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Andres Valencia, Bertrand Lecordier, Alexis Coppalle. Velocity and temperature measurements in a vertical wall flame. *Journal of Physics: Conference Series*, 2018, 1107 (3), pp.032006. 10.1088/1742-6596/1107/3/032006 . hal-01935652

HAL Id: hal-01935652

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Submitted on 21 May 2024

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To cite this article: Andres Valencia *et al* 2018 *J. Phys.: Conf. Ser.* **1107** 032006

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Velocity and temperature measurements in a vertical wall flame

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ABSTRACT

To study the combustion of vertical solids, a laboratory setup has been built in order to produce stationary and easily repeatable experiments. It consists of a rectangular porous burner fed with a mixture of methane and ethylene, which produces a sooting and luminous flame. That system has been already used to determine the soot concentration in a vertical flame [1,2].

Velocity and temperature measurements were performed inside the reactive boundary layer. The average velocities (horizontal and vertical), as well as their fluctuations, were measured thanks to the 'Particle Image Velocimetry' laser diagnostic. Temperature profiles were obtained using fine thermocouples placed at different heights.

The visual appearance of the flame shows that it is fully turbulent from a height of about 20cm. In this turbulent zone of the flame, the profiles of the vertical velocity and the temperature evolve similarly according to the height. Near the wall, the velocity and the temperature increase rapidly and reach a maximum located a few millimeters to the wall. For the velocity, this maximum increases with the height in the flame because of the entrainment of the hot gases by the effects of gravity. For the temperature, such evolution of the maximum is not observed. Far away the wall, the velocity and temperature profiles widen toward the outside of the boundary layer, because of the dilution with the air. On the other hand, the horizontal velocity fluctuations are high compared to the mean values and at each height the profiles have a maximum which is more shifted from the wall.

A heat flux sensor was placed just above the burner to determine the total heat flux received. The mean value is 23.6 kW / m². The latter value will be analyzed and compared, as well to the velocity and temperature measurements, to other values obtained for the same wall flame configuration [3-5].

KEYWORDS: *heat transfer; fluid dynamics; wall fire; PIV, temperature*

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INTRODUCTION

An important case of fire is the propagation of a flame on a vertical combustible wall. For such configuration, the fluid is mainly driven by gravity effects, and the velocity is low. The emission of combustible vapors is due to the thermal degradation of the solid and the heat release is provided by their combustion in the flame zone. These phenomena are coupled by the heat fluxes exchanged at the wall by convection and radiation. Many works have been devoted to the study of vertical heated walls and wall-flames [3-9]. However for these last ones, few of them have allowed to study experimentally the fluid flow and its temperature near the wall and in the reactive boundary layer. In order to deal with this, a rectangular porous burner fed with a mixture of methane and ethylene was built in order to produce a sooting and luminous vertical flame. In the first part of the paper, the burner device, the velocity (PIV), temperature and total flux measurements are described. In the second part, the results are presented, discussed and compared to some values found in other works.

EXPERIMENTAL SETUP

Burner

The fig.1 shows the vertical burner used in this work. The burner has been used in previous research, and is described in detail in references [1,2]. In resume, it consists of a porous burner installed vertically with dimensions of 20 cm of width, 40 cm of height and 2 cm of thickness. This burner is fed with a mixture of Methane (0.243 g/s) and Ethylene (0.512 g/s). A steel wall cooled with water at ambient temperature have been placed around the burner, and an ignition line supplied Methane (0.017 g/s) on the bottom of the burner, in order to stabilize the flame.

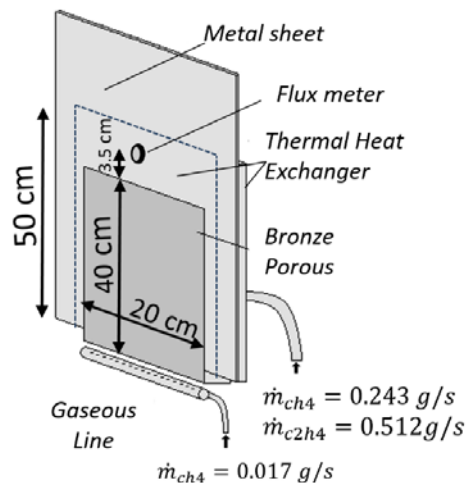


Figure 1: burner layout.

