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An Experimental Approach For A Fine Visualisation Real-Time Of The Thermal Boundary Layer To The Top Of A Grooved Disc

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Abstract:
This study is based on the design and use of an experimental set-up dedicated to make visible and treat the thermal boundary layer above a heated horizontal grooved disk in ambient air. The shadowgraph technique is used in order to visualize the flow and get quantitative data. On the one hand a remotely controllable camera, installed carefully on a rail which maintains the camera with a meticulous position compared to the screen, enabled us to carry out sockets of sight in the vicinity immediate of the interface. In addition we quantified the vertical gradients of the temperature in the viscous sublayer, with less few pixels of the upper surface of the disc thanks to a system of image processing. The results present a fine description of the evolution local structure of the flow along the convection since the viscous sublayer until the limits of the turbulent boundary layer.

Key words*: Natural convection, grooved Disc, shadowgraph, Image processing, thermal imaging , Thermal boundary layer*

1.Introduction

The convection is determined by the movement of the elementary particles of fluid between the areas having different temperatures. This movement involves an intense mixture of the fluid particles which swap energy in the form of heat and of momentum between them.

We distinguish: the natural convection which has like origin the movement produced by the differences in density between the hot particles and those which are cold in a fluid located in a field of gravity. In general the hot fluid is less dense and tends to rise in the field of gravity. In the first time the air and the upper surface of the disc are at the same temperature. But let us suppose for example that the ambient conditions are at a uniform temperature T_∞, and that the disc is maintained at a T_p temperature also uniform but different of T_∞. By exploring the field of temperature T perpendicular to the disc, according to the ordinate y, the theory informs us on a progressive variation of T_p, initially fast then increasingly slow as one penetrates in the external medium.

Fig.1.1 illustrates the case where T_p, is higher than T_∞, [1]. The area in which T varies to a significant degree is called thermal boundary layer. It jumps to the eyes which the preceding definition has a quite vague character. A conventional definition thickness of boundary layer δ_T will be approached. First of all, to locate the relative temperature T at the boundary conditions T_p and T_∞, an adimensioned size is introduced:

$$\frac{T - T_p}{T_\infty - T_p} = T^+ \qquad (1)$$

Who is positive and lower than 1 $\forall$ T_p and T_∞ .

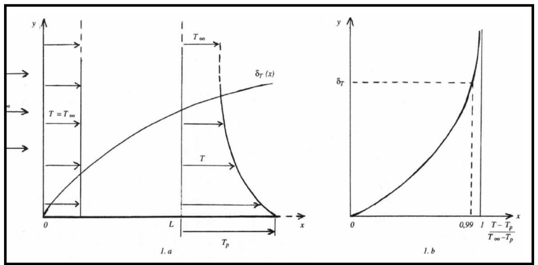


Figure 1

FIG. 1.1 – *Couche limite thermique. 1a : répartition transversale de température T-T_p à une distance L de l'origine (T_p>T_∞) et évolution de l'épaisseur de couche limite thermique δ_T. 1b : caractérisation de δ_T ; la notation T signifie "T (y) pour L donnée".*

The thermal boundary layer has a thickness $\delta\ (T)$ such as:

$$\frac{T(\delta_T) - T_p}{T_\infty - T_p} = T^+(\delta_T) = 0.99 \qquad (2)$$

This normative condition is completely general, and does not refer to the dynamic characteristics of the boundary layer, which can be laminar or turbulent.

The structure of the boundary layer conditions the heat transfer in close wall and its comprehension is the key of the control of heat exchange by convection. For this reason, a description based primarily on a phenomenological and experimental approach of the boundary layer will be the purpose of this item.

2.Method Of Visualization By Shadowgraph

2.1.General Principle [2]

The principle of the shadowgraph consists in using the space variations of optical index $N(T)$ like tracer of the space dependence of the field of temperature T. For example, a periodic optical index in the field where the convection develops led to a periodic deviation of a beam of initially parallel light. Under certain conditions, one can recover downstream on a screen a signal whose intensity will reproduce the space dependence of the temperature. The ascending currents convectifs have space dependence according to the great vertical managements and it is natural to clarify the field of convection by a beam of parallel light vertical.[5]

The index of refraction of a transparent medium for a radiation wavelength λ is related to the density ρ of this medium by the relation of Lorentz:

$$\frac{n^2\ - 1}{n^2 + 2} = \text{b}.\rho \qquad (3)$$

Where the parameter b depends only the wavelength λ and on the medium considered.

Let us introduce the normal density ρn (temperature, zero degrees Celsius; pressure, 76 cm of mercury);

The law (3) is written:

$$n - 1 = k\frac{\rho}{\rho_n} \qquad (4)$$

Where K is a number without dimension which depends only on the transparent medium and the wavelength.

Local variations of density and, consequently, index of refraction, occur in all the no uniform flow of the air. The highlighting of the local variations of index of refraction is possible by the shadowgraph, which constitutes, so a process of study of the convection.

3.Experimental Study

3.1.Description Of The Device (Fig.1)

The system is composed of a source of light S, punctiform but very brilliant, is placed at the focus of a lens L. the beam of parallel rays thus obtained crosses the interests areas comes to meet a screen. A direct visual examination of the image which has just appeared on the screen (beautiful to see) can constitute a control sufficient for the detection of local and surface heterogeneities developed on the vertical plan of the disc. However, the examination purely visual present of the limitations of various natures which justify the blossoming of a whole range of processes of sight check, whose, among main automatic visualization by image processing. From where need for a remotely controllable camera and a TV.

Figure 2: Socket Of Sight Of The Experimental Set-Up

3.1.1.Positioning And Troubleshoot Of The Camera

A good visualization as of precise measurements require a careful and meticulous positioning of the camera, and the possibility of adjusting these coordinates constantly. To meet this need, the camera and the source of light are related to the same rail in order to preserve them always orthogonal with the screen. The rail makes it possible to relocate in a linear way the camera towards the interest area. Vertical positioning is carried out by means of two metric elevators of precision, on which the rail is fixed.

The tuning of the diaphragm of the camera is carried out so as to obtain a good contrast between the socket of sight of the interest area and the background noise, necessary to optimize the product of correlation.[6]

3.1.2.Television

We cannot be satisfied of a visual examination of which we underlined limit in particular related to the fatigue of the research worker. For that, the television, fitted with a pallet rich in option, brings an invaluable help to the visual control.TV connected to the camera via its port TV allowing a remote observation real-time from what occurs to the top from the heated disc by the means of the image induced on the screen having for aim sufficiently to improve contrasts of the image of a detected phenomena, so that its presence can be automatically announced or recorded. [7]

3.1.3.Image Processing [8,9,10,11]

Image processing associated with: (numeric camera HD; software of processing) is essential. Indeed, the outgoing video signal of any camera of socket of sight is practically always disturbed so that a simple analog processing is enough to deliver a signal reliable defect. A simple thresholding in amplitude for example is often ineffective, leading to a rate of false prohibitory alarms.

