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Experimental study of the structure of a thermal plume inside a rectangular tunnel

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Abstract: *The objective of this work is to experimentally simulate a plume developing inside a horizontal tunnel. The experimental device used in this simulation is essentially constituted of a hot disk, a rectangular tunnel and a ventilation system. The hot disk is heated by Joule effect to a constant and uniform temperature, and placed inside the tunnel. The hot source generates a thermal plume. We first studied the evolution of the thermal plume without ventilation system. The study of the average and fluctuating thermal and dynamic fields shows three zones during the vertical evolution of the free plume. A first zone close to the source, serving to the plume supply in fresh air, is characterized by the apparition of three escapes of the thermal plume. Followed by a second zone where the main escape undergoes a contraction. Finally, a third zone where the thermal plume accumulates and undergoes a flow upstream named backlayering and a flow downstream that borders the ceiling to leave by the free part of the tunnel.*
Keywords *Fire plume, Fire tunnel, Thermal plume, turbulent natural convection.*

I. INTRODUCTION

The thermal plume model is an experimental methodology usable easily to simulate the fire plume [1, 2]. The thermal model contributes to better understand many practical fire problems such as problems associated with fire tunnel and flow encountered in fires of structural elements of buildings. The interaction of these material surroundings with the fire plumes reveals very complex physical mechanisms.

From a fundamental viewpoint, the study of the interaction of the thermal plume with the vertical walls that surrounds it began with Agator's work [3] on the influence of a wall placed in the vicinity of the plume source. He noted that the plume is attracted toward the wall. A. O. M. Mahmoud and al. [4, 5, 6] are the first who were studied the evolution of a thermal plume in semi-confined geometry. They studied the evolution of a thermal plume produced by a flat disc heated at 300° C and placed at the entrance of an open-ended vertical cylinder. They noted that the plume interacts narrowly with the thermosiphon flow which develops along the internal wall of the cylinder. Contrary to previous works [7, 8, 9, 10], they noticed the appearance of a supplementary zone in addition to the two classic zones which characterize the vertical evolution of the free plume. Just above of the source, the instability zone is characterized by the formation of rotating rolls and by the existence of three extrema of temperature and velocity profiles. Higher, a second zone of turbulence pre-established followed by a last zone where the turbulence is fully established. J. Zinoubi et al. [11, 12] continued this experimental work by studying the form factors effect of the plume evolution inside a vertical cylinder.

Using the visualization and analysis of the thermal and dynamic profiles of the flow, they showed the existence of three zones described previously. By studying the influence of the cylinder height, J. Zinoubi et al. [13] noted a blocking of the ascending flow in the third zone due to the lateral expansion of the plume. They also showed that a choice of the cylinder height not exceeding the second zone of the flow let us avoid this blocking. In order to determine the geometry effect, N. Taoufik et al. [14] studied the evolution of a thermal plume generated by a flat disc inside an open-ended rectangular canal.

They noted the existence of the three zones observed in the cylindrical geometry. Also, they noticed the contraction of the rotating rolls size located in the first zone of the flow.

Recently, A. O. Mahmoud et al. [1] studied the effects of source air entrainment on the flow structure induced by two heat sources, one placed at ground level, the other at a height above the ground. The experimental results permitted to specify that the additional vertical contribution of the air entrainment especially entails a substantial change of the flow structure of the plume, an important elongation of the height of the plume spread, a considerable increase of the flow rate of the plume and an important elevation of the thermal flux absorbed by the air.

It is clear that these works were essentially interested to the determination of the effects of the emplacement, the heat release of the fire and the tunnel geometry on the critical ventilation velocity. The physical structure of the plume inside tunnel has not been studied. A fire plume inside tunnel has very complex flow structure because it is a physical phenomenon that is affected by geometry of tunnel and ventilation system. The complex structure of a tunnel fire has not been clearly understood because of its physical complexity. For better understanding, more fundamental research will be realized.

The objective of this experimental work is to understand better the physical mechanisms that characterize the structure of a fire plume evolving in a horizontal tunnel.

