Influence of a secondary, parallel, low Reynolds number, round jet on a
turbulent axisymmetric jet

A. Vouros, Th. Panidis *
Laboratory of Applied Thermodynamics, Mechanical Engineering and Aeronautics Department, University of Patras, Greece

ABSTRACT
The influence of a secondary, parallel, low Reynolds number, round jet on the development of a turbulent axisymmetric jet with $Re=5500$ is studied experimentally by means of 2D laser Doppler anemometry. Two weakly turbulent jets of Reynolds numbers, 1200 and 1800, are considered. In both test cases the secondary jet is fully absorbed by the primary one. The mean and turbulent flow structure of the standalone primary jet is compared to previous studies referring to the jet’s development before and inside the self-similarity region. The flow field of interacting jets is then analyzed and discussed. Characteristic profiles are presented at locations within the merging and the mixing zones. In the early stages of development, the patterns of both jets can be identified. Within the merging region, besides the absorption of the secondary jet, the measurements indicate a spatial suppression of primary jet’s characteristics. Further downstream, the profiles resemble to those of a standalone jet. Higher values of the mean and turbulent terms are observed while the profiles extend over a wider region, in accordance with the secondary jet’s Reynolds number. Results of the present study demonstrate that skewness and flatness factors can be used as indicators of small scale mixing.

1. Introduction

Due to their significance as fundamental turbulent flows, and their implication in a wide range of applications, turbulent axisymmetric jets have been studied extensively during the last decades. Recent studies relate variations of jet’s development and self-preserving state to Reynolds number’s effects. This paper also presents measurements on an axisymmetric jet, however, its main objective is to study the influence of a secondary, low Reynolds number, jet on a turbulent round jet, a scheme that is encountered in several fluid processes.

Wygnaski and Fiedler [1] and Hussein et al. [2] presented hot-wire anemometry (HWA) and laser Doppler anemometry (LDA) measurements within the self-similarity region of jets with high Reynolds numbers. The first reported significant discrepancies in jet’s momentum conservation in the farfield while the latter, repeating the same experiments in a significantly larger area, remarked that some “inconveniences” occur due to momentum losses, when strongly confining boundaries are imposed on the flow. Panchapakesan and Lumley [3] also presented measurements within the self-similarity region of an axisymmetric jet using HWA. By measuring significantly lower second and third order terms than the previous investigators, they attributed the differences to the lower Reynolds number of the jet studied in their experiments.

Weisgraber and Liepmann [4] reported particle image velocimetry (PIV) measurements in the transition to self-similarity region of a water jet for two Reynolds numbers (16,000, 5500). Based on vector maps, they discussed the differences for these Reynolds numbers, comparing also their measurements to those of previous authors. Results from their study showed that the second order turbulent terms were close to those measured by Panchapakesan and Lumley and lower than those presented by Hussein et al. The third order terms were, also, significantly lower compared to those of Hussein et al. The authors surmised that these trends reflect the Reynolds number’s effect, assuming that the influence of the surrounding walls was negligible. Although the objective of the present work is not to assess the Reynolds number’s effects, the measurements presented here are also verifying the trends observed in Weisgraber and Liepmann [4] study.

In contrast to the abundance of studies on turbulent round jets, only a small number of studies have been devoted to jets’ interaction flow fields. Becker and Booth [5] reported on the field of interaction of equal round jets by measuring smoke concentration with a scattered light technique. They evaluated mixing by introducing indices based on relative concentration fluctuations measured when one or both streams were seeded. Moustafa [6] presented the velocity field of equal round jets using Pitot diagnostics. His study is relevant to the present study since he also compared the
field of the interaction with that of a single jet. Comparing the spreading rate’s features, he concluded that the combined field covers a wider extent. Koller-Milojevic and Schneider [7] focused on the intersection of low Reynolds number jets. Flow visualization images and measurements were used in their study to illustrate the enhanced entrainment of the combined structure compared to single jet flows.

Configurations involving round jets with different Reynolds numbers became rather recently a subject of research. Grandmaison et al. [8] introduced a simplified model to estimate the “weaker” jet’s trajectory, assuming that the “stronger” jet remains unaffected. Yimer et al. [9] presented laser sheet visualization and laser Doppler measurements up to the merging zone to evaluate the accuracy of the model for high Reynolds numbers. Measurements on the central axis of the “stronger” jet showed that the latter was not significantly affected by the “weaker”, since the axial mean velocity decay was similar in comparison to that of a single jet.

