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PIV and CTA Measurement of Constant Area Mixing in Subsonic Air Ejector

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Abstract. The article deals with experimental study of constant area mixing in subsonic axi-symmetric air ejector. Particle Image Velocimetry (PIV) and Constant Temperature Anemometry (CTA) measurements of four different mixing regimes, each with different ejection ratio were performed. For PIV measuring, the velocity fields inside the constant area mixing chamber were taken through the vitreous wall of the chamber, while the laser beam entered it from the opened outflow of the ejector. For CTA measuring, probe perpendicular to the ejector axis was used. Data obtained from both methods are compared. Basic descriptions of the results are given and it is claimed that results are reliable.

1 Introduction

The article deals with experimental investigation into the flow in a subsonic axi-symmetric air to air ejector with constant area mixing. Quite a number of researchers were concerned with ejectors and a great number of publications have been produced. For example, Sun and Eames [1] named over 100 citations in their overview from 1995. In a review carried out by Bonnington and King [2], 413 references dating prior 1976 were cited. Porter and Squyers [3] compiled a list of more than 1600 references relating to ejector theory and performances.

First methods of ejector design were based on experience. The first analysis of mixing was made by Keenan and Neumann [4]. They consider only the simplest form of ejector, a constant area mixing chamber without diffuser. They calculated the performance of an ejector using the one-dimensional continuity momentum and energy equations. Although the analysis was simplified, the results were consistent and compared well with experimental results. Later Keenan, Neumann and Lustwerk [5] in a follow up to their earlier work, considered mixing at constant pressure. This work produced the first comprehensive theoretical and experimental analysis of the ejector problem, and is the basis of much of what has taken place since. The constant pressure design method is used in the majority of ejector applications, and has caused the most problems for researchers. The main reason for this is the complex nature of the flow structure in the constant pressure mixing section. Also the determination of the mixing chamber geometry to ensure constant pressure mixing and best mixing is problematic. Only few authors were concerned with optimization of ejectors. Dvořák in work [6] optimized an ejector with the help of Fluent and verified a manufactured ejector experimentally.

The ejector was optimized by using turbulence model realizable k-ε with enhanced wall treatment. Model realizable k-ε seemed to be the most suitable for axi-symmetric mixing problems according the results in work of Dvořák [7], also many researches use it, e.g. Rusly, Aye, Charters and Ooi [8], while e.g. Bartosiewicz, Aidoun, Desevaux and Mercadier used turbulence model SST k-ω to simulate the flow in supersonic ejectors in work [9]. However, it was found out in work [6] that all numerical results for various turbulence models varied as compared with experiments.

This study follows work made by Dvořák and Kotek [10] in which PIV method was used to investigate flow in cylindrical mixing chamber. Complex experimental data of four various ejector regimes were obtained and velocity contours and vectors for them were presented. The aim of this study is to compare and complete mentioned data with CTA measuring.

