The effect of sidewalls on rectangular jets

M. Alnahhal, Th. Panidis *

Laboratory of Applied Thermodynamics, Mechanical Engineering and Aeronautics Department, University of Patras, University Campus, Rio 26504, Greece

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**A B S T R A C T**

An experimental study is presented regarding the influence of sidewalls on the turbulent free jet flow issuing from a smoothly contracting rectangular nozzle of aspect ratio 15. "Sidewalls" are two parallel plates, flush with each of the slots’ short sides, practically establishing a bounding wall extending the nozzle sidewalls in the downstream direction. Measurements of the streamwise and lateral velocity mean and turbulent characteristics have been accomplished, with an x-sensor hot wire anemometer, up to an axial distance of 35 nozzle widths, for jets with identical inlet conditions with and without sidewalls. Centreline measurements for both configurations have been collected for three Reynolds numbers, \(Re_0 = 10,000\), \(20,000\) and \(30,000\). For \(Re_0 = 20,000\) measurements in the transverse direction were collected at 13 different downstream locations in the range, \(x = 0–35\) nozzle widths, and in the spanwise direction at three different downstream locations, \(x = 2, 6\) and 25 nozzle widths.

Results indicate that, the two jet configurations (with and without sidewalls) produce statistically different flow fields. Sidewalls do not lead to the production of a 2D flow field as undulations in the spanwise mean velocity distribution indicate. They do increase the two-dimensionality of the jet increasing the longevity of 2D spanwise rollers structures formed in the initial stages of entrainment, which are responsible for the convection of longitudinal momentum towards the outer field, establishing larger streamwise mean velocities at the jet edges. In the near field, up to 25 nozzle widths, lower outward lateral velocities in the presence of the sidewalls are held responsible for the decrease of turbulent terms including rms of velocity fluctuations and Reynolds stresses. Skewness factors increase monotonically across the shear layers from negative values to positive forming sharp peaks at the outer edges of the jet, illustrative of the presence of well defined 2D roller structures in the jet with sidewalls.

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1. Introduction

The rectangular jet is one of the basic flow configurations, of importance to fundamental fluid mechanics but also of interest to many technological applications. Rectangular jets have therefore received attention over the past decades. One of the most important attributes of the jet flow is related to its ability to entrain and mix with ambient fluid. Rapid mixing is essential for efficient performance in most jet applications.

The flow field of a jet issuing from a rectangular nozzle is characterized by the presence of three distinct regions, defined by the centreline mean streamwise velocity, \(U_c\), decay [1], namely: (a) the potential core region (\(x/D = 0\) to 4–5), with almost constant \(U_c\), which ends when the two shear layers along the short dimension of the nozzle meet, (b) the two-dimensional region (\(x/D = 4–5\) to 25–30) in which the velocity decays at a rate roughly the same as that of a planar jet, and (c) the axisymmetric region, in which the velocity decays as in an axisymmetric jet, originating at \(x/D = 25–30\), the location where the two shear layers along the long dimension of the nozzle meet.

The ideal plane jet is statistically two-dimensional, in the dominant direction of the mean flow, \(x\), and the cross-stream coordinate, \(y\), whereas statistics are expected to be independent of the spanwise coordinate \(z\). A rectangular jet may approximate the behaviour of a plane jet, given that its aspect ratio, \(AR = L/D\) (where \(L\) is the long side of the nozzle in z direction and \(D\) is the short side of the nozzle in \(y\) direction) is large enough, to minimize the importance of entrainment in the spanwise direction, \(z\), and hence establish a statistically two-dimensional flow [2].

Sidewalls are two parallel plates attached to the short sides of the nozzle, practically establishing a bounding wall extending the nozzle side walls in the downstream direction of jet propagation. Many investigators (Heskstad [3], Bradbury [4], Gutmark and Wygnanski [5], and Browne et al. [6]) have emphasized on the use of the sidewalls along with the turbulent jet issuing from rectangular nozzles to force the jet to entrain only in the streamwise and lateral direction and therefore enhance the two-dimensionality of the flow. Although sidewalls have been used in many previous investigations at various initial conditions (e.g., different aspect ratio and Reynolds numbers), few experiments have been

* Corresponding author. Tel.: +30 261097242; fax: +30 2610997271. E-mail address: panidis@mech.upatras.gr (Th. Panidis).
devoted to study the effect of the sidewalls on turbulent jets issuing from rectangular nozzles [7,8]. Some of the previous investigations on rectangular jets are shown in Table 1, indicating also the usage of the sidewalls.

Experimental results of Hitchman et al. [7] (AR = 60 and Re = 7230), focusing on the differences due to the presence or absence of sidewalls, indicate that the decay rate is slower, but the spread rate is higher without sidewalls (NS). This is an interesting result since intuitively one would expect a jet, which spreads faster to also decay faster. These investigators also found that although the kinematic momentum flux is nearly conserved in a free jet (NS), it is decreasing significantly in the presence of the sidewalls (WS). One of the reviewers remarked that this behaviour may be related to the “starving jet” effect discussed by Hussein et al. [9] for jets enclosed or confined in a room.

