Flame characterization by PIV in microgravity conditions

Jean-Michel MOST, Aurélien MOST, Arnaud SUSSET, Jacques BAILLARGEAT
and Pierre JOULAIN

Laboratoire de Combustion et de Détonique
UPR 9028 au CNRS, ENSMA
BP 40109
F-86961 FUTUROSCOPE Cedex
Most@lcd.ensma.fr

ABSTRACT

The influence of the air supply on the behavior of a diffusion flame representative of a fire is studied. The natural or forced ventilation of the reactive zone controls the chemical processes and acts on the flame properties. To have a better understanding of the phenomena involved in such a combustion, an experimental setup was designed and built to stabilize a buoyancy driven laminar diffusion flame over a flat burner. The flame behavior is characterized when the air supply of the combustion zone decreases to an under-ventilated environment. Conditions of a non shear flow were determined to limit vortex formation and to reach a diffusion controlled situation. For these purposes, tests were performed in microgravity to avoid any buoyancy effects leading to convection of air into the reaction zone. This reduced buoyancy environment allows diffusion transport to be developed without any flow perturbations.

Temperature (thermocouples) and velocity (Particle Image Velocimetry P.I.V.) fields are determined in normal and reduced gravity environments (parabolic flights). The PIV technique was successfully adapted to the study of such a reacting system despite many constraints: safety regulation., hostile environment, the short duration, and limited number of measurement tests.

The obtained results show a drastic modification of the behavior (location, size, color) and of the thermal properties of the flame when both buoyancy forces fall to zero and the flame becomes under-ventilated. The velocity flow measurements confirm the effects of natural convection on the flame structure inducing air supply at normal gravity, and attest that the reaction is stabilized in an non-shear zone. Consequently, the information on the flame behavior (temperature variation through the flame zone) can be used to model the involved combustion phenomena. The obtained information should be introduced into a fire safety analysis numerical code both for ground or spatial applications.

1. GENERALITIES

Diffusion flames are generally defined as any flame in which the fuel and oxidizer are initially separated (or non-premixed), the reaction occurs in a narrow zone that can be approximated as a surface, the mixing rate between the reactants is slower than the chemical-reaction rate, the latter is often of negligible importance for diffusion flame. Flames representative of fire stabilized over a solid (or liquid) fuel material present such characteristics. The convective flow induced by gravity serves to both extract the burned gases from the reaction zone and to provide fresh air which is diffused to the reaction zone. Thus, natural convection and diffusion processes are linked. To model such phenomena, we generally use the Burke Schumann theory [Kuo, 1986, Burke Schumann, 1928]. The classical example of this kind of jet diffusion flame is provided by a system in which fuel and air flow with the same linear flow velocity in coaxial cylindrical tubes. During this experiment, two classes of flames were observed. As a function of the respective ratio of the duct radii, if more air is available than what is required for complete combustion, then, an over-ventilated flame is formed and the flame boundary converges to the cylinder axis. On the other hand, if the air supply is not sufficient for complete burning, then an under-ventilated flame is obtained and its surface extends to the outer tube wall. These results show the modification of the reaction zone location and flame characteristics with the local equivalence ratio of the reactants. This theory is used for most diffusion flame modeling.

A similar flame behavior has been observed in our laboratory. In the currently practical case of a fire in a confined environment, when the air supply decreases and becomes insufficient for a complete combustion [Bertin, 2000, Coutin, 2000]. For example, it was observed [Audouin, 1997] that a flame stabilized over a pool fire leaves its burning surface, and moves through the compartment towards the room aperture. This flame phenomenon is sometimes called “a ghosting flame”. This behavior was reported again in the laboratory by Bertin et al [2000]. They also observed another scenario, during the simulation of the burning of a fuel material located in the non-ventilated upper zone of a laboratory scale compartment [Coutin, 2000]. For given conditions, a ghosting flame is stabilized at the interface between the vitiated hot layer composed of combustion products, trapped by a soffit, and the ventilated lower region of the room. In these last two fire configurations, hydrocarbon burning, soot formation and oxidation are strongly modified by the environment conditions and air supply. In these compartment fires, the flame modeling requires a complete understanding of the flame structure.

Many authors have studied the diffusion flame structure [Bilger, 1976, Pagni, 1980] in a normal gravity environment. Under such conditions, the air entrainment into the reactive zone is completely controlled by the entrainment of the combustion products induced by gravity or forced convection [Weckman, 1986, Delichatsios, 1987, 1988]. The flame is located at the stoichiometry of the global reaction. Dynamic gravitational (Kelvin-Helmoltz) and thermal (Bénard – cold gases above flame zone) instabilities induce the formation of large scale vortex structures which improve the reactant mixing and heat dissipation. But, only a few experiments in reduced gravity environment have been conducted [Torero, 1994 and Vietoris [1-2], 1999] concerned experiments without or reduced buoyancy.

