Modern fluid motion physics
Laminar flow instability criterion and turbulence in pipe

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The identification of stream in the straight pipe as a flexible rod has allowed to present the criterion expression for determination of transition of the laminar flow to the turbulent as a loss of stability of the rectilinear static structure of translational motion of stream in pipe and its transition to the flexural-vortical dynamic structure of translational motion, just as a flexible rod buckling. The introduced criterion allows taking into account an influencing of the inlet geometry, the pipe length, the flow velocity, and also of any physical factors onto stability of the rectilinear flow structure. It is ascertained that the Reynolds number is the number of local hydrodynamic similarity, and it is displayed that one is constituent part of the introduced stability criterion. The developed approach to a problem of stability is applicable for a problem solving on internal flow and external streamline.

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Introduction

The fluid has such essential property as its intra-structural mobility in contrast to the solid body. In other words, the number of degrees of freedom of the fluid motion is much more, than that for the solid body. In this connection, a description of the fluid motion is much more complicated than that description of the solid body motion. In the beginning, we shall view the liquid flow (for example, water), remaining at that within framework of a mechanics. The conservation of its volume is naturally for liquid and at the same time the liquid takes any shape, depending on the form of vessel or the flow element, in which one is contained. The phenomenon of transition from rectilinear structure of laminar translational motion of liquid in pipe to vortical structure of turbulent translational motion, accompanied with increase of resistance to its motion, was ascertained by experiment.

This is, in basic, traditional information, on the basis of which the attempts of description of the considered phenomenon were undertaken during more than 100 years.

«Many hypotheses are offered for explanation of origin of the turbulence, often very witty hypotheses from mathematical point of a view, however...» L. Prandtl [1].

Till now it is not ascertained:

-- What is the turbulence from a physical point of view?

-- What is the reason of origin of the turbulence?

The insolvability of these questions, having the obviously mechanical nature, causes necessity at least of a short revision of experience, accumulated in mechanics during last about 400 years.

At the beginning of the XVII century, G. Galilei was researching some laws of the free motion of the solid body by means of throwing it's by bevel way to horizon in the gravity field. The first principle of mechanics was subsequently formulated on the basis of these experiments.

In 1641, E.Torricelli has repeated the Galilei experiments with the liquid free jets. These experiments have shown fundamental uniformity of a free motion of the solid body and the liquid (water) jets in the gravity field. So, the class of problems of mechanics under a title the ballistics was established.

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The results of use of instrument, invented by H. Pitot (1732), allow D-I. Bernoulli (1738) expressing the thought, saying in modern terms: the correlation of the potential and kinetic energy in the water stream in a pipe and a falling body is identical. In the middle of the XIX century, this thought was affirmed by the J. Weissbach and H. Darcy experiments with such feature, that the contact interaction of the stream with the pipe wall influences onto the correlation of the potential and kinetic energy in the stream and onto the magnitude of the outflow velocity. Thus, the liquid stream is appeared capable, to a certain extent, to maintain the ballistic properties at motion in pipe.

To the middle of the XIX century, it was also revealed (G. Hagen 1839, 1854) that the disturbance of rectilinear structure of headway of the water stream in the straight pipe happens during increase of the motion velocity.

To 1895, O. Reynolds has published results of his own experiments on investigation of the transition of motion of the water stream in the straight pipe from rectilinear to vortical structure. Reynolds visualized the flow along its axis by injection of a tinctured jet, and he determined that the flow maintains rectilinear structure of motion at low velocities, and the vortical structure of flow appears at the certain high velocity. To determination of the mentioned transition, Reynolds offered the dimensionless expression, linking the inertial forces of stream with forces of its viscosity. In accordance with Reynolds' expression, the transition of laminar structure of motion of the liquid stream to the turbulent happens by that earlier, than more the velocity of the stream. (It means, in a context of our comprehension, the more the intensity of the contact interaction of stream with a pipe wall, the earlier transition happens.) The pipe inlet in the Reynolds' experimental set up is realized in the form of the fluently convergent nozzle. Reynolds did not know apparently, that the inlet convergent mouthpiece can excite the initial turbulence, despite of the smoothness of the streamlined contour, because of high sensibility of it to asymmetry of the inflow. The similar inlet can provoke so-called «bath effect » in the kind of swirl of stream at inlet into pipe and then the swirl may be not detected by the centrally injected tinctured jet. Similar to it case was reproduced by G.I. Taylor in his experiment in which the tinctured jet moved almost rectilinearly through a local curvature of a straight glass pipe with its deflection close by the pipe diameter [2].