The field of the interaction depends on the jets’ Reynolds numbers, the distance between port axes and the offset angle. Alternatively, the jets’ momentum ratios can be used as a controlling parameter. In Table 1 the characteristic conditions of previous research efforts on jets’ interaction are presented. As the literature related to the strength and the spatial extent of the turbulent properties in the combined structure formed by unequal jets is rather limited, conditions imposed in this study have been selected to provide fundamental and complementing knowledge on jets’ interaction flow field, while they are also addressing specific applications. Low Reynolds number jets’ interaction is considered as a means to enhance the mixing process by triggering turbulence in small mixers and combustors. The concept is also based on previous studies demonstrating that low Reynolds number jets can provide turbulent fields with enhanced mixing properties [10].

In this study, results on the flow produced by a secondary low Reynolds number, round jet developing in parallel with a turbulent jet are presented. The investigation is focusing on the effect of the secondary jet’s Reynolds number. Other significant parameters such as the nozzles’ dimensions and the relative position of the two jets are presently kept constant, and they have been selected based on visualization experiments and numerical simulations (not presented here) indicating the efficient mixing and full absorption of the secondary jet by the primary one. The experimental results confirm that during the absorption of the weaker jet, enhanced mixing is provoked, superior to that of the corresponding single jets.

Two types of experiments are included. In the first part, laser Doppler anemometry measurements of the standalone jet with Reynolds number 5500 are presented for reference, but also for comparison to the existing literature. In the second part, the jets’ interaction field is studied for two exit velocities of the secondary jet, corresponding to Reynolds numbers 1200 and 1800. Measurements were conducted at three locations, 15, 20, and 30 cm from jets’ exit on the symmetry plane to demonstrate characteristic features of the flow field. Results include the distributions of mean and turbulent statistics of two velocity components up to the third moments. Profiles are presented in comparison to the measure-

Table 1
Flow and geometry conditions in jets’ interaction studies

<table>
<thead>
<tr>
<th>Authors</th>
<th>$Re_D$</th>
<th>$Re_S$</th>
<th>$Re_D/Re_S$</th>
<th>Momentum fluxes ratio</th>
<th>Distance</th>
<th>Offset angles (deg)</th>
<th>Technique</th>
</tr>
</thead>
<tbody>
<tr>
<td>Becker and Booth [5]</td>
<td>$7 \times 10^4$</td>
<td>$7 \times 10^4$</td>
<td>1</td>
<td>1</td>
<td>24 D</td>
<td>30, 60, 90 (converging angles)</td>
<td>0</td>
</tr>
<tr>
<td>Moustafa [6]</td>
<td>$4.2 \times 10^4 - 1.3 \times 10^5$</td>
<td>$4.2 \times 10^4 - 1.3 \times 10^5$</td>
<td>1</td>
<td>1</td>
<td>2.86 D, 3.81 D, 4.29 D, 5.24 D</td>
<td>0, 10, 20 (converging angles)</td>
<td>Flow visualization LDA HWA</td>
</tr>
<tr>
<td>Koller-Milojevic and Schneider [7]</td>
<td>500</td>
<td>500</td>
<td>1</td>
<td>1</td>
<td>1.5 D, 1.67 D, 1.67 D</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Lin and Sheu (plane jets) [11]</td>
<td>$9 \times 10^3$</td>
<td>$9 \times 10^3$</td>
<td>1</td>
<td>1</td>
<td>30 D, 40 D</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Grandmaison et al. [8]</td>
<td>$3 \times 10^4$</td>
<td>$5 \times 10^3$</td>
<td>1/14, 1/10, 1/7</td>
<td>0.005, 0.01, 0.02</td>
<td>1</td>
<td>0, 10, 20 (diverging angles)</td>
<td>LDA</td>
</tr>
<tr>
<td>Yimer et al. [9]</td>
<td>$3 \times 10^4$</td>
<td>$5 \times 10^3$</td>
<td>1/6</td>
<td>0.027</td>
<td>13 D (20 d)</td>
<td>0</td>
<td>0, 10, 20 (diverging angles)</td>
</tr>
<tr>
<td>Present experiments</td>
<td>$5.5 \times 10^5$</td>
<td>$1.2 \times 10^5, 1.8 \times 10^3$</td>
<td>1/4.58, 1/3.05</td>
<td>0.048, 0.107</td>
<td>3 D</td>
<td>0</td>
<td>LDA</td>
</tr>
</tbody>
</table>
ments of the basic jet, in order to reveal the influence of the secondary jet in characteristic regions, such as the merging and the mixing zones.

