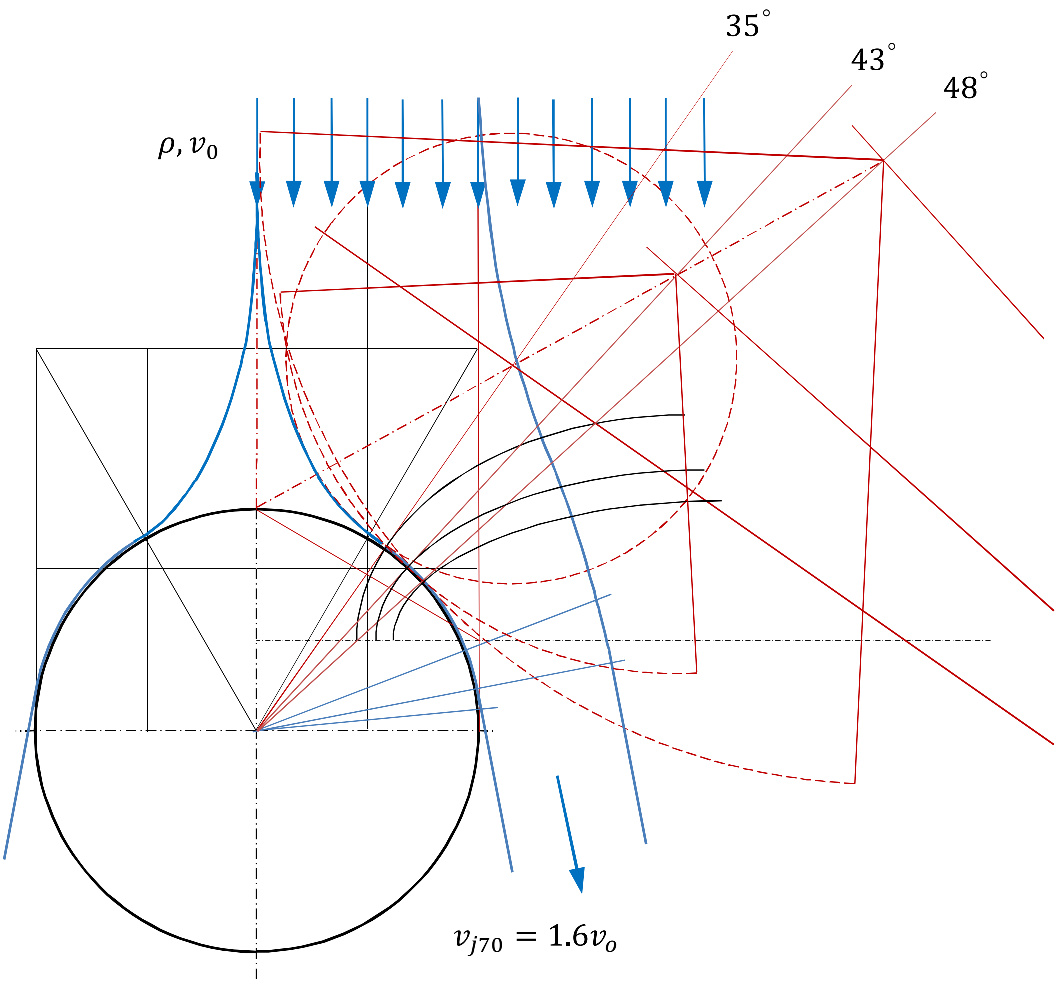


Fig.10. Construction of effective internal boundary of the jet stream at M << 0.6, M = 0.6 and M = 0.8 as well as at $1 \cdot 10^5 < Re < 2 \cdot 10^5$ according to Ferri experiments [5]

