

# Some Measurements in Multiple Jets



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## 1 Introduction

Turbulent jets are fundamental flows which have a variety of applications (Ball et al. 2012). Conventional jets are flows that emanate from circular nozzles/orifices. There are a large numbers of studies about axisymmetric jets in the past (Lipari and Stansby 2011). The simplicity of the nozzle and its easiness to produce circular jet is one of the main reasons that attracted various experimental and computational studies.

Most of the studies on circular jets concentrate on certain characteristic properties of jets such as the velocity decay constant from inverse mean axial velocity decay, the spread rate constant from variation of half-velocity widths and entrainment rate. These experimental studies served as standard data for validation of various turbulence models. Wygnanski and Fiedler (1969) conducted some measurements in the self-preserving region of an axisymmetric jet. The measurement technique used by Panchapakesan and Lumley (1993) is flying hot-wire anemometry (FHW). This method of measurement avoids errors due to flow reversals and hence the reliability of the data produced. The data produced from the above-said method was used to calibrate third-order models. The entrainment characteristics of circular jets are reported in the experimental study conducted by Ricou and Spalding (1960).

The effects of initial conditions on a circular jet are reported by Antonia and Zhao (2001). Similarly, the effects of nozzle shaping on the near-field region and the development of axisymmetric jets were conducted by Quinn (2006). There are

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studies that report the effects of grids (various grid sizes) placed on nozzle exit and its influence on the development of jet. From the above studies, we can deduce that the initial conditions that we provide or the nozzle shaping can influence the flow downstream of nozzle (Quinn et al. 2013).

Non-circular turbulent jets are produced from nozzles/orifices that have cross-sectional shapes like square (Quinn and Militzer 1988), rectangle, triangle (Quinn 2005), ellipse (Quinn 2007), astral and cross (Quinn and Azad 2013). These nozzle/orifice shapes produce a turbulent jet that gives rise to large-scale mixing and small-scale mixing (Quinn 2005). Turbulent jets from non-circular nozzles/orifices have several advantages over the axisymmetric jets in terms of decay rate and spread rate (mixing), efficiency, noise reduction, pollution control, etc.

The flow field of turbulent jets can be altered by placing tabs at the nozzle exit. The tabs produce disturbance that propagates downstream. This is a passive method of controlling the flow field. Control of jet nozzles based on passive techniques was introduced by using lobed structures around the nozzle lip (Nastase and Meslem 2009). Lobed nozzles produce turbulent jets that are found to be efficient in mixing and have entrainment characteristics compared to other nozzles. The deflection angle of lobes in lobed jets can significantly affect the downstream flow. The reason for better mixing was found to be the production of streamwise vortices. The difficulties associated with the manufacturing of complex nozzle shapes and higher cost of the same made researchers explore multiple jets with elementary nozzle shapes for better flow modification/control.

Experimental studies on jet flows were carried out by using various techniques that include pitot-static tubes, multi-hole probes, hot-wire anemometry (HWA), particle image velocimetry (PIV) and laser Doppler anemometry (LDA). Based on the literature published on the techniques above, we can conclude that HWA is an ideal choice for jet flow measurements. The main aim of the present study is to generate first-hand information of mean axial velocity for multiple jets using pitot-static tube and differential pressure transducer.

## Nomenclature

$V, U$	Velocity ( $\text{m.s}^{-1}$ )
$E$	Voltage (volts)
$D$	Equivalent diameter (m)
$d$	Diameter of individual nozzle (m)
$dp$	Differential pressure ( $\text{N.m}^{-2}$ or Pa)
<i>Greek letters</i>	
$\rho$	Density ( $\text{kg.m}^{-3}$ )
<i>Subscripts</i>	
max	Maximum
e	Exit

