Journal of Applied Fluid Mechanics, Vol. 11, No. 4, pp. 877-883, 2018.
Available online at www.jafmonline.net, ISSN 1735-3572, EISSN 1735-3645.
DOI: 10.29252/jafm.11.04.28311

Large Scale Fluctuations in an Axisymmetric Sudden Pipe Expansion with Large Aspect Ratio

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(Received August 12, 2017; accepted January 24, 2018)

ABSTRACT

The aim of the present work is the investigation of the turbulent flow field downstream of an axisymmetric sudden expansion with a large aspect ratio of D/d = 12,3. For the fundamentally understanding of the flow some numerical results are presented. They were achieved by using the RANS approach and SST turbulence model. The flow field is characterized by a jet-like flow near the nozzle exit and a large toroidal recirculation zone. The x-component of the velocity u was measured using one-component laser Doppler velocimetry. Axial and radial velocity distributions as well as some velocity spectra were measured. The spectra were calculated from the velocity signal using the Sample-And-Hold method together with the refinement technique. At the axial half length of the recirculation zone at the edge of the jet flow a narrow band peak was observed in spectra, suggesting the existence of large-scale fluctuations or instability of the flow field. Further investigations reveal that this effect is locally limited and shows no sensitivity against changes of the inlet conditions, e.g. the Reynolds number and velocity profile.

Keywords: Axisymmetric sudden pipe expansion; Laser Doppler velocimetry; Sample-and-Hold; Incompressible turbulent flow; Large scale fluctuations; Narrow-band peak spectra.

NOMENCLATURE

d	nozzle diameter	Sr_{dom}	dominant Strouhal number
D	pipe diameter	t	wall thickness
f	frequency	T	period length
f_c	particle cut-off	U_J	jet nozzle velocity
l_{BW}	focal length	U_0	velocity along the pipe axis
n	burst rate	u'	velocity fluctuations
N	number of bursts	x_R	reattachment point
P	laser power	x_S	length of jet-like region
Re_d	Reynolds number	κ	wave number
S_{11}	power spectral density	λ	wave length
Sr	Strouhal number	μ	molecular viscosity
		ρ	fluid density

1. INTRODUCTION

The axisymmetric sudden expansion is characterized by its inlet of diameter d and the circumferencial wall (pipe) of diameter D (Fig. 1). The inlet flow is affected by the design of the inlet which could be a smooth contraction nozzle or a straight pipe and will cause a significantly different inlet profile. The inlet flow is characterized by the average velocity U_J and the decay of the jet by the velocity along the pipe axis U_0. Due to the pipe wall a toroidal recirculation zone encloses the jet flow and reattaches at x_R. The straightened flow goes downstream and leads to a developed pipe flow.

By the use of the π-theorem of Buckingham and under consideration of the molecular viscosity μ and the fluid density ρ a set of two similarity parameters can be found - the Reynolds number (1) and the aspect ratio (2).

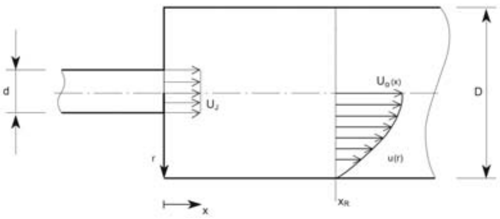

Fig. 1. Schematic of sudden pipe expansion flow

$$\pi_\mu = \frac{\mu}{\rho \cdot d \cdot U_J} = \mathrm{Re}_d^{-1} \tag{1}$$

$$\pi_D = \frac{D}{d} \tag{2}$$

Furthermore, for unsteady flows another parameter for the description of its characteristics is necessary, the periodic time T or its correspondent frequency f = 1/T. Therefore, an additional similarity parameter can be found - the Strouhal number Sr (3).

$$\pi_f = \frac{d}{U_J} f = Sr \tag{3}$$

For small aspect ratios (e.g. D/d < 3) and for a wide range of Reynolds numbers ($10^1 < \mathrm{Re}_d < 10^5$) this type of flow is very well investigated. Gould *et al.* (1990) presented a data set of two-dimensional laser Doppler velocimeter (LDV) measurements for a diameter ratio of D/d = 2 and a Reynolds number of Re_d = 56,000. In this study numerous radial profiles of the axial velocity u and radial velocity v, it's normal stresses, Reynolds stresses and turbulent kinetic energy are given up to a distance of x/d = 14 downstream the nozzle. It makes the study suitable for validation of the present experimental apparatus also because of a detailed description of the used flow system.

