EXPERIMENTAL STUDY OF A THERMAL PLUME EVOLVING IN A FREE AND SEMI-CONFINED ENVIRONNEMENT: APPLICATION TO FIRES

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ABSTRACT. The investigation purpose an experimental study of the natural convection flow. This study simulates the fires evolving in a free and unlimited environment then in interaction with their material surrounding. The fires met such as in the forests in the oil fields and in the tower blocks create a thermal plume which extends in space. The pollutants transported by the fires flows threaten the inhabitants' health and cause a natural imbalance of the environment.
In reality the thermal plume generated by these fires undergone the influence of the neighbouring walls. Indeed, the walls which surround it are heated by thermal radiation thus creating a thermosiphon flow which interacts with the plume.
According to former work, the researchers [16, 20] noticed that the fires can be simulated by a hot source heated by Joule effect. For that, we studied the thermal plume flow generated by a hot rectangular source placed in a free then in a semi-confined environment.
To better understand the development mechanisms of the free fire flow and in interaction with surrounding, we simulated these phenomena at the laboratory.
In a first time we studied a thermal plume generated by a rectangular source heated uniformly by Joule effect.
In a second time the same source is placed at the entry of a vertical canal which it's the two Duralumin walls are heated at a constant temperature.
The visualization by laser plane enables us to follow the vertical evolution of the flow for two studied configurations. Using hot wire anemometry, we explored the thermal and dynamic field of the flow. In order to better describe the fine structure of the flow, we analyzed the spectra of temperature fluctuations.

NOMENCLATURE

A	shape ratio, ($A=\dfrac{b_2}{L_2}$)
b_1	width of the source, m
b_2	half width of the canal, m
D_f	diameter of the sensitive wire, m
g	gravitational acceleration, $m.s^{-2}$
Gr	Grashof number, ($Gr=\dfrac{g\beta(T_s-T_a)b_2^4}{L_2\nu^2}$)

Gr^* modified Grashof number, ($Gr^* = A.Gr$)

H height of the canal, m

I_t thermal turbulent intensity, ($I_t = \frac{\sqrt{\overline{T'^2}}}{T_s - T_a}$)

L_1 length of the source, m
L_2 length of the canal, m
L_f length of the sensitive wire, m

M* dimensionless flow rate, ($M^* = \int U^* \, d X^*$)

T average temperature, K
T' temperature fluctuating, K
T_a ambient temperature, K
T_s temperature of source, K

T* dimensionless average temperature, ($T^* = \frac{T - T_a}{T_s - T_a}$)

U average velocity, $m.s^{-1}$

U* velocity fluctuating, ($U^* = \frac{U}{U_{ref}}$)

U_{ref} reference velocity, ($U_{ref} = \frac{L_2 \nu (Gr^*)^{\frac{1}{2}}}{b_2^2}$), ms^{-1}

(x,y,z) cartesian coordinates

X * dimensionless length $X^* = \frac{x}{b_2}$

Y * dimensionless length $Y^* = \frac{y}{L_1}$

Z * dimensionless height $Z^* = \frac{z}{H}$

β thermal expansion coefficient, K^{-1}

ν kinematics fluid viscosity, $m^2.s^{-1}$

INTRODUCTION

This work is a contribution to understanding the development mechanisms of a thermal plume generated by a fire. The thermal plume evolved in a free and semi-confined environment. This kind of the flow is encountered in nature and industry such as the fires in forest and oil fields and the fires in buildings and tunnels.

To simulate this phenomenon, several researchers used a different generating source. P.H.Thomas [16-20] studied the development of the flames and the thermal plumes produced by many flame sources. He noticed that the structure of a plume generated by flame can be deduced from a thermal plume when the initial conditions of the flow are similar. Moreover, the smoke movement of a fire is related to the characteristics of a free plume that represents a smoke source [18]. J.M.Agator [13]