In a recent study undertaken by Deo et al. [8] to identify the differences between rectangular jets with and without sidewalls for aspect ratio 60 and Re = 7000, based on hot wire measurements, it was found that shorter potential core lengths, higher spread and decay rates are associated with the jet without sidewalls (NS). They also observed that, the jet with sidewalls (WS) has a longer region of statistically two-dimensional behaviour.

It is worth noting that both of the above investigations have focused on the same aspect ratio (AR = 60) and similar Reynolds number (∼7000). For this large aspect ratio, the jet centreline velocity is expected to have planar jet behaviour up to a considerable

### Nomenclature

- **A1**: Spread rate constant
- **A2**: Spread virtual origin constant
- **AR**: Nozzle aspect ratio, AR = L/D
- **B1**: Decay rate constant
- **B2**: Kinematic virtual origin constant
- **D**: Width of the nozzle, m
- **L**: Long side length of the nozzle, m
- **NS**: No sidewalls
- **Re**: Reynolds number, Re = U0D/ν
- **Sv**: Skewness of the lateral velocity
- **U**: Mean streamwise velocity, m/s
- **U0**: Mean exit centreline velocity, m/s
- **Uc**: Mean streamwise velocity of the centreline, m/s
- **u’**: Root-mean-square (rms) of the fluctuating streamwise velocity, m/s
- **(u’v’)**: Turbulent transport of (u’v’) by u, m³/s³
- **(u’2)**: Turbulent transport of (u’) by u, m³/s³
- **(v’3)**: Turbulent transport of (v’) by v, m³/s³
- **(v’2)**: Turbulent transport of (v’) by u, m³/s³
- **V**: Mean lateral velocity, m/s
- **ν**: Root-mean-square (rms) of the fluctuating streamwise velocity, m/s
- **x**: Streamwise or axial coordinate, m
- **x_p**: Potential core length, m
- **y**: Lateral coordinate, m
- **y_c**: Half-velocity width in the lateral direction, m
- **z**: Spanwise coordinate, m

### Greek letter

- **ν**: Kinematic viscosity of air, m²/s

### Table 1

Jet characteristics including far field mean stream wise velocity decay, B₁ and spread rate, A₁ of the present investigation compared to other published data.

<table>
<thead>
<tr>
<th>Source</th>
<th>Aspect ratio, AR</th>
<th>Reynolds number, Re</th>
<th>Jet condition</th>
<th>Decay rate, B₁</th>
<th>Spread rate, A₁</th>
</tr>
</thead>
<tbody>
<tr>
<td>Present investigation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Krothapalli et al. [1]</td>
<td>16.7</td>
<td>12,000</td>
<td>NS</td>
<td>0.109</td>
<td></td>
</tr>
<tr>
<td>Bradbury [4]</td>
<td>47</td>
<td>30,000</td>
<td>WS</td>
<td>0.11</td>
<td></td>
</tr>
<tr>
<td>Gutmark and Wygnanski [5]</td>
<td>38</td>
<td>30,000</td>
<td>WS</td>
<td>0.10</td>
<td></td>
</tr>
<tr>
<td>Browne et al. [6]</td>
<td>19.6</td>
<td>7700</td>
<td>WS</td>
<td>0.112</td>
<td></td>
</tr>
<tr>
<td>Hitchman et al. [7]</td>
<td>60</td>
<td>7230</td>
<td>NS</td>
<td>0.106</td>
<td></td>
</tr>
<tr>
<td>Deo et al. [8]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deo et al. [22]</td>
<td>15</td>
<td>18,000</td>
<td>WS</td>
<td>0.055</td>
<td></td>
</tr>
<tr>
<td>Deo et al. [23]</td>
<td>60</td>
<td>7000</td>
<td>NS</td>
<td>0.112</td>
<td></td>
</tr>
<tr>
<td>Namer and Ötügen [24]</td>
<td>56</td>
<td>1000</td>
<td>NS</td>
<td>0.179</td>
<td></td>
</tr>
<tr>
<td>Everitt and Robins [25]</td>
<td>32</td>
<td>30,000</td>
<td>WS</td>
<td>0.11</td>
<td></td>
</tr>
</tbody>
</table>
downstream distance from the exit nozzle, whereas for rectangular jets of smaller aspect ratio a weaker planar jet behaviour may be anticipated [10]. In other words, the downstream location where the centreline velocity first assumes axisymmetric character is expected to move upstream, toward the exit of the jet, with the decrease of the aspect ratio [1,11].

The objective of the present experimental investigation is therefore, to provide information on the influence of the sidewalls on the development and mixing, in the near field (i.e., potential core) and in the two-dimensional region (i.e., self-preserving), for jets issuing from rectangular nozzles of moderate aspect ratio, \( AR = 15 \). Moreover the dependence of the sidewalls’ effect on aspect ratio can be assessed in comparison with the results of previous investigations on higher aspect ratio jets (\( AR = 60 \)) [7,8].

