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Effects of Synthetic Jet Turbulence on Heated Line Plumes

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Abstract - Heated horizontal wires are employed in a synthetic jet turbulence chamber in order to study the influence of ambient turbulence on the plane plumes produced. Temperature distributions along the plume centerlines are presented for various turbulence intensities, heating powers and source sizes. The plume structure is affected by turbulence and it may be completely destroyed for sufficiently high intensities. In such cases the temperature distribution in the modified flow resembles that of a line plume in grid turbulence.

***Keywords*:** Buoyant Plume, Horizontal Heated Line Source, Laminar Plume, Turbulent Plume, Synthetic Jet Turbulence.

1. Introduction

Plumes are shear flows dominated by buoyancy, caused by temperature or density differences, or both. Initial momentum may be imparted to the plume in the case of buoyant discharge, as it happens in a large smoke stack. The momentum can promote or delay the evolution of the buoyant plume, but at sufficiently large distances from the origin the plume has "forgotten" its early history.

One of the simplest plume flows is that found in the wake of a horizontal heated cylinder or thin wire (line source) placed in a quiescent environment. The free-convection temperature field within the plume was explored by a number of workers, Fugii (1963), Brodowicz and Kierkus (1966), Forstrom and Sparrow (1967), Gebhart et al. (1970), Schorr and Gebhart (1970), Noto (1989), Lauriat and Desrayaud (1994), both theoretically and experimentally, many years ago. Experiments showed that the plume was initially laminar, exhibiting a slow swaying motion. At higher elevations above the heated wire turbulent bursts occurred, signalling the onset of transition. Forstrom and Sparrow (1967) introduced a modified Grashof number, Gr_M , and reported that transition occured for Gr_M values around $5x10^8$, while fully turbulent conditions prevailed for $Gr_M > 5x10^9$. The definition of Gr_M is as follows :
$Gr_M = (g\beta z^3 Q)/(\rho c_p \nu^3)$ where g = acceleration of gravity (9.81 m/s^2), β = coefficient of thermal expansion = 1/T ($^0K^{-1}$), where T is the fluid temperature, Q = heating Power per unit length of wire (W/m), z = elevation relative to the heated wire (m), ρ = fluid density (kg/m^3), c_p = specific heat at constant pressure (W/ kg ^{0}K), ν = kinematic viscosity of fluid (kg/m^3)

The maximum centerline temperature (or species concentration) Θ_c dropped as $z^{-3/5}$ for fully developed laminar conditions and as z^{-1} for turbulent conditions, while the plume widths b increased as $z^{2/5}$ and z^1 respectively, Rodi (1986) , Fisher et al. (1979). The experimental results for laminar plumes are in good agreement with boundary layer type solutions assuming the Boussinesq approximation.

The overall plume spreading mechanism can be thought of as consisting of the "meandering" of the plume centerline and the "spreading" of the plume relative to that centerline position. Time averaged plume images alone cannot provide information about these two mechanisms, because for example a thin plume that has a lot of meandering and a thick plume that remains straight result in the same averaged picture. There is no characteristic length scale in the pure plume as described above. If there is buoyancy flux or momentum at the source (the origin), then there are length scales which indicate over which distance buoyancy still has an effect on the plume or over which distance the flow changes nature, from a buoyant jet to a buoyant plume Fischer et al. (1979) , Morton (1959).