2. Background

The field of interaction produced by two equal jets is customarily divided into three regions, namely: the converging, the merging, and the combining or mixing zone. Becker and Booth [5] distinguished these regions for equal round jets based on concentration measurements. Lin and Sheu [11], who measured the velocity field of equal plane jets, proposed another classification. According to their suggestions, the converging region, which covers the initial development of jets, extents to a critical distance where the jets merge. The merging point is defined as the distance where the negative values of the streamwise velocity observed due to the recirculation between the jets in the early stage of interaction, are eliminated. The merging zone, which follows, reaches to the distance where the streamwise velocity on the central axis takes a maximum value. Further downstream extends the combining zone, where the mixing of the jets continues until completeness.

Velocity profile, in this final region, is similar to a jet flow, but the combined structure is more effective with respect to entrainment and mixing with the ambient, in comparison to single jet flows.

In the case of equal round jets interaction, the recirculation in the converging region is expected to diminish or even disappear.

Fig. 1. Velocity field of the interaction produced by jets at different Reynolds numbers.

Fig. 2. Experimental apparatus.

Fig. 3. Details of the jets’ arrangement (not in scale).
due to three dimensional effects absent in plane jets. Furthermore, the definition of the merging point of jets’ merging suggested by Lin and Sheu [11] for a symmetric field is not adequate for unequal jets. To overcome these problems, a different classification is proposed here. The end of the converging zone is defined as the location where the 10% internal isocontours of the non-dimensional, with respect to the maximum, streamwise velocity merge and vanish. Thereafter follows the merging zone, which ends at the location where the second local maximum that denotes the central part of the secondary jet in the axial velocity distribution is no longer apparent. At this point begins the mixing or combining zone. The 10% isotach along with some of the most characteristic velocity profiles located in these regions as they have been predicted in a previous study [12] are shown in Fig. 1.
Fig. 8. Distributions of turbulent lateral normal stress, $\overline{v^2}$ (for symbols see Fig. 6).

Fig. 9. Distributions of turbulent shear stress, $\overline{uv}$ (for symbols see Fig. 6).

Fig. 10. Distributions of turbulent transport terms, $\overline{u^2}$, $\overline{v^2}$, $\overline{uv}$ and $\overline{w^2}$.
3. Experimental facility

The two round jets are issuing vertically inside an open-top cavity with dimensions $1 \times 1 \times 1$ m$^3$ (Figs. 2 and 3). Both jets emanate from 50 cm long cylindrical pipes, in order to ensure fully developed velocity profiles at exits. Exit diameters are 10 and 4 mm and the distance between port axes is 3 cm. Two frequency inverters are used to adjust the speed of variable speed blowers, and control airflow rates. The jets are seeded with water and glycerine fog of 4 µm mean diameter droplets generated by medical nebulizers (OMRON NE-U17).

Velocity measurements were carried out using two single-component forward scattering LDA systems. These systems were designed and built using the same components, while the sending and receiving optics lie on opposite sides [13]. The concept is based on the fact that forward scattering light intensity is about three orders of magnitude higher than the backward one. Two 30 mW He–Ne laser sources with 632 nm wavelength and two TSI 9186A dual beam optical systems with beams lying on the vertical and horizontal plane, respectively, were used to produce two ellipsoidal control volumes adjusted to coincide. Beams have 1 mm diameter and 50 mm spacing. Frequency shifting of 40 MHz was used in both systems. The focal length of all transmitting and receiving optics was 605 mm and off-axis angles of $10^\circ$ and $15^\circ$ were used for the receiving optics. Two DANTEC 9057X0081 photomultipliers, with 0.2 mm pinholes, connected to a DANTEC 58N80 Burst Spectrum Analyzer, were used to measure simultaneously the two components of the velocity vector on the flow’s symmetry plane.

