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Experimental Study of a Thermal Plume Evolving Inside a Rectangular Tunnel: Effects of the Source Height

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Abstract

The aim of this work is to simulate experimentally a plume of fire placed at different heights evolving inside a horizontal tunnel, in order to determine the effect of the source site on the plume structure. The plume is produced from an electrically heated disc at a constant and uniform temperature. It is then placed inside the tunnel. First, we studied the evolution of the thermal plume while placing the source at a height above the ground. The study of the thermal and dynamic fields of the flow shows the existence of 3 zones during the vertical evolution of the thermal plume. In the first zone, the flow is strongly influenced by the presence of the thermal plume generating source. Followed by a second zone where the plume undergoes a contraction which prepares the flow to be passed in a third zone where the thermal plume divides into 2 parts by touching the ceiling. The first part (backlayering) moves towards the side blocked by the blower and the second moves towards the free side while going along the ceiling. We then determined the effect of the source site compared to the ground level on the behavior of the thermal plume inside the tunnel. For that, 3 sites of the source (h = 2 cm, h = 7, 5 cm and h = 15 cm) were studied. The comparative study shows that the structure of the flow is influenced by the site of the hot source.

Keywords: Fire plume, fire tunnel, thermal plume, turbulent natural convection

Nomenclature

b	tunnel width;
d	source diameter;
F_d	skewness factor $F_d = \dfrac{\frac{1}{N}\sum_{i=1}^{N}(X_i - \overline{X})^3}{[\frac{1}{N}\sum_{i=i1}^{N}(X_i - \overline{X})^2]^{3/2}}$
I_t	thermal turbulent intensity ($I_t = \dfrac{\sqrt{\overline{T'^2}}}{T'_m}$)
L_1	length between the channel output and the source;
L_2	the length between the inlet channel and the source;

H_1 tunnel height;
H_2 distance between the surface of the source and the channel ceiling;
T_m instantaneous values of temperature;
T_a ambient temperature;
T_s temperature of disc;
T' temperature fluctuating;
T'_m maximal fluctuating temperature;
Vm average velocity
Z section height studied relative to the heat source;
Z_1 studied section at 3 cm of the hot source;
Z_2 studied section at 8 cm of the hot source;
Z_3 studied section below the ceiling by 2 cm.

Introduction

The thermal plume model is an experimental methodology used to easily simulate the fire plume [1,2]. The thermal model contributes to a better understanding of many practical fire problems such as problems associated with tunnel fire and flow encountered in fires of structural elements of buildings. The interaction of the fire plumes with materials which surround it reveals very complex physical mechanisms.

Fundamentally, the first survey was carried out by Agator *et al*. [3] who studied the influence of a wall placed near to the plume fire. They noticed that the plume is attracted to the wall. Mahmoud *et al*. [4-6] 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 showed that the plume interacts narrowly with the thermosiphon flow which develops along the internal wall of the cylinder. Contrary to previous research [7-10], the authors found the appearance of a supplementary zone in addition to the 2 classic zones which characterize the vertical evolution of the free plume. Just above the source, an instability zone is characterized by the formation of rotating rolls and by the existence of 3 extremes of temperature and velocity profiles. A second zone of turbulence pre-established is followed by a last zone where the turbulence is fully established. Zinoubi *et al*. [11,12] continued this experimental research by studying the form factors effect on 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 3 zones described previously. By studying the influence of the cylinder height, Zinoubi *et al*. [13] noticed 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 lets us avoid this blocking. In order to determine the geometrical effect, Taoufik *et al*. [14] studied the evolution of a thermal plume generated by a rectangular source inside an open-ended rectangular canal. They observed the existence of the 3 zones in the cylindrical geometry and the contraction of the rotating roll sizes located in the first zone of the flow.

Recently, Mahmoud *et al*. [16] studied the effects of source air entrainment on the flow structure induced by 2 heat sources, one is placed at ground level and the other is placed 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 plume flow structure such us the plume height elongation, the increase of the plume flow rate and an elevation of the thermal flux absorbed by the air.

The aim of this experimental research is to continue the previous study by providing an investigation on the development of thermal plumes at different heights inside a horizontal rectangular tunnel. This study provides a better understanding of the physical mechanisms that characterize the structure of a plume fire evolving in a horizontal tunnel. Thereafter, we determine the source height emplacement effect on the plume structure.

Experimental apparatus for simulation

The experimental apparatus is shown in **Figures 1** and **2**. It is essentially constituted of a horizontal channel having a length of 2 m and a rectangular section (0.30×0.15 m), a ventilation system and a hot source. The source is constituted of a flat disk (1) having a diameter of 7×10^{-2} m and electrically heated by a 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. Three thermocouples (Al–Cr) are used to measure the surface temperature of the disk. The first thermocouple is placed in the center, the second is at the extremity and the last is between them. The temperature difference between the center and the extremity of the disk is less than 5 °C. Verifications performed using surface thermocouple show a difference lower than 3 %.

To explore the thermal and the dynamic average fields of the plume, a resistance wire anemometer at constant current (2) is used. This technique was adopted a long time ago by Doan *et al*. [19], in the natural convection study, and 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 2 parameters that change the electrical resistance of the wire. Doan *et al*. [19] 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. In order to avoid the disturbance of the flow, the probe is introduced vertically so that its sensitive wire is perpendicular to the ascending average flow. Errors due to the probe calibration are lower than 2 %. In order to avoid the disruption of the flow, the probe is introduced vertically so that its sensitive wire is perpendicular to the ascending flow.

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

A computer (5) equipped with a data acquisition card acquires instantaneous signal values at 15 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. The time interval (15 ms) is found from the theorem of Shannon.