In Furuichi *et al*. (2002) the ultrasound Doppler velocity profiling (UVP) method was used for measurements of a flow with D/d = 1.8 and a moderate Reynolds number of Re_d = 3,820. In the recirculation zone complex large-scale structures were observed that interact with the separated shear layer upstream and grows further downstream.

For similar diameter ratios two numerical studies deal with flows at much higher Reynolds numbers of $\mathrm{Re}_d \geq 50{,}000$. Sagar *et al.* (2011) applied the renormalized group (RNG) k-ε turbulence model and found good agreement of the skin friction factor in comparison to experimental results. Bae *et al*. (2013) compared several turbulence models and pointed out that the standard k-ε model and Reynolds stress model (RSM) provide better agreement with experimental data than the SST model.

Hammad *et al.* (1999) used the particle image velocimetry (PIV) technique for the investigation of the same diameter ratio of D/d = 2, but at a much lower Reynolds number of $20 < \mathrm{Re}_d < 211$, which caused laminar flow. The paper contained vector plots as well as streamline plots that will help to gain an understanding of the two-dimensional velocity field. A major issue is the knowledge that the reattachment length of the recirculation zone increases linearly with Re_d. The same flow was used by Ray *et al.* (2012) and Carrillo *et al*. (2014) for the validation of their numerical studies. Both showed grid studies and confirm good agreement between their numerical results and the experimental results of Hammad.

However, a comparable data base for larger aspect ratios (e.g. D/d > 6) does not exist. This was firstly stated in a study by Rinaldi (2003), where a jet ends in a rectangular space with large length ratios (approx. 10 times the nozzle diameter). He presented LDV measurements that proof a self-similarity of the flow in terms of free jet flow.

A study of a confined jet flow with large diameter ratios of D/d = {15.7; 24; 40.8} is given by Khoo *et al.* (1992). Using the PIV method, they investigated the turbulent spatial length scales and pointed out the existence of isotropic turbulence. But the differences in the experimental setup should be noted. In Khoo a grid at the nozzle wall at x = 0 was used, which allows a backward flow. Moreover, a linear decay of the root mean square (rms) velocity up to x/D = 5 was observed.

The effect of the inlet design on the flow field for the jet flow was studied by Mi *et al.* (2001). Due to the nozzle contraction a block velocity profile result in the nozzle exit with a laminar shear layer that become instable downstream the nozzle and result in a vortex roll-up of the shear layer. This effect can be detected as a narrow-band peak in the velocity spectra near the nozzle exit.

The aim of the present work is the investigation of the turbulent flow of an axisymmetric sudden pipe expansion with a large diameter ratio of D/d = 12.3 and a nozzle Reynolds number of $\mathrm{Re}_d = 10^4$. At the axial half-length of the recirculation zone at $x = x_R/2$ a narrow band peak in the velocity spectra can be observed, which will be discussed in detail. Upstream, the flow shows characteristics of the free jet flow, where the flow is parallel to the pipe axis. Downstream, a strong velocity decay due to the end of the recirculation zone can be observed.

2. EXPERIMENTAL INVESTIGATION

2.1 Apparatus and Instrumentation

A one-component laser Doppler velocimeter (LDV) of typ fp50Shift (ILA Intelligent Laser Applications GmbH, Juelich, Germany) was used to measure the axial component of the flow velocity u. The LDV probe was arranged in backward scattering mode (Fig. 2) and uses a laser of typ Nd:YAG with a maximum power of P = 75 mW, a wave length of λ = 532 nm and a focal length of l_{BW} = 140 mm. A pipe of silica glass with a wall thickness of t = 1.5 mm was used as optical access. The accuracy of the test facility was evaluated for adjusting the flow rate or rather the nozzle Reynolds number Re_d. Therefore, the measurement error can be determined to be about $\Delta Re_d = 4\%$, which leads to an overall measurement error for the Doppler frequency f_D of the LDV system of $\Delta f_D = 7\%$.