In real life pure plumes seldom exist, since there would quite often be present some kind of environmental parameter like ambient density stratification, cross flow, turbulence, solid or porous boundaries, interfaces etc. Of particular importance and also relevant to the present work is ambient turbulence, as it would be the interaction of the plume from a large plume stack with atmospheric turbulence. The mechanisms of spreading and mixing are now more complicated because of the interaction of the turbulence generated within the plume itself with the surrounding turbulence. Again it is easier to examine the passive plume of a thin heated wire in a turbulent flow than the plume with significant buoyancy flux and momentum. The former has received considerable attention both experimentally and theoretically Uberoi and Corrsin (1952), Townsend (1954), Warhaft and Lumley, (1978), Stapountzis et al., (1986), Durbin (1980), Anand and Pope (1985), Livescu et al. (2000), Ching et al. (1995). Experiments in wind tunnels with grid turbulence indicate that the thermal plume begins near the source (a heated wire of diameter less than the Kolmogorov length scale) as a smooth distribution of material which flaps about only slightly. Further downstream, meandering prevails over instantaneous plume width growth. Concentration fluctuations are dominated by meandering over travel times from the source of the order of a Lagrangian time scale of turbulence, T_L. Sufficiently far downstream (many T_L) the internal turbulence structure ("patchiness") dominates concentration fluctuations and meandering diminishes.The mean centerline concentration (mean temperature) for the last two stages drops with distance x from the source as x^{-1} and as $x^{-0.4}$ respectively.

Similar experiments in a water tank with an oscillating grid (zero mean flow), Ching et al. (1995), showed that turbulent line plumes (from sources larger than the Kolmogorov length scale) can be completely destroyed by background turbulence when the convective velocity of the plume w_c ($\approx$ the velocity of ascend of the plume cap) is roughly less than twice the ambient turbulent intensity, u_{RMS} , i.e when $w_c < 2u_{RMS}$. If $u_{RMS} > w_c$ (a case relevant to the present experiments) then the plume is destroyed from the onset. Similar findings are reported for plumes with initial buoyancy flux and momentum, Huebner (2004) that is, ambient turbulence significantly increases the plume width b.

In the present work we examine experimentally the influence of ambient turbulence on heated line sources exposed to a zero mean flow nearly homogeneous and isotropic turbulent field generated by synthetic air jets, Stapountzis et al (2013). The advantage over oscillating grids in a water tank is that the region of homogeneity and isotropy is more uniform, turbulence intensities are comparatively higher and the alteration of the turbulence characteristics more straightforward. Compared to decaying wind tunnel grid turbulence, synthetic jet turbulence has homogeneity of the Lagrangian time scales, therefore the travel time of marked fluid particles can be directly associated with distances from the source. The experimental work is still in progress and in this paper the turbulence effects on the mean centerline temperatures of the plumes are presented.

2. Experimental Setup

2. 1. The Turbulence Chamber

The experiments were conducted in a "Turbulence Chamber" which is formed by eight loudspeakers in a cubic arrangement, all pointing towards the center, Fig. 1. It is described in detail in Stapountzis et al (2013). See Fig. 1 for the coordinate system used. The plain plumes are generated by heated horizontal wires placed in the central region of the chamber, where turbulence is nearly homogeneous and isotropic over a space approximately $\pm$ 0.1 m wide in all directions. The turbulence intensity depended on the sinusoidal forcing frequency of the loudspeakers and the differences between the RMS values of the u,v,w components were less than 12 %, while the mean velocity was found to be an order of magnitude smaller. Fig. 2 shows the dependence of the u_{RMS} velocity on the forcing frequency. Best results are obtained for low f, between 40 and 60 Hz. Three different turbulence intensities were utilized in the present work i.e. u_{RMS} = 0.78, 0.67 and 0.42 m/s, corresponding to f = 40, 50 and 100 Hz. The convection speed, w_c , of the plume cap was estimated from video analysis of the plume flow visualization.

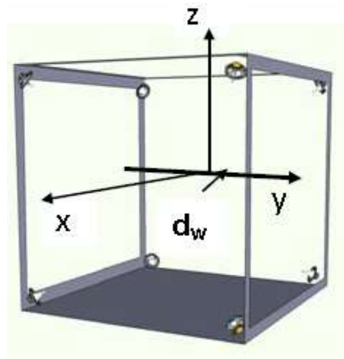

Fig. 1. Turbulence Chamber with eight loudspeakers for the generation of Synthetic Jet Turbulence and coordinate system used. The heated line source is along the y direction.