Thus, in practically all the cases of visualization optical, it is necessary, to obtain reconstituted images of good quality and to consider an auto-sensing of the faults on those, to implement an elaborate system of image processing. The purpose of this system is first to improve quality of the image within contrast and of the noise level; it must in the second place very often take into account the morphology of heterogeneity sought in order to make the image reconstituted perfectly exploitable.

These processing, which can be relatively complex, can be implemented only by numerical channel, which involves the need for having behind the camera a fast system of digitalization, of one or more framebuffers (video-RAM, card CSD,…) and of a minicomputer adapted to the image processing real-time. The mathematical tools usable many and are varied, we will be satisfied to mention here the linear metric operators (cardinal filter, filter of Laplace), and nonlinear (filter of Sobel, Kirsh, Prewitt) and statistics (Markovian), the two-dimensional convolution, the frequential analysis of Fourier… etc.

After thresholding, the processing is carried out on a binary image and implements the tools of mathematical morphology such as, for example, the operations of retraction-dilation, squelettisation or bridging-closing. Correlations between images can also be used in order to lead to the reconnaissance and possibly to the classification of the required faults.

3.2.Experimental Results

1- Before approaching the phase of convection; we wanted to make sure that the mode of conduction either establishes in any point of the upper surface of the disc. To meet this need, we called upon the thermal imaging to justify and prove all the assumptions which can be quoted in the literature: Fig. (3, 4).

* The internally heated disc is placed in a room of experimentation of which the air velocity ambient is low.
* Thermal conductivity on the disc is rather large so that all the points of the surface of the disc are with the same temperature T_s .

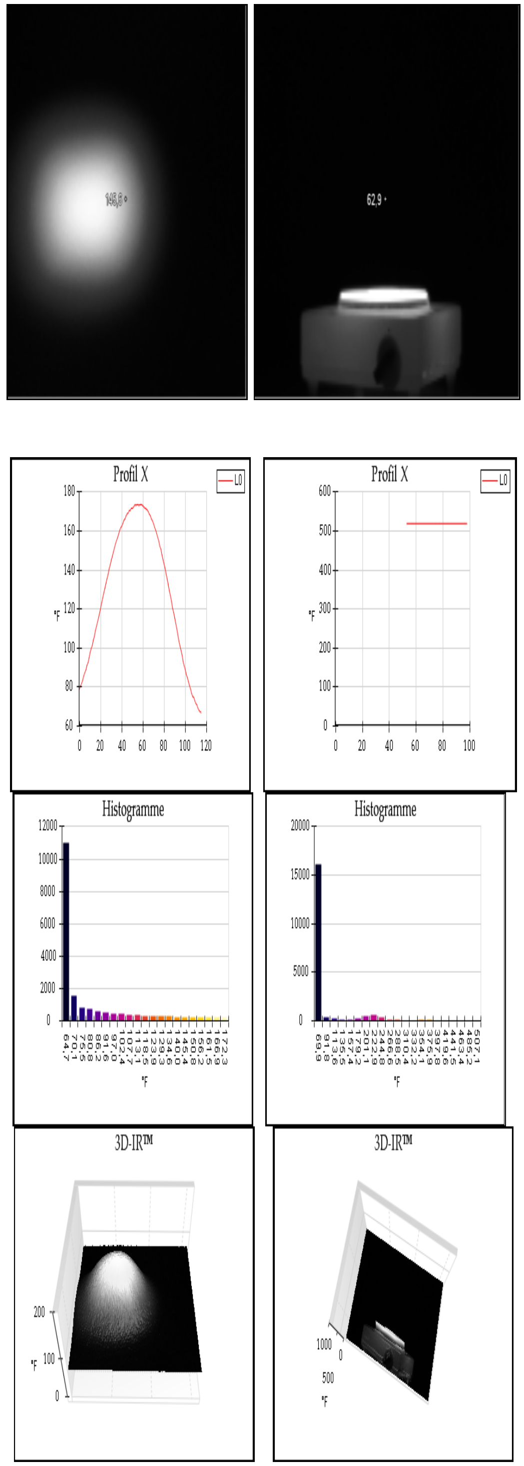


Figure3 : Transitory Mode Of Conduction To The Top Of The Disc &
Figure 4: Stationary Mode Of Conduction To The Top Of The Disc

4.Study Of The Convection

At first, let us try to describe in a purely phenomenologic way the temporal behavior of the disturbance of temperature which leads to the establishment of the image of the Fig. (5).

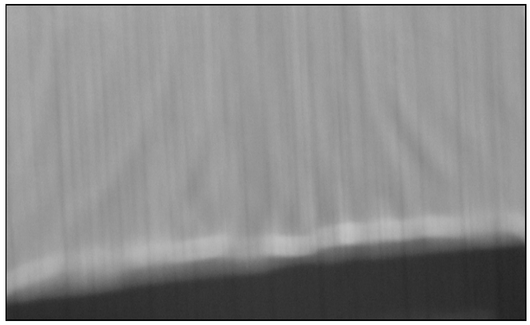


Figure 5: Rough Temporal Shadowgraph Image

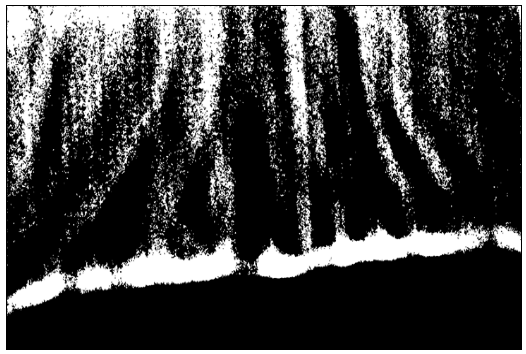


Figure 6: Treated Shadowgraph Image

The Fig. (5, 6) represent the shade of the disc as well as the masses of air moved by convection on the screen placed at a well calculated distance. This image illustrates the concentration of the light to the top of the disc in the form of a thin luminous tape. This optical phenomenon is due to the negotiable instruments of the refraction on the light rays and makes it possible to materialize the border of the thermal boundary layer. Thus the assembly allows, by the observation of the illumination of the screen, to locate the areas where the gradient of density varies and to know in which direction the variation is carried out. The image Fig.5 illustrates a very intuitive mechanism. The air at rest undergoes a fluctuation of temperature; the density varies and is accentuated when one rises in the fluid: this situation is potentially unstable, because in the field of gravity, the natural tendency is to put the heavy one in bottom and the light one in top. This redistribution results in the appearance of a circulation in the form of an alternation of area where the air goes up and goes down. This bounce is well illustrated in the Fig. (7).