In 1929, J. Nikuradse visualized the water stream in a straight chute and shown by means of the filming with cine-camera, moved along a stream, that the structure of motion of turbulent flow has the dynamic flexural-vortical character. In 1933, Nikuradse has presented results of his experiments by the water stream in pipes with a different roughness in the form of diagram in coordinates “hydraulic friction coefficient -- Reynolds' number”. The transition of the laminar flow to the turbulent is legibly seen on this diagram. However the problem is remained unclosed: how can engineer use the diagrams of Nikuradse, C. Colebrook and L. White, C. Moody and the other, if the laminar flow in pipe can be within the limits $2320 < Re_{cr} < 40{,}000$?

To investigation of transition of the laminar flow to the turbulent, the experiments are being realized, as a rule, with use of long pipes (up to 2000 calibers and more). For example, J.M.T. Thompson has utilized an almost 6-m pipe (more than 910 calibers) even in the home conditions [3]. The next problem is: how does the pipe length influence on transition of the laminar flow to the turbulent?

The guesses on the mechanism of transition of laminar flow in the straight pipe to the turbulent as on the phenomenon of a static buckling of the flexible solid body are raised only to the end of the XX century. The buckling of cylindrical and spherical shells had been compared with the flow stability in the plastic curved pipe [3].

Alongside with it, on the other authoritative scientists’ opinion [4], “there is the large group of problems on stability of the liquid jets. The problem of stability of the water jets (fountain, for example, *notice of the author*) in air is classical. In particular, what height can be reached by the jet if its exit velocity and diameter are assigned?” That is, in the end of the XX century, it is difficult to distinguish: what are the problems on ballistics by Galilei – Torricelli, and what are the problems on a contact interaction?

Approach

In view of above stated, it is necessary to return to consideration of motion of the free liquid jets in the gravity field. We shall be watching the free high-viscous liquid jet, falling vertical, for example, of the melted bitumen at the temperature closely to its solidification point, into accumulative vessel in contrast to the Torricelli and Reynolds experiments. We can ensure an outflowing jet with its circular cross-section and the flat jet. We can see that the circular cross-section jet deviates from the vertical because of gyration and one is being packed by rings at sufficient height of falling, at contact with the accumulative vessel bottom. The flat jet swings similarly to a pendulum and, being bended, one is being packed up with formation of ream of the folds at contact with the above-mentioned vessel bottom. We observe the stability loss phenomenon of foot of the free high-viscous jet similarly to the flexible rod buckling under action of own weight in these experiments. We note the dynamical character of the stability loss phenomenon of the jet in contrast to the static buckling of flexible rod. At the same time we cannot detect the above-mentioned features at carrying out of the same experiment with the falling water jets. The distinction in the results of the compared experiments can be explained by influencing of viscosity. In this connection, the viscosity is necessary to interpret not only as the factor of resistance to a motion, but also as a physical property of fluid to conduct the mechanical energy. Viscosity, from such point of view, is the energy-flux density of the mechanical energy, spreaded in fluids with the sound speed in accordance with dimensionality $[\eta] = \mathrm{kgf} \cdot \mathrm{m}/(\mathrm{m}^2 \cdot \mathrm{s})$. The ratio of viscosity to the normal elastic modulus of fluids in a direction of spreading of a mechanical energy determines the relaxation time

$$T_r = \frac{\mu}{E} \sim \frac{kgf \cdot s}{m^2} \cdot \frac{m^2}{kgf} = s.$$

Having multiplied the sound velocity in the jet material by a relaxation time, we find the height of a lower part of the free falling jet, which one, not discontinuing the flow, was turned into the flexible rod having the buckling under action of own weight by L. Euler. The free falling jet of the low-viscous liquid (for example, water) cannot make such effect, as a height of action of an braking impulse for it is practically equal to a zero because of its very low viscosity. At the same time the conditions for loss of stability of rectilinear structure of translational motion of a fluid stream as the flexible rod are being created at motion of the low-viscous stream (such as water) in the straight pipe. This is stipulated by that the pipe wall, constraining the static head of a stream, transmits it along the stream with increase from the end of stream to its start. The continuity of static head along the pipe length and correspondingly along the stream length transmutes the stream into the rod, loaded by the longitudinally distributed forces of the contact interaction with pipe. The straight pipe plays the dual role in the given situation: on the one hand, the pipe guides the stream and shapes the form of the straight rod to it, on the other hand, the pipe loads the stream with longitudinal forces of the contact interaction with it and instigates thereby the loss of stability of rectilinear structure of translational motion of stream as a buckling of the flexible rod under action of own weight by Euler. By the way, Euler reached the correct formulation of problem on the elastic stability of the rod under action of own weight for 34 years (1744 -- 1778), and exact solution of the problem was obtained after 150 years [5].

