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Tulip flame - the mechanism of flame front inversion

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ABSTRACT

The paper explains the mechanism of tulip flame formation in horizontal combustion chambers closed at the ignition end. The explanations are based essentially on the PIV images and the direct visualization of the process. The obtained results demonstrate that the tulip flame is a purely hydrodynamic phenomenon which results from the competition between the backward movement of deflected burned gases expanding from the lateral flame skirts and the forward movement of unburned gases accelerated in the phase of finger-shaped flame. In some configurations a supplementary global movement imposed by the confinement (for example: acoustic waves) is superposed on the two above mentioned, and modifies the parameters of the process. The results also prove that the intrinsic instabilities of the flame front (Rayleigh–Taylor, Richtmyer–Meshkov or Darrieus–Landau) are not involved in this process. The convex shape of the flame front has no influence on the phenomenon.

1. Introduction

The so-called tulip flame is a particular shape of the flame front with inverted curvature, which can be often observed during the laminar flame propagation in elongated, closed or half-open (at the end opposite the ignition) combustion chambers.

The process of flame propagation in such a chamber was described by many researchers and will be discussed in detail later in the paper. Here we just mention its four essential phases: (a) hemispherical expansion of the ignition kernel; (b) axial expansion of elongated finger-shaped laminar flame front with continuously growing surface area; (c) rapid reduction of the flame surface area (when the flame skirt reaches the side walls) and deceleration of the flame front followed by the inversion of its curvature; (d) oscillatory propagation of the tulip flame up to the end of the chamber. In long chambers, a kind of tubes, the inversion of the flame front curvature can reverse and repeat itself a number of times in any one ignition.

Since more than eighty years, when first images of tulip flame were published by Ellis and his colleagues [1–3], this phenomenon puzzles researchers in the domain of combustion and gives occasion to various interpretations and hypotheses.

One of the earliest suggested an interaction with pressure waves generated by the flame. Indeed, Markstein [4,5] demonstrated that the inversion of the flame shape can result from the interaction of a curved flame front with a counter propagating planar shock wave.

However, shock waves of pressure ratio 1.3 or higher, like those generated artificially in Markstein's experiment, are hardly observed in the early phase of laminar flame propagation when the inversion of the flame front occurs, and Markstein himself indicated [5] that earlier investigation [6] with weaker, sound wave used as disturbance gave rather inconclusive results. Latter experimental works [7–13] put into evidence that a first significant pressure perturbation in the above described process of flame propagation may be produced (in the form of rarefaction wave) at the moment of the rapid decrease of the flame surface area due to the extinction of lateral flame skirt in contact with chamber side walls. Before this moment only a monotonous smooth pressure increase is observed. A series of weak compression waves generated in the phases of flame acceleration and then reflected at the chamber ends can only slightly modify the flame speed and the pressure growth in the chamber.

There is no doubt that the rarefaction wave triggers subsequent acoustic oscillations but the question remains open whether this wave is directly involved in the onset of the tulip-shaped flame front.

Leyer [7], on the basis of his experiments with short rectangular ($10 \times 4 \times 2.5$ cm^3) closed chamber hypothesized that the interaction of the rarefaction wave and previously emitted compression waves may lead to the backward motion of the unburned gases which brings about the inversion of the flame front curvature. Measurements of instantaneous flow velocity performed by Dunn-Rankin et al. [13] and Starke and Roth [9] using laser Doppler

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anemometry did not permit to confirm or reject this hypothesis. They showed indeed that the far-field unburned gas motion was always positive but were less conclusive concerning the flow field in the vicinity of the flame front because the position of the front was difficult to determine precisely (the run-to-run variations in flame arrival time were about 10% in their experiments). However, numerical study [9,13,14] seem to indicate that the axial component of the unburned gas velocity remains positive, at least until the beginning of the inversion of flame front curvature. Furthermore, if the flame front inversion was linked with the interaction of pressure waves the time of this inversion, should depend on the chamber length and the acoustic losses, while experiments of Clanet and Searby [10] demonstrated that this time was mainly function of the laminar burning velocity and the radius of the chamber.

Starke and Roth [9] relate the onset of tulip flame with Markstein's experiments through the effect of Taylor instabilities. They consider that the deceleration in unburned gas velocity resulting from the reduction of the flame front area is comparable with that found behind the shock wave in Markstein's experiments, and acts in similar way via the instability. This idea was later taken up by Clanet and Searby [10] who tried to provide a quantitative proof. On the basis of the Taylor oscillator equation coupled with a simple geometrical model for flame propagation they calculated the time of the tulip inversion occurrence and compared it with the measured one. The discrepancy between both results was about 10%. The model demands however some experimental data like the moment at which the flame touches the side walls of the chamber, position of the flame tip at this moment, variation in time of the position of trailing edge of flame skirt, which are not easy to determine with good precision.