and B.Guillou [4] studied the thermal plume induced by a spherical calotte heated at a uniform temperature of 500 °C. They noted that the flow is divided in two different zones. Close the hot source, a first zone of flow development is characterised by the dominance of the buoyancy forces. Higher, a second zone of turbulence where the average profiles of temperature and velocity are similar. By studying a thermal plume produced by a burner for various diameters, B.M.Cetegen et al. [5, 6] noted the existence of three zones of the flow. Near to the burner surface, a first zone where the drive rate of the plume is independent of the fuel rate. Above the top of the flame, a second zone followed by an intermediate zone where the flow drives is similar to that of a thermal turbulent plume. H.Y. Wang [10] studied the fire propagation creates by a burner of a rectangular surface along a vertical wall. He noticed that the heat flux of thermal radiation produced by the flame is sensitive to the injection rate of the fuel. In addition, he noted the convection mode dominate the heat transfer of flow for the weak flux. L.Dehmani [14] simulated a thermal plume by air-helium jet. She showed the flow is divided into three zones. Near to the injector, a first zone where the plume evolves in an environment of constant density. Higher, a second zone is supplied by air-helium mixture. An intermediate zone of flow stratification where the density undergoes a stable strong gradient. In addition, A.O.M.Mahmoud [3] simulated a fire produced by a hot disc. Initially, it is installed on the ground then above the ground at 0.80 m. In first case where the source is placed on the ground, the plume structure is divided in three zones. In second case, the thermal plume evolves in two distinct zones. In addition, he showed an improvement of the flow rate and the energy absorbed by the fluid when the generating source is placed above the ground.
In reality the thermal plumes generated by these fires are influenced by their material environment. J.M.Agator [13] studied a thermal plume initially in the presence of a second identical plume. Then, he was interested at the plume interaction with a vertical plane wall placed in the vicinity. He noted a strong interaction between two plumes and plume-wall. Thereafter, M.Brahimi [15] studied the interaction of two identical plumes generated by two flat and electrically heated discs. He noticed also the subdivision of the resulting flow in two distinct zones. By studying the evolution of a thermal plume inside a vertical cylinder, A.O.M.Mahmoud [2] showed the appearance of a supplementary zone in addition to the two classic zones. This zone is characterized by the contraction flow. Compared to free plume, he noted an intensification of the energy absorbed by the fluid and an increase of the flow rate inside the cylinder. After that, J.Zinoubi [11] studied the development of a thermal plume between two vertical plane plates. He noticed the existence of the three zones.

The former works bring many interesting information of the development mechanisms of fires, but the thermal plume generated by a rectangular source is not studied yet. For that, we simulated a fire in our laboratory by a rectangular source heated by Joule effect. Initially this source is placed in a free and unlimited environment then at the entry of a vertical canal.

EXPERIMENTAL DEVICE

The experimental device is presented in Fig.s.1 and 2. It consists of a rectangular source and a vertical canal (Fig.2). The thermal plume created by a rectangular flat source (1) is electrically heated by the Joule effect to a surface temperature of 300°C. This source, which has a length of $L_1 = 0.42$ m and a width of $b_1 = 0.06$ m, is placed horizontally at the entrance of the open ended vertical parallelepipedic canal (2).
The uniformity of the source surface temperature is obtained by the use of wire resistors mounted behind the surface. A thermal regulation apparatus keeps the surface temperature as uniform as possible within a good approximation (the temperature difference between ends and in the middle is

less than 1%). In order to reduce the heat losses from below and minimise the temperature variation of the ambient air, this source is insulated at this side.

The canal is constituted by two Duralumin (AU4G) square parallel flat plates of side L_2 = 0.40 m and two rectangular Plexiglas plates (0.40 x 0.15 m^2). The system is placed on a frame at 0.80 m above the ground to allow air supply from below (3). The temperature of canal internal walls heated by thermal radiance of the hot source is controlled by thermocouples type-K introduced in the back of each plate.

In a similar way, the canal walls are thermally insulated at the back to minimise heat losses.

The strong dependence of the flow on the surrounding conditions requires conducting the experiment in a quiet atmosphere. To this effect, the experimental apparatus is placed in an independent closed room. In order to check the thermal stability of ambient air several thermocouples are fixed at different heights in the room.