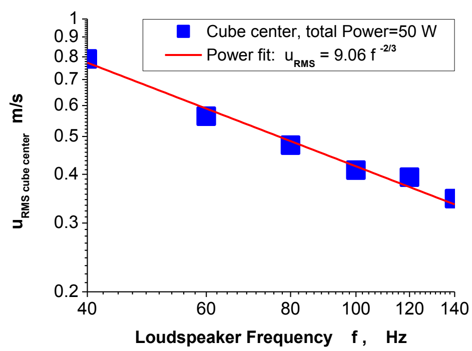

Fig. 2. Turbulence intensity u_{RMS} at the Turbulence Chamber center.

2. 2. Line Source Arrangement

The wires were electrically heated and stretched along the horizontal y axis. They had diameters d_w= 0.1 mm ("thin" wire) and 6.5 mm ("thick" wire). Tests were made with values of the electrical power equal to 140, 215 , 305 and 485 W/m, however in most runs 305 W/m was used. The thin wire was comparable in size to the Kolmogorov microscale η, while the thick wire was much larger. In the unforced case ("quiescent environment") the pure plume extended upwards over a long distance. When turbulence was applied, the increased plume dispersion limited the measurable temperature field within the homogeneous region (approx. ± 0.1 m) except for high frequency forcing and very low turbulence intensities. In those cases, the plume break-up occurred outside the homogeneous region, Ching et al. (1995) and will not be presented here.

2. 3. Monitoring the Plumes from the Line Sources

The thermal field of the plume, Θ(x,y,z) , and of the ambient air, Θ_a , far from the plume, was measured with thermocouples 0.2mm in size. An infrared camera was additionally employed in order to find the temperature on the wire surface itself, Θ_w (wall temperature). The application of strong turbulence caused the breakup of the pure plume into a dispersing cloud, increased heat transfer from the wire and significant drop in the wire surface temperature. Measurements with a hot wire operating in the constant current mode are planned for the examination of the fluctuating temperature field. The plume development was visualized with smoke which was produced after a small oil droplet was layered on the wire surface. Image analysis of the videos taken provided information about the mean plume characteristics, but also about the plume centroid and its standard deviation (related to the meandering and spreading of the plume - Stapountzis et al 2013). The centerline mean temperature distributions Θ(x,0,0) , Θ(0,0,z) are presented in a dimensionless form $T^* = (\Theta - \Theta_a) / (\Theta_w - \Theta_a)$ for various turbulence intensities u_{RMS}, (as a result of changing frequencies), heating Powers Q (W/m) and source sizes (wire diameter d_w).

3. Temperature Measurements and Discussion

3. 1. Temperature Distributions in the Vertical Direction - Thick Wire

Fig. 3 demonstrates the profound influence that turbulence has on the dimensionless centerline mean temperature T^* of the thick wire plume in the vertical, z direction at a heating rate of 305 W/m.

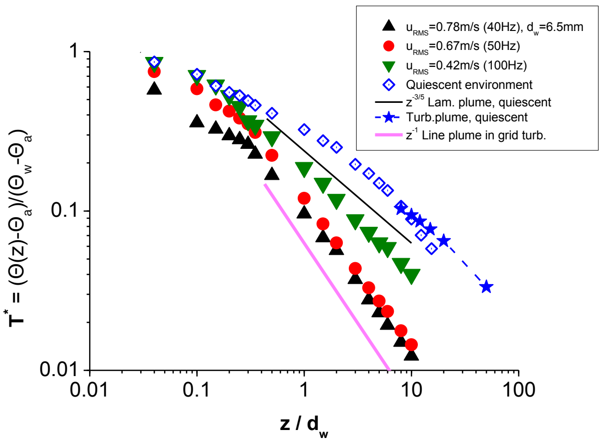

Fig. 3. Distribution of dimensionless centerline temperature in the z direction for thick wire, Q=305 W/m. Theoretical power laws for laminar and turbulent plumes in a quiescent environment are shown , Noto (1989), Fisher et al (1979), and plumes in grid turbulence , Stapountzis et al (1986)

