



Research article

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Diverging flow in Y-junctions: laminar, transitional and turbulent

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Abstract. This investigation is aimed at determining flow regimes in Y-junctions with flow division. Air velocity and velocity pulsations are measured using a hot-wire anemometer in a wide range of Reynolds numbers $Re = 400\text{--}6000$. A junction with diameter $d = 6$ mm is chosen as the object of study for the inlet and two outlet channels: a symmetrical arrangement of the outlet channels with an angle of 50° between them. A long tube with diameter $d = 6$ mm and length $l/d = 333$ is connected to the junction inlet. Two techniques of the flow regime diagnostics have been developed. For the inlet channel of the junction, the critical Reynolds number is $Re = 2000$ (puff-type vortex structures appear for the first time). For two outlet channels, a significant increase in velocity pulsations occurs at lower Reynolds numbers $Re = 1640\text{--}1660$. By analogy with diagnostics of the flow movement in a round tube, the following classification of flow regimes in a junction is proposed: laminar flow at $Re < 1640\text{--}1660$, transitional flow at $Re = 1660\text{--}2800$, and turbulent flow at $Re > 3000$. The obtained data can be used to clarify the range of data for laminar, transitional, and turbulent flow regimes in round Y-junctions with flow division.

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1. Introduction

When liquids and gases move along tubes and channels, various elements of supply line systems (confusers, diffusers, turning channels, junctions, etc.) are widely used. It is known that hydraulic losses in these elements depend on three flow regimes: laminar, transitional and turbulent [1, 2]. However, determining the boundaries of the laminar-turbulent transition region in complex supply lines elements remains a complex problem, in particular, this applies to junctions. A junction is a part of a supply line that connects one supply line with two channels. Such an element is widely used both in ventilation air supply systems and in hydraulic mains [1, 2]. Thus, the object of research of this work is the diagnostics of flow regimes in a Y-junction.

It should be noted that junctions have a wide range of applications in industry, for example, in two-phase flow devices [3, 4], in micro-reactors of chemical technologies [5]. Junction systems are also found in medicine in the form of the human circulatory [6] and respiratory system [7].

One of the important questions in designing supply lines with junctions is determining local hydraulic resistance [2, 8, 9]. A review of the literature showed that in practice, mainly large Reynolds numbers are encountered; therefore, total pressure losses are most well studied for the turbulent flow regime [1, 2, 8–11]. Since large Reynolds numbers are most common in practice, the total pressure losses have been

studied best for the turbulent flow regime [1, 2, 8–11]. Thus, the well-known book [1] mainly provides data for $Re > 10000$. Laminar regimes usually correspond to low Reynolds numbers ($Re < 2000$) [10, 12] and are effectively implemented by numerical modeling using modern commercial codes [12–15]. For the case of turbulent flow at large Reynolds numbers ($Re > 4000$), both empirical correlations based on experimental data and numerical methods for various turbulence models are used [15–18]. At the same time, laminar-turbulent transition regimes in Junctions have been studied insufficiently [1, 12, 19].

The relevance of this problem is related to the unclear of determining the boundaries of the laminar-turbulent transition in complex flows. This state of research in turn depends on the achievements of the modern theory of hydrodynamic stability. This is due to the problem of determining the boundaries of the laminar-turbulent transition in complex flows. There are numerous factors that affect the flow pattern. The curvature of the streamlines can lead to the formation of Dina vortices: due to a change of geometry in the dividing edge area, separated and secondary flows arise, local non-stationarity, spiral and vortex flows, etc. are possible [9, 15, 16]. Recently, new data on the laminar-turbulent transition in pipes and channels have been obtained [20–24]. In particular, a new scenario of transition in pipes through the intermittency mechanism associated with the formation of large-scale structures (puff) has been discovered [20–22]. In this regard, the main idea of this study was to apply the latest achievements to clarify the boundaries of the laminar-turbulent transition in junctions. Thus, the purpose of the work is to diagnose flow regimes in Y-junctions. In this case, two problems were solved. First, to determine the criterion by which three flow regimes can be distinguished (laminar, transitional and turbulent). Second, to diagnose the flow regime both in the inlet channel and in the two outlet channels of the junction.

