The use of Langmuir probe for diagnostics of flame quenching

Marc Bellenoue[1], Sergei Labuda[1], Maxime Makarov[2], Julien Sotton[1]

[1]Laboratoire de Combustion et de Détonique, UPR 9028 CNRS,
ENSMA, BP 40109, 86961 Futuroscope, France

[2]RENAULT Technocentre, F-78288 Guyancourt Cedex, France

1 Introduction

Electrical properties of flame are studied intensively already almost one century. The interest to ionization processes in combustion front was stimulated e.g. by an attractive idea to use probe signal for combustion diagnostic. Since in the flame charged particles (ions and electrons) are produced, the combustion front can be considered as high pressure plasma. Insertion of an electrical probe in combustion zone could, in principle, yield information on the combustion conditions. Although ion sensing is one of the cheapest and most simple methods for monitoring of combustion event in a spark engine, but still the physical processes of ionization current formation are not fully understood, although there are a number of probe theories trying to explain the evolution of probe current at different conditions (see [1] among others). These theories are based on Langmuir probe theory adapted to the diagnostics of high pressure plasmas. Because flame behaviour near the probe surface is affected by flame/wall interaction, we supposed that namely process of thermal flame quenching on the surface of probe electrode controls the probe current.

In this paper a simple model of ion current to Langmuir probe surrounded by combustion plasma is proposed. Model taking into account the thermal flame quenching on the surface of probe electrode is proved by experimental data of probe current variation with pressure for methane/air mixtures of different equivalence ratio. Experimentally demonstrated that probe current-voltage characteristics (CVC) is affected by the phenomenon of flame quenching on the probe surface.

2 Theory

It is well known that near wall combustion is strongly influenced by the presence of the wall. For example, premixed flame stops propagating towards to the wall because heat losses are large enough to slow down combustion reactions. The flame front is thus quenched. Flame quenching occurs at some distance from the wall. This distance is related to the heat flux from flame to wall as [2]:

$$\delta_q = (1 - \frac{Q_W}{Q_\Sigma}) \cdot \frac{\lambda \cdot Y_{fuel} \cdot \Delta H}{c_p \cdot Q_W} \quad (1)$$

here δ_q, Q_w, Q_Σ, λ, Y_{fuel}, c_p and ΔH are the quenching distance, the heat flux from flame to wall, the flame power, the thermal conductivity, the fuel content in the mixture and the heat of combustion, respectively. Because probe ion current is related to the flame characteristics, Langmuir probe signal must be affected by the flame quenching phenomenon. For the analysis of probe current let us consider the simplest quenching configuration, i.e. head-on flame quenching on a single wall. This type of flame/wall interaction occurs when probe has flat sensitive surface flush mounted with the combustion chamber wall and flame front propagates obliquely to the wall. At quiescent mixture combustion, combustion plasma near the probe is at rest during quenching. We consider that probe electrode is biased negatively relatively to the flame and all drop of potential between flame and probe electrode is located in quenching layer. At these conditions the probe ion current density j_+ is

$$j_+ = \mu \cdot e \cdot n_+ \cdot U / \delta_q \tag{2}$$

where μ, e, n_+ and U are the ion mobility, the elementary charge, the ion density and the biased voltage, respectively.

One of the intrinsic problems to model positive ion current is related to the ionisation density of quenched flame. Modelling of ion composition and ionisation density of quenched flame is rather difficult. Nevertheless, to simplify our consideration, we can suppose that n_+ depends on the critical power retained in flame to support combustion reactions, i.e. $(Q_\Sigma - Q_W)$, as

$$n_+ = K \cdot (Q_\Sigma - Q_W) \tag{3}$$

where K is dimension coefficient. Finally, combining Eqs.(1)-(3) one can obtain the expression for probe ion current j_+ which is related to the flame energetic characteristics and quenching parameters in vicinity of probe:

$$j_+ = K \cdot \mu \cdot e \frac{U \cdot c_p}{\lambda \cdot Y_{fuel} \cdot \Delta H} \cdot Q_\Sigma \cdot Q_W \tag{4}$$