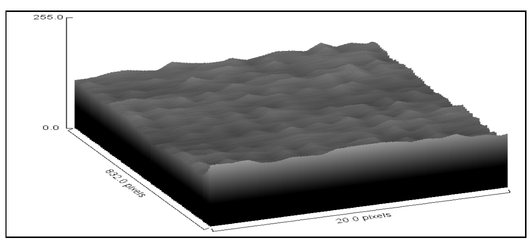
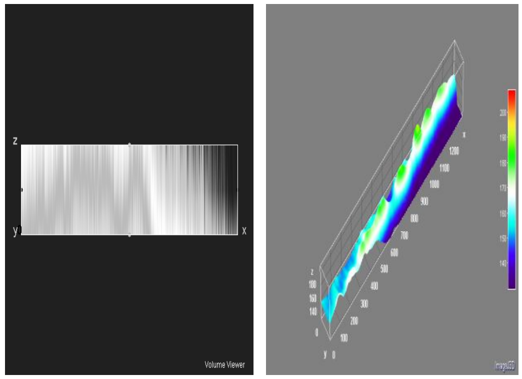
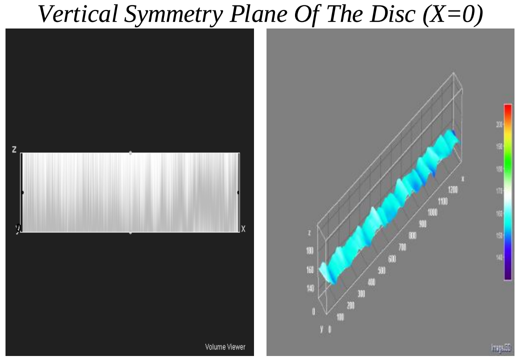


Figure 7: Plot 2D Of The Convection Area

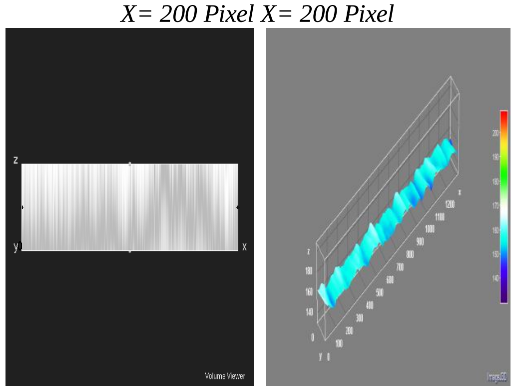
These areas are characterized by currents convectifs which appear under the effect of thorough of differential Archimedes. The morphology of these currents varies from one area to another according to the vertical Fig. (10, 11) and the horizontal Fig. (8, 9). That results in the competition between the mechanism of amplification of the disturbance and the mechanism of amortizement combining the negotiable instruments of viscosity and diffusion of heat. If the variation in temperature applied between the disc and the ambient medium is too small, acceleration to the top is weak and the dissipative processes carry it. The layer of air turns over in its basic state. As the variation in temperature increases, the destabilizing mechanism increases intensity. It ends up carrying it beyond gap criticizes ΔTc called threshold of convection. The experiment shows that, sufficiently meadows of threshold, this circulation is organized in currents length h which represents the height of the layer of air on which the trajectories of these currents become all parallel with the vertical and asymptotic.



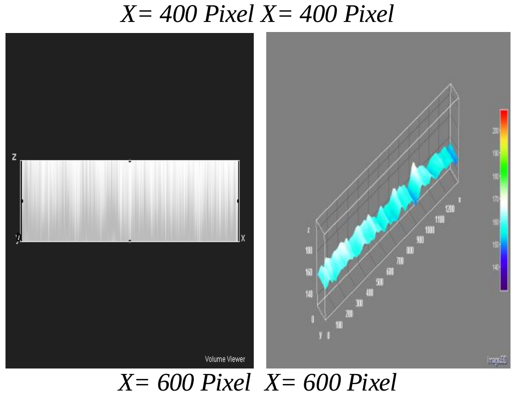
Thermal Boundary Layer
Vertical Symmetry Plane Of The Disc (X=0)



X= 200 Pixel X= 200 Pixel

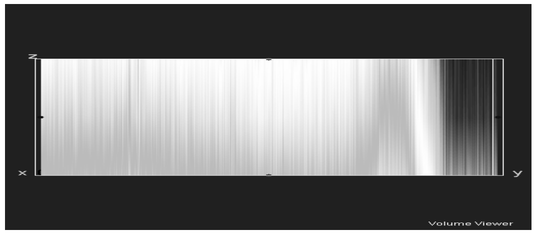


X= 400 Pixel X= 400 Pixel

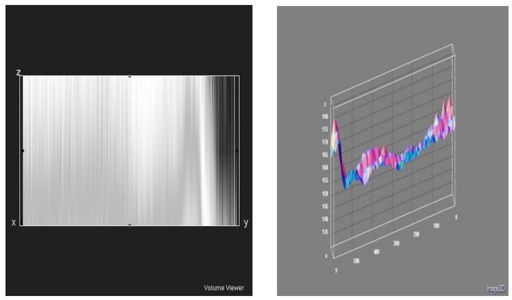


X= 600 Pixel X= 600 Pixel

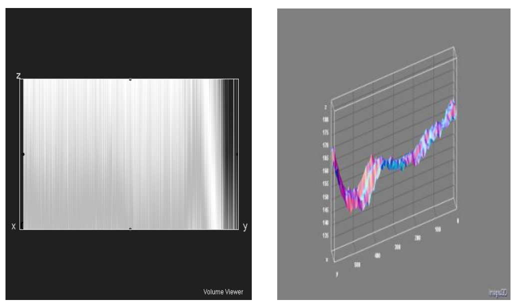
Figure 7: Temporal Samples For The Horizontal Linear Distribution Of The Luminous Intensity Along The Convection Area
Figure 8: Temporal Samples For The Horizontal Profiles 2D Of The Luminous Intensity Along The Convection Area



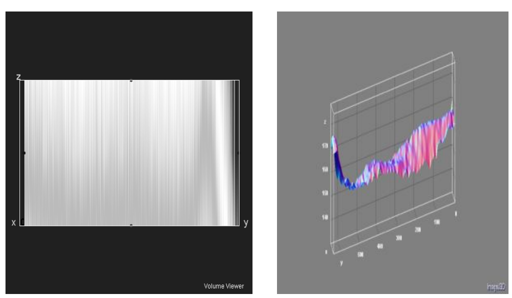
Leftt / Symmetry Plane
Vertical Symmetry Plane Of The Disc (X=0)