2. Experimental setup and procedure

The jet nozzle facility used for the present investigation (described in detail elsewhere [12]) is shown in Fig. 1. It consists of a centrifugal blower air supply system, of 1.5 kW power, used to provide the airflow to a diffuser, which decelerates the flow and converts the dynamic pressure to static in order to minimize the energy losses and preserve the uniformity of the flow field. Before reaching the nozzle, the air is passed through a settling chamber, which contains a honeycomb and five screens (1 mm square mesh, 0.3 mm diameter wire) at 5 cm spacing to reduce disturbance at the inlet of the nozzle. A honeycomb installed in the settling chamber assists the smoothing and alignment of the flow resulting to turbulence reduction. Large scale eddies break to smaller ones and the mean velocity cross variations are minimized in this section. A 2D Boerger nozzle is used to accelerate the flow. The nozzle exit is rectangular of length \( L = 300 \) mm and width \( D = 20 \) mm, with aspect ratio \( AR = L/D = 15 \).

The set up facilitated the implementation of sidewalls when needed. Sidewalls are two parallel plates made of Perspex of 5 mm thickness, 2000 mm length and 1200 mm width (see Fig. 1). Sidewalls were attached to the slot short sides extending in the axial direction, supported by a suitable frame to minimize vibration during operation.

Hot wire anemometry with a Dantec x-wire sensor, was used to conduct all the measurements. The probe was supported by a three-dimensional, traversing mechanism driven by stepper mo-
tors in order to assure smooth and accurate movements of the sensor. The x-wire sensors are 5 μm in diameter and 1 mm in length. The x-wire was calibrated at nozzle exit in comparison with Pitot tube measurements under identical inlet flow conditions with the measurements. The ambient conditions in the laboratory were isothermal at 30 °C. An overheat ratio of 1.4 was used as a good compromise avoiding thermal interference without increasing probe sensitivity to ambient temperature variations. Hot wire measurements may suffer due to calibration drift, which undermines accuracy and therefore care was taken during measurements to identify, exclude and resample pathological data sets using calibration tests before and after each measuring session. Errors estimated by means of reverse computation of calibration data were of the order of ±1.5% of \( U \) for mean velocities on the centreline, resulting in uncertainties of ±3% and ±5% for the second- and third-order velocity fluctuation statistics [13]. It has to be noted that hot wire measurements near the edge of a jet issuing into still fluid, where very small or even negative streamwise velocities may be present, should be considered with some reservation.

Both configurations were tested for three Reynolds numbers, \( Re = U_0 D / \nu = 10,000, 20,000 \) and 30,000, where \( U_0 \) is the exit velocity from the nozzle, \( D \) is the nozzle width and \( \nu \) is the kinematic viscosity of air at ambient temperature. The longitudinal turbulence intensity distribution at the nozzle exit was uniform and had a constant value of about 1%, except in the boundary layers adjacent to the nozzle lips, where the maximum value was about 3.1% for the jet with sidewalls and 3.8% for the jet without sidewalls. Streamwise velocity and lateral velocity component measurements along the centreline were conducted for all test cases, providing information about the mean and statistical properties of the flow. For \( Re = 20,000 \), transverse measurements across the jet, on the central \( xy \) plane were conducted for both configurations at 13 different distances from the jet exit (\( x / D = 0, 1, 2, 2.5, 3, 4, 5, 10, 15, 20, 25, 30 \) and 35). Measurements were also conducted for \( Re = 20,000 \) in the spanwise direction along the jet, on the central \( xz \) plane, at three different downstream locations, \( x / D = 2, 6 \) and 25.

3. Experimental findings

3.1. Mean velocity field

Mean streamwise velocity, \( U \), profiles measured along the transverse direction on the central \( xy \) plane are presented in Fig. 2, for \( Re = 20,000 \). Measurements for both cases (with no sidewalls, NS, and with sidewalls, WS) are depicted at downstream locations \( x / D = 2 \) and 3, \( x / D = 5 \) and 10 and \( x / D = 25 \) and 35 in Fig. 2a–c, respectively. Profiles are plotted as \( U / U_c \) (\( U_c \) is the streamwise mean velocity at the centreline) against \( y / y_c \) (\( y_c \) is the distance where the streamwise velocity is half of the centreline velocity at the same \( x / D \) location). Near the exit (\( x / D = 2 \)) both configurations, in accordance with previous investigations comprising smoothly contracting nozzles, produce uniform (\( U / U_c \approx 1 \)) “top-hat” mean velocity profiles. Both of the test cases exhibit similar trends at each downstream location and measurements almost collapse for most part of the distributions (\( y / y_c < 2 \)). The major difference appears at the edges of the jets where the profiles of the jet with sidewalls (WS) attain systematically larger values, except at the furthest \( x / D \) location. A similar behaviour of non zero mean streamwise velocities for \( y / y_c \geq 2 \) has been reported in investigations where sidewalls were used such as Chua and Lua [14], Davers et al. [15] and Moum et al. [16]. Chua and Lua [14] investigating rectangular jets of aspect ratio six, issuing with velocities 10 and 20 m/s into a closed cavity with an outlet, characterized this phenomenon as an “upward trend” and attributed it to the presence of the sidewalls that cause a cavity effect resulting in accelerating or reducing the deceleration of the jet.

The corresponding plots of the non-dimensional lateral mean velocity are presented in Fig. 3a–c. As expected zero values are observed at the centre at all stations, extending in a larger area at the closest to the exit locations, depicting the presence of the potential core. Maximum values of outward lateral velocities, at most 5% of the streamwise component, have been measured close to and inside of the shear layers, systematically higher for the jet without sidewalls (NS). At the outer edges of the jet negative values, indicative of inward velocities [1,17], always prevail for the jet with sidewalls (WS), whereas the jet without sidewalls (NS) presents lower negative values. Results of Krothapalli et al. [1] and Gutmark and Wygnanski [5] are included in Fig. 3c for comparison.

