PIV MEASUREMENTS WITH CONDITIONAL SAMPLING IN AXISYMMETRIC IMPINGING JET

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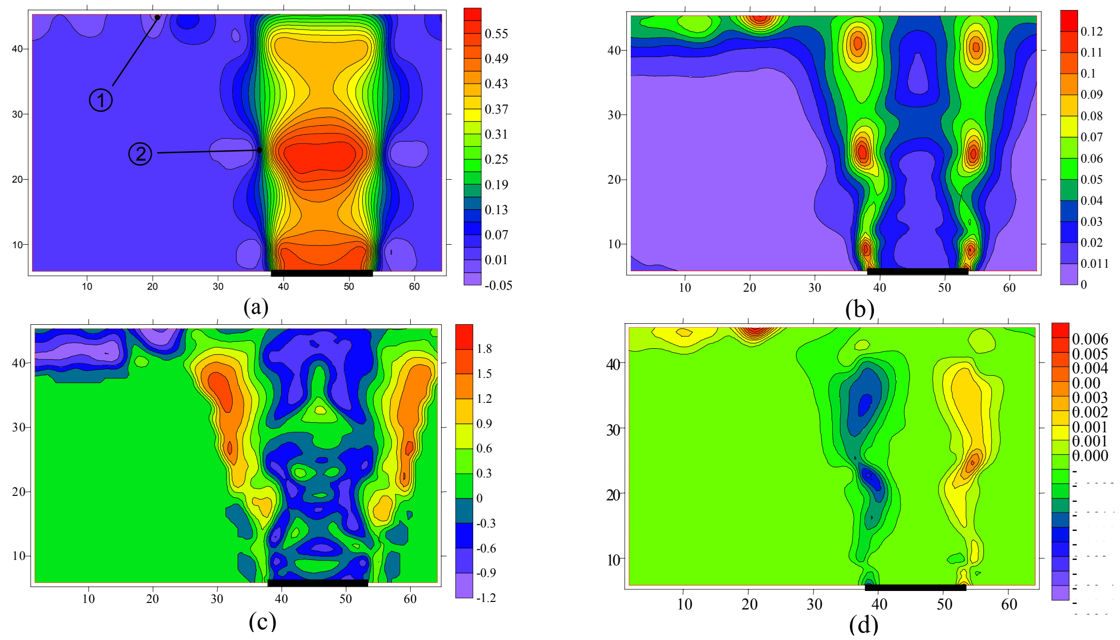
Conditional sampling technique is found to be applicable for diagnostics of flows with strong pronounced hydrodynamical events. As examples, the flows with time-dependent (or periodical) changing of boundary conditions, propagation of some spatial (phase) heterogeneities and coherent structures can be considered.

Turbulent jet shear layer is unstable and this leads to formation of Kelvin-Helmholtz instability waves near the nozzle edge. The amplitude of these waves grows downstream and after several acts of paring the large scale vortex structures (LSVS) form. At natural conditions the process of vortex formation is quasi periodical hence the conditional sampling in this case should be accompanied by trigger detection of each vortex. However, external periodical excitation of the jet with the frequencies from the range of most jet's sensitivity leads to resonant amplification of LSVS and formation of strictly periodical flow structure.

Present work is devoted to the experimental study of an axisymmetric submerged impinging jet under the conditions of external low-amplitude periodical forcing. Measurements of instant velocity fields were performed using 2D PIV system (Dantec FlowMap PIV System based on PIV1100 processor, ES 1.0 Kodak camera 1K x 1K and double 50 mJ NdYAG laser). As an additional tool the software package has been developed allowing calculation the statistical characteristics of turbulent flow of impinging jet including high-order (up to 4th) statistical moments. This package includes the novel technique for data validation (filtration procedure) based on the analysis of whole statistics of velocity fields. To obtain more precise estimation of high statistical moments the large number of instant frames of



(a) (b) (c) (d)

Fig. 1. *Spatial distributions of conditionally averaged characteristics of forced impinging jet flow field. Re = 7600, H/d = 3. (a) –* v *velocity component, (b) –* v *component of velocity dispersion -* Dv*, (c) – skewness factor* Sv*, (d) – Reynolds stresses. Averaging over 9000 instant frames of velocity field recorded at the same phase.*