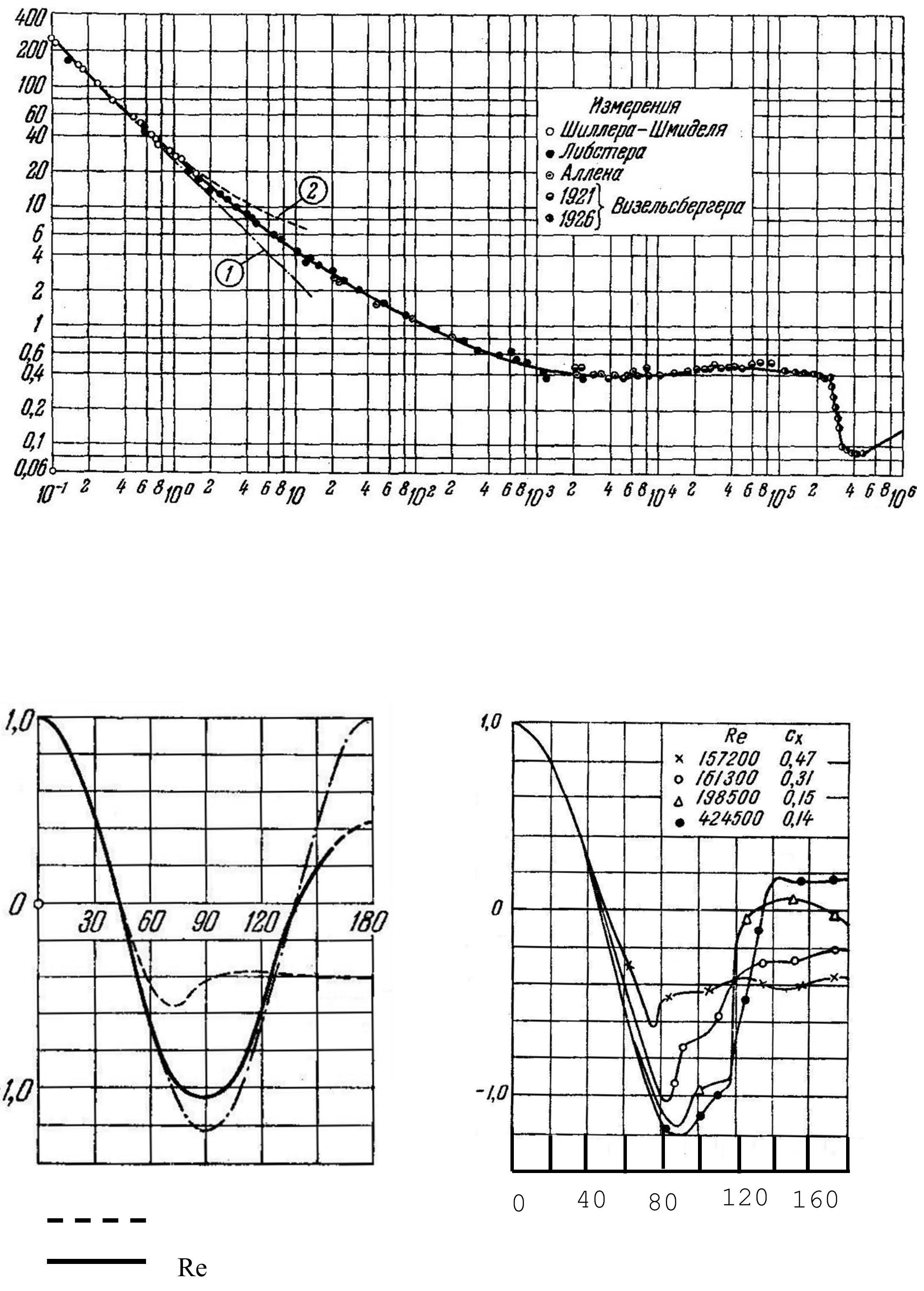
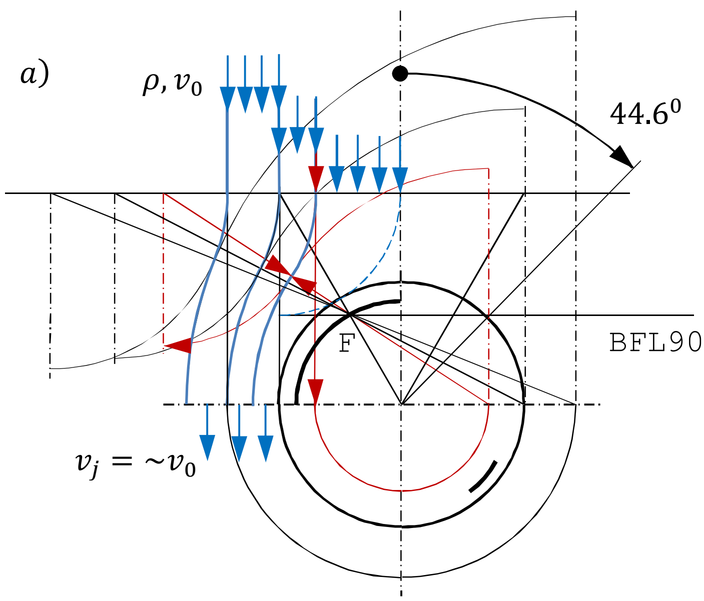