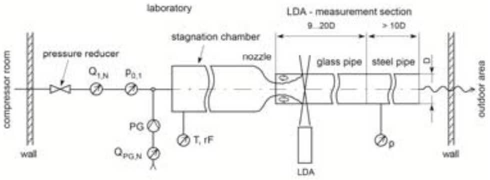

Fig. 2. Schematic of the test facility and LDA probe

For the present study two types of nozzles were used. First, a smooth contraction nozzle (illustrated in Fig. 2) with an inlet diameter d (nozzle or pipe) of $d = 0.006$ m. A contraction ratio of the diameter of the stagnation chamber to the nozzle diameter of 23 results. Therefore, a block-like velocity profile can be expected that is similar to Fig. 3. Second, a straight pipe expansion of the nozzle with a length to diameter ratio of $l/d = 13.2$ was applied. This will cause a non-fully developed turbulent pipe flow and a sufficiently developed turbulent boundary layer can be expected. The exact jet exit conditions were not measured. While Mi *et al* (2001) used a contraction ratio of 5.7 and a length to diameter ratio of $l/d = 72$, similar jet exit conditions can be assumed.

The aspect ratio of the pipe and nozzle diameter was chosen to be $D/d = 12.3$ to establish a typical large aspect ratio flow field. For air flow a Newtonian viscid behavior can be assumed, the viscosity amounts to $\nu = 1{,}6 \cdot 10^{-5}\ \mathrm{m^2/s}$. An appropriate flow velocity U_J was chosen to achieve turbulent flows with Reynolds numbers of $Re_d = \{5 \cdot 10^3;\ 1 \cdot 10^4;\ 2 \cdot 10^4\}$. While a maximum Reynolds number of $Re_d = 2 \cdot 10^4$ lead to a velocity of $U_J \approx 53$ m/s incompressible flow ($Ma < 0.3$) can be assumed.

2.2 Experimental Procedure

The power spectral density S_{11} was calculated by using the software „kern.exe" that is provided by Nobach (2015). Hence, the Sample-And-Hold (S+H) reconstruction method in combination with the refinement technique was applied. The S+H is one of the fundamental strategies for estimating a power spectral density (PSD) based on a non-equidistant sampled velocity-time signal like it is caused by LDV measurements, wherein the velocity at each Doppler burst is sampled and held. A detailed investigation of the S+H is given for instance in (Adrian and Yao 1987). The PSD estimation using the S+H method is limited due to the mean particle rate, the so-called particle cut-off frequency f_c. The so-called refinement technique overcomes this limitation (Nobach *et al*. 1998). Thus, the measurement system noise can be estimated that leads to a valid PSD estimation above the particle cut-off frequency. The velocity signal was low pass filtered with a cut-off frequency of $f_{LP} = 10 \cdot f_c$. The particle cut-off $f_c = n/2\pi$ is caused by the burst rate n and amounts for all measurements approximately $f_c = 80$ Hz. The number of bursts was $N = 10^5$.

2.3 Data Validation

The performance of the experimental apparatus and the applied LDV technique were validated for the mean and variance of the velocity component u at the sudden pipe expansion with experimental data provided by Gould *et al*. (1990). Therefore, the nozzle diameter amounts to $d = 13.05$ mm, the diameter ratio to $D/d = 1.9$ and the nozzle contraction ratio to 10.6. A block profile of the mean axial velocity (Fig. 3) that causes a thin layer profile of its axial fluctuations (Fig. 4) can be observed at the nozzle exit, like it can be expected from a smooth nozzle contraction. These inlet conditions are very close to that one of Gould.

