A Review of Effects of Initial and Boundary Conditions on Turbulent Jets

ADEL ABDEL-RAHMAN
Department of Mechanical Engineering
Beirut Arab University (BAU)
Beirut, P.O.B: 11-5020
LEBANON
a.abdelrahman@bau.edu.lb

Abstract: - On the basis of available knowledge, it is shown that different mechanisms may have control in different jet flows or in different regions of a jet flow. In free jet flows, the downstream region is dominated by turbulence structure whereas coherent eddy-structure can have a strong influence on the near field, particularly for low-Reynolds number jet flows. At present, however, it has become a common belief that coherent-eddy structures determine, to a large degree, the evolution and dynamics of turbulent jet flows. The following article is an attempt to review the current information on round turbulent jet flows. In so doing, the influence of the jet origin (initial conditions) and the boundary conditions (presence or absence of endplate, side walls, and/or jet enclosure) on the jet flow structure is considered.

Key-Words: - Jets, Turbulent jets, Jet initial conditions, Jet structure, Coherent structure

1 Introduction

Turbulent jet flows are encountered in a variety of engineering applications including combustion, chemical processes, pollutant discharge, and cooling, mixing and drying processes. Jets have played a key role in turbulent research since the early work of Liepmann and Laufer [1]. Measurements of mean and turbulent flow fields have provided insight into the physics and served as a testbed for turbulent models. Interest has been primarily focused in the self-similar region since the theoretical problem becomes more tractable and ideally all jets will asymptotically approach this state.

It is now accepted that the evolution and behavior of any shear flow may be controlled by coherent structures, which are of varying size and are responsible for the energy exchange between the mean flow and the turbulence, especially in the near-field region of a jet. Their evolution and interaction creates a complex three-dimensional flow field that eventually evolves to a self-similar state in the far-field. In spite of numerous experimental investigations of turbulent jet flows, many aspects of the flow remain unexplored because of the difficulty of accurately predicting the interaction of flow structures.

2 Free Jets

The simplest forms of jets are those where the mean flow can be characterized by two spatial independent variables and include the plane and round jets. In the seventies, interest has been mainly focused in the downstream (self-similar) region of the jet flow since all jets will eventually approach this state and the theoretical nature of the flow becomes simpler. Moreover, in the eighties, the picture reflected that the plane jet has been more investigated than the round jet, probably owing to its slower rate of mean velocity decay which has led to measurements at downstream distances in excess of 1000 slot widths; this is in contrast to round jets where measurements have been confined to downstream distances less than 120 diameters. Nowadays, however, the picture is different where both jet flows are receiving equal attention from investigators. This is likely due to advances in measurement techniques, as well as signal processing and analysis.

The round free jet, shown schematically in Fig. 1, is part of a large family of free shear flows, which include wakes and mixing layers. The boundary in the figure represents the outer ‘‘edge” of the shear layer between the jet flow and the stagnant surrounding fluid.

There are three different regions that can be defined in the round jet: the near-field, the intermediate-field and the far-field. The near-field region (often referred to as that region that contains the potential core) is where the flow characteristics match those of the nozzle-exit, and is usually found within $0 \le x/d \le 6$. The far-field region, located at approximately x/d ≥ 30, [2], is the fully-developed or self-similar region. The intermediate-field region lies between the near- and far-fields of the jet. The near- and intermediate-fields together comprise the development portion of the jet, where it often dominates practical applications of jets for which upstream conditions can significantly influence heat, mass, and momentum transfer. Therefore, the ability to control the flow development in this region would have a vital impact on many of those engineering applications. In the shear layer vortex cores will form, evolve and pair-up to form large eddies because of the large velocity gradient in the radial direction. These large eddies break down and form smaller and smaller eddies, and the turbulence structures decrease in scale. Throughout this process, energy is transferred from the large-scale structures to the smaller scales in the outer layer. It is noteworthy here that the regular vortex formation and pairing processes are important for the mixing and entrainment of the surrounding medium, where it should be emphasized that the thicker the initial shear layer, the weaker the vortex formation it gets.

From available knowledge in the literature, research work on the jet flow may be mainly categorized into two streams; one stream is directed to the study of the jet flow structure, particularly in the far, self-similar region. The other stream is directed to the study of the influence of the flow at the jet origin, often termed initial conditions, on the jet flow; particularly in the near and intermediate regions. The initial conditions of a jet are conventionally defined to be the exit Reynolds number, nature of exit profiles of mean velocity and turbulence intensity, nozzle-exit geometric profiles, and aspect ratio (noncircular jets). The downstream development of a jet is also dependent on the boundary conditions, e.g., the presence or absence of a screen enclosure around the jet flow and/or a wall setting flush at the nozzle exit plane and the conditions of the surrounding environment; such as: background turbulence and large-scale motions (draughts) that may exist in the laboratory environment. Moreover, some recent attention has moved to the near-exit flow field to study the effects of mixing due to large-scale vortical structures (e.g., [3] and [4]) after it has become a common belief that coherent-eddy structures determine, to a large degree, the evolution and dynamics of turbulent jet flows. The existence of such large-scale vortical structures in the near-exit field has been recognized for some time (see, for example, [5] and [6]).

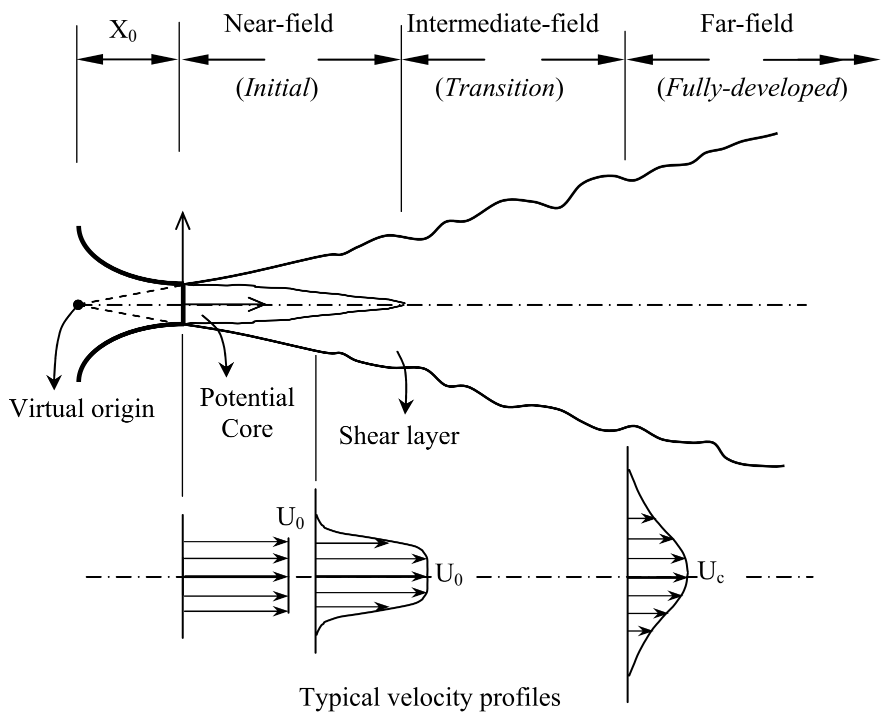


Fig. 1. Schematic of the free turbulent jet and coordinate system

The far-field of the jet has been extensively studied ([7]-[14]). In spite of the large number of studies on the far-field, there are conflicting results regarding the universal self similarity. Dowling and Dimotakis [10], Pitts [15] , Richards and Pitts [12] and Antonia and Zhao [16] support the hypothesis of universal self-similarity. They showed that the self similar-region is independent of the initial conditions. In other words, the spread rates of all jets are universal and the asymptotic normalized scalar and velocity fields of all jets are identical, regardless of jet initial conditions.

Other studies claim that the self-similar region is not universal, but it depends on the initial conditions, especially George [9]. In contrast to the classical treatment of Hinze [17], in a theoretical analysis it is suggested by George [9] that turbulent flows can become asymptotic to a variety of self-similar states that are determined by initial conditions. With respect to both passive scalar and vector quantities, there have been significant efforts to clarify the classical hypothesis of universal similarity and to reconcile it with the analytical result of George [9]. Review articles on self-similarity of the scalar field provide inconsistent results. For example, the conclusions of Richards & Pitts [12] support the hypothesis of universal self-similarity of a jet flow; the asymptotic state of the scalar field (as characterised by mean spreading rate, centreline mean decay rate, and locally normalised r.m.s fluctuations) has minimal dependence on initial conditions. Meanwhile, Dowling & Dimotakis [10] found a Reynolds number dependence of the far-field decay rate of the mean concentration field and the radial distribution of the r.m.s. concentration fluctuations. In a comparison of flow from an axisymmetric jet (Re = 16, 000) with two different initial conditions, Mi *et al.* [18] examined the flow field over $0 < x/D < 70$ to verify the analytical result of George [9]. By comparing two jet flows (one with a top-hat, the other with a fully-developed pipe flow initial conditions), it was confirmed that turbulent scalar properties throughout the jet flow are dependent on initial conditions. Furthermore, they re-affirmed that a universal asymptotic state of turbulence, independent of initial conditions, is unlikely to exist. In a direct numerical simulation (DNS) of a round jet (Re = 2, 400), Boersma *et al.* [19] found that different nozzle exit conditions would affect the mean and fluctuating velocities, thus supporting the hypothesis of George [9]. Another support to George's analytical result was given by Ferdman *et al.* [20] who investigated the effect of initial mean velocity profiles on downstream mean and turbulent statistics. From their results, it was found that the far-field decay rates of the pipe-jets are less than those with initial top-hat velocity profiles. A similar finding was provided by Xu and Antonia [21], where they compared the characteristics of a jet from a smooth-contraction nozzle (top-hat velocity profile) to a jet from a pipe (fully-developed turbulent velocity profile). It was found that the smooth-contraction jet reached the self-similarity state more rapidly than the pipe jet. This is, likely, due to the weak formation of vortical structure in the near-exit of the pipe-jet case. Actually, and as pointed out by the authors, the vortical structure which enhances both the entrainment and mixing processes was absent in the pipe-jet case. Also, Uddin and Pollard [14] from their study on the co-flowing jet flow, concluded that the mean statistics do not appear to depend on initial conditions, but turbulence statistics significantly do.