## 2 Experimental Facility

### 2.1 Setup

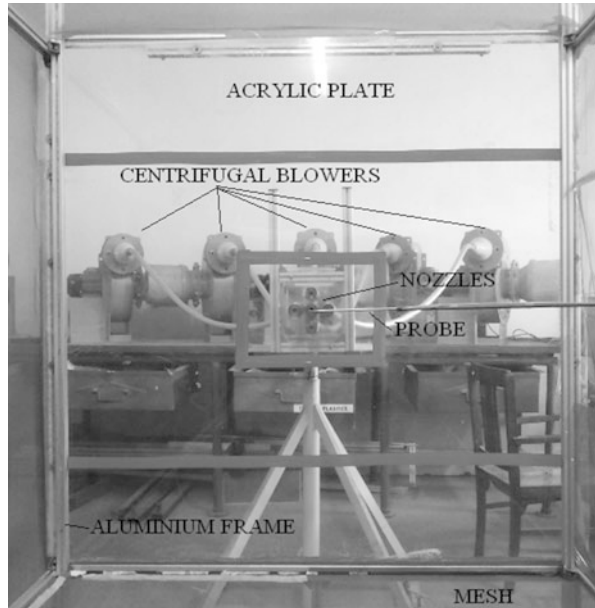
The experimental facility for jet measurements has certain requirements, which are listed below:

- Flow control – to control the velocity of air
- Large domain – to allow proper entrainment
- Prevent ambient gust from entering the domain
- Accurate positioning system

The experimental setup (refer to Fig. 1) for the present study is a blow-down type facility. This setup consists of the following items:

1. Centrifugal blowers with controllers
2. Flow conditioning units (FCU)
  - (a) Reducers
  - (b) Flexible hose
  - (c) Honeycombs
  - (d) Grids
  - (e) Nozzles
3. Measurement cage

**Fig. 1** Experimental setup for multiple jet measurements



- (a) Aluminium frame
  - (b) Mesh
4. Motion control system
- (a) Traverse
  - (b) Stepper motors
  - (c) Control drives
  - (d) Universal Motion Interface
  - (e) Motion control card (PCI)
5. Data acquisition system
- (a) Probes
  - (b) Transducers
  - (c) Converters
  - (d) DAQ cards (PCI)
6. NI Labview software tool

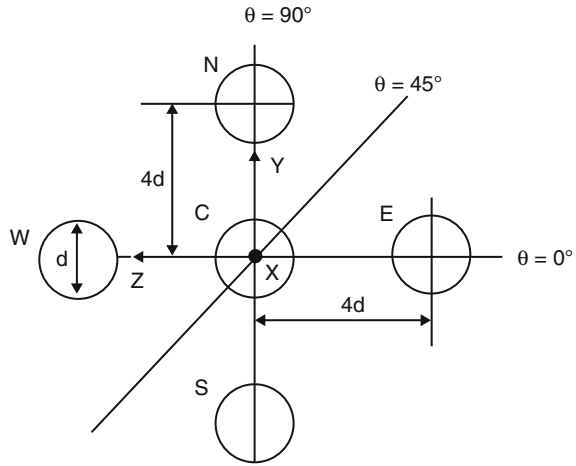
The centrifugal blowers are connected to the variable frequency drives. The outlets of the blowers are connected to the reducers. The reducer outlet is connected to the FCU through the flexible hose. The FCUs have honeycombs and meshes to reduce swirl and turbulence. The ends of the FCUs have contoured nozzles that exit in the measurement cage. The measurement cage has an acrylic plate on one end where the nozzles are placed. The lateral sides are covered by meshes to prevent atmospheric gust from entering the measurement cage, and the end opposite to the acrylic plate is open.

The probe is fixed to the positioning system and the position is controlled by stepper motors connected to control drives. The motion control drives are connected to the Universal Motion Interface, which is connected to the workstation through the PCI card. The probe used is a pitot-static tube that is connected to the differential transducer. The signal from the transducer is sent to the workstation through the BNC connector and the DAQ card.