In this paper, three flow regimes in a round Y-junction with a symmetrical arrangement of outlet channels and an angle of 50° between them in the range of Reynolds numbers $Re = 400$ – 6000 is experimentally studied. The main attention is paid to measuring the air flow velocity and its pulsations using a hot-wire anemometer, both at the inlet and outlet of the junction. Two criterion and accordantly two original methods for determining the region of laminar-turbulent transition during air movement in a junction with flow diverging are considered. Such diagnostics allow us to consider the flow regimes in the junction inlet and outlet channels.

2. Methods

The scheme of setup for experimental study of air flow regimes in a round Y-junction with symmetrical arrangement of outlet channels consists of the pneumatic and electrical parts (Fig. 1).

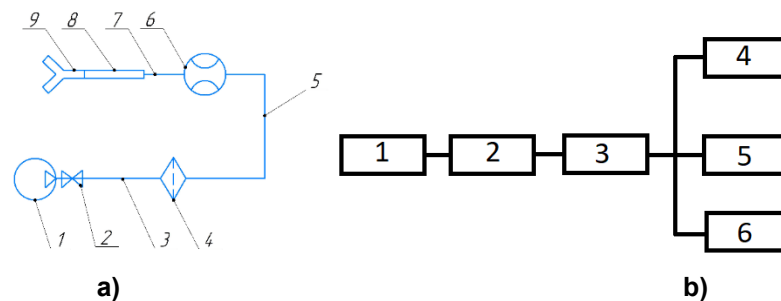


Figure 1. Experimental setup: a) Pneumatic diagram: 1 – compressor; 2 – valve; 3 – supply line; 4 – filter system; 5 – supply line; 6 – flow regulator; 7 – supply line; 8 – tube; 9 – Y-junction; b) electrical circuit: 1 – probe; 2 – bridge; 3 – linearizer; 4 – average-reading voltmeter; 5 – RMS voltmeter; 6 – oscilloscope.

The operating principle of the pneumatic part of setup is as follows. Air from the atmosphere is compressed by the SB4/S-200.LB40 compressor and enters the 200-liter receiver (1). Valve (2) supplies air from the compressor under a pressure of 3.5 bar via supply line (3) to a system of three filters (4) (AME 350C–F04, AME 350C–F04, and AME 350C–F04–T) to remove oil and moisture. Then, air via supply line (5) enters the Bronkhorst Mass View flow regulator (6). As a result, air via supply line (7) enters a straight aluminum round tube (8) (length $l = 2$ m, internal diameter $d = 6$ mm, $l/d = 333$) and then flows out of the Y-junction (9). Connecting lines (3, 5, 7) are made of polyurethane plastic round tube with internal diameter $d = 6$ mm and length of 2, 15, and 10 m, respectively. The Y-junction (9) is printed on a 3D printer with internal diameters at the inlet and outlet of 6 mm, inlet channel length of 30 mm and two symmetrically located outlet channels 50 mm long (N1, N2); the flow separation angle is 50° . All measurements are carried out with the compressor off; the receiver used as the source of compressed air. The thermodynamic parameters of air in the experiments correspond to atmospheric pressure and room temperature.

The electrical part of the setup is designed to record the air flow velocity. For this purpose, a constant temperature hot-wire anemometer (CTA) from Disa Elektronik was used; it consisted of: a miniature

DISA55P11 probe (1), a 55M01 bridge (2), a DISA55D10 linearizer (3), and DISA55D31 (4) and DISA55D35 (5) average-reading and root-mean-square voltmeters. The CTA operating principle is based on the dependence of the probe wire heat transfer on the gas flow velocity. The main part of the hot-wire anemometer is a measuring bridge (1), where a sensitive element in the form of a tungsten wire attached to thin conductive rods (2) is included in one arm. Then, after linearization (3), the bridge voltage is recorded by average-reading “ Ea ” (4) and root-mean-square “ e ” (5) voltmeters. The hot-wire anemometer sensor was calibrated on this setup (with the disconnected junction) using the tested flow regimes at the outlet of the tube (8). The calculation was performed using the linear formula: $Ua = a \cdot Ea$, $u = a \cdot e$, where Ea and e are the average-reading and root-mean-square values of the hot-wire anemometer bridge voltage, a is the calibration coefficient. Thus, the average velocity Ua and root-mean-square values of velocity pulsations u and air flow turbulence degree $Tu = (\overline{u}/Ua) \cdot 100\%$ were measured using the sensor calibration and the readings of two voltmeters. The RIGOL DS1054Z digital oscilloscope (6) was used to observe the hot wire anemometer signal in real time [$E = f(t)$]. Then, using the Ultra Scope program, the data from the oscilloscope were transferred to the computer and processed in the Excel program.