Fig. 11: a) the ball drag depending on Reynolds number, M << 0.6 [4]; line 1- according to Stokes [4], curve 2 – according to Oseen [4]; b) the pressure distribution along the ball longitudinal section contour according to Flachsbart experiments, M << 0.6 [4]; c) the same according to Povch experiments [9]



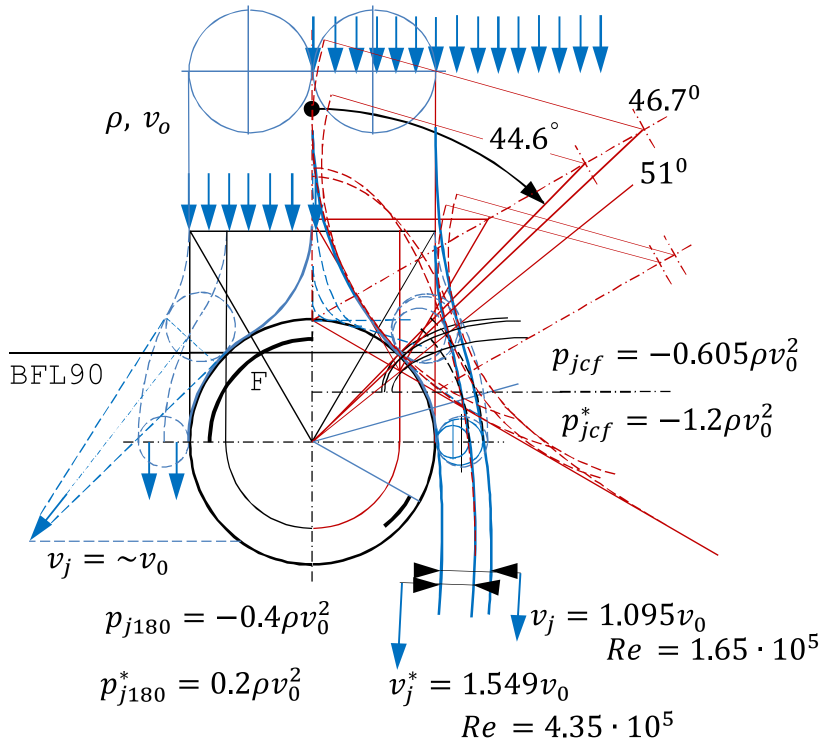


Fig. 12: a) geometrically possible construction of the flow lines of the unrestricted uniform fluid flow, interacting with the ball; b) a combined diagram of constructing the effective boundaries of the jet mantle at "sub-" and "critical" interaction of the unrestricted flow of real fluid with the ball, M << 0.6

