UDC 532.517.4

EXPERIMENTAL STUDY OF COMPLEX CURRENTS (THREE-DIMENSIONAL JET AND BODY WAKE)

G. Toleuov, M.S. Issatayev, Zh.K. Seidulla

Scientific Research Institute of Experimental and Theoretical Physics (IETP), Almaty,
Muhtar.Isataev@kaznu.kz

The studies of the heat transfer of a finite size streamlined surface were conducted. The experimental results of the investigation of the large-scale formations development in complex currents (body wake) are shown. The general patterns (analogy) of such flows with a three-dimensional free jet are finding. The distribution of velocity fields in vortices and vortex clusters in turbulent free three-dimensional jets had been identified as one of the varieties of complex jet streams. A comparison of varieties of complex jet streams is given.

***Keywords**:* autocorrelation function, vortex, large-scale vortices, body wake, three-dimensional free jet, vortex cluster, complex jet stream

Introduction

At present, more in-depth studies of the parameters of the vortex structures of different types of flows are necessary because of changes in the approach to the nature of formation of turbulent flows [1-5]. Also, some phenomena were observed in the process of mixing and transfer of heat in three-dimensional jets and wakes formed during installation of finite length cylinders streamwise, with no reasons given without studies of the vortex structure of these flows.

After the spectral and correlation analysis, generalized data on the scales and intensities of the characteristic frequencies of the vortex structure were obtained. It was noted that degradation of the vortex structures, propagating along the nozzle's larger and smaller sides, has different intensity values in both cases. There was also a difference in flow rates observed. More detailed information on the dynamics of the development of vortex structures can be obtained by using the phase averaging technique in converting flow velocity and temperature signals.

In this paper an attempt to understand the physics of the mentioned above effects is made by deeper investigation of vortex structures which are formed at the initial and transitional parts of the three-dimensional jet and wakes behind the cylinders of finite length.

1. Experimental technique

Experiments on the study of free turbulent jets were carried out on the apparatus shown in Fig.1. To measure the average speed and dynamic pressure, a Pitot 8 tube and MMN-240 micro-manometer 12 are used, as well as the equipment, earlier developed by RIETP employees at al-Farabi KazNU. It includes a two-channel thermo-anemometric system with a linearized output speed signal, a temperature transducer, an inductive pressure transducer and a phase-selector unit.

The measurement of the pulsation characteristics of velocity is made using the above-mentioned thermo-anemometric system using the phase selector. In the process of experiments, automatic recording of autocorrelation functions of velocity pulsation is performed using X6-4-type digital correlator, which is used in experiments.

Adjustment of synchronous illumination phase is carried out using a phase sampler. The sensor position and illumination phase are adjusted so that the sensitive part of the sensor is on the motion line of the vortex centers. Then registration system and automatic recording of probability distribution functions and correlation function is launched. Simultaneously, a memory oscilloscope is launched to record the oscillogram of the signal under study.

Visualization of the flow for the purpose of observing the evolution of vortex clusters is carried out with the help of IAB-451 shadow device, in whose testing section the investigated region of the flow was located. During the experiment using x-y recorder equipped with auxiliary devices, the dynamic and thermal characteristics are recorded in the form of spatial distributions.

Displacement of the Pitot tube and the sensors along the three axis of nozzle symmetry is carried out with the help of a three-dimensional coordinate spacer. Since for a free jet the static pressure is almost absent, the experiment in its essence reduces to measuring the velocity head. To measure this pressure and velocity, two types of measuring nozzles are used. To determine mean velocity values in a fixed point, starting from one gauge (*x/b*), total pressure Pitot tube with an inlet diameter of 0.8 mm is used. When determining the pressure profiles on the nozzle cross section, with regard to the boundary layer formed on the lateral inner nozzle surfaces, a microtube with a flat top made of a thin-walled tube is used by flattening the measuring end.