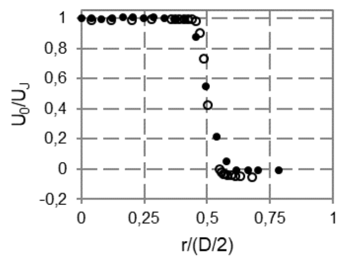

Fig. 3. Mean axial velocity profile at x/d=0.5

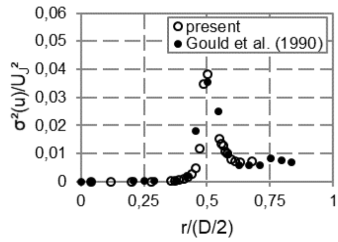

Fig. 4. Normalized axial fluctuations at x/d=0.5

The overall deviation was smaller than 5%. In regions of large gradients ($\partial u/\partial r$ or $\partial u'^2/\partial r$, e.g. at the edge of the jet flow) the maximum difference of the mean value is less than 20% and of the variance less than 30%. Especially in the region of the recirculation zone, what is important for the spectral results that presented later on, the present measurement results are in very good agreement with the data of Gould (Figs. 5 and 6). There, the maximum difference of the mean value is less than 6% and of the variance less than 25%.

The estimation of the power spectral density was validated on the free jet with data provided by Mi *et al*. (2001). Therefore, measurements were performed at $Re_d = 16{,}000$ (nozzle) in the shear layer of the laminar core at $x/d = 3$ and $r/d = 0.25$. The signal length was $N = 10^5$ and the particle cut-off was approximately $f_c = 200$ Hz. In comparison

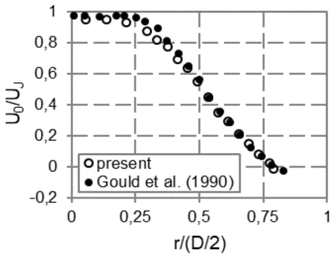

Fig. 5. Mean axial velocity profile at x/d=2.5

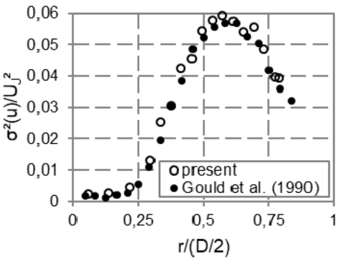

Fig. 6. Normalized axial fluctuations at x/d=2.5

to the experimental data provided by Mi a similar spectrum could be measured (Fig. 7). The observed large-scale structures which were caused by a nozzle formed inlet lead to a spectrum with a local maximum and a dominant frequency. The present apparatus and procedure shows a dominant frequency at Sr = 0.37 which corresponds to the results of Mi where Sr = 0.4 was found.

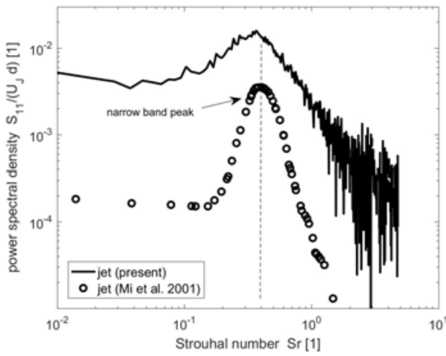

Fig. 7. Spectra in the laminar shear layer of a jet

3. Numerical Simulation

The numerical simulations were carried out by using the software STAR-CCM+® version 8.02. Therefore, the RANS approach and the standard SST turbulence model were applied. The flow was described as a 2D region due to its axisymmetric behavior. At the inlet a velocity boundary condition was set. According to the experimental data (see Fig. 3) an ideal block profile of the velocity was assumed. Neglecting the fluctuations profile a uniform turbulence intensity of 1% was set. At the outlet a pressure boundary condition with a reference pressure of zero was adopted. A detailed description of the numerical procedure e.g. mesh data and validation on test cases is given in Ringleb *et al.* (2016).

4. Results and Discussion

For the investigated diameter ratio of D/d=12.3 a flow field with a large recirculation zone can be expected (Fig. 8), which extends downstream up to a length of 36 times the diameter (x/d = 30). In the upstream corner a smaller recirculation zone is simulated. Both are arranged circumferentially around the jet flow at the pipe axis, which leads to the description of a toroidal recirculation zone.

The jet flow exits the nozzle at x = 0 and forms a jet-like flow up to an axial distance of x/d = 20. Further downstream the jet spreading increases due to a stronger streamline curvature that is caused by the end of the recirculation zone, which is marked by the point of reattachment at $x = x_R$. For $x > x_R$ pipe flow develops.