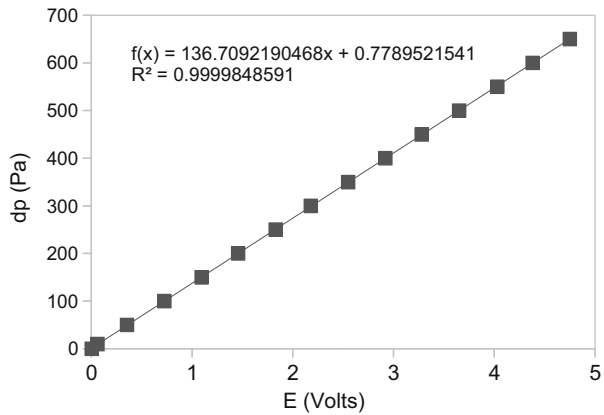
The measurement chain is controlled by a virtual instrument program created using the measurement and automation software, namely, NI Labview. The existing tools of Labview are used in a virtual instrument program to control the linear motion of the positioning system. This program also has the DAQ module that is used for data acquisition.

The schematic of nozzle arrangement is shown in Fig. 2. The nozzles are arranged such that there is a central nozzle and four surrounding nozzles. The distances between the nozzles are maintained at four times the diameter of individual jet nozzles. The spacing between the nozzles is large enough to allow jets to develop without destructing the flow structures of individual jets.

**Fig. 2** Sketch of nozzle arrangement with various details



**Fig. 3** Calibration graph for differential pressure transducer



## 2.2 Calibration of the Transducer

The pressure transducer used for measuring differential pressure has to be calibrated using a known source before using it for jet flow measurements. Hence, we connected a syringe and a calibrated digital manometer on either side of the differential transducer. By applying pressure in the syringe, the voltage from the differential pressure transducer and the corresponding pressure from the calibrated digital manometer are noted. The above procedure is repeated for the required jet measurement range. The values of differential pressure are plotted against the indicated voltage. The slope of the curve gives the calibration constant (Fig. 3).

The formulas for differential pressure and velocity are given as below.

$$dp = 136.7 \times E \quad (1)$$

and

$$V = \sqrt{\left(\frac{2 \times dp}{\rho}\right)} \quad (2)$$

During measurements, the differential pressure is obtained as voltage. The voltage is converted into velocity based on the above formulas.

### 2.3 Validation for Single Round Jet

To know the validity of our experimental setup, we performed mean velocity measurements of a single round jet at a Reynolds number of 11,000 to compare with the previously published experimental results. The measurements of mean axial velocity along the geometric centreline and the radial profile were made.

The mean axial velocity is made non-dimensional with the exit velocity of the jet and inverse of the same is plotted along the centreline. Figure 4 shows the validation of a single round jet for inverse mean axial velocity decay. The present experimental data is compared with the experimental results of Quinn and Azad (2013) and Panchapakesan and Lumley (1993). It is to be noted that the former experimental results are from stationary hot-wire for a Reynolds number of  $1.7 \times 10^5$  and the latter are from flying hot-wire for a Reynolds number of 11,000. The present measurements match well with the experimental results of Quinn and Azad (2013). The experimental data is also compared with the numerical simulations performed using the standard k-epsilon turbulence model. The simulated results overpredict the decay rate but preserve the linear behaviour in the far-field region (Fig. 5).