PIV measurements

The PIV setup is shown in fig. 2. A dual-head 532 nm Nd:Yg laser (Quantel Twins BSL) was used with a repetition rate of 10 Hz and a pulse duration of about 7 ns. The optical arrangement and the dichroic mirror shown on fig.2 have been set up in order to generate two overlapped and Gaussians laser sheets separated by 200 μ s, and propagated vertically through the flame. These sheets had a dimension of \sim 800 μ m x 45 mm (FWHM) in the x and y axis respectively. The laser sheet were located at 8 cm from one side, and were in contact with the wall in order to measure the near-wall region, and in the y direction only the most homogeneous portion (3.3 cm) of the laser sheets was used. The PIV signal was recorded with a 2048 x 2048 pixel CCD camera (JAI RM/TM- 4200CL) equipped with a 50 mm Nikon lens. The dimensions of the observed field have been set with a resolution of 71 μ m/pixel. Because of the low velocity in the flame (about 2 m/s), the time between pulses was set to $\Delta t = 200 \mu$ s. The images were recorded with the DynamicStudio (Dantec Dynamics) software application, and the velocities vectors have been calculated with a home-made algorithm. The instantaneous minimum velocity measurable with the optical device and the PIV algorithm used is \sim 6 cm/s. Low-velocity seeded air was injected in the flame through three injectors; two of the injectors, located at $y = 1$ cm and at the bottom of the burner, ensured a sufficient particle density throughout the flame. The third seeding injector, placed in the ignition line located below the burner, improved seeding near the wall at the bottom of the burner. In this way, the flame dragged particles from the bottom to the top.

Six different acquisitions were performed, with about 430 pairs of images for each case. So the mean and RMS values of the velocity components were calculated from this dataset. However, as seen in fig. 2, the particle seeding in the boundary layer is not homogeneous. Inside each pair of image used to determine the particle displacements, the percentage of valid points is greater than 23% for $y > 5\text{mm}$ and, in some cases, less for $y < 5\text{mm}$.

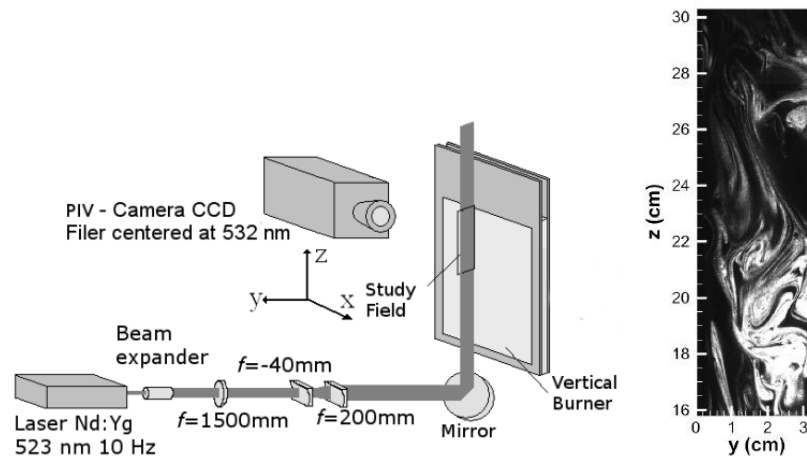
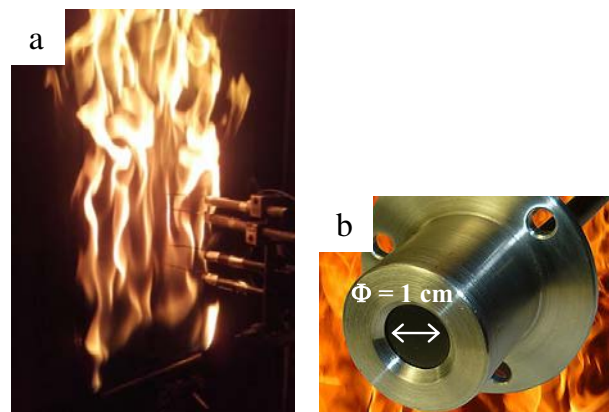


Figure 2: schematic view of the PIV system (right) and example of a raw seeded image detected by the camera.