Quiescent environment temperatures (i.e. those of the pure plume, without background turbulence) are significantly higher than those with turbulence applied over the whole range of the upward elevation positions z/d_w examined. Turbulence caused the plume to break up and spread randomly in all direction (see also following Fig. 9 in section 4), lowering the surrounding fluid temperature. As the applied ambient turbulence weakens (u_{RMS} = 0.42 m/s in Fig. 3) the T^* distribution looks more similar to the undisturbed plume T^* distribution. The undisturbed plume centerline distribution attained a power law decay with an exponent of -3/5 after about $2d_w$ upwards, which means that the plume was laminar, in accordance with the theoretical predictions of Fujii (1963) and the experimental findings of Noto (1989) and of other workers at later times. This trend is changing at roughly 10 diameters from the source, showing a sharper decay in T^* a sign of transitional behaviour. In contrast, the dispersing temperature cloud driven by external turbulence exhibits a power law decay with a slope -1 as early as $0.5d_w$ far from the source. Undisturbed turbulent plumes in the fully developed region are also characterized by the -1 power law decay of the centerline scalar concentration distributions, Fisher et al (1979), but also passive plumes from thin wires in grid turbulence, Stapountzis et al (1986). However, in this latter work (Fig. 12 in their paper) the -1 slope region emerges hundreds of diameters downstream of the horizontal source (a thin wire 0.15 mm in diameter d_w in a turbulent field with length scales L_x two orders of magnitude higher than d_w). In the present experiments the source size (=6.5 mm) is much greater than the Kolmogorov microscale but also comparable to the turbulence length scale. An attempt was made to calculate T^* using the undisturbed turbulent plume expression , Fisher (1979), with our data of source size and heating power (blue asterisk symbol inFig. 3) accepting a virtual origin value $z_0 \approx 5d_w$. Since at those distances the real plume is in a transitional state the agreement is only fair.

Increasing the heating power causes the laminar plume to become more unstable, exhibiting a swaying motion (Noto (1989), also observed in the present flow visualization, Fig. 9). The considerable scatter in the T^* data of Fig. 4 for the undisturbed plume beyond the $10d_w$ elevation support this observation.

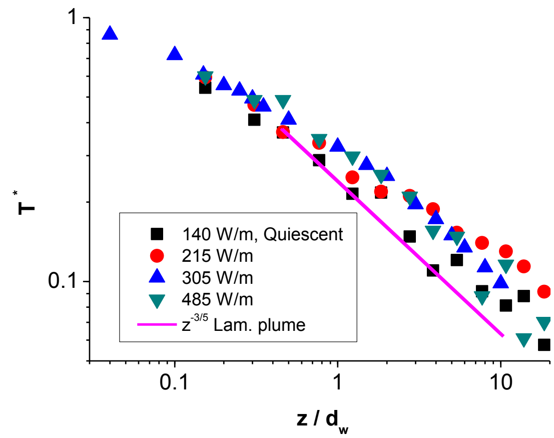

Fig. 4. Distribution of dimensionless centerline temperature in the z direction for various heating powers Q, thick wire, quiescent environment (no turbulence)

Values of the modified Grashof number Gr_M at various elevations z are shown in Fig. 5. Gr_M is computed with the local fluid properties and not the film temperatures, because when external turbulence is applied Θ_a is found very far from the source. Therefore the present Gr_M values are expected to be smaller than the ones computed with the film temperatures, Forstrom and Sparrow (1967). The fact that the region of $5x10^8$ is not reached indicates that the undisturbed plume has not become turbulent yet. Background turbulence causes an increase in the Gr_M values.