The first objective of this work was to design an experiment in which a laminar diffusion flame representative of a fire can be stabilized in a non shear region (as Burke Schumann’s experiment). The aerothermal properties should be determined. The Burke Schumann’s conclusions should be extended to flow conditions corresponding to small values of the characteristic Froude number Fr (ratio of the inertia and buoyancy forces) of the system.

$$Fr = \frac{u^2}{Lg}$$

where:

u	characteristic velocity of the flow	(m/s)
L	characteristic length of the system	(m)
g	buoyancy acceleration.	(m/s^2)

The second objective was to study the modification of the diffusion flame behavior when the buoyancy field tends to zero (flame shape, length, color, soot concentration, radiation, air entrainment into the reacting diffusion zone). During the tests, the air supply to the flame is controlled. By limiting the flow shear stress, the flame is investigated without any stretching of the reacting zone where the diffusion phenomenon is evaluated at various convection level. Then, the temperature and velocity fields of the flame region should be precisely described simultaneously to the evaluation of the radiative heat exchanges. The obtained results both at normal and microgravity conditions are compared; the buoyancy and air supply effects on the flame behavior are evaluated. A hypothesis on the efficiency of the reactant mixing processes is proposed. This study follows previous works developed in the laboratory on pool fire in micro and hyper gravity conditions [Chen, 1994, Most, 1996, Most, 1998, Mandin, 1999].

This research finds its applications in fire safety analysis both for ground and space conditions.

2. EXPERIMENTAL SETUP

2.1. Flame configurations

The two standard configurations representative of a fire are the pool and the wall fire on horizontal or along vertical burning surfaces respectively. In natural convection, the hot combustion products are driven away by buoyancy which induces the air entrainment towards the reacting zone to feed the flame. In microgravity conditions, the reaction zone is no longer supplied with the oxidizer, that leads theoretically to flame extinction.

An experimental setup was designed to impose a controlled air supply by forced convection, at low velocity, at the base of the flame of a two-dimensional pool fire (square surface). A complementary flame behavior is investigated without air injection. This case allows an observation of the transition from a ventilated to an underventilated flame in microgravity, which then generally leads to the extinction.

2.2. Experimental setup description

During the burning of a solid material, the heat flux from the flame sustains the solid surface pyrolysis. Then the degradation products diffuse to the flame and feed the combustion zone. In order to both decorrelate the heat feedback to the surface from the pyrolysis mass flow rate and to study an equilibrium system at the time scale of the test, the degradation of the material is simulated by injection of a fueled gas through a porous surface burner.

2.2.1. The burner

A two-dimentional flow situation is expected (Figure 1.). The burner is composed of a 5x5 cm^2 porous bronze material (4.5x4.5 cm^2 effective porous surface) laterally bordered with two plates of the same dimension. Ethane was used as the fuel because its density is close to that of air. Air necessary for combustion is introduced, at low velocity, parallel to the porous surface and close to its leading edge. The 2D flow is obtained by air injection upstream of a honey comb followed by a convergent nozzle (Figure 1.) with a contraction factor equal to 5. This settling chamber is divided in three similar parts, one at the center and two laterals. The section of the nozzle exit at the burner edge is, for each settling chamber compartment, 0.02m in height and 0.05m in width. A wall is installed downstream the burner surface forming a stagnation in plane flow. Two lateral pyrex windows close the test section.

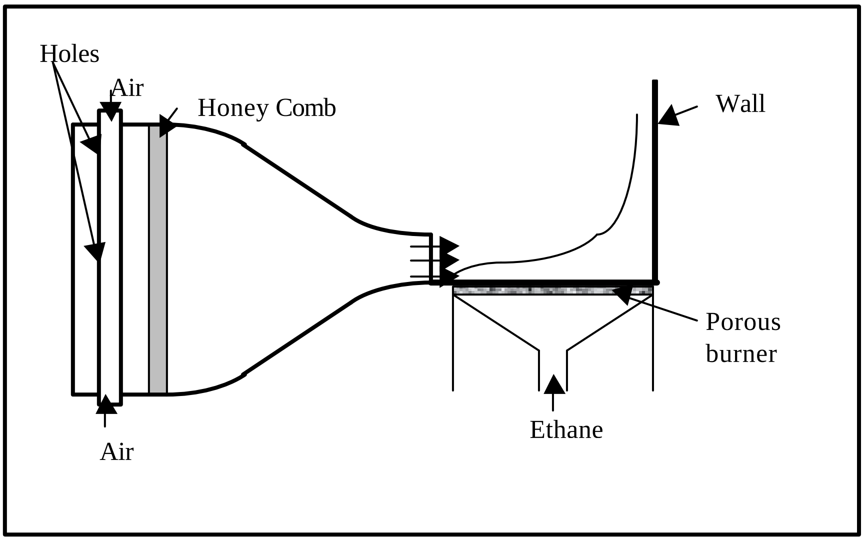

Figure 1. The burner and the settling chamber

2.2.2. The combustion chamber

The burner is placed inside a cylindrical combustion chamber (Figure 2. - 0.30m diameter, 1.2m height). Pyrex windows allow flame visualization and the use of optical diagnostic methods. An outlet, open to outside of the plane, keeps the indoor pressure to the room constant at one atmosphere.

To fill up the chamber after a complete depressurization, air is introduced through the lower part of the chamber.

2.2.3. Working parameters

The main parameters during a test are the fuel mass flow rate through the porous material and the air velocity flowing at the leading edge of the flame. All the fuel mass flow rates are controlled by mass flow meters. The air velocity are respectively set to 0.083, 0.167, 0.25, and 0.33 m/s. The ethane injection velocity is 9.05 10^{-5} m/s that corresponds to a thermal output power of 1.11 kW. The blowing coefficient (ratio between ethane and air velocities) is included between 0.10 and 0.02. During the present study, the chamber pressure is 0.1MPa for laboratory and 0.08MPa for parabolic flight conditions. For ground based laboratory situation, this parameters correspond to a Froude number of 10^{-4}.