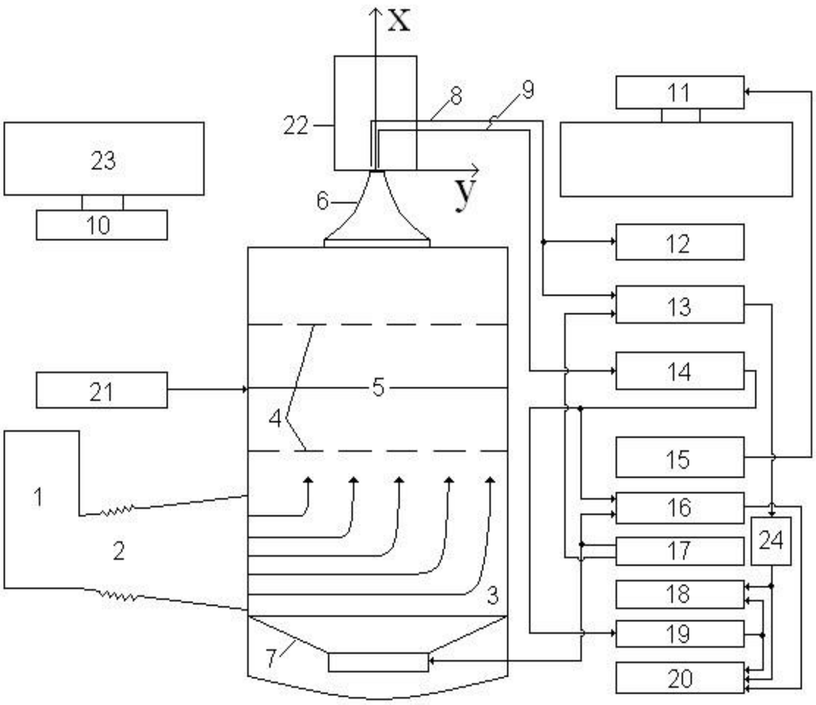

Fig. 1. The scheme of experimental equipment:

1-fan; 2-vibration damping junction; 3-stilling chamber; 4-field mesh; 5- heated grid; 6-nozzle; 7-speaker (N = 50 W); 8-Pitot tube; 9-sensor; 10-photorecorder; 11-illuminator; 12- MMH-240 brand micromanometer; 13-inductive pressure transducer; 14-CTM-02-type block thermo-anemometric system; 15-strobe; 16-BEV-03phase selection block; 17-GZ-34 sound generator; 18- CB-13 universal memory oscilloscope; 19-device for studying correlation characteristics of X6-4; 20-PDP4-002 two-coordinate potentiometer; 21- LATR type auto-type transformer; 22-end plates; 23- Tepler IAB-451 shadow device; 24-differential amplifier.

Such a nozzle design ensures high accuracy of local pressure measuring in the boundary layer with the smallest flow perturbations. The dimensions of the fore part of the microscope are 0.3 mm x 1.5 mm. Wall thickness ~ 0.05 mm. A simple and fairly reliable method of measuring velocities and pressures with acoustic action is the counter Pitot tubes method. Practically the measuring nozzle consists of two Pitot tubes fixed on a common assembly so that their spouts are directed towards each other and slightly apart.

The recording of pressure and velocity is made using a MMN-240 type micromanometer or an inductive pressure transducer, the flow diagram of which has been developed. The diagram contains the following components: a measuring bridge, a G3-34 sound generator, an amplifier, an SV-13 oscillograph, two-coordinate recorder PDP4-002, a power supply unit. In the process of experiments, the data will be adjusted by plotting a calibration curve to calculate the temperature values (displacement of the recorder along *y* coordinate will be calibrated based on the mercury thermometer readings).

In the experiments on the investigation of a finite size body wake, the working bodies, which represent short cylinders with flat ends with different elongations, will be used. To measure pressure distribution along the bodies' surface, there are drainage holes drilled at equal distances along the generating cylindrical part. By successively opening each hole, a complete picture of pressure distribution across the cylinder surface can be obtained in longitudinal and transverse streamlining.

The velocity field in the wake behind the cylinder is measured with a T-shaped nozzle. A visual investigation of the flow past a short cylinder was carried out on the basis of the IAB-451 type device. The correlation properties of the vortex breakdown were measured using a digital BK-OZU type correlator.

The diagram of experimental apparatus for measuring the distribution of temperature comprises the following: copper-to-constantan thermocouple, digital voltmeter universal B7-21, x-y- recorder PDP4-002. The circuit of the experimental apparatus for measuring the distribution of temperature is the following constituent parts: copper-constant thermocouple, digital voltmeter universal B7-21, two-coordinate recorder PDP4-002.

To measure temperature distribution of the jet, copper-constant thermocouple is used, the "hot" junction of which is placed in the flow, and the other, the so-called "cold" junction, is at room temperature. EMF thermocouples are measured with a digital voltmeter B7-21. The signal from the thermocouple is also fed to PDP4-002 x-y recorder, where continuous records of temperature changes along the axis of the string and in the cross sections are produced.