II. EXPERIMENTAL APPARATUS FOR SIMULATON

The experimental apparatus is shown in Fig.1 and 2. The numbers in the description presented below refer to the part numbers of Fig.1. It is essentially constituted of a horizontal channel having a length of 2 m and a rectangular section (0.30 m x 0.15 m), a ventilation system and a hot source. The source is constituted of a flat disk (1) having a diameter of 7 x 10-2 m and electrically heated by Joule effect to a surface temperature of 300 °C. The fire plume is simulated by the hot source placed at ground level and in the central part of the channel. The uniformity of the source surface temperature is obtained by the use of wire resistors mounted behind the disk. A thermal regulation apparatus kept the temperature of the disk as uniform as possible with a good approximation. Al–Cr thermocouples are used to measure the surface temperature of the disk. The temperature difference between the center and the extremity of the disk is less than 5 °C.

To explore the thermal and the dynamic average fields of the plume, a resistance wire anemometer at constant current (2) is used. This technique adopted for a long time by Doan et al. [17], in natural convection study, is based on the principle of the resistance variation of a platinum wire (9 µm in diameter, 3 mm in length). The velocity and the temperature of the fluid are the two parameters that change the electric resistance of the wire. Doan et al. [17] showed that a supply current, delivered by a generator (3), of 1.2 mA makes the probe slowly sensitive to the temperature (cold wire), and a supply current of 75 mA, makes it sensitive to the temperature and the velocity (hot wire). The probe calibration allows the determination of the velocity and the temperature of the flow from the voltage across the probe [3, 9]. The wire thermal inertia (the wire time constant is of the order of 1 ms) does not introduce any measurement errors, especially at the low frequencies found.

A computer-driven displacement system (4), allowing the traversing of the probe in two directions, is used to explore the thermal and dynamic average fields at every level of the flow. The minimal displacement in the vertical direction is 10-3 m, whereas in the horizontal direction it is $2x10^{-5}$ m.

A computer (5) equipped with a data acquisition card acquires instantaneous signal values at 10 ms intervals and records the digitized signals for further statistical processing. A statistical treatment of these data permits calculation of average values of temperature, velocity and different moments.

A ventilation system (8) is installed in the left extremity of the tunnel. This system permits to send in the channel a longitudinal air flow to adjustable velocity. In order to get a uniform flow, a nest of bee (7) and a set of grids (6) are placed behind the ventilation system.

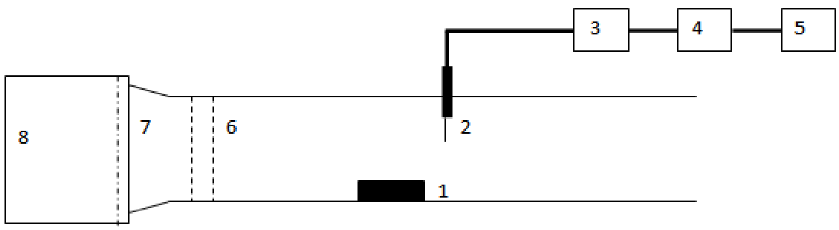

Fig.1. Studied configuration

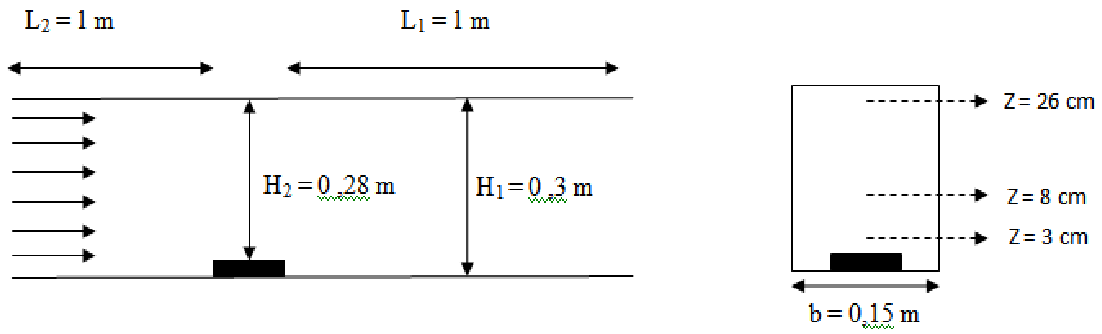

Fig.2. Experimental apparatus

III. RESULTS AND DISCUSSIONS

The experimental results which we present in this work are carried out with air. The Grashof number of the flow is Gr = 2.01 x 109, the Froude number is Fr = 0.96 and the Prandtl number is Pr = 0.75. For the determination of the reference parameters, the physical properties of the air have been evaluated at the inlet temperature (T0). **3.1. Development of a thermal plume inside a tunnel without ventilation system**

