Characteristics of the turbulent/non-turbulent interface of a non-isothermal jet

BY JERRY WESTERWEEl*, ALBERTO PETRACCI, RENÉ DELFOS AND JULIAN C. R. HUNT

J. M. Burgers Centre for Fluid Dynamics, Laboratory for Aero and Hydrodynamics, Delft University of Technology, Mekelweg 2, 2628 CD Delft, The Netherlands

The turbulent/non-turbulent interface of a jet is characterized by sharp jumps (‘discontinuities’) in the conditional flow statistics relative to the interface. Experiments were carried out to measure the conditional flow statistics for a non-isothermal jet, i.e. a cooled jet. These experiments are complementary to previous experiments on an isothermal jet, where, in the present experiments on a non-isothermal jet, the thermal diffusivity is intermediate to the diffusivity of momentum and the diffusivity of mass. The experimental method is a combined laser-induced fluorescence/particle image velocimetry method, where a temperature-sensitive fluorescent dye (rhodamine 6G) is used to measure the instantaneous temperature fluctuations. The results show that the cooled jet can be considered to behave like a self-similar jet without any significant buoyancy effects. The detection of the interface is based on the instantaneous temperature, and provides a reliable means to detect the interface. Conditional flow statistics reveal the superlayer jump in the conditional vorticity and in the temperature.

Keywords: free-shear turbulence; entrainment; mixing

1. Introduction

Free turbulent flows, such as wakes, mixing layers and jets, are bounded by regions of irrotational fluid. The interface between the turbulent and non-turbulent fluid is usually very sharp. The interface is continuously deformed by the turbulent flow, so it has a strongly contorted shape over a wide range of scales. The sharp interface is in strong contrast to the mean flow properties, which show a very gradual change from the turbulent to the non-turbulent-flow region. This gradual change is the result of intermittency, in which turbulent and non-turbulent-flow regions pass along a fixed point. A long-standing problem about these unconfined, but localized, turbulent flows is to describe and quantify the characteristic features of the inhomogeneous interface [1–4], and to identify the nature of the entrainment process by which irrotational fluid becomes turbulent. Until recently it had been unclear whether this occurs as the result of outward spreading of small-scale vortices (‘nibbling’) or large-scale engulfment by the inviscid action of the dominant eddies in the turbulent-flow region. Results obtained from numerical

*Author for correspondence (j.westerweel@tudelft.nl).

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simulations indicate that engulfment is not the dominant process [5], in contrast to conclusions from many earlier studies [2,6]. Bisset et al. [7] analysed the flow properties in relation to the instantaneous position $y_i$ of the interface. This showed that there is a jump in the conditional flow statistics at the interface. This jump is related to the laminar superlayer that was first described by Corrsin & Kistler [8].

Recent experimental findings [9] revealed the existence of a superlayer at the turbulent/non-turbulent interface of a submerged jet. The measurements also indicated that the motion at the interface is dominated by small scales, and that entrainment is predominantly a small-scale process (i.e. nibbling). Similar observations were done for the progressing turbulent/non-turbulent interface in a tank with an oscillating grid [10,11], and in the simulation of a time-evolving planar jet [12]. Close examination of the laser-induced fluorescence (LIF) images reveals possible nibbling events, where previously detrained fluid (in which the vorticity has dissipated) is re-entrained, as shown in figure 1. This shows how the fluid becomes gradually turbulent, rather than being engulfed by the large-scale eddy motion.

