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An Investigation into Air Ejector with Pulsating Primary Flow

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***Abstract*—**The article deals with pneumatic and hot wire anemometry measurement on subsonic axi-symmetric air ejector. Performances of the ejector with and without pulsations of primary flow are compared, measuring of characteristic pressures and mass flow rates are performed and ejector efficiency is evaluated. The pulsations of primary flow are produced by a synthetic jet generator, which is placed in the supply line of the primary flow just in front of the primary nozzle. The aim of the pulsation is to intensify the mixing process. In the article we present: Pressure measuring of pulsation on the mixing chamber wall, behind the mixing chamber and behind the diffuser measured by fast pressure transducers and results of hot wire anemometry measurement. It was found out that using of primary flow pulsations yields higher back pressure behind the ejector and higher efficiency. The processes in this ejector and influences of primary flow pulsations on the mixing processes are described.

***Keywords*—**Air ejector, pulsation flow

I. Introduction

THE article deals with experimental investigation of mixing in axi-symmetric subsonic ejector with included device generating pulsations of primary flow. The aim of pulsations is to intensify the mixing process. The mixing can by intensified by many ways that can be divided into two groups, passive and active, as they were in publication by authors Ginevsky, Vlasov and Karavosov [1]. Shaping of the primary nozzle trailing edge belongs to the passive methods, generating of flow pulsation is the active method. The work [1] deals with free streams from jets, number of works dealing with active or passive control of mixing in ejectors are quite limited. E.g. Havelka *et al.* in experimental work [2] used a device inserted into the primary nozzle to add a tangential velocity component into the primary stream. Measuring showed that the secondary mass flow rate is increased for certain range of tangential velocity and the shorter mixing chamber is satisfactory. Waitz *et al.* investigated intensification of mixing with the help of a lobe nozzle in work [3]. Dvořák [4] optimized the lobe nozzle for mixing and found out that the nozzle with low number of big lobes is advantageous for high efficiency of the ejector. Chang and Chen [5] used a petal nozzle in a supersonic ejector and compared it with common diverging nozzle. They showed that the ejector with petal nozzle is better for higher area ratio $A_3/A_{1kr} \geq 150$ than the ejector with common nozzle.

Tylor and Williamson [6] divided the mixing into two regions. In the initial region of mixing, the shear layer between the primary and the secondary stream does not reach the mixing chamber wall or the boundary layer. In the main region of mixing, the shear layer spreads across the whole mixing chamber cross section. The momentum decay is slow in the initial region and static pressure changes only slightly. We can consider a free stream here. But the momentum decay and also static pressure rise are accelerated in the main region. Optimizations made by Dvořák in work [7] showed that only choosing the velocity ratio $\omega = c_2/c_1 \approx 0.3$ can lead to the high efficiency of the ejector. Unfortunately, the length of the initial region of mixing is than relatively long ($L_0 \approx 3D$) in this case and causes high friction losses. The length of the main region depends less on the velocity ration. To intensify and accelerate the mixing processes, it is essential to generate fluctuations either at the beginning of the mixing chamber or even in front of it, i.e. in the primary flow supply pipeline.

The former work by authors Dvořák and Dančová [8] dealt with an ejector with only one synthetic jet. The aim of the study was to determine the influences of the synthetic jet (SJ), which was placed in the beginning of the mixing chamber. The purpose of that work was to investigate the possibility of using SJ to accelerate the mixing processes by the intensification of momentum and mass transfer, as it was shown by Trávníček and Vít in work [9].

In work [8], it was proved, that the influences of the operating SJ on the flow in the ejector were follows: SJ accelerated the mixing process only negligibly, but for the regimes with high ejection ratio, SJ stabilizes the flow fluctuations in the diffuser and thus the higher back pressure and higher efficiency are achieved. SJ placed in the beginning of the mixing chamber influenced the flow in the diffuser positively, but when placed at the end of the mixing chamber, the improvements were reduced. Velocities of the primary stream in the centre of the mixing chamber were affected during the operation of SJ, but the secondary stream and the mixing shear layer were affected only in the immediate vicinity of SJ. The aim of current study is to use SJ actuator to generate pulsation in the primary flow in front of the mixing chamber, i. e. in the primary flow supply pipeline.