A microscope focusing on beam intersection and a digital oscilloscope were used during the alignment and the operation of the system to guarantee the coincidence of the control volumes. Gains were carefully adjusted to ensure that the back scattering light intensity was under the threshold limits, eliminate biasing errors, obtain good quality Doppler bursts with high signal to noise ratio and provide sufficient sampling rate. Validated samples ranged from 5000 to 20,000 depending on the data rate, which also varied from 0.2 to 1.2 kHz according to the local data density and flow field’s characteristics. However, data rate fluctuations do not affect the measurement of turbulent statistics related to the moments of

**Fig. 11.** Distributions of mean axial velocity, $U$, at 15, 20 and 30 D.

**Fig. 12.** Distributions of mean lateral velocity, $V$, at 15, 20 and 30 D (for symbols see Fig. 11).
the probability density function [2]. As higher data rates emerged in measuring points within the central part of jets, and low data rates in more intermittent regions, all the recorded measurements were conducted using fixed time settings. The instantaneous velocity values were weighted by the particles transit times, in order to correct velocity bias effects due to the random sampling [14]. Since most of the bias errors during the operation were carefully alleviated, the errors in mean velocities, velocity fluctuations and third order statistics are estimated to be less that 1%, 2% and 3.5%, respectively.

4. Results and discussion

4.1. Primary jet’s flow field

The initial profile of the mean axial velocity of the primary axisymmetric jet of Reynolds number 5500 is shown in Fig. 4a. The distribution is compared to the empirical power law \((1 - 2 \frac{r}{x})^2\), indicating that the velocity profile at the exit of the pipe corresponds to a fully developed turbulent flow. The root mean square of the axial fluctuating velocity, \(u_{rms}\), is plotted in a non-dimensional form with respect to the mean centreline velocity \(U_c\) in Fig. 4b. In this form, the characteristic peaks far from the central axis depict the strong shear layer at the edges of the jet. The non-dimensional turbulent intensity at each measurement point, \(u_{rms}/U_c\), plotted in Fig. 4c ranges from 5% in the central region and 20% at jet’s boundaries. The mean velocity measurements demonstrate the symmetry of the flow field while minor variations of turbulent intensities are observed at the jet’s outer edges.

Non-dimensional mean axial velocity profiles at 20 and 30 diameters from the jet exit are presented in Fig. 5. Fitting curves are estimated by the product of an exponential and an even or an odd polynomial function of \(r/x\), according to the expected symmetry properties imposed by the power of the radial velocity component included in each particular variable [2]. Weisgraber and Liepmann’s [4] measurements at 25 diameters for a higher Reynolds number (16,000) are also plotted. Curves of the present experiments pass over the reference curve close to the central axis. The values decrease more rapidly towards the outer edges as the distance from the exit increases. The distributions of the mean radial velocity component, presented in Fig. 6, show the opposite

---

Fig. 13. Distributions of turbulent axial normal stress, \(\overline{u'^2}\), at 15, 20 and 30 D (for symbols see Fig. 11).

Fig. 14. Distributions of turbulent lateral normal stress, \(\overline{v'^2}\), at 15, 20 and 30 D (for symbols see Fig. 11).
trend, since at the furthest location the profile expands in a wider region attaining a lower maximum.

The radial profiles of the turbulent axial normal stresses, $\overline{u^2}$, at 20 and 30 D are presented in Fig. 7. The magnitude of the distributions increases with the distance from the orifice indicating that the profiles are not self-similar in this region. In comparison to the distributions presented by Weisgraber and Liepmann [4], the present measurements differ, mainly, in the region close to the central axis, where the data of the previous authors reach higher values. Similar characteristics are observed in the distributions of the radial normal stresses, $\overline{v^2}$, shown in Fig. 8. However, the off-axis peak that is clearly shown in the $\overline{u^2}$ profiles is barely noticeable only at 20 D.

The profiles of the Reynolds shear stresses, $\overline{uv}$, are presented in Fig. 9. An increase of the values with the distance from the orifice is also observed, although, the differences diminish at the outer edges of the jet. In line with the maximum normal stresses, the higher values occur within the region of the high mean axial velocity gradients. The distributions always attain lower values in comparison to the data of Weisgraber and Liepmann [4], in contrast to the profiles of the normal stresses that reach comparable values close to the edges of the jet.