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

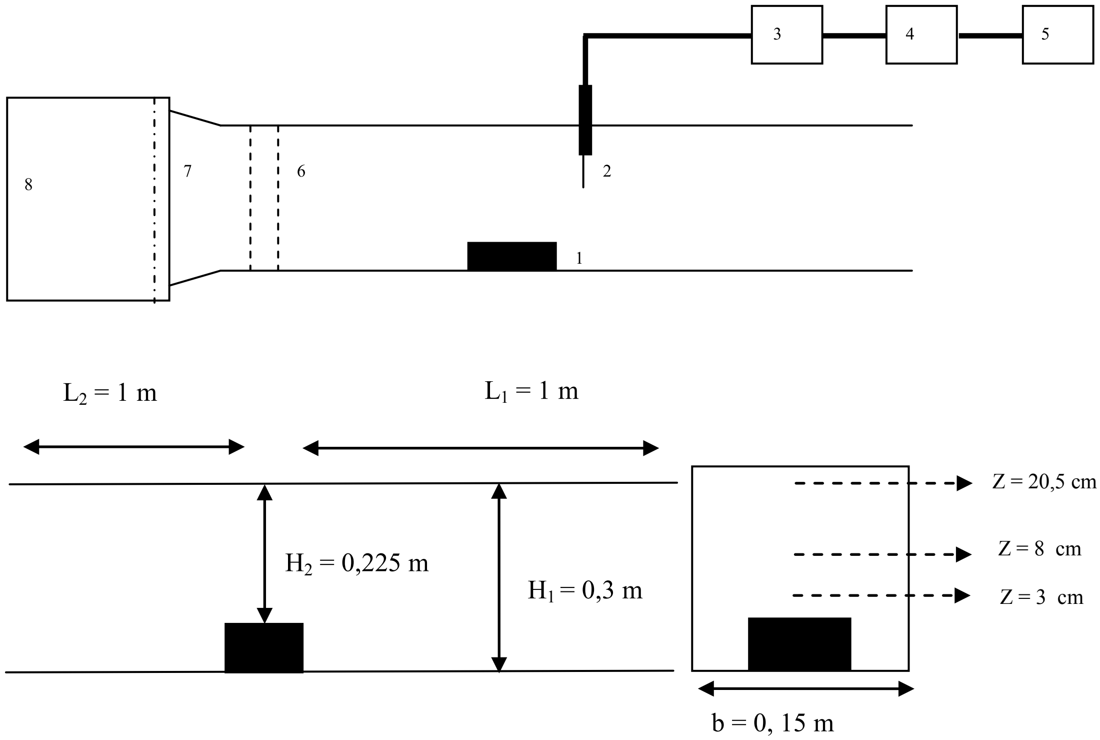

Figure 1 Experimental apparatus.

Results and discussion

The experimental results presented in this research constitute a contribution to source site effect study, taking the ground as a reference, on the evolution of a thermal plume in a horizontal tunnel. We will study the evolution of the plume without blowing air. First, the source of the plume is placed at a height of 7, 5 cm to the tunnel floor top. Then, we will study the site effect among h = 2, 7, 5 and 15 cm.

Average fields

Vertical evolution of the temperature and the velocity

Figure 2 presents the average temperature and the velocity evolution of the flow at the middle level of the plume generating source to 7, 5 cm of the tunnel floor. The profiles show 3 different behaviors of the flow which lets us suppose the existence of 3 zones. In the first zone ($Z < 8$ cm), the flow is strongly influenced by the presence of the thermal plume generating source. Indeed, very close to the source, the flow undergoes an important vertical acceleration due to the brutal transformation of the fresh air into hot air by reaching the source. This acceleration reaches its maximum at the limit of this zone. For the intermediate zone ($Z < 13$ cm), the profile in **Figure 2a** shows a reduction in the temperature with weaker gradients and a deceleration of the flow due to the downward flow of the air through the axis of the source for its supply. In the superior part of the tunnel ($Z > 13$ cm), the temperature and velocity continue their reduction but slowly. This behavior is identical to that observed by Mahmoud [4] and Zinoubi [15] in their studies on the evolution of a thermal plume inside a vertical cylinder.

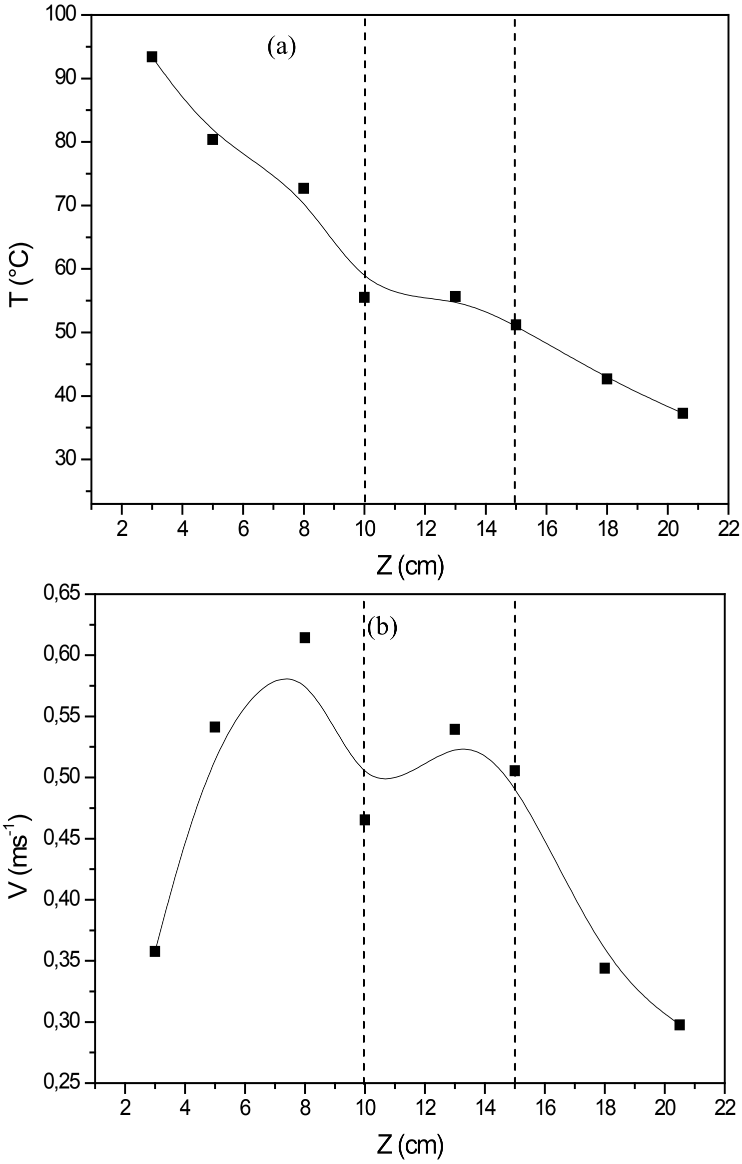

Figure 2 Axial evolutions of the temperature (a) and velocity (b).