II. Methods

Dimensions of the synthetic jet actuator used for generating of primary flow oscillations and its position on the primary

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nozzle are obvious from Fig. 1. SJ actuator consists from a sealed cavity and two loudspeakers (MONACOR SP-8/4SQ) with nominal parameters: 4Ω, 20Wmax. These loudspeakers have the same power and diameters (Dc = 70mm, membrane diameter Dm = 68mm) and are parallel-connected. Loudspeakers membranes have stiff cone shape and they can be considered to be pistons, which control the jet. Actuator was fed with sinusoidal signal with electrical power P = 9.2W. Signal was generated from Tektronix AFG 3102 signal generator and was amplified with Omnitronic MPZ-180 amplifier.

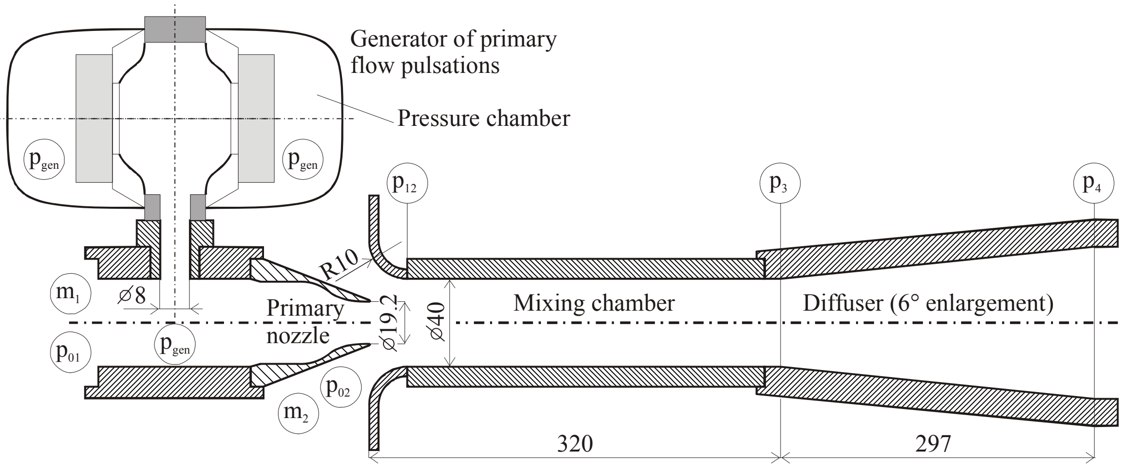

Fig. 1 System of the ejector and the generator of primary flow oscillations

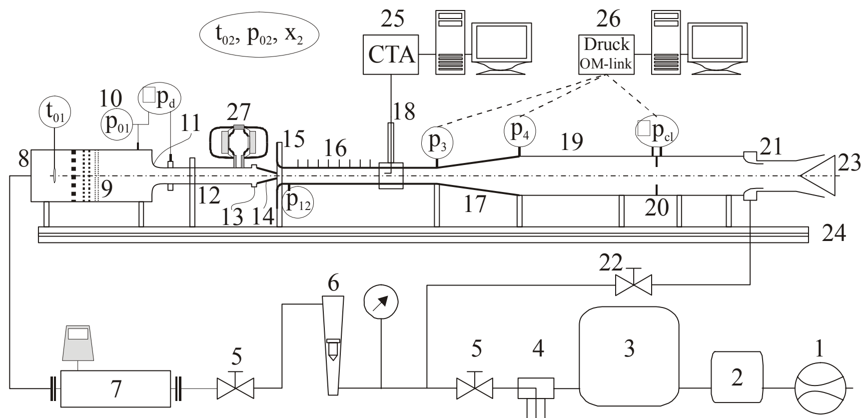

Fig. 2 Experimental arrangement: 1 - compressor, 2 - air dryer, 3 - tank, 4 - reduction valve, 5 - filter, 6 - rotameter, 7 - Coriolis mass flow meter, 8 - stilling chamber, 9 - stilling riddles, 10 - measuring of primary stagnation pressure p_{01}, 11 - measuring of primary mass flow rate, 12 – primary flow supply tube, 13 – holder of primary nozzle, 14 – primary nozzle, 15 - secondary nozzle, 16 - mixing chamber with static pressure taps, 17 – diffuser, 18 - CTA probes, 19 – outflow pipe, 20 - measuring of total mass flow rate, 21 - suction ejector, 22 - control valve, 23 – chocking, 24 - bed, 25 - CTA measuring, 26 – pneumatic measuring, 27 – generator of primary flow pulsations

A circular converging nozzle with diameter $d = 19.2$ mm was used. The mixing chamber had diameter $D = 40$ mm. The area ratio of nozzles was $\mu = A_1/A_2 = 0.3$ and the relative length of the mixing chamber was $L/D = 8$. A diffuser with 6° enlargement and with outlet diameter 71.2 mm was placed behind the mixing chamber. First step of the measurement was the determination of the system nominal frequency – i.e. frequency on which ejector works with the highest power. Nominal frequency was found as $f = 69.1$ Hz. This low frequency is given by the length of the pipeline behind the ejector, which ends by orifice used for measuring of mixed mass flow rate m_3, see position 20 in Fig. 2.