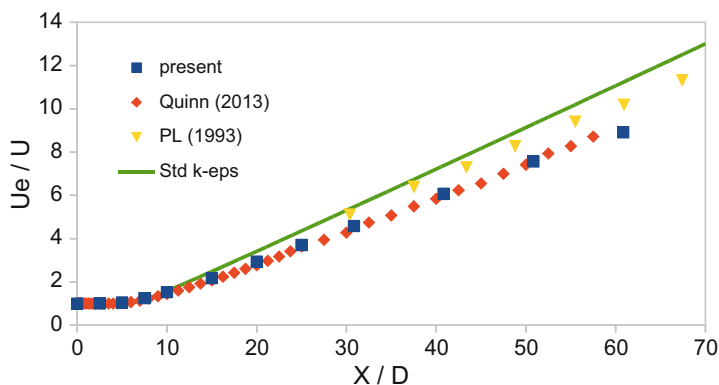
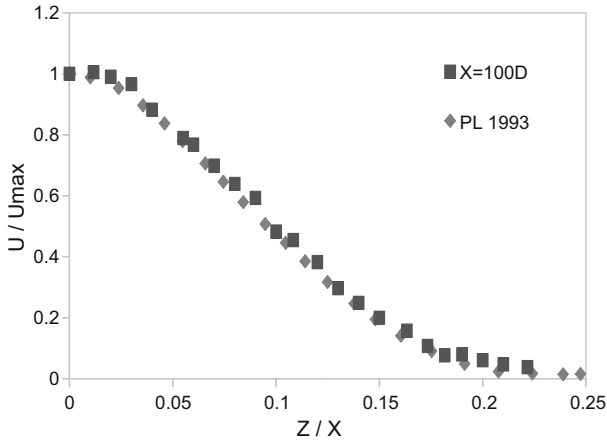


Fig. 4 Inverse mean axial velocity decay for a single round jet



**Fig. 5** Validation plot showing the mean axial velocity profile

Figure 5 shows the comparison of the mean axial velocity profile of a single round jet along a radial line from the jet axis in the self-similar region. The plot shows that the present experimental data is in good agreement with the previously published experimental data.

### 3 Multiple Jet Measurements

The measurements for multiple jets are carried out at a Reynolds number of 25,000 based on the equivalent diameter. The flow configuration considered for the present study consists of five jet nozzles exiting in a semi-infinite plane, i.e., the acrylic plate. The cases considered are from a single jet to five jets arranged in a particular fashion. For multiple jet cases, the unused nozzles are sealed with scotch tape to prevent air from being entrained from those nozzles. The initial conditions, equivalent diameters and nozzles used for various cases in multiple jet measurements are listed in the following table (Table 1).

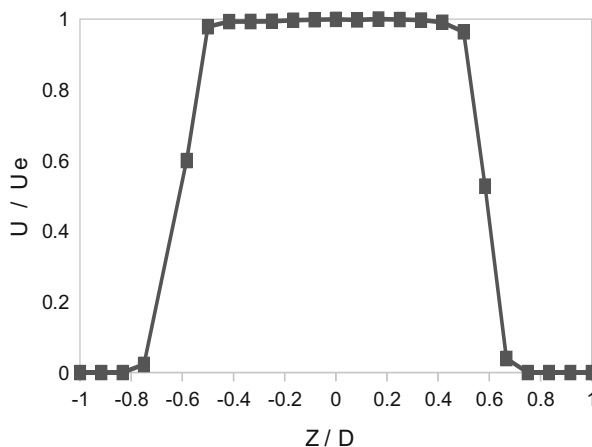
The velocity measurements are carried out from a location downstream the nozzle to avoid blockage effect. The exit velocities are measured from the location which is half the diameter of individual round jet. The nozzles have a contoured profile which provides uniform or top-hat velocity distribution across the nozzle diameter. A typical velocity profile measured for a single jet case is shown in Fig. 6.

The figure shows uniform velocity across the middle span and a steep gradient around the edges. We can predict that the velocity profile at the nozzle exit will be uniform. Hot-wire measurements can be made very close to the nozzle exit to confirm the uniformity of the velocity profile and also to get intensity distribution. The measurements of mean axial velocity are made along the centreline and along the radial line in a horizontal plane for multiple jet cases.