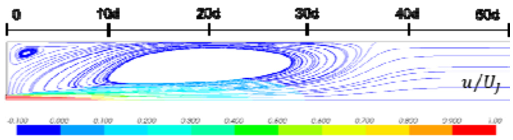

Fig. 8. Numerical prediction of streamline distribution and normalized mean axial velocity

In the proximity to the nozzle exit the laminar core region extends up to x/d = 5. At its edge the shear layer expands downstream, where the axial velocity fluctuations have their maximum (Fig. 9). The fluctuations preserve much far downstream beyond the reattachment point. Caused by the strong curvature of the streamlines the jet flow spreads and must slow down because of mass continuity. The turbulent fluctuations cannot slow down in the same way because of their mass inertia. This leads to a high amount of fluctuations, whereas the flow velocity is quite small, which causes a high amount of normalized fluctuations.

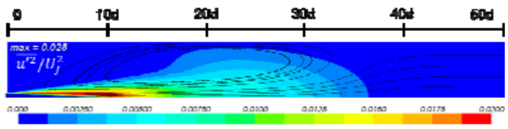

Fig. 9. Numerical prediction of the normalized axial fluctuations

The static pressure upstream the reattachment point is strongly subjected to the jet flow (Fig. 10). In the core region a significant pressure gradient (∂p/∂r) is caused by the jet shear-layer. A much more constant radial pressure distribution arises for x/d ≥ 15, where the center of the recirculation zone is located, that will become more smooth further downstream. The main pressure drop occurs at the end of the recirculation zone between 20 < x/d < 30, where a maximum streamline curvature exists and the flow velocity slows down.

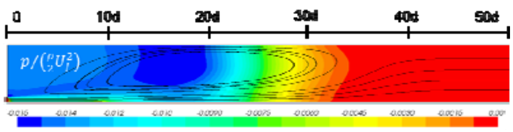

Fig. 10. ***Numerical prediction of normalized static pressure field***

For sufficiently large aspect ratios a spectrum with a narrow band peak can be observed at the edge of the jet flow at the axial half length of the recirculation zone (Fig. 11). Its maximum is located at approximately $Sr = 5 \cdot 10^{-4}$ and corresponds for $Re_d = 10^4$ to a frequency of approximately 2 Hz. This seems to be a locally restricted effect because it could only be observed at the edge of the bounded jet at the end of the jet-like region. The jet-like region extends ap-proximately to $x_S/d \approx x_R/2$ and shows a similar decay of the centerline velocity U_0 as well as a similar progress of the turbulence degree at $u'/U_0 \approx 0{,}3$ to the free jet. After the jet-like region a transition from jet to pipe flow follows, which includes the reattachment of the recirculation zone at $x_R/d \approx 50$. In contrast to the jet edge spectra (Fig. 11), the spectra in the proximity to the inlet and to the reattachment point do not show any peak. Especially the latter shows turbulent like spectra with its typical -5/3 decay of the cascade process (Fig. 12).

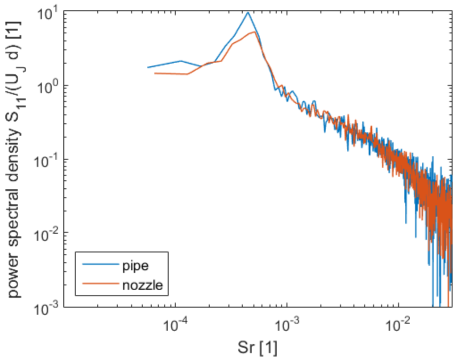

Fig. 11. Spectra at the edge of the jet flow at r/d=2 and x/d=20

The results described above refer to an inlet formed as a smooth contraction (nozzle) which results in a block velocity profile and a sharp shear layer at the inlet. The use of a straight pipe upwards the inlet leads to a turbulent velocity profile with a typical boundary layer and an appropriate turbulence profile. For the free jet problem, the change from nozzle to pipe inlet leads to different flow structures. Caused by the nozzle a vortex roll-up in the laminar shear layer of the core region can be observed (Mi *et al*. 2001) which leads to spectra with a narrow band peak. The vortex roll-up results in large-scale turbulent structures and causes a faster decay of the centerline velocity than the pipe inlet flow. The latter one causes sufficiently smaller turbulent structures and a softer decay of the centerline velocity. This phenomenon is known as “jet inlet anomaly” (Boersma *et al*. 1998). Such a behavior cannot be determined in any spectra of the present flow field. Both spectra for pipe and nozzle inlet look similar to each other and show no indication to different turbulent structures (Figs. 11 and 12).