To explore thermal and dynamic average and fluctuating fields inside the canal, a resistant wire anemometer at constant current is used (4). Doan Kim-Son et al. [8] adopted this technique for a long time in natural convection measurements. It is based on the principle of the resistance variation of a platinum wire. The sensitive platinum wire of the probe has a diameter of D_f = 7.5 μm and a length of L_f = 0.003 m. In order to avoid the disturbance of the flow, the probe is introduced vertically through the system exit, so that its sensitive wire is perpendicular to the ascending average flow.

A probe displacement system in the x and z directions, is used to explore the thermal field inside the canal. The minimal displacement in the vertical direction is 1 mm, whereas in the horizontal direction it is 0.20 mm.

On the other hand, a computer provided with a data acquisition card permits to take the instantaneous measures of temperature and velocity and to record signals for further statistical processing (5, 6). In application of the Shannon theorem, the period of sampling of 15 ms was chosen.

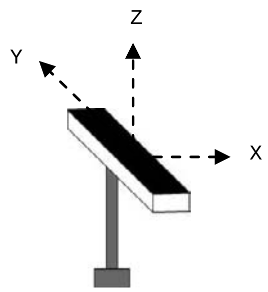

Figure 1. Experimental device of a free plume

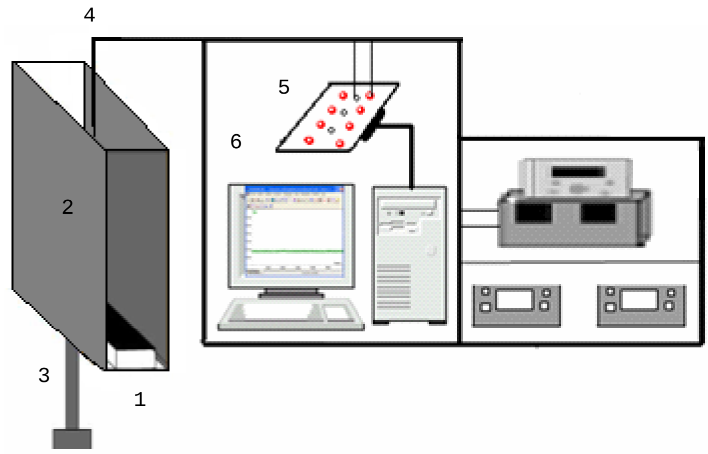

Figure 2. Experimental device of a plume inside the canal

The visualisation system used during this study is represented in Fig.3. It is constituted of a He-Ne Laser with a power of 35 mW (1), an electric vibrant plate (2), a digital camera (5) and a smoke distributor (4). On the vibrant plate is glued a plane mirror of good quality, that receives a horizontal laser beam and it reflects according to the canal vertical axis. The displacement of the plate makes revolve the mirror around a horizontal axis creating a plane laser sheet (3) on the entire transverse section of the canal. By natural aspiration, the distributor allows smoke to impregnate all the flow without any disruption. Preliminary studies of visualization and measurements by the hot wire anemometry made it possible to notice that the smoke introduced at the entry of the system does not disturb the flow. To record video sequences from visualization a numerical camera (5) is used.

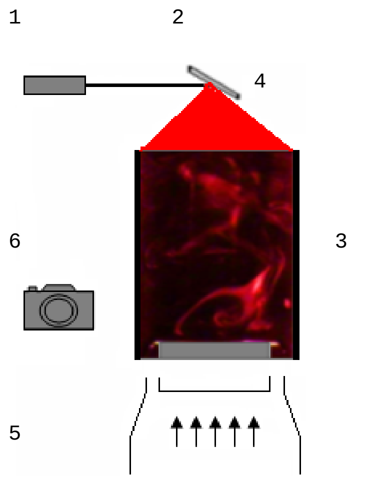

Figure 3. Visualisation system used

To explore the thermal and dynamic fields of the fluid inside the canal, we used the technique of hot wire anemometry at constant current (CCA). The principle of this method is based on the resistance variation of the sensitive wire according to the temperature and velocity when it is supplied by a constant current [8].

The measurements of the thermal field are carried out by cold wire anemometer supplied by a current of 1.2 mA instead of using thermocouples. Indeed, the time-constant of the sensitive wire is 1 ms and that of thermocouple of 25 μm in diameter is 50 ms.