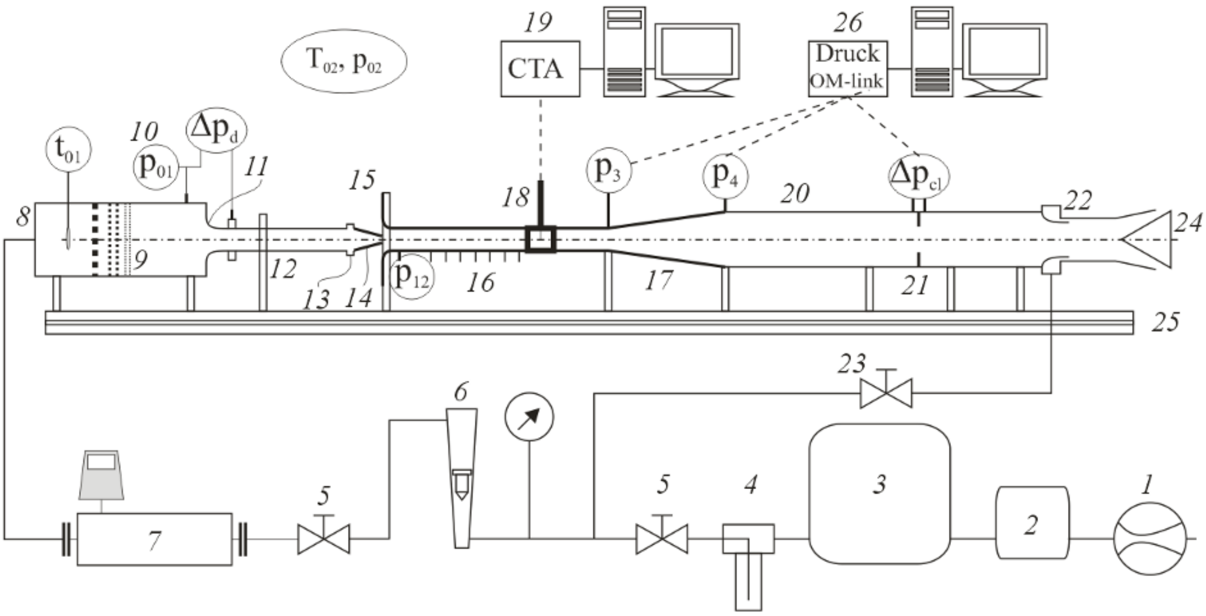

Fig. 1. Experimental arrangement: 1 - compressor, 2 - air dryer, 3 - tank, 4 - filter, 5 - reduction valve, 6 - rotameter, 7 - Coriolis mass flow meter, 8 - stilling chamber, 9 - stilling riddles, 10 - measuring of primary stagnation pressure p_{01}, 11 - measuring of primary mass flow rate, 12 – primary flow supply tube, 13 – holder of primary nozzle, 14 – primary nozzle, 15 - secondary nozzle, 16 - mixing chamber with static pressure taps, 17 – diffuser, 18 – probe of constant temperature anemometry, 19 – CTA measuring, 20 - outflow pipe, 21 - measuring of total mass flow rate, 22 - suction ejector, 23 – control valve, 24 - chocking, 25 - base, 26 – pneumatic measuring.

2 Methods

2.1 Experimental setup

A circular converging nozzle with diameter d = 19.2 mm was used as a primary nozzle. The mixing chamber had diameter D = 40 mm. The area ratio of nozzles was $\mu = A_1 / A_2$ = 0.3. The relative length of the mixing chamber was L / D = 9. A diffuser with 6° enlargement and with outlet diameter 71.2 mm was placed behind the mixing chamber.

For pressure measuring, we used pressure sensors Druck LP 1000 with range 100, 500, 1000 and 2000 Pa. These low pressure sensors with high accuracy 0.25% are slow, so only mean value of pressures were measured. Experimental arrangement for investigation of mixing processes in ejectors is displayed in figure 1. The primary air flowed from compressor through air dryer, control valves and stilling chamber, which guaranteed constant value of stagnation pressure. Measuring of primary mass flow rate was behind the stilling chamber. The secondary air was sucked in to the mixing chamber directly from the laboratory. A diffuser to obtain higher back pressure and a measuring orifice to measure total mass flow rate were placed behind the mixing chamber. Chocking placed in the end of tube was used for set-up of high back pressure and additional suction ejector was used for set-up of low or even negative back pressure. The over pressure of primary flow was $p_{01} - p_{02}$ = 1000 Pa, where p_{01} and p_{02} are stagnation pressures of primary and secondary flow.

2.2 PIV Experimental setup

Experimental study of flow field in ejector was realized with Particle Image Velocimetry system (PIV) from Dantec Dynamics. Investigated area was illuminated with New Wave Gemini double pulse laser. Images were captured with HiSense 12 bit camera. To reach sufficient spatial resolution, the flow field in mixing chamber was recorded sequentially in four steps. Figure 2 describes the arrangement of measuring PIV system and experimental setup.

The 1.3 Mpixels camera covered the area of 80 mm × 60 mm in each step. This setup led to approximately 30 points (velocity vectors) in velocity profile of mixing chamber (glass tube of 40 mm diameter). Self designed assembling algorithm was used to reconstruct the overall image of the almost whole mixing chamber with length of 320 mm. This method had the same effect as a high sensitive PIV camera with an extreme spatial resolution of 5000 × 1024 pixels.