Thus, the fluid can be in state of translational motion and simultaneously lose the stability of the static rectilinear structure of this motion similarly to the flexible rod, because of the greater number of degrees of freedom in contrast to solid body. At that the dynamic character of loss of stability detected in the above-mentioned experiments with the falling jets of high-viscous liquid is remained at motion of stream of low-viscous fluid in pipe. Moreover, the bending oscillations of the low-viscous fluid stream in pipe lead to the formation of vortices accompanying the translational motion of stream. The described pattern of motion of the turbulent stream quite corresponds to the above-mentioned cinema sequences obtained by Nikuradse.

Solution

We imagine the fluid flow kernel in pipe in the form of the straight flexible rod. The hydrodynamic sublayer, coating the roughness of the pipe wall and enveloping the stream kernel, loads the kernel by the axial (longitudinal) compressing forces of viscosity, distributed along the pipe length, but the sublayer is remained indefinitely compliant in radial direction and is assumed in the form of the clearance space between the stream kernel and pipe. We receive that one end of flexible elastic rod, simulating the stream kernel, is rigidly fastened, and its other end has possibility for the axial and -- in the limits of the clearance radial space -- transversal pliability, taking into account the peculiarities of the starting hydrodynamic zone of fluid flow in pipe. We receive simplistically the equality of the stream kernel diameter to the pipe diameter because of small thickness of hydrodynamic sublayer. The condition of transition of the fluid flow in pipe to turbulent regime consists in equality of the total of the viscosity forces, applied to the stream kernel from the pipe wall side, to the Euler critical force at which one the flexible rod loses the stability of the rectilinear shape of equilibrium under action of the own weight.
The overall value of axial force corresponding to static head of the laminar flow of fluid in the straight pipe with the round cross-section is expressed by the J. Poiseuille formula

$$N_P = h \cdot \gamma \frac{\pi \cdot D^2}{2 \cdot 4} = \frac{32}{d^2} \mu \cdot L \cdot V \frac{\pi D^2}{2 \cdot 4} = 4\pi \cdot \mu \cdot L \cdot V, \qquad (1)$$

where h -- pressure drop, m; γ -- weight density of fluid, kgf/m^3; D -- inner diameter of pipe, m; μ -- coefficient of dynamic viscosity, $kgf \cdot s/m^2$; L -- pipe length,m; V -- average velocity determined by the flow rate in pipe, m/s.
The minimum quantity of the resultant of the uniformly distributed along length compressing forces, applied to flexible rod, when this rod, having the rigidly fastened end, loses stability by Euler, is determined by expression

$$N_E \leq \frac{\pi^2 \cdot E \cdot J}{(0.723 \cdot L)^2}, \qquad (2)$$

where E -- modulus of elasticity, kgf/m^2; J -- moment of inertia of the flexible rod cross-section, m^4. Euler's stability condition has the appearance for rod with the round section

$$N_E \leq \frac{\pi^2 \cdot E}{(\nu \cdot L)^2} \cdot \frac{\pi D^2}{64}, \qquad (3)$$

where ν- reduction coefficient of the length of flexible rod, dimensionless quantity.
We obtain the criterion expression for determination of transition of stream in pipe from laminar to turbulent regime, equating forces N_P and N_E under condition of equality of the rod and stream diameters and realizing the elementary transformations

$$25.9 \frac{\mu}{E} \cdot \frac{V}{L} (\nu \cdot \bar{L}^2)^2 \geq 1, \qquad (4)$$

where $\bar{L}$ -- relative length of pipe, expressed in calibers of its cross-section, $\bar{L} = L/D$.

