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Flame ion generation rate as a measure of the flame thermo-acoustic response

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ABSTRACT

Similarly to chemi-luminescence, a chemi-ionization mechanism is imbedded in the chain of carbon oxidation (heat release) for hydrocarbons–air flames which involves fast reactions between radicals. This fact suggests to use this chemi-ionization rate as an alternative to the conventional OH*, CH* or C_2^* emission method to characterize the dynamic response of the flame to flow perturbations. To evaluate the idea, a systematic comparative study of the dynamic response of premixed methane-air burner surface stabilized flat and Bunsen-type flames subjected to external acoustic perturbations was conducted. The flame response was determined using the emitted OH* or CH* chemi-luminescence and the ion generation rate of the flame, characterized by measuring the saturation current. The flame thermo-acoustic behavior was described using the flame transfer function concept.

It is found that both gain and phase of the measured transfer functions using both methods show an excellent agreement for lean flames. For higher equivalence ratios a quantitative difference in gain was measured which was pronounced in the low frequency range. To elucidate a possible reason of this phenomenon a dedicated experimental study was conducted. Results suggests that the difference is caused by the shortcomings of the chemi-luminescence rather then the chemi-ionization signal as a measure of the dynamic response of near stoichiometric and rich flames.

The obtained results indicate that the chemi-ionization process can be considered as a promising alternative indicator for thermo-acoustic instabilities and the dynamic flame response in combustion applications.

1. Introduction

During the design and commissioning of combustion equipment, combustion associated instabilities are commonly encountered. These thermo-acoustic instabilities may cause undesirable noise, vibrations and local thermal and mechanical stresses in the combustor. In severe situations, the oscillations can lead to an off-design operation of the combustor and might result in serious damage to the hardware.

In the last few decades different ideas to prevent combustion instabilities have been explored. These methods include active and passive measures to control the instabilities. To create a combustor control system, which may react on the instability via a predefined action, the occurrence of these instabilities has to be continuously monitored via a sensor which accurately estimates the parameters of the thermo-acoustic oscillation in the combustor. Therefore there is a need for a cheap and reliable measurement method to accurately estimate these parameters.

Combustion instabilities are governed by the complex dynamical interaction between unsteady heat release, acoustic fluctuations and hydrodynamics in the combustor. Oscillatory combustion occurs when a feed back loop is formed between the heat source and flow field oscillations. The establishment of such a feedback loop may occur via various routes and is therefore dependent on the flame/burner configuration and the acoustics of the combustion chamber.

This paper focuses on two types of laminar premixed flames, burner surface stabilized flames and Bunsen-type flames. For these flames the governing mechanisms of the flame thermo-acoustic response are reviewed by de Goey et al. [1], Candel [2] and Lieuwen [3]. It is shown that the forced dynamics of Bunsen-type flames are controlled by flame surface area fluctuations regulating the heat release fluctuations. For flat flames, the thermo-acoustic response is determined through the formation of enthalpy waves between the burner and flame.

The electric nature of combustion is known since the sixteenth century, where Gilbert, a physician to Queen Elizabeth, showed the presence of charged particles by demonstrating that a flame would discharge an electroscope [4]. The electric aspects of

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combustion are also used to change the flame behavior using plasma assisted combustion, for diagnostic purposes and to adapt the dynamic response of flames using electric fields. A recent review about plasma-assisted combustion is given by Starikovskiy et al. [5]. Bertrand et al. [6] showed that the electrical nature of flames can be used to determine the adiabatic burning velocity. Abrukov et al. [7,8] investigated the effects of electric fields on acoustically unstable flames and have shown that electric fields can cause damping of the acoustic vibrations by disturbing the feedback mechanism in the self-oscillatory system of the flame. Volkov et al. [9,10] showed that the dynamics of flat and Bunsen-type flames can be altered under the influence of strong electric fields and Yuuki et al. [11] reported a damping behavior of the flame current from a burner stabilized flame to a step response in gas velocity.

For safety reasons an ionization sensor is often installed in combustors, and for practical reasons it would be an advantage to use the available hardware to determine the parameters of the instability. Therefore the goal of this study is to determine if the electrical nature of combustion can be utilized as a measure for the dynamic response of flames. Two types of laminar premixed gaseous flames (burner surface stabilized flames and multiple Bunsen-type flames) are selected because the physics governing the dynamic response of these flame types differ and both types are practically relevant as they are frequently found in domestic, small and moderate power appliances. The focus is on burner surface stabilized flat flames, as these flames are among the simplest examples of a 1-D premixed flame, both hydro- and electrodynamically and therefore attractive from a fundamental point of view.