As the PIV method calculates the velocity of tracking particles, the seeding of both air flows should be designed. The main primary pressured air was seeded with Sciltek oil droplets generator. Into the secondary flow, the seeding particles were brought with a system of pipes and a special seeding ring surrounded the main nozzle, just before the inlet to the mixing chamber. Secondary flow seeding particles were produced by Safex generator. Both particle types have same size distribution (2 ÷ 5 μm) and similar light scattering, so they can be combined in one PIV measurement.

One hundred images were recorded for each step position and regime setup to ensure satisfactory data for statistical evaluation. Crosscorrelated PIV images were validated using Range and Moving average filter. Two statistical methods were used to calculate the mean velocity in each interrogation area. Mean value provides statistical information (standard deviation), but produces inaccurate values in the region of poor seeded flow. Better results of these poor seeded areas were obtained using Median. Extreme velocity values of some wrong correlated records do not influence the resultant value so dramatically.

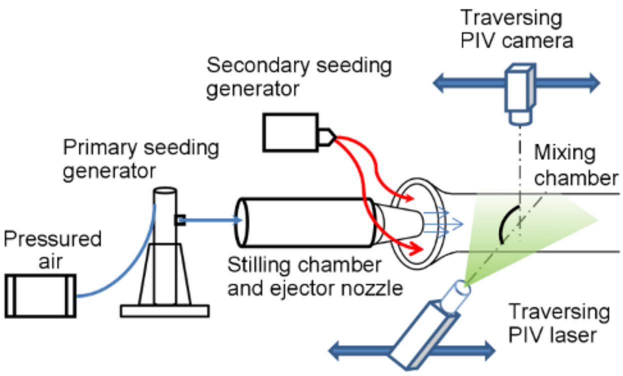

Fig. 2. Scheme of PIV experimental arrangement.

2.3 CTA Experimental setup

The hot wire measuring is realized with the help of shifting device enabling traversing of CTA probe. This mechanism, which is displayed in figure 3, was screwed directly into the special part of sectional mixing chamber.

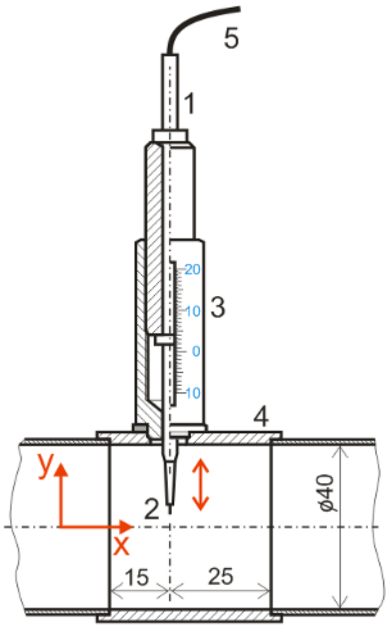

Fig. 3. Scheme of shifting device for traversing of CTA probe; 1 – probe holder, 2 – DANTEC probe 55Pll, straight prongs, sensor perpendicular to probe axis, 3 – shifting screw with a scale, 4 – modified part of the mixing chamber, 5 – cable for connecting hot wire probe with PC.

The Hot Wire Anemometry Method (HWA) was used for our measurement. This method can be used for velocity measurement in different fluids. HWA is based on the heat transfer convection from heated probe, which is set into the flow of surrounding fluid. The heat transfer depends on the flow velocity and fluid temperature [11]. We have used the anemometry regime with Constant Temperature (CTA), i.e. the wire temperature was kept on constant value. We used a Dantec constant-temperature hot-wire anemometer system (90N10 frame and 90C10 module), AD card – NI-PCI-MIO-16E-1 and the Dantec streamware software for velocity measurement. We used a Dantec 55P11 hot-wire probe, which has straight prongs 5 mm long and one tungsten wire sensor perpendicular to probe axis. The sensitive length of the wire is 1.3 mm and 2 μm in diameter [12]. The signal of the hot-wire probe had the sample frequency of 2.4 kHz and the number of samples was 16384.