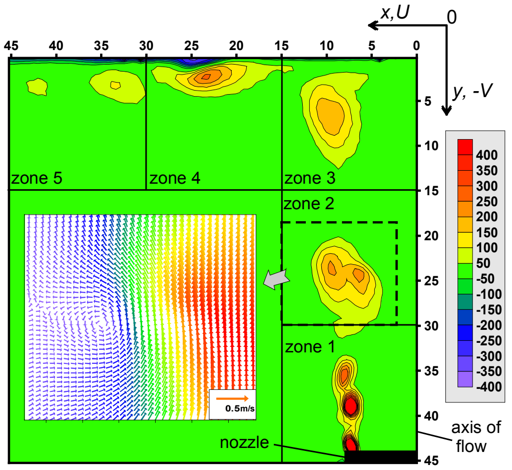


Fig. 2. *Vorticity distribution and flow field for the forced impinging jet. Re = 7600, H/d = 3, d = 15 mm, Sh = 0.5. Spatial resolution – 0.26 mm. Phase locked measurements. Averaging over 1000 instant frames.*

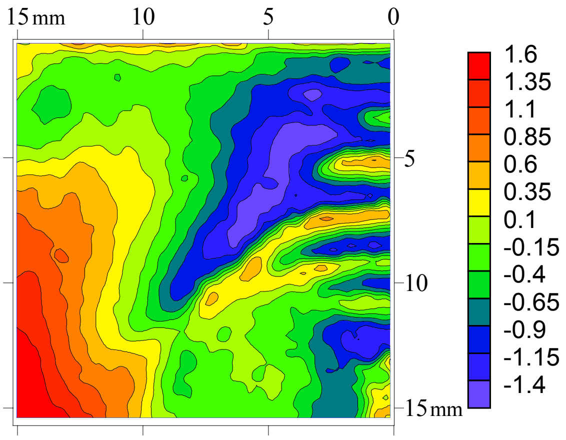


Fig. 3. *Skewness factor distribution for the forced impinging jet. Zone 3. Flow conditions as in Fig. 2.*

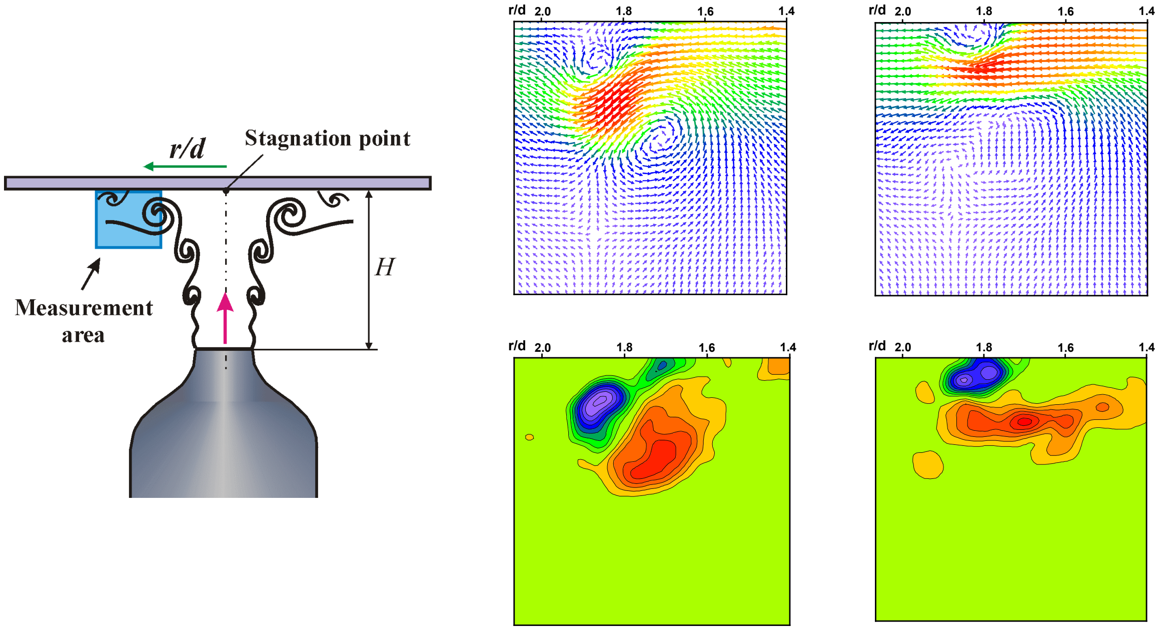
velocity distributions were processed (up to 9,000 for separate phase and 20,000 for whole statistics). The spatial resolution in present experiments was changed from 0.17 to 1.1 mm. Previous authors works (see, for example, Alekseenko et al., 1997) have shown that for impinging jet flow forced at the frequencies from the range mentioned above (Strouhal number Sh based on nozzle diameter lies in the range 0.4 ÷ 0.6), the period of LSVS propagation coincides with the period of flow excitation at whole flow field if the jet impinges on the surface within initial region. This fact allowed us to carry out phase-locked measurements with using synchronization of external forcing signal and laser pulses. The triple decomposition of velocity components (Hussain and Reynolds, 1972) was applied in order to separate the coherent and broad-band components.