**Table 1** Initial conditions and details for multiple jets

Case	Nozzles used	Diameter (m)	Velocity (m/s)
1	C	0.012	32.10
2	W & C	0.017	22.70
3	W, C & E	0.020	18.53
4	N, W, S & E	0.024	16.00
5	N, W, S, E & C	0.027	14.36

**Fig. 6** A typical velocity profile at location  $X/D = 0.5$  from nozzle exit



## 4 Results and Discussions

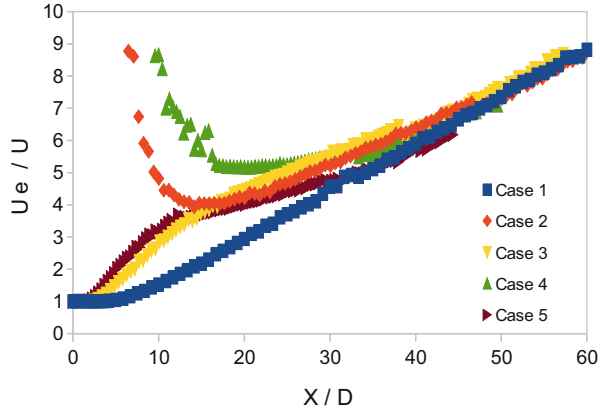
### 4.1 Inverse Mean Axial Velocity Decay

The mean axial velocity is made non-dimensional with the nozzle exit velocity. The axial distance is made non-dimensional with the equivalent diameter for every case. The inverse of the abovesaid non-dimensional mean axial velocity for all the cases is plotted against the non-dimensional axial distance along the geometric centreline. The inverse mean velocity decay for all the five cases is compared in the following figure (Fig. 7).

The inverse mean velocity decay of a single jet is linear outside the potential core. The multiple jets show non-linear decay in the near-field region, i.e., outside the potential core region. The configurations with central jets, i.e., cases 3 and 5, have some similarity. Similarly, the configurations without central jets, like cases 2 and 4, have some similarity. The axial velocity of cases 3 and 5 decays faster compared with single jets just outside the potential core and then slows down. Finally, these jets grow like an equivalent single jet in the far-field region. The jets from cases 2 and 4 do not have flow from the wall located between the nozzles. Hence, the inverse of mean velocity decays from infinity towards becoming like an equivalent single jet. In this region, the entrainment of jets creates a flow that grows to behave like an equivalent single round jet.



**Fig. 7** Comparison of inverse mean axial velocity decay



### 4.2 Velocity Profiles

The profiles of mean axial velocity are measured along the radial line in the horizontal plane, i.e., along the ‘0’ degree line. Strictly one should measure axial velocity profiles along radial lines inclined at various angles from 0 to 360 in order to study the multiple jet evolution at various downstream locations. But due to the symmetry and long measurement durations, we have considered only one radial line for the present study. Another reason for measuring along this line is that the ‘0’ degree line behaves like a major axis for some cases. The axial mean velocity profiles for multiple jet cases are plotted at various axial downstream locations and also for various cases. Case 1 has been validated using the previously published data in the previous section. So, in this section, only multiple jet cases will be discussed in detail. The mean axial velocity profiles for case 2 are plotted as below (Fig. 8).