3.1.1. Average fields

Fig.3 presents the isotherms, traced in the median plan of the hot source (xOz), and the transverse distribution of the average temperature of the flow for three different levels (Z = 3, 8, 26 cm). This isotherm shows a global view of a thermal field of the plume flow. Indeed, the figure shows three different behaviors during the vertical evolution of the plume in the tunnel. Also, it high lights the existence of three distinct zones. Just above the source, a first development zone of the flow is characterized by high thermal gradients. Downstream, a second zone of contraction of the plume where the thermal gradients are relatively weak. This zone prepares the flow to pass in a third zone where the flow is intercepted by the hot ceiling of the tunnel.

In the first zone (Z < 8 cm), the isotherm shows a main escape of the thermal plume that moves toward the obstacle constituted by the ventilation system before continuing its path toward the tunnel ceiling. This effect has been observed by J. M. Agator [3] while studying the interaction of a vertical wall with a thermal plume flow generated by a hemispheric hot source. On the other hand, the confinement of the air inside the channel is characterized by the formation of rotating rolls just above the hot source [5, 14]. The isotherm shows two secondary exhausts of these rolls on both side of the source. This plume behavior has been noted by several authors [4, 5, 11]. At a level close to the source (Z = 3 cm), the temperature profile shows an important peak at the level of the source side indicating a brutal transformation of the fresh air in thermal plume. Also, at the over of the source, one notices the existence of a region to weak temperature spreading on the whole width and that will serve to the supply source of the plume.

In the intermediate zone (8 ≤ Z ≤ 18 cm), the isotherm shows a contraction of the plume and the existence of a region to weak temperature crossed by the exhausts of the air nets at the over of the source. This zone constitutes a source of provision, in fresh air, for the plume and the hot source. This flow structure comes closer of the one observed by J. Zinoubi [11] relative to a thermal plume evolving inside a vertical cylinder. At the level Z = 8 cm, the temperature profile shows a peak less important correspondent to the net of exhaust of the hot air.

In the superior zone (18 < Z ≤ 26 cm) situated at the vicinity of the tunnel ceiling, one notices the existence of a mixture of hot air and fresh air. This indicates the thermal plume occupation of the whole zone in the neighborhood of the wall. Very close to the ceiling (Z = 26 cm), the thermal profile becomes flat, indicating a quasi homogenization of the plume flow.

