Observables for the Response of Laminar Flames to Acoustic Disturbances

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Abstract

The detection of the response of flames to acoustic disturbances is of importance for both laboratory situations and practical equipment. For the main observables of interest, heat release and velocity, the detection is quite difficult and too costly to implement in real life applications. This paper presents an experimental and numerical study into a number of observables that show instationary effects when a flame is acoustically disturbed. The flame configuration is very basic, consisting of a flat laminar premixed methane-air flame, stabilized on a porous ceramic material. The observables of interest are velocity, heat release, chemoluminescence of CH and OH, and temperature. The conclusions are that velocity and chemoluminescence are in principle excellent indicators for the flame’s response, but for the given specific setup there is a too large discrepancy between the experimental and numerical results with regard to chemoluminescence. Temperature fluctuations are significant but are, due to the strong position dependence, not very suitable as an observable.

Introduction

Lean premixed natural gas flames are commonly used in condensing boilers for domestic purpose in combination with burner decks that can handle a wide range of burner load. Feedback coupling in the system can lead to an acoustic unstable operation of the boilers leading to noise problems varying from a light whistle up to a loud roaring from the appliance. The modulation technique is indirectly the cause for these noise problems since each load setting requires a different geometry of the boiler in order to be acoustically silent.

The key quantity in understanding the acoustic behaviour of flames in closed systems is the so-called flame transfer function (TF). To be more specific, one would likes to know the TF between some upstream acoustical variable (i.e. pressure or velocity fluctuations) and a downstream acoustical variable. Acoustic transfer models of the flame/burner combination in terms of velocity have been developed by Rook et al [1] and have been validated with measurements by Schreel et al. [2, 3]. These TF’s can be used for an analysis of a boiler system, but are quite unpractical when cheap online detection is needed (e.g. for active control purposes). What is needed therefore is a good understanding of the relation of all observables such that a measured signal can be translated into an acoustical variable.

In this study again a flat premixed methane/air flame, stabilized on a porous ceramic material, is used, with an equivalence ratio (φ) of 0.8 and a burning velocity of 18 cm/s. The properties of the ceramic material are presented in Table 1.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>porosity</td>
<td>$\phi$</td>
</tr>
<tr>
<td>volumetric heat</td>
<td>$\alpha$S</td>
</tr>
<tr>
<td>tortuosity of the gas</td>
<td>$\tau_g$</td>
</tr>
<tr>
<td>conductivity</td>
<td>$\tau_\lambda$</td>
</tr>
<tr>
<td>heat capacity</td>
<td>$c_{p,s}$</td>
</tr>
<tr>
<td>density</td>
<td>$\rho_s$</td>
</tr>
<tr>
<td>extinction coefficient</td>
<td>$K$</td>
</tr>
<tr>
<td>emissivity</td>
<td>$\epsilon$</td>
</tr>
</tbody>
</table>

Upstream of the burnerdeck, the acoustical wave is characterized by the two-microphone technique. Downstream the following techniques are used. For the velocity measurements, use is made of Laser Doppler Velocimetry (LDV) directly above the flame front [2]. The chemoluminescence is measured with a Photo-Multiplier Tube (PMT), fitted with an appropriate filter for OH (UG11), and CH (432 nm bandpass). At this time, no temperature measurements are available.

Numerical

Numerical computations are performed using the software package Chem1D [4] in combination with the detailed chemistry of GRI 2.11 [5]. With this program, a one dimensional flame can be calculated time resolved with complex chemistry. Several add-ons can be used to include for example radiation, strain, or surface chemistry. The normal equations for species and momentum conservation are solved. In this case, the enthalpy equation is (in the flame holder) split into two parts. The enthalpy
reaction rates are mentioned in table 3. Shown in table 4 were in agreement with the experiments. The reactions and their reaction rates are generally accepted. The quenching reactions and their reaction rates for the Stettner ceramics are displayed in Table 1. The resulting formation reaction set is displayed below and is therefore investigated again.

\[
\text{CH} + h\nu \rightleftharpoons \text{CH} + \text{hv}
\]

\[
\text{OH} + \text{H}_2 \rightleftharpoons \text{OH} + \text{H}_2
\]

\[
\text{OH} + \text{N}_2 \rightleftharpoons \text{OH} + \text{N}_2
\]

\[
\text{OH} + \text{O}_2 \rightleftharpoons \text{OH} + \text{O}_2
\]

\[
\text{OH} + \text{H}_2\text{O} \rightleftharpoons \text{OH} + \text{H}_2\text{O}
\]

\[
\text{OH} + \text{CH}_4 \rightleftharpoons \text{OH} + \text{CH}_4
\]

\[
\text{OH} + \text{CO} \rightleftharpoons \text{OH} + \text{CO}
\]

\[
\text{OH} + \text{CO}_2 \rightleftharpoons \text{OH} + \text{CO}_2
\]