Because the probe was perpendicular to the direction of the flow and the insertion of probe was changed during measuring, we used a compensation to prevent a change of ejector regime during measuring of a simple velocity profile. The compensation method, which was described by Dvořák and Dančová in work [13], is based on keeping the total mass flow rate through the ejector constant.

3 Results and Discussion

The velocity profiles measured by both methods, PIV and CTA, are presented in figures 4 to 11. There are profiles of axial (*u*) and radial (*v*) components of velocity measured by PIV and mean (*U*) and fluctuation (U_{RMS}) components of velocity measured by CTA. Four regimes of mixing in the ejector, the same as in previous work [10], were chosen to be investigated. The regimes are determined by ratio of mass flow rate, i.e. the ejection ratio defined as $\Gamma = m_2 / m_1$.

Velocity profiles were measured by CTA and compared with PIV in two places in the mixing chamber for each regime. These places specified by the distance behind the trailing edge of primary nozzle were selected to satisfy following demands: The first measuring position was in the initial region of mixing, while the second was in the main region of mixing. Both regions of mixing were described by Tyler and Williamson in work [14] and differ from each other subsequently: In the initial region of mixing, the area of secondary (sucked, driven) flow is still distinguishable, the shear layer does not reach the mixing chamber wall and the mixing is slow. In the main region of mixing, the mixing area extends across the whole mixing chamber and the mixing processes are fast.

Results of measuring in the initial region of mixing, for all regimes x = 55 mm, i.e. x / D = 1.375, behind the trailing edge of the primary nozzle, are in figures 4 to 7. We can see from figure 4, which was obtained for regime with Γ = 1.9, that the radial velocity is negligible and so we can compare velocity profiles of u and U. We can observe from the figure that both profiles are in good agreement, but there are some interesting differences.

The axial velocity *u* measured by PIV has unrealistic values close to the walls, while profile of mean velocity *U* measured by CTA does not have symmetrical shape, velocity increased for bigger probe insertions ($y < 0$) into the mixing chamber. Therefore, values of *u* measured near the walls were removed from diagrams. The velocity profile of U_{RMS} corresponds with others: The fluctuations increased in the shear layers (free mixing layer and boundary layer) and decreased in free unaffected primary stream in the middle of the mixing chamber and in secondary stream.The second regime in figure 5 was obtained for higher back pressure and with $\Gamma = 1.4$.

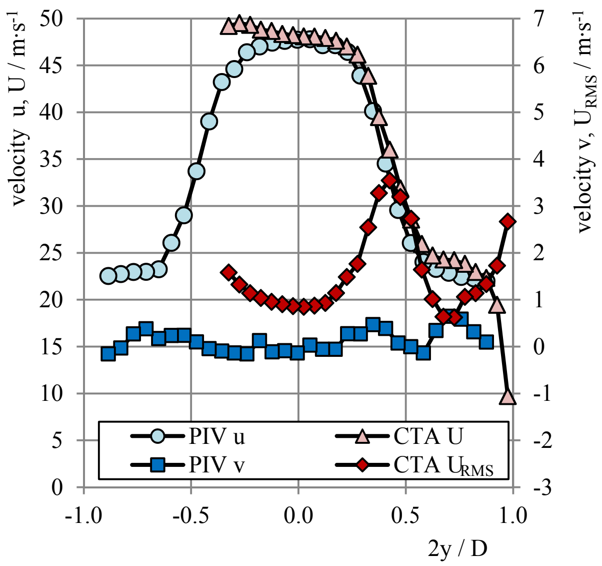

Fig. 4. Velocity profiles, $x = 55$ mm, regime $\Gamma = 1.9$.