Previous work [13] contained a theoretical analysis that relates the magnitude of the jump $\Delta U$ at the interface to the boundary entrainment velocity $E_b$ and the turbulent flux $F$ towards the interface [15], i.e.

$$E_b \Delta U = -F, \quad \text{with} \quad F = \nu_T \frac{\partial \langle U \rangle}{\partial n},$$

(1.1)

where $\langle U \rangle$ is the conditional velocity relative to a fixed distance from the instantaneous position of the interface, $n$ is a coordinate normal to the interface, and $\nu_T$ is the eddy viscosity. In a frame of reference relative to the position of the

Figure 1. Example of possible nibbling observed in an LIF time series of a self-similar jet. A previously detrained patch of fluid (indicated by the arrow) is being entrained by the turbulent fluid. The flow is from left to right. Adapted from data of Westerweel et al. [13,14]. (Online version in colour.)
interface, the gradient \( \partial(U)/\partial n \) on the turbulent side of the interface appears to be constant [13], and is represented as \( U_S/\ell \), where \( \ell \) is a relevant length scale over which the gradient is constant. The expression in equation (1.1) is also valid for a scalar \( \theta \) that is advected by the turbulent flow, with a jump \( \Delta \Theta \) at the interface. Given that there is a single interface for both momentum and scalar transport that propagates at a rate \( E_b \), it is easy to derive that [13]

\[
\frac{\Delta \Theta/\Theta_S}{\Delta U/U_S} = \frac{D_T}{\nu_T},
\]

where \( D_T \) is the eddy diffusivity of the scalar. This implies that the jump in a scalar is proportional to the turbulent diffusivity. Since in general \( D_T/\nu_T > 1 \) for most turbulent jet flows in liquids [1], it is expected that a jump in a (passive) scalar, like concentration or temperature, is larger than the jump in a momentum.

In this paper, we present the continuation of the jet experiments. Rather than using a dye with a high Schmidt number (\( Sc \sim 2300 \) for fluorescein dissolved in water), we use a cooled jet to investigate the mechanics of the interface for a scalar with a higher diffusivity (the Prandtl number for water is about 10). The experiment and the measurement approach are described in §2. The results on the turbulent-flow statistics, the interface detection and the conditional flow statistics relative to the turbulent/non-turbulent interface are described in §3. The main conclusions are summarized in §4.

**2. Experimental**

The experimental configuration is almost identical to the one described by Fukushima et al. [16] for the measurement of the mixing of the turbulent jet fluid, marked by means of a fluorescent dye, with the ambient fluid. We now apply a temperature-sensitive fluorescent dye, i.e. rhodamine 6G, to both the jet fluid and the ambient fluid. The characteristics of this dye are described by Walker [17]. The fluorescence intensity of this dye is inversely proportional to the fluid temperature with a sensitivity of \(-1.8\% K^{-1}\). For the purpose of the particle image velocimetry (PIV) measurements, the fluid has been seeded with small 8–12 \( \mu \)m diameter neutrally buoyant tracer particles.

The test section consists of a rectangular chamber of \( 110 \times 110 \times 300 \) mm. The jet fluid flows through a small stainless-steel tube with a 1 mm inner diameter into the test section. Glass windows on four sides of the test section allow for optical access for both the illumination light sheet and the LIF and PIV cameras.

The flow is illuminated with a thin light sheet (1 mm thickness) through the jet axis. The light sheet is generated from a double-cavity pulsed neodymium-doped yttrium-aluminium-garnet (Nd:YAG) laser with a maximum pulse energy of 200 mJ, with a light wavelength of 532 nm and a maximum repetition rate of 15 Hz. (The actual repetition rate is lower and is determined by the framing rate of the cameras.) The rhodamine 6G absorbs (part of) the (green) illumination light, which is emitted at a longer wavelength around 590 nm (viz. orange/red light). Two cameras are used to record the LIF signal (i.e. the light emitted by the fluorescent dye) and the PIV signal (i.e. the light scattered by the PIV tracer particles) separately. A diagram of the optical configuration is shown in figure 2.
Figure 2. Schematic of the optical configuration for the combined LIF and PIV measurements. The flow direction of the jet is normal to the diagram.

