Hot – wire study on the axisymmetric free jet dependence on the nozzle shape.

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Abstract. The paper presents the results of experimental research in axisymmetric free jet performed in order to verify the previous numerical calculations. During the study the influence of the initial conditions at the outlet of the nozzle on the formation of self-sustained oscillations in free jet was determined. The variables affecting the initial conditions were: the shape of nozzle tip (free – slip and no - slip), contraction ratio (C = 128 and 144) and Reynold’s number (Re = 5 000 – 40 000). Measurements were taken using the CTA probes. An analysis of the distributions of mean velocity at the nozzle exit shows that a laminar boundary layer was obtained, values of integral boundary layer parameters were not significantly affected by the type of nozzle tip. Some differences were observed in the turbulence intensity distributions in the exit plane and along the jet axis, where characteristic plateau could be noted for case with the free – slip nozzle tip, which indicates the presence of coherent structures in the flow. These results suggest that for almost the same initial conditions obtained for plane and profiled nozzle tip the modification of organized structures in the far flow field was obtained. For physical explanation of these phenomena it was necessary to perform spectral and spatio – temporal correlation analysis (not discussed in the present paper).

1. Introduction

The paper presents the results of research devoted to the experimental verification of the self-sustained oscillations in axi – symmetric jet, which were found in numerical experiment of Boguslawski et al. [1]. Preliminary experiments and LES calculations reported in the above paper allowed to formulate the idea that in the free axisymmetric jet there is a possibility to obtain the regime of self-sustained oscillations, provided that the boundary layer at the nozzle exit is sufficiently thin and the perturbation level sufficiently low. In particular it was found that the thickness of the exit shear layer is of great importance for the existence of regime of self-sustained oscillations.

The main problems with the comparison of experimental and numerical investigations in free jets is the identity of initial conditions, which in the flow considered should be a matter of extreme care. As it was stated in the recent review paper by Ball et al.[2] the round jet is extremely sensitive to inlet conditions, which change not only the near flow field but this influence may propagate even to the far field. As it was also noticed by Nathan [3] “...jet never forgets...”, that is attributed to the underlying structure of turbulent inlet motion, which is carried throughout the entire flow field. The reason is that even small changes of inlet conditions cause considerable modification of large – scale vortices, it concerns in particular their shape and convection velocities, as it was proved by many researchers e.g. by Verzicco and Orlandi [4] and Romano [5]. That is why not only experimental values of Re number
and turbulence intensity $T_u$ but also the $D / \delta^{**}$ had to match numerical calculations, where $\delta^{**}$ is the momentum thickness of initial shear layer, while $D$ is the diameter of jet nozzle outlet.

![Figure 1](https://via.placeholder.com/150)

**Figure 1.** The sketch of possible inlet condition for round jet, Ball et al. [2].

As far as the initial flow geometry is concerned two aspects are important, the first is the shape of nozzle, which affects the initial velocity profiles, the second aspect is the shape of the nozzle end (tip). Ball et al.[2] distinguish three shapes of jet nozzle, the first (‘figure 1a’) is the classical contoured nozzle widely used in aerodynamic research, the second (‘figure 1b’) is the pipe flow and the third one (‘figure 1c’) is the sharp edge orifice. In the present research the contoured nozzle was selected because in this case only a sufficiently low level of turbulence could be achieved.

The additional problem related to comparison of numerical and experimental initial conditions results from the fact, that in LES calculations, which allowed to establish the idea of self-sustained regime, the moderate degree of coflow was used, it was necessary because periodic boundary conditions were applied. The numerical tests performed by da Silva and Metais [6] suggest that the coflow up to 5 % of mean velocity does not influence the results of computations, but it was decided to verify experimentally whether this numerical “trick” may exert some influence upon the behaviour of the free jet. The case without a coflow corresponds to “free – slip boundary condition” (‘figure 1d’), while the case with coflow is mimicked by “no – slip b.c.” (‘figure 1e’). Both types of boundary conditions were investigated during the present research as it will be discussed later.