The hot wire anemometer is used to measure the local velocity of the flow. In this case the probe is supplied by a current of 50 mA which makes it sensitive simultaneously to the temperature and the velocity [8]. The thermal inertia of the probe does not introduce any measurement errors especially at the low frequencies found in thermal plume [8]. The other sources of errors coming from the probe calibration are lower than 1 % [8].

RESULTS AND DISCUSDION

In this work, the results, which we present here, are carried out with air. The Grashof number of the flow is Gr = 2.10^{5} and the shape ratio is A = 0.09.

Flow visualization For the free thermal plume, Fig.4 indicates the existence of two different zones of the flow structure. Near the hot source, a first development zone of the plume. This source is supplied in fresh air from below and at the sides. The fluid pursues its path directly towards the central region of the flow. Just above the source, this fluid is consisted by big vortexes evolving mainly in the vertical direction. A second zone of lateral expansion of the ascending flow is localised in the higher of the hot source, where the vortexes size is small.

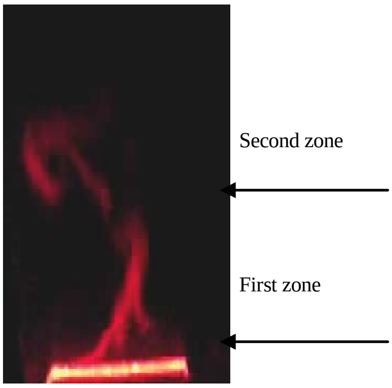

Figure 4. Visualization of the free plume

For the plume evolving inside the canal, Fig.5 shows the existence of two zones. In first zone of instability, the development of the flow is strongly influenced by the hot source. This behaviour changes completely in the second zone where the flow is homogeneous in upper part of the canal. However, the system in supplied in fresh air only by the low. The aspiration of the fresh air on both sides of the source is not symmetrical. When the source of the plume is supplied from one side, the feeding thread of the other side pursues its path along the canal wall. The feeding thread prevents the air into contact with the source to escape. The trapped air rotates on itself to form a big vortex. The fresh air near the source heats up rapidly by the contact of the hot surface. After, it goes up again under the effect of buoyancy forces. When the vortex escapes at the side, the feeding thread is attracted by the other canal wall. During its rise, this thread is blocked in the upper part of the canal by a descending flow. In addition, the figure shows the existence of smaller vortexes at the exit canal.

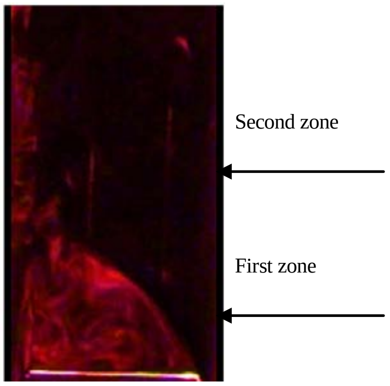

Figure 5. Visualization of the plume in interaction

Average field of the flow The dimensionless average temperature of the flow for a free and semi-confined thermal plume is plotted in Figs.6 and 7. In the case of a free plume, Fig.6 shows two different evolutions. For the level close to the source Z * = 0.10, the profile presents a maximum of temperature and a strong thermals gradients in the central part of the flow. This maximum is due to a transformation of the ambient air in plume. Higher of the source and for a level Z * = 0.92, the profile is flattened and the thermals gradients are weak. This indicates an establishment of a new flow mode.

When the plume evolves inside the canal, Fig.7 shows the existence of two evolutions. Just above the hot source and for a level Z * = 0.10, Fig.7 shows a weak thermal gradients. In intermediate space between the source and the vertical walls of the canal, the fresh air dominates the flow. In the vicinity of the canal walls, we record a light rise of temperature due to the heating of these last by thermal radiation of the hot source. The profile relating to the second zone (Z *= 0.92), show an attenuation and a light stabilisation of the temperature.

