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UNCONFINED HELICAL JET ISSUING INTO STAGNED AIR

The helical jet is generated in a tangential pipe nozzle having the tangential and the axial inlets and the axial outlet. The flow directions in free jet spreading in the stationary air was measured by means of a flag type probe. The flow was visualized using the planar scattering technique.

It was found that due to asymmetrical distribution of the tangential velocity in the jet leaving the nozzle, the air particles spread in the ambient with various intensity depending on the azimuthal angle. The result is that the jet has a spiral shape with bean-like cross-section.

1. Introduction

In the last decade much attention has been focused on the characteristics of the swirling jet issuing from a nozzle into stationary air. This interest arose out of important applications of swirling jets in industrial and engine burners, where the swirl is used to enhance mixing of reacting gases and stabilize the flame. Various flow patterns of swirling jet have been distinguished depending on the swirl intensity, the Reynolds number and the geometry of the nozzle. In most cases, a rigid core (bland body) was located in the centre of the nozzle to generate a recirculation zone inside the annular jet. It was observed that the recirculation zone considerably changes when the swirl intensity is increased or decreased which results in variations of its shape, dimensions and structure. The experiments with swirling jets were conducted using the swirl generators prepared to obtain an axisymmetric flow of high quality [1], [2], [3], i.e. characterized by uniform flow velocity distributions on concentric circles. The axisymmetric flow, however, does not exist in the majority of industrial flow

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systems in which swirling is employed. Frequently, the swirl is generated in a very simple way using a jet from a single nozzle tangentially flowing into a pipe. Due to the asymmetric supply, a screw-like (helical) jet superimposed on the mean swirling flow occurs in the pipe.

In the previous paper [4] the Authors investigated the effect of pipe length (the distance between its tangential inlet of the jet to its axial outlet) on the characteristics of the helical jet leaving the pipe. It was observed that depending on relative pipe length (pipe length related to its diameter) the largest asymmetry of the jet appears on the circles near the pipe wall or in the middle part of the exit cross-section for short and a long pipes, respectively. The present paper aims at investigating the characteristics of the helical unconfined jet issuing from a short pipe of the relative length $L/D=1$. Flow properties of the jet, varying as it spreads in stationary air, are measured and discussed.

2. Experimental Set-Up

Figure 1 shows the schematic diagram of the experimental set-up. The pipe (70 mm in diameter) was supplied with compressed air from two nozzles. One of them was placed coaxially with the pipe and the other tangentially to the pipe wall (normally to the pipe axis). By changing the proportion of flow rates of the air supplying the nozzles, one adjusted the swirl intensity of the jet issuing into the ambient.

The flow under investigation is three-dimensional with very high turbulence. In such a case, the results produced by instruments mostly used to measure the flow velocity (hot wire x-probe, 5-points sphere and the like) are of low reliability. This takes place, first of all, because of strongly varying flow direction.

The present work is focused on the investigation of the jet flow structures that change as the jet spreads in the surrounding air. This is achieved here by measuring the spatial distribution of the time mean flow velocity directions. To meet this objective, a probe shown in Fig. 1e has been developed. It contains a rigid flag made of metal sheet (0.2 mm thick) fastened to a rod 3 mm in diameter. The rod that can rotate around its axis is connected to a potentiometer of low mechanical resistance. The inertia of the moving elements of the probe was sufficient to maintain the flag in almost stable position independent of the turbulence. The probe was kept in a support driven by a step motor around the axis of the system. In this way, the azimutal coordinate of the flag was adjusted. The remaining coordinates (axial and radial) were changed by shifting the rod in the arm of the support.

Two series of flow direction measurements were conducted. In the first one, the rod was set perpendicular, and in the other one - parallel to the pipe axis. This allowed us, with a certain accuracy, to estimate the flow direction in the

x,θ and r,θ plane, respectively. By measuring the angles indicated by the flag in the considered planes, the time mean flow direction can be obtained.

The total pressure distribution was measured by means of the Pitot tube. The spatial position of the tube was adjusted to be approximately consistent with the time mean of flow direction measured with the flag.