Having designated $\mu/E = T_r$ and $L/V = t_r$, we write the criterion expression (4) in the form

$$25.9 \cdot \frac{T_r}{t_r}(\nu \cdot \bar{L}^2)^2 \geq 1. \tag{5}$$

Symbol T_r means the time of mechanical relaxation of fluid by its dimensionality and quantity, and t_r is the time of passage of pipe by the stream particles in the obtained expression. Thus, the physical constant of fluid, the generalized geometrical parameter of pipe with allowance for reduction coefficient and the kinematic parameter of stream are introduced into correspondence at the obtained expression.
The analysis of the obtained expressions (4, 5) shows that influence of length of the fluid stream in pipe on the stability of the form of its motion is much higher, than influence of length of flexible rod onto its buckling.
The turbulent regime cannot come into being under any increase of velocity in the sufficiently short pipe (nozzle), according to expression (4). Such property of this expression predetermines a presence of the initial zone of stream possessing an absolute stability similarly to the short rods, for which the problem of stability is not actually. The obtained expression indicates also that the flow will be only laminar at diminution of pipe diameter to the size of capillary, because of the dominant action of the adhesion-cohesion forces of solid surface in this case. Well-known phenomenon of the obliteration, stopping the outflow of fluid in the course of time, is natural for such, even of short channels. The obtained criterion expression (4) can be reduced to the form suitable for gas stream and containing the Reynolds number. It is enough to introduce the substitution $E = p = \frac{1}{k}a^2 \cdot \rho$ in it and also one's numerator and the denominator to multiply by V and D for this purpose

$$25.9\frac{k \cdot \mu \cdot V^2 \cdot D}{a^2 \cdot \rho \cdot V \cdot L \cdot D} \cdot (\nu \cdot \bar{L}^2)^2 = 25.9\frac{k \cdot M^2}{Re}\left(\nu \cdot \bar{L}^{3/2}\right)^2 \geq 1 \tag{6}$$

where k -- adiabatic exponent, a -- sound speed, ρ -- fluid density, M -- Mach number.
The obtained expression (6) is wider than expression for a Reynolds number at the expense of the more complete and generalized taking into account of the form of pipe by the non-dimensional parameter, containing not only the diameter of pipe, but also its length with allowance for the length reduction coefficient.
Comparing the transition to the turbulence with buckling of the flexible rod located in pipe with the clearance space, it is necessary to note also difference between them. The stress in such rod is the total of the longitudinal compressing forces and the bending forces at its buckling under action of the axial compressing force

$$\sigma = \frac{P}{A} + \frac{E \cdot J \cdot \Delta \cdot \pi}{l^2 \cdot W}, \tag{7}$$

where P -- axial compression force, A – the rod cross-section area, $E \cdot J$ – the bending stiffness of the rod, Δ -- clearance space between the rod and the pipe, l -- length of quarter of wave of the incurved rod up to the point of contact with the pipe wall after its buckling [6],
W – moment of resistance of the rod cross-section.
This stressed state of the rod is reversible, as the elastic buckling is considered.

The above-adduced expression (7) is to certain extent valid also for the fluid stream in pipe at the transition to the turbulent flow regime. The difference from behavior of the flexible solid rod is in that, the bending oscillations of the fluid flow kernel are bound not only with the bending of its motion trajectory, but also with the formation of vortices at periodic running of the stream against the wall of the straight pipe. Both of these kinds of the diversion from rectilinear structure of the translational motion form the irreversible part of the power losses in turbulent flow. At the same time the direct and reverse transition between the laminar and turbulent flow of a fluid stream in the straight pipe (so called ’’intermittent turbulence”) is characterized by inequality of the pressure drops applied to the pipe flow system in accordance to the experiment results. This feature accompanies also the buckling of the flexible solid rod, located into tough pipe with gap and loaded by longitudinal forces of own weight [6].
The features of loss of stability of the laminar flow regime in pipe under action of frictional forces (as well as of flexible solid rod under action of own weight) can be traced during viewing of the fluid flow in the light diverged and light converged mouthpieces (nozzles).
Let us compare three flexible rods under action of own weight -- one cylindrical and two conical -- by the elastic stability condition. We accept to be identical an average diameter and length of all three these rods. We accept also to be identical the elastic modulus, density of material of rods and character of fastening of the bearing end. It is possible to think, that the weight of all three rods is practically identical under the small cone angle; in other words, the total force (resultant) of the action of rods to its support is approximately identical.
We are noting that the part of a cylindrical rod near its support is the most critical from a point of view of elastic stability. We are also noting, comparing the viewed rods, that the second rod has the little more section near its support in contrast to the first, and the third rod has the little less section near its support. It is not difficult to establish, taking into account that the ultimate load by Euler is proportional (with other things being equal) to the fourth degree of diameter for rods with its circular cross-section, that the small cone angle of the equally supported rods under action of own weight leads to essential odds in its stability. The similar phenomena of the protracted laminar flow regime in the light converged mouthpieces and the early transition to the turbulent flow regime in the light diverged mouthpieces are well-known in experimental hydro-mechanics. In this connection a factor, which takes into account quantity and character of the mouthpiece cone angle, is necessary to introduce into the criterion expression (4). In result, the expression (4) will accept a view