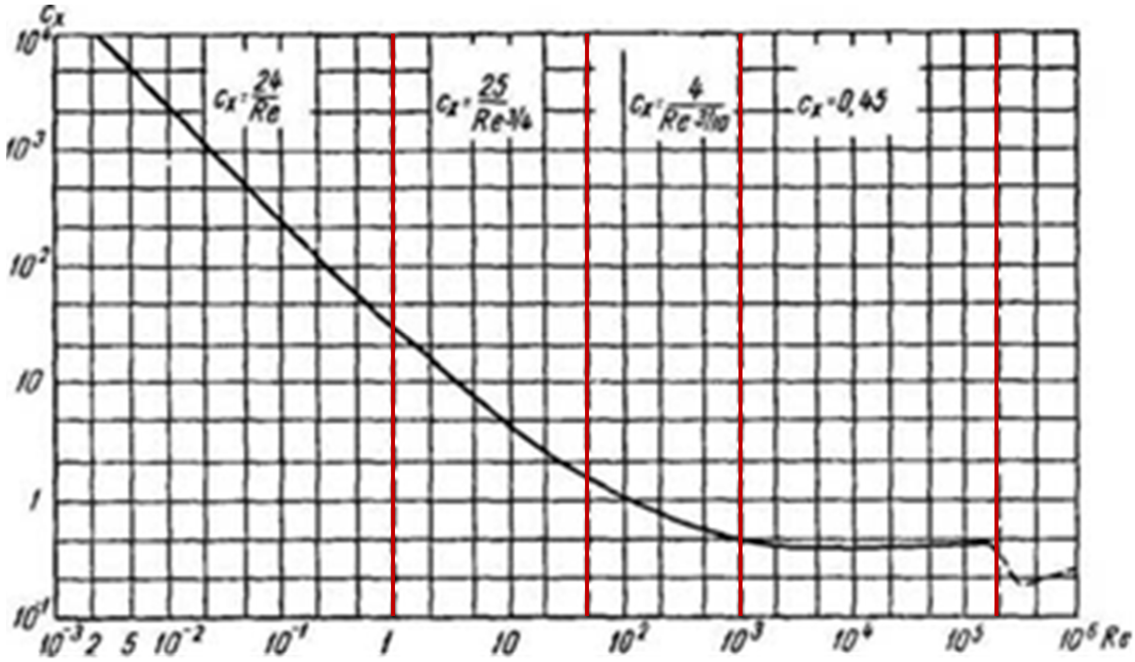


Fig. 13. A drag of the ball depending on Reynolds number at M << 0.6, produced by Povch [9] according to experimental results