For further exploring the mechanisms produced by the sidewalls, the mean streamwise velocity was measured on the central

\[ \text{Fig. 3. Mean lateral wise velocity profiles on the central xy plane.} \]
xz plane at three downstream locations for both configurations at \( Re = 20,000 \). Profiles of \( U/U_c \) versus \( z/D \), where \( z \) is the spanwise axis, are shown in Fig. 4a–c for downstream locations \( x/D = 2, 6 \) and 25, respectively. Velocities on the \( xz \) plane for the jet configured without sidewalls (NS) were measured in the spanwise direction between \(-8.5 \leq z/D \leq 8.5 \) for \( x/D = 2 \) and 6 and between \(-13 \leq z/D \leq 13 \) for \( x/D = 25 \). Velocity measurements on the \( xz \) plane in the case of the jet with sidewalls (WS) span in the range \(-6.75 \leq z/D \leq 6.75 \), due to traversing system limitations. Therefore no measurements within the boundary layers developing on the sidewalls are presented. As shown in Fig. 4a at \( x/D = 2 \), both jets exhibit similar characteristics having approximately a uniform mean streamwise velocity profile. For the jet without sidewalls a rather thin shear layer is observed. At further downstream locations (\( x/D = 6 \) and 25) differences are observed between the two test cases. At \( x/D = 6 \) the distribution in the case of the jet with sidewalls presents a local minimum at the central axis and a peak close to the wall. In the case of the jet without sidewalls a local minimum is observed between the centre and the edge of the jet where a thicker shear layer is developing. At \( x/D = 25 \) both test cases present a local maximum at the centre and a local minimum in between the centre and the edges. For the jet with sidewalls the maximum of the distribution observed very close to the wall. For the jet without sidewalls the distribution reaches close to the shear layer a local maximum of the same order as the values at the centre on the wall. In this case the shear layer thickness has become comparable to the dimensions of the jet in \( z \) direction. Similar undulations of the spanwise profiles of the mean streamwise velocity, indicating that the flow field is not two-dimensional even in the presence of side walls, have been also observed in previous investigations, characterized as saddle back profiles [18–20].

The growth of the jet half-velocity width, \( y_c \), defined as the distance from the jet centreline to the point at which the mean streamwise velocity becomes half of the centreline value at the same \( x/D \) location, is shown in Fig. 5, for \( Re = 20,000 \). The measurements for both test cases in the first stages of the development almost collapse, the values of the jet without sidewalls (NS) being slightly lower, within the uncertainty limits. In the far field the values for the jet without sidewalls (NS) become clearly larger than those of the jet with sidewalls (WS), indicating a larger spreading rate. Beyond a certain distance from the jet exit the half width of a jet is expected to vary linearly with the streamwise coordinate, \( x \), the slope depending on initial and/or boundary conditions such as aspect ratio, nozzle geometry and Reynolds number [1,21–23]. This linear evolution is usually described with a relation of the form:

\[
\frac{y_c}{D} = A_1 \left( \frac{x}{D} + A_2 \right)
\]

The spread rate, \( A_1 \) and spread virtual origin, \( A_2 \) deduced from Fig. 5 for \( x/D \geq 10 \) are shown in Table 1. It is seen that the jet with no sidewalls spreads faster having a spread rate \( A_1 = 0.126 \), com-

![Fig. 4. Mean streamwise velocity profiles in the central xz plane at different downstream locations at Re = 20,000.](image-url)
pared to the jet with sidewalls, \( A_1 = 0.105 \). These findings agree with those of Deo et al. [8], in their investigation on the influence of the sidewalls on a plane jet of \( AR = 60 \) and \( Re = 7000 \), where similar trends were observed. They found that the jet without sidewalls spreads at a faster rate of 0.14 compared to 0.11 for the jet with sidewalls. Results of Deo et al. [8] are included in Fig. 5 for comparison. These findings are also in good agreement with Hitchman et al. [7] who obtained a spread rate of 0.106 for the jet without sidewalls and 0.083 for the jet with sidewalls.

The decay behaviour of the centreline mean velocity presented by \((U_0/U_c)^2\) versus \(X/D\) where \(U_0\) is the mean streamwise velocity at the exit plane, for three Reynolds numbers, \( Re = 10,000, 20,000 \) and 30,000, is shown in Fig. 6a–c, respectively. An inverse square relationship of the form \((U_0/U_c)^2 = B_1[x/D + B_2]\) is demonstrated in Fig. 6 for \(X/D\) greater than five, where \(B_1\) is a measure of the centreline mean velocity decay rate and \(B_2\) is the jet’s virtual origin, which are also depending on initial and/or boundary conditions [21–23]. These variables along with the length of the jet potential core, \(x_p\), deduced from Fig. 6 are also shown in Table 1.