X= 200 pixel

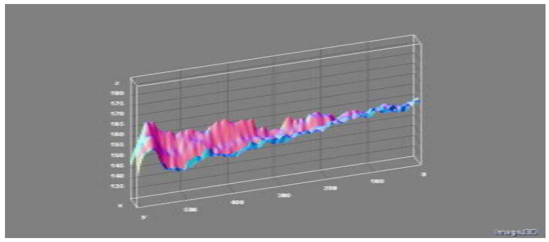


X= 400 pixel



X= 600 pixel

Figure 9(a): Temporal Samples For The Linear Vertical Distribution Of The Luminous Intensity Along The Convection Area On The Left Of The Symmetry Plane Of The Disc &
Figure 9(b)': Temporal Samples For The Vertical Profiles 2D Of The Luminous Intensity Along The Convection Area On The Left Of The Symmetry Plane Of The Disc



Right / Symmetry Plane

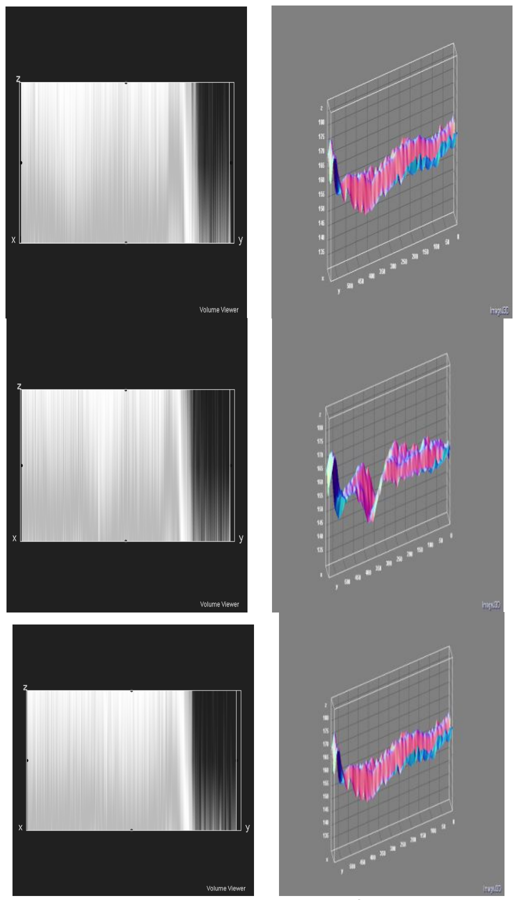


Figure 10(a)': Temporal Samples For The Linear Vertical Distribution Of The Luminous Intensity Along The Convection Area On The Right Of The Symmetry Plane Of The Disc &
Figure10(b)': Temporal Samples For The Vertical Profiles 2D Of The Luminous Intensity Along The Convection Area On The Right Of The Symmetry Plane Of The Disc

4.1.Structure Of The Thermal Boundary Layer

The observations of which we initially made state related to the total aspect of the convection. Let us examine now what occurs to the top from the disc. A first observation reveals a qualitative difference between layers. Contrary to the laminar boundary layer, which is not distinguished from the external flow by any tangible element, the turbulent boundary layer appears separate external flow by an irregular and fluctuating interface in time Fig.11. The convection is strongly swirling in the turbulent boundary layer. But a very fine analysis makes it possible to highlight two rather distinct areas in the turbulent boundary layer.

* An external area, accounting for approximately 90% the thickness total δ, illustrated by jets where the variation in temperature $\partial T / \partial y$ starts to be weakened, and where the distribution of the temperature T is hardly influenced by the conditions with the wall (it depends primarily on the fluid and the external flow).Fig.6.

* A deep layer very near to the wall, of which the thickness is about a few millimeters. Contrary to the external layer, the convection depends here mainly on the conditions to the wall (roughness of surface in particular) thus obviously that nature of the fluid. In this area, the law of temperature $T\ (y)$ is called law of wall.

A careful examination still results in visualizing three regions in this deep layer. We clearly distinguish two laws from temperatures. One applicable very meadows of surface, the other in the external part of the inner layer Fig .12. The corresponding areas are called respectively:

- Viscous sublayer is an area where molecular viscosity ν becomes dominating compared to turbulent viscosity ν_t which tends towards zero in the vicinity of the wall: indeed, the turbulent macro-scale of the structures is more and more limited by the proximity of material surface. In this area the flow is thus laminar. In this type of flow the particles do not mix and the trajectory of each particle of fluid is parallel to the different one. The thickness of this laminar film depends on the physical characteristics and nature on the flow but in this film the transfer made by conduction. The essence of the fall of temperature is carried out in this boundary layer which opposes an important resistance to the passage of heat.
- The log-law region (fully turbulent region) constitutes the external part of the deep layer. As its name indicates it, the temperature T varies like $Log(y)$. In this area, turbulent viscosity took the pitch on molecular viscosity.
- The buffer region (Bleeding region): Finally an intermediate area, between viscous sublayer and the log-law region associates the effects of turbulence and the effects of viscosity, is defined.

We can define an average thickness in time, δ_s, which is very small, about 1% or less total thickness δ. Therefore, for $y < \delta_s$ the flow is regarded as dominated by friction. In this area the temperature is practically linear with y and the shear stress is equal to its value with the wall [14].

In the area $y > \delta_s$, the effect of viscous friction in the average transfer of temperature in the flow decreases in a gradual way with the distance to the wall, and finally we arrives at an area where the flow is completely turbulent and the viscous effect become negligible. It is about the completely developed region or turbulent area, where there exists a broad range of sizes of swirls and frequencies.