In a recent article, George and Davidson [22] wrote, "*one of the most persistent ideas of turbulence research is that turbulence forgets its initial conditions*". They showed that mean velocity profiles of simple free shear flows collapse to the same curve when plotted using a velocity scale and an appropriately defined length scale. This collapse, they said, doesn't necessary mean independence of the initial conditions, rather it does indicate to the streamwise dependence of the normalizing scales, which is different for different experiments. They briefed by stating that the initial conditions show up in the spread rate and other coefficients. It is worth mentioning here that a literature survey by Kotsovinos [23] shows the existence of scatter in the values of spread rate measured in plane jets. The measured spread rates were seen to increase with the streamwise distance, in contrast to the expected constant value consistent with self-similarity. This should not be surprising since the experimental conditions are usually different for different experiments. However, Kotsovinos attributed such scatter to the influence of probable draughts induced by the jet laboratory-arrangement, and the background turbulence intensity, both difficult to avoid in practice.

A scatter similar to that shown in [23], in the values of spread rate measured in plane jets, exists for round jets (see table 1). Table 1 provides the decay rate parameter, spread rate parameter and the virtual origin for a number of round jet investigations in the literature, together with the reported initial and experimental conditions. The scatter in the values of the measured parameters, seen from table 1, can not possibly be attributed to the experimental uncertainties. Indeed, at least partly, these differences in the measured values are because of initial, experimental, and/or boundary conditions which are normally different from one experimental investigation to another. Recently, for example, Mi and Nathan [24] stated that the magnitudes of the mean-velocity decay parameter and virtual origin location depend on the jet exit conditions. The scatter seen from the table reflects the effect of all such conditions, combined, on the measured values (A, d, xo) in round jets. It should be pointed out that the assessment of the effect of one condition, independent of the others, seems far impossible. However, the information in table 1 agrees with the concluding remark, made by George and Davidson [22], that the initial (as well as boundary and experimental) conditions appear to control the spread rate and scaling parameters and the other moments profiles.

In the following sections, the available literature is surveyed and reviewed with the objective of highlighting the effects of both the initial and boundary conditions on the jet evolution and behavior.

2.1 Effect of initial conditions

2.1.1 Exit Reynolds number

In the eighties and nineties, research activity on the low Reynolds number jet flow was limited (see, for example, Abdel-Rahman et al.[25] and Fellouah et al.[26]). The beginning of modern investigations of the Reynolds number effect on round jets goes back to Ricou and Spalding [27]. They noted that as the Re number increased from 20,000 and beyond, the entrainment in the jet was constant. Nowadays, however, there appears to be numerous studies available on the influence of Reynolds number on jet flows and/or on the low-Reynolds number jets (e.g.; [3], [26], [28] - [33]).

The documented publications on jet flows seem to agree that if the Reynolds number at the jet exit is greater than a few thousand, the radial spread of the mean velocity field and the decay of the mean centerline velocity in the downstream direction are independent of Reynolds number. Further, if Reynolds number is less than 30, the jet is laminar, normally called "dissipated laminar jet". For Reynolds number greater than 500, the jet has a laminar length after which it becomes turbulent. This laminar length decreases with increasing Reynolds number. However, for Reynolds number greater than about 2000, the jet becomes turbulent very close to the exit as, for example, shown in Fig. 2 and [34], with the spread rate of the jet becoming constant.

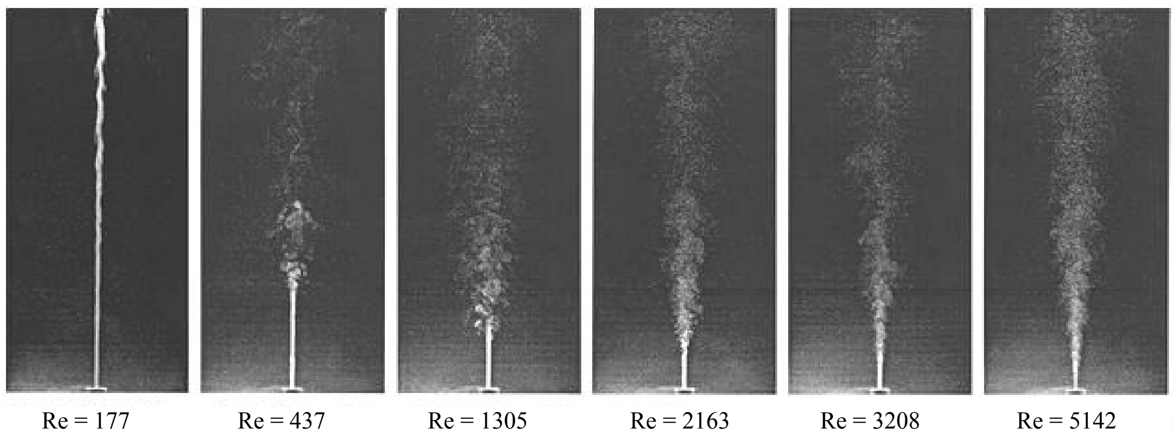


Fig. 2. Evolution of the round jet with increasing Reynolds Number [34]

The mean flow in the near-field (up to 10 nozzle exit diameters) of round jets at two moderate Reynolds numbers; 13000 and 22000 has been studied by [35], where the main objective was to investigate the effect of the nozzle geometry, rather than exit Reynolds number, on the jet behavior. However, it was reported that entrainment for each nozzle studied was found independent of the exit Reynolds number. This is in agreement with [27] where it was shown that the entrainment coefficient decreases with Reynolds number up to a Reynolds number of 10,000 beyond which the entrainment coefficient takes a constant value. It is to be noted here that the same conclusion on the entrainment by the jet flow, but for the plane (slot) jet was made by Subramanian and Makhijani [36].

Oosthuizen [37] has undertaken an experimental study on isothermal jets, having a wide range of exit

Reynolds numbers (Re = 1500 to 15000). Significant variations of all measured quantities at Reynolds number of 5000 and lower have been reported. The decay of centerline velocity and radial spread of velocity field were shown to increase as Reynolds number decreases. Rajaratnam and Flint – Petersen [38] investigated the variation of the spread rate of circular jets with Reynolds number. They found that the spread rate decreases continuously with Reynolds number, reaching an asymptotic value of 0.16 at Re = 10,000. Apparently, the asymptotic spread rate value of 0.16 obtained by the authors is higher than that for a high Reynolds number jet (= 0.09). The reason for this difference is not clear, as already pointed out by the authors.

Sami et al. [39] have investigated experimentally the turbulent structure in the developing region, up to 10 nozzle exit diameters, of an air jet issuing from a short nozzle, but for a relatively high Reynolds number of 22 x 10^4. They measured all turbulent and mean flow quantities. They have found that the maximum turbulent intensity occur for the station of x/d=6; approximately at the end of the potential core. Albertson et al. [40] have derived analytical expressions for the mean flow characteristics of slot and round jets. They have also presented experimental data which justified their analytical work. The Reynolds number in their study was high (ranged between 2.2 x 10^4 and 5.3 x 10^4). They have reported a velocity decay constant of 6.2 along the jet axis for the jet developing region. This pioneer value is still the most reliable and recommended value, [41].

Lemieux and Oosthuizen [42] and Outgan and Namer [43] have carried out two similar experimental studies on the low Reynolds number jet, but for the plane case. Both studies have reported variations in all measured jet quantities, albeit not monotonic, with Reynolds number. The asymptotic behavior of the jet flow was reached at Reynolds number of 6000.

Abdel-Rahman et. al [25] investigated experimentally the effect of Reynolds number at the jet exit on the near-field region (up to 10d) of a round turbulent air jet using a LDA system. Measurements were performed for a number of jet-flow cases, having exit Reynolds numbers in the range of 1400 to 20000. The decay of centerline mean velocity of the jet was found to increase as exit Reynolds number decreased (see Fig. 3). This was attributed to the enhanced mixing and interaction with the surrounding environment due to the vortex structure which gets enhanced with decreased Reynolds number. They also showed (Fig. 4) that there is greater energy at the high frequencies with increasing Reynolds number. Since these high frequencies correspond to smaller eddies, thus, the figure demonstrates that smaller eddies appear at higher Reynolds number which is consistent with the notion of increased vortex stretching at higher Reynolds number. Matsuda and Sakakibara [3] used a stereo particle image velocimetry (stereo-PIV) system to visualise turbulent vortical structures ($20 \leq x/d \leq 50$) over a Reynolds number range of Re_d = 1500–5000, based on the nozzle exit diameter. In this Reynolds number range and in the region considered, there was a Reynolds number dependence on the shear stress distributions. Flow visualisation showed hairpin vortices and vortex strings. The typical spacing between the legs of the hairpin was independent of the Reynolds number. O'Niell et al. [33] used Multigrid cross-correlation digital particle image velocimetry (MCCDPIV) to investigate the stability and structure of low Reynolds number axisymmetric jets. The in-plane velocities, out-of - plane vorticity and some of the components of the Reynolds stress tensor are measured. Two Reynolds numbers based on the orifice outlet diameter are examined (680 and 1,030) at two different positions: one close to the orifice, ranging from 2d to 5d (d is the orifice diameter); and the other farther from the orifice, ranging from 10d to 14.4d (Fig. 5). The results showed that the lower Reynolds number jet (Re=680) was marginally unstable in the near-orifice region and was described as laminar. Further downstream, some intermittent structures were observed in the jet, and the growth in integrated turbulent kinetic energy with axial position indicates that the jet is also unstable in this region. For the higher Reynolds number jet (Re=1030) the increasing size and intensity of vortical structures in the jet in the near-orifice region observed from the MCCDPIV data and the growth in integrated turbulent kinetic energy indicate that the jet is unstable. Further downstream this jet is best described as transitional or turbulent. From flow visualization images in the near-orifice region it seems that, for both Reynolds numbers, shear layer roll-up occurs when the jet exits the orifice and enters the quiescent fluid in the tank, resulting in vortical structures that appear to grow as the jet proceeds. This is indicative of instability in both cases and is consistent with previous flow visualization studies of low Reynolds number round jets. On the basis of flow visualization results they generally assumed that round jets are unstable at very low Reynolds number.