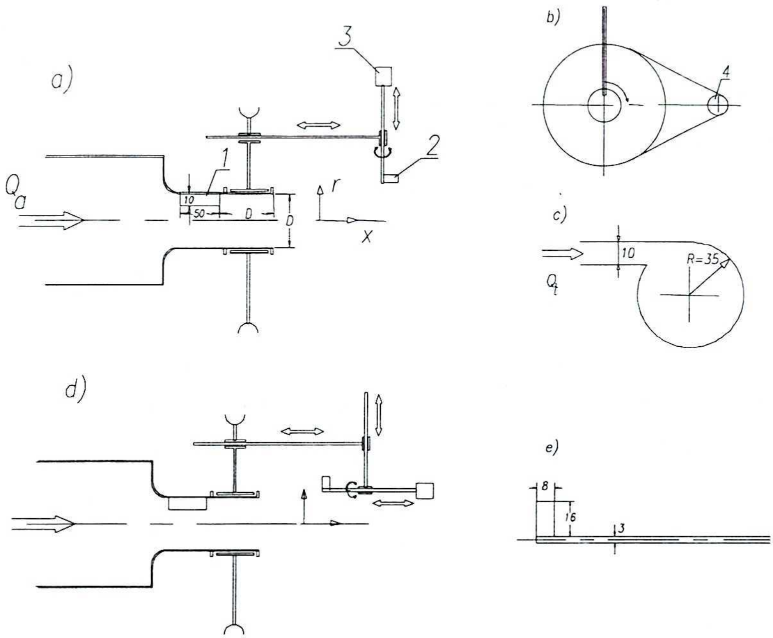


Fig. 1. Experimental set-up, (a) general scheme with flag probe arranged to measure flow direction in x,θ plane, (b) drive of the probe, (c) pipe cross-section with tangential nozzle, (d) flag probe arranged to measure flow direction in r,θ plane and (e) flag probe, 1-tangential nozzle, 2-probe, 3-precize potentiometer, 4-step motor. Dimensions in mm

The jet was visualised using the planar laser scattering (PLS) technique. The laser and the optical system were mounted on a traversing platform which enabled one to illuminate the jet in selected cross-sections. Several photographs were also taken with the light sheet in the pipe axis plane. Aluminium powder was added to the air to make the flow visible.

3. Results

Figures 2 and 3 present the azymuthal distributions of the flow direction in the x,θ and r,θ planes, respectively. The flow direction denoted by 90° corresponds to the case when one from three flow velocity components is equal to zero: the axial component for the x,θ plane and the radial component for the r,θ plane.