For slow pressure measuring, we used pressure sensors Druck LP 1000 with range 100, 500, 1000 and 2000Pa. These low pressure sensors with high accuracy 0.25% are slow, so only mean value of pressures were measured. Arrangement of the experiments is obvious from Fig. 2. We also used very fast miniature pressure sensors Kulite XTL-123B-190M with MDAQ-OR16-BRIDGE-D and PC card DEWE-ORION-1616-100 for fast pressure measuring with frequency of 10 kHz.

III. RESULTS

The results for ejector with pulsation generator switched OFF and ON are in Fig. 3, 4, 5 and 6. The efficiency of the ejector is defined by relation

$$\eta = \frac{m_2}{m_1} \frac{\left(\frac{p_4}{p_{02}}\right)^{\frac{\kappa-1}{\kappa}} - 1}{1 - \left(\frac{p_4}{p_{01}}\right)^{\frac{\kappa-1}{\kappa}}} \frac{T_{02}}{T_{01}}, \tag{1}$$

where m is mass flow rate, p static pressure, p_0 stagnation pressure, T_0 stagnation temperature and κ ratio of specific heats. Subscript 1 denotes primary flow, 2 secondary flow, 3 mixed flow and 4 state behind the ejector, i.e. behind the diffuser. For incompressible fluid, or for compressible fluid when $T_{01} = T_{02}$ and $(p_{01} - p_{02})/p_{02} <\approx 0.05$ the relation (1) can be simplified to

$$\eta = \Gamma \frac{p_4 - p_{02}}{p_{01} - p_{04}}, \tag{2}$$

where ejection ratio Γ is used. The ejection ratio is given by relation

$$\Gamma = \frac{m_2}{m_1} = \frac{c_2}{c_1} \frac{A_2}{A_1} \frac{\rho_2}{\rho_1}, \tag{3}$$

where c is velocity, A area of inlet nozzle and ρ density.

A. Results of Slow Pressure Measuring

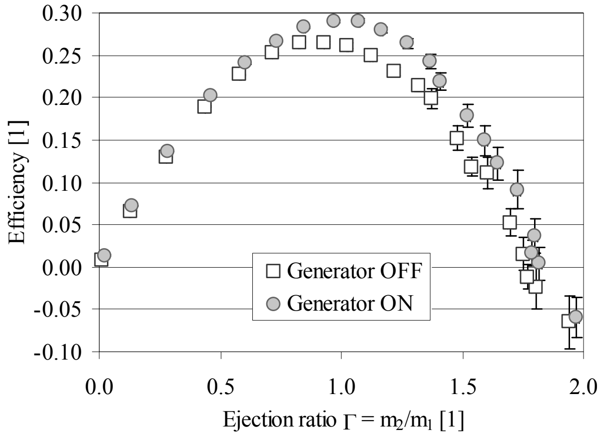

Fig. 3 Results of slow pressure measuring, ejector efficiency.

The evaluation of the ejector efficiency from measured data is in Fig. 3. We can see that with pulsation generator turned ON the efficiency are higher. It means that higher back pressure and ejection ratio are obtained. This is visible also in Fig. 4, where the relative back pressure is carried out. We can also see that the fluctuations of back pressure are not decreased while pulsation generator is operating. These results contrast with work [8], where fluctuations of back pressure were strongly suppressed with operating synthetic jet actuator.