2.2.4. Microgravity facility

The reduced gravity conditions were obtained during the parabolic trajectory of an airplane (AirBus A300 O-G NOVESPACE-CNES – Fig. 3.). A gravity level of $\pm 10^{-2}$ g_0 (g_0 is the normal earth gravity) is obtained during the 22 seconds of the parabola, between the pull up (before the microgravity period) and recover (after the microgravity period) phases where the gravity reaches $1.8g_0$. Each flight campaign includes 3 flights of 31 parabolas each.

The safety instructions related to experiments in an airplane require that the experiment setup can withstand a longitudinal acceleration of $9g_0$. The working conditions are often difficult for the experimenters who may become airsick. So the control and safety procedures should be simple and dependable. A minicomputer has control of the gas mass flow rates, the flame ignition and extinction and data acquisition through a specific software. A photography of the setup aboard the airplane cabin is given in Figure 4.

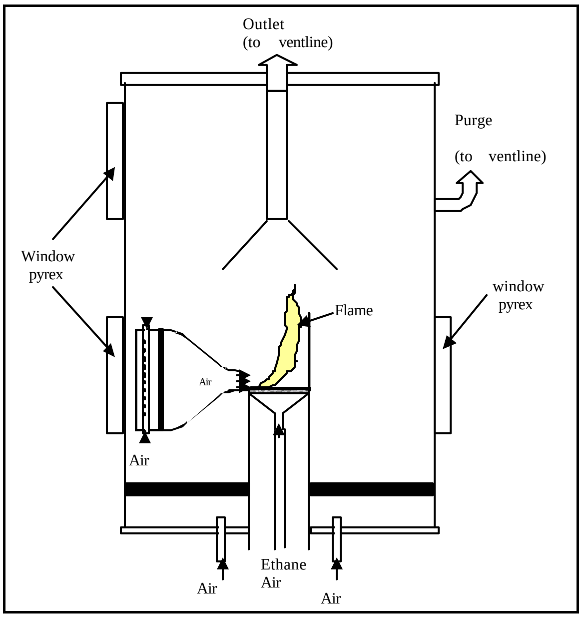

Figure 2.The combustion chamber

Figure 3. Airbus A300 0G

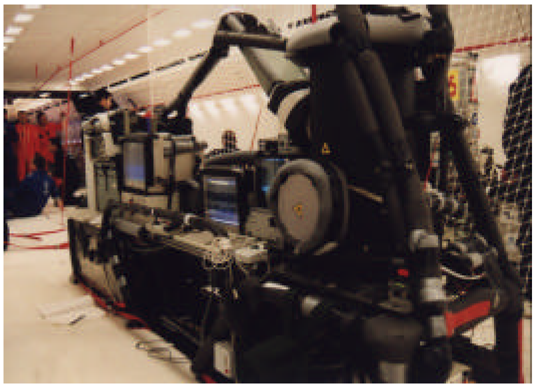

Figure 4. The experimental Setup

3. DIAGNOSTIC METHODS

Diagnostic methods concern the spontaneous flame emission image processing and the determination of temperature and velocity fields.

3.1. Spontaneous flame emission

A CDD camera is used to visualize the flame shape, length and color. A yellow color of the flame attests to soot formation in a hot region, while the blue color is characteristic of the C_xH_y or C_2 radicals emission.

3.2. Temperature measurements

A set of four thin wire Pt/Pt-Rh type B thermocouples (75µm diameter) mapped the temperature in the reaction zone. For that, this set is moved vertically by a motion of the burner (7.5mm step), and horizontally by moving the thermocouple set (2.5mm step). No correction of the thermocouple time constant and of the radiation losses are applied on the temperature data.

3.3. Velocity measurements

The velocity field was determined by the Particle Image Velocimetry (P.I.V.) technique. The double cavities Nd-Yag laser source (λ=532nm), 25mJ per pulse, was fixed on the combustion chamber. The thin laser sheet allows an measuring surface of 50x50 mm² (Figure 5.). The pictures of the flow are acquired, after reflection on a mirror, by a 1300x1000 pixels ^{2} high resolution CCD camera placed behind the window. This spatial resolution is very good considering the size of the processed image. In order to avoid recording the flame emission on the image, a Ferroelectric Liquid crystal (FLC) shutter was preferred to a classical interferential optical filter centered on the laser wave length. The laser pulses, the shutter and the camera are electronically triggered. Two milliseconds of the shutter aperture was found to be sufficient to erase the flame shape on the particle images. Unfortunately, the maximum transmission of the shutter is 30%, (100% adsorption when not excited) that requires a more sensitive camera. Since it was both difficult to predict the flame emission intensity during the reduced gravity period, and to adjust the camera parameters in real time, the optical shutter gave the opportunity to prepare the camera settings, before the flight. In conclusion, the use of the optical shutter gave a high quality image of the particle cloud for the PIV processing. The experimental setup is shown in Figure 6.