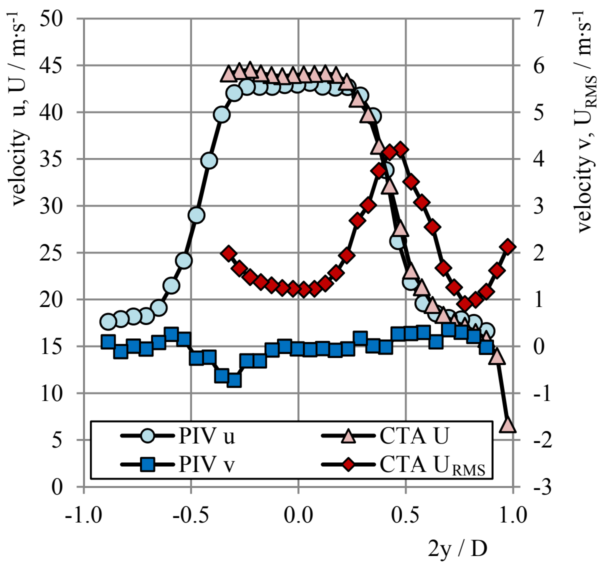

Fig. 5. Velocity profiles, $x = 55$ mm, regime $\Gamma = 1.4$.

Therefore velocities *u* and *U* are lower and U_{RMS} higher than in figure 4 generally. Again radial velocity *v* is negligible.

These tendencies can be observe also in figures 6 and 7 for regimes with even higher back pressures and ejection ratios of $\Gamma = 1.1$ and $\Gamma = 0.5$. However there is a deviation in radial velocity in figure 7. It seems that for this regime, which has very high back pressure, the flow in the secondary stream tends to flow from the walls of the mixing chamber. This is probably an evidence of flow separation caused by adverse pressure gradient resulting from fast mixing. As we can see, the differences between axial velocity *u* measured by PIV and mean velocity *U* measured by CTA are significant in this area. The question is, whether these differences are caused because of different mixing regime appointed for both method or because of affection of flow while using CTA probe. Nevertheless it is clear that PIV method is more suitable and capable to reveal the flow separation than CTA method.

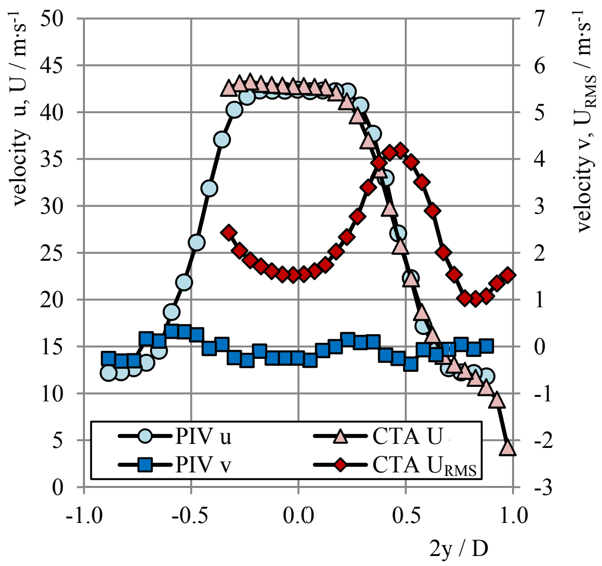

Fig. 6. Velocity profiles, $x = 55$ mm, regime $\Gamma = 1.1$.

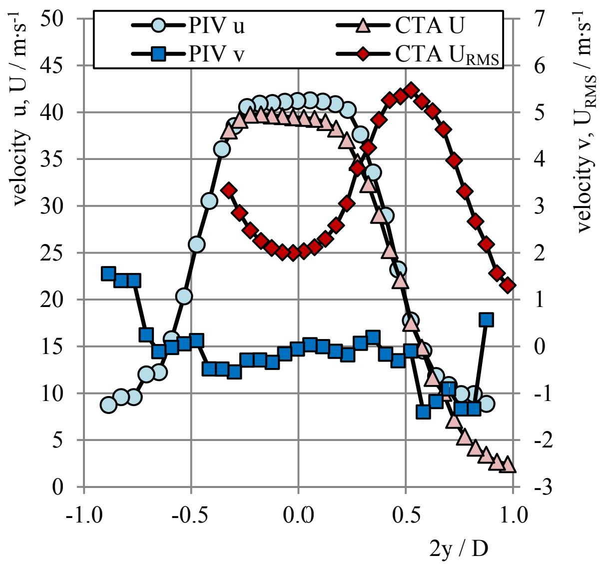

Fig. 7. Velocity profiles, $x = 55$ mm, regime $\Gamma = 0.5$

Results of measuring in the main region of mixing are in figures 8 to 11. Because the mixing processes are faster for lower velocity and ejection ratios, the second measuring place in the main region of mixing was chosen in various positions for different regimes.