$$25.9\frac{\mu}{E}\cdot\frac{V}{L}\cdot\left(\frac{D_{ex}}{D_{in}}\right)^4(\nu\cdot\bar{L}^2)^2\geq 1, \qquad (8)$$

where D_{ex}, D_{in} -- diameters of the outlet and inlet sections of the conical mouthpiece.
It is also known in experimental hydrodynamics that the transition to the turbulent flow regime occurs much earlier in the hose lines (for example, rubberized-fabric) than in the metal tough pipes. Reynolds' number can be descended up to ~ 150 in the hose lines. This feature is bound with the low bending stiffness of hose lines. The factor is necessary also to introduce into the expression (4) in the form of ratio of bending stiffness of the viewed hose line and tough pipe, which one was used in experiments of Nikuradse, Colebrook and White, Moody and other, for taking into account of this feature. Now the obtained criterion expression in the form (8) accepts a view

$$25.9\frac{\mu}{E}\cdot\frac{V}{L}\cdot\left(\frac{E_s\cdot J_s}{E_r\cdot J_r}\right)^{1/m}\cdot\left(\frac{D_{ex}}{D_{in}}\right)^4(\nu\cdot\bar{L}^2)^2\geq 1, \qquad (9)$$

where $E_s \cdot J_s$ and $E_r \cdot J_r$ -- bending stiffness of the hose line and tough pipe respectively,
$1/m$ -- degree of influence of relative flexibility of pipe on transition to the turbulence.
Influence onto the "stream-pipe" system of the different factors and actions should and can be taken into account by a similar way in the obtained initial criterion expression (4):
- damping of pipe,
- action of oscillations onto the pipe, onto the stream in it and onto the outflowing jet [5, 7],
- relative increase of the gas stream velocity in the pipe with constant value of its cross-section area,
- heat exchange of stream with the pipe wall (with allowance for the opposite change of the viscosity of liquid and gas under thermal action),
- the laminarizing and turbulizing devices in pipe and at inlet to its,
- acceleration of pipe under action of external forces,
- sucking off or injection of the additional mass flow rate and action of other factors, which ones can exert the stabilizing or destabilizing influence onto a flow regime.

Coefficient ν characterizes influence of an inlet profile onto the calculated length of a fluid stream in pipe, and one can be within the limits $0.715 \leq \nu \leq 1.12$. The smaller value will match to the smooth inlet into pipe, the greater value will match to the abrupt inlet into pipe.

The presented analysis and the developed physical model of transition of the laminar flow to the turbulent in pipe allow applying it to development of physical models of the mentioned transition for other forms of the internal flows.

We shall consider the problem on the stability of laminar motion of stream in the flat channel in the qualitative aspect. The stream should be presented in the form of the flexible plate located with the backlash in the flat tough channel in this case. It is necessary to note the distinction of the buckling of rods from the buckling of plates from a position of the theory of the elastic static stability of plates. This distinction is in that the elastic stability of the one-piece plate under the longitudinal compression load appears much above, than the elastic stability of such "plate" composed from the separate rods. It means physically that the total force of buckling of the rod gang, simulating the plate, is equal to the force of buckling of the one rod, multiplied to the quantity of these rods. Such result reflects the independence of the transversal deformation of each rod at its buckling. The rods, constituting the one-piece plate, are bound among themselves, and this connection restricts the freedom of their transversal deformation under action of the compressing forces. Therefore the one-piece plate is steadier, than the compounded one.

Hydrodynamic experiment displays that the stability of the laminar flow is much higher in the flat channel, than in the ordinary pipes [7]. The replacement of static rectilinear structure of the translational motion by the dynamical flexural-vortical structure of the translational motion of stream happens at the transition of flat flow to turbulent regime. The running bend waves of the stream kernel make the alternating zones of periodic running of it's against the flat walls of the channel with formation of vortices and the separation zones from walls. Hydraulic resistance to the stream motion is determined by roughness of walls of the flat channel in this case, as this takes place in pipes.