To measure the average heat exchange factor, copper cylinders with the same parameters as in the flow aerodynamics study will be used. Heat transfer factors of the cylinders are determined by the method of steady state of the first kind. Body temperature was measured by a copper-constantan thermocouple, one of which is caulked into a cylinder, and the other one is blown over by an airflow. The thermocouple voltage is measured by a digital B7-21 milivoltmeter.

When conducting experimental tests on free jets, nozzles with a quadrangular cross section of the outlet with side proportions were used: λ = 1.65; 2.77; 5.07; 7.61; 11.0; 16.0; 25.2 and a round nozzle (diameter = 22.5 mm). The values of the outlet cross section of all the nozzles were approximately equal. In the study of flow past cylindrical bodies, working bodies were used, which were short cylinders with flat and spherical ends with *l/d* elongation from 0.2 to 20.0.

2. Discussion of results

Using the available equipment, it was possible to trace and photograph the shadow image of the flow by means of a pulsed flash of light synchronized with the vortex frequencies that are formed in the initial and transition zones of the jet. The thermoelectric anemometer system was used to determine arithmetic and pulsation characteristics of the flow velocity. A complete set of the system was used, including electronic micromanometer and a phase averaging device, which made it possible to measure the averaged periodic and chaotic components of the rapid pulsation.

A visual examination of the wake behind cylinders of different lengths in the thickening section in the working part of the device with a shadow pointer and during the experiments on determining the length was also carried out. For a more in-depth study of the relationship between mixing processes and the dynamics of the development of vortex structures, the existing experimental apparatus was modernized so that it was possible to synchronize the frequencies of formation of the vortex structures and visualize the impulse flash in the investigated flow zone.

The results of measuring axial flow velocities in the jets leaving the nozzles with different lateral sides in the output cross-section are shown in Fig. 2.

Data analysis indicates a zone of gradually decreasing flow velocity. This zone was detected in front of the main zone, where the flow velocity drops to about $\sim x^{-1}$. The lower the value of λ becomes, the closer this zone is to the point of outflow. This dependence can be more accurately tracked when the results are put out in the following form: $U_{mi} = f(\lambda)$ (Figure 3). Here, U_{mi} is the selected flow rate level.

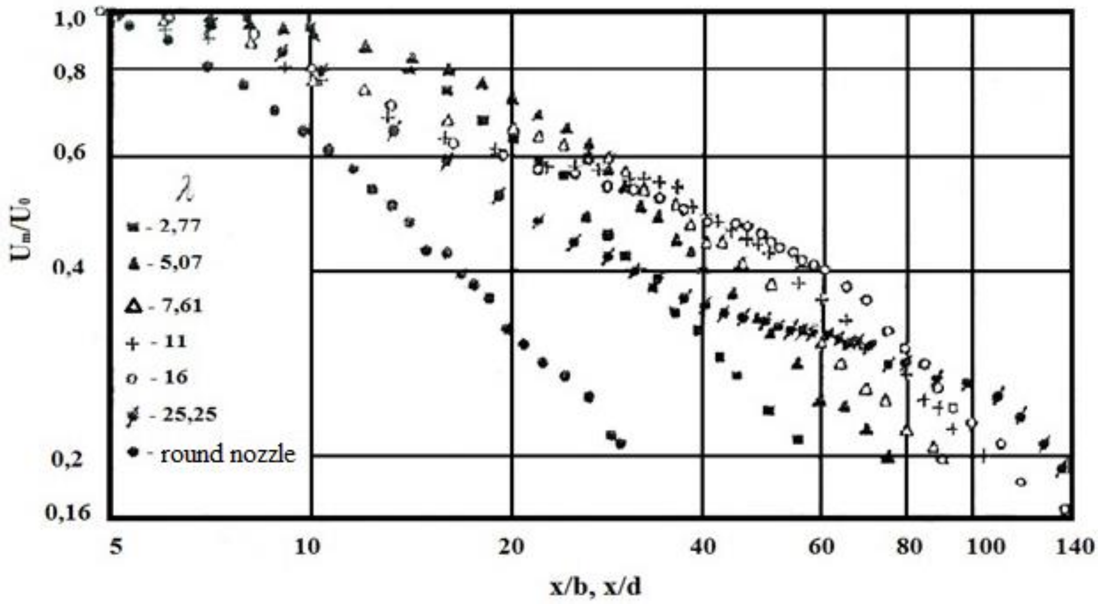

Fig. 2. The nature of the change in the axial flow rate at various values: λ = *a/b*, U_o = 20 m/s, where U_o is the axial flow velocity.