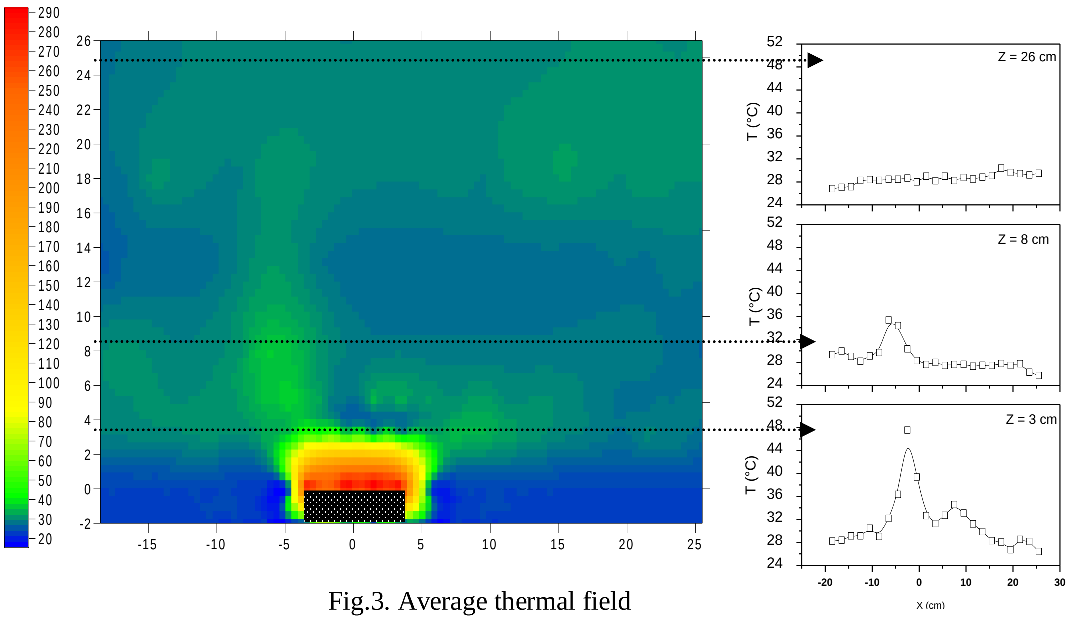

Fig.3. Average thermal field
Without ventilation

In Fig. 4 are presented the iso-values, traced in the median plan of the hot source (xOz), and the profiles of the average velocity of the flow for three different levels (Z = 3, 8, 26 cm). The iso-values show relatively important velocities at the level of the main exhaust and the weaker values on both side of the plume.

This main exhaust, that realized by puff slightly baffled toward the obstacle, heads vertically toward the tunnel ceiling to contact of which it divides in two parts: a first part (backlayering) moves toward the ventilation obstacle whereas the second part heads toward the free part of the tunnel. This behavior is similar to the one of smokes descended of a fire developing inside a tunnel, observed by several authors [15, 16]. In the first zone, one notices a fresh air flow to weaker velocity that heads toward the plume source for its supply. In the second zone, one notes the existence of a region to weak circulation acting as fresh air reservoir for the source supply as well as the thermal plume during its development.
For a level close to the source (Z = 3 cm), the temperature profile shows a peak at the level of the source side and the elevated values to the downstream of the source indicating the easiness of the fresh air penetration of free part of the tunnel. In the intermediate zone (Z = 8 cm), one notes the coexistence of the peak at the level of the source side with a more important gradient due to a contraction of the plume flow. In the superior part of the tunnel (Z = 26 cm) and in the sense of the obstacle, the profile indicates weak velocities whereas of the opposed sense it shows the relatively elevated velocities indicating an easiness of escape toward the outside of the plume by the free part of the tunnel. Indeed, as arriving to the level of the ceiling the thermal plume tries to escape toward the outside while wrapping the ceiling.

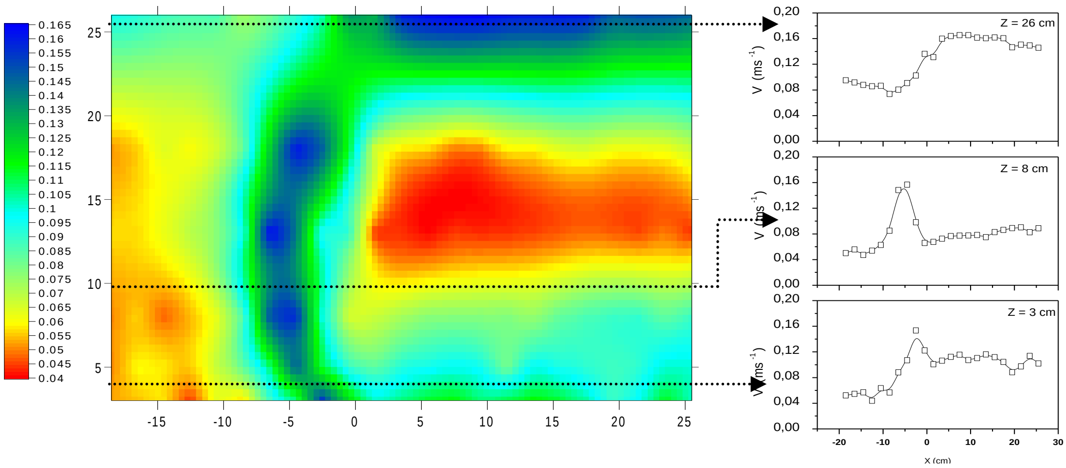

Fig.4. Average dynamic field
Without ventilation

3.1.2. Fluctuating fields

In order to better characterize the flow structure of the plume, the study of the thermal and dynamic fluctuating fields is necessary.