TABLE 1 Decay and Spread Rates

Authors	Working fluid	Measurement Technique	Nozzle type	Re	Endplate	x/d	x_o/d	A	b
Wygnanski and Fiedler, 1969	air	HW	Contoured	864000	No	>50	7	5.0	
Wygnanski and Fiedler, 1969	air	HW	Contoured	864000	No	<50	3	5.7	
Quinn, 2006	air	HW	Contoured	184000	Yes	18-55	3.65	6.1	
Burattini et al., 2005	air	HW	Contoured	130000	No	>30	4.4	6	
Hussein et al., 1994	air	FHW and LDA	Contoured	100000	No	30-120	2.7	5.9	0.095
Panchapakesan And Lumley, 1993	air	SHW	Contoured	95500	No	15-100		5.9	0.102
Panchapakesan And Lumley, 1993	air	LDA	Contoured	95500	No	70-120		5.8	0.094
Xu and Antonia, 2002	air	X-wire	Contoured	86000	No	20-75	3.7	5.6	0.095
Fellouah et al., 2009	air	SHW and FHW	Contoured	6000-30000	No	15–29	2.5	5.59	
Weisgraber and Liepmann, 1998	water	DPIV	Contoured	16000	No	17-27	0	6.7	
Mai and Nathan, 2009	air	HW	Contoured	15000	No	20-40	1.7	6.25	
Abdel-Rahman et al., 1997	air	LDA	Contoured	1.32×10^4	No	0-30	--	5.95	0.097
Abdel-Rahman et al., 1997	air	LDA	Contoured	1.32×10^4	Yes	0-30	--	5.9	0.08
Panchapakesan And Lumley, 1993	air	FHW	Contoured	11000	No	30-150	0	6.06	0.096
Kwon and Seo, 2005	water	PIV	Contoured	5142	No	15-75		5.5	0.106
Shinneeb et al., 2008	water	H.Res. PIV	Contoured	21900	Yes	10-50	-0.98	5.84	0.106
Ferdman et al., 2000			pipe	24000	No	>15	2.5	6.7	
Xu and Antonia, 2002	air	X-wire	pipe	86000	No	20-75	2.6	6.5	0.086

$$\frac{\overline{U}_C}{U_o} = A\left(\frac{x}{d} - \frac{x_{o1}}{d}\right)^{-1} \qquad \frac{r_{0.5}}{d} = b\left(\frac{x}{d} - \frac{x_{o2}}{d}\right)$$

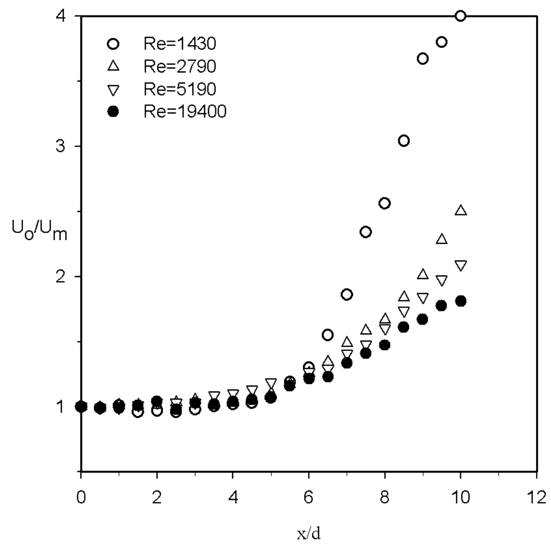


Fig. 3. Decay of centerline velocity [25]

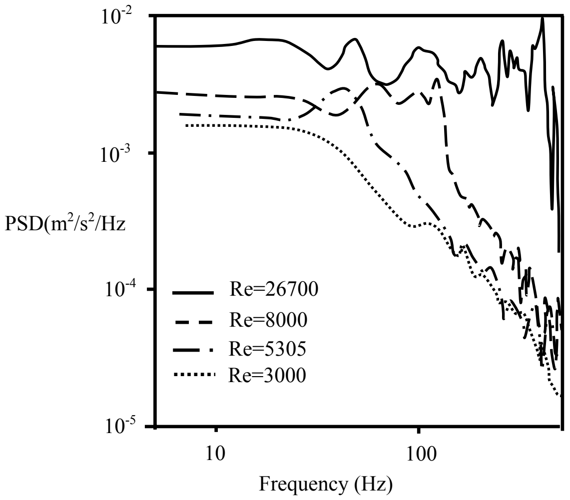


Fig. 4. Velocity spectrum at x/d=6 [25]

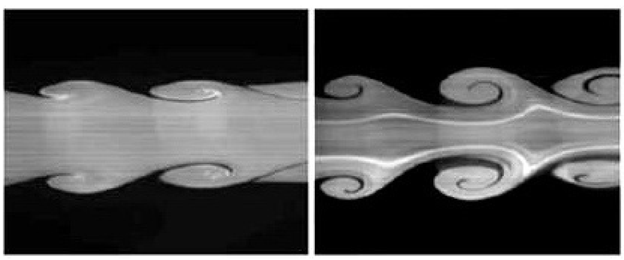


Fig. 5. Typical flow visualisation image at a Reynolds number of 680 (left) and 1030 (right) in the near orifice region (2 < x/d < 5).
Direction of flow is from left to right [33].

For a Reynolds number range, Re=177-5142, and for a region extending from the near to the far-field, Kwon and Seo [34] used PIV to report the Reynolds number dependence on several turbulence statistics. They found that as the Reynolds number increased the length of the near-field region decreased, the centerline velocity decayed more rapidly, the spreading rate for the turbulent flow cases decreased gradually, the normalized turbulence intensity along the centerline increased more rapidly with axial distance and the Reynolds shear stress level increased (see Figs. 6 & 7).

Bogey and Bailly [32] used large eddy simulations of a transitional round jet, Re = 1700–400000, and showed that as R decreases, a jet develops more slowly within the potential core, but more rapidly further downstream. Their round jets achieved self-similarity closer to the exit plane at low values of Re. Fellouah et al. [26], using a novel flying hot-wire apparatus, experimentally studied the near- and intermediate-fields ($0 \leq x/d \leq 25$) of a free round jet for a Reynolds number range that spans the mixing transition; $6000 \leq Re \leq 30000$. The length of the potential core region was found to decrease with increasing Reynolds number. In the near-field, the downstream variation of the mean centreline velocity is independent of the Reynolds number. As the jet evolves downstream, the axial mean velocity evolves faster to the self-similar state than the turbulence intensities and the streamwise turbulence intensity was greater than the transverse turbulence intensity. The increase of the radial development of the jet downstream was visible in the Reynolds stress results, where its maximum was shifted away from the jet centerline. Todde et al. [28] used a hot-wire technique to analyzes the features of a low-Reynolds number free submerged jet over a Reynolds number range of 850 to 6800. One-dimensional velocity measurements were performed on the centerline of the jet. It was shown that, at low Reynolds numbers, the initial region of the jet is dominated by well-defined vortices in the shear layer. This result is substantiated by both the statistical moments and the spectral analysis. Several flow visualizations were performed in order to obtain a qualitative description of the flow (Fig. 8).

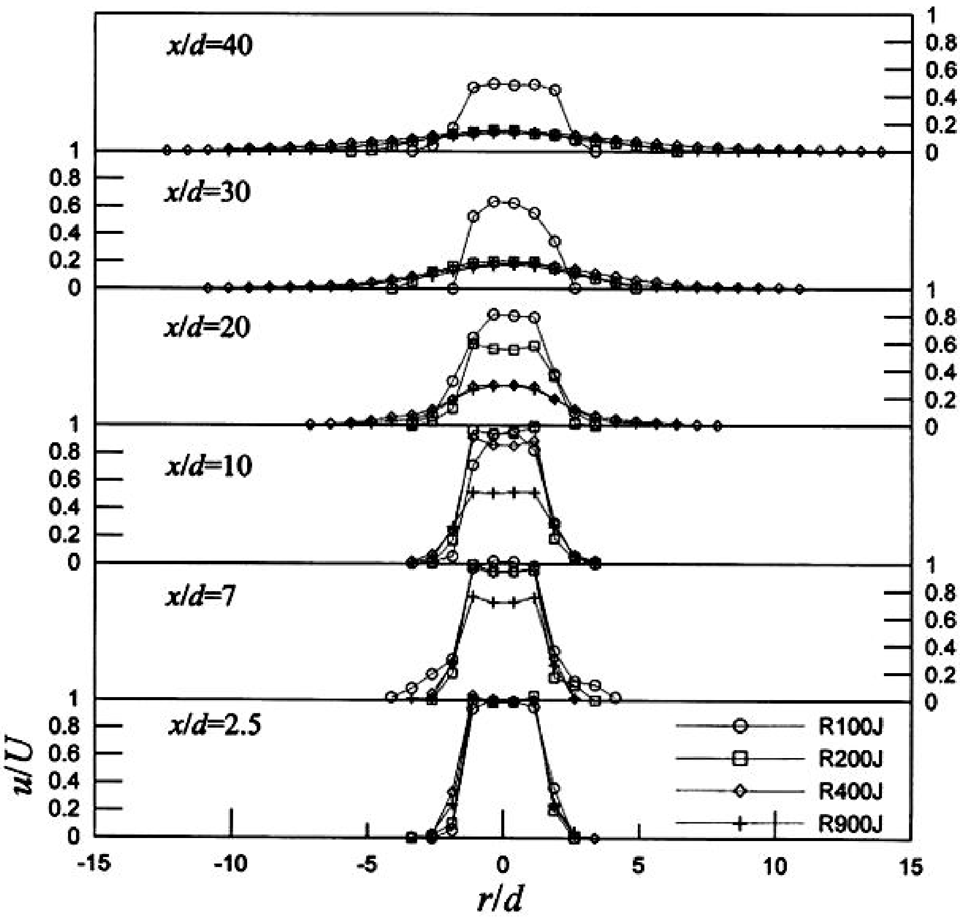


Fig. 6. Cross-sectional velocity distributions [34].