At \( Re = 10,000 \) the centreline velocity of the jet with no sidewalls decays faster than that of the jet with sidewalls after the potential region, in accordance with Deo et al. [8] findings. A switch is observed at \( Re = 20,000 \) regarding the trends of the two test cases. The curves in Fig. 6b almost collapse and a scarcely discernible difference is observed in a small area after the potential core, where the centreline velocity of the jet with no sidewalls takes higher values. At \( Re = 30,000 \) the relation observed at \( Re = 10,000 \) has been completely reversed, and the centreline mean velocity of the jet with no sidewalls decays at a slower rate than in the presence of the sidewalls, in agreement with the work of Hitchman et al. [7], in which slower decay rate was associated with the jet without sidewalls. It is interesting to assess the Reynolds number-dependence on the decay rate, \( B_1 \). In the case of the jet with no sidewalls, \( B_1 \) increases from 0.121 for \( Re = 10,000 \) to 0.152 for \( Re = 20,000 \) perhaps reaching an asymptotic value, since it takes the value 0.150 for \( Re = 30,000 \). On the contrary for the case of the jet with sidewalls (WS), \( B_1 \) increases monotonically taking values 0.107, 0.149, and 0.164 for \( Re = 10,000, 20,000 \) and 30,000 respectively, indicating that \( B_1 \) in this case starting from a lower value increases at a higher pace with \( Re \) and is not reaching an asymptotic behaviour in the range considered here. The present results indicate a Reynolds dependence notably different to that found by Namer and Ötügen [24] for moderate Reynolds number jets (\( Re = 1000–7000 \)) of \( AR = 56 \) without sidewalls and Deo et al. [23] in a large range of Reynolds numbers (\( Re = 1500–57,500 \)) for jets of aspect ratios \( AR = 36 \) or 60 with sidewalls. Both these investigations indicate a decrease in \( B_1 \) as well as in \( A_1 \) with increasing Reynolds number. Taking into account the findings of Deo et al. [22] which indicate that at \( Re = 18,000 \), whereas jets of high aspect ratios (\( AR > 20 \)) decay faster as the \( AR \) is increased, lower aspect ratio jet may exhibit different trends, it is plausible to surmise that the different dependence of \( B_1 \) on Reynolds number, should be mainly attributed to the low aspect ratio of the currently presented jet and the resulting interplay between \( AR, Re \) and the effect of sidewalls.

3.2. Turbulent velocity field

At the exit plane the root-mean square (rms) of the longitudinal velocity fluctuations, \( u' \), in the shear layer was found to be 3.8% in the absence of the sidewalls, higher than the corresponding value of 3.1% found in the presence of the sidewalls. Deo et al. [8], in their investigation on the influence of the sidewalls on plane jet with aspect ratio 60 have also found that at the exit nozzle \( u' \) is 3.6% and 2.8% in the absence and presence of the sidewalls, respectively. This difference is confirming the influence of the sidewalls even on the very near flow field.

Fig. 6. Axial mean velocity decay at different Reynolds numbers.
The distributions of the root-mean square (rms) of the streamwise velocity component fluctuations for both configurations at Re = 20,000, on the central xy plane are shown in Fig. 7a–c for x/D = 2 and 3, x/D = 5 and 10 and x/D = 25 and 35, respectively. Values are non-dimensionalised by the mean streamwise velocity component at the centreline of each location and presented versus y/yc. Peak values reach ~20% of Uc, increasing slightly with the distance from the nozzle. In the early stages of development peaks are close to y/yc = 1 moving towards the centre of the jet at subsequent locations. Values at the centre are quite low in the potential zone increasing gradually downstream and reaching values close to peak values at the furthest locations measured. The measurements compare well with those of Cavo et al. [12] at Re = 21,000 for a jet with AR = 6 as shown in Fig. 7b.

In the early stages of development higher values are observed for the jet without sidewalls, especially in the shear layer and towards the edges of the jet. At 25D the distributions are very close to each other whereas further downstream at 35D the presence of the sidewalls leads to higher values at the central part of the distributions.

A major difference between the two test cases is evidenced in Fig. 9 showing that although the u' profiles for the jet without sidewalls are almost indistinguishable in the range x/D = 15–35 the profiles of the jet with sidewalls indicate a monotonic increase of the values in the central area of the jet accompanied with a displacement of the peak values location towards the centreline as x/D increases.
Similar observations hold for the lateral velocity component rms distributions presented for the same locations $x/D = 2$ and $3$, $x/D = 5$ and $10$ and $x/D = 25$ and $35$ in Fig. 8a–c, respectively. The shape and the values of the distributions are very close to those of the streamwise velocity component. In this case the value at the centre becomes the maximum of the distributions from $x/D = 10$ onwards. Higher values are observed for the jet without sidewalls even at $25D$, where the distributions coincide at the edges of the jet. At $35D$ the distributions are almost identical.

The Reynolds shear stress profiles on the central $xy$ plane at $x/D = 2$ and $3$, $x/D = 5$ and $10$ and $x/D = 20$ and $30$ are shown in Fig. 10a–c, respectively, presented by $\langle \nu \nu \rangle / U_c^2$ against $y/y_c$. The same variable non-dimensionalised by $U_c y$ and thus depicting the correlation of the fluctuations is presented in Fig. 11a–c. The presence of the lateral velocity fluctuations in this term makes it anti-symmetric, forcing zero values on the central axis. Following the trends of the velocity components’ rms distributions, peak values of the shear stress are observed close to $y/y_c = 1$ in the early stages of the development moving towards the central axis downstream. Again the distributions of the jet without sidewalls are higher until $x/D = 25$, whereas at $35D$ an inverse relationship is observed. The correlation distributions reach high values of almost $50\%$ in the area of the shear layers whereas in the outer field the two test cases present different trends.