Temperatures in the flame

Four thermocouples (type K) have been used to measure at the same time the temperature in the flame at heights $h = 17\text{-}20\text{-}25.5\text{-}28\text{ cm}$, as shown in fig. 3-a. Each thermocouple is tied to a steel rod, and there is 4 cm bare-wire length, corresponding to the distance between the junction and the end of the rod. The thermocouple tree is fixed and the burner is moved in order to measure the temperature at different y locations in the reactive boundary layer. The displacement accuracy is about 0.5mm. The size of thermocouple junction is 0.5 mm, so the time-response is too long to be able to measure the temperature fluctuations. So only the mean temperatures are given. When the junction is inside a combustion zone, the gas temperature is high and the junction emits radiation. Based on the reference [10], the mean maximum radiation correction is estimated to be 80k. For each experiment, the temperature at one location is averaged over 30s, and the mean profiles given below correspond to the average of four experiments. The reproducibility between these dataset is $100\text{ }^{\circ}\text{C}$ (= standard deviation).



Figures 3: (a) view of the 4 thermocouples (height = 17-20-25.5 and 28cm) on their support in order to measure the temperatures in the flame, (b) view of the heat flux sensor.

Heat flux measurement

An heat flux sensor (CAPTEC manufacturer) has been installed just above the burner as shown in fig 1. The sensible surface diameter is 1 cm and covered with black paint (fig. 3-b). It is based on a differential measure and not sensitive to the sensor temperature. It gives the total flux (convective and radiative). A mean value has

been calculated by averaging the data obtained during the four experiences of temperature measurement. The value is 23.6 ± 3.3 kW/m².

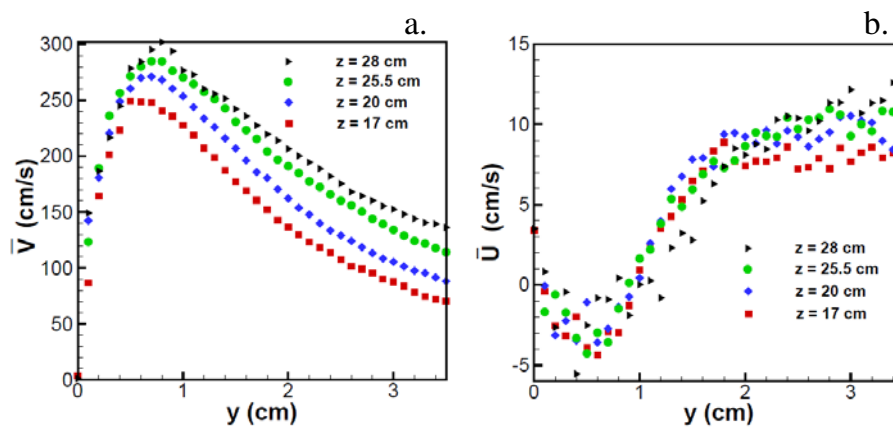
RESULTS AND DISCUSSIONS

Velocities

Fig. 4-a shows the profiles of the average vertical velocity \bar{V} at 4 different heights. As expected, the velocity is very low close to the wall of the burner and it increases with the distance to the wall. However inside the boundary layer, the velocity profiles show the influence of the buoyancy forces. Compared to the forced convection case, the maximum is located inside the boundary layer and close to the wall, as seen for the case of an heated wall [9], or in wall-flame [2,3,8]. Three main zones can be identified:

- 1- Near-wall zone ($y < \sim 5$ mm): In these first millimeters, there is a sharp increase of the velocity, their fluctuations are low, as shown below in fig. 5-b. This zone can be qualified as laminar, the transfers of energy, species and momentum take place mainly by diffusion, and they are influenced by the viscosity.
- 2- Overlapping zone (~ 5 mm $< y < \sim 10$ mm): This region is identified as the combustion zone, the heat release accelerates the flow thanks to the buoyancy forces. Thus the maximum of velocity is located in this zone.
- 3-Far from the wall ($y > \sim 10$ mm): In this zone, the fluxes (energy, quantity of movement and species) are mainly turbulent. There is a slow decrease of the velocity when y increases, and this decrease spreads over several centimeters away from the wall.