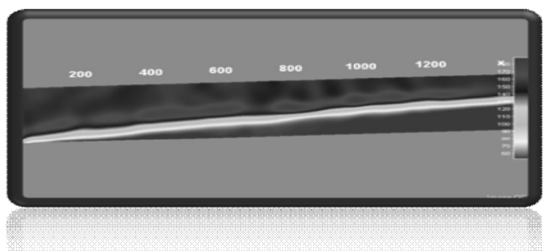


Figure 11 : Structure Of The Thermal Boundary Layer

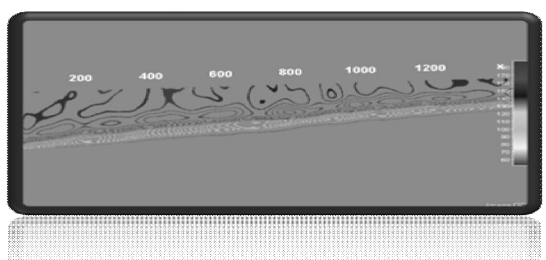


Figure 12 : Structure of the inner layer

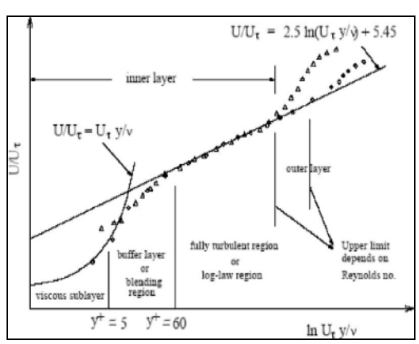


Figure 13: Structure Of The Inner Layer [4] (Smooth Surface)

4.2.Evolution Of The Inner And Outer Layer

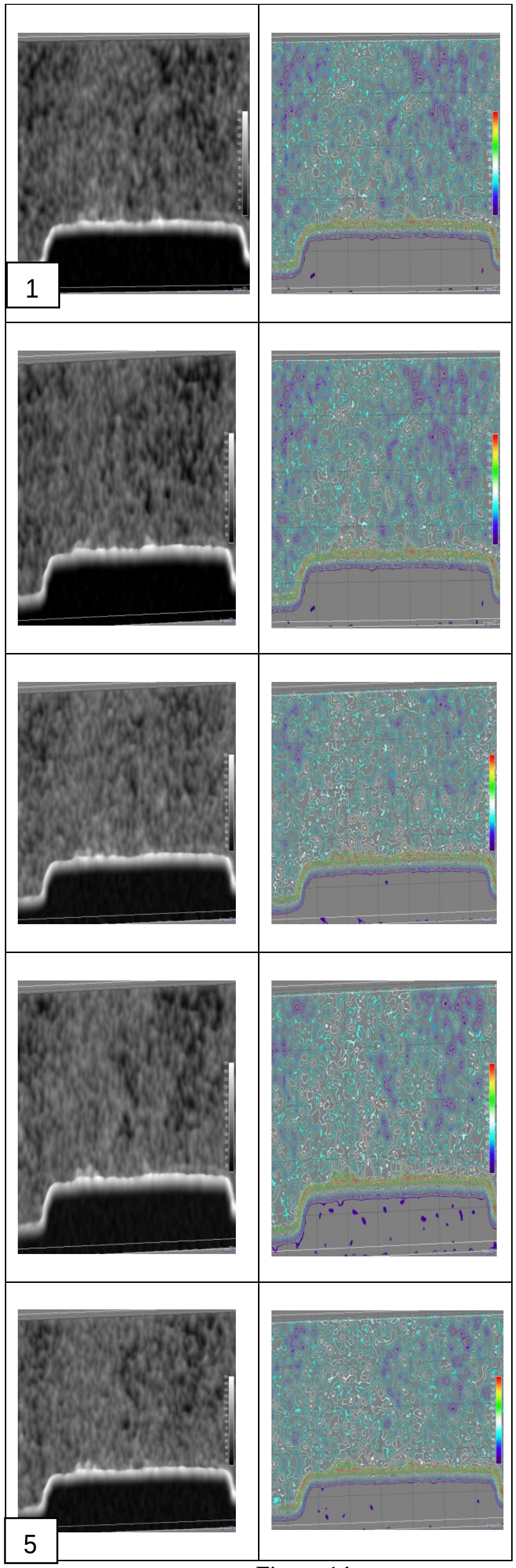


Figure 14

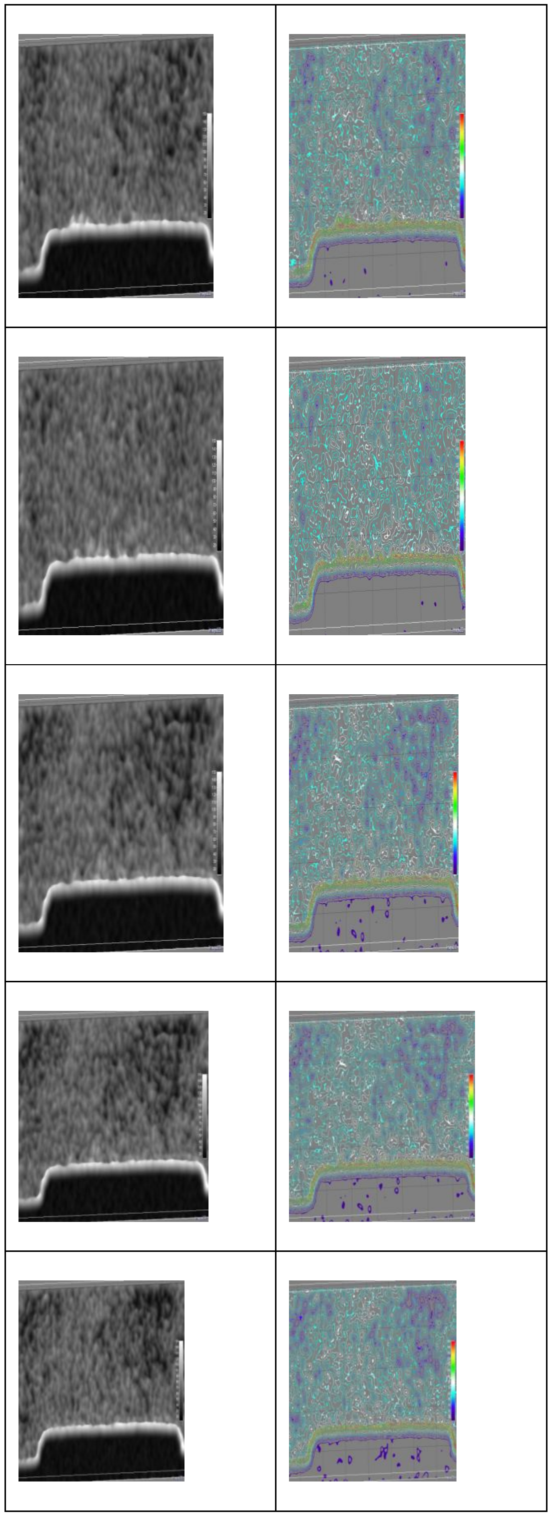


Figure 15

Starting from these images we can deduce the following:

- The present experiment confirmed the existence of a cyclic sequence, dependant on the production of the turbulence, which links the external regions and intern. Thus, the flow near the wall consists of a whole of alternate longitudinal thin straps characterized by varied speeds (streaks), as we can observe in Fig. (14,15). It is thus generally accepted that the streaks contribute to the generation of turbulent energy. However, the mechanisms of generation of the streaks are always a discussion topic.