The ion mobility in Eq.(4) would be calculated using the following expression proposed by Fialkov [3]:

$$\mu = \frac{3}{8} \cdot \frac{e}{n_o \cdot \sigma} \left[\frac{1}{2} \cdot \frac{\pi}{kT} \cdot \frac{m+M}{mM} \right]^{1/2} \tag{5}$$

Here m and M are the masses of the main ion and inert molecule, respectively, $n_o = P/kT$ is the gas density, T is the gas temperature, σ is the collisional cross-section and k is Boltzmann constant. Thus, Eq.(4) allows prediction of ion current evolution with pressure for different combustible mixtures when evolution of Q_W is known. Using the ratio between quenching parameters given by Eq.(1), one possible to obtain relative variation of wall heat flux or quenching distance from probe current evolution. It is worth noting that thermal conductivity, heat capacity and gas temperature used in Eqs.(1)-(5) are mean characteristics of medium across the quenching layer.

3 Experimental

Experiments have been performed in a steel rectangular vessel of 70x75x120mm (Fig.1) with quiescent CH_4/air stoichiometric or lean fuel mixture of equivalence ratio 0.7 at a pressure 0.08-0.5MPa. Two designs of Langmuir probe have been used. Ionization density of free propagating flame has been studied with thin cylindrical probe having measuring electrode of 0.6mm in diameter and 10mm in length. This probe is placed in the centre of combustion chamber, at a distance 40mm from the spark plug. Probe is oriented in parallel with propagating combustion front. The measurement of ionization density is based on the theory of Clements and Smy [4], who derived the relation between ion current to cylindrical electrode in a flowing plasma-environment and flame ionization density:

$$j_+ \approx 5.3 \cdot (\varepsilon_o \cdot \mu \cdot r_p)^{1/4} \cdot (e \cdot V_g \cdot n_+)^{3/4} \cdot U^{1/2} \cdot l, \tag{6}$$

where ε_o – vacuum permittivity; r_p – probe radius; V_g – gas velocity (velocity of plasma relatively to the probe), l - probe length. For reconstruction of n_+ from ion current the gas velocity ahead of combustion front must be known. In zone of probe location, this velocity has been measured by LDV Dantec unit.

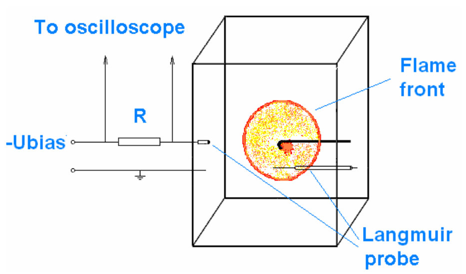

Fig.1. Arrangement of Langmuir probe current measurements.

Another Langmuir probe of 5mm in diameter mounted in a side wall of combustion chamber, flush with the wall surface, has been used to study its interaction with flame quenched on the chamber wall, in head-on quenching regime [2, 5]. In these tests spark plug is placed at symmetry axis of probe, at a distance 30mm from plane probe sensitive surface. Biased voltage of Langmuir probes has been varied in the range -40÷0V. Both probes have similar electrical circuit to measure probe ion current using the resistance 220kOhm (see Fig.1).

4 Results and discussion

For validation of our suggestion on linear relation between ionization density and energy retained in flame, the measurement of ionization density in free propagating flame has been carried out. In these tests cylindrical probe placed in the centre of combustion chamber has been used. Results of measurements are presented in Fig.2 where normalize data of ionization density are compared with calculated normalized values of flame power. Ionization density is evaluated from experimental value of ion current using Eq.(6). For the flame power retained in flame during interaction with cylindrical probe, (Q_Σ -Q_w), we supposed that this power is proportional to the flame power Q_Σ, i.e. (Q_Σ -Q_w)$\propto Q_\Sigma$. Really, in accordance to [2, 5] dimensionless wall heat flux to probe surface, Q_w /Q_Σ , varies about 5-7% within the pressure range 0.05-0.5 MPa and one would suppose that $Q_w /Q_\Sigma \approx const$. Then, the expression for power retained in flame can be represented as (Q_Σ -Q_w) = $Q_\Sigma \cdot (1\text{-}const)$, so ($Q_\Sigma$-$Q_w$)$\propto Q_\Sigma$.