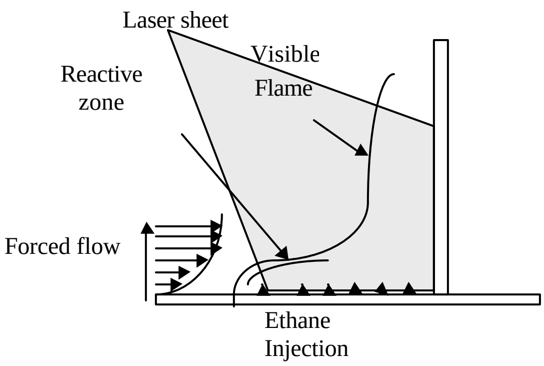

Figure 5. The laser sheet

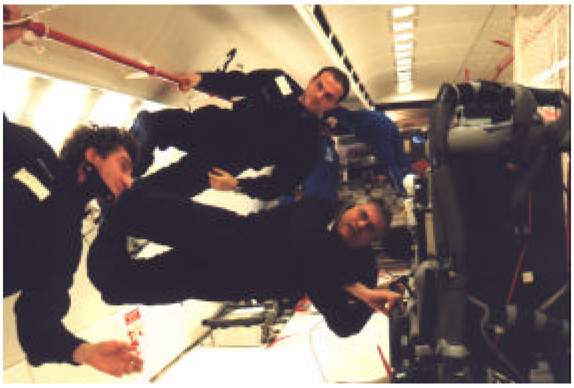

Figure 6. The experimental setup and the staff during microgravity period

3.3.1. The PIV processing

The standard PIV image processing method uses a FFT algorithm to calculate the cross correlation between two images. This technique requires an analysis of windows of 2^n x 2^n pixels ^{2}. In this work, to increase the spatial resolution and the measurement accuracy, an iterative cross correlation algorithm was developed. This method has the advantage of allowing the correlation windows to be adapted to the size and shape of the flow. This algorithm is iterative and improves the detectability of the correlation peak and of the spatial resolution. The iterative process improves the accuracy of the Minimum Quadratic Difference (MQD) method [Gui, 2000]. This algorithm has already been validated on synthetic images [Susset, 2000]. The algorithm is optimized and the calculation time for 3000 velocity vectors (30x30 pixels ^{2} window) is around 10s on a 450MHz PC450 minicomputer. The time interval between the two successive laser pulses was set between 1.5 and 2ms in order to have a maximum displacement of 10 pixels. These settings enable the use a 30x30 pixels correlation windows (1x1mm^2) for the first step of the iterative cross correlation tracking algorithm.

During the parabolic flight, a maximum of two minutes separates two consecutive parabolas. The software recorded on hard disk the pairs of PIV images acquired during each microgravity period. A synchronization was made between the times of test data acquisition (gases mass flow rates, gravity level) and the image processing time.

A post processing software of the measured velocity was developed for the determination of the mean and fluctuating velocity fields, and flow vorticity.

3.3.2. Flow seeding

The velocity measurement by PIV requires a seeding of the reacting flow by refractory material ($T_{melting}$=2700°K). Zirconium oxide particles, with 2μm mean diameter, which are supposed to follow the flow (low inertia) are introduced in the air flow. Unfortunately, ethane cannot be seeded, even with small scattering centers as incense, since the porous plate acts as a particle filter. It is always difficult to find a system to seed homogeneously a low mass flow rate of gas with solid particles. None of the cyclone seeders, fluidized bed or rotating brusher seeders, is perfect. The best system seems to be the brush seeder despite difficulties to fill it in flight. Both to avoid the particle concentration of the injected air, and to reduce the lateral window particle deposition, only the central section of the convergent nozzle is seeded.

4. RESULTS

4.1. Standard stagnation in plane flow (Hiemenz flow)

This flow type leads to a stagnation plane (two-dimensional flow) as shown in Figure 7. An exact solution of the Navier-Stokes equations was proposed by Hiemenz [Schlichting, 1960], by using a similarity approach for the viscous flow. The resolution of the differential equation set gives the complete velocity field. The present flow configuration Case 2 is slightly modified from the standard case (Case1). In the plane x = 0, the Case 1 considers a plane of symmetry, the Case 2, a boundary layer is formed a long the porous burner with mass transfer at the wall. The second difference concerns an air flow limited to the height of 0.02m of the convergent rather than an unlimited air flow (Case 1).