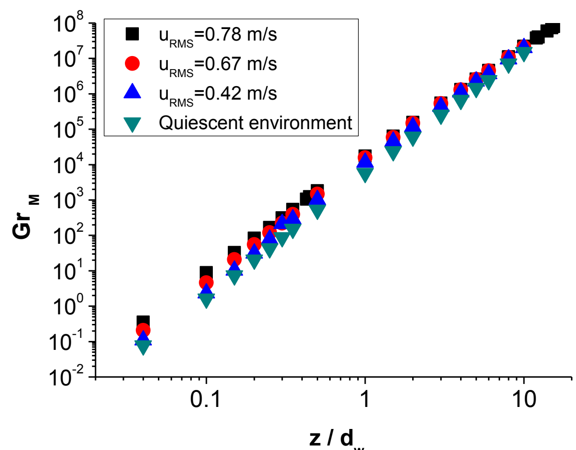

Fig. 5. Effect of turbulence on the modified Grashof number, Q=305 W/m , thick wire

3. 2. Temperature Distributions in the Horizontal Direction - Thick Wire

The centerline temperature distribution of the thick wire in the horizontal , x, direction is shown in Fig. 6. As soon as the measuring location falls away from the immediate strongly heated region round the wire (Gebhart et al 1970, their Fig. 5) the temperatures in the undisturbed laminar plume drop dramatically with horizontal distance compared to the forced plume temperatures. In the undisturbed plume the local velocity field around the plume, excluding the area just above it is characterized by relatively low velocities (Brodowicz and Kierkus 1966, their Figs. 1, 3) and the thermocouple signal is more likely to be influenced by radiation effects. When turbulence is applied, the breakdown of the laminar plume causes turbulent diffusion of heat in the same manner as in grid turbulence. Due to the zero mean flow , heat is not convected is any particular direction (the direction of the free stream speed in a wind tunnel) but it is dispersed nearly isotropically. For comparison the mean centerline temperatures behind a horizontal heated wire in grid turbulence is shown as well (d_w=0.71mm, Q=105 W/m, Stapountzis et al 1986), the x^{-1} decay law appearing appearing in those and the present measurements at sufficiently large distances from the source.

The "isotropizing" effect that the imposed turbulence exerts on the laminar plume is demonstrated in Fig. 7. T^* values corresponding to the same values of the x and z coordinates are plotted against each other. Background turbulence, when applied to the plume, creates a nearly uniform temperature field roud the source. The stronger the turbulence, the more isotropizing is this influence. For weaker turbulence (e.g. u_{RMS} = 0.42 m/s), there is evidence of the plume breakup at some later stage and not immediately as it happens for strong imposed turbulence.

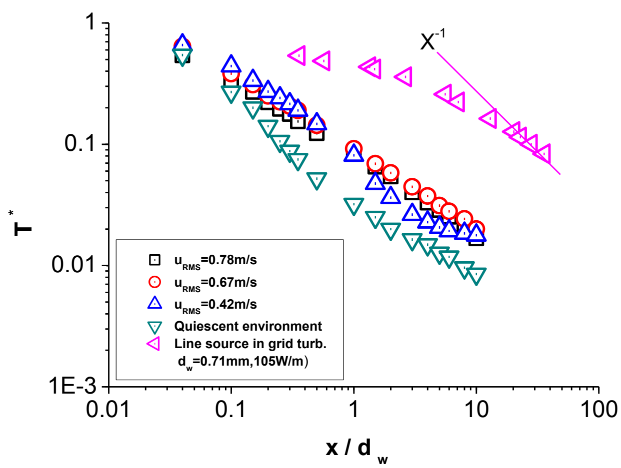

Fig. 6. Distribution of dimensionless centerline temperature in the x direction for thick wire, d_w =6.5 mm ,Q=305 W/m. Comparison with experimental result for line source of diameter d_w= 0.71 mm , Q=105 W/m, in grid turbulence, Stapountzis et al (1986).