Thermal average field

Figure 3 represents the iso-values of the average temperature, drawn in the longitudinal hot source middle plan median plane throughout the tunnel length. The isotherms give a general idea of the global structure of the flow. Indeed, this figure confirms the existence of the 3 different behaviors during the vertical evolution of the plume in the tunnel mentioned previously. We notice a vertical release which divides the tunnel into 2 parts (before and after the source). In the first part, near the obstacle (blower) the ascending flow of the plume, while touching the ceiling, moves towards the blower to go down thereafter along the wall and creates a zone of weak circulation in the bottom. In the second part, the flow moves towards the exit of the tunnel while skirting the ceiling. On both sides of the plume release, there are 2 zones of fresh air that are used for the system supply. Secondly, we note below the upper surface of the source the appearance of 2 hot air zones. This is due to the phenomenon of blocking of the supply fillets of the source which occurs intermittently. Indeed, when the source is fed from the upstream side, the supply fillets blocks part of the plume that requires him to descend to the bottom, the downstream side plume emerges without any problems. The part blocked continues to turn on itself when she finds the energy to break the fillets and block the air on the downstream side. In this case the source will try to feed by the downstream side and the cycle continues between the 2 parties.

To clarify the plume structure we will present the profiles of the temperature. **Figure 4** shows 3 profiles of temperature for the 3 zones of the study. These profiles show only one peak over the source. On the level of the first zone (**Figure 4a**) the peak, due to a brutal transformation of the fresh air into a thermal plume in contact with the source, is slightly inclined towards the obstacle to return thereafter towards the axis at the level of the higher zones. This peak decreases as while moving away vertically from the source. In addition, low values of temperature were noticed on both sides of the source. For the first zone ($Z < 8$ cm), these values are close to that of the ambient conditions thus indicating the fresh air flow for the system supply; for temperature of other zones, it increases gradually due to a mixture of the thermal plume with the entrained fresh air.

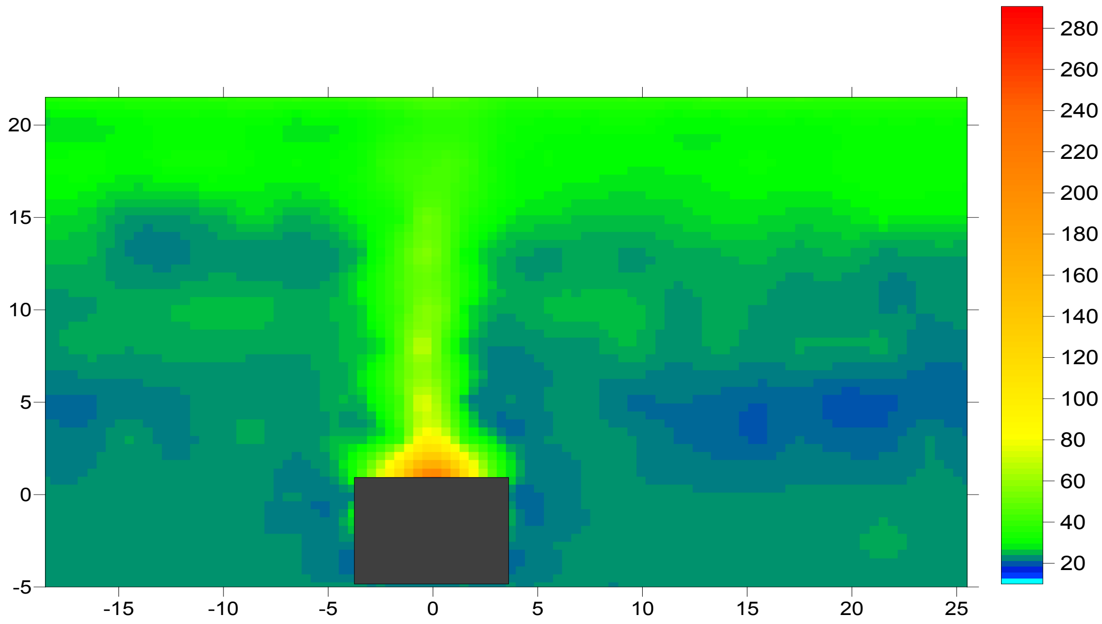

Figure 3 Average thermal field (Colors are available in online format).

