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CHARACTERISATION OF A LAMINAR FLAT PLATE DIFFUSION FLAME IN MICROGRAVITY USING PIV, VISIBLE AND CH EMISSIONS

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INTRODUCTION

Motivated by fire safety concerns and the advent of long-term micro-gravity facilities, a cooperative program has been developed to study the mechanisms and material properties that control flow assisted (co-current) flame spread. This program has used as a common fire scenario a reacting steady-state boundary layer. Preliminary studies explored the aerodynamics of a reacting boundary layer by simulating a condensed fuel by means of a gas burner. Stability curves for ethane air flames were obtained and different burning regimes were identified [1,2]. An important feature of this study was the independent identification of the different mechanisms leading to the instability of the flow. It was observed that fuel injection velocity and thermal expansion independently contributed to the separation of the flow at the leading edge of the burner. The occurrence of separation resulted in complex three-dimensional flow patterns that have a dominant effect on critical fire safety parameters such as the stand-off distance and flame length. This work was extended to a solid fuel (PMMA) [3] leading to a Sounding Rocket experiment (Mini-Texus-6) [4]. The solid phase showed similar flow patterns, mostly present at low flow velocities (<100 mm/s) but the results clearly demonstrated that the thermal balance at the pyrolyzing fuel surface is the dominant mechanism that controls both stand-off distance and flame length. This thermal balance could be described in a global manner by means of a total mass transfer or "B" number. This "B" number incorporates surface re-radiation, radiative feedback and in-depth heat conduction as first prescribed by Emmons [5]. The mass transfer number becomes the single parameter that determines the evolution of these fire safety variables (flame length, stand-off distance) and therefore can be used as a ranking criterion to assess the flammability of materials. The particular configuration is representative of the NASA upward flame spread test (Test 1 [6]) therefore this approach can be used in the interpretation of the results obtained from this test. Nevertheless, complete validation of this approach has not been fully achieved due, mainly because all the measurements necessary to compare with the theoretical predictions have not been obtained.

Following these studies two different directions have been taken. The first attempts to elucidate the details of the gas phase combustion reaction and the associated flow field by means of quantitative and qualitative measurements. The second approach, a more practical one, is to apply this methodology to the assessment of material flammability. The former is currently being conducted with a gas burner because it allows for easier control and longer experimentation time. The results obtained so far will be presented in more detail. The latter is a new program therefore only a brief summary of the objectives will be presented.

CHARACTERIZATION OF THE LAMINAR DIFFUSION FLAME

The experiments are conducted in a test facility that involves a small scale, horizontally oriented, combustion tunnel along with the supporting instrumentation, already described elsewhere [2]. Ethane, 99.4% pure, is uniformly injected through a porous burner (50mmx50mm) mounted on the centre of the flat plate. Compressed air flows through a settling chamber before entering the test section. The air and fuel velocities are governed with controlled mass flow meters and varied respectively from 20 to 70 mm/s and 1 to 5 mm/s. Information on the flame and the flow is obtained from three CCD video cameras. A standard colour CCD video camera is used to obtain images of the visible flame. Hydrocarbon emissions are recorded with a high speed intensified CCD video camera, 50Hz, 256x256 pixels with an interferential filter centred at 532nm. And a high definition CCD video camera (1300x1000 pixels) is used for flow velocity measurements using PIV. For PIV measurements air is seeded with zirconium oxide 5μm particles illuminated by a 26mJ mini-YAG.

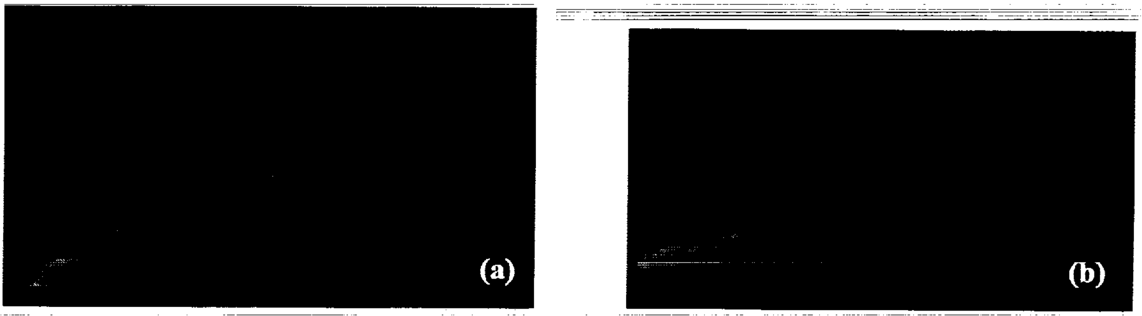

Figure 1 - Image obtained by a CCD camera of a flame for ethane-air and air velocity of 20 mm/s and a fuel velocity of 4 mm/s (a) visible flame (b) CH emission from the reacting zone.

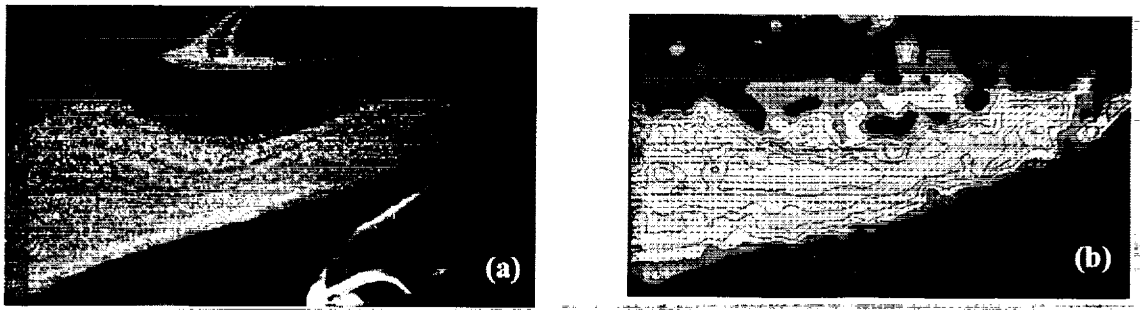

Figure 2 – (a) Image obtained by a CCD camera of the illuminated seeding particles for an ethane-air flame (air velocity of 20 mm/s and a fuel velocity of 4 mm/s) (b) corresponding velocity vectors after a PIV treatment.