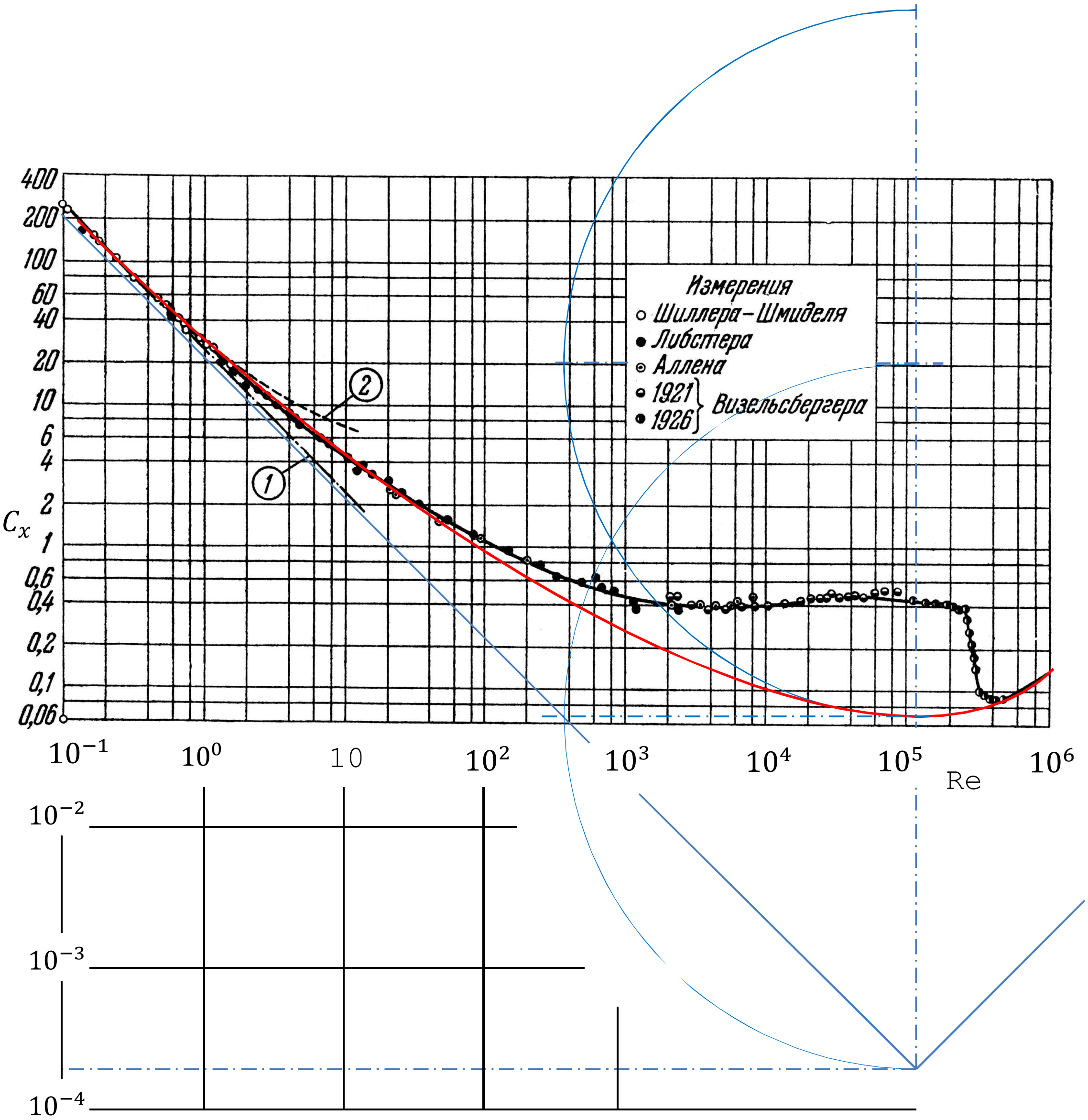


Fig.14. Hyperbola as a diagram of a drag of a ball depending on Reynolds number in supposition that the unrestricted flow around the ball is going on without separation