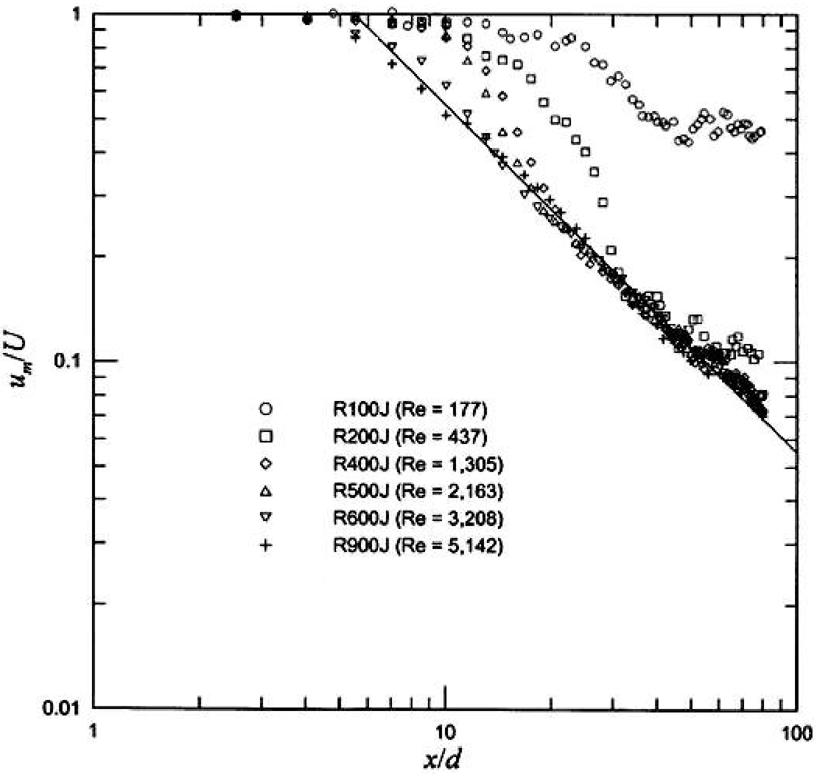
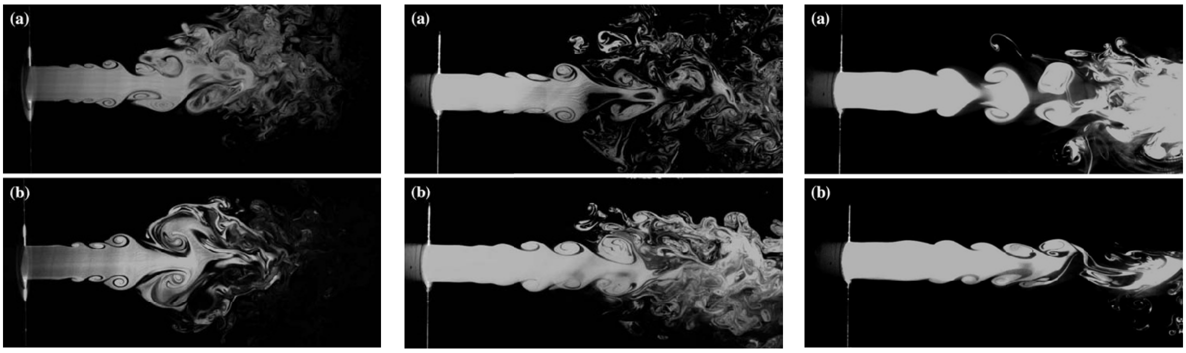


Fig. 7. Longitudinal variation of centerline velocity Decay [34].



Re = 2700 Re = 1620 Re = 1050

Fig. 8. Flow Visualizations, two separate Realizations [28].

Recently, and using hot-wire anemometer, the influence of Reynolds number on a plane jet flow was investigated ([29]- [31]). Suresh et al.[30] performed their investigation on a plane jet issuing from a rectangular nozzle of AR = 20, and for Re over the range 250 – 6250. They concluded that for low Reynolds numbers, velocity profiles, turbulence intensities, centerline decay rates, and length scales are strong functions of Reynolds number and axial distance. However, in the far field, at high Reynolds numbers the state of turbulence becomes independent of inlet Reynolds number and axial distance (Figs. 9-12).

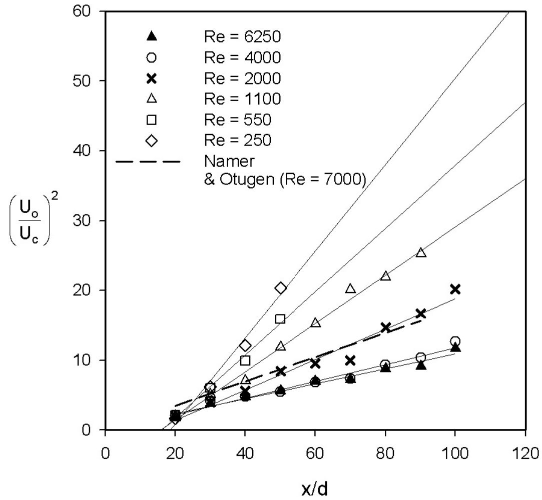


Fig. 10. Development of the mean centreline velocity in the far field [30].

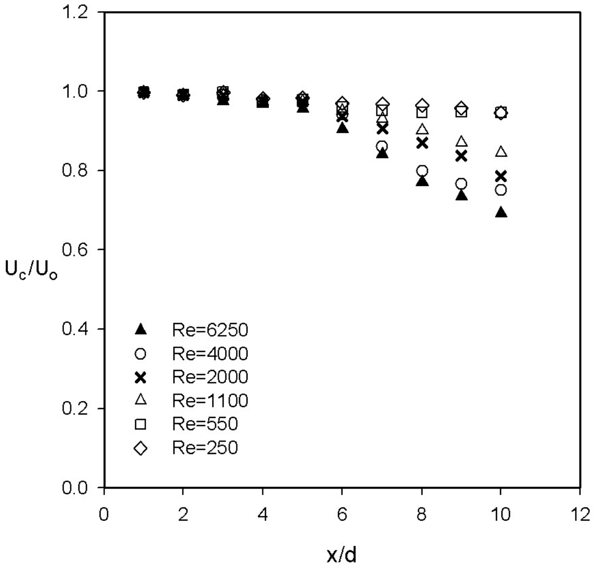


Fig. 9. Development of the mean centreline velocity in the near field [30].

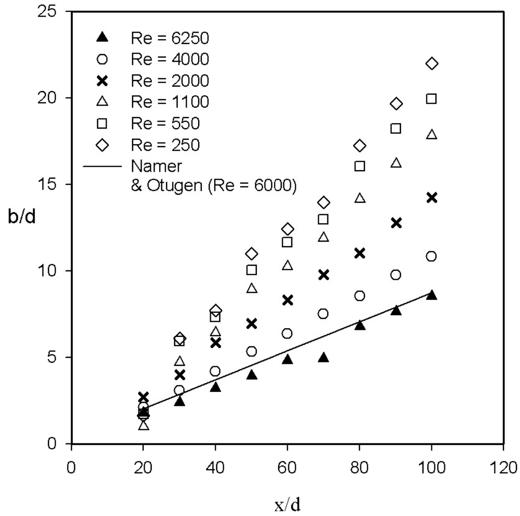


Fig. 11. Variation of half width with axial Distance [30].

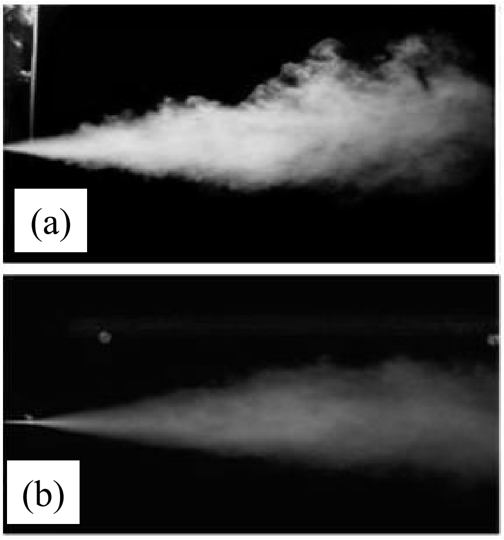


Fig. 12. Reynolds number dependence of a plane jet [30].
(a) Re =250;   (b) Re = 6250.

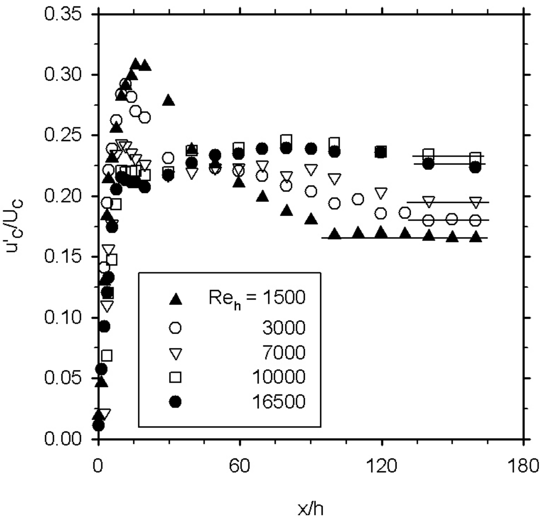


Fig. 13. Streamwise evolution of streamwise turbulent intensity for Re =1500–16500 [56].

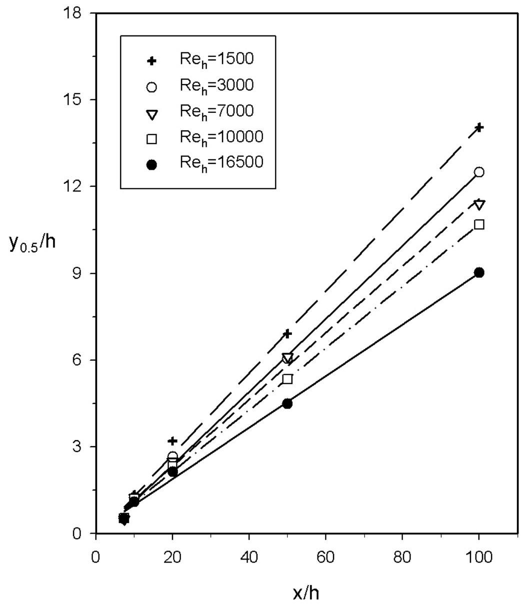


Fig. 14. Streamwise evolution of the jet spread rate for Re = 1500–16500 [56].

Deo et al. [29] collected data from previous investigations and plotted them, and showed that there were significant inconsistencies even for comparable Re and initial conditions. They made measurements of the centerline mean velocity, turbulent intensity, and high-order moments of the velocity fluctuations for plane jets (1500 < Re < 16500) over a greater distance downstream than it has been covered in previous studies (0 ≤ x/h ≤ 160), with the aim of examining the dependence on Re of the quantities measured, where they used a nozzle with AR=60. They found that an increase in Re caused a decrease in the potential core length and an increase in the near-field spreading rate. They also found that, in the far-field, mean velocity decay and spread rates exhibit the opposite dependence on Re to the near field. That is, they decrease asymptotically as Re is increased (Figs. 13 and 14).

A closing remark of this section is that the influence of Reynolds number on the jet development is not a straight forward to understand. This is partly because the Reynolds number affects the development of the boundary layer through the nozzle, making it difficult to independently assess jet development; and partly because of the possible differences from laboratory to another such as surface finish, measurement techniques and associated uncertainties. Thus the wide range of different operating/experimental conditions used in the different studies makes it a challenging to isolate the effects of Reynolds number from those of other conditions.

2.1.2 Nature of Exit velocity profiles

Investigations on the effect of the exit velocity profiles on the jet behavior can be found in [16], [20], [21], [44] and [45]. Ashforth-Frost and Jambunathan [44] studied the effect of both the exit velocity profile and the exit turbulence intensity on the development of the jet flow, particularly in the near-field region. They found that the jet potential core is up to 7% longer for the fully developed jet exit profile when compared to that of the flat jet exit profile. The spread of the jet flow for the flat exit velocity profile was found to occur sooner than in the jet of fully developed exit velocity profile. They attributed that to the more entrainment due to the high velocity gradients at the edge of the jet with flat exit-profile. They also reported a longer potential core for a lower exit turbulence.

