EXPERIMENTAL INVESTIGATION ON THE SELF-PRESERVING BEHAVIOUR OF A TURBULENT PLANE JET WITH CO-FLOW

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ABSTRACT

Air curtains are often used because of their ability to limit transfers between two atmospheres without the use of physical barriers. A typical air curtain is reproduced in a wind tunnel as a submerged plane jet in a uniform co-flow. This flow is explored by crossed Hot-Wire Anemometry for different Reynolds numbers and velocity ratios. The influence of these control parameters on the self-similar behaviours is discussed.

INTRODUCTION

A turbulent plane jet has several industrial applications, particularly in limiting transfer between two atmospheres without physical barriers (for example air curtains in tunnels and refrigerated cabinets). Depending on the application, the turbulent plane jet can be formed by various nozzle geometries ejecting into the same or different fluids. It can be warmed or cooled and pass successively forced, mixed and natural convection regimes. It can be semi-confined like wall or impinging jets. We aim to study the effect of plane jet between two parallel streams with different velocities and temperatures in the mixing layer. As prior study, we present in this paper an experimental investigation of a turbulent plane jet discharging into an uniform co-flow.

A plane jet is defined as a statistically two-dimensional flow, with the dominant flow in the streamwise ($x$) direction, spreading in the lateral ($y$) direction and zero entrainment in the spanwise ($z$) direction. The turbulent plane jet discharging into a quiescent atmosphere was first studied by Van Der Hegge Zijnen (1958), Heskested (1965) and Gutmark & Wygnanski (1976) and a similar jet discharging into an uniform co-flow was studied by Bradbury (1965), Everitt & Robins (1978) and Le Ribault et al. (1999). The former is referred to as a self-preserving pure jet type of flow. The latter can exhibit a self-preserving structure in two limited regions of the flow.

First, a self-preserving flow is possible when the velocity on the jet centreline is much greater than the free stream. This strong jet is referred to as the self-preserving pure jet type of flow. The second region in which a self-preserving flow is possible when the jet centreline velocity is approaching the free stream velocity. This weak jet is a self-preserving wake flow type. Rajaratnam (1976) shows that for a strong jet ($\frac{\langle u \rangle_{cl} - U_e}{U_e} \gg 1$) with $\langle u \rangle_{cl}$, the mean velocity on the centreline and $U_e$, the co-flow velocity), the mean velocity on the centreline decreases as $x^{-1/2}$ and the width of the jet increases linearly. For a weak jet ($0 \leq \frac{\langle u \rangle_{cl} - U_e}{U_e} \ll 1$), the mean velocity on the centreline still decreases as $x^{-1/2}$, but the width of the jet increases as $x^{1/2}$. A plane jet discharging into a quiescent atmosphere always behaves as a strong jet whereas a plane jet with co-flow can behave as a strong jet near the exit and, due to the decrease of the mean velocity on the centreline, behaves as a weak jet farther downstream. The results in the literature do not show a clear behaviour of the constants (rate and virtual origin) involved in these self-similarity functions according to the Reynolds number $Re$ and the velocity ratio $r$.

In this paper, the turbulent plane jet discharging into an uniform co-flow is explored by HWA (Hot-Wire Anemometry) in the region $0 \leq x/H < 37.5$, with $H$ the jet width at the exit, for various control parameters ($Re, r$). This region includes the potential core, the transitional region and the self-similar region in which the turbulence is fully developed. The main objective is to determine the influence of these control parameters on the self-similar behaviour in the fully turbulent region.

EXPERIMENTAL SET UP

Besides the industrial and research interests of this flow configuration, the presence of the co-flow has numerous advantages for the experimental study of the jet. Temperature...
stratification and large convective motions are suppressed to prevent any perturbation in the jet development. There is no evenly back-mixing flow at the interface of the jet which allows HWA measurements. The flow can be homogeneously seeded everywhere to increase the quality of PIV (Particle Image Velocimetry) measurements. Moreover, a slight co-flow is often added in numerical simulations (see Le Ribault et al. (1999)) to avoid numerical difficulties. In this study, experiments consist in taking measurements by HWA for different configurations defined by a Reynolds number and a velocity ratio. HWA measurements are done in a specifically designed wind tunnel with lab-made constant temperature anemometers and crossed wires probes. This section described the wind tunnel and the HWA system and summarizes the characteristics of the different experiments.