A beam splitter separates the light from the test section along two optical paths. The fluorescent light is separated from the light scattered by the tracer particles by means of a suitable optical band-pass filter that transmits the (red) fluorescent light and blocks the (green) light scattered by the tracer particles. Along the other optical path, a narrow-band interference filter only passes the monochromatic scattered light with a 532 nm wavelength from the tracer particles. This configuration effectively separates the LIF and PIV signals without any unwanted cross talk.

In this experiment, we use a single laser for both the LIF and PIV measurements. It is more common to use two different lasers for combined LIF and PIV, as the LIF generally requires a laser source with a good beam quality, whereas the PIV requires a high-energy pulsed laser [18]. Pulsed lasers generally have poor beam quality, and the total energy can vary substantially between subsequent pulses. A possible solution is to use a two-dye LIF approach, in which two fluorescent dyes are combined: one that is sensitive to the temperature, and one that is insensitive to temperature, i.e. to measure the local laser intensity [19]. However, this makes the whole optical configuration and experimental procedure rather complicated. Instead, we apply a single-laser and single-dye LIF method using the pulsed Nd : YAG laser for both the LIF and PIV measurements. The pulse-to-pulse variations of the beam intensity and profile are accounted for in the data-reduction procedure.

In order to achieve a significant fluorescence signal for the given coefficient of variation of fluorescence intensity with temperature (i.e. $-1.8\%\text{K}^{-1}$), we need to use a rather high dye concentration ($0.45 \text{ gm}^{-3}$) in combination with the largest possible temperature difference between the jet fluid that enters the nozzle and the fluid in the test section (see below).
Figure 3. Example of instantaneous fluorescence image (in false colour; red is high intensity, blue is low intensity). Image processing by means of a spatial filter is used to remove the striations in the LIF image. (a) Original, (b) detail of (a) and (c) after filtering of (b). (Online version in colour.)

Figure 3a shows an example of an individual measurement of the fluorescence intensity; a detail of this result is shown in figure 3b, which clearly shows that the fluorescence image contains striations. These are the result of several combined effects, such as the shadows cast by particles on the wall of the test section where the light sheet enters, and refraction owing to the local variation in fluid density (i.e. optical refractive index of the fluid). These striations complicate the accurate measurement of the temperature fluctuations, but can be accounted for by means of a two-dye LIF implementation [14]. Instead, we use a simplified approach in the form of digital image processing using a spatial filter that suppresses the effects of these striations. Here, we make use of the fact that our laser light sheet is collimated so that all light rays are parallel to the pixel lines in the digital image, and suppress the DC components of the horizontal Fourier transforms over a specific wavenumber range. Figure 3c shows the result after application of the spatial filter.

Experiments were carried out on a jet flow at a Reynolds number of $2 \times 10^3$. The jet fluid is cooled to a temperature 5°C before it enters the test section through the nozzle. The test section contains fluid (i.e. water) at a room temperature (approx. 20°C). The jet fluid is extracted from the test section before the experiment, which ensures that both the jet fluid and the ambient fluid contain the same dye concentration and tracer-particle concentration. Buoyancy effects in the cooled jet can be ignored for a distance from the nozzle $z$ that is smaller than the Morton length scale $\ell_M$ defined as [20]

$$\ell_M = \frac{M_0^{3/4}}{B_0^{1/2}}, \quad (2.1)$$

where $M_0$ is the momentum flux at the nozzle exit and $B_0$ the buoyancy flux at the nozzle exit, given by

$$M_0 = Q_0 U_0 \quad \text{and} \quad B_0 = Q_0 g \left( \frac{\Delta \rho}{\rho} \right), \quad (2.2)$$