2. Experimental Setup and Signal Processing
The sketch of the test rig is presented at ‘figure 2’, in fact two rigs with different contraction ratios were investigated but both rigs were of identical design. The air is supplied at the bottom, the fan, filter, ducts and acoustic silencers are located outside the measuring area and are not shown at the sketch. The air first passes through the heater, where electric heaters are filled with iron pellets which are designed to increase the heat capacity and to make the flow more uniform. Then the air enters the settling chamber where 6 wire gauzes are located, which makes the flow more uniform and reduces the turbulence level at the outlet.
Table 1 summarizes the main flow parameters applied in the experiment. One should notice the large contraction ratio of nozzles, which is much larger than in most experiments described in literature. The rig allows to perform measurements at the range of Reynolds numbers from 5 000 to 40 000, the Reynolds number is based on the outlet nozzle diameter. The values of shape parameter H confirm that the shear layer is laminar, the values of $\delta^{**}$ integral parameter are given in millimetres.

Two different values of contraction ratio C were used (see table 1), these two designs are supposed to provide different values of initial turbulence intensity at the nozzle outlet. The wire gauze surrounding the jet facility was used to prevent the disturbing influence of draughts and possible convective motions in the room.

Table 1. Inlet parameters for both experiments.

|        | C  | $\delta^{**}$[mm] | H          | D/$\delta^{**}$ |
|--------|----|------------------|------------|-----------------|
| Exp.No.1 | 128 | 0.080 – 0.199    | 2.50 – 2.66 | 75 - 188        |
| Exp.No.2 | 144 | 0.088 – 0.193    | 2.56 – 2.68 | 78 - 171        |

As far as the influence of the shape of the nozzle tip is concerned, it was decided to investigate both free - slip and no-slip initial nozzle shapes shown at ‘figure 3’. The no-slip nozzle tip (‘figure 3a’) corresponds to the case without coflow, while the free – slip (‘figure 3b’) imitates the case with coflow at the nozzle edge.
Figure 3. The sketch of free – slip (a) and no – slip (b) nozzle tips.

The thickness of the exit shear layer was among the important flow parameters, so the contoured nozzle was combined with cylindrical extensions. The CTA single and “X” wire probes with wire length to diameter ratio 250 were used, the accuracy of probe positioning was 0.01 [mm]. The sketch of CTA equipment together with traversing mechanism is shown at ‘figure 4’. For CTA measurements dual-channel acquisition was carried out, the first channel was connected directly to the CTA bridge and contained both DC and AC signals, while the second channel contained the AC signal only. Data from first channel were used to calculate the average velocity and from the second one to calculate the turbulence intensity.

Figure 4. The sketch of CTA equipment.
3. Discussion of results

Velocity profiles measured at the nozzle exit are presented at ‘figure 5’ in universal coordinates for all values of Reynolds numbers used in the experiment. The results obtained close to the wall were corrected for wall proximity, one may notice that all the points follow the linear velocity distribution \( U^+ = y^+ \), the corresponding values of shape parameter \( H \) collected in table 2 confirm that we have here an undisturbed laminar shear layer and that the type of nozzle tip does not influence the integral parameters of the exit shear layer.

Figure 5. Velocity profiles in exit shear layers for various Re and C as well as for free – slip (a) and no – slip (b) nozzle tips.

| Exp.No. | Re = 5 000 | Re = 10 000 | Re = 20 000 |
|---------|------------|-------------|-------------|
| Exp.No.1| free - slip| 2.652       | 2.363       | 2.630       |
|         | no - slip  | 2.664       | 2.594       | 2.617       |
| Exp.No.2| no - slip  | 2.591       | 2.567       | 2.617       |