Wind Tunnel

The wind tunnel was specifically designed for the experimental study of a plane jet in different configurations. This tunnel measures 5m high and has a section of $2 \times 2m^2$ in its basic configuration, the plane jet discharging into a parallel moving airstream. This tunnel is made up of three vertical and adjacent open-circuits. Each circuit has a centrifugal blower which supplies air to a plenum chamber followed by a convergent. The three plenum chambers are furnished with foams, honeycombs and screens to make the flow uniform with a validity. This formulation links the norm $||\vec{u}(t)|| = \sum_{i,j=0}^{i+j \leq 3} p_{ij} (e_1^* + e_2^*)$ and the angle $\alpha(t) = \sum_{i,j=0}^{i+j \leq 3} q_{ij} (e_1^* + e_2^*)$ (1)

The main advantages of such a system are the explicit formulation for fast computing and the large velocity range of validity. This formulation links the norm $||\vec{u}(t)||$ and the angle $\theta$ of the velocity vector at the voltage $e_1^*$ and $e_2^*$. The double asterisk denotes a temperature and drift compensation of the output voltage $e$ measured across the anemometer. The temperature compensation is modeled by:

$$e_k^2(t) = e_k^2(t) \left[ \frac{\theta_k^o - \theta_v}{\theta_k^o - \theta(t)} \right]$$  (3)

where $\theta_k^o$ is the wire temperature and $\theta_v$ is any reference temperature. The drift compensation is defined as :

$$e_k^2(t) = \frac{e_k^2(t) - (a_k + a'_k)}{1 + b_k}$$  (4)

The coefficients $a_k$, $a'_k$ and $b_k$ come from the King’s law $e_k^2 = a_k + b_k \cdot u_k^2$ where $u_k$ is the cold velocity, $a_k = a_{ok} + a'_k$ and $b_k = (1 + b'_k) b_{ok}$.

The coefficients $p_{ij}$, $q_{ij}$, $a_k$ and $b_k$ and the exponents $n_k$ are determined by calibration in a wind tunnel dedicated to the calibration of our sensors. The coefficients $d'_k$ and $b'_k$ related to the drift compensation are initially set to zero. They are regularly recomputed during the experimental campaign in situ, namely in the plane jet wind tunnel.

The calibration wind tunnel is a semi closed-loop wind tunnel. The test section has a length of 200cm and a square section of $28 \times 28cm^2$. The velocity profile at the entrance
nature was constant. The parameter was varied following a sawtooth mode while the flow temperature \( \alpha_{\text{cl}} \) angles and temperature compensated voltage using eqns 1 and 2. For the norm and the angle velocity vector are related to the drift vibration run. The second step is the angular calibration where is that the produced from least-squares fit. The advantage of this procedure

\[
\frac{\langle u' \rangle}{\langle v' \rangle} = \frac{k_0}{b_j} \]

Figure 1. Normalized profiles of the main statistical quantities for \( Re = 30,000 \) and \( r = 0.15 \):

- top-left, mean velocity \( \langle u \rangle \); top-right, mean velocity \( \langle v \rangle \); bottom-left, mean turbulent kinematic energy \( k = \frac{1}{2} (\langle u'^2 \rangle + \langle v'^2 \rangle + \langle w'^2 \rangle) \); bottom-right, Reynolds shear stress \( \langle u'v' \rangle \).

is uniform with a free stream turbulence intensity below 1%. A centrifugal blower supplies air to the test section with an adjustable velocity ranging from 0.5 to 12 m/s. The temperature of the flow is controlled by an air-water heat-exchanger located at the blower inlet. This temperature can be varied between 5 and 40°C. The reference velocity \( u_r \) is deduced from the blower rotational speed previously calibrated by PIV. The reference temperature \( \theta_0 \) is given by a type T thermocouple.

The calibration procedure is done in two steps. The first step is the linear calibration of the probe (at zero incidence) where the output voltage is related to the cooling velocity and flow temperature using King’s law. The flow velocity was varied following a sawtooth mode while the flow temperature was continuously decreased with a lower change rate to provide an equiprobable distribution of \((\|\mathbf{u}\|, \theta)\). The coefficients \(a_k\) and \(b_{ij}\), the exponents \(n_k\) and the wire temperatures \( \theta^w_k \) (with \( d'_{k} = 0 \) and \( b'_{k} = 0 \)) could be determined in a short single calibration run. The second step is the angular calibration where the norm and the angle velocity vector are related to the drift and temperature compensated voltage using eqns 1 and 2. For 13 angles \( \alpha \) ranging from \(-30^\circ\) to \(+30^\circ\), the flow velocity was varied following a sawtooth mode while the flow temperature was constant. The \( p_{ij} \) and \( q_{ij} \) coefficients could be deduced from least-squares fit. The advantage of this procedure is that the \( p_{ij} \) and \( q_{ij} \) coefficients, determined in a dedicated wind tunnel, depend only on geometrical characteristics of the probe and has practically no drift while the linear calibration is come out \textit{in-situ} and can easily be re-calibrated when a drift is observed.