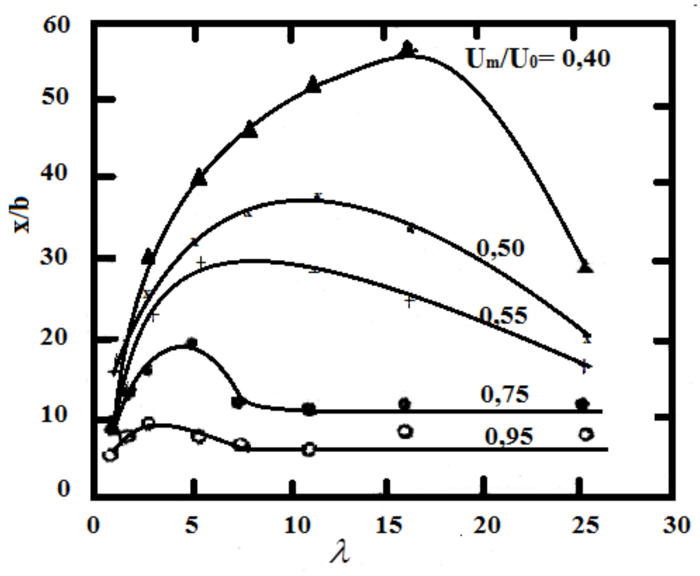

Fig. 3. The length of the section with equal flow velocity levels is shown as a function of the parameter λ = *a/b*, with U_o = 20m/s.

Since the above-described zone has already been determined, it can be called the zone of deformation termination of a three-dimensional jet, i.e. this zone is in front of the main zone, in which there is no deformation of the jet, this zone extends further along the free and axially symmetric scheme. Determining the autocorrelation functions of the longitudinal axial pulsations of flow velocity in the investigated region, where deformation process is completed, proved the existence of a negative maximum. The results of determining the Ri value in the jet at $\lambda = 2.27$ are shown in Fig.4. The time corresponding to the value of the negative R maximum can be called the half-period of the typical frequency $n_{char}=1/\tau_{char}$ of this periodically repeating process. In the above-described case, this time equals 5.6×10^{-3}, and this value corresponds to a frequency of 89 Hz.

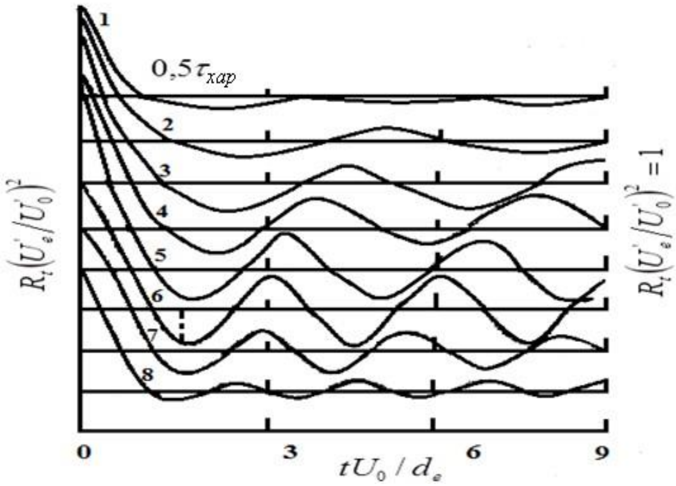

Fig. 4. Values of autocorrelation functions of speed oscillations flow along the jet axis at different values of disturbance frequencies at Uo = 6.03 m/s; $\lambda = 2.77$; x/b = 10:
1 - in the undisturbed state; 2 - beginning of disturbance at a frequency of 50 Hz; 3 - 63; 4 - 70; 5 - 80; 6 - 89; 7 to 100; 8 - 120. The index *e* is an effective.