The profiles of the triple velocity products representing the turbulent transport of the Reynolds stresses by the turbulent field are presented next. The streamwise velocity triple product $\langle u^3 \rangle$ normalised by $U_c$ on the central $xy$ plane for the two configurations are shown in Fig. 12a–c for downstream locations of $x/D = 2$ and $3$, $x/D = 5$ and $10$ and $x/D = 25$ and $35$, respectively. The corresponding distributions of the skewness factor, i.e., $\langle u^3 \rangle / u^2$ are also shown in Fig. 13a–c illustrating the underlying statistics. Close to zero values are observed at positions neighbouring to those where $u'$ attains maximum values. From these points towards the centre of the jet, values decrease reaching a negative minimum, close to the inward limit of the shear layer. In the early stages of jet development $\langle u^3 \rangle$ is increasing closer to the centreline, attaining zero values in the potential core. Further downstream at $30D$ and $100D$ the distributions reach the centreline before attaining zero value, whereas at subsequent locations ($25D$ and $35D$) the negative minimum is observed on the jet axis. From the location of maximum $u'$, the $\langle u^3 \rangle$ values increase towards the edge of the jet reaching a positive maximum outside $y$, increasing to zero at larger distances from the centreline. Maximum values in this area, generally increase with $x/D$. The jet without sidewalls presents higher positive maxima at all downstream locations except at $35D$ where it seems to have reached saturation, whereas the maximum of the jet with sidewalls is still increasing. On the negative $y$ side the distribution is symmetric to the central axis. The most characteristic attributes of skewness distributions, distinguishing the two test cases are the minor differences in the central area of the jet for the very near field locations and the sharp peaks of the jet with sidewalls at the outer edges.

The profiles of the lateral velocity triple products $\langle v^3 \rangle$ non-dimensionalized by $U_c^3$ and by $\nu v^2$ (skewness), presented in Figs. 14 and 15, respectively, follow similar trends with those of the streamwise velocity. In this case maxima in the distributions of $v'$ are associated with zero values of $\langle v^3 \rangle$, whereas symmetry properties (symmetric around $(0, 0)$ point) enforce zero values on the central axis.

The distributions of $\langle u^2 v \rangle$ presented in Fig. 16 also attain almost zero values close to locations of maximum $u'$. The trends are very similar to those of $\langle u^3 \rangle$ with two main differences. Values are significantly lower and the symmetry properties of this variable always enforce zero values on the central axis. The features of the $\langle u^2 v \rangle$ profiles presented in Fig. 17 are very similar to those of $\langle u^3 \rangle$ although amplitudes are significantly lower.

4. Discussion of the experimental findings

Sidewalls have been used in many previous investigations [4–6,22,25], in most of the cases as a plausible means to increase the two-dimensionality of the jet and generate a flow field resembling that of an infinite plane jet. This latter objective is only partly satisfied. The sidewalls indeed seem to increase the two-dimensionality, but establish distinct boundary conditions due to the shear on the wall and also impose a length scale equal to the length of the exit slot.

The entrainment mechanism dominating jet evolution is initiated by a Kelvin–Helmholtz instability of the shear layer between the jet and the ambient fluid which leads to the formation of vortices along the jet-ambient interface [26]. These vortices range from roller type linear vortices to ring vortices for the limiting cases of a 2D [27] or a round jet [28,29], whereas skew ring vortices have been observed in rectangular jets of finite aspect ratio [30]. At further stages the entrainment is dictated by the interaction (pairing) [31,32] and the instabilities developing in these vortices [17], whereas in the fully developed far field no easily identifiable structures can be found any more in the turbulent shear layers [33]. Since the jet is constantly entraining fluid, an inward transverse velocity field is established outside the edges of the jet to replace the fluid masses that have been carried away and preserve continuity [1,5].

The entrainment process is also closely related to the spreading of the jet [24]. The initial momentum is redistributed to account for
the mobilization of the entrained fluid resulting in lower velocities of the flow masses imparting momentum. Thus the original mean mass flow emanating from the nozzle along with the entrained fluid need to be constantly redistributed downstream, through an outward mean transverse velocity component within the edges of the jet, to even larger cross sectional areas.

During the initial stages while the shear layer is thin the internal jet flow remains unaffected in the potential core region. There is evidence that at this stage the shear layer has in fact a confining effect on the internal flow [26]. The mean streamwise velocity remains constant in the core region, or can even increase in a similar way that the velocity increases in the potential core in the entrance section of a pipe, to preserve continuity, due to the development of the boundary layers and the consequent mass flux reduction close to the boundaries [34]. In a jet this effect is competing with the tendency of the jet to spread and increase its effective cross section. If the spreading is not sufficiently quick the velocity may increase downstream in the potential core. Thereafter, once the long side shear layers meet at the centre of the jet, the spreading becomes dominant and the centreline velocity is decreasing downstream [24]. In the case of the jet with no sidewalls, the development of the shear layers on the short sides forces the internal fluid towards the central part of the jet. Again the jet spreading assisted by the outward increased lateral velocity component is the competing mechanism maintaining lower velocities at the central area. It is interesting that these effects have not a clear and monotonic impact on the decay and spreading characteristics [1,20,24].