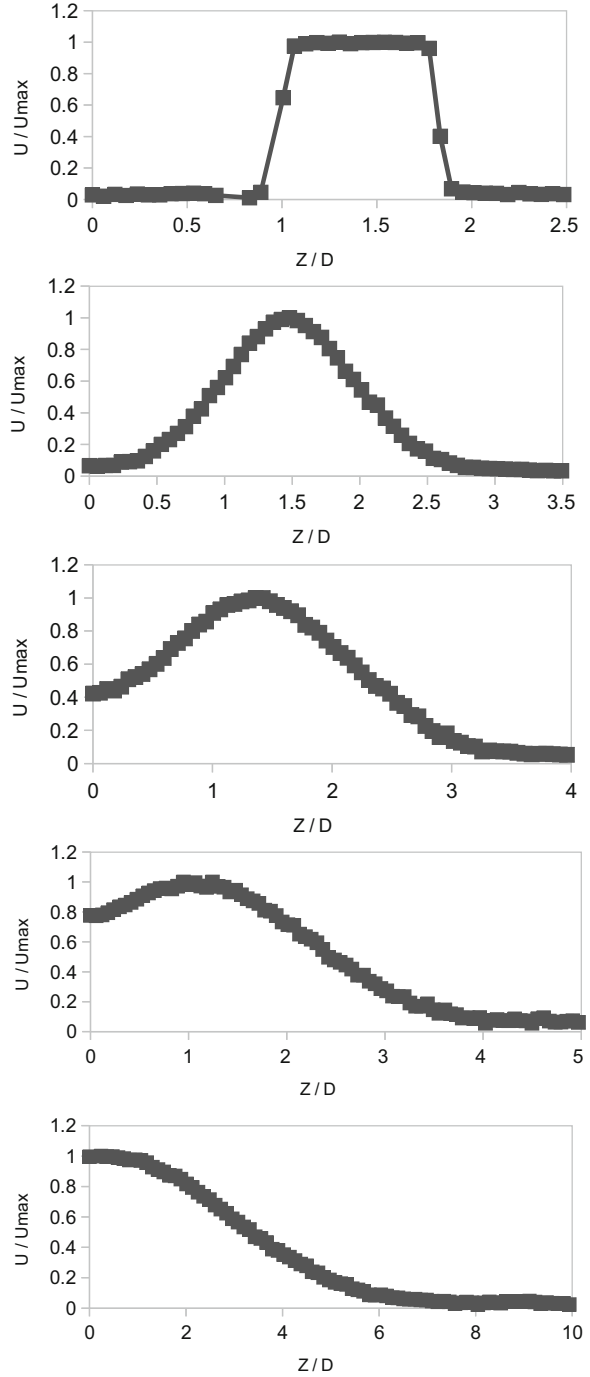
The velocity profiles for the second case indicates the merging phenomenon of individual jets within 20D. Around 30D, the merged jets grow as a single jet. The merging region shows the shifting of peaks towards the geometric centreline. The plots are the mean axial velocity profiles for case 3. This case also shows similar behaviour of merging and combined growth (Fig. 9).

The mean axial velocity profiles for case 4 are plotted below (Fig. 10).

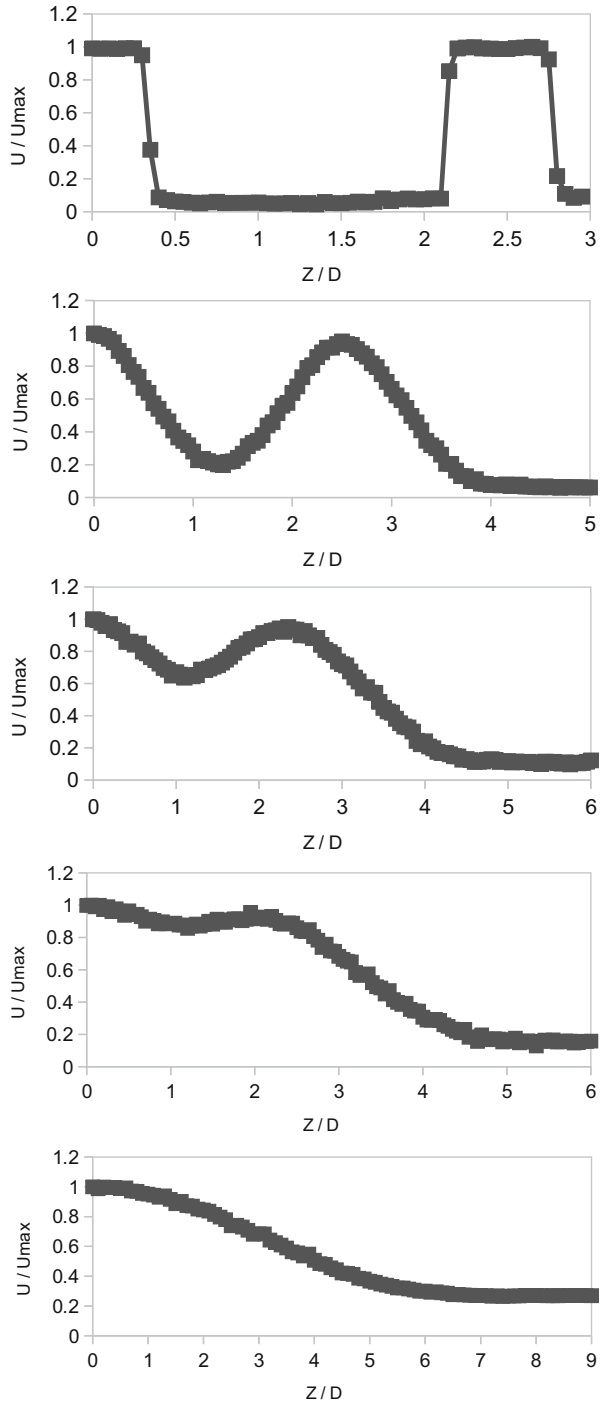
The axial mean velocity profiles for case 5 are plotted below. The mean axial velocity profile plots shows that all multiple jets considered in the present study show the merging of individual jets and combined jet growth phenomenon (Fig. 11).