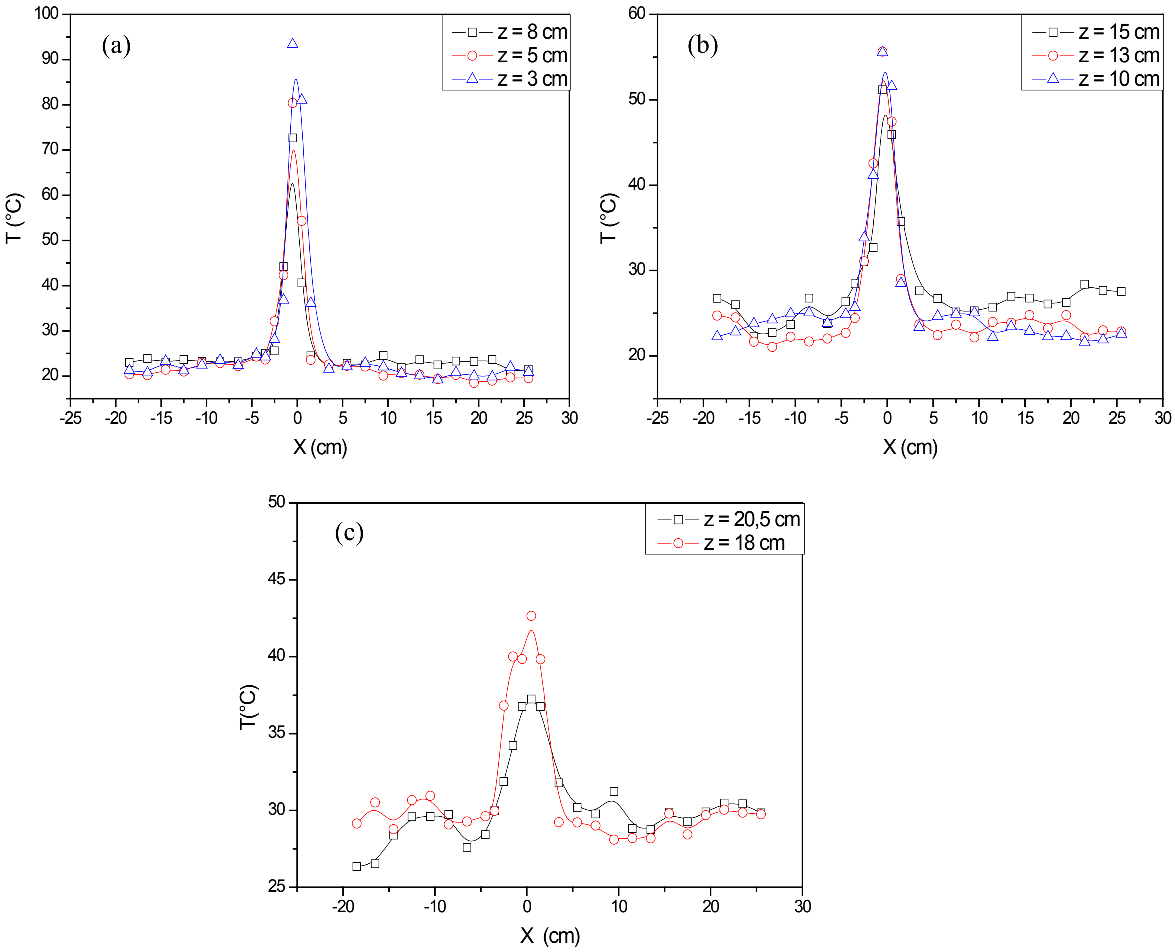

Figure 4 Transverse distribution of the average flow temperature (a) for sections z = 3, 5 and 8 cm, (b) for sections z = 10, 13 and 15 cm and (c) for sections z = 18 and 20.5 cm.

Dynamic average field

Figure 5 depicts the network of iso-values average velocity of the flow, traced in the longitudinal median plan of the hot source. This figure also confirms the existence of the same zones which were described previously and shows significant velocity values on the level of the release of the thermal plume due to a significant acceleration of the air after its heating in contact with the source. On both sides of the source, moderate values are noticed. At the level of the ceiling, the thermal plume which is divided into 2 parts gives rise to a flow before the source (backlayering) and a flow after the source which moves towards the exit of the tunnel to emerge. In addition, low velocity values, were noticed showing clearly the existence of the weak circulation zones noted previously. After the source, the zone of weak circulation made up of fresh air will serve to supply the system. On the other before the source side, this zone was created by the descent of the backlayering. This behavior is similar to that reported by several authors [17,18] in a fire developing inside a tunnel.

In addition, the flow velocity presentation on **Figure 6** for various sections of the studies shows profiles with only one extreme over the source. This maximum velocity, moves slightly towards the obstacle in the first zone, which clearly indicate the great influence of the source. This peak returns thereafter towards the axis and remains there until the plume reaches the ceiling. This peak decreases as much as we move away from the plume source. While arriving at the level of the ceiling, the plume flow which is divided into 2 parts, creates an after the source flow of moderate velocity indicating a kind of plume release from the open area (**Figure 6c**).

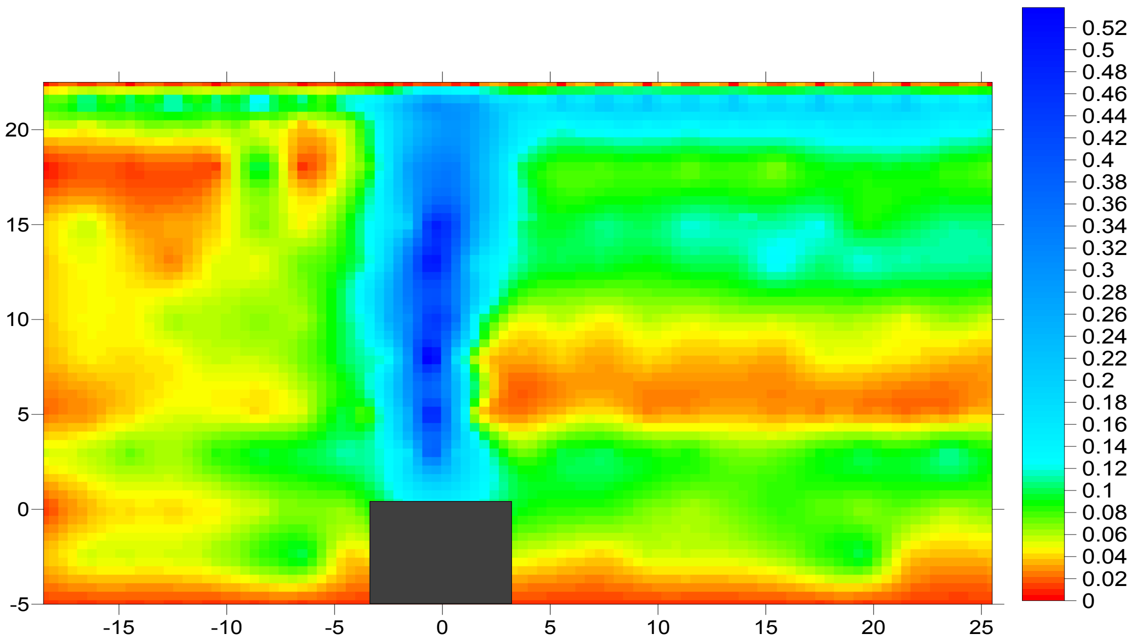

Figure 5 Average dynamic field (Colors are available in online format).