The combustion is sustained by fuel injection throughout the burner height. This causes a continuous acceleration of the flow. This is suggested by the maximum of V which increases with height, as can be seen in fig. 4-a. An increase in the thickness of the dynamic boundary layer with the height is also observed. This is the consequence of the turbulence which generates velocity fluctuations, with the formation of large vortices, allowing more and more air to be mixed in the boundary layer. The order of magnitude of vertical velocities reported here are in agreement with previous results obtained in wall flames [3,8].



Figures 4 : Average velocity profiles for 4 different heights in the flame (17, 20, 25.5 et 28 cm).

a.: Vertical, b.: Horizontal.

Fig. 4-b shows the average horizontal velocity profiles \bar{U} at 4 heights in the flame. There is more than one order of magnitude between the values of two velocity components. Close to the wall ($0 < y < 1$ cm), the means of the U velocity are low, close to zero. Knowing that the instantaneous minimum velocity measurable with the optical device and the PIV algorithm used is 6 cm / s, some of the instantaneous U values calculated in this area have to be interpreted with caution. However for the average, the low values shown in fig. 4-a are mostly the result of a balance between large positive and negative fluctuations, as will be shown in the next figure. For $y > 1$ cm, the average horizontal velocity is positive, which corresponds the hot gas expansion towards the outside of the boundary layer.

Fig. 5-a-b show the profiles of the RMS values of the vertical and horizontal velocities at 4 different heights in the flame. The RMS values obtained for $y < 0.5$ cm, close to the wall, are too sensitive to the small number of validated velocity vectors, as previously explained. Therefore, profiles of RMS values are only given for $y > 0.5$ cm. The variations of the RMS values have strong similarities with those observed for the average values. Indeed for $RMS V(y, z)$, we note that the velocity fluctuations increase with the height. At 28 cm height, the

maximum value is 80 cm/s, corresponding to a turbulence intensity $\frac{RMS V}{\bar{v}}$ equal to 40%. With increasing height, the $RMS V$ profiles spread progressively in the horizontal direction. For $RMS U$, strong fluctuations are observed, the maximum RMS value is equal to 40 cm / s at 28 cm height, which is 4 times the average value, obtained in the same zone of the boundary layer ($y > 2$ cm). Similar profiles have already been observed, numerically for a reactive case [5], but also experimentally for a case without combustion [9] (only $RMS V$). For these two cases, $RMS V$ values have a sharp increase with increasing distance from wall, and the maximum is observed near the wall.

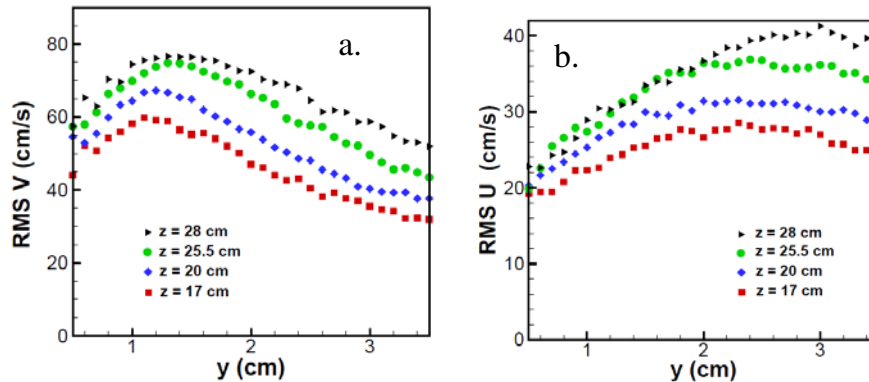


Figure 5 : Velocity RMS profiles at 4 different height in the flame (17, 20, 25,5 et 28 cm).

a.: Vertical, b.: Horizontal.