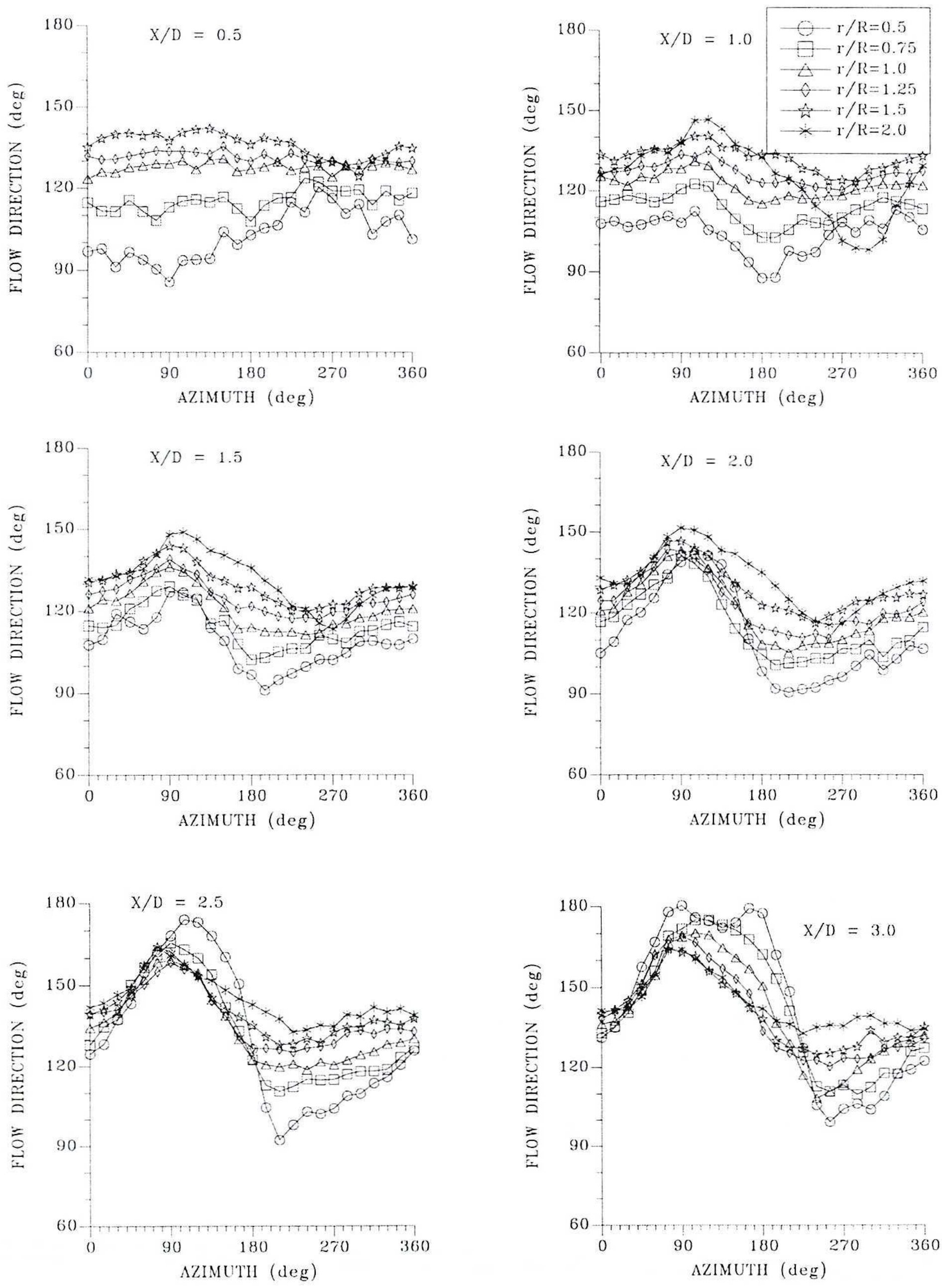


Fig.2. Azimuthal distributions of flow velocity direction x,θ plane, Axial flow rate Q_a=0.04 m^3/s, tangential flow rate Q_t=0.03 m^3/s; r – circle radius, $D=2R$ – pipe diameter, x – axial coordinate of jet cross-section