$$a(\vec{x},t) = \bar{a}(\vec{x}) + \tilde{a}(\vec{x},t) + a'(\vec{x},t)$$

where first, second and third terms in the left part of equation are correspondingly average, coherent (periodic) and stochastic components of pulsations.

Figure 1 presents the phase averaged distributions of longitudinal velocity component, its dispersion, skewness factor and Reynolds stress. The averaging for selected phase was performed with using 9000 fields of velocity vectors. Presented distributions show the "frozen structure" of the flow, averaged only over the stochastic part of turbulent pulsations. One can clearly observe the periodic spatial flow structure caused by large vortices. The areas with maximum values of second moment of velocity pulsations (Fig. 1, b) correspond to the regions with large velocity gradients (Fig. 1, a). The distribution of Reynolds stress has also strong nonuniform character with location of maxima in the centre of mixing layer. The picture with 3rd moment distribution (Fig. 1, c) can manifest the areas with largest asymmetry of pulsations for given location of “frozen” large scale vortex. Zero values of 3rd (and higher moments) correspond to Gauss PDF (green colour at Fig. 1, c). The greatest deviation from the normal distribution takes place at the edge of the mixing layer in the areas where two neighbouring large vortices are located.

Figure 2 demonstrates conditionally averaged vorticity field determined from the velocity field (averaging by 1000 LSVS). The flow field was separated into 5 zones with the dimensions 15x15 mm^2 where measurements were



(a) (b) (c)

Fig. 4. *Local separation in an impinging jet flow. Instant velocity and vorticity fields for zone 4 (see Fig.2). (a) – sketch of the flow, (b) and (c) - different scenarios of secondary vortex development at the same phase. Flow conditions as in Fig. 2.*

performed with application of the conditional sampling technique. For the case shown in Fig. 2 the spatial resolution was equal to 0.26 mm. The results for five tested zones were combined into one field in order to obtain general spatial distribution for each phase of flow. The development of vortex structures in the mixing layer of a jet has been described on the basis of “frozen” flow patterns analysis beginning from the nozzle exit and up to the area where structures interact with the impingement wall.

On the basis of triple decomposition for velocity fluctuations the coherent (periodical) and stochastic contributions of turbulent kinetic energy have been estimated.

The use of conditional sampling technique together with high resolution PIV approach has allowed obtaining the principally novel information on the structure of pulsation field in the core of impinging jet including the vicinity of stagnation point. The spatial periodical structure of 2nd, 3rd and 4th order statistical moments distributions for velocity components has been observed. At the same time the phase averaged velocity components (1st moment) do not show any sub-periodical structure. In Figure 3 the spatial distribution of the skewness factor (3rd order moment) of the phase-locked pulsations of normal-to-wall velocity component is presented for zone 3 of the flow.

Observed “wave pattern” appears in the region of a jet (approximately at the distance of one nozzle diameter – zone 2 in Fig. 2) where large scale structures are completely formed and developed. Pulsation “waves” move further downstream convectively up to region of stagnation point where they undergo changings due to re-forming of the flow structure. At the same time the statistical characteristics stored and processed without conditional sampling do not show any peculiarities. The physical nature of such periodical pattern of pulsation field is not completely clear at the moment, however the analysis of obtained distributions of phase-locked pulsations fields show that such a behaviour can’t be described in the frames of the closure models of gradient type.

The observed early phenomenon (Didden and Ho, 1985, Alekseenko and Markovich, 1996) - appearance of small secondary vortex in the near-wall region was directly registered by PIV velocity measurements (see Fig. 4). It is characterised by negative velocity values and localised negative vorticity. This phenomenon is caused by local pressure gradient induced by propagating large scale vortex. Secondary vortex is clearly seen at the instant velocity and vorticity distributions (Fig.4, b, c). With taking into account the small-scale oscillations of flow characteristics around phase-averaged "frozen" distributions the statistical processing of an array of phase-locked instant velocity fields was performed and several scenarios of secondary vortex birth were detected.

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