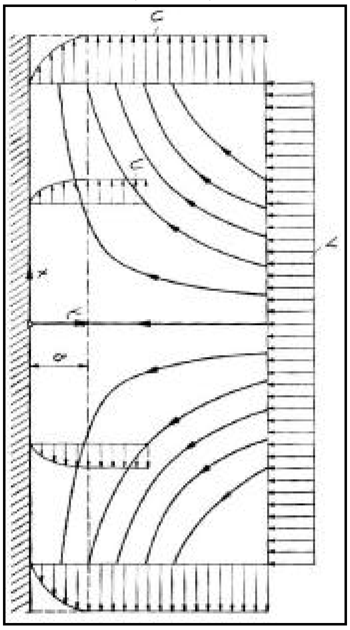

Figure 7. Standard Stagnation in plane flow
Case n°1

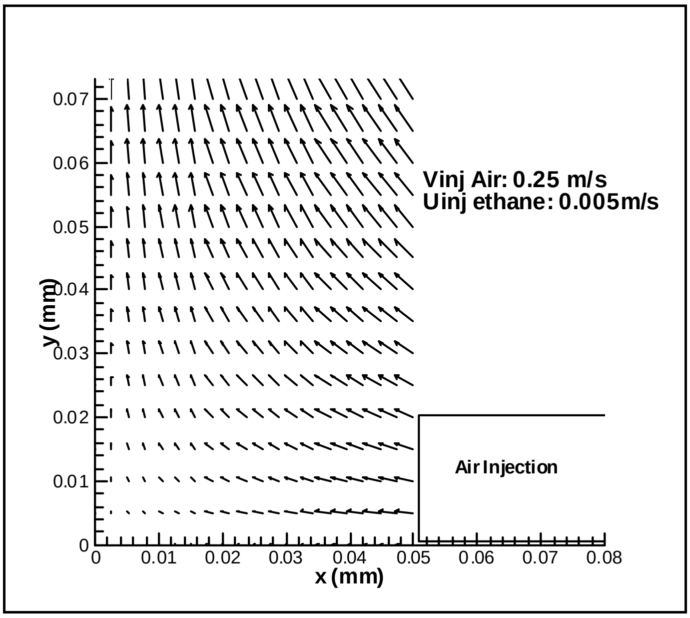

Figure 8. Calculated flow field
Case n°2

The numerical result (Figure 8.) shows a similar solution for the dimensionless velocities V/V_{inj}, U/V_{inj}, where U and V are respectively the vertical and horizontal velocity components, and V_{inj} the mean velocity of the incident air flow.

For non-buoyant flow, the flame zone should follow the streamlines, then the flame will be located in a non-shearing region and should be invariant with a modification of the air flow.

The mean velocity field and streamlines, measured by PIV without flame (injection of ethane but not ignited), are presented Figure 9 for an air velocity of 0.25m/s. The experimental results show both, the formation of a counter-rotating vortex in the burner-wall corner not predicted by the similar solution, and the deflection of the air flow by the wall. The dimensionless velocity vectors present a similarity for all air mass flow rates, only the vortex size is flattened by an increase of V_{inj} . The velocity field evolution displays an unsteady motion of this vortex core.

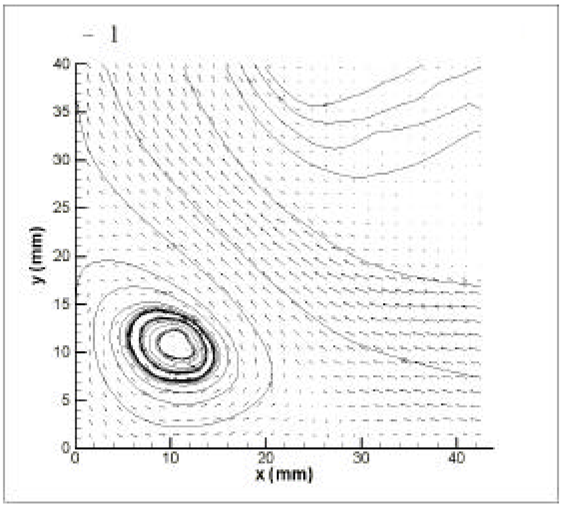

Figure 9. Dimensionless U/V_{inj} mean velocity field without flame for V_{inj}=0.25m/s

4.2. Spontaneous flame emission

In ground and hypergravity conditions, a blue flame is anchored at the burner leading edge (hydrocarbon radical emission) followed downstream by yellow flamelet structures, characteristic of the emission of soot (Figure 10). The reactive flow presents gravitational hydrodynamic instabilities which disappear without gravity, at least for small air mass flow rates.

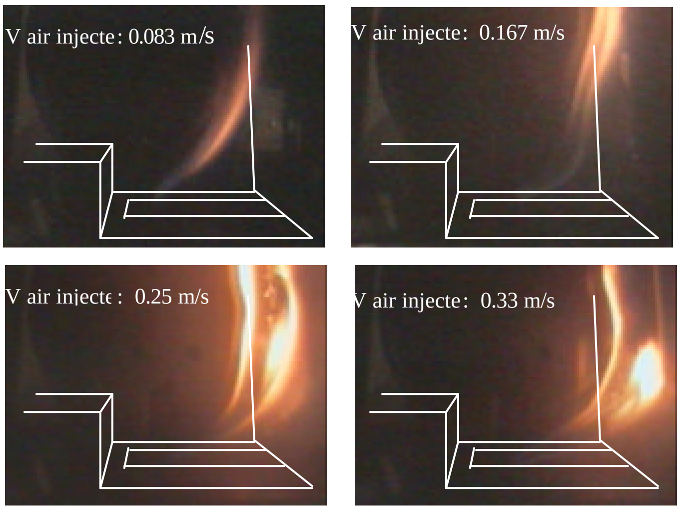

Figure 10. Spontaneous flame emission in Microgravity

In reduced gravity, a front view of the flame attests to the two-dimensional character without any twisted structure. An increase of the incident air flow velocity V_{inj} moves the flame nearer to the burner surface, decreases the flame-burner angle as a function of the square root of V_{inj}, and induces a cyclic phenomenon of sooty yellow flame structures growing (flame reactant ignition) and disappearing. The flame takes a parabolic shape at the burner edge, which is a function of the blowing coefficient of the boundary layer, and then follows the streamlines of the stagnation in plane flow. This modification of the reacting zone location with V_{inj} is not in agreement with the similar solution for the non buoyant and non reactive flow which predicts an invariant flow with V_{inj}. In conclusion, the flame visualization shows that both the aerodynamic and chemical processes control the flame behavior.