where $Q_0$ is the volume flow rate at the nozzle, $U_0$ is the mean velocity at the nozzle, $g$ is the gravitational acceleration, $\rho$ is the fluid density and $\Delta \rho$ is
the fluid density variation owing to the temperature difference. For the present experimental conditions, we have $U_0 = 2 \text{ m s}^{-1}$, $Q_0 = 1.5 \times 10^{-6} \text{ m}^3\text{s}^{-1}$ and $g = 10 \text{ m s}^{-2}$. The density of water at 20°C and 5°C is 998.2 kg m$^{-3}$ and 1000 kg m$^{-3}$, respectively, so despite the large temperature difference, we have a relative density variation of $\Delta \rho / \rho \approx 1.8 \times 10^{-3}$ only. This is primarily owing to the fact that for water, the variation of density as a function of temperature vanishes at 4°C, which allows us to use fairly large temperature differences without unwanted large density differences and associated buoyancy effects. Substitution in equation (2.1) yields a Morton length scale of $\ell_M \approx 0.3 \text{ m}$. This is equal to the length of the test section. Given that all our measurements are carried out at a distance $z$ from the nozzle that is smaller than $\ell_M$, buoyancy effects should be negligible. In order to achieve a significant temperature signal from the LIF measurement, a rather high concentration of the dye was used, and the measurements were taken at a rather short distance from the nozzle, i.e. between 17 and 47 nozzle diameters. In general, one expects that a submerged isothermal jet becomes self-similar at distances larger than about 20–40 nozzle diameters. This is evidently a limitation of the present measurements, and this is discussed in §4 of this paper. To compensate for the reduction of the temperature of the fluid in the finite-volume test section owing to the injection of cooled jet fluid, a small heater coil at the top of the test section adds an equal amount of heat to the total system. We thus maintain an almost constant overall mean temperature of the system fluid.

3. Results

(a) Flow statistics

In total, 398 simultaneous sets of LIF/PIV images were recorded in 20 subsequent runs. After processing, we determined the conventional turbulence statistics, such as the mean centreline velocity $U_c$, mean centreline temperature difference $\Theta_c$ and mean jet width $b$, all as a function of the downstream distance from the nozzle. The actual variations of the fluorescence intensity are rather small, around 20 grey levels, relative to an overall mean fluorescence intensity of about 1000 grey levels. The variation in fluorescence intensity corresponds to local variations of the temperature of around 1K, and is significantly above the r.m.s. grey-level fluctuations of the sensor of about six counts.

Figure 4a,b shows the mean centreline velocity $U_c$ and temperature difference $\Theta_c$ as a function of the distance from the nozzle. The jet centreline velocity decays slightly faster than $z^{-1}$. This is in agreement with an increasing spreading rate ($b_u$ in figure 4c). This may be attributed to the fact that the jet at short distances from the nozzle is not yet fully developed and to the increasing effect of negative buoyancy relative to the jet momentum with increasing distance from the nozzle. The mean centreline temperature difference (figure 4b) scales as $z^{-1}$ within the experimental uncertainty, while the jet growth rate based on the temperature data ($b_\theta$ in figure 4c) decays with downstream distance. If it is assumed that the mean axial velocity and the mean temperature difference are well approximated by Gaussian curves, the effective half-width of the heat flux is given by $b_u = (b_u^{-2} + b_\theta^{-2})^{-1/2}$, which is also plotted in figure 4c. This shows a nearly constant growth

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Figure 4. The reciprocals of the (a) mean centreline velocity $U_c$ and of the (b) mean centreline temperature difference $\Theta_c$; solid line, linear fit, (c) the jet half-widths for the momentum ($b_u$, solid line), temperature ($b_q$, dashed line) and heat flux ($b_\ast$, dashed-dotted line), and (d) the fluxes of momentum (solid line) and heat (dashed line) as a function of the distance $z$ from the nozzle relative to the nozzle diameter $d$. The fluxes are normalized by the source fluxes at the nozzle.

with downstream distance. In figure 4d, the total momentum flux and total heat flux computed from the data in figure 4a–c are shown. Although the momentum flux and the heat flux are not exactly constant, their variation with downstream distance is small. Note that a linear extrapolation of the fluxes to $z = 0$ appears to be in agreement with the measured fluxes. The fact that the fluxes are significantly higher in the measurement domain may be attributed to the fact that there is a significant variation of the transport coefficients (i.e. viscosity and heat-transfer coefficient) between the fluid in the measurement domain and nozzle exit.