Graphical dependences of the flow velocity on time $U = f(t)$, as well as dependences on the Re number were plotted for the average velocity (Ua) and the root-mean-square pulsations of velocity (u). Here, $Re = 4 \cdot Q / \pi \cdot d \cdot \nu$, where Q is the volumetric air flow rate, d is the internal diameter, and ν is the kinematic viscosity of air.

To study the flow in a junction, two measurement techniques were modified. The first technique is based on the registration of large-scale turbulent structures, which are called “puff” in the literature [20–22]. They are formed during the laminar-turbulent transition in long round tubes [20–24]. The change in velocity over time ($t = 1–1.5$ s) in such a structure is shown in Fig. 2a. The measurements were performed at the outlet of the tube (8) on the axis for $Re = 2109$ without a junction. A puff has characteristic features that distinguish it from other types of disturbances: a smooth leading edge and a steep trailing edge. A significant decrease in the instantaneous velocity by 30–40% is also observed, and the puff length can reach 20–40 d . In Fig. 2a, a laminar section of the flow is observed at time intervals $t = 0–1$ s and $t = 1.5–2$ s. With increasing Reynolds number $Re > 2109$, the number of such structures increases. When turning to turbulence through the intermittency scenario, the flow becomes completely chaotic and there are no laminar regions [20–22]. These characteristic features of the puff were observed in our experiments [23–24], indicating a laminar-turbulent transition in the tube (8). The second technique is based on recording velocity pulsations with increasing Reynolds number [23, 25]. This method is used for stochastic behavior of velocity pulsations, i.e., when there are no characteristic vortex structures in the flow. An example of such velocity behavior is shown in Fig. 2b. The measurements were performed at the outlet of the junction (9) on the axis for $Re = 1664$. As can be seen, a chaotic change in the instantaneous velocity value over time is observed and there are no signal features that differ from a random process. In this case, the main flow characteristic is the root-mean-square pulsations of velocity u and the degree of flow turbulence Tu . The growth of these parameters with increasing Reynolds number indicates flow turbulence intensification, and a decrease in these parameters indicates turbulence attenuation.

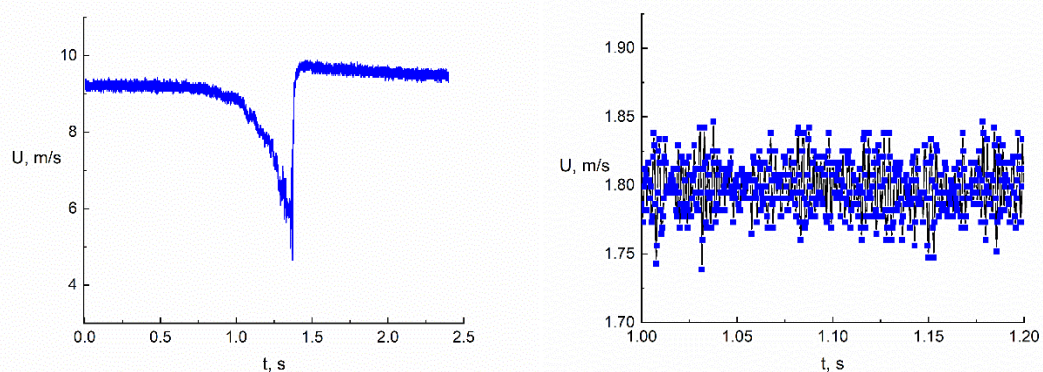


Figure 2. Variation of instantaneous velocity over time:
a) round tube outlet, $Re = 2109$; b) Y-junction outlet, $Re = 1664$.

3. Results and Discussion

The work is aimed at determining the flow regimes in a Y-junction with flow division. Two methods were used for analyzing the data obtained. The velocity and velocity pulsations were measured both at the inlet and two outlets (N1, N2) of the Y-junction in the range of Reynolds numbers $Re = 400–6000$. The

ranges of Reynolds numbers characteristic of laminar, transitional and turbulent flow regimes in such a junction were obtained.