**Experiments**

A plane jet discharging into a parallel moving airstream is defined by a Reynolds number \( Re = U_c |\mathbf{U}_j - \mathbf{U}_e| H \) and a velocity ratio \( r = \frac{U_j}{U_e} \) where \( U_c \) is the co-flow velocity, \( U_j \) and \( H \) are the velocity and the width of the jet at the exit and \( v \) is the kinematic viscosity. Far downstream from the origin, the mean behaviour of the jet becomes independent of the initial conditions (nozzle geometry, velocity profile, boundary layer) and depends only on the jet momentum thickness \( J \) and volume flow rate \( Q \) at the exit. For any form of mean velocity profile at the exit, \( U_j \) and \( H \) can be defined as:

\[
J = \int_{-\infty}^{+\infty} \langle u \rangle (\langle u \rangle - U_e) \, dy = U_j (U_j - U_e) H
\]

\[
Q = \int_{-\infty}^{+\infty} (\langle u \rangle - U_e) \, dy = (U_j - U_e) H
\]

where \( \langle \cdot \rangle \) denotes the temporal average operator. In the present work, the mean velocity profiles at the exit is a “top-hat” function of height \( U_j \) and width \( H \).
\[ \frac{\langle u \rangle - U_e}{\langle u \rangle_{cl} - U_e} = \exp \left[ -\ln(\frac{\delta}{\delta_{0.5}}) \left( \frac{y}{\delta_{0.5}} \right)^2 \right] \]  

(7)

with \( \delta = 0.5 \) to define the velocity half-width of the jet \( \delta_{0.5} \) as the \( y \) value for which \( \frac{\langle u \rangle - U_e}{\langle u \rangle_{cl} - U_e} = 0.5 \). Particular attention was paid to the estimation of these characteristic quantities \( (H, U_j, U_e, \langle u \rangle_{cl} \) and \( \delta_{0.5}) \) that express the overall behaviour of the flow and are used to normalize profiles of statistical quantities.

Figures 1 show normalized profiles of the main statistical quantities for \( Re = 30,000 \) and \( r = 0.15 \). The results of the other configurations \( (Re, r) \) and the results of Bradbury (1965) for the same configuration (not shown here) present the same behaviours. The normalized profiles of the mean velocity \( \langle u \rangle \) (figure 1 top-left) are well fitted by the Gaussian

RESULTS

The jet width \( H \) is given by the distance between the two separator plates. The jet velocity \( U_j \) and the co-flow velocity \( U_e \) are extracted from the mean velocity profiles at the jet exit which are shaped as a top-hat function. The centreline mean velocity jet \( \langle u \rangle_{cl} \) and the velocity width of the jet \( \delta \) are estimated by fitting a Gaussian function to the mean velocity profiles in the fully turbulent region (typically \( \frac{y}{H} \geq 8 \)). This Gaussian function is expressed as:

To characterize the influence of the two control parameters on the behaviour of this flow, several configurations were explored. The velocity ratio is set at \( r = 0.15 \) for 5 Reynolds numbers \( (Re = 10,000, 15,000, 20,000, 25,000 \) and \( 30,000) \) and the Reynolds number is set at \( Re = 15,000 \) for 7 velocity ratios \( (r = 0.00, 0.05, 0.10, 0.15, 0.20, 0.25 \) and \( 0.30). With the jet width \( H = 4.8 \) cm and the kinematic viscosity \( v = 15 \cdot 10^{-6} \) m\(^2\)/s, the jet and co-flow velocity ranges are \( 0 \leq U_e \leq 2 \) m/s and \( 3.8 \leq U_j \leq 11.5 \) m/s. One experiment consisted of measuring in the central plane of the jet \( z = 0 \) (\( z \) is an homogeneous direction) 13 velocity profiles (ranging from \( x/H = 0 \) to \( 37.5 \)) with 101 points, ie 1,313 points. The acquisition frequency was 12,500Hz, the cutoff frequency of the anti-aliasing filter was 6,250Hz and the number of acquisitions per point was 500,000, given an acquisition time per point of 40s. These values can be related to the shedding frequency of the order of 10Hz in the experiments. The total duration of an experiment (acquisition and probe displacement) is about 20h.
which the mean velocity gradient of the centreline symmetry emphasizes the mean velocity on either side of the jet centreline. The well recovered and virtual origin symmetric and antisymmetric with the same extreme stream than for the mean velocity profiles.

quantities, the self-similar behaviour appears further downstream. These two effects seem to be self-similar with this scaling.