Fig. 10. Reynolds shear stress profiles normalized to \( U_c \) at different downstream locations.

Fig. 11. Reynolds shear stress profiles normalized to \((\overline{u'v'})\) at different downstream locations.
The development of a jet is dictated by the interplay of the above described mechanisms which are closely related. Key parameters in this interaction are the geometry of the nozzle (including its dimensions and aspect ratio) [35], and the dynamic characteristics of the jet (including jet momentum and Reynolds number [24,25], as well as the initial boundary layers’ characteristics and the initial turbulence levels) [36]. Comparing the jet with sidewalls with the corresponding free jet the investigation is focused on the effect of the boundary layers developing on the side-walls in the first case in contrast to the short side shear layers of the latter case.

Regarding the mean flow field the most characteristic differences due to the presence of the sidewalls are the larger streamwise velocities established in the outer field (especially just after the potential region, at \( x/D = 5 \) and 10), along with the systematically smaller transverse velocities at all stations. The combination of these characteristics is rather surprising since the larger outward transverse velocities of the jet without sidewalls would be expected to transfer momentum to the outer field more effectively assisted by the larger turbulent diffusion indicated by the turbulence terms \((u',v',(uv'))\). The only mechanism capable to produce the observed differences, counter fighting those mentioned above is the convection of longitudinal momentum by 2D roller structures established more stably in the case of the jet with sidewalls. These rollers seem to constantly carry fluid from the inner field to the outer and vice versa, pumping momentum from the inner jet to the outer field, whereas the net outward flow is maintained lower than that of the free jet. In this latter case of the jet without sidewalls the shear layers developing on the sort side edges of the jet are responsible for the destruction of the 2D rollers, increasing tur-

![Fig. 12](image1.png)

![Fig. 13](image2.png)
bulence levels and decreasing the efficiency of momentum exchange by convection. The concept described above finds support in the work of Davies et al. [15] and Moum et al. [16] who have concluded that organized motions that exist in the fully developed plane turbulent jet play an important role on the spread of the flow and transport processes.

Based on the work of Grinstein [21], 3D ring like vortices can be suspected to develop at the edges of a rectangular jet. The presence of such structures is also evidenced by the undulations of the streamwise velocity profiles on the \( xz \) plane at \( x/D = 6, 25 \). The sidewalls seem to alleviate but not completely suppress these characteristics, indicating that even in the presence of sidewalls the flow field is not two-dimensional. According to Marsters [18] the saddle back shape, observed in the spanwise distributions, may be due to the pressure field associated with curved streamlines, which would have a peak value along the centreline (\( xz \) plane) in the jet flow. This centrally located high-pressure region would drive secondary flows that could move high velocity fluid from the central part to the outer ends of the flow field. Tsuchiya et al. [19] postulated that the saddle back profile is probably due to the formation of a retarded mixing region. In contrast to previous investigations the velocity undulations in the present work incorporate a lower peak at the central area of the profile.

Besides the presence of ring like structures a plausible mechanism explaining these attributes could be the instability of the jet front. The jet impulse is not sufficient to maintain a uniform velocity along the jet length. In an infinite jet the instability length scale would be dictated by the jet and fluid characteristics, and the instability effects would have been smeared out in the mean field. In rectangular jets either bounded by sidewalls or not, the length of...
the jet’s long side imposes an additional length scale. Besides the shear layers developing at the sort sides of the jet, either as a boundary layer on the sidewall or as a free shear layer entraining fluid in the unbounded case, provide specific locations for the stabilization of instability undulations. The presence of a secondary peak in the present results for higher aspect ratio jet in comparison to the clear saddle back profiles of the previous lower aspect ratio investigations is compatible with this concept.

Regarding the spreading, the results presented in Fig. 5 for $Re = 20,000$ indicate very similar behaviour for the two test cases in the first stages of development and different trends in the far field where the jet with no sidewalls spreads faster (e.g., $A_L = 0.126$ compared to $A_L = 0.105$ for the jet with sidewalls). Given that in the far field the roller structures have been destroyed even for the case of a jet with sidewalls, this effect may be attributed to the accumulated result of the higher outward transverse velocities, which eventually spread longitudinal momentum in a larger transversal area in the jet with no sidewalls [8]. The velocity decay presents a different behaviour at $Re = 20,000$. Differences in the decay rate between the two test cases are scarcely discernible just after the potential core where the centreline velocity of the jet with no sidewalls takes higher values, probably due to the confining action of the shear layers on the short sides of the jet, which lead to the relative increase of the longitudinal velocity in the central part of the jet as already discussed. It is interesting to note that the interplay of the mechanisms outlined in the previous, lead to different trends in relation to the Reynolds number. Thus at $Re = 10,000$ the centreline velocity of the jet with no sidewalls decays faster than that of the jet with sidewalls after the potential region, whereas at $Re = 30,000$ this trend is reversed.