Figure 5 shows the scaled profiles of the mean velocity, turbulence intensity and Reynolds stress. The profiles appear to be self-similar within the experimental error.

Although the jet may roughly show characteristics that are indicative of a self-similar jet, the measurement of the temperature field is not straightforward. This is illustrated in figure 6, which shows the mean relative intensity variation (converted to temperature by means of the relative intensity variation per kelvin). The profile is distinctly asymmetric to the left side. It should be noted that the laser light sheet enters from the right, and the asymmetry is attributed to the scattering of light by the variation in density (i.e. refractive index) of the
Figure 5. (a) Scaled profiles of the mean velocity, (b) turbulence intensity in the axial, (c) radial velocity component and (d) Reynolds stress, for different distances from the nozzle.

Figure 6. (a) The mean variation of the fluorescence intensity relative to the intensity of a calibration measurement at constant temperature. The variation of intensity is proportional to the mean temperature of the jet. (b) Radial profiles of the normalized temperature difference obtained from the measured mean fluorescence intensity profiles for different downstream distances from the nozzle. The inset shows the measured mean temperature on the right side of the images (i.e. where the light sheet enters the jet) relative to the temperature \( T_0 = 19.8^\circ\text{C} \) of the fluid for the calibration measurement. (Online version in colour.)
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Figure 7. The scaled profiles of the (a) r.m.s. temperature fluctuations and (b) turbulent heat flux for different distances from the nozzle. The laser light sheet is passing the jet from right to left.

turbulent jet fluid; the scattering reduces the relative intensity of the light sheet. The reduction of intensity on the left side of the jet is then interpreted as an ‘increase’ of the temperature on the right side of the jet. (When a measurement was taken of an isothermal jet, no distinction could be found between the intensity (i.e. temperature) to the left and to the right of the jet.)

Figure 7 shows the scaled profiles of the r.m.s. amplitude of the temperature fluctuations and the turbulent heat flux. It is evident that the measurement of the temperature fluctuations at the left side of the jet is strongly affected. The scattering of light from the turbulent jet itself (i.e. due to variations in local temperature-dependent refractive index) primarily affects the measurement result for the amplitude of the temperature fluctuations. The turbulent heat flux (figure 7b) appears to be self-similar, although the amplitude of the scaled heat flux profile appears to be lower than found in other flows. This may be attributed to the fact that we do not resolve all scales in the combined LIF/PIV measurement.

Since the measurement of the temperature in the left side of the image is obviously corrupted, it was decided to perform measurements on the turbulent/non-turbulent interface only on the right side of the jet where the light sheet approaches the jet and no scattering owing to variations in density inside the jet has occurred.

(b) Interface detection

In order to investigate the flow behaviour at the interface of the turbulent/non-turbulent fluid motion, it is necessary to detect the interface. In a previous study where only the jet fluid contained a fluorescent dye, it was possible to detect the interface in a simple manner [13,14]. In the present experiment, this is no longer the case, and we have to revert to a more indirect method. We make use of the alternative detection methods proposed by Holzner et al. [21]. They propose to use either the magnitude of the estimated vorticity fluctuations or the magnitude of the velocity fluctuations to indicate the turbulent-flow region.
Figure 8. (a) Instantaneous kinetic energy \(u_z^2 + u_r^2\) and (b) temperature fluctuations \(T - T_{\text{ref}}\). (c) The detection of the jet fluid by applying the detection criterion proposed by Holzner et al. [21]. (Online version in colour.)