Obviously, disturbances frequency of 89 Hz corresponding to the τ_{char} period, because the growth and decrease in frequency with respect to a given value with equal degrees of perturbation leads to a decrease in R_t (U_{me}/U_m) value (see Figure 4). This explains the presence of variability of the flow velocity under the influence of perturbation and makes it possible to estimate perturbation result. It should be taken into account that the change in the degree of the disturbance frequency and the corresponding d_e / U_o $\times\tau_{char}$ value in the range of 0.25 – 0.36 results in a change of the result of the action by only 10%. Here we have $d_e = 2\ (ab/\pi)^{0.5}$, (*a* is the long side of the nozzle, *b* is the short side of the nozzle, and d_e is the effective diameter). Therefore, it is recommended to take this measurement interval as the area with the most pronounced disturbance.

Figure 5 shows the shadow photographs of the flow made from the small and large sides of the nozzle in various stages of development, when the signal of the disturbance frequency turned out to be in the visible spectrum. The shape of the vortex perturbation formed near the tip of the nozzle is clearly seen in the images. It is also easy to see the initial phase of the vortex perturbation from the larger side of the nozzle. This process continues until a vortex is formed in a 3D format, both sides of which are at different cross sections of the jet.

The average instantaneous profiles of periodic and random components of flow velocity fluctuations U" value, which could be detected using the phase averaging technique, prove the existence of different levels of these quantities corresponding to the larger and smaller sides of the nozzle. This difference for the U' value is shown in Figure 6. These data were obtained at two different stages of vortex development. The upper lines correspond to the moment when the measuring device passed through the center of the vortices, and the lower lines correspond to the measurements between eddies.

For a comparative analysis with a three-dimensional jet, experimental investigations of the flow past cylindrical bodies were conducted.

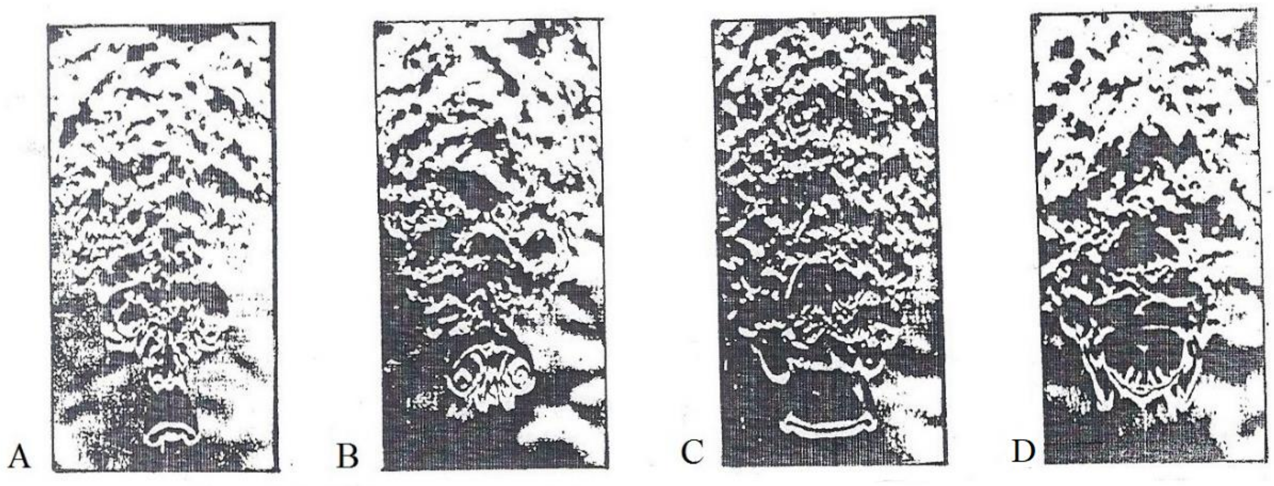

Fig. 5. Shadow images of the flow in a 3-dimensional jet format with perturbation frequency corresponding to S = 0,27: U_o = 4,3 m/s; n = 60 Hz;
A, B - view from the small side of the nozzle; C, D - view from the larger side of the nozzle.