Moreover, there is a significant sensitivity to the inlet velocity or rather the Reynolds number Re_d which is one of the similarity parameters (1). The spectra for $Re_d = \{5 \cdot 10^3; 1 \cdot 10^4; 2 \cdot 10^4\}$ are shown in Fig. 13. Both - the power spectral density and the

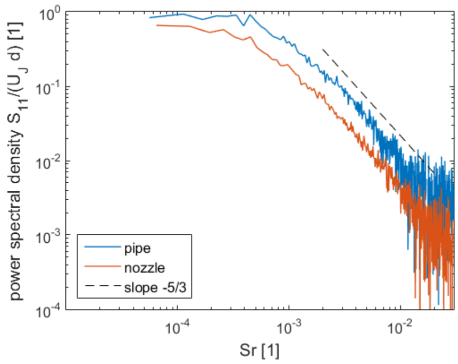

Fig. 12. Spectra at the end of the recirculation zone at x/d=40 and r/d=4

frequency - are normalized to the large scales of the flow problem (the inlet velocity U_J and inlet diameter d). The normalization of the frequency results in the Strouhal number Sr (3). The spectra look quite similar and the characteristic narrow band peak is located at the same range of Strouhal number $10^{-4} < Sr < 10^{-3}$. The resulting constant dominant Strouhal number at $Sr_{dom} = 5 \cdot 10^{-4}$ refers to a doubling of the dominant frequency f_{dom} by doubling the inlet velocity (Table 1). It can be assumed that this peak is caused by large scale structures. However, a more profound understanding about its underlying mechanism has to await further investigations.

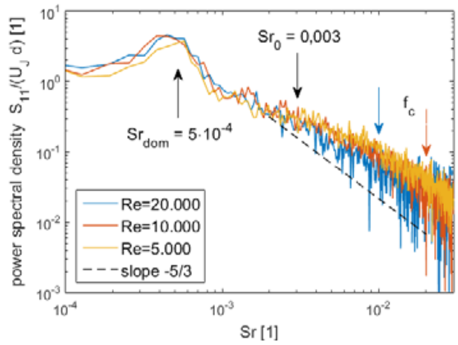

Fig. 13. Spectra at x/d=20 and r/d=2 for different Reynolds numbers

For a better understanding of the underlying flow structures a few further considerations will be discussed.

Firstly, in comparison to the present flow the unsteady flow around a cylinder, also known as Karman vortex shedding, leads to a Strouhal number of $Sr = 0.2$. The vortex roll-up of the jet flow results in Strouhal numbers of $Sr = 0.4$ which corresponds to Karman vortex shedding.

The Strouhal number can also be comprehended as a length scale by the use of Eq. (4). For Karman vortex shedding wave numbers of $\kappa = 2/5\pi \cdot d^{-1} \approx 1.3/d$ result and amount approximately the reciprocal cylinder diameter. The same characteristic can be determined for the vortex roll-up of a jet. The present flow results in Strouhal numbers with two orders of magnitude less than the cylinder or jet flow. Hence, the resulting wave number is $\kappa = 0{,}5\ m^{-1}$ and its reciprocal corresponds to 100 times the inlet diameter or 10 times the pipe

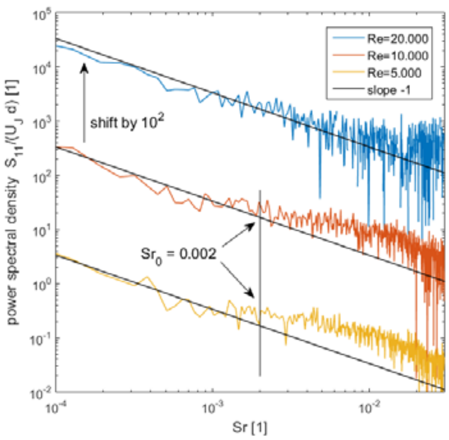

Fig. 14. Spectra at x/d=20 and r=0 for different Reynolds numbers

diameter. Therefore, turbulent structures as a reason for the spectrum peak are hardly conceivable.