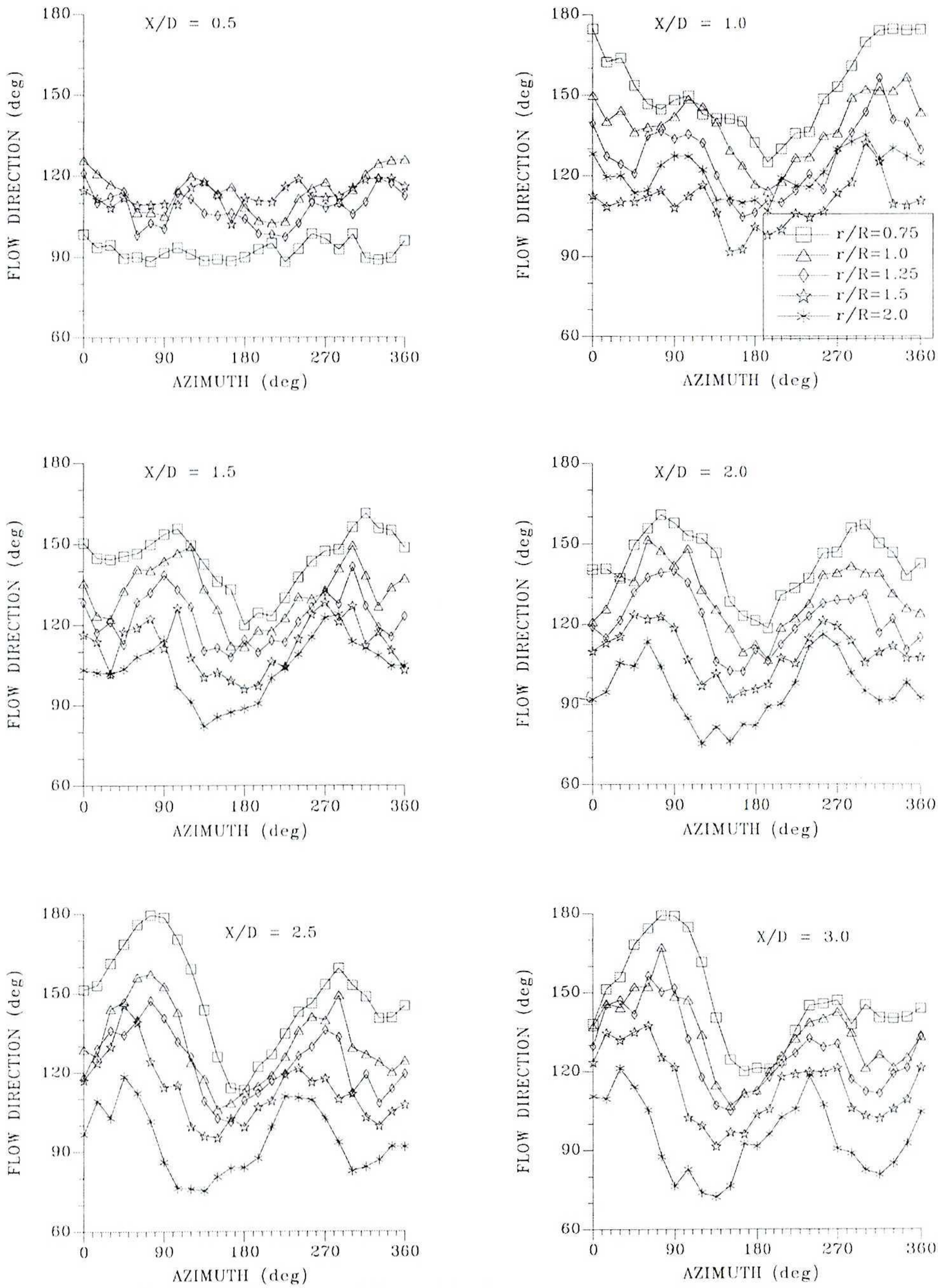


Fig. 3. Azimuthal distributions of flow velocity direction in r,θ plane. For data see Fig. 2