Ferdman et al. [20] experimentally considered the effects of non-uniform initial-velocity profiles on the downstream evolution of round turbulent jets over $0 \leq x/d \leq 80$. They found that the evolution of both jets, one with an axisymmetric fully developed inlet profile and the other with an asymmetric initial profile, evolved toward a self-preserving state more rapidly than that of a jet with a top-hat initial velocity distribution although the initial growth in the turbulence quantities is higher for a uniform inlet condition. On the other hand, the initial growth of turbulence intensities and the far-field decay rates were larger for the jets with uniform initial-velocity profiles. Antonia and Zhao [16] used an X-array hot-wire anemometer to make measurements in two round jets; one issues from a contraction with a laminar top-hat velocity profile, and the other exits from a pipe with a fully developed turbulent mean velocity profile, see Fig. 15. The major conclusion was that the three Reynolds stresses were different for the two jet flows. The jet out of the contraction showed larger peak values compared to the pipe jet; thus reflecting a stronger shear in the mixing layer of this flow. Xu and Antonia [21] compared the characteristics of a jet issuing from a nozzle with a smooth contraction to a jet exiting from a long pipe. The former produced a top-hat velocity distribution while the latter produced a fully developed turbulent profile. It was found that the jet produced by the smooth contraction approached self-preservation more rapidly than the jet produced by pipe flow. Furthermore, they indicated that the streamwise vortices which enhance entrainment and mixing are absent in the case of initially turbulent boundary layers.

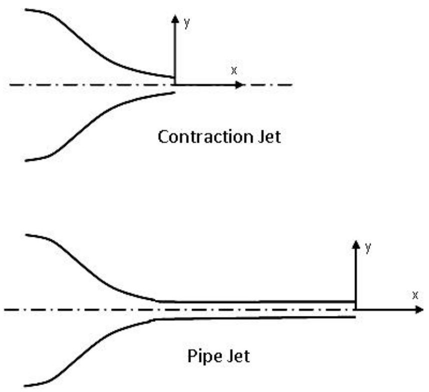


Fig. 15. Sketch of the two configurations

Burattini et al. [45] examined the effects of using different grids, placed at the nozzle exit plane, on the development of a round air jet. Placing different grids at the nozzle exit plane suppressed the initial shear layer instability, thus modifying the initial development of the jet. As a result, the streamwise decay and radial spreading of the jets were reduced, the potential core being lengthened by nearly 50%. They attributed this to the direct consequence of the weaker coherent structures, arising from the initial instability of the flow, which are less capable of entraining still fluid from the surroundings.

2.1.3 Nozzle-exit geometric profiles

The exit geometry of the jet flow and its influence on the behavior of the jet flow took the attention of researchers and, accordingly, resulted in some published research studies (e.g.; [24]; Mi et al. [46]; Quinn [47], [48]; Mi et al. [49]. The exit geometry has a direct effect on the profile and nature of the inlet jet; top-hat, fully developed, laminar, or turbulent. Quinn [48] used a hot-wire and Pitot static tube to experimentally investigate the near fields of jets issuing from a sharp-edged orifice and from a contoured nozzle. The objective was to determine the effects of upstream nozzle shaping on the evolution of the jets. The exit Reynolds number for both jets was 1.84×10^5. The jet-exit profiles of the mean velocity and turbulence intensity are shown in Figs. 16 and 17. The results obtained for the “potential core lengths”, the mean streamwise velocity decay rates, the jet spreading rates, and the Reynolds normal and shear stresses showed that mixing, which governs the evolution of the jet, is higher in the sharp-edged orifice jet than in the contoured nozzle jet. As well, the results for the distribution of the autocorrelation coefficients of the streamwise fluctuating velocity showed a marked difference in the evolution of the two jets. Measurements of the velocity field using a PIV in a jet (Re=72000) issuing from sharp-edged orifice were made by Mi et al. [46], in the near and transition regions. The major finding was that the flow structure of the orifice jet in the near field is more three-dimensional than that of the contoured nozzle jet, and that primary coherent structures appeared non-symmetrical with respect to the nozzle axis (Fig. 18), and symmetrical for the contoured nozzle jet (Fig. 19).

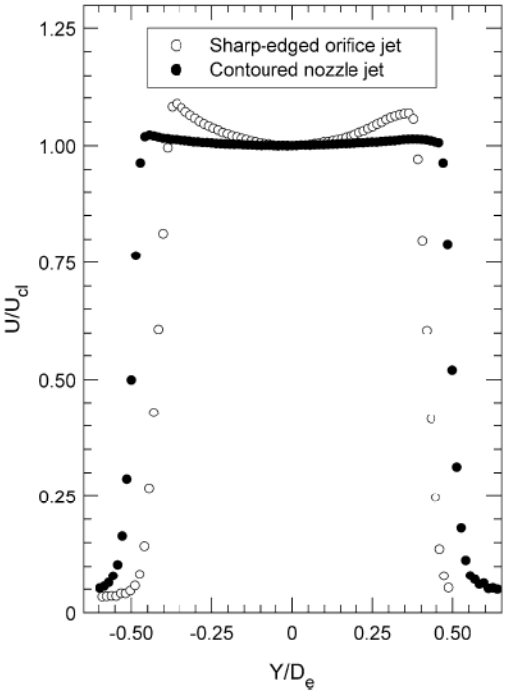


Fig. 16. Streamwise velocity profiles at exit [48].

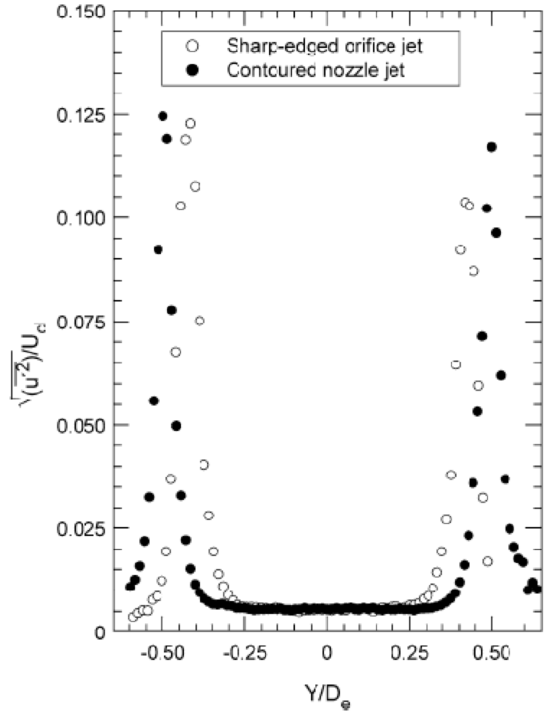


Fig. 17. Streamwise turbulence intensity at exit [47].

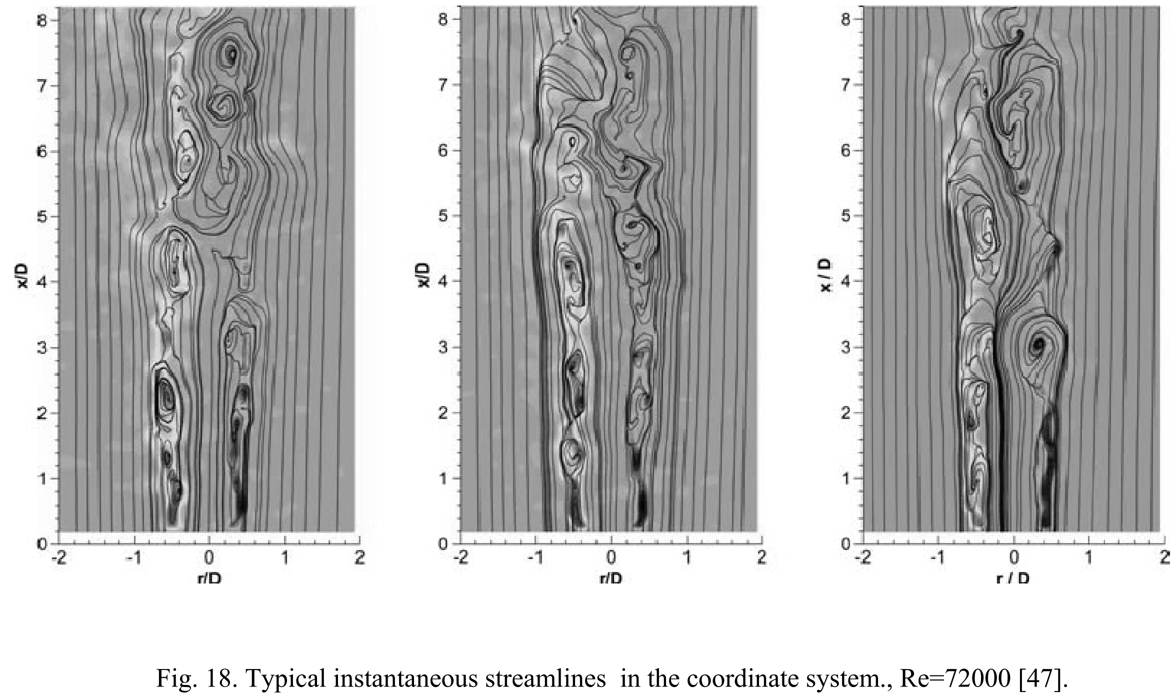


Fig. 18. Typical instantaneous streamlines in the coordinate system., Re=72000 [47].
Orifice plate

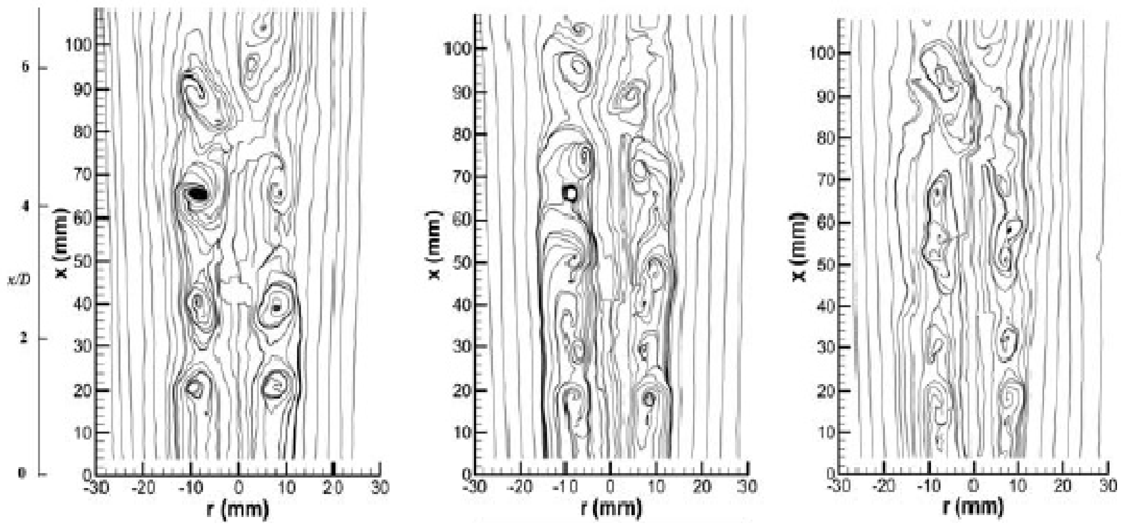


Fig. 19. Typical instantaneous streamlines in the coordinate system, Re=56000 [47].
Contoured nozzle