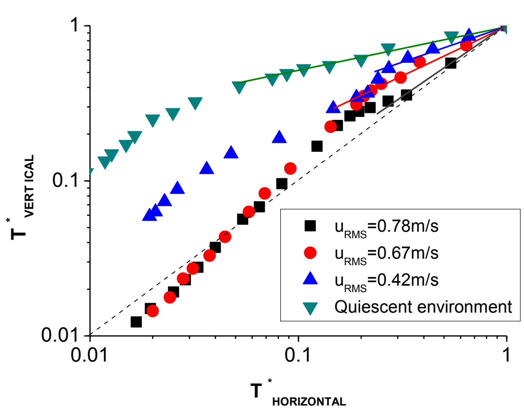

Fig. 7. Comparison of dimensionless centerline temperatures in the horizontal and vertical directions for the same values of x and z coordinates , thick wire, Q=305 W/m

3. 2. Temperature Distributions in the Horizontal Direction - Thin Wire

Tests with a much thinner wire (d_w = 0.1 mm, Q=50 W/m) were carried out and the results for the horizontal T^* distribution are shown in Fig. 8, along with the wind tunnel data of Stapountzis et al (1986) ((d_w = 0.15 mm, Q=105 W/m, grid turbulence). Here the source sizes and heating powers are matching closer, however there are differences in the length and time scales of the two imposed turbulent flows. The x^{-1} decay law exists in both experiments.

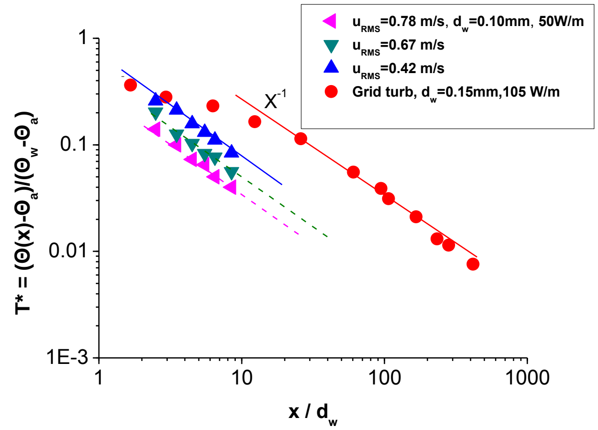

Fig. 8. Distribution of dimensionless centerline temperature in the x direction for the thin wire, d_w=0.10 mm, Q=50 W/m. Comparison with exp. result in grid turbulence , d_w=0.15 mm, Q=105 W/m, Stapountzis et al (1986)

4. Flow Visualization of the Plume

The thick wire plumes were illuminated with a vertical laser light sheet and smoke streaklines are shown in Fig. 9 for both quiescent conditions (Fig. 9a, b, c) and imposed turbulence (Fig. 9d,e,f, with Q=305 W/m , u_{RMS} = 0.78 m/s). Video analysis is in progress in order to determine the centroids of the plume and their standard deviation (Stapountzis et al , 2013). The immediate breakup of the laminar plume and the subsequent spreading in all directions is the supporting evidence from these pictures. Flow visualization showed that the upward convective velocity of the plume cap (w_c) was less than twice the turbulence intensity u_{RMS}. Therefore the plume is destroyed from the onset, as also found by Ching et al (1995).

a b c d e f

Fig. 9. Laminar plumes with transition region for the thick wire, Q=305 W/m , quiescent environment (a,b,c) and the subsequent effect of turbulence with u_{RMS} = 0.78 m/s (d,e,f)

5. Conclusions

Laminar plane plumes of heat are greatly influenced by externally imposed turbulent disturbances. Depending on the turbulence level, there could be immediate breakup of the complete plume for strong turbulence, or a postponement of this process for a certain vertical elevation for weaker turbulence. After the breakup the temperature decay laws are similar to those found in grid wind tunnel turbulence.

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