The profiles of the mean turbulent kinetic energy \( k = \frac{1}{2} \left( \langle u'v' \rangle + \langle v'w' \rangle + \langle w'u' \rangle \right) \) (figure 1 bottom-left) and the Reynolds shear stress \( \langle u'v' \rangle \) (figure 1 bottom-right) are respectively symmetric and antisymmetric with the same extreme value on either side of the jet centreline. The well recovered shape due to the centreline symmetry emphasizes the measurement quality. These extrema occur at the location for which the mean velocity gradient of \( \langle u \rangle \) present also an extremum. In others words, the energy is maximum where the energy production is also maximum. For these two turbulent quantities, the self-similar behaviour appears further downstream than for the mean velocity profiles.

Figures 2 show the mean velocity decay of \( \langle u \rangle \) on the centreline at \( r = 0.15 \) for various Reynolds numbers and at \( Re = 15,000 \) for various velocity ratios. With the chosen representation, the constant velocity which can be used to define the potential core region is plotted as a constant function and the \( x^{-1/2} \) decay of strong or weak jet in the fully turbulent region is plotted as an increasing linear function. In the potential core region, the length of the potential core \( x_p \) is roughly \( 6H \) but this value seems to depend slightly on the Reynolds number and the velocity ratio. In the fully turbulent region, the mean velocity profiles on the centreline follow a \( x^{-1/2} \) decay as expected for a strong or weak jet. The centreline decay rate does not depend of the Reynolds number but decreases strongly with the velocity ratio, as for a mixing layer. The variation of the centreline mean velocity is represented as:

\[
\left[ \frac{(U_j-U_e)}{(U_j)_c - U_e} \right]^2 = K_u \left( \frac{x}{H} \right) - C_u \tag{8}
\]

where \( K_u \) is the slope that describes the centreline decay rate and \( C_u \) is the location of the virtual origin. Figures 3 present this centreline decay rate \( K_u \) and virtual origin \( C_u \) of the mean velocity with respect to the Reynolds numbers at \( r = 0.15 \) and velocity ratio at \( Re = 15,000 \). The strong velocity ratio depen-
The normalized profiles of velocity excess seems to grow rapidly from the exit value to a width of a plane jet is known to meet: \[ \frac{\delta_{0.5}}{H} = K_\delta \left( \frac{x}{H} - C_\delta \right) \] (9)

where \( K_\delta \) is the slope which describes a linear expansion of \( \delta_{0.5} \) and \( C_\delta \) is the location of the virtual origin. \( K_\delta \) is taken to be a measure of the jet spreading rate. Figures 5 show the jet spreading rate \( K_\delta \) and virtual origin \( C_\delta \) for the velocity half-width for \( r = 0.15 \) with various Reynolds numbers and for \( Re = 15,000 \) with various velocity ratios. As for the centreline decay rate \( K_u \), the jet spreading rate \( K_\delta \) decreases with the velocity ratio and seems to be Reynolds number independent.

Figures 6 displays the evolution of the mean turbulent kinetic energy \( k \) on the centreline at \( r = 0.15 \) for various Reynolds numbers and at \( Re = 15,000 \) for various velocity ratios. As \( x/H \) is increased, \( k \) normalized by the local mean velocity excess seems to grow rapidly from the exit value to a constant value in the far field. In the region of constant value, the normalized profiles of \( k \) are self-similar. For example, the normalized profiles of \( k \) are self-similar beyond \( x/H \simeq 20 \) for the configuration \( (Re, r) = (30,000, 0.15) \) (see figure 1 bottom left). The location of the beginning of the self-similar region for the second order moments depends mainly on the velocity ratio.

**CONCLUSIONS**

The completed work had generated a database on the plane jet with co-flow for large range of \( (Re, r, x/H) \). In the current study, we focus mainly on the first and second order moments. It appears than the plane jet behaves as a strong jet in the self-similar region explored \( (x/H < 37.5) \). In this region, the centreline decay rate \( K_u \) and jet spreading rate \( K_\delta \) depend slightly of the Reynolds number but strongly of the velocity ratio. Self-similarity occurs farther downstream for the turbulent flow that suggests the initial conditions have much more persistent effects on turbulence. The current work is a prior study preparing the investigation of the cold/warm plane jet developing between two co-flow with different velocity and temperature. For the future study, a new variable temperature HWA method is being developed to allow simultaneous measurement of velocity and temperature at the same point with a single wire (see Ndoye et al. (2010)). This new anemometer may be able to characterize the mechanisms of scalar transfer of a forced and even-mixed convection regime.

**REFERENCES**