Using an X-wire and Pitot-static tube, Quinn [47] experimentally investigated the jet issuing from a sharp-edged elliptic orifice, in the near and transition regions. Some more experiments were performed in round jets issuing from a sharp-edged orifice and from a contoured nozzle for the sake of comparison. The Reynolds number of all jet flows was 1.88 x 10^5. The objective was to put in perspective the mixing of the jet out of the elliptic orifice. The results showed that mixing in an elliptic jet issuing from a sharp-edged orifice plate is higher than in elliptic jets issuing from contoured elliptic nozzles and in round jets. The mean streamwise velocity decay rates along the jet centerline (Fig. 20), the behavior of the turbulence intensities and the mean static pressure on the jet centerline, the potential core lengths and the spreading rates (Fig. 21) provide the evidence for this conclusion.

Mi and Nathan [24] carried out an experimental investigation to measure the statistical properties on the centerline in nine air jets issuing from differently-shaped nozzles into still air surroundings (Fig. 22). All nozzles of investigation have nominally identical opening areas, and measurements were made at Re= 15,000. Results showed that the loss of jet axisymmetry at the exit generally causes the mean velocity decaying faster (Fig. 23), and the fluctuating intensity growing, in the near field , thus indicating the increased overall entrainment rate. It is also shown that a change of shape of the nozzle exit does not affect the asymptotic decay rate of the centerline velocity in the far field. The near field structure of the isosceles-triangular jet was deduced to be most three-dimensional, compared with the circular counterpart from smooth contraction being least. These discrepancies, however, weakened as the downstream distance x is increased.

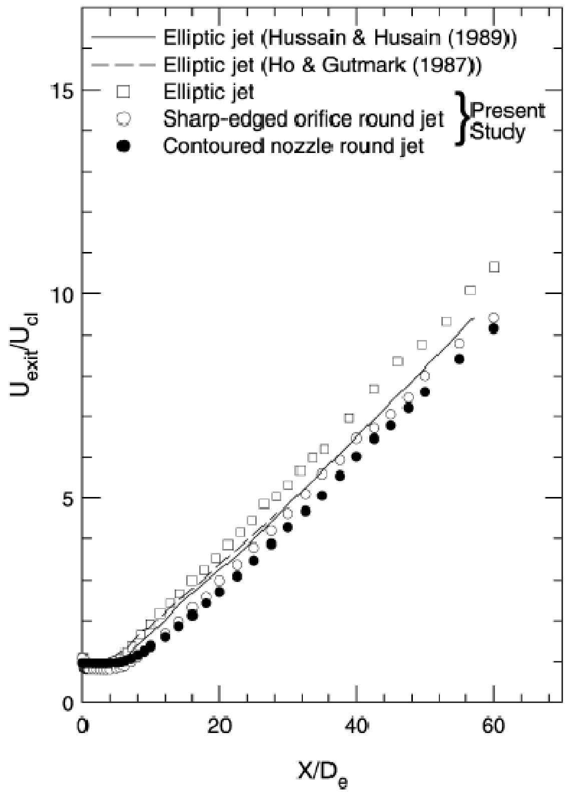


Fig. 20. Mean streamwise velocity decay on the jet Centreline [47].

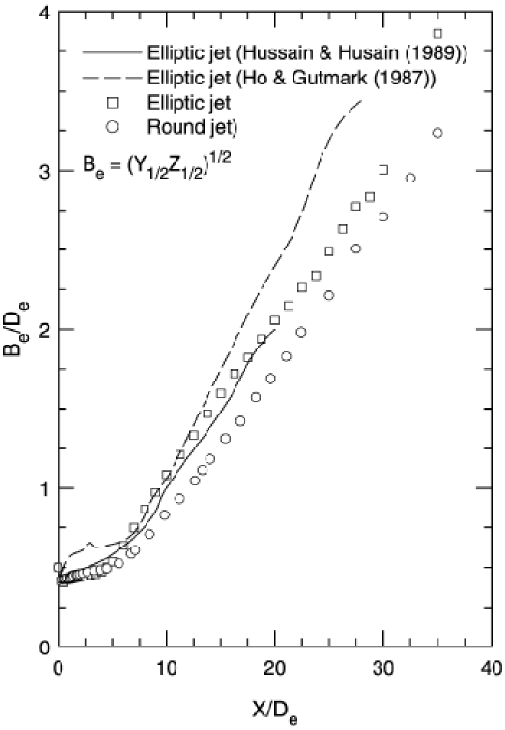


Fig. 21. Jet half-velocity widths [47].

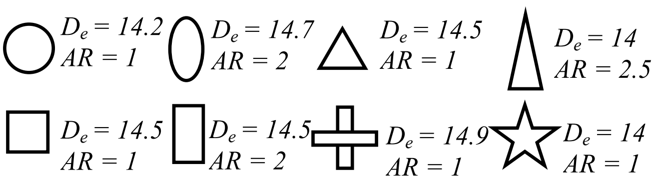


Fig. 22. Eight orifice shapes with their equivalent diameter D_e (mm) and aspect ratio AR [24].

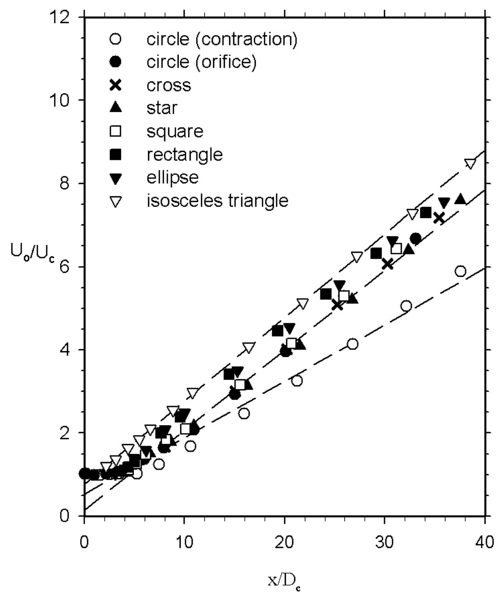


Fig. 23. Centerline evolutions of the normalized mean velocity for the different jets [24].

2.2 Effect of boundary conditions

Common boundary conditions of the jet flow are the cases of using an endplate at the nozzle exit plane (Fig. 24), and/or sidewalls (for the case of a plane jet only) to ensure the two dimensionality of the jet flow (Fig. 25). An endplate (or front plate) is

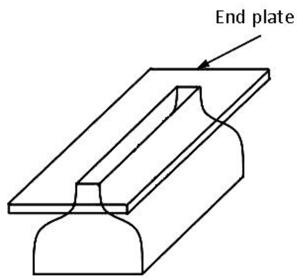


Fig. 24. Nozzle with an endplate

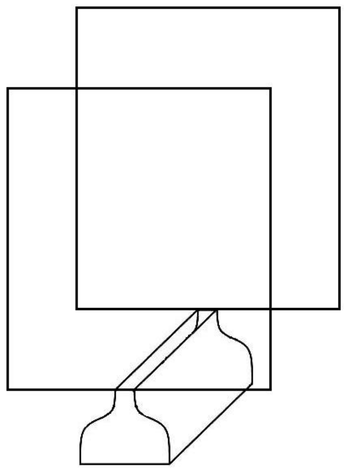


Fig. 25. Nozzle with sidewalls

a plate setting flush at the jet exit plane, normally used to avoid the influence of the structure of the jet flow facility which will be different from one setup to another. It is generally expected that introducing a jet through a plate causes a decrease in velocity spread and decay rates due to the endplate's effect. Moreover, it was shown (Kotsovinos [50] and Schneider [51]) that the endplate results in a momentum reduction in the streamwise direction. Although endplates have been used in many previous investigations, only few articles focusing on the comparison of the flow field in the presence or absence of endplates are available in the literature.

Abdel-Rahman et al. [52] investigated the use of a front plate at the exit plane of an axisymmetric round nozzle. Their LDA measurements showed that a reduction in velocity spreading rate (Fig. 26) and reduced kinematic mass flux (Fig. 27) occurred in the case with front plate. This was attributed to reduced interaction of the jet with ambient fluid due to the front plate. Motivated by the lack of

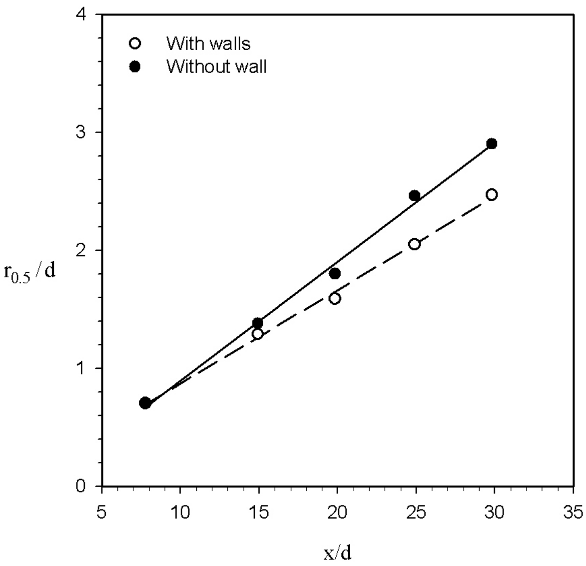


Fig. 26. Variation of velocity half-width [52].