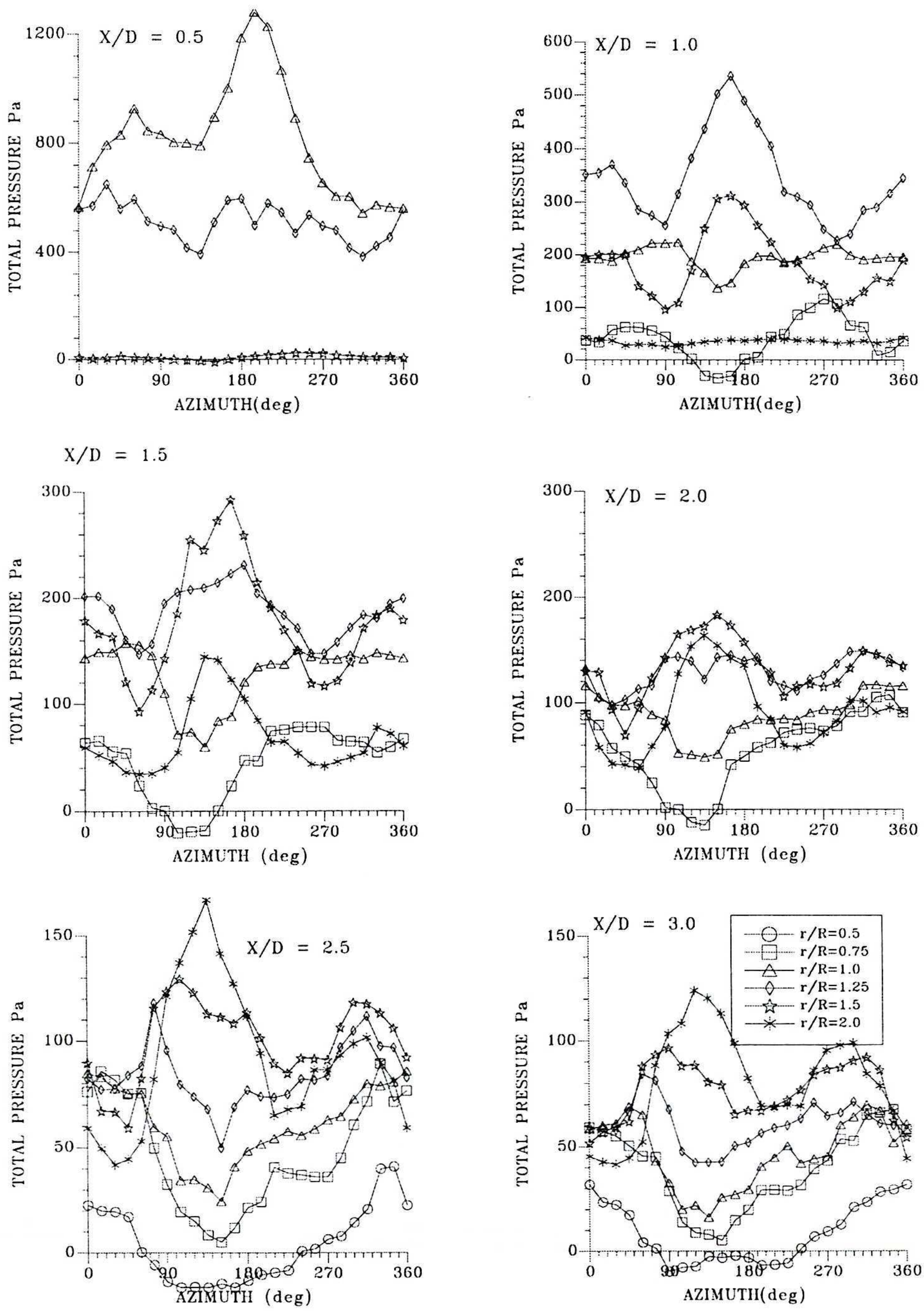


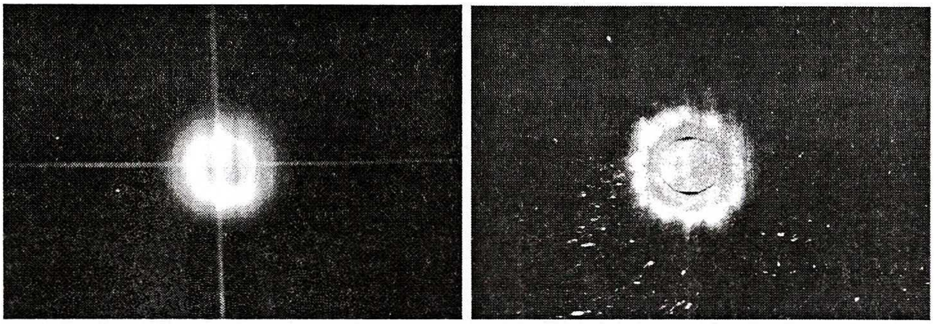
Fig. 4. Azimuthal distributions of total pressure. For data see Fig. 2

Considering the curves presented in these figures one can note the existence of relatively weak variations of the flow direction in the circles distributed in the jet cross-section located in the vicinity of the pipe exit (x/D=0.5). For the smallest circle (r/R=0.5) in this cross-section, the tangential component appears to be the largest among the remaining ones (axial and radial). However, this proportion considerably changes along a short distance traveled by the jet, i.e. at x/D=1 the radial component becomes predominant over the tangential one (flow direction angle 180° in Fig.3 means that the tangential component does not exist). The two peaks existing in the curves in Fig. 3 correspond to the maximum values of the radial flow velocity component (related to the tangential one). The difference of azimuthal angles for these peaks is about 180°. It means that the jet spreads radially, first of all, into two opposite azimuthal directions. This effect can be also noted in the flow photographs shown in Fig. 5; the jet cross-section shows a bean-like profile. The "bean" rotates with decreasing rotation velocity due to decreasing tangential flow velocity component along the jet.