Figure 8a,b shows the instantaneous planar kinetic energy, i.e. \(u_z^2 + u_r^2\), of the jet and the instantaneous temperature variations, i.e. \(T - T_{\text{ref}}\). Figure 8c shows the result when applying the threshold criterion, as defined by Holzner et al. [21]. A complication of this approach is that irrotational velocity fluctuations exist, which may compromise the proper identification of the interface. We therefore also applied a threshold detection on the instantaneous temperature, where jet fluid was identified as the region where the instantaneous temperature has dropped by more than 0.1°C relative to the local ambient temperature (see inset of figure 2). Figure 9c shows the mean position of the interface based on the velocity data and on the temperature data. The mean position of the interface as obtained from the velocity and temperature data is shown in figure 9a.

In figure 9, we compare the statistics of the detected interface positions in the velocity data and in the temperature data. Figure 9a,b shows scatter plots of the interface positions accumulated over all image frames. Note that the velocity data are obtained at a 16 pixel data spacing, while the temperature data are obtained at single-pixel data spacing. In figure 9c, the mean position of the interface as detected in the velocity and temperature data is shown. The data almost coincide with the interface detected in the temperature data at a slightly larger distance from the jet centreline. It should be noted that the detection of the interface in the velocity data is affected by the presence of irrotational velocity fluctuations.

In figure 9d,e, we compare the cumulative probabilities of finding the interface within a distance \(y_i - y_0\) from the jet centreline. The cumulative distributions for the velocity data appear to be self-similar.

(c) Conditional statistics

After identifying the turbulent/non-turbulent interface in the temperature data, a conditional average of the temperature field is performed by averaging data that are located at equal distances with respect to the instantaneous location of the interface, as proposed by Bisset et al. [7]; see also Westerweel et al. [9,13]. The result for the temperature data is shown in figure 10. The conditional temperature is approximately constant at the irrotational side of the interface \((y - y_i < 0)\), while at the turbulent side of the interface \((y - y_i > 0)\), the
temperature difference increases linearly with the distance from the interface. At the interface itself, a clear jump $\Delta \Theta$ in temperature can be observed. However, the jump, when scaled with the mean centreline temperature difference $\Theta_c$, varies between 0.1 and 0.2. The largest value of $\Delta \Theta$ occurs closest to the nozzle. This is in rough agreement with the result obtained by Bisset et al. [7], who found a jump of about $0.15 \Theta_c$ at the turbulent/non-turbulent interface of a time-developing turbulent wake.

One of the major difficulties in interpreting the present result is that the observed jet flow is in a developing state. This makes it difficult to make a conclusion on the magnitude of the jump in relation to the boundary entrainment velocity. The jet half-width for the momentum $b_u$ shows a different growth rate than the jet half-width for the temperature $b_\Theta$; see figure 4c. Yet, the larger growth rate in $b_\Theta$ close to the nozzle and a smaller growth rate farther from the nozzle are in qualitative agreement to the reduction in magnitude of $\Delta \Theta/\Theta_c$ with downstream distance.

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Figure 10. The conditional temperature \( \langle T - T_{\text{ref}} \rangle \) as a function of the distance \( y - y_i \) from the turbulent/non-turbulent interface for increasing distance from the nozzle. Filled circles, \( z/d = 19.6 \); filled squares, \( z/d = 31.8 \); filled triangles, \( z/d = 44.0 \). (Online version in colour.)

The result in figure 10b shows that \( \Delta \Theta/\Theta_c \approx 0.15 \) and that \( \Theta_S/\Theta_c \approx 0.6 \) (at \( z/d = 32 \)). Given that in previous measurements, it was found that \( \Delta U/U_c \approx 0.09 \) and \( U_S \approx 0.9 \), substitution in equation (1.2) gives a ratio of about 2. This is roughly in correspondence with reported values of 1.6–2 for the turbulent Prandtl number [1]. It should be noted that our measurements are not in a part of the jet that can be considered as a fully developed state.

(d) Discussion

In this subsection, we will discuss some aspects of the experiment that requires further attention.