In Figs. 5 and 6, the transverse evolutions of the thermal and dynamic turbulent intensity are, respectively, presented at different levels. These profiles again show three different zones of the flow.
In the first zone and just above the hot source (Z = 3 and 5 cm), Fig.5 shows the important values of the turbulent intensity. This is attributed to a strong interaction between the air fresh attracted by the source and the flow plume. For the intermediate zone (Z = 8 and 13 cm), the profiles reveal an important turbulence rate with raised fluctuations due to a more or less strong interaction between the thermal plume and the fresh air coming from the outside. Concerning the superior part of the tunnel (Z = 18 and 26 cm), the profiles are nearly similar with weaker fluctuations than those previous indicating a thermal homogenization of the flow.

In the first zone (Z = 3 and 5 cm), Fig.6 shows values raised of the dynamic turbulent intensity of the flow situated at the level of the source side (X = - 5 cm). These important values are due to a strong interaction between the escape of the thermal plume and the regions to weak circulation situated on both side of the plume source. For the second zone (Z = 8 and 13 cm), the profiles show important values of the dynamic turbulent intensity. This is attributed to an interaction between the plume flow and the two regions of fresh air supply previously noted. Concerning the superior part of the tunnel, the profiles also show important values due to the interaction of the main flow of the plume with the backlayering.

3.1.3. Thermal skewness factor

The study of the skewness factor allows the characterization of the difference between the probability density law governing the fluctuations distribution of the flow temperature and the ideal Gaussian probability for which the skewness factor is Fdt = 0.

In Fig.7 is presented the transverse distribution of the thermal skewness factor of the plume flow. At the level of the zone close to the source (Z = 3 cm), Fig.7 shows an important peak correspondent to the main escape of the plume indicating a strong dominance of the hot air. Whereas for the level Z = 5 cm, the peak moves slightly toward the obstacle and becomes less accentuated confirming the observations relative to the dynamic and thermal profiles previously mentioned. On both side of this peak, less important values are noticed indicating the dominance of the hot air resulting from the secondary exhausts at the level of the hot source. For the intermediate zone (Z = 8 and 13 cm), the profiles show the positive values corresponding to the levels near of the source. This behavior indicates a light dominance of the hot air coming from the thermal plume. On the other hand, the profiles show negative values relatively distant of the source confirming the existence of the two regions of weak circulation acting as reservoir in fresh air to supply the hot source. Concerning the superior part (Z = 18 and 26 cm), negative values have been noted in different regions indicating the existence of fresh air at the vicinity of the tunnel ceiling. It already confirms the behavior of the thermal and dynamic fields previously noted.