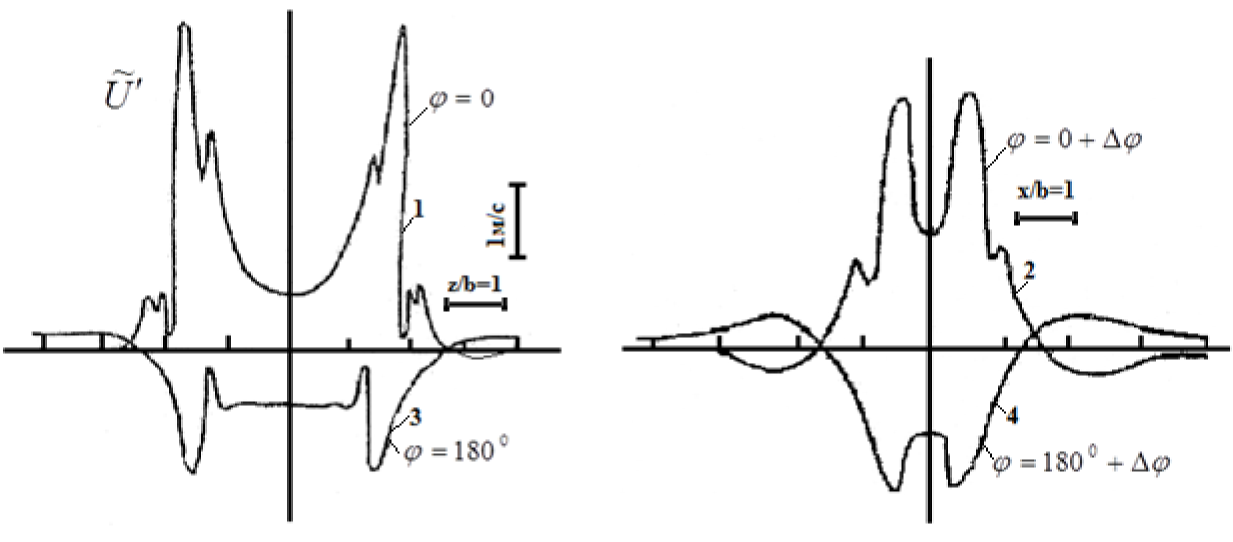

Fig. 6. Velocity pulsations wave component distribution diagram in disturbance:
Uo = 4.27m/c; n = 60Hz; S = 0.27;
1, 2 - dimensions of the cross-section in the center of the eddy; 3, 4 - between vortices

The values of correlation factors were determined at the time when the cylinder wake was investigated. These measurements were taken using two devices placed at the two ends of the cylinder near the section where the flow is detached from the surface. The obtained data are shown in Fig. 7. The positive value of the correlation factor in the range of $0<l/d<12$ proves the symmetrical separation of eddies as they move away from the cylinder surface. The sign of the correlation factor varies with the ratio $l/d>12$.

The absolute value of the factor increases as the ratio $l/d = 07$, is reached, at least, when two limiting walls are established at both ends in the presence of large l/d ratios. A negative R value indicates the presence of an antisymmetric separation of eddies (T. Karman vortices table).

A shadow photograph of the flow with insignificantly heated cylinders, obtained using an impulse flash, confirms the conclusion that is based on determination of correlation factors' values.

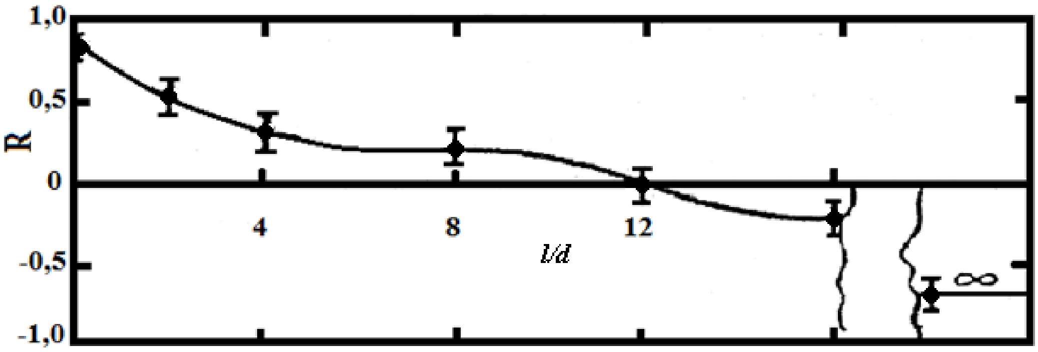

Fig. 7. Factor of velocity fluctuation correlation expressed as the *l/d* function

It was mentioned above that have been discovered that some phenomena were observed in the process of mixing and transfer of heat in three-dimensional jets and wakes formed during installation of finite length cylinders streamwise, with no reasons given without studies of the vortex structure of these flows.

One of the proofs of existence of such phenomena is the presence of a maximum in the dependence of the length of the reciprocating flow zone on the aspect ratio parameter λ=*l/d*. This dependence, resulting from the transformation, it is shown in Figure 8.