‘Figure 6’ shows the comparison of turbulence intensity measured at the nozzle exit with the free – slip nozzle tip for all Reynolds numbers, turbulence intensity \( Tu \) is presented versus the \( r / D \) relative radial coordinate, the value \( r / D = 0 \) corresponds to the jet axis, the value \( r / D = 0.5 \) corresponds to nozzle edge. The distributions of \( Tu \) reveal that for the lowest values of Reynolds number there is almost no increase of \( Tu \) in the shear layer, in fact \( Tu \) level is identical as in the potential core, the increase of Reynolds number brings about the higher level of \( Tu \) in the shear layer, one may also notice that the increase of \( Re \) shifts the maximum \( Tu \) towards the outer region of the shear layer. Very similar are the results for the no - slip nozzle tip (not shown here), but contrary to the previous case the increase of \( Re \) shifts the maximum \( Tu \) towards the inner region of the shear layer.
Figure 6. Turbulence intensity Tu profiles in exit shear layers for various Re and for the free–slip nozzle tip.

Figure 7. Sample comparison of mean velocity profiles (a) and turbulence intensity Tu (b) at the exit shear layer for Re = 20 000 and for free–slip and no–slip nozzle tip.

‘Figure 7’ shows the comparison of mean velocity and turbulence intensity at the nozzle exit for both free–slip and no–slip nozzle tips for sample value of Re = 20 000 and for C = 128 (Exp. No.1). One may easily notice that both these distributions are in fact identical, one may conclude therefore that the shape of nozzle tip does not affect the jet initial mean velocity and Tu profiles.

‘Figure 8’ presents the downstream evolution of turbulence intensity at the jet axis for the sample value Re = 20 000, one may notice a substantial difference in Tu profiles, in particular the plateau visible for plane tip becomes much more pronounced for the profiled nozzle tip. This plateau is related to the presence of coherent structures, that means that no–slip nozzle tip creates more favourable conditions for the development of large scale structures. This comparison is to some extent surprising, because it suggests that even if initial conditions are the same for free–slip and no–slip conditions the amplification of organized motion may be substantially different. In order to explain these findings the
spectral and spatio-temporal correlations was performed, which allowed to identify the development of large scale vortices.

Figure 8. Sample comparison of turbulence intensity profiles along the jet axis for $Re = 20\,000$ and for free-slip and no-slip nozzle tip.

The next part of the research was devoted to analysis of the influence of nozzle contraction ratio, which was performed by comparative tests of rigs No. 1 and 2. The higher contraction ratio applied in the test rig No. 2 allowed to expect the lower turbulence level at the jet exit. However, the data presented at ‘figure 9’ do not support this expectation. ‘Figure 9a’ presents a comparison of $Tu$ measured at the exit plane for both test rigs, ‘figure 9b’ presents the mean turbulence intensity at the potential core, for test rigs No. 1 and 2. One may notice that for all Reynolds numbers the mean value of $Tu$ in potential core and maximum value in the shear layer are identical, with the exception of the smallest Re number 5 000, where the increase in the nozzle contraction caused the visible increase of mean turbulence intensity.

Figure 9. Evolution of mean (a) and maximum value (b) of turbulence intensity at the exit plane versus Re number for two test rigs with different nozzle contraction ratio.
Figure 10. Downstream evolution of turbulence intensity at the jet axis for two nozzle contraction ratios applied for Re = 10 000.

However, the data presented at ‘figure 10’ reveal, that despite identical Tu mean and maximum values at the jet exit a substantial difference in Tu downstream distribution along the jet axis was observed for Re = 10 000. These results suggest the need to apply more advanced characteristics of the jet initial conditions, in particular the spectral contents of turbulence and the analysis of turbulence scales will be necessary.

4. Conclusions
The investigations confirmed the sensitivity of free jets to initial conditions for a broad range of relative boundary layers thicknesses and Re, the importance of the shape of cylindrical nozzle tips has also been confirmed. For physical explanation of these phenomena it was necessary to perform spectral and spatio–temporal correlation analysis.

5. References
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