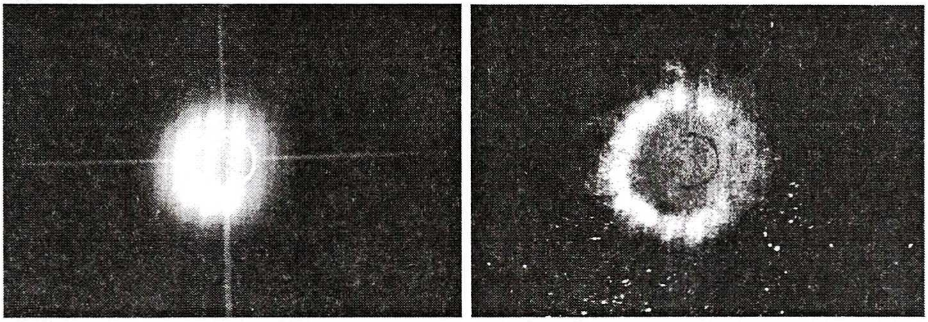
The phenomenon described above can be explained as follows. Due to the tangential component of the flow velocity in the jet issuing from the pipe, the air particles spread radialy in the surroungings. However, the spreading is not uniform for each azimuthal direction, because the distribution of the tangential velocity in the jet is asymmetric (it shows a distinct maximum [4]). The spreading for the azimuthal angle corresponding to the maximum tangential velocity is the most intensive. On the other hand, the total radial component of the momentum of the jet leaving the pipe is approximately equal to zero. Therefore, the radial momentum for the azimuthal angle corresponding to the maximum tangential velocity of the issuing jet must be balanced by the momentum transferred in the opposite azimuthal angle. Because the energy of the gas particles during their motion in the region of the „opposite angle" must be maintained, the increase of radial velocity component takes place due to the decrease of the other components. This concerns first of all the axial velocity; therefore the second maxima of the curves in Fig. 3 correspond to the minima in Fig. 2.

The total pressure distributions are shown in Fig. 4. The total pressure can be assumed to be proportional to the square of the flow velocity. (Due to relatively small rotation, the static pressure remains close to the ambient pressure). As it could be expected, the total pressure and thereby the flow velocity is distributed nonuniformly. This happens owing to the flow characteristics described above and the high turbulence of the jet. One can note that the maximum flow velocity of the jet shifts from the circle $r=R$ at x/D=0.5 to larger circles for subsequent jet cross-sections. The azimuthal angle of the maximum velocity shows small difference in relation to the azimuthal angle for the maximum of the flow direction angle. The former slowly changes along the axis of the system.

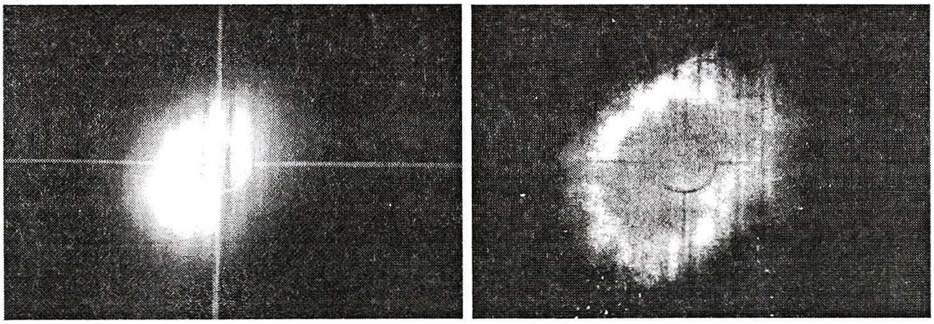
The effect of swirl on the jet contour and the mixing layer is displayed in Fig. 6.