The spatial resolution of the PIV measurements is determined by the size of the interrogation domain (in-plane) and the thickness of the light sheet (out-of-plane). The interrogation domain is 32 × 32 pixels, which corresponds to 0.47 × 0.47 mm, while the light sheet has a thickness of 1 mm. This implies that the PIV spatial resolution is limited by the thickness of the light sheet. Since the same light sheet is used for the LIF measurements, the spatial resolution of the temperature fluctuations is also determined by the thickness of the light sheet. The finite spatial resolution affects the ability to resolve the small flow scales, as is evident from the reduced amplitude of the turbulent heat flux in figure 7b.

However, it is noted that the temperature gradients at the turbulent/non-turbulent interface are in-plane, so that the finite thickness of the light sheet does not pose a severe limitation when it comes to estimating the location of the interface. In this paper, we compare the location of the interface determined individually from the velocity and temperature data. Then, the spatial resolution of the velocity data is the limiting factor. Hence, the local averaging of the temperature data over 16 × 16 pixel domains (to reduce the effect of random noise) does not reduce the spatial resolution of the temperature data in comparison to the velocity data. The relatively high noise level (in comparison to the velocity data) that remains in the spatially averaged temperature data is likely to be responsible for the variation in the cumulative probability in figure 9e.
In §2, arguments are given why buoyancy effects can be neglected within the evaluated measurement domain. Yet, as the jet evolves downstream, eventually buoyancy effects will become important. Typically, buoyancy will have an effect on the spreading rate, and thus on the entrainment rate, of the jet. This is evident in the data presented in figure 4. The variation in jet width with downstream distance, as determined from the velocity and temperature data, appears to be in qualitative agreement with the observation that the jump at the interface decreases with downstream distance (see §3c).

In the far field of the jet, momentum can no longer suppress the effects of buoyancy, and baroclinic effects may generate (or suppress) the generation of turbulence; this has been demonstrated by Bhat & Narasimha [22] and Agrawal & Prasad [23]. This can have significant effects on the behaviour of the jet in the far field. However, in the present case, the cooled jet has negative buoyancy with respect to the ambient flow, and it is unclear whether the same mechanism applies as in buoyant jets and plumes. Further research may provide the dynamic relevance of turbulent/non-turbulent interfaces in buoyant jets and plumes [24].

4. Conclusions

The present paper describes the experimental investigation of a cooled turbulent jet. The aim of the experiment is to investigate the flow characteristics near the turbulent/non-turbulent interface, and to validate whether a jump that was observed in the momentum and concentration also occurs in the temperature field. A combined LIF/PIV method was used for the simultaneous measurement of the instantaneous velocity field and temperature field in a planar cross section through the jet centreline. The measurements are taken in a region where buoyancy effects can be neglected, and the jet in our experimental facility has the characteristics of a (neutrally buoyant) self-similar round jet. The detection of the turbulent/non-turbulent interface is based on the evaluation of the instantaneous magnitude of the kinetic-energy fluctuation, as suggested by Holzner et al. [21]. Also, a detection threshold was applied to the temperature field. These two independent detection criteria yielded interfaces that almost coincided and that had almost identical statistical properties, i.e. mean location and r.m.s. width. Conditional averages of the temperature difference relative to the detected turbulent/non-turbulent interface were computed. The conditional averages for the temperature show the same characteristics as previously found for the concentration and axial momentum [9–13]. The relative jump in the temperature appears to decrease with increasing distance from the nozzle. There appears to be a correlation between the measured growth rate in a fixed reference frame (figure 4c) and the magnitude of the jump. This is in agreement with a prediction that the magnitude of the jump is proportional to the turbulent transport coefficient, i.e. eddy viscosity for axial velocity, eddy thermal diffusivity for the temperature and eddy mass diffusivity for the concentration, as proposed by the scaling in equation (1.2). Although the present data show that the turbulent/non-turbulent interface coincides with a jump in the temperature field (most probably for the first time), the extreme conditions of the measurement complicate the measurements. Further
investigations should aim to improve the experimental conditions, in particular, the dynamic range of the temperature measurements and the development of the jet.

References

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