Both components of the rms velocity present higher values in the shear layers for the case of the jet with no sidewalls in the early stages of development. This trends may be associated with the

![Fig. 16. Profiles of triple velocity product of $(u^2v^i)$ at different downstream locations.](image)

![Fig. 17. Profiles of triple velocity product of $(u^2)$ at different downstream locations.](image)
more intensive outward transverse velocity observed in these areas although they are of a more limited and progressive nature. Close to the centreline, values may also indicate a small increase of the potential core in the case of the jet with sidewalls, since both rms components increase (i.e., penetrate) at a slower pace in this area.

Adopting the dependence of the transverse pressure distribution to the lateral velocity rms component one, predicted by Tennekes and Lumley [37] based on order of magnitude analysis in developed flows, a plateau of lower pressure is established in the area within the shear layers after the potential region. Initially values are lower for the jet with no sidewalls but this relation is alleviated or even inverted downstream.

It is interesting to note that although the jet without side walls is expected to change its mode attaining three-dimensional characteristics as the short side shear layers are going to meet, it is the jet with sidewalls which is still developing in this region as the distributions of the longitudinal velocity rms depicted in Fig. 9 are indicating. Thus it can be surmised that self-similarity attributes depend also on the presence or absence of the sidewalls, besides the aspect ratio dependence suggested by Everitt and Robbins [25]. Reynolds stresses distributions support the same conclusions with those based on the rms values.

The triple velocity products represent turbulent transport of the Reynolds normal stresses by the turbulent velocities whereas the corresponding correlation is the skewness factor. The monotonic increase of the skewness factor across the shear layers from negative values to positive and especially the formation of sharp peaks at the outer edges of the jet are illustrative of the presence of well defined roller structures in the case of the jet with sidewalls. On the contrary in the free jet case the early destruction of the 2D rollers and the increase of turbulence, smooth out the sharp peaks.

5. Conclusions

The influence of sidewalls on the development of a rectangular jet of aspect ratio 15 has been studied experimentally. Jet evolution is expected to depend in general on the geometry of the nozzle (including its dimensions and aspect ratio), and the dynamic characteristics of the jet (including jet momentum and Reynolds number), as well as on the initial boundary layers’ characteristics and the initial turbulence levels. Based on these characteristics the development of a jet is determined by the interplay of several physical mechanisms which are closely related. The balance of these mechanisms is altered by the sidewalls, which modify the flow at the short sides’ edges of the jet due to the boundary layers developing on them (in contrast to the short sides’ shear layers of the free jet) resulting in distinct modifications of the characteristics of the flow field briefly recapitulated in the following.

A key difference observed in the measurements and distinguishing the two configurations (without, NS and with sidewalls, WS), at $Re = 20,000$ is the larger mean streamwise velocities established in the outer region of the jet with sidewalls (WS) in the near field, along with smaller outward lateral mean velocities. This effect has to be associated to the increased longevity, in the presence of sidewalls, of the 2D roller structures formed in the initial stages of entrainment. These structures seem to constantly carry fluid from the inner field to the outer and vice versa, pumping longitudinal momentum from the inner jet to the outer field, whereas the net outward flow is maintained lower than that of the free jet. On the contrary in the jet without sidewalls the increase of the lateral shear layers developing over the short sides of the jet is responsible for the early destruction of the 2D rollers.

The mean streamwise velocity distributions on the spanwise central plane present undulations similar to the saddle back profile shown in other investigations, which indicate that the flow field is not two-dimensional even in the presence of sidewalls. These effects could be attributed to the ring like structures developing in the shear layers or to instabilities of the jet front stabilised at the side boundaries (wall or shear layers) of the jet.

Different trends are observed regarding the spreading of the jets at $Re = 20,000$ only in the far field where the jet with no sidewalls spreads faster, probably due to the accumulated effect of the higher outward transverse velocities, which eventually spread longitudinal momentum in a larger transversal area in the jet with no sidewalls. At $Re = 10,000$ the centreline velocity of the jet with no sidewalls decays faster than that of the jet with sidewalls after the potential region, whereas at $Re = 30,000$ this trend has been reversed passing through a state at $Re = 20,000$ where differences are scarcely discernible. The present results show an increase of decay with Reynolds number increase, a trend opposite to that of other investigators who have found a decrease in decay and spreading rate with increasing Reynolds number, for higher aspect ratio jets.

Both components of the rms velocity present higher values in the shear layers for the case of the jet with no sidewalls in the early stages of development a trend which can be associated to the more intensive outward transverse velocities. Similar observations hold for the transverse velocity fluctuations and the shear stresses.

An interesting observation distinguishing the two test cases, is that although the rms distributions of the streamwise velocity assume a fully developed distribution in the range $x/D = 15–35$ for the free jet the corresponding distributions of the jet with sidewall are still developing indicating that self-similarity attributes depend also on the presence or absence of the sidewalls.

Another distinctive attribute of the jet with sidewalls is the monotonic increase of the skewness factor across the shear layers from negative values to positive and especially the formation of sharp peaks at the outer edges of the jet, illustrative of the presence of well defined 2D roller structures in the case of the jet with sidewalls, whereas in the free jet case the sharp peaks are smoothed due to the early destruction of the rollers and the increase of turbulence.

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