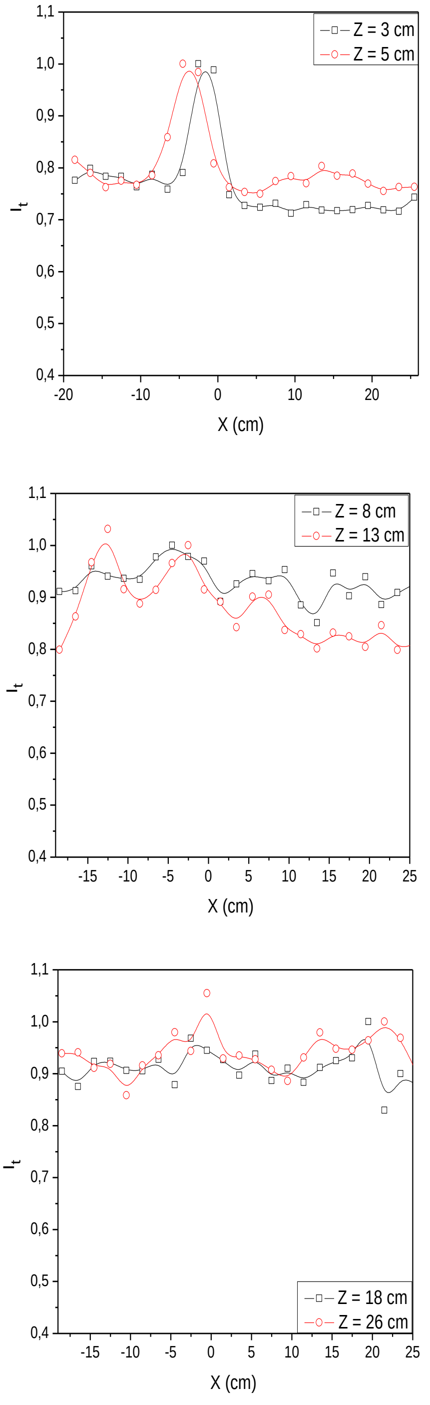

Fig.5. Thermal turbulent intensity

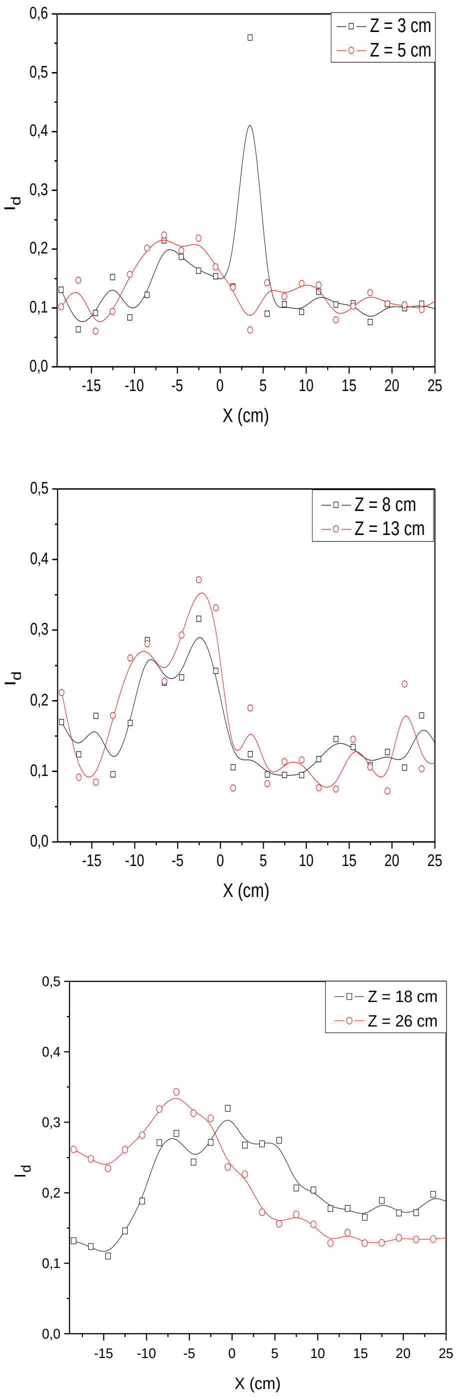

Fig.6. Dynamic turbulent intensity

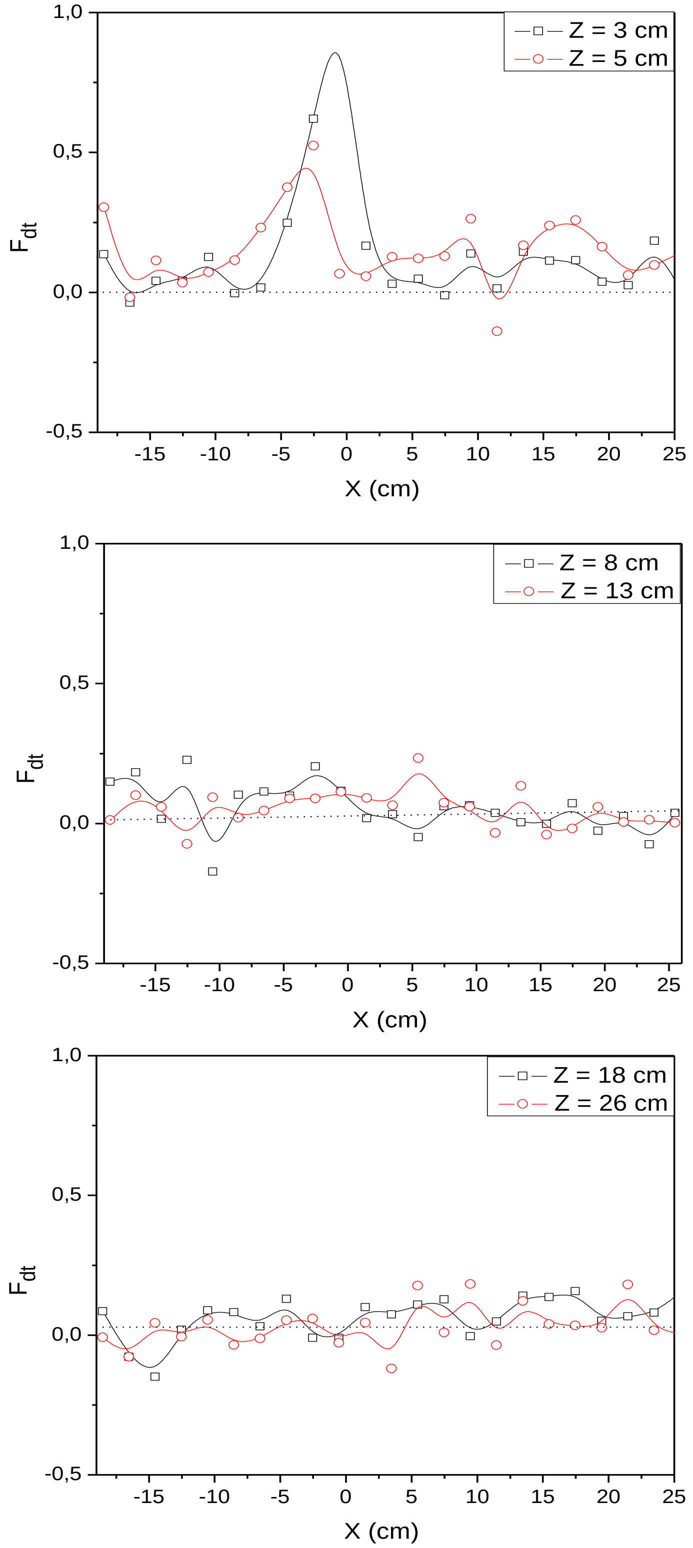

Fig.7. Thermal skewness factor
Without ventilation

IV. CONCLUSION

This experimental work is a contribution to the understanding of the physical behavior of a fire releasing inside a tunnel in absence and in presence of longitudinal ventilation.

The development of the thermal plume generated by the hot source inside a rectangular tunnel without ventilation system show that the flow structure is divided in three zones. In a zone close to the source the thermal plume escapes from the source in three places: a main exhaust clearing vertically above the source and two secondary exhausts clearing at the source borders. In a second zone the main clearing of the plume follows a contraction.

Thereafter, in the superior part of the tunnel, the ascending flow of the plume is divided in two senses: a flow upstream named backlayering and a flow downstream that borders the ceiling to leave by the free part of the tunnel.