4.3. Temperature variation trough the diffusion flame zone

At normal gravity, the temperature fields in the reacting flow corroborate the flame visualization observations for the flame shape and location. Both the maximum temperature lines and flame shape closely follow the same stagnation in plane flow streamlines, except at the burner leading edge, on the one hand, where the flame-burner angle varies with V_{inj}, and on the other hand, downstream, where the natural convection forces become dominant. The increase of the air flow velocity induces an augmentation of the maximum flame temperature and brightness. A similar behavior is also obtained in microgravity. A drastic modification of the flame characteristics is observed between the smaller and higher injection air velocities. For V_{inj}=0.083m/s, a thin zone (0.012m thickness) of constant low temperature (700°C maximum) follows the flow streamlines (Figure 11-Left). With an increase of V_{inj} (Figure 11-Right), the maximum flame temperature reaches 1050°C for V_{inj}= 0.25m/s that corresponds to temperature values measured in normal gravity. At these conditions the reaction zone was ventilated both by forced and natural convection. The air injection rate slightly modifies the flame thickness and location: the position of the flame maximum temperature is pushed downstream by the air flow. This result is interpreted as a modification of the flame stabilization processes at the injection zone leading edge (boundary layer with mass transfer) which changes the initial shape of the reaction zone. The increase of the flame temperature with V_{inj} is related to a better ventilation of the reaction (improvement of the reactant mixing) and convection of the burnt gases. For the lowest V_{inj} value, the convective heat transfer decreases and the diffusion phenomenon is predominant.

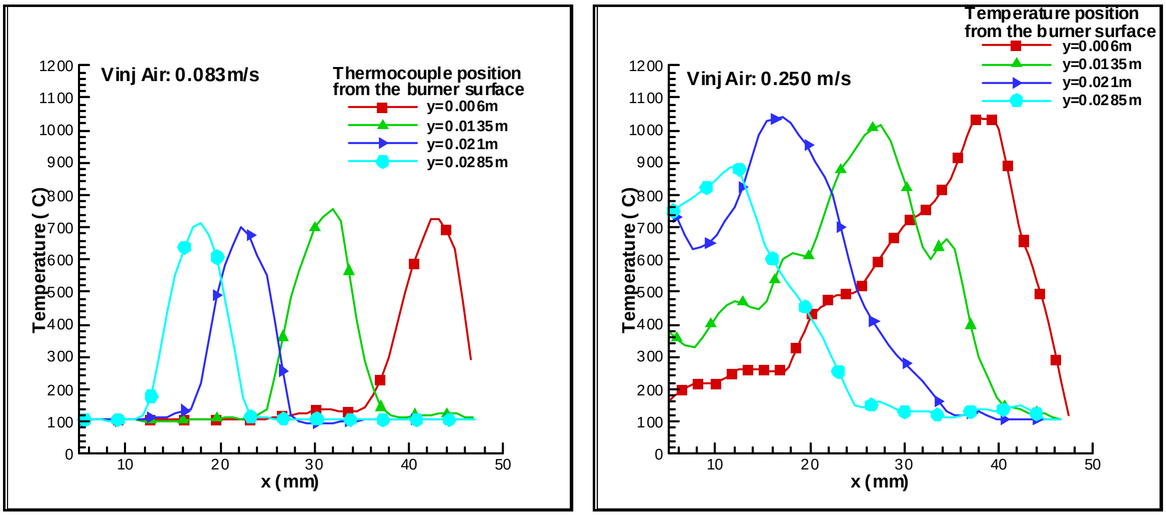

Figure 11. Temperature profiles in the x direction for various distance y from the burner surface during the microgravity period
Left: V_{inj}=0.083m/s – Right V_{inj}=0.250m/s

4.4. Velocity fields

Velocity measurements by PIV have been performed in the diffusion flame both on ground and during parabolic flight tests. The optical system remained focused despite the airplane vibrations at the take off. The main difficulty in obtaining high quality PIV images was to maintain an homogeneous and steady seeding of a low velocity flow. Moreover, it seems that in microgravity, particles showed a tendency to agglomerate resulting in a decrease in the number of scattering centers.

At normal gravity, Figure 12-a Left shows that the removal of combustion products by natural convection induce a pressure deficit at the flame stabilization zone not completely filled up by the air injection, air is then sucked from the chamber. The same phenomena is observed downstream. The natural convection forces become dominant with a suction of air from the inner part of the flame (Figure 12a- Left). For greater V_{inj} values (Figure 12b- Right) the flame ventilation is always sufficient to feed the reaction zone with reactants. The natural convection forces move the thermal plume away from the theoretical Hiemenz flow near the wall.

In micro gravity, only a few particles seeded the inner part of the flame, no three dimensional flow motion was induced by natural convection. Figure 13 represents the velocity field of the reactive flow. In all the cases, the velocity vectors are tangential to the flame position and show stagnation point flow characteristics. As the maximum temperature zones are located in a non shear zone, no vortex structures are formed by thermal instabilities. Despite the low air injection velocity (V_{inj}=0.083m/s), the injected air mass flow rate is not sufficient to feed the flame, which explains the measured low temperature (dilution of the reactants with the combustion products). For an air velocity higher than 0.25m/s (Figure 13b- Right), the velocity field shows the same behavior but the flow becomes more unsteady. This result confirms the great influence of the convection motion on the chemical activity in the flame. Without any buoyancy force, the diffusion processes are not sufficient to self feed the flame and to lead to a complete hydrocarbon oxidation and soot formation.