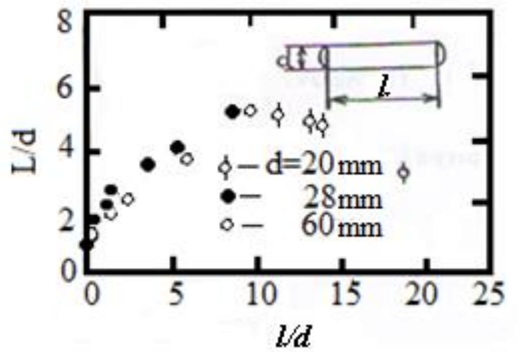

Fig. 8. Length of reciprocating flow zone in the wake of the cylinder, depicted as a λ= *l/d* parameter

A similar process of increasing the length of the original and transition zones with a certain proportion between lengths of the lateral sides of the output cross-section is marked on three-dimensional jets (analogy).

Conclusion

After the spectral and correlation analysis, generalized data on the scales and intensities of the characteristic frequencies of the vortex structure were obtained. It was noted that degradation of the vortex structures, propagating along the nozzle's larger and smaller sides, has different intensity values in both cases. There was also a difference in flow rates observed. More detailed information on the dynamics of the development of vortex structures can be obtained by using the phase averaging technique in converting flow velocity and temperature signals.

Therefore, the presence of a maximum in the L/d = *f* (*l/d*) relation is directly linked to the transformation of vortex separation and the processes of vortex formation, starting with a symmetric vortex corresponding to the flow around the sphere and ending with a two-dimensional vortex corresponding to the flow around the infinite length cylinder.

Acknowledgment

The work was carried out within the framework of a project funded by the Ministry of Education and Science of the Republic of Kazakhstan on the topic 3096/GF4 «Research of heat transfer and heat-and-mass exchange in complex jet flows»

REFERENCES

1 Vlasov E.V., Ginevsky A.S. Coherent Structures in Turbulent Jets and Wakes. *Science an Technology Summary. Mechanics of Liquid and Gas Series*. Moscow, Nauka, 1986, Vol. 20, pp. 3 –84. [in Russian]

2 Issatayev S.I., Toleuov G., Issatayev M.S., Bolysbekova Sh.A. Experimental Study of three-Dimensional Turbulent Jets Flowing from a Nozzle with a Rectangular Outlet Cross Section. *Engineering and Physics Journal*, 2016, Vol. 89, No.2, pp. 383 – 387. [in Russian]

3 Hussain A.K.M.F. Coherent structures and turbulence. *J. Fluid Mech*, 1986, No. 173, pp. 303 – 356.

4 Issatayev S.I., Tarasov S.B., Toleuov G., Issataev M.S, Bolysbekova Sh.A., Baigalikyzy B. Dynamics of Vortex Perturbations at the Initial and Transitional Sections of Three-Dimensional Jets. *Bulletin of NAS RK. Physics and Mathematics Series*. Almaty, 2015, No.3 (301), pp. 125 – 131. [in Russian]

5 Lhendup Namgyal and Joseph W. Hall. Coherent streamwise vortex structures in the near-field of the three-dimensional wall jet. *J. Fluid Eng*., 2013, Vol. 135, No. 6, pp. 120 – 126.

Article accepted for publication 20.11.2017

ЭКСПЕРИМЕНТАЛЬНОЕ ИССЛЕДОВАНИЕ СЛОЖНЫХ ПОТОКОВ
(ТРЕХМЕРНАЯ СТРУЯ И СЛЕД ЗА ТЕЛОМ)

Г. Толеуов, М. Исатаев, Ж. Сейдулла

Научно-исследовательский институт экспериментальной и теоретической физики
(НИИ ЭТФ), Алматы

Проведены исследования теплообмена обтекаемой поверхности конечного размера. Показаны экспериментальные результаты исследования развития крупномасштабных образований в сложных потоках (след за телом). Обнаружены общие закономерности (аналогия) таких потоков с трехмерной свободной струей. Распределение полей скоростей в вихрях и вихревых кластерах в турбулентных свободных трехмерных струях были идентифицированы как одни из разновидностей сложных струйных потоков. Показано сравнение разновидностей сложных струйных потоков.

Ключевые слова: автокорреляционная функция,вихрь, крупномасштабные вихри, след за телом, трехмерная свободная струя, вихревой кластер, сложный струйный поток