The radial profiles of the third order velocity moments are shown in Fig. 10. According to Tennekes and Lumley [15], these terms represent the transport of the turbulent stresses by the axial and radial fluctuations. In the distributions of $\overline{u^3}$, negative and positive values occur inside and outside the location of maximum shear, respectively. The maximum shear region, as defined by the radial position of the local maxima in turbulent shear stresses, is also, characterized by small values of transport terms. Quinn [16] referred to a gradient type transport process regarding the third order velocity moments in a more general context, suggesting that negative values of $\overline{u^3}$ occur in the flow regions where gradient of $\overline{u^2}$ is positive and vice versa.

In comparison to the results of Hussein et al. [2] and Panchapakesan and Lumley [3], the shape of the curves is similar. Differences are apparent close to the central axis due to the negative values measured in the present study. This attribute is rather reasonable, since the present data are located in the transition to self-similarity region. The distributions at 20 and 30 D differ slightly near to jet’s axis, while the local maximum increases with the distance from the orifice. However, even within the self-similarity region, it is not confident that the values will not reach those reported by the previous authors, since the Reynolds number of the present jet is lower. This speculation is supported by the distributions reported by Panchapakesan and Lumley, which attain significantly lower values in comparison to those of Hussein et al., who studied a significantly higher Reynolds number jet. In the $\overline{u^3}$ distributions, zero values are imposed on the centre of the fitting curve, due to the odd power of the radial velocity component. In comparison to $\overline{u^2}$, significantly lower negative values are observed within a small region near to the central axis mainly at 20 D. The value of the local maximum increases with the distance. The distributions of $\overline{u^3v}$ and $\overline{uv^2}$, have similar characteristics to those of $\overline{u^2}$ and $\overline{v^2}$, respectively. In contrast to the previous terms however, the magnitude of the profiles at 30 D lies closer to the curves of Panchapakesan and Lumley.

The featured axisymmetric jets, described above indicate the influence of flow and geometry conditions used in each particular experiment. From this point of view, the present data are rather complementing to those of other investigators, and they can be used as reference for jets of similar Reynolds numbers. Nevertheless, these measurements constitute the frame of reference to study the modified flow field produced by jets’ interaction.

### 4.2. Jets’ interaction field

Mean axial velocity profiles of jets’ interaction field at 15, 20 and 30 D are presented in Fig. 11. At 15 D, the distributions coincide to those of the standalone jet within the largest part of its extent, indicating that the primary jet’s flow field remains at this stage unaltered. Secondary Gaussian-like profiles are formed in the secondary jet’s development region. The local maxima increase with its Reynolds number, although, their lateral locations stand close to each other. The distributions at 20 D show that at this distance the weaker jet has a significant influence on the formation of the flow field. In comparison to the measurements of the basic jet, the distributions reach higher values within its central part, which seem to be independent of secondary jet’s Reynolds number. Considering a turbulent jet as a result of successive eddies of fluid moving forward and responding to the resistance they meet, these higher peaks may be interpreted as the result of the resistance applied by the secondary jet, which forces primary jet’s eddies to develop within its central region. The presence of the secondary jet is
primarily evidenced by the low-level humps observed within the region that covers its development. In this area, a local maximum is noticeable for the higher Reynolds number.

At 30 D, no secondary hump is discernible and the distributions become bell shaped, although not totally symmetric. The distributions are higher and wider compared to those of the single jet while their shape indicates that they represent profiles after the jets’ merging. Maximum values increase with the Reynolds number of the secondary jet, however, their ratio to the single jet’s maximum is always smaller than that observed at the previous distance.

The profiles of the mean lateral velocity component are presented in Fig. 12. In accordance to the mean axial velocities, the profiles at 15 D show that the secondary jet has small effect on the main field, since the values also coincide within the basic jet’s development region. On the side of the secondary jet, the profile of an axisymmetric jet is repeated with smaller amplitude, which increases with the Reynolds number. At 20 D, the maximum of the distributions is displaced towards the centreline of the primary jet, indicating the suppression of the latter as already discussed. In contrast to the axial velocity, close to the centreline, no considerable differences are observed in comparison to single jet’s measurements. Since this location is located within the merging zone, it seems that as the main jet is sorting to the weak, the latter plays a constraining role on the development of the first structure. The values that correspond to the edges of the main jet are lower compared to those measured during its sole action. At 30 D, the influence of the secondary jet after the jets’ merging is clear. In agreement with the axial velocity profiles, the distributions are similar in shape to those of the primary jet, but higher maximum values and wider distributions are observed, depending on the Reynolds number.

