EXPERIMENTAL INVESTIGATION OF TWO HEATED OBLIQUE JETS INTERACTING WITH A TURBULENT FLOW

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ABSTRACT

The objective of this study is to analyse experimentally the thermal field of two air-jets inclined at 45° interacting with a turbulent longitudinal flow. The heating of the air-jets before their entrance simulates the passive scalar. At the outlet, the air-jets generate some vortexes in the longitudinal flow. The measurement of temperature and fluctuations are carried out with the help of a hot wire anemometer. The mean temperature fields and fluctuations are represented in the 0yz plane in different positions on longitudinal axis. The results show that the mode of the passive scalar dispersion verified previous works carried out. The temperature fluctuations increase with the passive scalar dispersion as the jets go away from the source.

KEYWORDS: Jets, thermal field, passive scalar, turbulent flow, temperature fluctuations, vortex, experiments.

I. INTRODUCTION

Air pollution has become over time a worrying phenomenon in the world. One of the factors contributing to this atmosphere pollution is the hot gas emitted by heat engines as jets. To better understand the movement of these jets and heat dispersion in the atmosphere, it is necessary to study its transport from the moment they are issued until their total dispersion. Now days, many studies have been done on the dynamic aspect. In preliminary studies made in the wake of Ahmed body, Gosse [1] showed that the velocity of the longitudinal flow dominated the jet velocity gradually as one moves away from the source. The jets may also be issued at an angle for generating vortexes in a longitudinal flow. On this subject, Küpper [2] used two numerical models to explain the control of boundary layer phenomena and heat transfer at the entrance of the reactors. Tilmann [3] showed in an experimental study the
influence that a discontinuous jet, emitted at a given frequency can have on a turbulent flow. Other experimental studies have shown that the heat contained in the jets moved in the longitudinal direction of the flow. For example those of Kothnur and Clemens [4], which in addition show that the directions of the scalar propagation and the normal shear stress are perpendicular. Despite these numerous studies, there are still gray areas including understanding the phenomena of temperature fluctuations on the passive scalar dispersion. The aim of our study is to make an experimental investigation of the thermal field of a turbulent flow interacting with two heated oblique jets. This will help to understand the influence of temperature fluctuations on the passive scalar dispersion in order to better explain the phenomenon of air pollution. The design and construction of the model were made in the laboratory. The choice of holes diameter jet emission has been based on the work of Gibb and Anderson [5], and more recently those of Gosse [1]. The jets’ emissions are inclined by 45°, based on the work of Bray and Garry [6], this inclination is an optimal position to have good quality jets and eddies in the longitudinal flow. To carry out this study, we first describe the experimental device, and then, we do an analysis of mean temperature fields and of standard deviation of the temperature.

II. MATERIAL AND METHODS

In this study, the main flow is the air generated by a blower longitudinal plane, type “open circuit” which can generate flow velocities \( U_\infty \), between 3 m.s\(^{-1}\) and 12.5 m.s\(^{-1}\). We used hot wire anemometry as measurement technique.

II.1 Blower type “open circuit”

This blower, built by Delta Lab, is shown in Figure 1. It consists of a motor-driven fan of the centrifugal type providing a maximum flow rate of 0.32 m\(^3\).s\(^{-1}\). The revolutions number of the fan is regulated by the intermediary of a variable speed transmission supplied with 220 V single-phase currents. The air circuit comprises a diffuser located in the rectangular fan discharge. The two gratings (wire cloth) located downstream of the dust filter to reduce the level of turbulence and homogenize the flow. In the output of the two-dimensional convergent (section 80x200 mm\(^2\)), the maximum velocity of the flow is set between 3 m.s\(^{-1}\) and 20 m.s\(^{-1}\). The level of turbulence at the nozzle outlet is in the order of 0.35%.

![Blower type “open circuit”](image)

Figure 1: Blower type “open circuit”
The two oblique jets are diverted 45° in a plane perpendicular to the main flow (flow in the outlet of the nozzle) through circular holes made on a plate fixed to the lower edge of the outlet nozzle. They have each one a diameter of 5 mm and are separate one of the other by 40 mm as figure 2a shows it. The emission of pollutants is simulated by injecting hot air through the two holes at a velocity $U_j$ through a small pipe with 5 mm of diameter under the plate as shown in Figure 2b. The temperature difference $\Delta T_{ref}$ between the jet and the outside is kept constant at 20°C using a regulated power supply. The thermostat of the heating system is connected to the thermocouple control chamber. This small temperature difference avoids effects gravitate. The velocity of the heated flow ($U_j$), is measured by a loss of load connected to a micro manometer Furness Control. This velocity is adjustable between 1 and 10 m.s$^{-1}$ as shown in figure 3. The origin 0 of the orthogonal axe (0x, 0y, 0z) is located equidistant from the two holes i.e, 20 mm of each axis. The two holes are symmetrical relative to the 0x axis oriented in the direction of the main flow. The 0y axis is vertical and the 0z axis is perpendicular to the main flow.