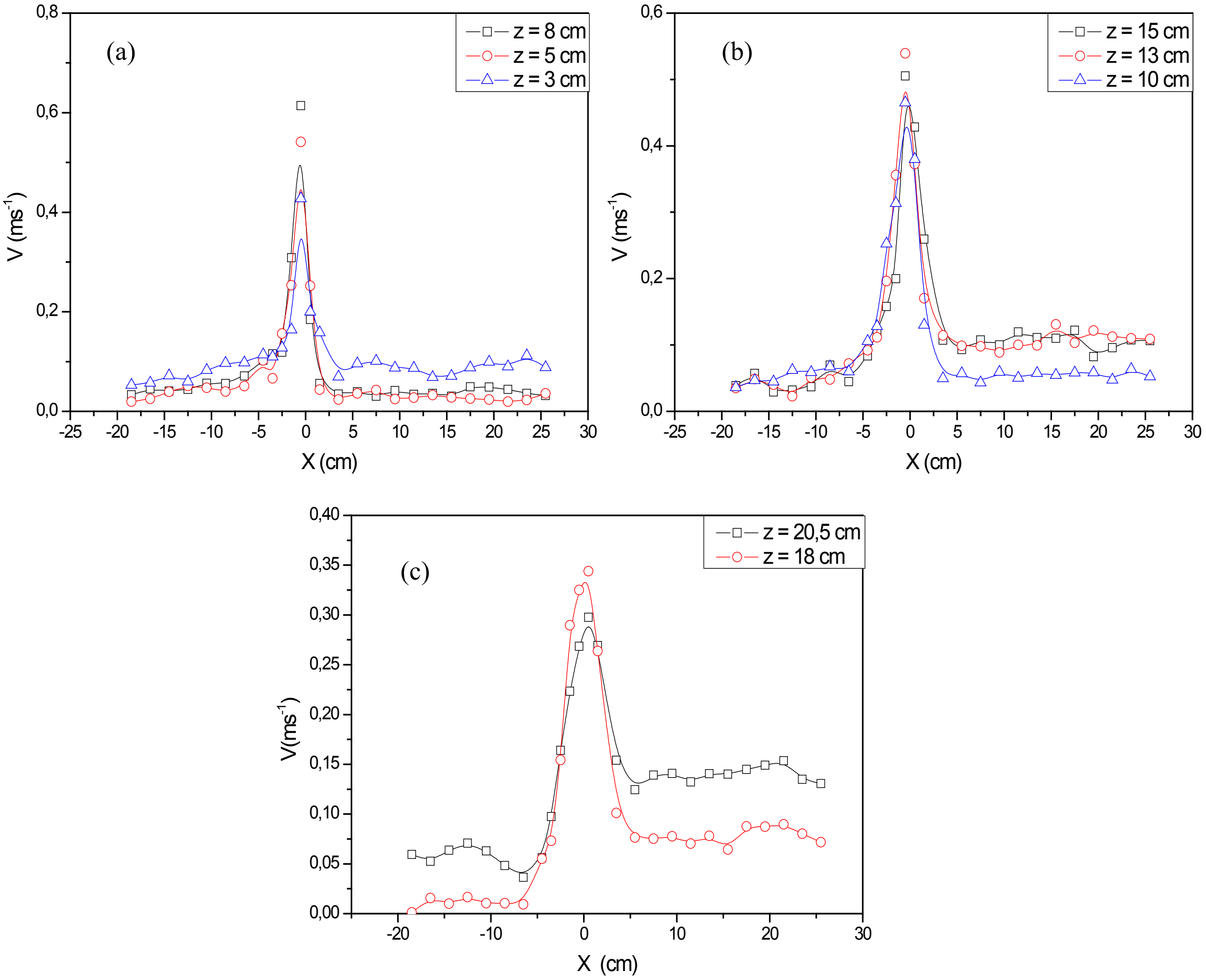

Figure 6 Transverse distribution of the average flow velocity (a) for sections z = 3, 5 and 8 cm, (b) for sections z = 10, 13 and 15 cm and (c) for sections z = 18 and 20.5 cm.

Fluctuating characteristics of the flow

Fluctuating thermal field

The comprehension of the development of the thermal plume inside the tunnel also requires a characterization of its fine structure by exploiting the fluctuations of the signals delivered by the hot wire probe. For this reason we illustrate in **Figure 7** the transversal evolution of turbulence thermal intensity. For the clearness of the results, we only depict one section for each zone. These profiles show a significant peak over the source translating the strong dominance of the thermal plume. While we move away from the central zone over the source, we notice that the intensity of turbulence decreases, indicating a plume effect attenuation which has become a profit for the fresh air.

Thermal skewness factor

To better understand the thermal plume development inside the tunnel, we will study the thermal skewness factor F_D. Indeed, the study of this factor allows us to compare the probability density law governing the distribution of fluctuations of temperature in the flow with the ideal law of Gauss, in which $F_D = 0$. Then we will do the same presentation for each zone.

Figure 8 shows the evolution of the thermal skewness factor of the plume flow. At the level of the zone close to the source (Z = 3 cm), the figure shows 3 extremes with a negative minimum on the axis indicating that the supply of the source of fresh air is only at the level of the axis. On both sides of the source axis, we observe peaks of positive values, corresponding to the plume release which is done by alternating: A supply on side of the source side that blocks the release of the plume which makes its release from the other side of the source possible and vice versa. This behavior is identical to that observed by other researchers [4,15]. The negative values, noticed on both sides of the source, show the dominance of the fresh air. In contrast, for the level (Z = 8 cm), **Figure 8** shows the same behavior as that obtained previously (Z = 3 cm). A reduction in the dominance of the fresh air is observed. Concerning the higher part (Z = 28 cm), the thermal plume remains dominating in the zone located at over the source and it leaves its place to the fresh air in the remaining parts towed by the ascending flow of the thermal plume.