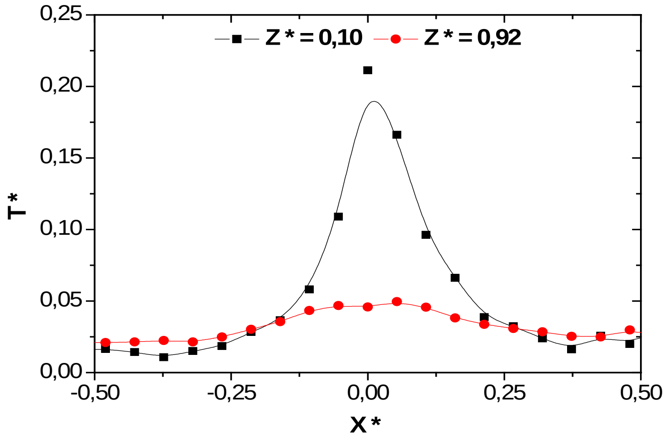

Figure 6. Transverse distribution of average temperature
of free plume

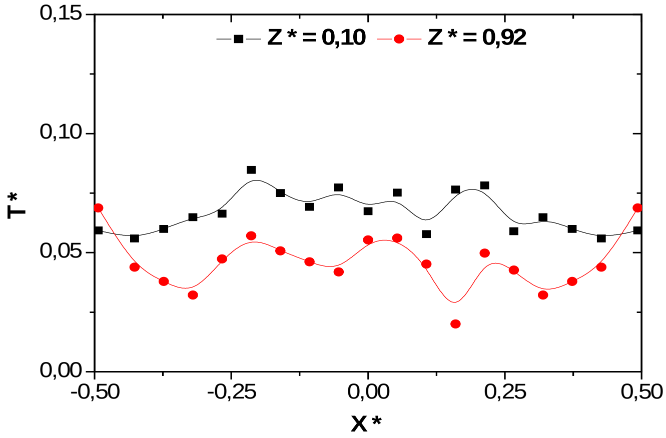

Figure 7. Transverse distribution of average temperature of plume in interaction

Figs.8 and 9 present the dimensionless average velocity for a free and semi-confined thermal plume. This representation confirms the existence of two zones described previously.
For a free plume, near to the source (Z * = 0.10), Fig.8 shows a strong dynamic gradients in the central flow region. These gradients are related to the drive of the ambient air at the plume borders. On both sides of the source, the velocity of the flow is weak. In the second zone where a new mode of the flow is established (Z * = 0.92), the profile is widened and the velocity increases relatively on both sides of the source. This indicates the lateral expansion of the plume towards outside.
In the case of interaction between the plume and the canal walls, a first zone (Z * = 0.10) is characterized by a strong dynamic gradient in the central region of the flow. Downstream (Z*=0.92), the dynamic profiles show same evolution except near the canal walls.