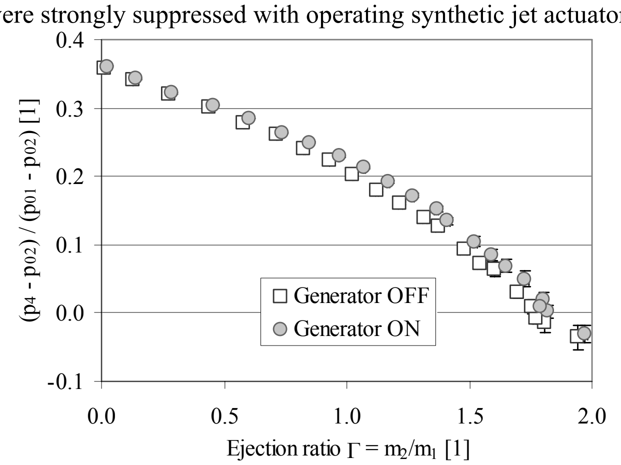

Fig. 4 Results of slow pressure measuring, relative back pressure $(p_4 - p_{02}) / (p_{01} - p_{02})$.

The relative suction pressure in the beginning of the mixing chamber is in Fig. 5. We can see that during operation of the generator the curve changes – it moves towards higher ejection ratios, while the suction pressure p_{12} decreases only negligibly. These results are rather surprising because suction pressure, which is measured in the beginning of the mixing chamber, is given by ejection ratio, see [8]. It is because the suction pressure determines the inlet velocity of both flows and thus, for used inlet area ratio $\mu = A_1/A_2$, the ejection ratio is given. It means that all measured data should fall into the single curve in Fig. 5. But in work [8], the SJ generator was placed behind the beginning of the mixing chamber, i.e. behind the place where pressure p_{12} is measured, while in this work, the generator is placed in front of this place.

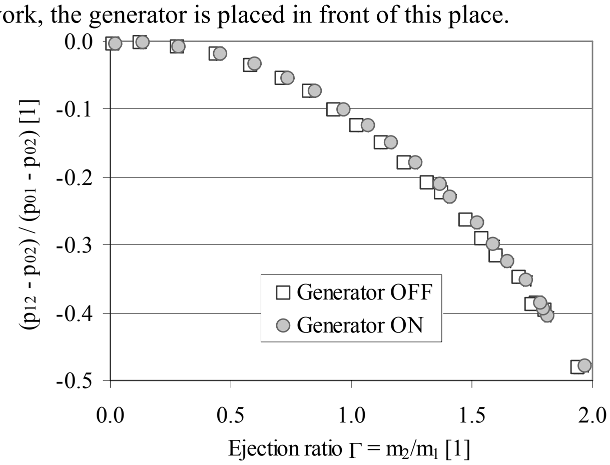

Fig. 5 Results of slow pressure measuring, relative suction pressure $(p_{12} - p_{02}) / (p_{01} - p_{02})$.

It indicated that during deceleration and acceleration of the primary flow, the velocity ratio $\omega = c_2/c_1$ changed while the effective inlet area ratio had to be constant. For given expansion pressure p_{12}, which is measured on the mixing chamber wall, the velocity of secondary flow c_2 should be almost constant. Velocity c_1 will oscillate because of pressure changes, but the mean velocity $\bar{c}_1$ should be lower. These required further investigation with the help of fast pressure transducers and hot wire anemometry.

The differences are also obvious on Fig. 6, where mixing pressure p_3, measured behind the mixing chamber, is carried out. Again, higher ejection ratio is obtained with almost the same mixing pressure while the generator of pulsations is operating. With the same static pressure, the dynamic pressure and mass flow rate behind the mixing chamber are higher and higher back pressure behind the mixing chamber is obtained. To further understand to the flow processes, we also performed very fast measurements of the pressures.

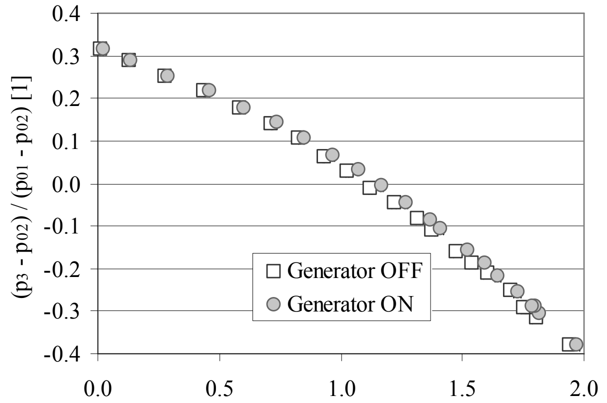

Fig. 6 Results of slow pressure measuring, relative mixing pressure $(p_3 - p_{02}) / (p_{01} - p_{02})$.