The measuring position was $x = 235$ mm behind the trailing edge of the primary nozzle for the regime with the highest ejection ratio $\Gamma = 1.9$ in figure 8. As we can see, the radial velocity component v is still of insignificant values, but differences between u and U are expressive. It can be caused by imperfections while setup of this regime which is obtained for approximately zero back pressure and is characterized by low frequency oscillations of the whole flow field. The fluctuational velocity component U_{RMS} is higher than in the initial region of mixing in figure 4 and the mixing layer extends almost across the whole mixing chamber as it should be in the main region of mixing. Regimes for higher back pressure and lower ejection ratio do not suffer from mentioned oscillation and therefore it is much simpler to adjust them more precisely.

The fluctuational velocity component U_{RMS} are generally grater in the main region of mixing than it is in figures 5 to 7 for corresponding regimes. Again, we can observe for these regimes that the mixing layer extended across the whole mixing chamber and that the free secondary stream and probably free primary stream were expired.

The radial velocity component v is insignificant for regimes in figures 9 and 10, while it indicates that the flow directs from the mixing chamber walls for regime of $\Gamma = 0.5$ in figure 11.

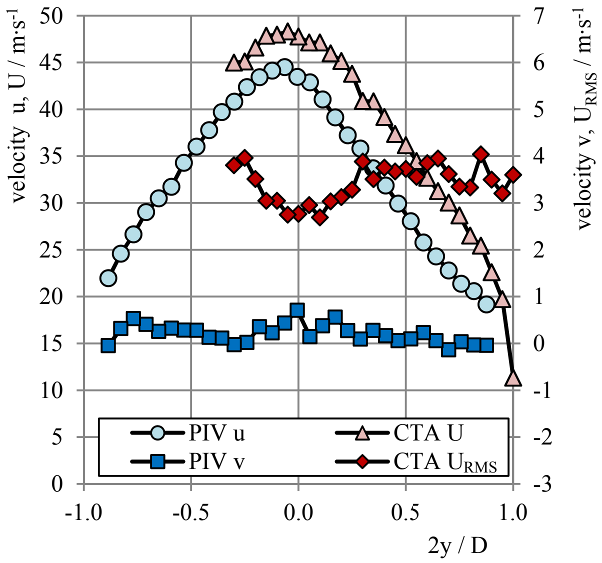

Fig. 8. Velocity profiles, $x = 235$ mm, regime $\Gamma = 1.9$.

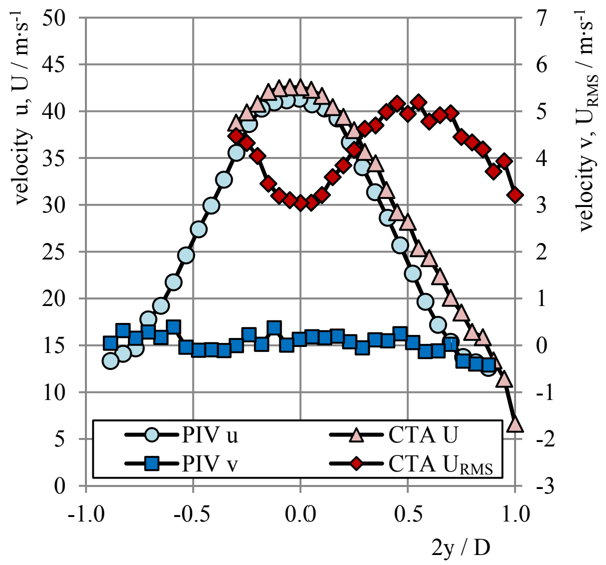

Fig. 10. Velocity profiles, $x = 135$ mm, regime $\Gamma = 1.1$.