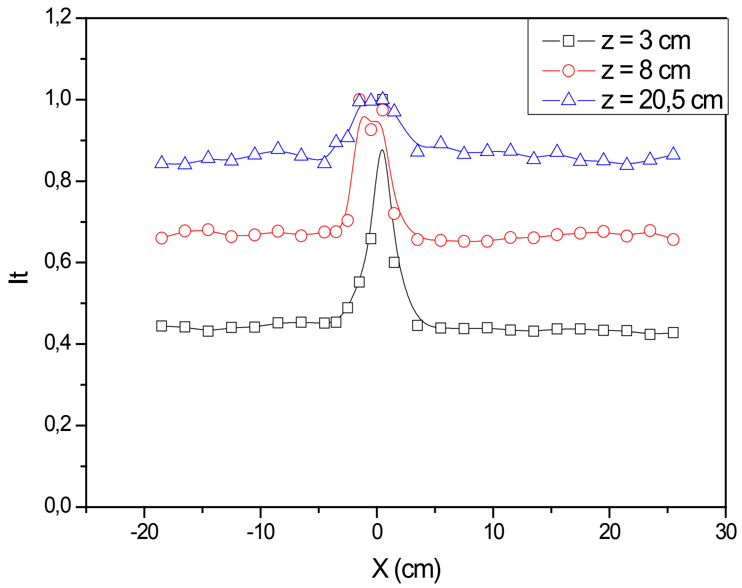

Figure 7 Transverse distribution of thermal turbulent intensity.

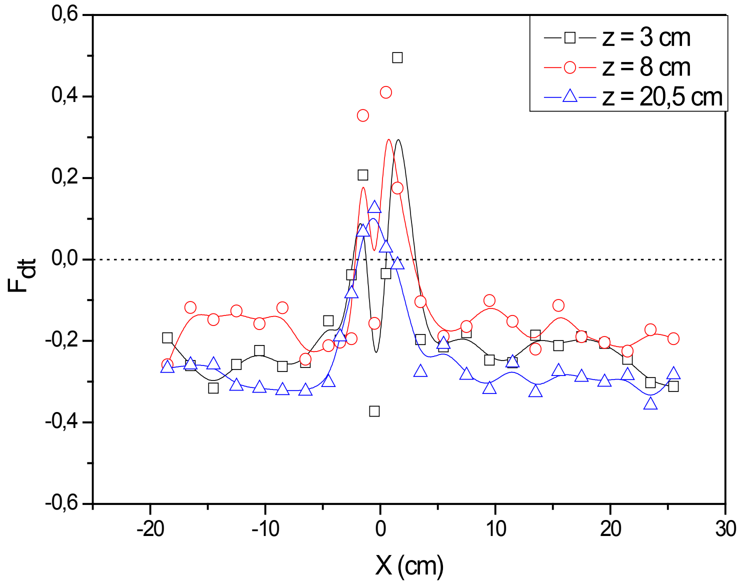

Figure 8 Transverse distribution of thermal skewness factor.

Source height effect

Figures 9 - 11 depict the isovalues of the temperature for the 3 studied cases. These figures show a principal release of the thermal plume which moves vertically towards the ceiling to be divided there into 2 parts taking 2 different directions skirting the ceiling. In the first case (h = 2 cm) we noticed in addition to this principal release 2 secondary releases on both sides of the plume source limits. This phenomenon disappears in the other cases of different heights. In addition, these figures reveal different behaviors. Indeed, as source site height decreases, the principal release of the plume spreads out more and more inside the tunnel causing a reduction in its temperature. In addition, 2 zones of fresh air were noticed on both sides of the source. The size of these zones decreases by raising the height.

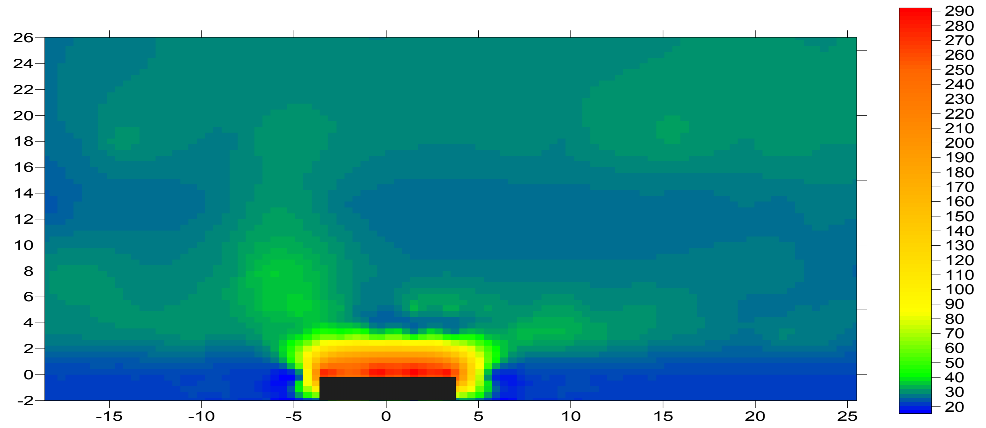

Figure 9 Average thermal field for h = 2 cm (Colors are available in online format).