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Nomenclature

b tunnel width (m)

d source diameter (m)

Fd skewness factor $F_d = \dfrac{\frac{1}{N}\sum_{i=1}^{N}(X_i - \overline{X})^3}{[\frac{1}{N}\sum_{i=i1}^{N}(X_i - \overline{X})^2]^{3/2}}$

g gravitational acceleration (m/s^2) ;

Gr Grashof number (Gr = $\dfrac{g\beta(T_S - T_a)H_1^4}{b\nu^2}$)

I t thermal turbulent intensity (I t = $\dfrac{\sqrt{\overline{T'^2}}}{T'_m}$)

I d dynamic turbulent intensity (I d = $\frac{\sqrt{V'^2}}{V_m}$)

L tunnel length (m)
H1 tunnel height (m)
H2 distance between the surface of the source and the ceiling (m)

Re Reynolds number (Re = $\frac{VD_h}{\upsilon}$)

Tm instantaneous values of temperature (°C);
Ta ambient temperature (°C);
Ts temperature of disc (°C) ;
T’ temperature fluctuating (°C) ;
T’m maximal fluctuating temperature (°C)
Vm average velocity (m/s)

Greek letters

  thermal expansion coefficient (K^{1})
  kinematic fluid viscosity (m^2/s)
ρ air density at average temperature (kg/m^3)