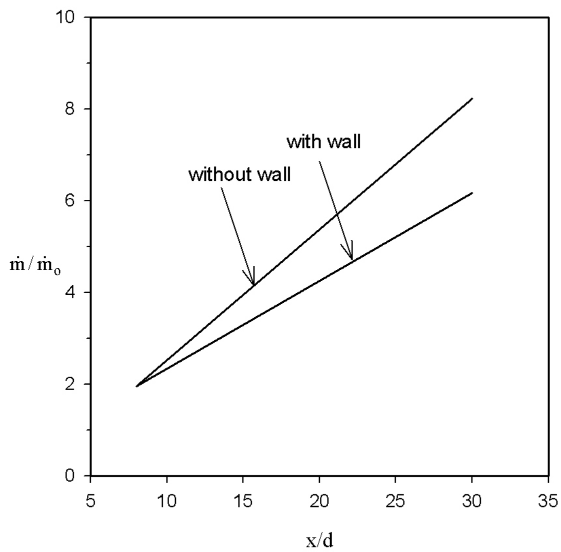


Fig. 27. Mass flux ratio along the jet axis [52].

information on the effect of endplates on rectangular nozzle jets of small or moderate aspect ratios, the objective of Alnahhal and Panidis [53] was to provide information on the influence of the endplates on jet development and mixing in the near field for two rectangular jets of aspect ratios, AR=6 and 15 at different Reynolds numbers; 10000, 20000, and 30000. Their x-wire measurements and results showed that the influence of an endplate is an aspect area dependent, having a stronger effect when used with rectangular nozzles of smaller aspect ratio. Measurements along the centreline or across the jet for aspect ratio (AR) of 15, showed a negligible effect of the endplate, Fig. 28. However, similar measurements along the centreline of a jet with AR=6 revealed significant influence of the endplate resulting in longer potential core lengths as well as slower decay rate of the centreline velocity (Fig. 29). They attributed that to a probable restricted mixing with ambient air due to the endplate. Intersecting to note that this is in agreement with the results obtained by [52]for a round jet.

Although sidewalls have been used in many previous investigations at various initial conditions (e.g., different aspect ratios and Reynolds numbers), few experiments have been devoted to study the effect of the sidewalls on turbulent jets issuing from rectangular nozzles ([54] – [57]). Experimental results of Hitchman et al. [54], 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. 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, it is decreasing significantly in the presence of the sidewalls. This behaviour may be to the ‘‘starving jet” effect for jets enclosed or confined in a room.

In a relatively recent study undertaken by Deo et al. [56] 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. They also observed that, the jet with sidewalls has a longer region of statistically two-dimensional behavior.

In a more recent study undertaken by Alnahhal and Panidis [57] to experimentally investigate the influence of sidewalls on the turbulent free jet flow issuing from a smoothly contracting rectangular nozzle for aspect ratio 15 and Re = 10000, 20000, and 30000, based on x-wire results, it was found that the two jet configurations (with and without sidewalls) produced statistically different flow fields. However, they concluded that sidewalls do not lead to the production of a 2D flow field as indicated by the spanwise mean velocity distribution.

Finally, Deo et al. [55] reported a systematic investigation of the effect of nozzle aspect ratio (15-72) on plane jets. It is to be mentioned that they used a nozzle with sidewalls in their experiments. They used hot-wire and made measurements for Re=1.8x10^4, over a downstream distance of up to 85 nozzle width. Results revealed that both the extent and character of statistical two-dimensionality of a plane jet depend significantly on AR. They have shown that in the self-similar region, both the mean velocity decay rate and spread rate of the jet increase as AR increases and do not reach an asymptotic value, even at AR = 72 (Fig. 30). Finally, they concluded that the classical hypothesis for round jets which argues that all jets should become asymptotically independent of the source conditions, at sufficiently large distances from the source, does not hold true for a plane jet.

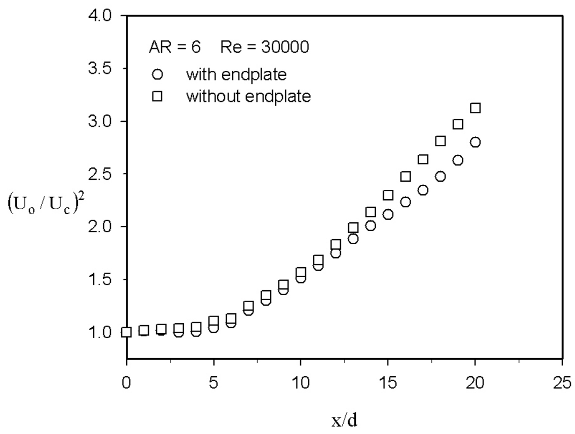


Fig. 29. Axial mean velocity decay, AR=6 [53].

3 Summary, Conclusions and Recommendations

In this article, the current knowledge of turbulent jet flows is reviewed. The article is concerned with flows of relevance to engineering practice. The main thrust was directed to the free jets and the effects of the different parameters, particularly the initial conditions on their behavior and characteristics. It demonstrates the considerable research activity currently devoted to turbulent free jet flows. Not surprising, however, since the free jet is considered the basic building brick through the turbulent processes.

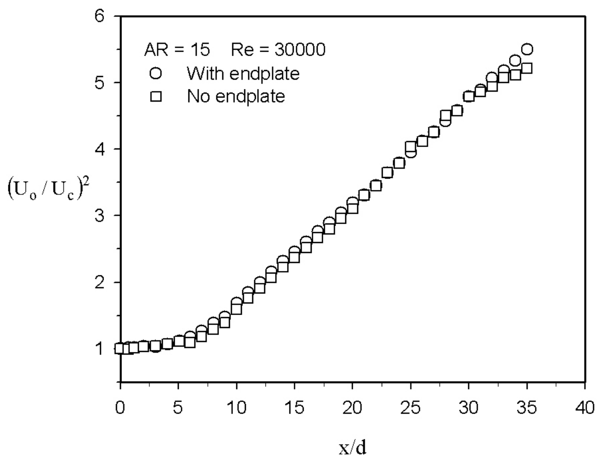


Fig. 28. Axial mean velocity decay, AR=15 [53].

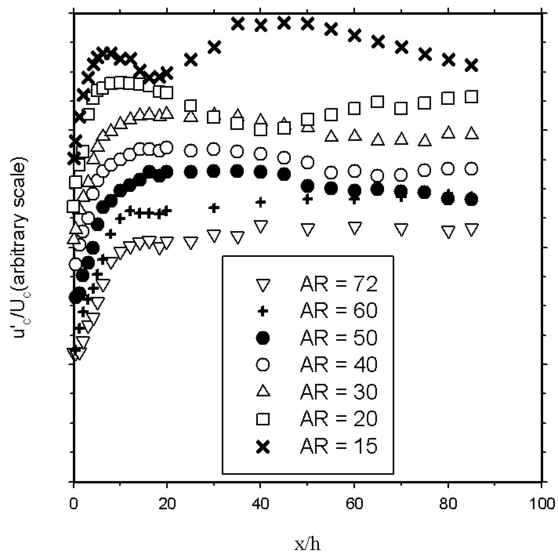


Fig. 30. Streamwise evolutions of turbulence intensity for different AR [55].

From the review, there appears to be numerous studies available on the influence of Reynolds number on jet flows and/or on the low-Reynolds number jets. Studies on the influence of exit velocity profiles on the jet flow are also there in a few reported works. The geometry of the jet exit (orifice plate, profiled nozzle, or a pipe) has received the attention of a few research investigations with the objective of exploring the effect of such geometry on the jet behavior and development. The boundary conditions of the jet exit have, as well, received a good deal of attention from the research community, with the aim of studying their influence on the jet development.

The boundary conditions here mean the case of using an endplate at the nozzle exit plane (an endplate, or front plate, is a plate setting flush at the jet exit plane) and/or using sidewalls (for the case of a plane jet only) to ensure the two dimensionality of the jet flow.

The present review shows that in the simplest jet flows, the downstream regions of jets in still surroundings, grow at rates that are dependent on the conditions at jet origin. The presence of coherent structures in the near field is confirmed for comparatively low Reynolds numbers and, where the initial velocity profile is not turbulent. Coherent structures can be a dominating influence in the absence of free-stream turbulence; they have lesser significance in the presence of turbulence, and are often unimportant for high Reynolds number.

Examination of the effect of using an endplate on the behavior of the jet flow is scarce, and even not assessed clearly. However, from the few available studies it appears that endplate restricts mixing with ambient air. This was seen in a slower jet spread rate and reduced downstream mass flux.

Experimental investigations on the effects of the sidewalls for a plane jet are somehow limited, and even showed conflicting results, refer to [54] - [57]. While it was found by Deo et al. [56] that shorter potential core lengths, higher spread and decay rates are associated with the jet without sidewalls, conflicting results have been provided by Hitchman et al. [54] much longer before.

To the author's knowledge, no systematic examination of the effect of aspect ratio on either the behavior or extent of the statistically 2-D flow region is currently available, except that of Deo, Mi and Nathan [55]. However, their study suffered other effects due to their use of sidewalls.

Based on the present review and the concluding remarks mentioned before, one can conclude that the 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. In other words, the development of a jet is determined by the interplay of several physical mechanisms which are closely related.

The gaps pointed to above need to be filled with well-designed experiments. Moreover, I guess a recommendation of having jet flows classified into well-defined and documented Bench Mark Jet Flows is a worthwhile idea. By so doing, any future research work on a jet flow should first adopt a Bench Mark Jet Flow. As a consequence, it is expected that the ultimate accumulated information will be less controversial, more beneficial to the scientific community, and inspiring to turbulence modelers. It should be emphasized that the documented Bench Marks should include clear details on construction of the experimental set-up, detailed information about the initial and boundary conditions of the jet flow, and a suggestion of the measurement techniques to be used.

References:

[1] H.W. Liepmann and J. Laufer, Investigation of free turbulent mixing, *NACA Tech. Note 1258*, 1947.

[2] H.E. Fielder, Control of free turbulent shear flows, In M.G. El-Hak, A. Pollard, J.P. Bonnet (Eds.), *Flow Control: Fundamentals and Practices*, Springer-Verlag, Germany, 1998, pp.335–429.

[3] T. Matsuda and J. Sakakibara, On the vortical structure in a round jet, *Phys Fluids*, Vol.17, 2005, pp.1-11.

[4] A.M. Shinneeb, J.D. Bugg, and R. Balachandar, Quantitative investigation of vortical structures in the near-exit region of an axisymmetric turbulent jet, *J. Turbulence*, Vol.9, No.19, 2008, pp.1-20.

[5] H.A. Becker and T.A. Massaro, Vortex evolution in a round jet, *J. Fluid Mech*., Vol.31, 1968, pp.435-448.

[6] G.S. Beavers and T.A. Wilson, Vortex growth in jets, *J. Fluid Mech*., Vol.44, 1970, pp.97-112.

[7] Wygnanski, I. and Fiedler, H., Some measurements in the self-preserving jet, *J. Fluid Mech*., Vol.38, 1969, pp. 577–612.