In Fig.2 one sees that normalized values of flame ionization density (experimental points, standard derivation is 0.15) correlate well with solid curve representing the evolution of flame power with pressure. This circumstance just validates Eq.(3).

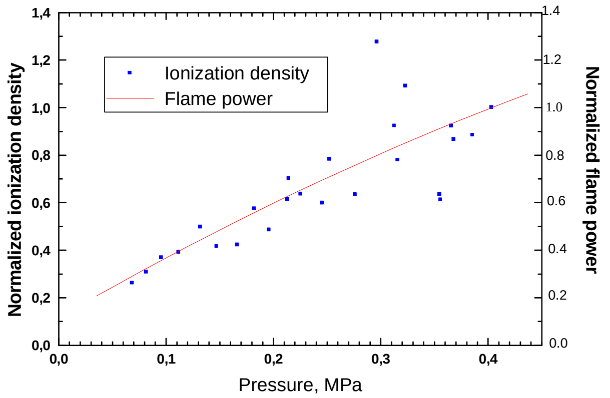

Fig.2. Normalized values of flame ionization density and flame power versus pressure: stoichiometric CH_4 /air mixture.

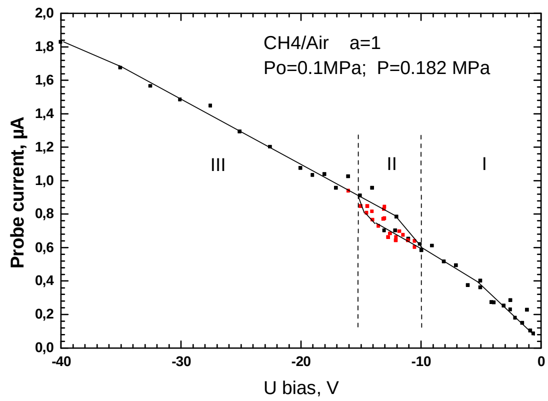

Fig.3 Current-voltage characteristics of ionization probe mounted in combustion chamber wall.

It is known that probe current is sensitive mainly to the plasma characteristics on the border of sheath layer. In one’s turn, sheath layer thickness is a function of probe biased voltage. So, varying the voltage applied to probe, it is possible “to scan” the quenching zone and, in principle, to obtain spatial distributions of some medium characteristics. To verify this suggestion, CVC of probe placed in combustion chamber wall has been studied. Each point of CVC obtained for stoichiometric CH_4 /air mixture (see Fig.3) corresponds to a single test at fixed value of biased voltage. In CVC depicted in Fig.3 tree zones would be marked out. Zone “I” corresponds to low biased voltage (-11÷0V). Within this region probe ion current is changing near linearly with change of biased voltage, although CVC slightly changes the slop at $U\approx$-5V. Standard derivation of experimental data obtained in this zone is ±0.04μA. In zone “II” the scatter of experimental data essentially increases: standard derivation here is twice as higher than in zone “I” and CVC becomes non-linear. Further increase of biased voltage up to U=-40V (zone “III”) leads again to linear increase of ion current. Different behaviour of CVC in zones “I”-“III” would be related to location of sheath layer in different flame zones. Probably, zone “I” may be associated with location of sheath layer in flame preheating zone whereas in region “II” sheath layer probably “touches” the reaction zone that explains non-linearity of CVC and increased scatter of experimental points. In zone “III” the increase of ion current would be due to increasing of sheath layer surface. Thus in all range of U variation (-40÷0V) CVC is not linear and probably affected by the flame structure in vicinity of probe. It allows conclusion on the reliability of Langmuir probe diagnostics of quenching zone.