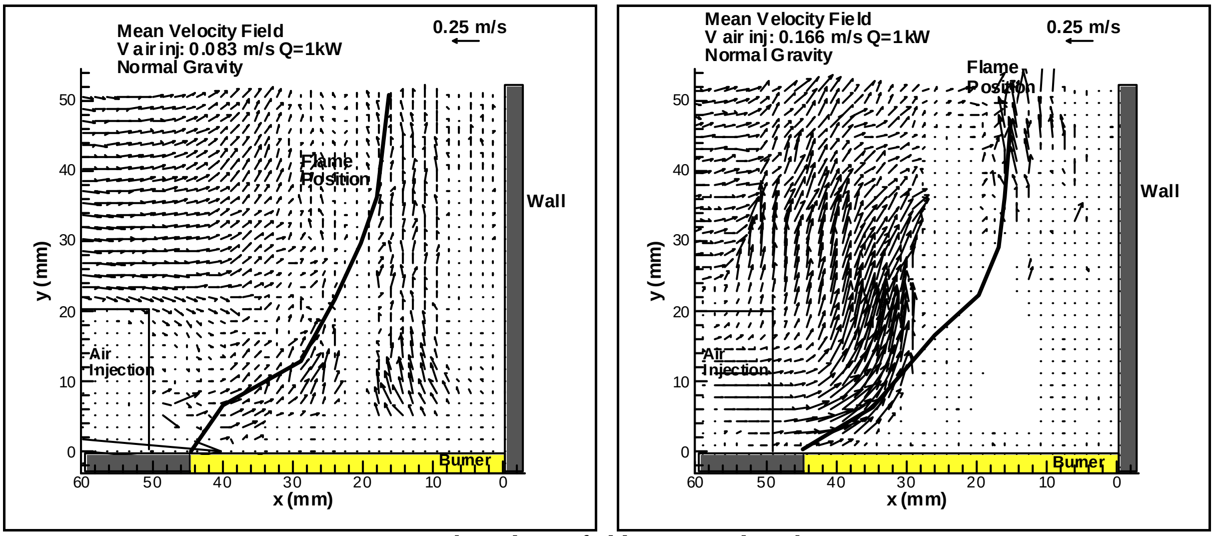

Figure 12 a-b. Velocity fields in normal earth gravity
Left: $V_{air\ inj}$= 0.083m/s – Right: : $V_{air\ inj}$= 0.166m/s

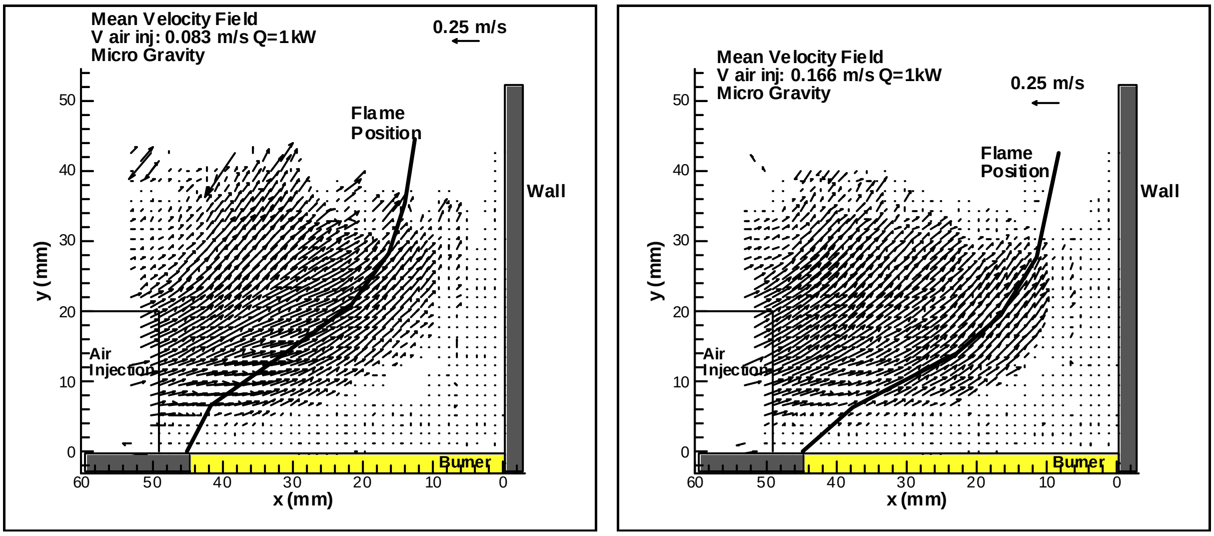

Figure 13a-b. Velocity fields in microgravity
Left: $V_{air\ inj}$= 0.083m/s – Right: : $V_{air\ inj}$= 0.166m/s

Presently, the velocity data are processed to evaluate the mean reaction progress variable as a function of the forced convective motion. These data should be used to propose a new combustion model for diffusion flames in the case of a fully developed diffusion phenomenon.

4.5. Ghosting flame

An exotic flame is observed when the air injection is suddenly stopped during the microgravity period (ethane injection is maintained). The flame emission (chemical reactivity) drastically decreases, the flame is reduced in length, it moves to the convergent exit, at low velocity, staying attached at the burner leading edge (Figure 14), and extinction occurs when the flame becomes perpendicular to the burner surface. This flame type is sometime called a "ghosting flame".