1.1. Electrical aspect of combustion

The origin of the charged particles in the reaction zone has been studied by many authors and it is shown (see for instance Calcote [12] and Bulewicz et al. [13]) that the charged particles are created in the flame via chemi-ionization reactions, which are sufficiently exothermic to ionize the reaction products. Furthermore, it is known that the contribution of thermal ionization to the total ion generation rate is negligible [14] and it is widely accepted (see Schofield [15] for further discussion) that the dominant chemi-ionization reaction in hydrocarbon flames is [12]:

$$\mathrm{CH} + \mathrm{O} \rightarrow \mathrm{CHO}^{+} + \mathrm{e}^{-}. \tag{1}$$

The chemi-ionization reaction in hydrocarbon flames is closely related to the overall reaction rate as it is found that within the reaction zone of the flame, the maximum ion concentration coincides with the maximum of the heat release rate [16]. Furthermore, the ion generation rate has been identified as a measure of the reaction area of laminar Bunsen-type flames [17]. Hence, there is evidence of a correlation between the flame heat release rate and ionization rate. For the ionization rate to be a suitable indicator of the dynamic behavior of the flame heat release rate, it should quickly react to the alterations of the reaction rate. As the main chemi-ionization reactions involve radical interactions, one may expect that the ion generation rate quickly adjusts to the instant heat release rate in the flame. It has been experimentally verified that in acoustically unstable Bunsen flames an oscillating ion generation rate [18] is present. The above mentioned considerations motivate the present examination to use the flame ionization rate as a candidate for measuring the flame response on acoustic perturbations of the flow.

The generation rate of the charged particles in a flame can be determined by applying an external electric field across the flame. The electric field will induce a body force on the charged particles in the direction of the field lines as illustrated in Fig. 1. Under the influence of this body force, the charged particles will move towards the electrodes. When the charged particles reach the electrode, their charge is neutralized, resulting in a net current flow between the electrodes. The value of the current flow is dependent on the applied electric field strength. The typical dependence between the applied field strength and the current measured for a burner stabilized flat flame is shown in Fig. 2. In this figure three regions can be distinguished; first the current increases with increasing field strength (Region I). When the electric field strength is large enough, all charged particles created in the flame are collected at the electrodes and the current does not increase anymore with increasing field strength (Region II). This saturation current is a measure of the ion generation rate in the flame. For very large field strengths, secondary ionization of neutral particles will occur through electron collisions and the current increases again with increasing field strength (Region III). Eventually for very high field strengths an avalanche increase of charged particles will be created, resulting in electrical breakdown.

1.2. Method of validation

The flame heat release rate is a key factor to investigate the mechanism of thermo-acoustic instability. In order to test if the saturation current is a good indicator for the thermo-acoustic response of the flame, the ion generation rate oscillation will be compared with the heat release oscillation when the flame is perturbed by acoustic waves within a practically relevant range of frequencies. As both the amplitude and the time delay (phase) of the response are important and the heat release rate response on acoustic velocity perturbations is a non-trivial function of frequency, it is more informative to compare the response of heat release rate and ionization rate to the acoustic velocity using the flame transfer function concept then comparing the heat release rate directly to the ionization rate.

The flame transfer function (TF) characterizes the thermo-acoustic response of the flame in the frequency domain and is defined as the ratio of the relative heat release rate oscillation (response) to the relative upstream velocity perturbation (stimulus). In the case of a perfectly premixed flame and acoustic forcing of the upstream velocity, the TF is routinely defined as [19,20]:

$$TF(f) = \frac{q'(f)/\bar{q}}{v'(f)/\bar{v}}, \tag{2}$$

where q is the heat release rate, v the velocity and f the frequency of the perturbation. A prime ($'$) denotes the perturbation and a bar ($\bar{\ }$) denotes the average value of the quantity. The transfer function is determined by applying acoustic fluctuations to the gas stream at a known forcing frequency and measuring the resulting heat release rate fluctuations.

The flame transfer function using the ion generation rate for the flame response is measured as the ratio of the relative saturation current (i_s) fluctuations to the relative velocity perturbation:

$$TF_{i_s}(f) = \frac{i_s'(f)/\overline{i_s}}{v'(f)/\bar{v}}. \tag{3}$$

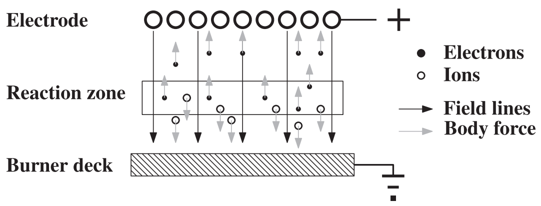

Fig. 1. Schematic representation of the influence of an external applied electric field on the charged particles in a flame.