The velocity profiles plotted for cases 2 and 4 are found similar but case 2 has a pronounced peak around 15D. Cases 3 and 5 are found to have similar velocity profiles, whereas case 3 has a pronounced peak around 15D. It is also to be noted that the peak due to the central jet has a higher value than peaks formed by side jets and it is clearly found in case 3. The jet nozzles of case 3 are in a linear arrangement but case 5 has four side jets surrounding the central jet. The side jets in case 5 can easily adjust themselves to make a circular profile like a single round jet. The side jets of case 3 initially create a profile like an elliptical jet because of their linear

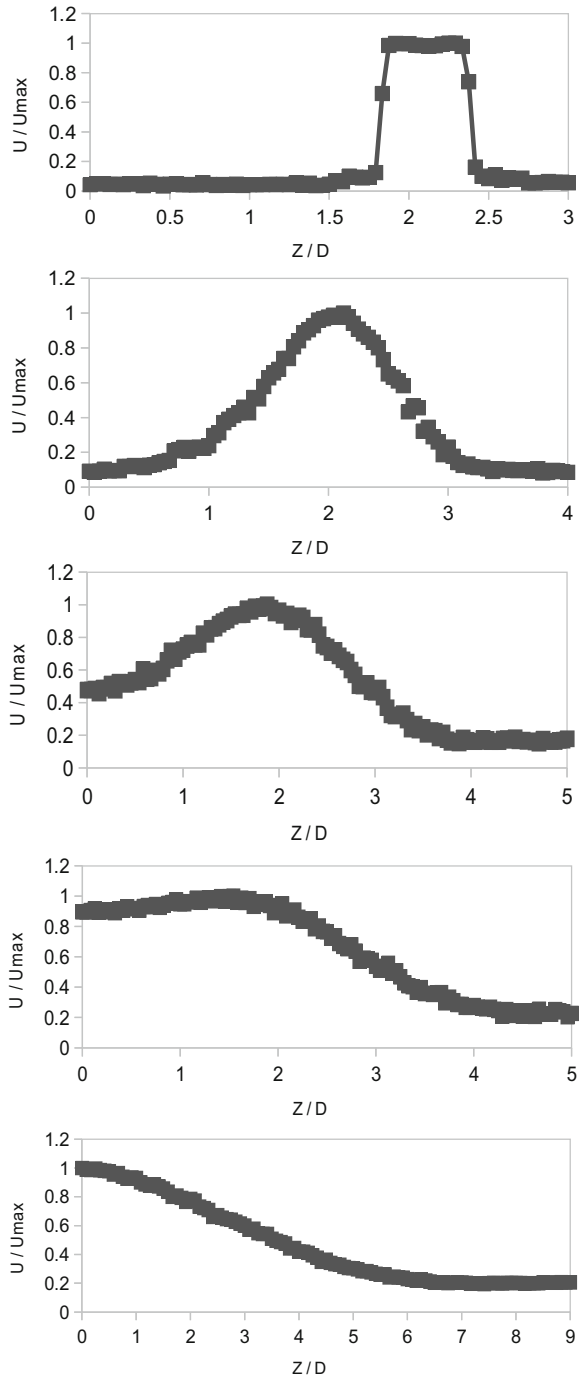
**Fig. 8** Mean axial velocity profiles for case 2 at various downstream locations (0.5d, 5D, 10D, 15D and 30D)