Temperatures

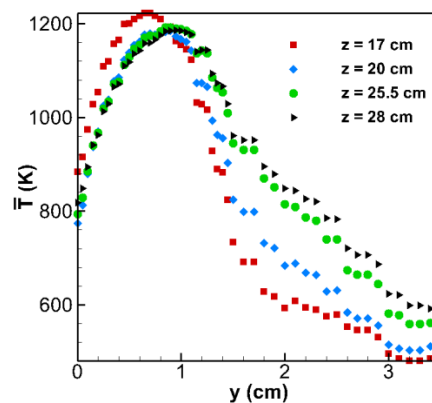


Figure 6 : Horizontal profiles of the mean temperatures at 4 heights in the flame: 17, 20, 25.5 and 28 cm.

On fig.6 is reported the mean temperature as a function of the distance from the wall, and at 4 heights in the flame. These profiles show a lot of similarities with those of the average vertical velocity as shown in fig 4. Three main zones can be also defined. Near the wall, there is a sharp increase of the temperature with no large difference between the different heights. Further from the wall (overlapping zone ~ 5 mm $< y < \sim 15$ mm), the temperature variations with the distance to the wall are small, and the maximum are observed here. This region is identified as the combustion zone, with a high heat release. Contrary to the vertical velocity profiles reported in fig. 4, the maximum temperature does not increase with the height. However, like for the velocity, the width of the temperature profile in the y direction is increasing with height. Finally, far from the wall ($y > \sim 15$ mm), the temperature increases with height, as already observed for the vertical velocity. In this zone, the flow is highly turbulent and intermittent.

Comparison with other studies

As said previously, this wall-flame has been already used to study soot concentrations in the flame [1-2]. However results provided here are focused on velocity and temperature, and it is interesting to compare them to values obtained in other works. However, the comparison that will be presented here has to be view as

qualitative. There are only a few studies for which experimental or numerical values of velocities and temperatures in the boundary layer and near the wall are available. The comparison uses the experimental results obtained by de Ris [3], with a higher-size burner and propylene as combustible, the numerical results of the simulation of this experiment [4,5], and the experimental results provided by Ahmad [8], with a smaller-size burner with ethanol as combustible. Firstly the comparison is about the maximum of velocity in the reactive boundary layer. A velocity scale may be defined as $(2gz)^{1/2}$. So the ratio $V_{max}^* = \frac{V_{max}}{(2gz)^{1/2}}$ is a mean to compare results obtained at different heights. At each top of the burners, the ratio is $V_{max}^* = 1.3$ in the present study at $z=0.3$ m, $V_{max}^* = 0.9$ in the de Ris's work at $z=0.77$ cm and $V_{max}^* = 1.8$ in Ahmad's work at $z=0.1$ m. Obviously, this scaling does not succeed for grouping these data. Further studies are necessary to take also in account the fuel flow and heat release rates, the former being very different (equal to 9.4 g/(m².s) in the present study, 17 g/(m².s) in the reference [3], and 2.9 g/(m².s) in reference [8]).

At each top of the burners, the maximum temperatures are 1220K, 1550K and 1550K for the present study, the Ris's and Ahmad's works respectively. This difference may be explained by the flow field which is more or less laminar in the Ahmad experiment, leading to a low mixing rate with air and higher temperatures, and by the higher fuel flow rate in the de Ris's experiment, providing a higher heat release rate and greater temperatures.

Finally, the total heat flux measured just above the top of the porous burner ($z=0.435$ m) is 23.6 kw/m² in this experiment, 22.3 kw/m² at $z=0.4$ m in the de Ris's experiment, and 26.9 kw/m² at $z=0.112$ m in the Ahmad's one. These values are close, indicating that the dependency of the total heat flux on the mass loss rate (or the heat release rate) is small at the lower part of the wall-flame.

CONCLUSION

A vertical flame has been produced by a 40cm high porous burner, fed with a mixture of methane and ethylene. The measurements of the velocity inside the flame zone show that the maximum is close the wall at about 1 cm, that the flow is highly turbulent in the horizontal direction (rmsU/U values greater 3 are possible). The temperature and velocity profiles at each height show similarities. Near the wall ($y < \sim 5$ mm), there is a sharp increase. The maximum are observed further from the wall ($y \sim 5$ mm $< y < \sim 15$ mm), in a zone being identified as the combustion zone, with a high heat release rate. Contrary to the vertical velocity of the flow, which is accelerated by the buoyancy forces, the maximum temperature does not increase with the height. The data presented here are suitable for the development of analytical and CFD models of turbulent wall fires.

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