$$\kappa = \frac{2\pi}{d} Sr \qquad (4)$$

Secondly, there are no streamwise convection effects of flow structures detectable as it can be seen from Figs. 11 and 12. Therefore, only diffusion or dissipation effects are possible reasons for transferring energy of the spectrum peak. Due to undetectable convection effects, a longitudinal wave structure through the pipe can be also eliminated, because the reciprocal wave length corresponds to six times the length of the recirculation zone or one time the pipe length.

Table 1 Influence of the Reynolds number Re_d on characteristic frequencies

Re_d	f_0 [Hz]	f_{dom} [Hz]
5.000	2,8	0,8
10.000	11,3	1,7
20.000	-	3,4

Thirdly, the observed peak is locally limited to the edge of the jet stream at the half length of the recirculation zone. That is why it cannot be caused by effects further upstream like vortex roll-up but rather by a local effect. Therefore, the recirculation zone itself could be responsible. One possibility is a time-dependent variation of the length of the recirculation zone that could result in a time dependent position of the reattachment point $x_R = f(t)$. This in turn may result in such large-scale fluctuations at the half length of the recirculation zone where streamlines are nearly parallel to the axis and the turbulence intensity is low, whereas, at the end of the recirculation zone the flow is much more turbulent and axial fluctuations could be surpassed by turbulent fluctuations.

In both spectra at the half length of the recirculation zone (at the centerline and the edge of the jet) a slight buckling of the spectrum can be identified which begins at the centerline for $Sr > 0.002$ (Fig. 14) and in the shear-layer for $Sr > 0.003$ (Fig. 13). Its behavior looks like the influence of added noise reported by Nobach *et al.* (1998). However, it can only be observed for $Re_d = \{5{\cdot}10^3;\ 1{\cdot}10^4\}$. Its non-appearance for the flow at $Re_d = 2{\cdot}10^4$ leads to the presumption that the buckling is triggered by a laminar to turbulent transition in the flow field.

Eventually, it should be noted, that the discussed large-scale fluctuations exist at low frequencies for a high power level that corresponds to high energy rates contained by the underlying flow structures. That is why it can be assumed that these velocity fluctuations also result in pressure fluctuations within the flow field.

5. Conclusion

A sudden pipe expansion flow with an underlying expansion ratio of D/d = 12.3 has been investigated. Large scale fluctuations have been observed at the edge of the jet stream at the axial half length of the recirculation zone. They show no sensitivity against the inlet design but a proportional sensitivity against the flow velocity. A doubling of the dominant frequency results in an increase of the Reynolds number by factor of 2. Dimensionless considerations lead to a longitudinal wave structure or an axial commutation of the recirculation zone as a possible reason. Transversal or vortex like structures are hardly to imagine because of the resulting large wave numbers and the local limited occurrence.

Further investigations on a wide range of Reynolds numbers Re_d and different diameter ratios D/d are in progress. The aim is to carry out much more detailed information about the sensitivity of this peak. Based on the present work it can be presumed that this peak shows a linear behavior against the Reynolds number. A similar observation was made by Anderson *et al.* (2003) for a parallel plane jet flow. Furthermore, it is necessary to get more knowledge about the underlying flow structure. Therefore, the ongoing investigations on Re_d and D/d will be helpful.
Moreover, the observed spectrum peak can be used for the development of a method for indirect flow rate measurements in an axisymmetric sudden pipe expansion flow with LDV. This technique will be very suitable for applications in rough industry environments such as flow rate sensors for chemical or process engineering. Because LDV is a so called non-invasive technique, no mechanical parts e.g. surfaces can be damaged due to corrosion or high temperatures. A disadvantage is the necessity of an optical access.

Acknowledgements

Financial support of the European Regional Development Fund (EFRE) through grant CIPP is gratefully acknowledged.

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