B. Results of Fast Pressure Measuring

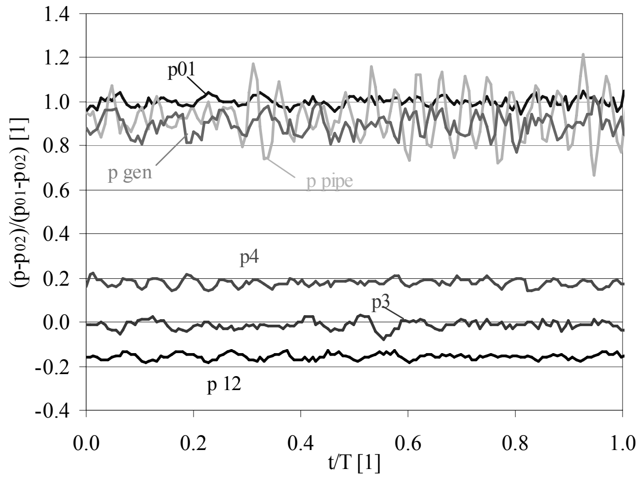

Fig. 7 Results of fast pneumatic measuring, generator turned OFF, instantaneous curves, $T = 1/69.1$ s. p_{pipe} – pressure behind the stilling chamber in the beginning of the primary flow supply pipeline, p_{gen} – pressure near the generator

Results of fast pneumatic measuring are carried out on Fig. 7, 8, 9 and 10. We measured only one particular regime characterized by the highest efficiency. In Fig. 7 and 8, results for generator turned OFF are carried out. We can see that the flow is not steady, but there is some periodic fluctuations in the primary supply tube with the frequency of 1560 Hz, while the fluctuations close to the generator are of the half frequency of 780 Hz. These fluctuations are generated in the beginning of the primary flow supply pipeline. Theirs frequencies are obviously given by the length of free space in the stilling chamber, see positions 8 and 9 in Fig. 2, i.g. it is the length between the stilling riddles and the end of the stilling chamber. It is obvious from Fig. 8 that these fluctuations spread downstream slightly at the beginning and more significantly at the end of the mixing chamber, see courses of suction pressure p_{12} and mixing pressure p_3 and values in Table 1.

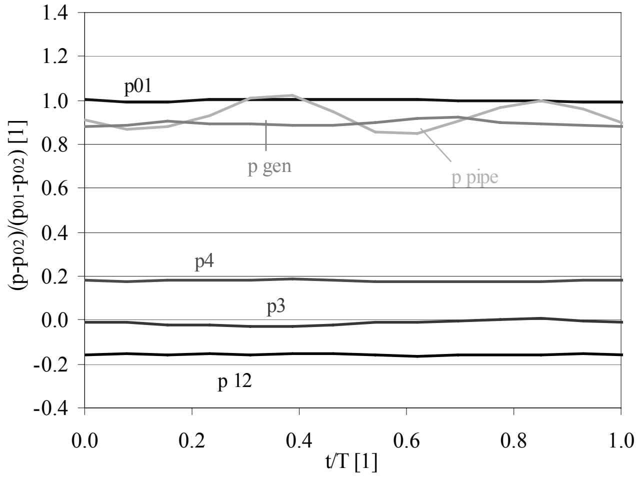

Fig. 8 Results of fast pneumatic measuring, generator turned OFF, instantaneous curves, $T = 1/780$ s.

Results for generator turned ON are carried out in Fig. 9 and 10. We can see that some courses change rapidly, but courses of pressure in the primary flow supply pipeline (p_{pipe}) and in the stilling chamber (p_{01}) are not affected by the operating generator. The former recorded oscillations of frequencies 780 Hz and 1560 Hz are still present and are superposed on courses affected by operating generator, see courses of p_3 and p_{gen}.

TABLE I
RESULTS OF FAST PNEUMATIC MEASURING FOR GENERATOR OFF AND ON, MEAN, RMS AND AMPLITUDE VALUES

		$(p - p_{02})/(p_{01} - p_{02})$					
		p_{01}	p_{pipe}	p_{gen}	p_{12}	p_3	p_4
OFF 780 Hz	mean	1	0.932	0.896	-0.157	-0.013	0.178
	amplit.	0.016	0.113	0.040	0.009	0.019	0.008
	phase	---	---	0	0.5	0.25	0.25
ON 69.1 Hz	mean	1	0.954	0.906	-0.152	-0.006	0.180
	amplit.	0.014	0.027	0.248	0.021	0.280	0.396
	Phase	---	---	0	0.5	0.25	0.25