The dependence of the average velocity change on the Reynolds number for the tube outlet and junction outlets N1 and N2 is presented in Fig. 3. At that, the Re number in all cases is determined by the air flow rate and the diameter of the inlet tube d . The flow velocity was measured on the tube axis and on the axis of the junction outlets. The data for the tube were obtained without a junction. Since the inlet part of the junction is 30 mm, and the length of the supply tube is 2 m, we believe that the data at the tube outlet correspond well to the flow parameters near the channel separation zone. In this case, the first method for determining the laminar-turbulent transition in the tube by diagnosing large-scale structures was applied; according to this method, the critical Reynolds number was $Re = 2000$. According to Fig. 3, three flow regimes can be distinguished for a round tube: a laminar regime at $Re < 2000$ (no puffs), a transitional regime (with puffs) at $Re = 2000-2800$; and a turbulent regime (no sections of laminar regime) at $Re > 3000$. For a round tube, a decrease in the velocity on the channel axis in the region of $Re = 2492-2800$ is associated with a change in the velocity profile from the parabolic one, characteristic of the laminar flow, to the power-law profile, responsible for the turbulent flow. These data correlate well with the works of other authors [20, 21]. For the case of junctions (outlets N1 and N2), an almost monotonic increase in the average velocity vs. the Reynolds number is observed, without any peculiarities in the region of $Re = 2000-2800$, when a laminar-turbulent transition is observed in the inlet tube.

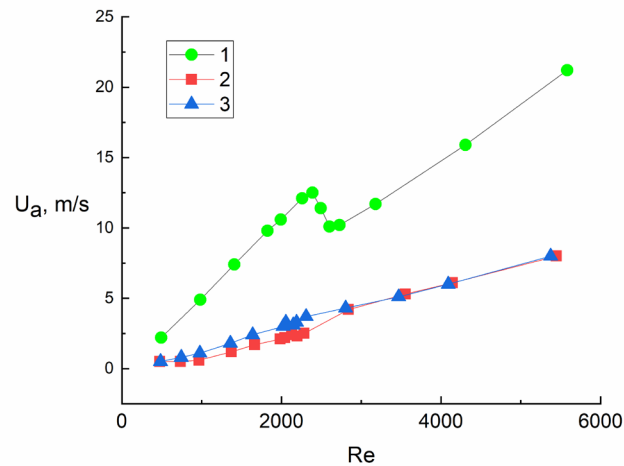


Figure 3. Velocity change in the junction:
1 – round tube outlet; 2 – outlet of junction No.1; 3 – outlet of Y-junction No.2.

In addition to the data on the average velocity, statistical data in the form of a dependence of the root-mean-square pulsations of velocity u on the Reynolds number Re were obtained in this work (Fig. 4). If the measurements are carried out at the tube outlet, the regime of laminar-turbulent transition is also well diagnosed using the second technique by a significant increase and decrease in velocity pulsations in a narrow range $Re = 2000-2800$, which corresponds to the known data for the transition in a tube [20, 23]. For $Re = 2800-6000$, an insignificant increase in velocity pulsations in the turbulent flow regime is observed.

For two junction outlets N1 and N2, the pulsations are approximately the same in the entire range of $Re = 400-6000$. A significant increase in u begins approximately at $Re = 1640-1660$, which is lower than the critical numbers for the tube outlet $Re = 2000$. For $Re = 1640-2000$, the flow regime on the oscilloscope looks like stochastic. An example of such a flow is shown in Fig. 2b. For the regime with puffs ($Re = 2000-2800$), the behavior of the velocity pulsations at the junction outlet correlates with a change in u for the inlet tube. At $Re > 2800$, a slight increase in u is observed both for the inlet tube and for the two junction outlets. At that, the values of velocity pulsations for the junction are higher than that for the inlet tube.

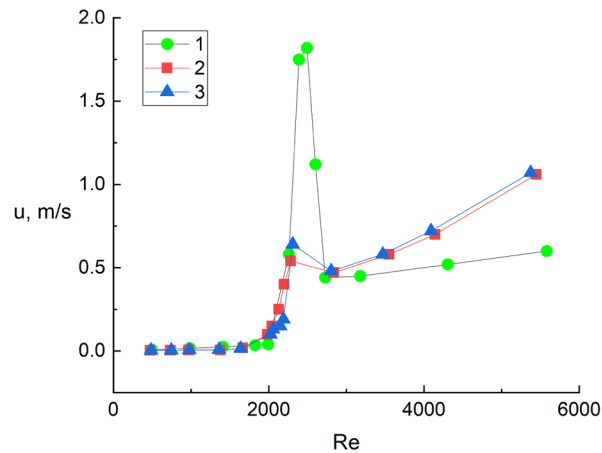


Figure 4. Velocity pulsations in the junction:
1 – round tube outlet; 2 – outlet of Y-junction No.1; 3 – outlet of Y-junction No.2.