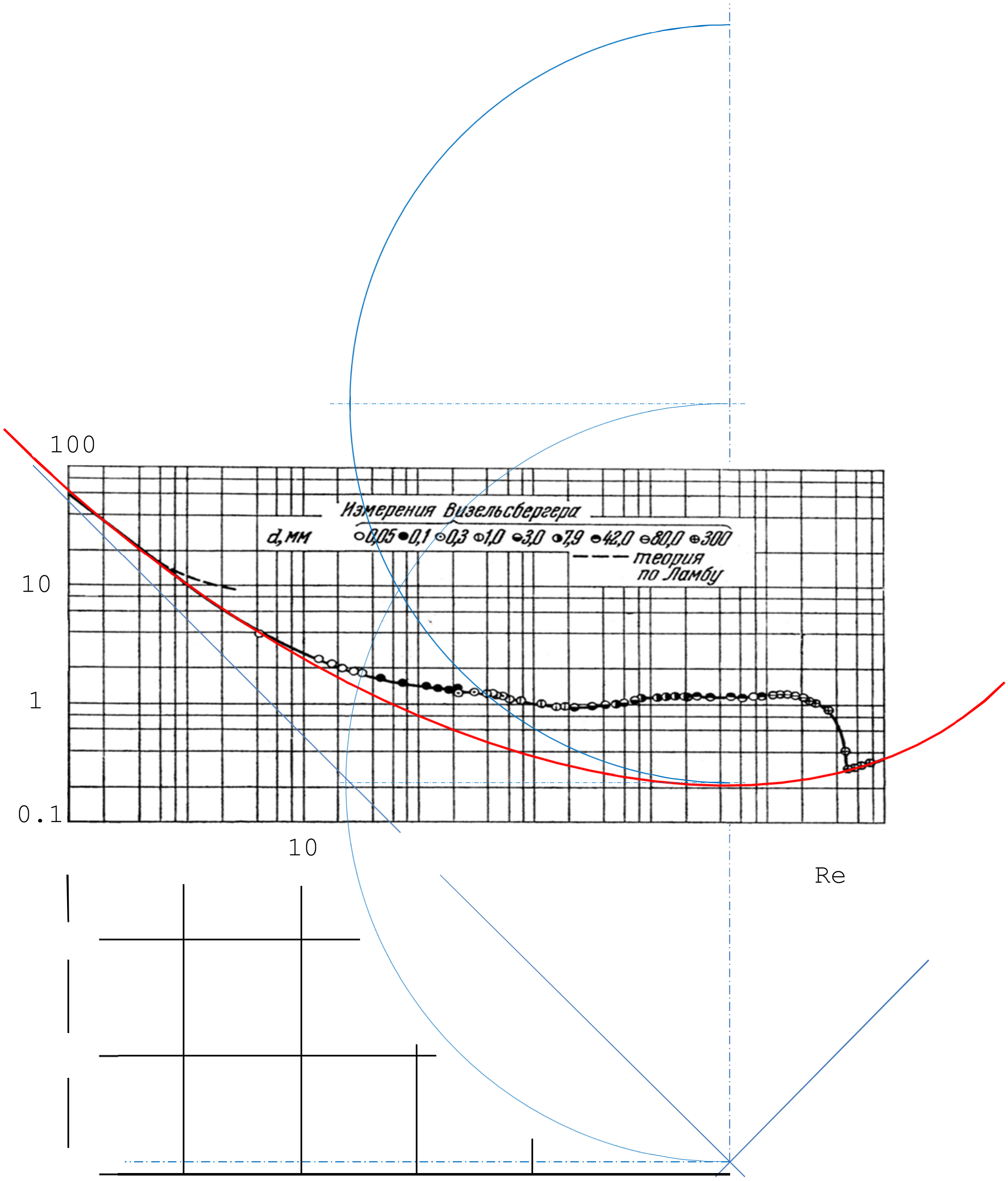


Fig.15. Hyperbola as a diagram of a drag of a cylinder depending on Reynolds number in supposition that the unrestricted flow around the cylinder is going on without separation

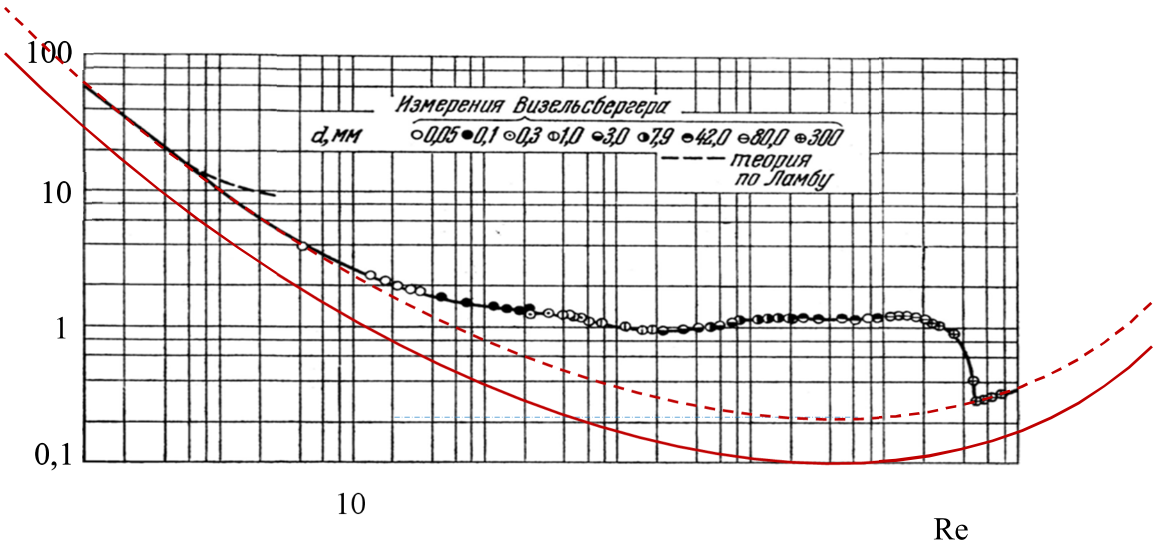


Fig. 16. The lower hyperbola is displaced down half the cylinder drag, and one means a drag of the fore part of the cylinder cross-section contour; a difference between the upper hyperbola and experimental curve is stipulated by an excess a drag of the cylinder back side in comparison with its fore part