CVC obtained (Fig.3) allows estimation of desirable value of biased voltage to study flame wall quenching: to “overlap” flame reaction zone by sheath layer in zone of probe location the value of biased voltage must be chosen to be at the “border” of zones “II” and “III”, i.e. $U\approx$-15÷-18V.

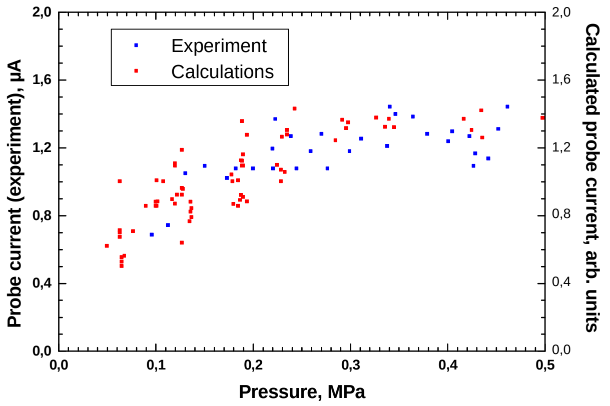

Fig.4. Pressure evolution of probe current: stoichiometric mixture; U=-18V.

In Fig.4 experimental values of probe current are compared with its predicted values calculated by Eq.(4). Because Eq.(4) doesn't allow calculation of absolute value of ion current, the results of calculation are represented in Fig.4 in arbitrary units. Each calculated value of ion current has been obtained using exact value of Q_W taken from [2]. Results presented in Fig.4 show that theoretical and experimental curves of current evolution with pressure correlate well in the pressure range 0.08-0.45MPa. Moreover, the scatter of experimental and calculated values both (±0.13μA and ±0.11μA, respectively) is about the same in all range of pressure variation that confirms our suggestion on the dominant role of flame wall quenching process in formation of probe current and correctness of thermal flame quenching approach to the modelling of probe current. It is worth noting that proposed theory of ion current to Langmuir probe immersed in combustion plasma also predicts well pressure evolution of current for lean fuel mixture of equivalence ratio 0.7 in the pressure range 0.05-0.5MPa.

4 Conclusion

Results obtained demonstrate that CVC of Langmuir probe is affected by the flame quenching phenomenon. It gives a hope to develop future probe diagnostics of near wall combustion including the detection of medium parameters within the flame quenching zone. Proposed simple theory of probe current based on the thermal approach of flame quenching in formation of probe current allows correct prediction of probe current evolution with pressure for stoichiometric and lean fuel methane/air mixtures. Because Eqs.(1)-(4) relates the probe current to quenching parameters, pressure evolution of wall heat flux and quenching distance would be obtained from probe current pressure evolution and vice versa. It is worth noting that practical use of Langmuir probes for diagnostics of flame quenching parameters needs proper choice of probe biased voltage to eliminate the influence of processes within the quenching layer on the probe current and, additionally, to limit zone of flame diagnostics by the area of probe location.

References

[1] Smy PR (1976). The use of Langmuir probes in the study of high pressure plasmas. Advances in Physics 25:517

[2] Boust B, Sotton J, Labuda SA, Bellenoue M (2007). A thermal formulation for single-wall quenching of transient flame. Combust. Flame. (in press)

[3] Fialkov AB (19972). Investigations of ions in flames. Prog. Energy Combust. Sci. 23: 399

[4] Clements RM, Smy PR (1970). Ion current from a collision-dominated flowing plasma to a cylindrical electrode surrounded by a thin sheath. J.Appl.Phys. 41: 3745

[5] Sotton J, Boust B, Labuda SA, Bellenoue M (2005). Head-on quenching of transient laminar flame: heat flux and quenching distance measurements. Combust. Sci. and Tech. 177: 1305