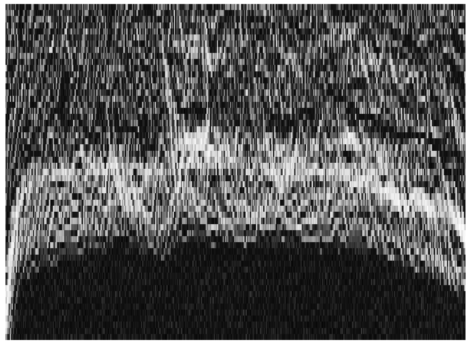
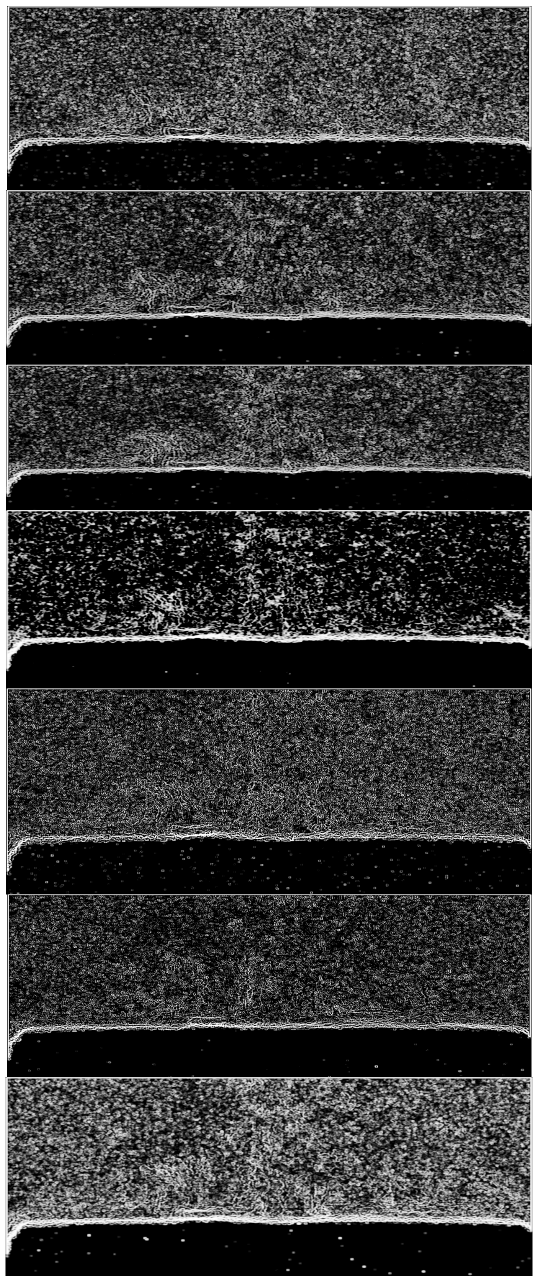


Figure 16: Generation Of Streaks

4.2.1..Evolution Of The Streaks



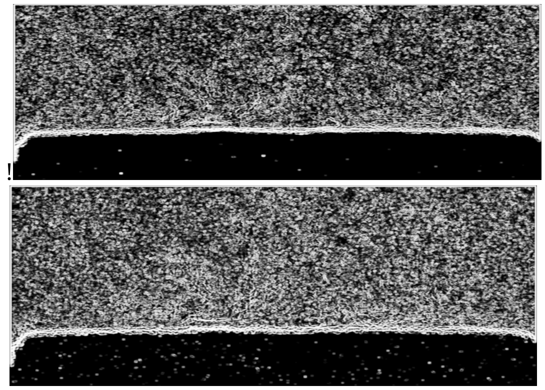


Figure 17: Evolution Of Streaks During 1sec

- Normal profile speed to the wall in a boundary layer is convex, while the profiles speed for the streaks parallel with the wall have points of inflection, as we can observe in Fig.(16,17).The disturbances grow much more quickly in the presence of such a profile.

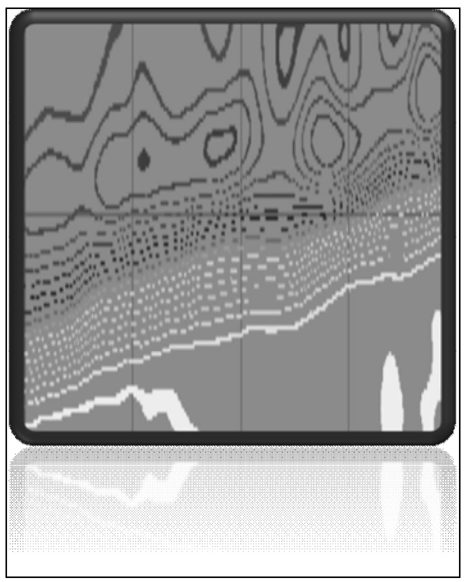


Figure 18 : Profiles Of Streaks

4.2.2.Evolution Of The Profile Of Streaks

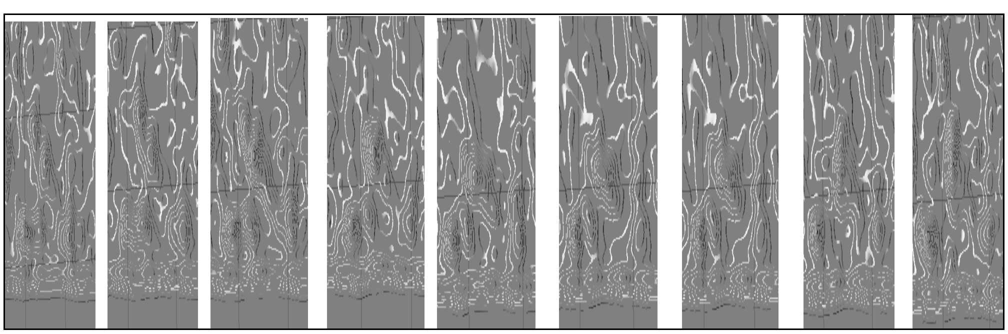


Figure 19 : Evolution Of The Profiles Of Streaks During 1sec

- It is observed that the flow starts to lose its homogeneity starting from the buffer region. The phenomena of the streaks is responsible for the generation of most of turbulent energy in the logarithmic area.

4.3.Passage Of The Inner Towards The External Area

The passage of the internal area towards the external area (layer of mixture) where the temperature varies in a random way in time is carried out by a series of instabilities: appearance of swirls which make the convection increasingly complex. With of a critical temperature, new structures appear in the interface during time. The trajectories of the elements of fluids start to be rolled up according to geometries complex but very beautiful to follow them (Fig.18).