The image of a flame obtained at the ZARM (5 sec.) Drop Tower is presented in Figure 1. The visible flame is presented in Figure 1(a) and Figure 1(b) shows the CH emission from the reacting zone. Figure 2 shows the corresponding velocity measurements.

Figure 2(a) shows an image of the particles captured by the CCD camera and Figure 2(b) shows the velocity vectors after PIV treatment. The example presented corresponds to an air velocity of 20 mm/s and a fuel velocity of 4 mm/s, with a $\Delta t = 4$ ms between two pictures. The ZARM drop tower in Bremen provides a stable gravity level of 10^{-5}g and the images presented were taken 3 s after the drop. For these low velocities at least 3 s are needed to completely annihilate the influence of the initial buoyancy forces. Therefore the image still shows perturbations of the flow above the flame. It is important to note that the area where the flame is present remains un-seeded, showing that the flames deflect the airflow. Figure 1 shows good coincidence between the visible flame and the recorded CH emissions, the CH zone being, as expected, slightly below the visible flame zone. The complete analysis of the different video and PIV recordings leads to a detailed description of the low velocity reacting flow, especially on the influence of the flame on the flow field. Furthermore, these measurements provide a better definition of the flame length and stand-off distance, since they allow to identify the presence of a reacting zone beyond the limits of the visible flame.

THE MASS TRANSFER NUMBER

The analysis of Test 1 equates the experimentally obtained stand-off distance for the upward propagating flame with the theoretical solution of an existing quasi-steady model of a reacting natural boundary layer. Comparison of theory [5] and experiments allows the determination of the evolution of the mass transfer number, B_T [4]. An expression for B_T was first provided by Emmons [5] and is given by: $B_T = \dfrac{(1-\chi)(\Delta H_C Y_{O2,\infty}) - Cp_\infty(T_{ig} - T_\infty)}{\Delta H_P + Q}$

where $Q = \dfrac{\left(\dot{q}''_C + \dot{q}''_{s,r} - \dot{q}''_{f,r}\right)}{\dot{m}''_f}$, the heat fluxes correspond to in-depth conduction, surface re-radiation and flame radiative feedback respectively. The denominator is the fuel mass production rate. The evolution of B_T can be obtained by matching the theoretical predictions to the experimental measurements of the stand-off distance. An example of this matching is shown in Figure 3.

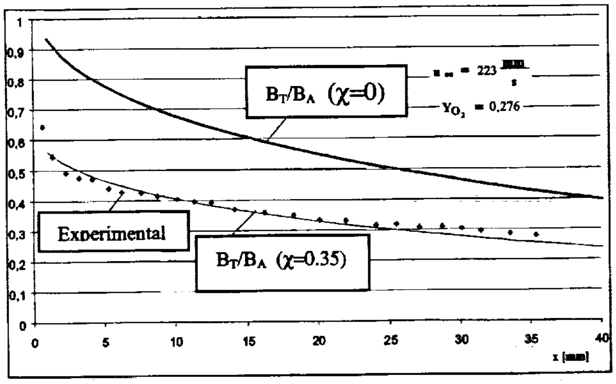

Figure 3 Variation of B_T/B_A as a function of the streamwise coordinate, x. The experimental data was extracted from Vietoris et al. [7].

Subsequently, three characteristic mass transfer numbers can be defined: $B_A = \dfrac{(\Delta H_C Y_{O_2,\infty}) - Cp_\infty(T_W - T_\infty)}{\Delta H_P}$, $B_R = \dfrac{(1-\chi)(\Delta H_C Y_{O_2,\infty}) - Cp_\infty(T_{ig} - T_\infty)}{\Delta H_P}$ and

$B_C = \frac{(1-\chi)(\Delta H_C Y_{O_2,\infty}) - Cp_\infty (T_{ig} - T_\infty)}{\Delta H_P + Q_C}$. B_A and B_C correspond to extreme values, the former being the resulting mass transfer number in the absence of all losses and the latter the lowest mass transfer number that can sustain a flame (non-propagation condition as defined by Test 1). Modelling of a fire using B_A will provide an estimate of the "worst possible scenario" and using B_C of the "best possible scenario." B_R corresponds to a "realistic scenario" that includes heat exchange between the flames and the environment. A similar approach can be followed in normal and micro-gravity leading to the quantification of the same parameters. The theoretical analysis of both natural and forced flow problems has been available in the literature since the 70's and leads to the same controlling parameters for both cases.

Evaluating independently all the properties involved in the mass transfer number (Heat of Combustion, Temperature and Heat of Pyrolysis) the theoretical value of B_A can be calculated. In a similar way, to obtain B_R, an effective heat of combustion needs to be determined and can be obtained by means of oxygen consumption calorimetry (Test 2 [6]). Estimation of the in-depth conduction and surface re-radiation by means of thermocouples and IR-Thermography provides the necessary information to compute B_C. Independent calculation of these "material properties" provides validation to this methodology.

Determination of these parameters is of great value for material selection and as criteria for the design of engineered materials since it provides a ranking criterion based on fundamental combustion principles. Furthermore, the definition of B_A, B_R and B_C allows to bound the possible evolution of a fire in a space facility and also serve as an estimate of the possible error.

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