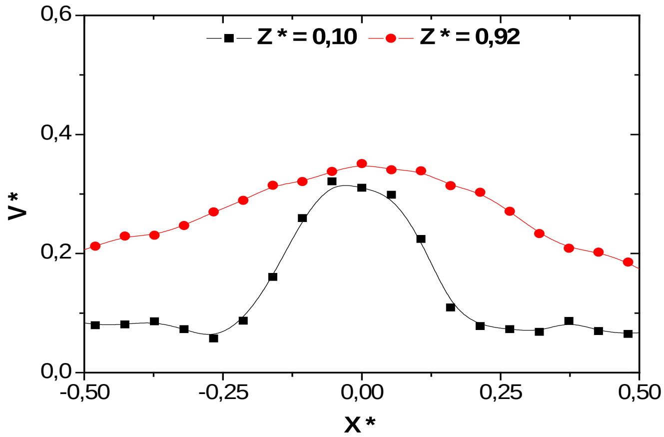

Figure 8. Transverse distribution of average velocities of free plume

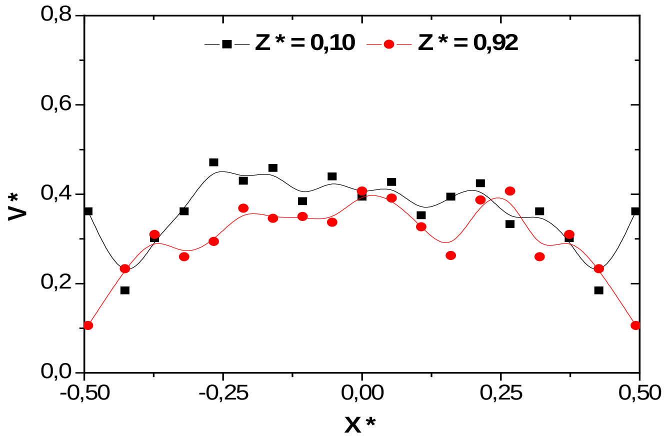

Figure 9. Transverse distribution of average velocities of plume in interaction

The vertical evolution of the flow rate, for a free and semi-confined thermal plume, is plotted in Figs.10. For a free plume, the profiles show an increase of the flow rate due to the drive phenomenon of the ambient air by the plume. These results were noticed by M.Brahimi [15] and by B.Guillou [4] by studying a thermal plume generated by a hot disc and a spherical calotte. In the case of the semi-confined plume, the flow rate remains constant inside the canal.

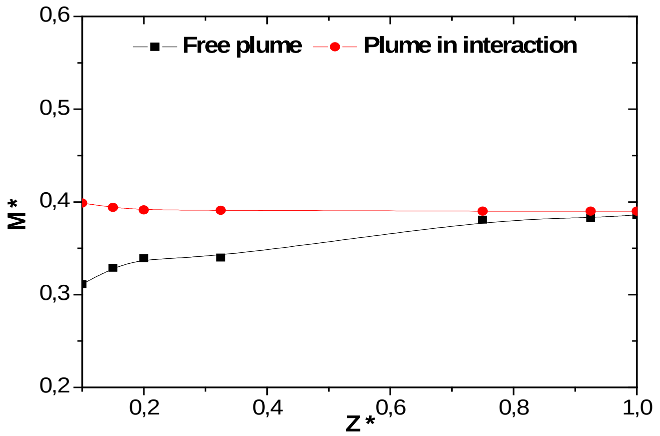

Figure 10. Vertical evolution of flow rate

Fluctuating field of the flow Figs.11 and 12 present the thermal turbulence intensity for a free and semi-confined plume. For a free environment, above the hot source (Z * = 0.10), Fig.11 shows the existence of three extrema. On both sides of the median plan of the source, the maximum is due to a strong interaction between the ambient air and the plume. The minimum of turbulence indicates a predominance of the hot plume in the central region of the flow. As we move away from the source (Z * = 0.92), the extrema of turbulence disappears. In addition, the turbulence rates are relatively weak thus translate the turbulence establishment.

When the plume evolves inside canal, Fig.12 shows the same evolution of the fluctuating profiles which is due to the confinement effect.

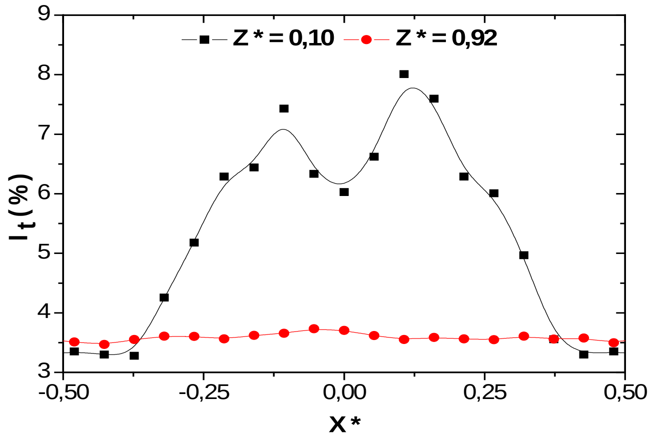

Figure 11. Transverse repartition of thermal turbulence intensity of free plume

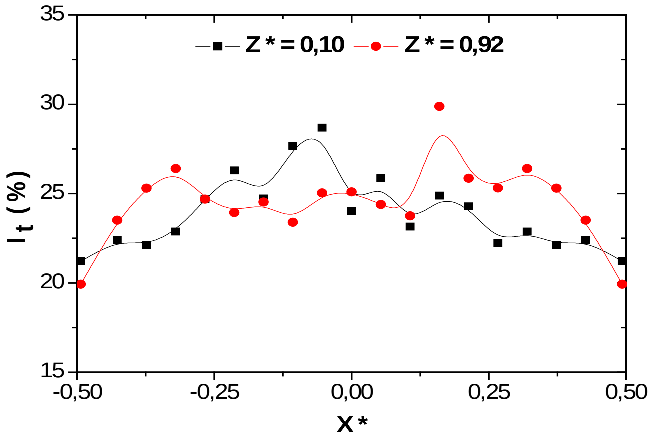

Figure 12. Transverse repartition of thermal turbulence intensity of plume in interaction