The distributions of normal stresses, $u^2$ and $v^2$, are presented in Figs. 13 and 14, respectively. In accordance to the mean velocity distributions at this distance, the profiles at 15 D reveal the coincidence between these measurements and those of the primary jet within the primary jets development region. In the region of the secondary jet’s development, typical distributions of a turbulent jet are repeated, indicating that the jets are issuing almost independently. In this area, magnitudes increase with the Reynolds number.
number. In all the test cases presented here, the lateral normal stresses reach significantly lower values in comparison to the axial normal stresses. Especially for the lower Reynolds number secondary jet, the profile seems to be distorted, since the characteristic peaks are eliminated. At 20 D, the shape of the distributions remains unchanged although, at this distance, the influence of the secondary jet on the main field is evident. In comparison to the single jet measurements, the values are significantly increased within the largest part of the profiles. Secondary local maxima are still observed within the secondary jet’s development region, indicating that the jets are not completely merged. For the lower Reynolds number secondary jet, the characteristics of the lateral stress distribution seem to diminish, since only a slight hump is observable. The distributions at 30 D are, in form, similar to those of the axisymmetric jet. However, in comparison to the stand alone primary jet, the values are higher within its central part, as well as within the region where the secondary jet is absorbed. In agreement to the mean velocity profiles at this distance, both normal stresses indicate that although the new structure has similar characteristics with that of the primary jet, the distributions become wider and higher, in accordance with the Reynolds number of the secondary jet.

The profiles of the turbulent shear stresses, $\tau_{uv}$, at 15, 20 and 30 D, are presented in Fig. 15. The maximum positive and negative values indicate the strong mixing layers formed at the edges of the jets and furthermore, the opposite rotation of eddies that promote the entrainment of the ambient fluid. At 15 D, the profile of the secondary jet is present, following the trends that characterize the early stages of interaction. Although this feature is observed in all the profiles of the variables described above, it is more evident here. In the secondary jets development region, the local maximum and minimum are clearly shown for both Reynolds numbers, while their amplitude increases accordingly. At 20 D, the shear stress profiles are characterized by local maxima within the secondary jet’s development region, which increase with the Reynolds number. These distributions can be regarded as the superposition of two individual jets profiles with different amplitudes. The negative values expected in the left side of the secondary jet result to the reduction of the positive values in the stronger jet’s right side. The secondary local maximum remains, depicting the shear

![Fig. 17. Distributions of turbulent transport terms, $u^3$, $u^2v$, $v^3$ and $u^2v$, at 30 D (for symbols see Fig. 11).](image-url)
layer between the secondary jet and the surroundings. In comparison to single jet’s measurements at this distance, the maximum of the distributions is higher and displaced towards the primary jet’s central axis, indicating the spatial suppression of the primary jet, in agreement to the lateral velocity distributions. The distributions at 30 D are similar, in shape, to those of the primary jet, but, in accordance to the previously presented variables, extend in a larger area on the right side, attaining higher values. In comparison to the single jet flow field, a more active shear layer is produced, depending on the secondary jet’s Reynolds number.

Figs. 16 and 17 show the profiles of the transport terms, \( u_3 \), \( uv \), \( v_3 \) and \( u^2v \), of both test cases of interacting jets, along with the distributions of the stand alone jet at 20 and 30 D, respectively. Following the symmetry constrains discussed previously, the distributions of \( u^2 \) and \( uv \) of the stand alone jet are symmetric with respect to the central axis whereas the distributions of \( v^2 \) and \( u^2v \) are symmetric with respect to the zero value on the central axis of the jet. The peaks in these terms indicate the regions of maximum turbulent transport in the flow field.