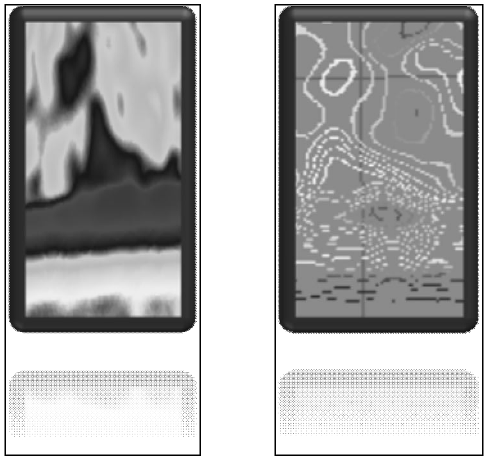


Figure 20 : Layer Of Mixture

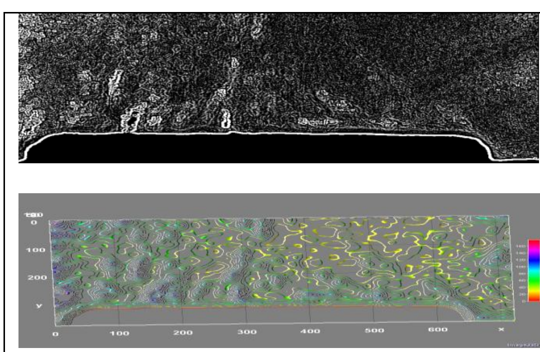
4.4.Evolution Of Instabilities

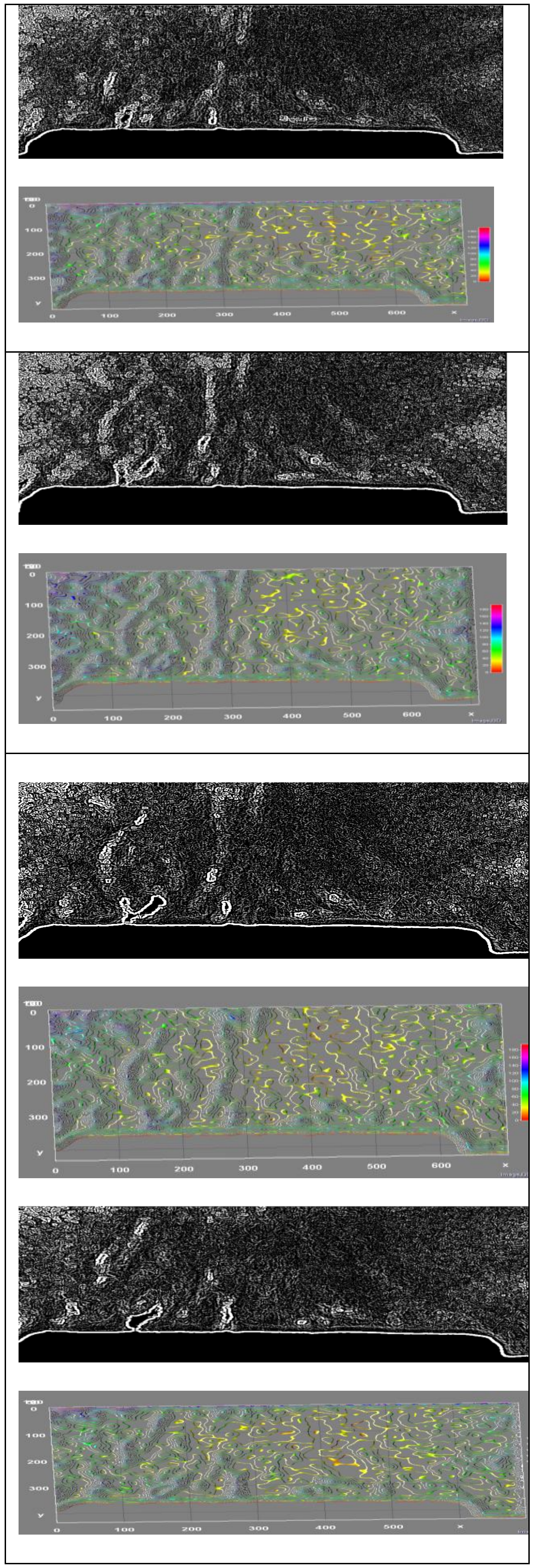
4.4.1.General Study

The viscous sublayer represents less than 1% total thickness of the boundary layer.

The dynamics of the viscous sublayer is rather complex. Its thickness tends to increase in the direction of the flow, until the appearance of instability. This mechanism of instability is thus generating of turbulence in the boundary layer since it causes to inject into the flow a package of fluid much slower, swapped to some extent against a faster package which comes to feed again the viscous sublayer. It follows the issuing of a swirling puff which involves its thinning, and a new cycle start again Fig.16.

Thus, the kinetic energy of turbulence is generated by the collision between the fluid of the boundary layer and the slower puff which arrives to him. During this time, in the laminar sublayer, molecular viscosity acts “to roll” the swirls, and transforms the turbulent kinetic energy into heat. A new more stable state settles, in which the turbulent kinetic energy production is of the same order of magnitude as dissipation.





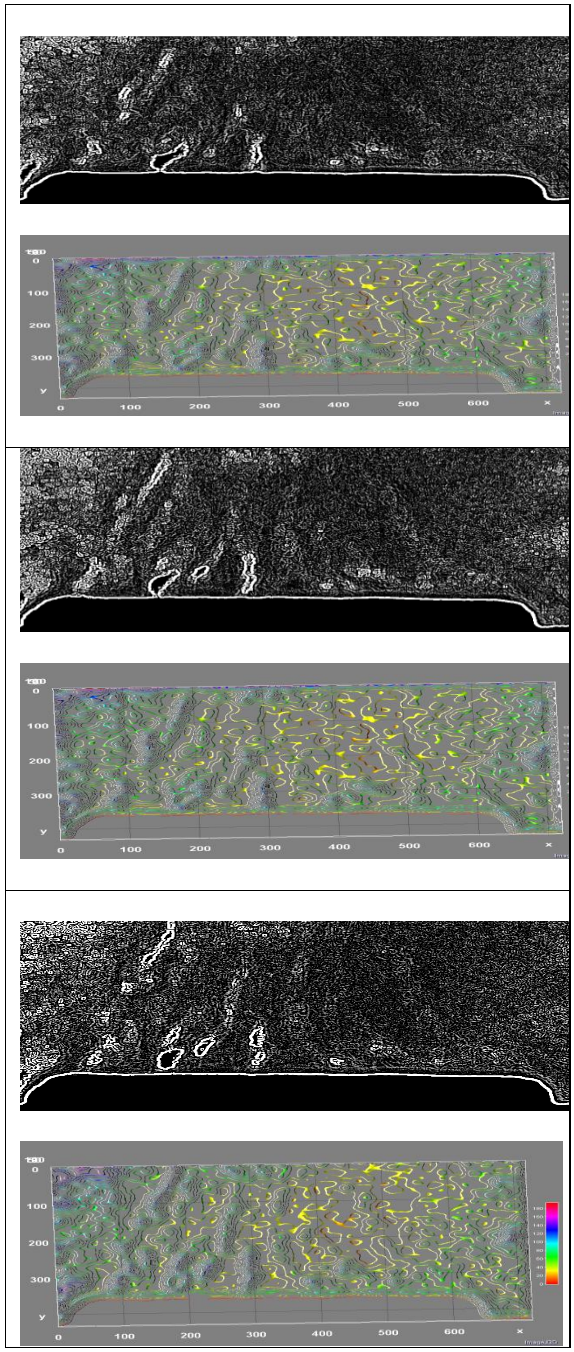


Figure 21:: Evolution Of Instabilities (The Following Photographs Are Taken Each 1/10sec)