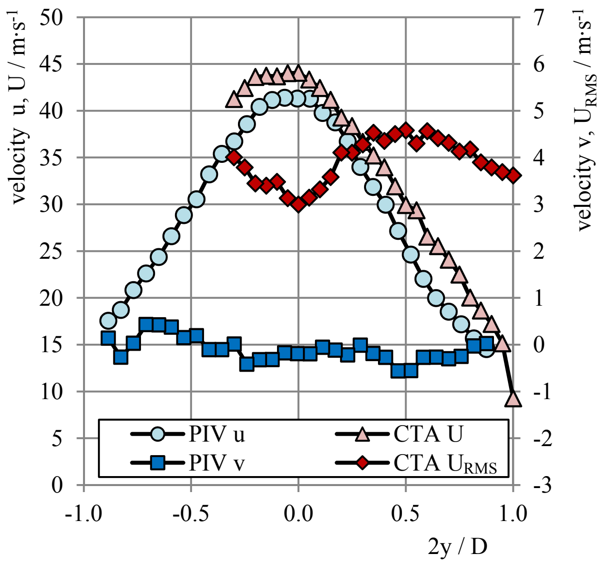

Fig. 9. Velocity profiles, $x = 175$ mm, regime $\Gamma = 1.4$.

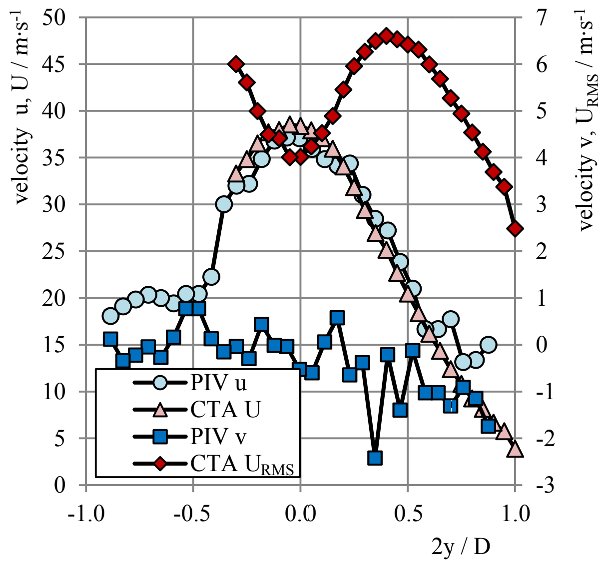

Fig. 11. Velocity profiles, $x = 95$ mm, regime $\Gamma = 0.5$.

Therefore, the differences between axial velocity u measured by PIV and mean velocity U measured by CTA are less significant for others regimes in figures 9, 10 and 11. Some differences are still observable, especially close to the wall and for regime with presumable flow separation in figure 11.

4 Conclusions

Air to air subsonic ejector with cylindrical mixing chamber was investigated. Particle Image Velocimetry was used to obtain fields of axial and radial velocity (u and v) and Constant Temperature Anemometry was used to acquire velocity profiles (U and U_{RMS}) in the initial and in the main region of mixing. Four regimes with various ejection ratios were measured and velocity profiles and contours obtained from both methods were compared.

Comparison of used method for investigation of flow in the mixing chamber of the ejector: The PIV measuring of radial velocity component v in cannot be in most cases used, because this velocity component is smaller by two orders than axial velocity component u. In other words, the radial velocity component is smaller than sensitivity of used method. The only exception is detection of flow separation in the beginning of the mixing chamber in cases of regimes with high back pressure. Also measuring near the mixing chamber walls is problematic while using PIV method. The advantages of using of CTA method for investigation of flow in the mixing chamber are possibility to obtain information of fluctuations and measuring close to the wall. On the other hand, it is almost impossible to indicate flow separation while using one component probe.

The agreement of both methods is quite good for measuring in the initial region of mixing. The only differences follow from restrictions of used methods. The agreements are worse for measuring in the main region of mixing. These differences can be caused by both, by the imperfections of setup of the same regimes, i.e. the same ejection ratio, or by affection of flow by methods themselves.

The development of velocity profile in the mixing chamber is well observable from data. Despite to some imperfections, the results are applicable for further work, i.e. for comparison with numerical calculations using various turbulence models. Data can be also confronted with pneumatic measuring of static pressure distribution on the mixing chamber wall and regions of mixing can be determined.

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