To interpret this flame behavior, two assumptions are proposed: either a flame propagates in premixed reactants, or a convected diffusion flame seeks oxygen in a quiet environment. To determine the flame structure, the flow field was characterized during the flame motion. Figure 15 represents PIV measurements close to the flame extinction time. The results show a fluid motion parallel to the flame structure with a decrease of the flow velocity with time. This behavior can be attributed to the diffusion of the reactants from each side of the flame in a non shear layer. A premixed flame structure is not probable: the fluid velocity is not perpendicular to the "flame front". Without any buoyancy forces, the diffusion processes become insufficient to feed the reaction zone and to extract the combustion products. Then, the reactants are diluted by combustion products, the thermal losses are greater than the heat released by combustion, the reaction zone temperature decreases and the flame dies away. This phenomenon seems to be similar to the formation of a ghosting flame in an under-ventilated compartment [Audouin, 1997, Bertin, 2000].

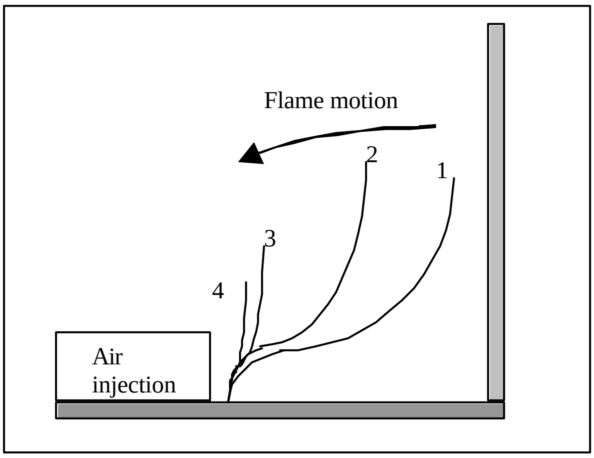

Figure 14. Ghosting Flame motion after a sudden stop of the air injection

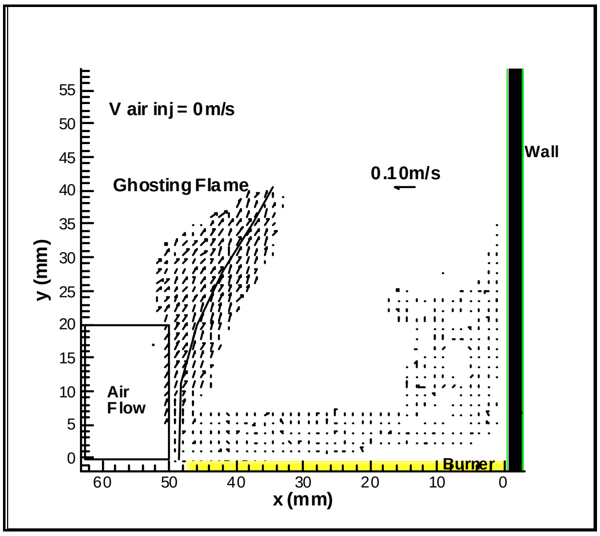

Figure 15. Velocity field in a ghosting flame

5. CONCLUSION

An experimental setup was designed to study the diffusion flame behavior representative of the first period of a fire in a microgravity environment. The degradation of a solid fuel is simulated by injecting ethane through a porous burner, the combustion is assisted by an air flow, at low velocity, parallel to the burner surface and opposite a wall (Hiemenz flow). Flame visualizations, measurements of temperature by thermocouples and velocity by PIV are performed in ground and reduced gravity conditions. For that, the PIV system was installed aboard an airplane (parabolic flights) despite the hostile environment, short duration and limited number of tests. The difficulties for the velocity measurements were linked to the flow seeding in microgravity: the particles seem to agglomerate in this low velocity flow. In reduced gravity, for medium and high air injection mass flow rates, the flame structure remains similar to those observed at normal gravity. The flame is always over-ventilated and its position and temperature seem to be nearly invariant with the ventilation factor. The air excess is deflected by the flame. A drastic modification of the flame behavior was observed for low air mass flow rates: the flame temperature, brightness, radiation and thickness decrease strongly. The flame presents a steady state structure following the flow streamlines in a non shear layer. This result shows the great effect of the natural or forced convective motion on the chemical reaction. For sufficient convective flow, the reactants are entrained in the reaction zone; for low convection, only diffusion phenomenon controlled the flame feeding which is not sufficient to lead to a complete oxidation of the hydrocarbon and soot formation.

At microgravity, when the air injection falls to zero, the flame emission decreases strongly, the flame seems to "propagate" to the air source and dies away when the fluid motion stops. PIV measurements characterize the structure of a convected diffusion flame moving to the fresh air (velocity vector parallel to the flame structure) and fed only by diffusion processes. When the fluid is at rest, the diffusion phenomena becomes insufficient to sustain the combustion.

This study of a diffusion flame shows that without any buoyancy and shear forces the combustion cannot be stabilized due to a poor efficiency of the diffusion processes. These observations can be extrapolated for a better understanding of the flame behavior in a confined compartment. From the present results, a new approach could be proposed to evaluate the combustion phenomena involved in diffusion flames and related to the reaction zone ventilation. The model can be proposed to represent the observed behavior and included in fire safety prediction tools.

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