First, we discuss the influences of operating generator on the suction pressure p_{12} in the beginning of the mixing chamber. By comparison of Fig. 7 and 9, we can see that the fluctuations of p_{12} are increased only negligibly. The amplitude of p_{12} is only 0.021 and the phase after the generator is 0.5, see table 1. It means that for the highest pressure near the generator, the lower expansion pressure p_{12} is obtained. It should be caused by the highest primary velocity c_1 from the nozzle and accordingly the strongest effect of suction of surrounding air. The working frequency of 69.1 Hz is not almost evident on the course for p_{12}, which is caused by the fact that the suction pressure is measured in the beginning of the mixing chamber, for $x = 0$, i.e. almost in unconfined space. Thus, the secondary flow, which is entrained into the mixing chamber, should not change its velocity during the working period of the generator. Changes of the primary flow velocity c_1 and alternatively secondary flow velocity c_2 were investigated with the help of hot wire anemometry.

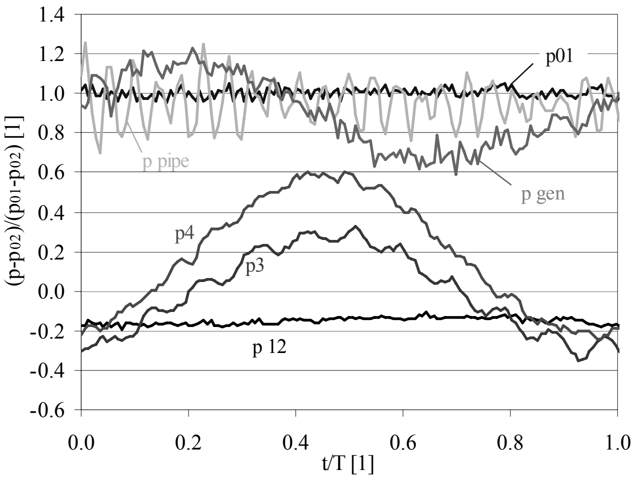

Fig. 9 Results of fast pneumatic measuring, generator turned ON, instantaneous curves, $T = 1/69.1$ s

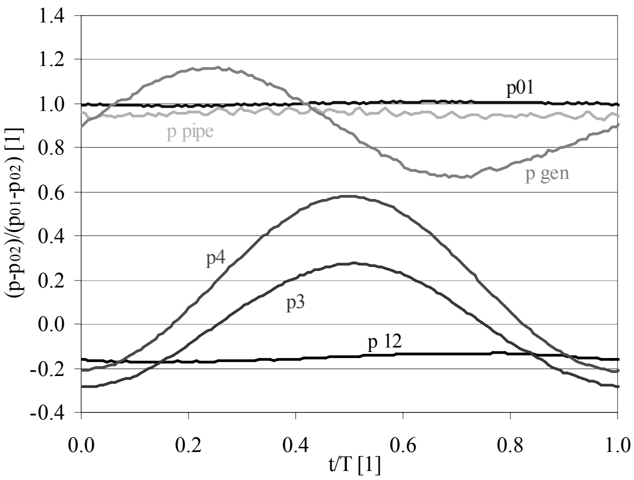

Fig. 10 Results of fast pneumatic measuring, generator turned ON, averaged curves, $T = 1/69.1$ s

The mixing pressure p_3 and the back pressure p_4 are influenced significantly by the pulsating primary flow. By comparison in Table 1, the amplitude of pulsations are increased from 0.019 to 0.28 for p_3 and from 0.008 to 0.396 for p_4. The delay after the generator is in both cases 0.25. It means that while the primary velocity is reaching its highest values, both pressures, p_3 and p_4, are still rising.

C. Static pressure distribution on the mixing chamber wall

Results of pneumatic measuring of static pressure distribution on the mixing chamber wall obtained by the help of both slow and fast pressure transducers are carried out in Fig. 11 for generator switched OFF and in Fig. 12 for generator switched ON. By comparison of both curves of mean values, we can see that the static pressure distribution is influenced by the operating generator only negligibly.