Regarding the profiles of \( u^3 \), at 20 D the influence of the secondary jet is evident, as the distance of the right local maximum from the central axis becomes smaller, and the minimum values in the vicinity of the centerline lower. Peaks are higher compared to those observed in the stand alone jet’s measurements within the whole field, and further, increase in magnitude with the Reynolds number. The same trends appear in all the distributions of the third order terms, but, in contrast to \( u^3 \), the effect of the Reynolds number on the remaining terms is less pronounced. At 30 D, the distributions of the third order terms, although they approach a shape similar to that observed for the stand alone jet, present slightly increased maxima that increase with the Reynolds number. The distributions of \( v^3 \) are shown to be more influenced by the presence of the secondary jet, since more intensive differences are observed close to the central axis of the primary jet.

Skewness \( S = u^3/u^{3/2} \) and flatness \( F = u^4/u^{2/2} \) distributions for both the axial and lateral velocity components are presented in Figs. 18 and 19. The axial symmetry of the stand alone jet is expected to lead to distributions symmetric with respect to the vertical axis, except for the lateral component’s skewness, which is symmetric with respect to zero value point on the central axis, due to the change of sign of this velocity component.
The skewness factors of the velocity components are closely related to the corresponding terms of transport of turbulent stresses. Furthermore, they provide information regarding the symmetry of the velocity probability density function (pdf). Distributions symmetric about the mean value, such as Gaussian distributions, have zero skewness. The negative values of skewness observed close to the axis of the standalone jet, indicate a skewed pdf with a long leg on the negative fluctuations side. This attribute is related to the presence of a limited number of velocities in the time series, which are significantly lower than the mean value. It is thus plausible to surmise that entrained ambient fluid, characterized by low velocities, is reaching the center line before losing its characteristics by local mixing and diffusion. Outside the shear, layer the same reasoning explains the positive values of skewness, since in this area high velocity fluid originating from the jet is responsible for skewing the positive side of the pdf, which is dominated by the low velocity values at the edges of the jet. Within the shear layer, the balance of these effects results to symmetric pdfs and values of skewness close to zero. In the outer region, skewness values, after reaching a maximum outside the shear layer, are expected to diminish towards zero, at distances from the centerline, where the influence of the jet becomes negligible.

The presence of the secondary jet produces at 20 D (Fig. 18) a skewness distribution, where minimum negative values designate the “centerline” of each jet. It is characteristic that skewness values in the primary jet’s area are higher than those of the standalone jet, since the entrained fluid, originating from the secondary jet is “quicker”. Regarding the distribution for the single primary jet, it is interesting to note that the intermittent presence of fluid originating either from jet’s interior or the surrounding air do not affect significantly the flatness of the pdf until well outside the shear layer, where values start to increase from the normal value of three. The distributions appear to be quite sensitive to the presence of the secondary jet, whose influence penetrates deeper into the primary jet’s area as the Reynolds number increases. Similar features, indicative of the same underlying mechanisms, can be observed in the skewness and flatness distributions of the lateral velocity component.

Fig. 19 shows the distributions of skewness and flatness at 30 D. At this distance, the profiles are quite similar to those of a typical axisymmetric jet, however, in the direction of the secondary jet
zero and three values for skewness and flatness cover wider region. As the Reynolds number of the secondary jet increases, this region expands further, indicating that the flow field after jets' merging becomes wider. Despite these observations, the slope within the area of secondary jet's development in $S_p$ profiles gives the most characteristic hint that merging is not fully completed.

5. Conclusions

The interaction of two parallel axisymmetric jets with different Reynolds numbers has been studied experimentally using two-dimensional laser Doppler anemometry. Measurements conducted during the sole action of the primary jet, supported by results of other investigators, are used for reference. The influence of the secondary jet and its Reynolds number is evaluated via the terms of turbulence in the combined structure. At 15 D, the mean velocity profiles indicate that the jets are evolving almost independently. However, the turbulent normal stresses show that the features of the secondary jet have been modified, especially for the low Reynolds number. At 20 D, where the jets' merging takes place, the secondary jet influences the mean velocity distribution even within the primary jet's region. The displacement of the secondary jet location towards the primary, in accordance with its Reynolds number is also evident. Turbulent velocity statistics and correlations, along with skewness and flatness measurements, reveal a more intense flow field, as well as the spatial suppression of the primary jet features, depending on the secondary jet's Reynolds number. At 30 D the merging is completed, since most of the distributions are similar to those of a stronger and wider single jet. However, the skewness distribution of the axial velocity reflects that mixing process is not complete, even at this stage.

References