The described approach allows to develop the physical model of loss of stability of laminar flow in the annular gap between two pipes as the elastic cylindrical shell in the rigid annular cavity under action of the axially applied own weight. The stability of such laminar flow depends appreciably on the size of the backlash between pipes enveloping a stream in this case. The stability of the laminar regime is considerably higher and it approaches stability of laminar flow in the flat channel in case of sufficiently small backlash. The stability of laminar flow is reduced up to a level of pipe flow in case of relatively major backlash. It is necessary to take into account of external influence at quantitative estimation of the stability criterion of laminar flow in the flat channel and the annular inter-tubular backlash as it is shown by an example of pipe flow.

Discussion of results

The stability theory by Euler allows establishing that the quantity of the ultimate load of flexible rod under action of own weight can vary in the ten times, depending on the conditions of fastening of rod. The results of well-known hydrodynamic experiments [8] also testify to that the laminar regime can exist at tenfold increase of the stream motion velocity in contrast to value of the Reynolds numbers 2,320-40,000.

Alongside with it is necessary to take into account that the action on rod of oscillations of the specified direction and frequencies can also rather appreciably change the quantity of the ultimate load, both in the direction of its increase, and in the direction of decrease. That is, the multifactor dependence of stability of flexible elastic rod in static conditions is obvious. The fluid medium has appreciably more number of degrees of freedom of motion because of property of the permanent and continuous intra-structural mobility. The dynamics of fluid appreciably exceeds dynamics of a solid body by variety of combinations of a state and motion and by the multi-factory of the influencing actions, thanks to mentioned property. The fluid at motion in pipe has a linear elastics modulus similarly to solid body. This property appears at passage of the flat longitudinal waves of elastic compression-distension in the pipe stream of fluid. Simultaneously fluid has the modulus of the volume elasticity under action of static head. The pipe shapes the fluid stream in the form of lengthy rod. The interaction of stream with the pipe wall loads the fluid rod by forces of longitudinal compression in the form of law of static head [8, 9] that is equivalent to action of own weight to the flexible rod. Thus, the fluid stream is moved by translational in pipe and simultaneously loses the rectilinear structure of laminar motion as the rectilinear shape of an elastic static balance. The combination of motion of the fluid stream in pipe with loss of static stability stipulates appearance of new structure of motion. This structure consists of the running waves of the many times incurved stream, which at such shape of interaction with wall of pipe generates, on the one hand, vortices, and, on the other hand, zones of flow separation from the pipe wall. Running waves of the flexure at pushing of stream under angle of attack on the pipe wall destroy the laminar hydrodynamic sublayer coating the roughness of pipe wall at the developed turbulence. Now tractive resistance of stream in pipe depends in the essential degree on the degree of roughness of the pipe wall in complete correspondence with the Nikuradse diagram. As to the multi-factor influence of external actions on transition of laminar structure of stream to the turbulent, it is stipulated by multiplicity of motion and state of fluid, specially such thermo-mechanical active medium as the gas.

The problem arises in connection with the above-mentioned: what is the Reynolds numbers? The dimensionless ratio of the inertial forces and the viscosity forces of fluid stream disregarding of any other factors and parameters of the "stream -- pipe" system is the number of local hydrodynamic similarity. This number not possesses indications of the stability criterion of rectilinear structure of a flow. Elucidation of nature of turbulence and determination of its origin criterion liberate the Reynolds number from unusual function to it and the same time not reduce in slightest degree the significance of this hydrodynamic similarity number in the everything else well-known cases.

After 120 years since O. Reynolds had carried out his illustrious experiments, the criterion expression, in its forms produced here, constructed theoretically on basis of physically adequate principle on unity of mechanics of a contact interaction of fluid flow with solid body and corresponding to the well-known results of experimental researches, is modern instrument for determination of laminar flow stability in practical problems of aero- and hydromechanics.

Final remarks

The methodology of approach to the problems of loss of stability of the laminar flow and the structure of the turbulent flow in pipe and resolution of these stated above problems are an example for the solution of similar problems of the internal flows and external streamlines of the

different form which ones will be enunciated in further publications of the author.
This work, alongside with previous [9, 10, 11, 12, 13] and future publications is executed initiatively and independently by the leading theorist of Physical-Technical Group within the framework of development of subject "Modern fluid motion physics" during the last 30 years.

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