A completely different approach to the tulip flame phenomenon was proposed by Dold and Joulin [15] who believe that the tulip flame has little or nothing to do with the deceleration in gas velocity caused by the reduction of the flame area. By means of numerical simulation based on the modified Michelson–Sivashinsky equation they demonstrated that combined influence of front curvature, geometric nonlinearity and Darrieus–Landau hydrodynamic instability are sufficient to produce the inversion of the flame front.

Darrieus–Landau instability itself or associated with other flame generated hydrodynamic instabilities is also put forward by some researchers to explain various results obtained in their numerical simulations without, however, convincing arguments. Bychkov et al. [16] suppose that the Darrieus–Landau instability is responsible not only for the first but also for all the subsequent inversions of the flame front curvature in a long half-open tube, while the experiments of Kerampran [11,12] proved that all the inversions except the first one result from the acoustic oscillations. In 1986, on the basis of experimental and numerical results with a closed rectangular chamber (38 mm × 38 mm × 155 mm), Dunn-Rankin et al. [13] arrived to the conclusion that the initial perturbation of the convex flame front comes from a radial gradient in the axial velocity created by the confinement of the chamber. According to the authors, when the flame reaches the side walls the faster flow near the walls, analogous to a squish flow, pulls the flame ahead while the leading edge of the flame begins to decelerate approaching to the closed downstream end of the chamber. The initial distortion is unstable (Darrieus–Landau instability!) and continues to grow, forming a cusp which develops into the "tulip". In his more recent paper Dunn-Rankin [17] associates the flame front inversion rather with a recirculation in the burned gases observed in schlieren images. He supposes that this recirculation is generated by the curved flame itself because the expansion of burned gases normal to the convex flame surface deflects the flow behind the flame front toward the center line. Similarly to his earlier conclusions, the recirculation acts here only as an initial trigger for the Darrieus–Landau instability which grows to the full tulip.

Results of numerical simulation performed by Gonzales et al. [14] confirm the presence of a reverse flow in the burned gases behind the flame. They also exhibit the transversal velocity gradient along the flattened front, subsequent to the squish flow near the side walls and the deceleration of the central part of the flame. However, according to the authors those phenomena are so intertwined that it is difficult to distinguish causes from consequences. Similarly, their paper neither confirms nor excludes the participation of the Darrieus–Landau instability in the tulip front inversion. The authors consider that although this instability is compatible with the tulip shape, it affects the flattened front less rapidly than the confined flow field can do during tulip formation process.

Different opinions concern also the role played by the dynamic viscosity and especially the wall friction. Marra and Continillo [18] find it important while other researches consider that this role is negligible [10,14] or even that an excessive wall friction precludes the tulip phenomenon [14].

Finally, two general conclusions may be drawn from the bibliographic analyse:

- there are many possible causes of the tulip phenomenon but none is certain;
- tulip flame is a very "complaisant" phenomenon. It can be reproduced by all presented models in spite of opposite assumptions (viscous or non-viscous flow, potential or rotational, compressible or incompressible).

In this situation it seems clear that a unique way to elucidate definitely the process of flame front inversion in the tulip flame phenomenon consists in returning back to the experiment. Indeed, the past 20 years have seen a rapid development of planar imaging techniques which offer a much more profound insight into the instantaneous local structure of the flow than the point probing techniques like LDV. In particular, we were interested by Time-Resolved PIV method which has achieved a good level of practical application to combustion engineering. We expect that the obtained results clarify definitely the mechanism of tulip flame formation.

2. Experimental set-up and procedure

The experiments were carried out in cylindrical elongated plexiglas transparent chambers of various length (L_C) and diameter (ϕ_C). The essential detailed analysis of flame transformation was performed with chamber $\phi_C = 0.1$ m, $L_C = 0.785$ m closed at both ends. Other configurations ($\phi_C = 0.1$ m, $L_C = 0.385$ m; $\phi_C = 0.1$ m, $L_C = 0.320$ m; $\phi_C = 0.07$ m, $L_C = 1.99$ m; $\phi_C = 0.07$ m, $L_C = 3.0$ m) were used to verify the influence of chamber dimensions. The chamber $\phi_C = 0.1$ m, $L_C = 0.785$ m was also tested with a simple opening at the downstream end (a kind of uncovered vent) or connected to a duct (like in ducted venting). The chamber $\phi_C = 0.1$ m, $L_C = 0.320$ m was tested only with a duct. The tube $\phi_C = 0.07$ m, $L_C = 1.99$ m was closed at both ends or opened at downstream end. The tube $\phi_C = 0.07$ m $L_C = 3.0$ m was used only as opened at downstream end.

All the experiments were carried out with stoichiometric propane–air mixture at initial atmospheric temperature and pressure. Before each experiment the chamber was first evacuated and then filled to atmospheric pressure with the mixture prepared earlier and stored under pressure (the open chambers and those with the vents were, during this manipulation, closed by a cap which was next removed just before firing).