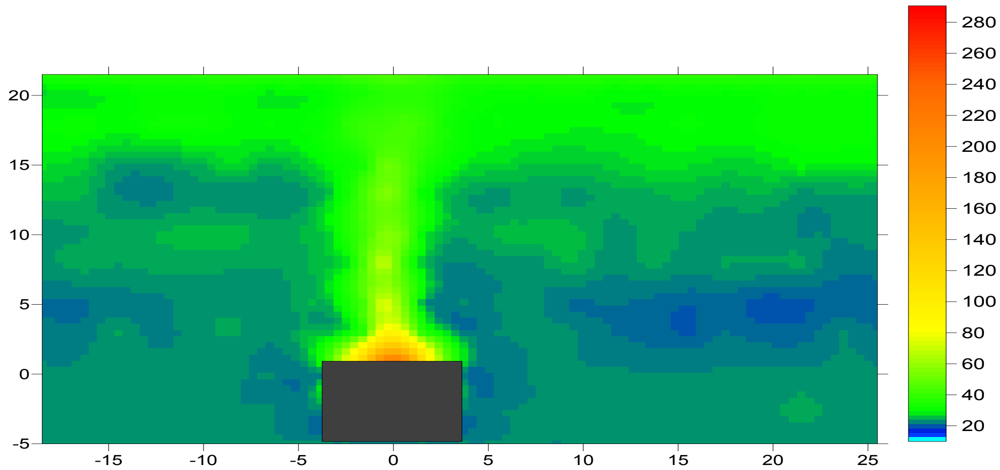

Figure 10 Average thermal field for h = 7, 5 cm (Colors are available in online format).

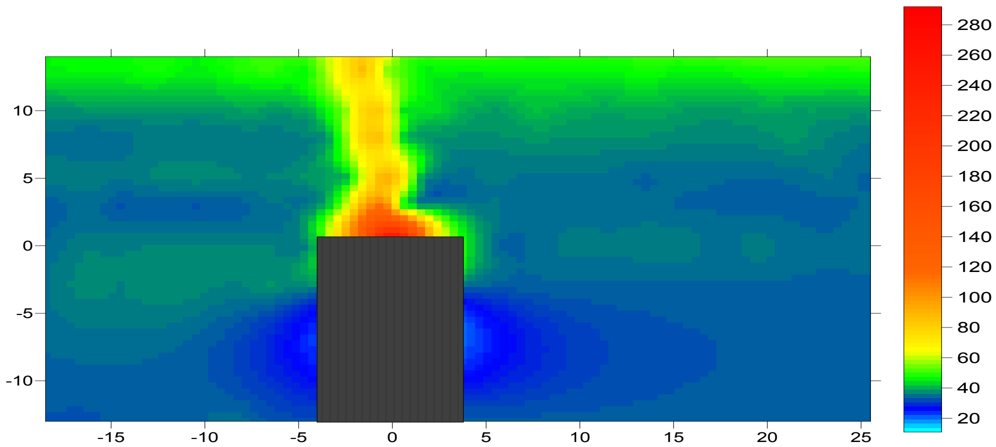

Figure 11 Average thermal field for h = 15 cm (Colors are available in online format).

For more precision about the source site effect, we will illustrate several profiles of temperature and velocity for the various studied cases. A section for each zone will be presented (Z_1 section located at 3 cm of the surface of the source, Z_2 located at 8 cm and Z_3 located at 2 cm below the ceiling). In **Figures 12** and **13** are described the thermal and dynamic fields inside the tunnel of the 3 studied heights.

These profiles show a significant peak over the plume source top which weakens the intensity when the height of the source decreases. This is due to the phenomenon of spreading out which was announced previously. This behavior is identical to that observed by Mahmoud *et al*. [1] during their studies on the evolution of a thermal plume evolving freely at the level of the ground and at a height of the floor.