By combining the data obtained in Figs. 3, 4, we can plot a diagram of the dependence of turbulence degree Tu on Reynolds number Re , which is shown in Fig. 5. Note that the value of u is normalized here to the value of the local velocity at the measurement point. The behavior of the turbulence degree for the tube corresponds to the data in Figs. 3 and 4, i.e., there is an extremum in the transition region. The Tu parameters for the junction outlets N1 and N2 are qualitatively the same in the entire range of Re numbers. This figure shows clearly that the growth of Tu for the junction begins with the Reynolds numbers significantly lower than the critical numbers for the tube outlet. The maximum values of velocity pulsations for the tube are $Tu = 16\%$; for the junction, $Tu = 12\text{--}22\%$, and they are located in the range $Re = 2300\text{--}2400$. Thus, extreme turbulence corresponds approximately to the maximum pulsations in the inlet round channel. At $Re > 3000$, a slight decrease in Tu is observed for the inlet tube. It should be also noted that at $Re > 3000$, the turbulence level for the junction outlets N1 and N2 is approximately twice as large as Tu for the round tube outlet. By analogy with the diagnostics of flow movement in a round tube, the following classification of flow regimes in the junction is proposed. Laminar regime occurs at $Re < 1640\text{--}1660$, transitional regime occurs at $Re = 1660\text{--}2800$, and the turbulent one takes place at $Re > 3000$.

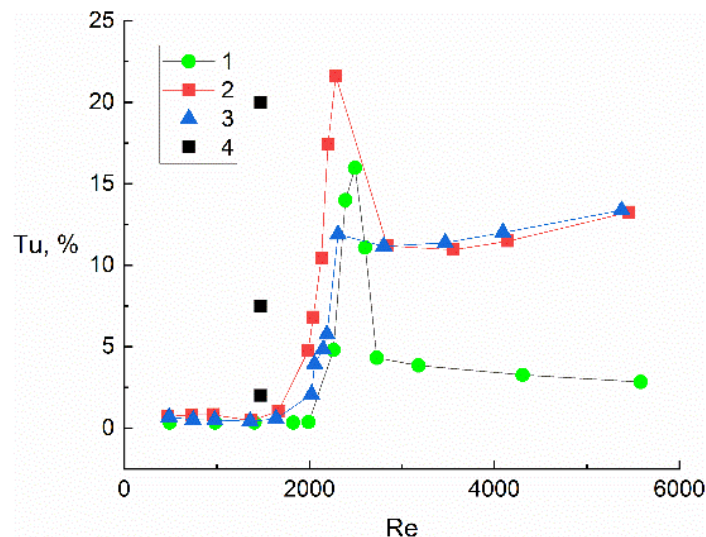


Figure 5. Degree of turbulence in the junction:
1 – round tube outlet; 2 – outlet of Y-junction No. 1; 3 – outlet of Y-junction No. 2, 4 – [26].

For comparison, data [26] are provided for a round Y-junction with an angle of 50° and a straight-through channel at $Re = 1475$. In this case, separated flow is observed. As a result, the turbulence level increases from $Tu = 2\%$ in the inlet channel to higher values in the outlet channels. Moreover, due to the asymmetry of the tee geometry, on the axis in the straight outlet channel $Tu = 20\%$, and in the inclined channel – $Tu = 7.5\%$.