To study the fine structure of the flow for two configurations, we analyzed the temperature fluctuations spectra by the Fast Fourier Transform. The thermal spectra for a free and semi-confined plume, is represented in a semi-logarithmic system in Figs.13 and 14. These spectra are plotted for two fixed points located on the median plan (X*=0). This representation permits the setting in evidence of the spectral strips containing a considerable energy, while taking in consideration the delimited areas by the spectra [9]. The transversal evolution of these spectra shows that most of energy is concentrated in a rather broad frequency band ranging between 1 and 10 Hz.
For a free plume, Fig.13 shows important peak which moves from 0.8 Hz to 4.14 Hz as we moves away from the hot source. This indicates the predominance of the big vortexes just above the source. When the plume evolves inside the canal, close to the source (Z* = 0.10), Fig.14 shows the presence of an important peak at 4.7 Hz. In the higher zone of the canal (Z* = 0.92), a general displacement of the spectra of energy towards the high frequencies is noted (9.6 Hz). This indicates that the

proportion of the small dissipative vortexes increases in front of that of the big structures. Indeed, the vortexes of big sizes carriers of energy, which depend on the conditions of entry, undergo a stretching in the direction of the ascending flow and give rise to vortexes of intermediate structures. During their progression, the later produce vortexes of lower size.

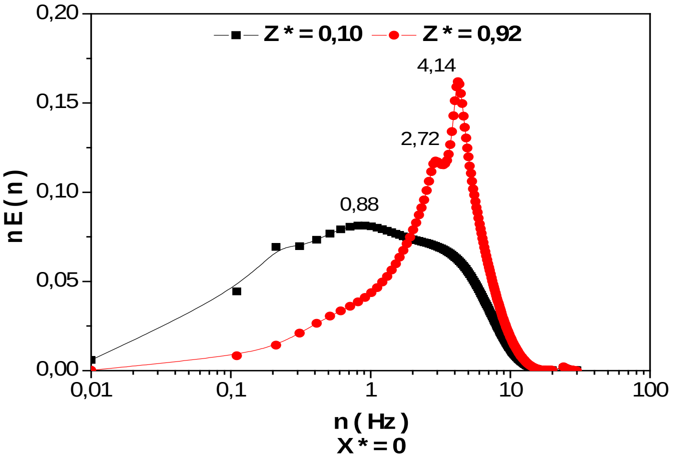

Figure 13. Spectra of temperature fluctuations for free plume

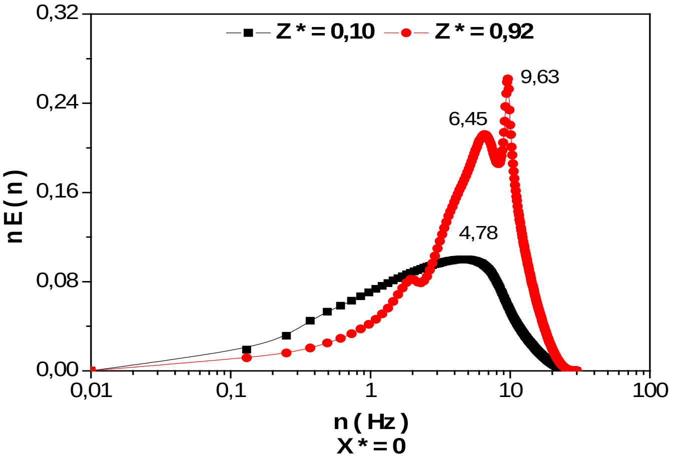

Figure 14. Spectra of temperature fluctuations
for plume in interaction

The representation of these spectra on a logarithmic scale, us made it possible to show the existence of spectral laws known in natural convection (Figs.15 and 16).
In the first zone (Z * = 0.10) where the production of energy is important, the law in n^{-1} of Tchen [7] is checked for the weak frequencies. The law in n^{-3} introduced by Lumley [12] is observed in two zones of the flow (Z * = 0.10 and Z * = 0.92). In these regions the size of the vortexes seems to be intermediate between that of the large structures carrying energy, which occur at the entry of the system, and that of the small dissipative vortexes, which develop downstream.
The law in n^{-7} of Heisenberg [8] is checked in upper region where the viscous forces dominate the flow. This indicates the predominance of the dissipative vortexes structures in this region.