Figure 2: Plate; a) Front view; b) Top view

Figure 3: the device of injection of the hot air

The measured variable in this study is the temperature difference between the heated zones and upstream fluid. In this study, the sign "+" indicates a normalized quantity. Lengths are normalized by the distance between the hole and the main axis H equal to 20 mm, and the temperature difference is normalized by the initial temperature difference $\Delta T_{ref}$. Molecular effects are negligible compared to the turbulence, the report $\Delta T/\Delta T_{ref}$ can be likened to a concentration $c$, will vary between 1 and 0 emission to infinity. For convenience, the time average and standard deviation of a quantity $X$ are denoted respectively $<X>$ and $<X'^{2}>^{1/2}$.

The outputs of the two jets heated are located respectively at the point S of coordinates $(X^+=0, Y^+=0, Z^+=-1)$, and S' of coordinates $(X^+=0, Y^+=0, Z^+=1)$.

II.2 Hot wire anemometry

The Measure of a velocity flow using hot wire anemometry is based on convective heat exchange between the hot wire and the flow. This exchange is used to connect the wire temperature to Nusselt number (Nu) which is a function of the flow velocity and the current power $I$ shown by the equation (1). The figure 4 below, illustrates well this principle of convective exchange. The detail is clear in Paranthoën and Lecordier [7], and Rosset, and al [8].
where,

\[ \text{Nu} = \frac{\text{hd}}{\lambda_g}. \]  \hspace{1cm} (1)

The hot wire anemometer operates at constant temperature. In this case, when the flow velocity varies, measuring the current I needed to keep the temperature \( T_w \) of the wire, constant. This technique provides a frequency response of approximately 100 kHz.

The electrode used is a set TSI, consisting of a sensor to a wire, a processor and an IFA conversion board 12-bit analog voltage, installed in a PC with high memory capacity and storage. Probes conducted in the laboratory are made with platinum-rhodium 10%, with 3 \( \mu \)m of diameter. A schematic of the probe used is presented in figure 5.

The response of the wire as a function of the velocity is not linear. Calibration of the hot wire placed in the outlet section of the jet; is performed before each series of measurements by varying the velocity of the flow. An example of a calibration curve is shown in figure 6. The experimental points are then approximated by a polynomial of order n or with a selected interpolation function type "Cubic Spline". The temperature of the flow is measured by a thermocouple type K and recorded. If there are any changes in the temperature of the flow, a correction can thus be applied to the measured voltage.

II.3 Temperature measurement

The instantaneous signal \( T(t) \) of temperature can be decomposed as:

\[ T(t) = <T> + T'(t) \]  \hspace{1cm} (2)

\( <T> \) is the temporal mean value and \( T'(t) \) is the temperature fluctuation. The signal is characterized by a mean value \( <T> \), and centered moments that allow access to the standard deviation.
deviation $<T'^2>^{1/2}$. In our case, each mean time is calculated on a sample of more than 200,000 points.

Mean temperature:
$$<T> = \frac{1}{N} \sum_{i=1}^{N} T_i$$

Variance:
$$<T'^2> = \frac{1}{N} \sum_{i=1}^{N} (T_i - <T>)^2$$

In the experiments of dispersion downstream from the linear sources or point sources, the variations in temperature which one must measure quickly become relatively weak. The temperature signal is thus influenced by the background noise as the distance from the source. This requires making corrections to background noise to accurately measure the actual signal. Assuming that the instantaneous value of the temperature can be written in the following form:

$$T_{\text{mes}}(t) = <T>_V + T'_V(t) + T'_{\text{BF}}(t)$$

The subscripts “mes”, "V" and "BF" correspond respectively to the measured values, true values and background noise values. To make the corrections of noise on the variance, we used the following equation:

Variance:
$$<T'^2>_V = <T'^2>_{\text{mes}} - <T'^2>_{\text{BF}}$$

III. RESULTS AND DISCUSSION

We conducted several series of temperature measurements by choosing a single longitudinal flow velocity $U_i = 5$ m/s for different jets velocities $U_j$, equal to 5 m/s, 10 m/s and 20 m/s, corresponding to the Reynolds number ($Re = Ud/\nu$), of 1200, 2400 and 4800. To show more details, we performed measurements in the plane ($Y^+$, $Z^+$) with a very small mesh. On the $Z^+$ axis, the scan was between -2.5 to +2.5 values with 1/20 of step of measuring. On the $Y^+$ axis, the scan was between 0 to 1.5 values with 1/20 of step of measuring. That makes a total of 3,000 points of space measurements.

III.1 MEANS TEMPERATURES

The figures 7a, 7b and 7c below represent the iso-values of mean temperature at the positions $X^+ = 0.5; X^+ = 2.5$ and $X^+ = 5$; for a jets velocity of $5$ m/s (in this case, the jets velocities are equal to the longitudinal flow velocity, ($U_j$ equal to $U_i$)). These figures show that the two jets are symmetric with respect to the axes $0X^+$ and $0Y^+$, and even when one is in a remote position ($X^+ = 5$). We observe a low dispersion of the passive scalar in this position and the area of the intermediate temperature ($<T> = 0.099$), becomes predominant. The two jets are still largely dominated by the longitudinal flow that prevents the plate off. The area where the temperature is high ($<T> = 0.3$) remains sticking to the plate along the longitudinal axis $0X^+$.

The figures 8a, 8b, 8c and 8d below represent the iso-values of mean temperature in the positions $X^+ = 0.5; X^+ = 1; X^+ = 2.5$ and $X^+ = 5$, when the jets have a Reynolds number of 2400. We note that the two jets take off from the plate upon release ($X^+ = 0.5$), and reach the coast $Y^+ = 1$ from the position $X^+ = 2.5$. The size of the hottest zone ($<T> = 0.3$), decreases as the distance along the longitudinal axis. It disappears almost completely at the position $X^+ = 5$, and the intermediate zone ($<T> = 0.099$), becomes very dominant and invades the entire area near the plate ($Y^+ = 0$). Coast $Y^+ = 1$ appears as the maximum height reached by the hottest zone of the jets. The two jets are no longer symmetrical relative to the axes $0X^+$ and $0Y^+$ from the position $X^+ = 1$, also considered as the position where the scalar begins to
undergo a dispersion. This is very important when the jets reach the position $X^+ = 5$, in the area where $Y^+ \leq 1$, the temperature is greater than zero.

The figures 9a, 9b, 9c and 9d below represent the iso-values of mean temperature in different positions of the plane $(Y^+, Z^+)$, for jets with a Reynolds number of 4800. We note that the two jets are less influenced by the longitudinal flow. They quickly take off the plate at the position $X^+ = 0.5$ and cross the coast $Y^+ = 1.5$ at the position $X^+ = 5$. The size of the hottest zone ($<T> = 0.33$), decreases significantly from the position $X^+ = 0.5$. It disappears completely in a jet and still a bit in the other, specifically one that is close to the axis 0X$^+$. This shows that the scalar disperses less rapidly than in the previous case (Re = 2400). The size of the intermediate zone ($<T> = 0.099$), becomes dominant and the asymmetry of the two jets with respect to axes 0X$^+$ and 0Y$^+$ is even more significant.

In these three sets of measures, we note that in the case where the jets could be less influenced by the longitudinal flow (Re= 4800), there are quick release streams of the plate but the scalar disperses less. This is obvious for all three positions because at $X^+ = 5$, the temperature is $<T> = 0$ (dark blue) on the wall of the plate, and different from zero in the region close to the wall for other cases Re = 1200 and Re = 2400. This heat dispersion on the plate is translated by the shape of the isotherms which spread much on the plate.

Figure 7: Iso-values of mean temperature fields $<T>$ in the plane $(Y^+, Z^+)$, Re= 1200

a): $X^+ = 0.5$; b): $X^+ = 1$; c): $X^+ = 5$
Figure 8: Iso-values of mean temperature fields $<T>$ in the plane $(Y^+, Z^+)$, $Re = 2400$

a): $X^+ = 0.5$; b): $X^+ = 1$; c): $X^+ = 2.5$; d): $X^+ = 5$
III.2 Standard deviation of means temperature

We obtain the temperature fluctuations shown in the previous paragraph that we represent through the standard deviations.