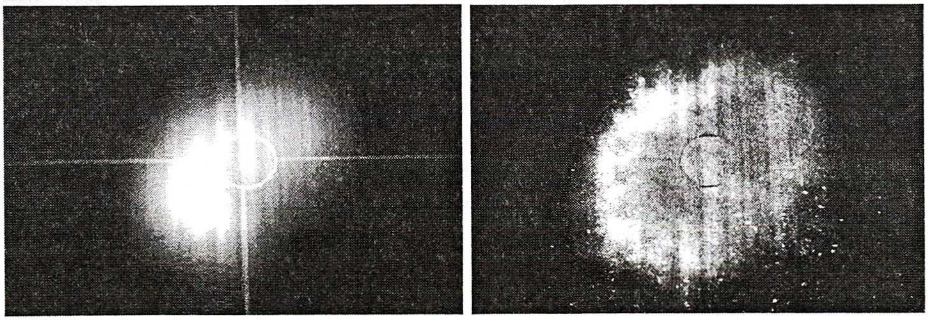
L/D=**0.5**



L/D=**1**



L/D=**1.5**



L/D=**2**

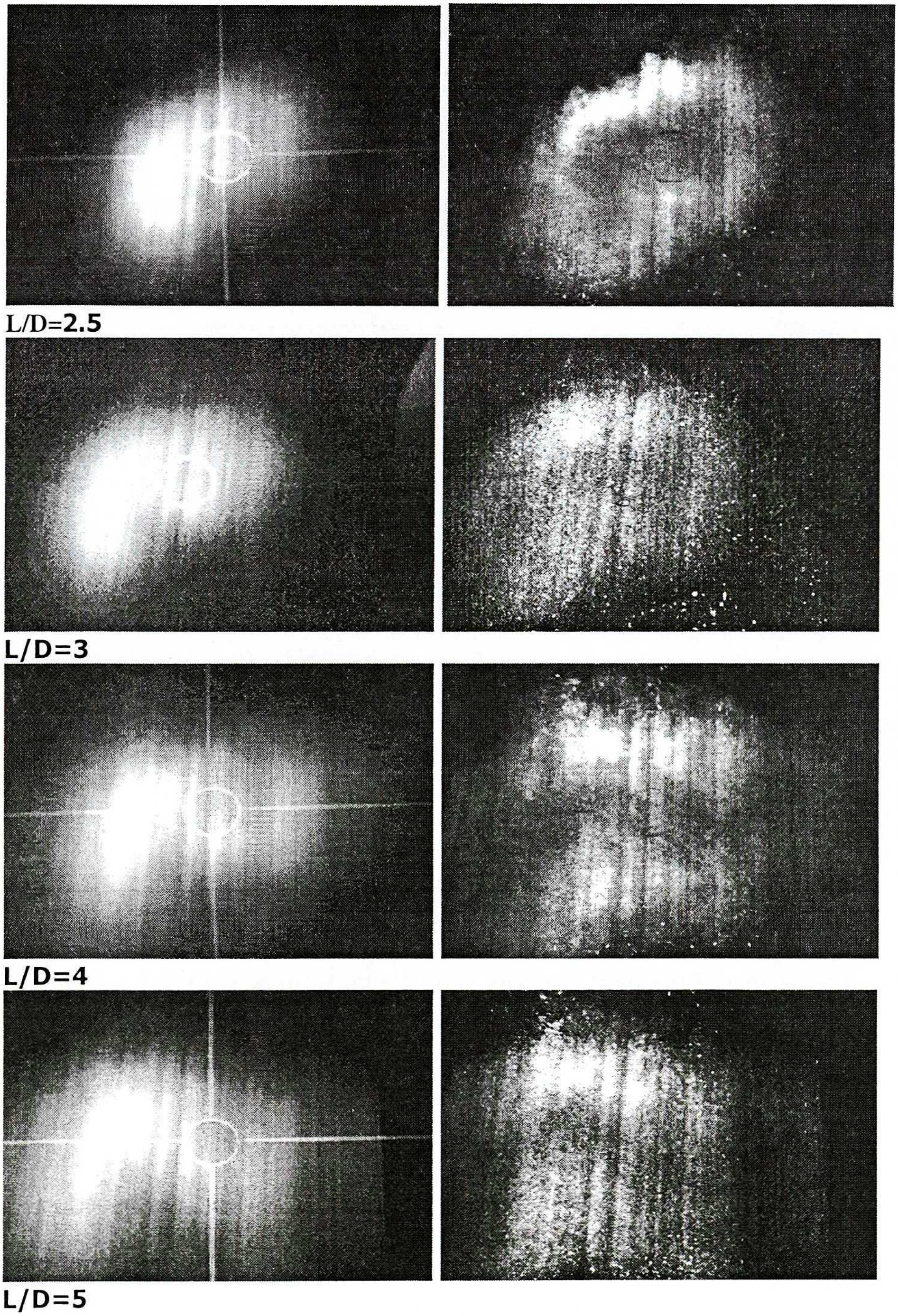


Fig. 5. Flow visualisation in several cross-sections of the jet, left column – averaged 60 flashes, right column – RMS of 60 flashes. For data see Fig. 2