4.4.2.Examples Of Instabilities

In these natural examples, thermal effects are also of fundamental importance and lead to various phenomena, from stratification to turbulent convection. The question is to understand the influence of this thermal effect on the growth of the instability and also how the instability could disturb the flow and the thermal transfers.

The importance of the streaks is fundamental for the development of turbulence near the wall. Then, the streaks interact with the outerlayer of the boundary layer through a process of separation of the wall, oscillation, explosion and finally ejection, which is represented on Fig. (17, 18).

It is necessary to look further into the fundamental physical comprehension of these mechanisms.

- Backdraft

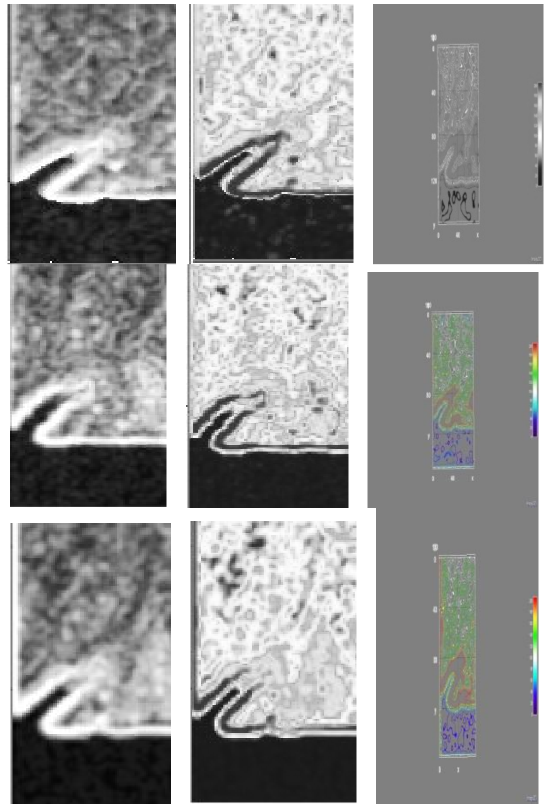
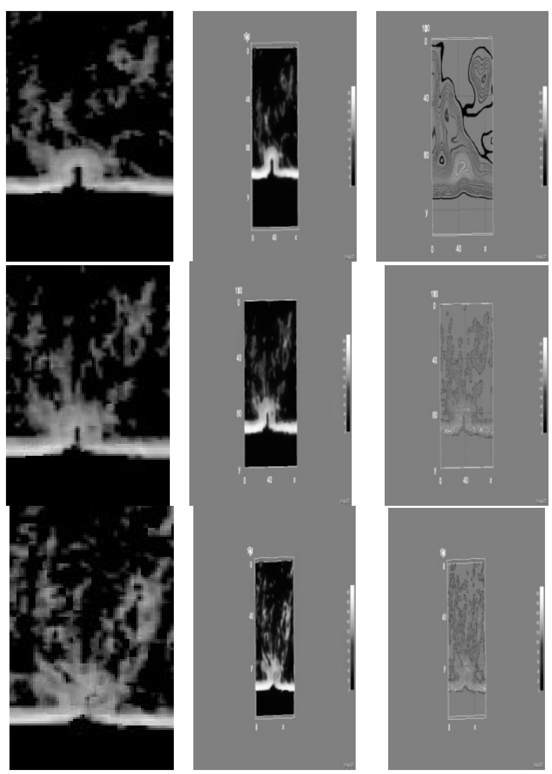


Figure 22 : Backdraft

- Explosion of a bubble of air



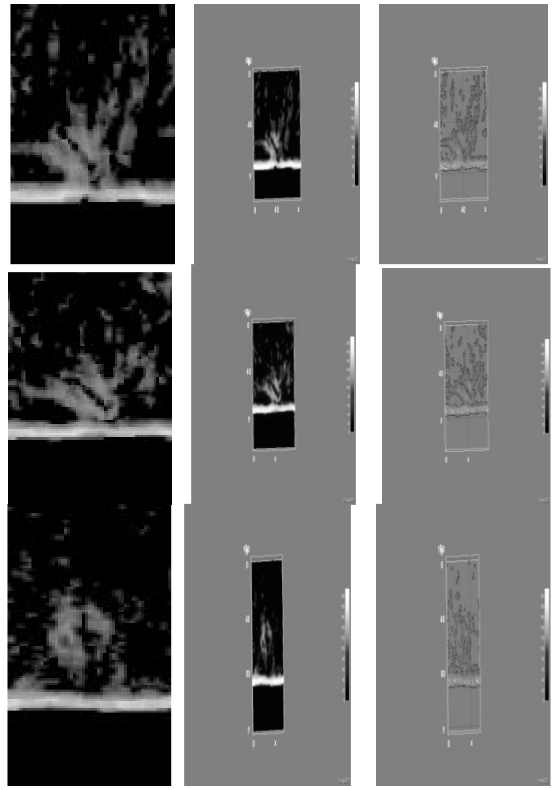


Figure 23 : Explosion Of A Bubble Of Air

5.Conclusion

This work aims to provide fine empirical information on the way by which is carried out the natural convection above a grooved disc, used for domestic needs (cooking) and the external medium (ambient air). In order to achieve this goal, we put at the point a display and quantification system of the fields of temperature. The first millimeters of the boundary layer could be thus observed via two means: an usual way (shadowgraph) and a recent numerical means (image processing real-time). The main conclusions are the following ones:

- To visualize and to follow the masses of air developed during the convection (with a scale of time arriving up to 1/10 seconds and a scale spaces in pixels).
- To explore the structure of the thermal boundary layer by the means of the image processing.
- Fine description of instabilities met (oscillation of the boundary layer, evolution of viscous sublayer, generation of the swirls).

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