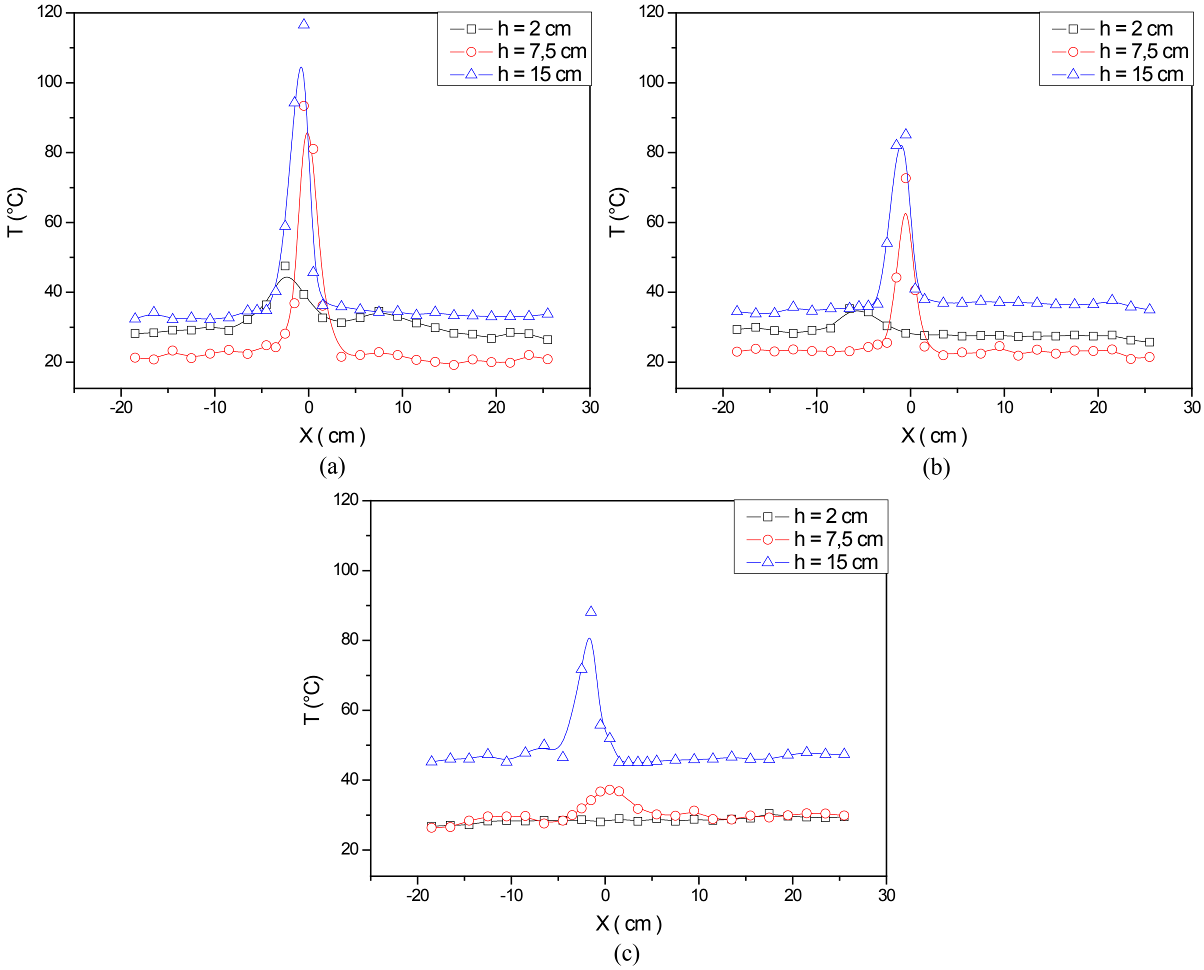

Figure 12 Transverse distribution of the average flow temperature (a) for section Z_1, (b) for section Z_2 and (c) for section Z_3.

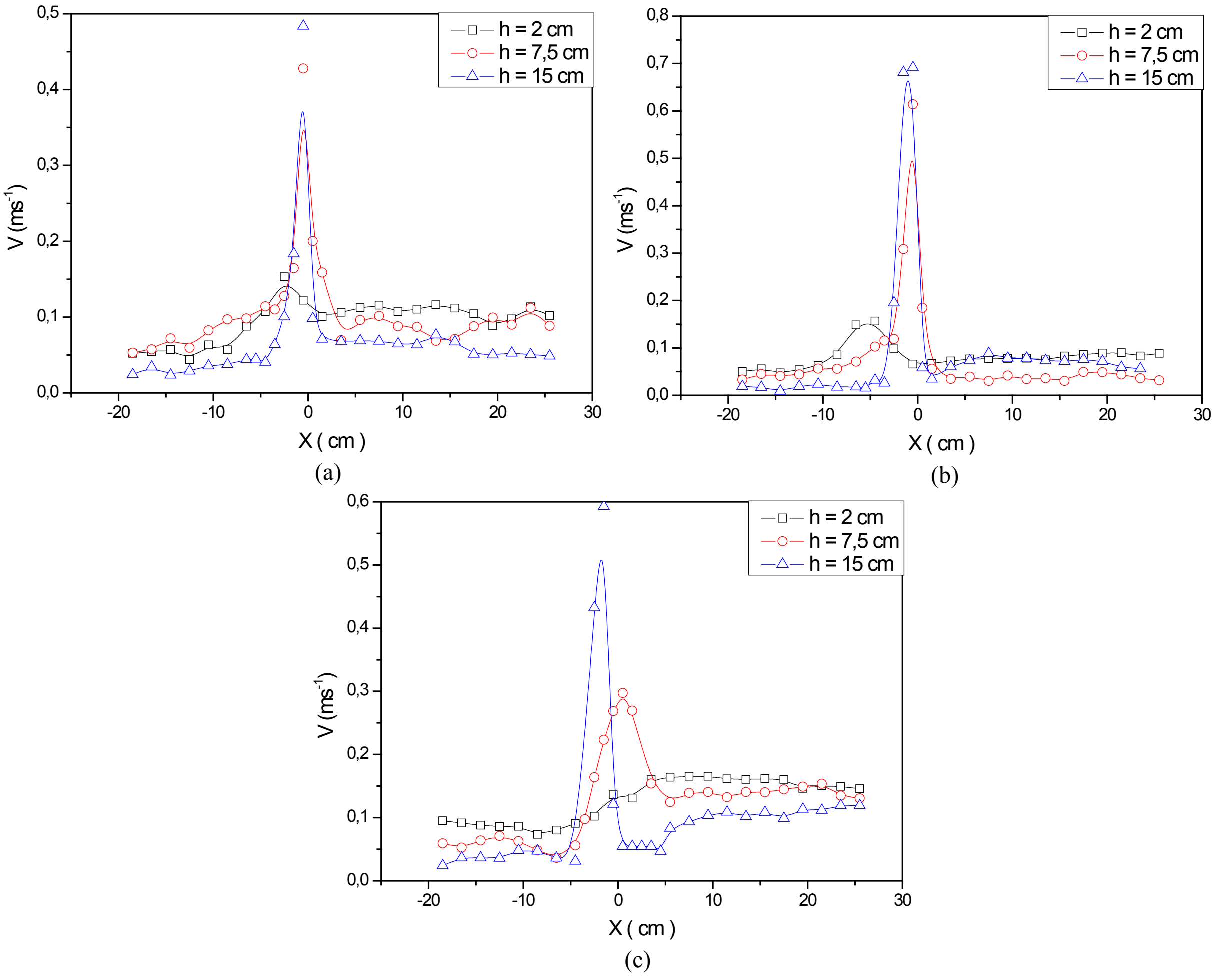

Figure 13 Transverse distribution of the average flow velocity (a) for section Z_1, (b) for section Z_2 and (c) for section Z_3.

Conclusions

This experimental work is a contribution to the comprehension of the behavior of a thermal plume developing inside a horizontal tunnel where the generating source of the thermal plume is placed at different heights. During the development of the thermal plume inside the tunnel without blowing, the results show 3 different behaviors. A first zone, just near to the source, is used for the fresh air supply of the flow. There in the thermal plume is exhausted vertically over the source. Then, a second zone where the principal releases of the plume undergoes a contraction. Thereafter, in the higher part of the tunnel, the ascending flow of the plume accumulates and undergoes a flow in 2 directions: a flow before the source called_backlayering and a flow after the source which skirts the ceiling to leave at the end of the free part of the tunnel. The results show that by increasing the height of the source on the ground level we notice that there is more acceleration of the flow with more heat transfer.

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