[8] W. Rodi, A new method of analysing hot-wire signals in highly turbulent flow and its evaluation in a round jet, *DISA Info*., Vol.17, 1975.

[9] W.K. George, The self-preservation of turbulent flows and its relation to initial conditions and coherent structures, *Advances in Turbulence*, Hemisphere, New York, 1989, pp.39-73.

[10] D.R. Dowling and P.E. Dimotakis, Similarity of the concentration field of gas-phase turbulent jets, *J. Fluid Mech*., Vol.218, 1990, pp.109–141.

[11] N.R. Panchapakesan and J.L. Lumley, Turbulence measurements in axisymmetric jets of air and helium, Part 1: air jet. *J. Fluid Mech*., Vol.246, 1993, pp.197–223.

[12] C.D.D. Richards and W.M. Pitts, Global density effects on the self-preservation

behaviour of turbulent free jets, *J. Fluid Mech*., Vol.254, 1993, pp. 417-435.

[13] H.J. Hussein, S. Capp, and W.K. George, Velocity measurements in a high-Reynolds number, momentum-conserving, axisymmetric, turbulent jet, *J. Fluid Mech*., Vol.258, 1994, pp. 31–75.

[14] M. Uddin and A. Pollard, Self-similarity of co-flowing jets, the virtual origin, *Phys. Fluids*, Vol.19, No.6, 2007, pp.68103/1–68103/4.

[15] W.M. Pitts, Reynolds number effects on the centreline mixing behavior of axisymetric turbulent jets, *Exp. Fluids*, Vol.11, 1991, pp.135-144.

[16] R.A. Antonia and Q. Zhao, Effect of initial conditions on a circular jet, *Exp. Fluids*, Vol.31, 2001, pp.319–323.

[17] J.O. Hinze, *Turbulence*, McGraw-Hill, 1975.

[18] J. Mi, D.S. Nobes, and G.J. Nathan, Influence of jet exit conditions on the passive scalar field of an axisymmetric free jet, *J. Fluid Mech*. Vol.432, 2001, pp. 91-125.

[19] B.J. Boersma, G. Brethouwer, and F.T.M. Nieuwstadt, A numerical investigation on the effect of inflow conditions on the self-similar region of a round jet, *Phys. Fluids*, Vol.10, No.4, 1998, pp.899–909.

[20] E. Ferdman, M.V. Otugen, and S. Kim, Effect of initial velocity profile on the development of the round jet, *J. Propul. Power*, Vol.16, No.4, 2000, pp.676-686.

[21] G. Xu, and R.A. Antonia, Effect of different initial conditions on a turbulent round free jet', *Exp. Fluids*, Vol.33, 2002, pp.677–683.

[22] W.K. George and L. Davidson, Role of Initial Conditions in Establishing Asymptotic Flow Behavior, *AIAA J*, Vol.42, No.3, 2004, pp.438-446.

[23] N.E. Kotsovinos, A note on the spreading rate and virtual origin of a plane turbulent jet, *J. Fluid Mech*., Vol.77, 1976, pp.305.

[24] J. Mi and G.J. Nathan, Statistical Properties of Turbulent Free Jets Issuing from Nine Differently-Shaped Nozzles, *Flow, Turbulence and Combustion*, published online on 14 November, 2009.

[25] A.A. Abdel-Rahman, S.F. Al-Fahed, and W. Chakroun, The near-field characteristics of circular jets at low Reynolds numbers, *Mech. Res. Commun*., Vol.23, No.3, 1996, pp.313-324.

[26] H. Fellouah, C.G. Ball, and A. Pollard, Reynolds number effects within the development region of a turbulent round free jet, *Int. J. Heat Mass Trans*., Vol.52, 2009, pp.3943–3954.

[27] F. Ricou, and D.B. Spalding, Measurements of entrainment by axisymmetric turbulent jets. *J. Fluid Mech*., Vol.11, 1961, pp.21-32.

[28] V. Todde, P.G. Spazzini, and M. Sandberg, Experimental analysis of low-Reynolds number free jets, *Exp. Fluids*, Vol.47, 2009, pp.279–294.

[29] R.C. Deo, J. Mi, and G.J. Nathan, The influence of Reynolds number on a plane jet, *Phys. Fluids*, Vol.20, 2008, pp.75-108.

[30] P.R. Suresh, K. Srinivasan, T. Sundararajan, and S.K. Das, Reynolds number dependence of plane jet development in the transitional regime, *Phys. Fluids*, Vol. 20, 2008a, 044105.

[31] P.R. Suresh, T. Sundararajan, and S.K. Das, Experimental investigation of the influence of momentum thickness on the development of a slightly heated plane jet, *Int. Commun. Heat Mass Trans*., Vol. 35, 2008b, pp.282–288.

[32] C. Bogey, and C. Bailly, Large eddy simulations of transitional round jets, influence of the Reynolds number on flow development and energy dissipation, *Phys. Fluids*, Vol.18, 2006, pp.1-14.

[33] P. O'Neill, J. Soria, and D. Honnery, The stability of low Reynolds number round jets, *Exp. Fluids*, Vol.36, 2004, pp.473–483.

[34] S.J. Kwon, and I.W. Seo, Reynolds number effects on the behaviour of a nonbuoyant round jet, *Exp. Fluids*, Vol.38, 2005, pp.801–812.

[35] N.T. Obot, M.L. Graska, and T.A. Trabold, The near field behaviour of round jets at moderate Reynolds numbers, *Canadian Journal of Chemical Engineering*, Vol.62, 1984, pp.587–593.

[36] V. Subramanian and V.B. Makhijani, A Test facility for a plane jet, Vol.12, No.5, 1985, pp.551-558.

[37] P.H. Oosthuizen, An Experimental study of low Reynolds number turbulent circular jet flow, *ASME applied mechanics, bioengineering, and fluids engineering conference*, Houston, TX, 20-22 June 1983, AMSE paper No. 83-FE-36, 1983.

[38] N. Rajaratnam and L. Flint-Peterson, Low Reynolds number circular turbulent jets, *Proc. Inst. of Civil Engineers*, London, Vol. 87, 1989, pp. 299-305.

[39] S. Sami, T. Carmody, and H. Rouse, Jet diffusion in the region of flow establishment, *J. Fluid Mech*. Vol.27, 1967, pp.231-252.

[40] M.L. Albertson, Y.B. Dai, R.A. Jensen, and H. Rouse, Diffusion of submerged jets, *Trans. ASCE*, Vol.115, 1950, pp.639-664.

[41] C.J. Chen, and W. Rodi, Vertical Turbulent Buoyant Jets, *A Review of Experimental Data*, HMT series 4, Pergamon, Oxford, 1980.

[42] G.P. Lemieux, and P.H. Oosthuizen, Experimental study of the behavior of plane turbulent jets at low Reynolds numbers. *AIAA J.*, Vol.23, 1985, 1845–1846.

[43] M.V. Otugen and I. Namer, The effect of Reynolds number on the structure of plane turbulent jets, *AIAA 24th Aerospace. Sciences Meeting*, Reno, Nevada, 1986.

[44] S. Ashforth-Frost and K. Jambunathan, Effect of nozzle geometry and semi-confinement on the potential core of a turbulent axisymmetric free jet, *Int. Commun.Heat Mass Trans.*, Vol.23, No.2, 1996, pp. 155-162.

[45] P. Burattini, R.A. Antonia, S. Rajagopalan, and M. Stephens, Effect of initial conditions on the near-field development of a round jet, *Exp. Fluids*, Vol.37, 2004, pp.56-64.

[46] J. Mi, P. Kalt, G.J. Nathan, and C.Y. Wong, PIV measurements of a turbulent jet issuing from round sharp-edged plate, *Exp. Fluids*, Vol.42, 2007, pp.625–637.

[47] W.R. Quinn, Experimental study of the near field and transition region of a free jet issuing from a sharp-edged elliptic orifice plate, *Eur. J. Mech. B Fluid*, Vol.26, 2007, pp.583–614.

[48] W.R. Quinn, Upstream nozzle shaping effects on near field flow in round turbulent free jets, *Eur. J. Mech. B Fluid*, Vol.25, 2006, pp.279–301.

[49] J. Mi, G.J. Nathan, and R.E. Luxton, Centreline mixing characteristics of jets from nine differently- shaped nozzles, *Exp. Fluids*, Vol.28, 2000, pp.93–94.

[50] N.E. Kotsovinos, A note on the conservayion of the volume flux in free turbulence, *J. Fluid Mech.*, Vol.86, No.1, 1978, pp.201-203.

[51] W. Schneider, Decay of momentum flux in submerged jets, *J. Fluid Mech.*, Vol.154, 1985, pp.91-110.

[52] A.A. Abdel-Rahman, W. Chakroun, and S.F. Al-Fahed, LDA measurements in the turbulent round jet, *Mech. Res. Commun.*, Vol.24, No.3, 1997, pp.277-288.

[53] M. Alnahhal and Th. Panidis, The effect of endplates on rectangular jets of different aspect ratios, *Proc. European Combustion Meeting*, 2009a.

[54] G.J. Hitchman, A.B. Strong, P.R. Slawson, and G. Ray, Turbulent planar jet with and without confining walls, *AIAA J*, Vol.28, No.10, 1990, pp.1699-1700.

[55] R.C. Deo, J. Mi, and G.J. Nathan, The influence of nozzle aspect ratio on plane jets, *Exp. Therm. Fluid Sci.*, Vol.31, 2007a, pp.825–838.

[56] R.C. Deo, G.J. Nathan, and J. Mi, Comparison of turbulent jets issuing from rectangular nozzles with and without sidewalls, *Exp. Therm. Fluid Sci.*, Vol.32, No.2, 2007b, pp.596–606.

[57] M. Alnahhal, and Th. Panidis, The effect of Sidewalls on rectangular jets, *Exp. Therm. Fluid Sci.*, Vol.33, 2009b, pp.838-851.

Nomenclature:

A	Decay rate of jet centerline mean Velocity
AR	Aspect ratio of plane jet orifice
b	Spread rate of a jet half-velocity
d	Jet exit diameter
D_e	Equivalent diameter of a jet orifice
h	Plane jet exit thickness
PIV	Particle Image Velocitimeter
PSD	Power Spectrum Density
$r_{0.5}$	Jet half-velocity width for a round jet
Re	A round Jet-exit Reynolds number
Re_h	A plane jet-exit Reynolds number
u'_c	rms jet centerline velocity
U_o	Jet exit velocity
U_c or U_m	Jet centerline mean velocity
x	Downstream distance
x_o	Virtual origion of the jet
x/d	Dimensionless downstream distance
$y_{0.5}$	Jet half-velocity width for a plane jet