The figures 10a, 10b, and 10c below represent the iso-values of the standard deviation of mean temperatures in different positions of the plane (Y+, Z+), for a Reynolds number of 1200. We note that the symmetry of the two jets with respect to axes 0X+ and 0Y+ is confirmed. The standard deviation of the mean temperature decreases when the jets move...
away along the longitudinal axis $0X^+$. At the position $X^+ = 0.5$, this iso-value is 0.04 in the hottest zone and it become 0.01 at the position $X^+ = 5$. The influence of longitudinal flow on the two jets is very important.

The figures 11a, 11b, 11c and 11d below represent these standard deviations in different positions of the plane ($Y^+, Z^+$) for a Reynolds number of 2400. The decrease of the standard deviation with distance along the longitudinal axis is confirmed. In the hottest zone, it is from 0.06 at $X^+ = 0.5$, and 0.02 at $X^+ = 5$. The asymmetry between the two jets is observed from the position $X^+ = 1$.

a)

b)

c)

Figure 10: Standard deviation of mean temperature $<T'^2>^{1/2}$ in the plane ($Y^+, Z^+$). Re= 1200. a): $X^+ = 0.5$; b): $X^+ = 1$; c): $X^+ = 5$
Figure 11: Standard deviation of mean temperature \(<T'^2>^{1/2}\) in the plane \((Y^+, Z^+)\). Re= 2400.

a): \(X^+=0.5\); b): \(X^+=1\); c): \(X^+=2.5\); d) \(X^+=5\).

The figures 12a, 12b, 12c and 12d below represent these standard deviations in the previous positions of the plane \((Y^+, Z^+)\) for a Reynolds number of 4800. In the hottest zone, the standard deviation increases when the two jets move along the longitudinal axis.

In general, we note that highest standard deviation of the mean temperature corresponds to the values of Reynolds number 2400. We saw in the previous section that this case of Re = 2400, was one where the dispersion of passive scalar was perfect.
Figure 12: Standard deviation of mean temperature $<T'^2>^{1/2}$ in the plane $(Y^+, Z^+)$. Re= 4800.

a): $X^+= 0.5$; b): $X^+= 1$; c): $X^+= 2.5$; d) $X^+= 5$

IV. CONCLUSIONS

The interaction between a longitudinal flow and two jets preheated has a great influence on the passive scalar dispersion. In view of the figures shown in the previous sections, we can say that when the two jets are issued, the scalar is transported directly downstream from a straight line by gradually dispersing. This has already been highlighted by Gosse [1], in the wake of Ahmed body. This dispersion is best done in the case where the jets are less influenced by the longitudinal flow. To further explore this issue, a study of the dynamic range must be made to understand the influence of the vortex on the dispersion of passive scalar in the turbulent flow.

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REFERENCES


NOMENCLATURE

Small letters
x = longitudinal coordinate (m)
y = vertical coordinate (m)
z = transversal coordinate (m)
d = diameter of the holes on the plate (m)

Capital letters
H = distance between one of the two holds from the principal axe (m)
ΔT_{ef} = Temperature difference between hot jet and the exterior (K)
T’ = Temperature fluctuations (K)
R_w = Hot wire resistance (Ω)
P_{ui} = Electrical power supplied (Watt)
U_i = Flow velocity at the outlet of the nozzle (m.s^{-1})
U_j = Jet exit velocity (m.s^{-1})
0x = longitudinal axis
0y = vertical axis
transversal axis
S The location point of the two jets sources

**Greek symbols**
- \( \nu \) Kinetic viscosity of air (m\(^2\).s\(^{-1}\))
- \( \rho \) Volume mass (Kg.m\(^{-3}\))
- \( \lambda \) Thermal conductivity (J.m\(^{-2}\))

**No dimensional numbers**
- \( Re \) Reynolds number
- \( Pr_t \) Turbulent Prandtl number
- \( Nu \) Nusselt number

**Exponents, indices and specials characters**
- \( + \) Normalized value (H for lengths) and (\( \Delta T_{\text{ref}} \) for temperatures)
- \( <T> \) Mean temperature \( T \)
- \( <X> \) Means time of a quantity \( X \)
- \( <X'^2>^{1/2} \) Standard deviation of a quantity \( X \)
- \( <X'^2> \) Variance of a quantity \( X \)