In addition, these spectra show the absence of the universal law of Kolmogorov [1] in $n^{-5/3}$ observed in forced convection. The absence of this law is due to the low values of the flow Reynolds [16].

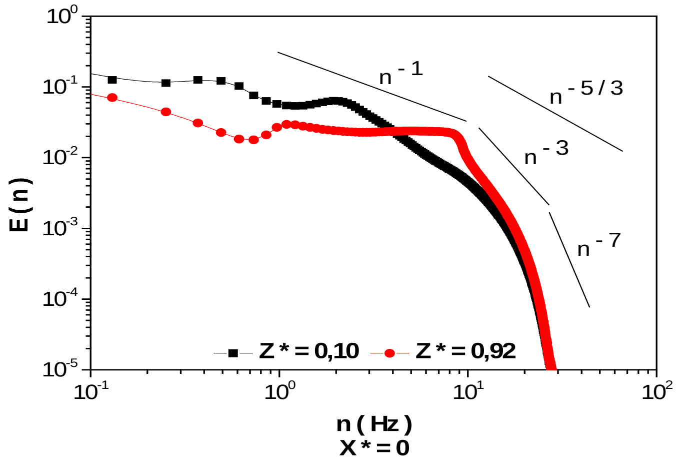

Figure 15. Spectra of temperature fluctuations for free plume

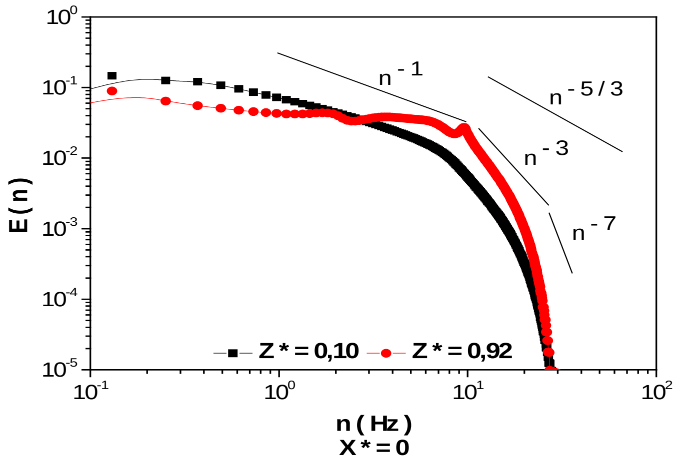

Figure 16. Spectra of temperature fluctuations
for plume in interaction

KEYWORDS

Natural convection, fires, thermal plume, interaction, spectral density

CONCLUSION

The present work is a contribution to the comprehension of the fire behaviour evolving in a free and semi-confined environment.

Flow visualization and study of thermal and dynamic fields showed that the structure flow is divided in two zones for the two studied configurations. A first development zone of the flow is characterized by big vortexes. A second zone of turbulence establishment is localised in the higher part where the size of vortexes is low. In addition, this study shows a blocking of an ascending flow at the higher part of the canal. On the other hand, the results show that the semi-confined environment accelerates the homogenisation of the fluid and increase the flow rate. The spectral analysis of the temperature fluctuations shows the dominance of a dissipative vortexes when the plume evolves inside the canal. However, this study allowed the checking of some known spectral laws in natural convection the n^{-1} law of Tchen [7], the n^{-3} law of Lumley [12] and the n^{-7} law of Heisenberg [8].

Thus, the semi-confined environment limits the arrival of air and cause the appearance of the dissipative vortexes structures. This enables us to better control the fires and improve the techniques of prevention.

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