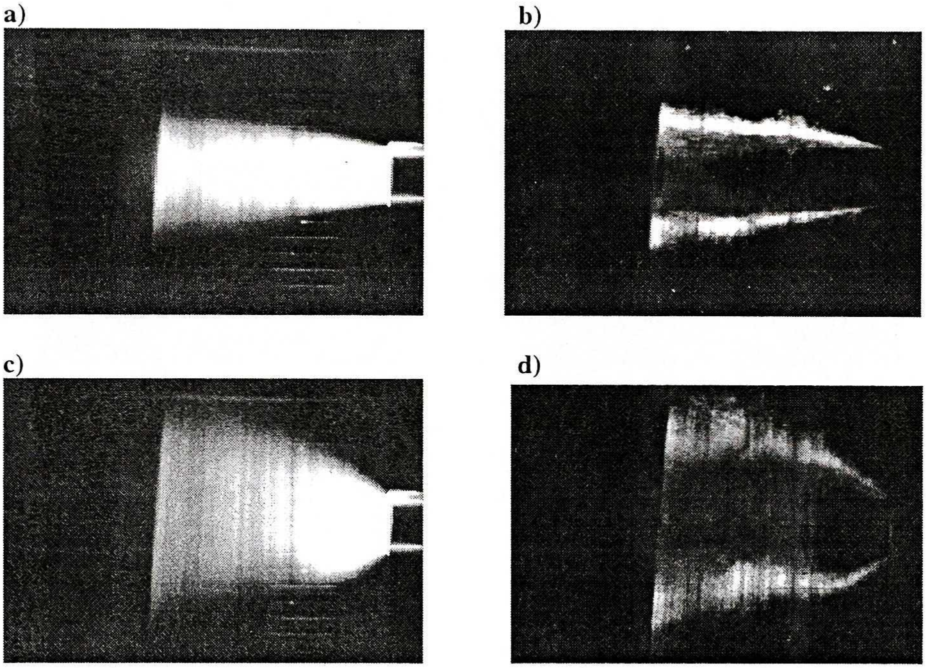


Fig. 6. Flow visualisation in axial section of the jet. (a,b) Q_a=0.03 m^3/s, Q_r=0, (c,d) Q_a=0, Q_r=0.03 m^3/s, (a,c) averaged 60 flashes, (b,d) RMS of 60 flashes

The upper and bottom photographs in this figure show the longitudinal sections of the axial (unswirling) and swirling jet, respectively. It is observed that the swirling causes a considerable increase of the jet diameter as the jet leaves the pipe. The jet is asymmetric due to its helicity (see discussion above). The mixing layer for the swirling jet is distinctly thicker than for axial one. The development of the mixing as the jet travels in the surrounding air is visualised in photographs in the right hand side column in Fig. 5. It is visible that the mixing layer continously increases. At x/D=3 and subsequent cross-sections, the root-mean-square of the light intensity is nearly uniform across the jet. It means that intensive mixing induced by turbulence exists across the whole jet.

4. Conclusions

The helical jet issuing into the stationary air shows asymmetrical structure. Due to this fact, the air particles spread nonuniformly in both the radial and axial directions. Two opposite azimuthal angles exist for which the radial spreading is the most intensive. One of them corresponds to the azimuthal angle of the maximum tangential velocity of the jet issuing from the pipe, whereas the other exists to maintain the total radial momentum of the jet equal to zero. The asymmetry of the rotating jet is the reason why the effect of mixing with surrounding air is considerably enhanced.

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Swobodny strumień helikalny w nieruchomym powietrzu

S t r e s z c z e n i e

Strumień helikalny generowany jest przy pomocy dyszy posiadającej dwa wloty: styczny i osiowy oraz wylot osiowy. Badane są rozkłady przestrzenne kierunków przepływu przy pomocy metalowej chorągiewki połączonej z potencjometrem. Ponadto prowadzona jest wizualizacja strumienia metodą noża świetlnego. Na skutek asymetrii osiowej rozkładów prędkości w strumieniu wypływającym z dyszy, strumień rozprzestrzenia się w otaczającym powietrzu z różną intensywnością zależną od kąta azymutalnego. W efekcie przestrzenna forma strumienia jest spiralna a jego przekrój jest zbliżony do kształtu ziarna fasoli.