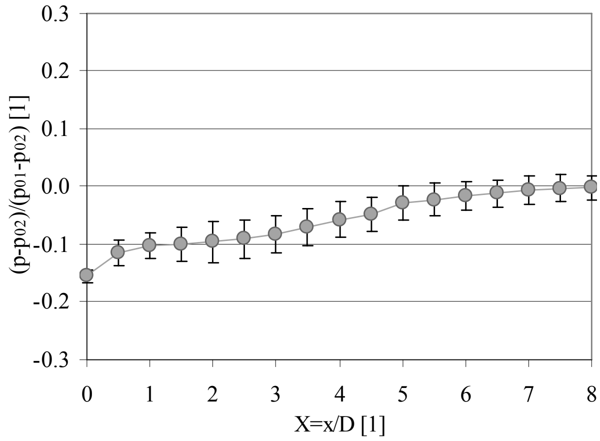

Fig. 11 Static pressure distribution on the mixing chamber wall, generator turned OFF. Mean values with shown amplitudes

On the other hand, the amplitudes of pulsations, which are also carried out in Fig. 11 and 12, are increased rather significantly. The amplitudes are from 0.006 to 0.013 for generator turned OFF, while the frequency is 780 Hz, and do not change notably along the mixing chamber, see Fig. 11.

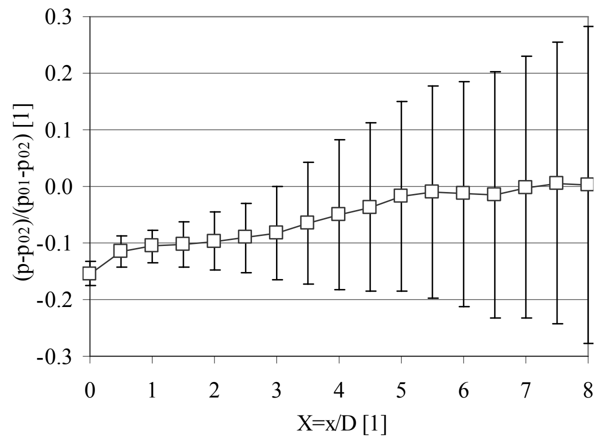

Fig. 12 Static pressure distribution on the mixing chamber wall, generator turned ON. Mean values with shown amplitudes

For generator turned ON, the amplitude is 0.021 in the beginning of the mixing chamber and it increases fluently to 0.28 at the end of the mixing chamber, see Fig. 12. The frequency is of 69.1 Hz. More detailed measuring for generator turned ON is in Fig. 13, where the curve for p_{gen}. Is carried out too. We can observe that for phase 0.15 and 0.85 the mixing can be almost considered as a constant pressure mixing. For the phase of 0, the static pressure even decreases during the mixing, while for the phase 0.5, the maximal static pressure gradient is obtained.

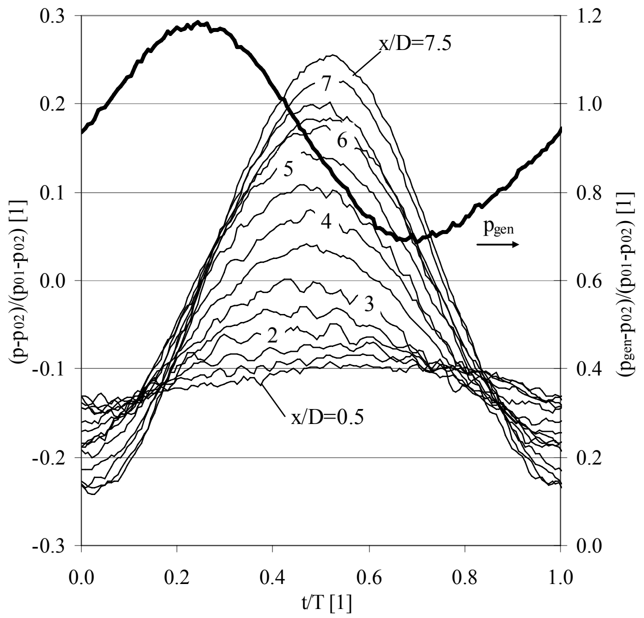

Fig. 13 Results of fast pneumatic measuring on the mixing chamber wall, generator turned ON, averaged curves for various positions in the mixing chamber, $T = 1/69.1$ s

D.Results of hot wire anemometry

Results of performed hot wire anemometry measuring are presented in Fig. 14 for generator turned OFF and in Fig. 15 for generator turned ON. We measured inlet velocity c_1 of the primary flow just behind the primary flow nozzle and in its axis, inlet velocity c_2 of the secondary flow in the beginning of the mixing chamber and the velocity c_3 at the end of the mixing chamber of the mixed flow.