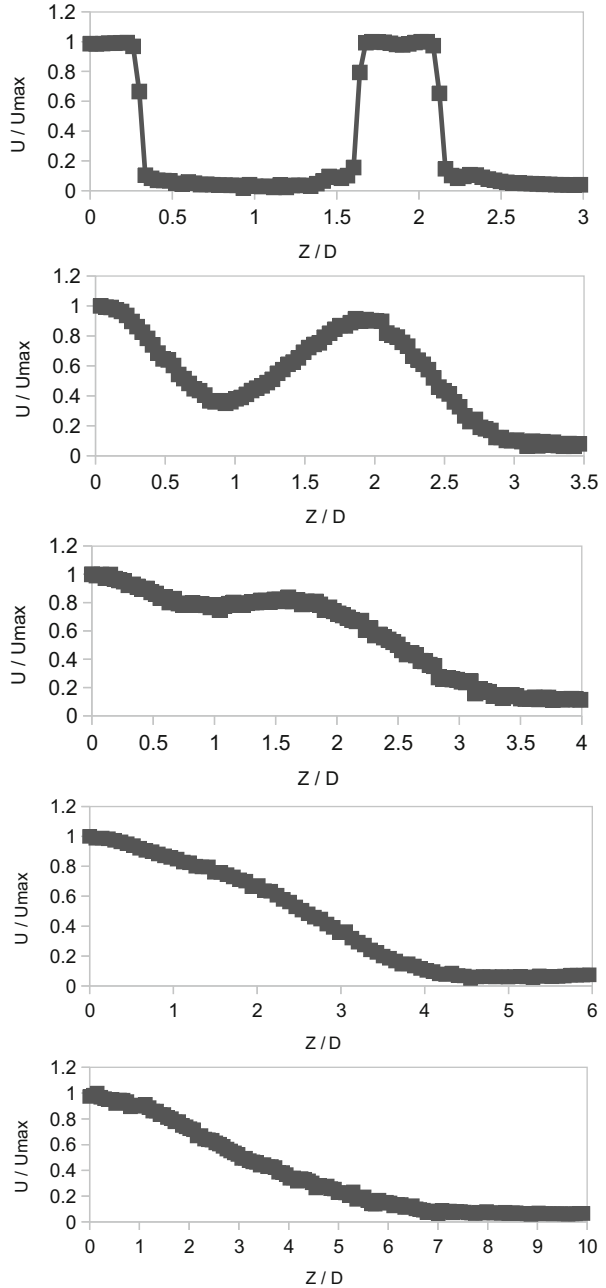
**Fig. 9** Mean axial velocity profiles for case 3 at various downstream locations (0.5d, 5D, 10D, 15D and 30D)



**Fig. 10** Mean axial velocity profiles for case 4 at various downstream locations (0.5d, 5D, 10D, 15D and 30D)



**Fig. 11** Mean axial velocity profiles for case 5 at various downstream locations (0.5d, 5D, 10D, 15D and 30D)



arrangement and then become like a single circular jet as it evolves further downstream. The far-field region measurements can provide details whether multiple jets have self-similarity or not. Also they can deduce where multiple jets behave like a single jet.

## 5 Conclusions

The mean velocity measurements for multiple jets are reported in the above study. The main conclusions are listed as below.

- The inverse mean axial velocity decay shows the non-linear behaviour of multiple jets in the near-field region.
- The profiles of measured mean velocity show jet merger and combined growth.
- The presence/absence of central jet plays a vital role in multiple jet flow evolution.

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