4. Discussion

The study is aimed at determining the boundaries for three flow regimes in a junction. The experiments were carried out using a constant-temperature hot-wire anemometer in an air flow. The values of instantaneous velocity, average velocity, and root-mean-square velocity pulsation were measured in a round Y-junction in a wide range of Reynolds numbers $Re = 400\text{--}6000$. A junction with diameter $d = 6$ mm for the inlet and outlet channels was chosen as the object of study for a symmetrical arrangement of the outlet channels with an angle of 50° between them. For the first time, two methods for diagnosing flow regimes during air movement in a junction were proposed. The first diagnostics is based on recording large-scale turbulent structures of the puff type [20–24], which are formed during the laminar-turbulent transition in long round tubes. It is used to determine the flow regime in the junction inlet channel, when intermitting single long vortex structures of the puff type appear along with the laminar flow. The second method is based on recording velocity pulsations with an increase in the Reynolds number [24, 25]. This method is used for chaotic behavior of velocity pulsations, i.e., when there are no organized vortex structures in the flow. The second diagnostics is used both for the inlet channel and for two outlet channels of the junction. The conditions at the junction inlet are of significant importance for determining the flow regime [9]. In this study, a long round tube ($d = 6$ mm, $l/d = 333$) was placed at the junction inlet; at the exit of this tube, a velocity profile corresponding to certain flow regimes was formed: parabolic profile for the laminar flow, the transitional profile in the region of intermediate Re numbers, and the power-law profile for the turbulent flow regime. The use of other geometries of the inlet section before the junction is a special problem and it requires additional study.

The flows in the inlet and outlet channels of Y-junctions must be considered separately. For the inlet channel, the critical Reynolds number is $Re = 2000$ (single puff-type structures appear for the first time). The transition to turbulence occurs at $Re = 2800$, when puff-type structures follow continuously and laminar sections are absent. These data are in good agreement with known works for the transition in a pipe [20, 23]. At the same time, for the two outlet channels, a significant increase in pulsations occurs at lower Reynolds numbers $Re = 1640\text{--}1660$. In this case, the behavior of the instantaneous velocity value is of a random character and puff-type structures are not observed. New data indicate that the laminar-turbulent regime in junctions can occur at Reynolds numbers significantly lower than $Re = 2000$. Such low critical Reynolds numbers for symmetrical Y-junctions have not been published in the literature before. Local turbulization is known in the literature at Reynolds numbers $Re = 1460\text{--}1475$ for fluid flow in an asymmetric Y-tee [26,27]. For pressure Y-junctions, for example, in [1], the values $Re = 2000\text{--}3000$ obtained in experiments are given, in the calculations [13, 19], the value $Re = 2200\text{--}2300$ was obtained. This difference may be due to the fact that the laminar-turbulent transition mode in experiments is determined by measurements of the average value of the pressure drop. At the same time, measurements of velocity pulsations have a significantly higher sensitivity [20]. From the point of view of numerical modeling, accurate calculations by the DNS (Direct Numerical Simulation) method in junctions have not yet been carried out.

Apparently, the reason for a decrease in the critical Reynolds number in the Y-junction is the complex three-dimensional flow in the separation region. It is known that in Y-junctions, separation and secondary flows, non-stationarity spiral and vortex structures can occur [9, 15, 16]. These processes can play the role a trigger for an earlier laminar-turbulent transition, but further study is required to determine the real causes of this phenomenon. In the region of high Reynolds numbers ($Re > 3000$), the turbulence level for the junction outlets is approximately twice as high as the turbulence level at the outlet of a round tube. This suggests that in a Y-junction, the generation of turbulent energy exceeds the pulsation energy generated by the formation of puff structures in round tubes.

5. Conclusions

Recently, new data have been obtained on the laminar-turbulent transition in pipes and channels [21, 22]. In this regard, the main objective of this study was to apply the latest achievements in the field of transition to clarify the boundaries of the three flow regimes in junctions. Based on the conducted research, the following conclusions can be drawn.

1. A new experimental method has been developed for determining the flow regimes (laminar, transitional and turbulent) in a junction based on two criteria: the presence of puff-type vortex structures and the degree of flow turbulence.
2. For the inlet part of the junction, the main criterion is the presence of puff-type vortex structures and the degree of flow turbulence.
3. For the two outlet parts of the junction, the main criterion is the degree of flow turbulence.

4. For the conditions of our experiment, the following values were obtained for the outlet part of the round Y-junction: laminar mode – $Re < 1640$ – 1660 , transitional – $Re = 1660$ – 2800 , turbulent – $Re > 3000$.

The program of further research includes the study of flow regimes and local hydraulic losses with variations in the main parameters of round junctions (flow separation angle, ratio of inlet and outlet diameters, effect of the dividing edge, and geometry of inlet part before the junctions). The obtained data can be recommended for specifying the range of laminar, transitional and turbulent flow regimes in round Y-junctions with flow separation.

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