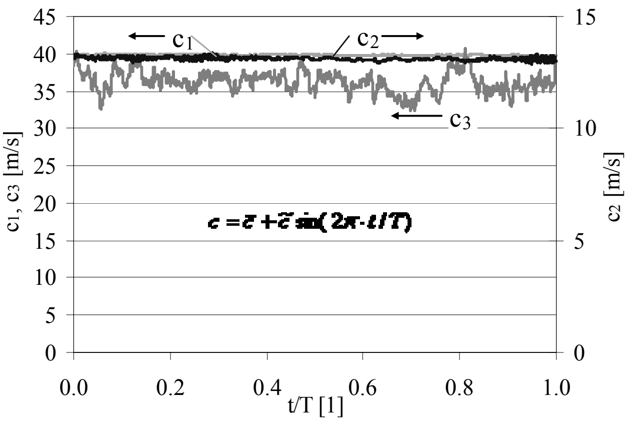

Fig. 14 Results of hot wire anemometry, generator turned OFF, $T = 1/69.1$ s

As we can see in Fig. 14, for generator turned OFF, the primary flow velocity c_1 and secondary flow velocity c_2 are almost stationary and the velocity ratio is $\omega = c_2/c_1 = 0.329$. The mixed flow velocity c_3 fluctuates as a result of mixing processes and high turbulence intensity at the end of the mixing chamber. Values of measured velocities are in Table 2.

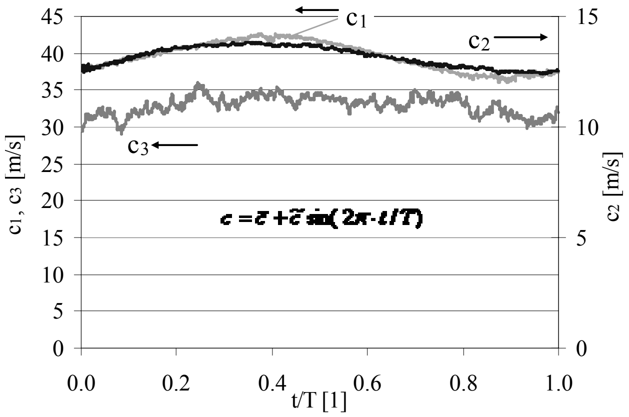

Fig. 15 Results of hot wire anemometry, generator turned ON, $T = 1/69.1$ s

As we can see in Fig. 15, for generator turned ON, the primary flow velocity c_1 and secondary flow velocity c_2 have nonzero amplitude of fluctuations. Again, the mixed flow velocity c_3 fluctuates as a result of mixing processes and high turbulence intensity at the end of the mixing chamber, while the periodic component of the velocity $\tilde{c}$ is small.

The velocity ratio increased to the value $\omega = 0.333$, though the increase is not as was expected according to results of slow pneumatic measuring, see ejection ratio in Fig. 5 and 6. This does not agree with our observation that ejection ratio increases more significantly while the generator is operating.

TABLE II
RESULTS OF HOT WIRE ANEMOMETRY MEASURING

		c_1	c_2	c_3	ω
		[m/s]	[m/s]	[m/s]	[1]
OFF	mean	39.8	13.1	36.2	0.329
ON	mean	39.6	13.2	32.9	0.333
69.1 Hz	amplitude	2.85	0.67	---	---

IV. CONCLUSION

Ejector with primary flow oscillation generator was investigated with the help of low and fast pneumatic measurements. We compared ratio of mass flow rates – ejection ratio, expansion pressure in the beginning of the mixing chamber, mixing pressure behind it, back pressure behind the diffuser and ejector efficiency for both generator turned OFF and ON. It was found out that for generator turned ON, the back pressure and the efficiency are higher. Of course we should keep in mind that operating generator adds extra energy to the ejector. During that, the ejection ratio is higher while expansion and mixing pressures do not change. It indicated that velocity ratio could be affected due to the operating generator. Therefore, we also performed a preliminary hot wire anemometry measuring, but our presumption was not confirmed.

We also performed slow and fast pneumatic measuring of static pressure distribution on the mixing chamber wall and the results illustrate how the pressure field in the mixing chamber pulsates. We have found out that the mixing processes are not significantly faster when the pulsation generator is operating, which was the main purpose of our investigation.

Still, we do not fully understand to the mechanisms how the primary flow pulsations influence the flow processes in the ejector. Further and more detailed investigation with the help of hot wire anemometry will follow and the changes of velocity and turbulence profiles will be inspected. Measuring of more nozzles with various inlet area ratio A_1/A_2 and regimes with various velocity ratio c_2/c_1 are planned.

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