Table 2: Formation of OH\(^+\) expressed as \(k = AT^n \exp(-E/RT)\)

<table>
<thead>
<tr>
<th>Formation reaction</th>
<th>A [cm(^3)/mole-s]</th>
<th>n [-]</th>
<th>(E_a) [cal/mole]</th>
</tr>
</thead>
<tbody>
<tr>
<td>O(^+)+H+M \rightleftharpoons OH(^+)+M</td>
<td>3.63\times10^{13}</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>HCO+O \rightleftharpoons OH(^+)+CO</td>
<td>2.90\times10^{11}</td>
<td>0.0</td>
<td>460</td>
</tr>
<tr>
<td>CH+O(_2) \rightleftharpoons OH(^+)+CO</td>
<td>4.04\times10^{13}</td>
<td>0.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>

The existence of CH\(^+\) and its emission (431.4 nm) is only observed in a hydrocarbon flame. From many literature references the intensity and sensitivity makes CH\(^+\) most applicable to study rich flames. Different sets of reactions are available in the literature to model the CH\(^+\) chemiluminescence. The reactions and their reaction rates shown in table 4 were in agreement with the experimental results. The available reference for quenching were in agreement and were generally accepted as displayed in table 5.

Devriendt is accounted as the only verified reference with regard to his direct measurements of the reactions rates. With regard to the available references, only the work of Walsh [10] has been verified in agreement with work of Devriendt et al. [11]. Comparable work of Smith [6] concluded that his CH\(^+\) mole fraction was over-predicted hugely and could not verify his numerical results with the work of Devriendt.

The reactions for formation and quenching of OH\(^+\) and CH\(^+\) in this section were added to the reaction scheme of GRI 2.11. With this extended reaction set the ceramic burner stabilised flame is first solved in a stationary situation. For the simulations of a timedependent response, a block wave is applied to the unburnt velocity. From the FFT analysis of the step response, the transfer function is calculated.
Experimental

The test rig consists of a 0.5 m long burner tube with a ceramic burner deck holder and flame holder. The inside diameter of the burner tube, burner deck and flame holder is 50 mm. The ceramic burner deck is operated at velocities below \( S_1 \) so that a flat burner stabilised flame occurs. The flame holder and burner deck holder are water cooled at a temperature of 50 °C. The methane-air mixture is injected on the bottom side of the burner tube. A ceramic burner deck from Stettner an a flame with a \( \phi \) of 0.8 and a burning velocity of 18 cm/s is used for the experiments. For more details pertaining the experimental setup, see the paper by Schreel citekoen.

The disturbance of the velocity during the measurement is a sinusoidal amplitude, added to the unburnt mixture velocity. The frequency range for the measurements is from 40 to 800 Hz. For the simulations of a time-dependent response, a block wave is applied to the unburnt velocity and from the FFT analysis of the observed properties, the step response or transfer function is calculated. The measured and calculated transfer functions are compared in the chapter containing the results.

The measurement of the transfer coupling the acoustic velocities before and after the flame-burner combination, involves the time-correlated measurement of the velocity upstream of the flame and downstream of the flame. An established way of determining pressure waves inside a tube is by means of multiple pressure transducers fitted in the wall of the tube [12]. If the medium in the tube has constant properties (density and temperature), two microphones suffice to characterize the waves traveling in both directions. From the pressure wave and the properties of the medium and the tube, the velocity wave can be reconstructed.

The upstream region of the flame does have the desired constant density and temperature, but the downstream region does not, because the hot gas cools down rapidly. Therefore, we have chosen to use the two microphone method only in the upstream region, but a direct measurement of the velocity in de downstream region by means of Laser Doppler Velocimetry (LDV). Observation of these local flame properties is preferably done by non-intrusive measurement techniques. In this case we use optical techniques which have eminent faster response than our field of interest which is limited to 800 Hz.

The emissions of \( \text{OH}^+ \) and \( \text{CH}^+ \) are measured with a photon multiplier tube (PMT) which is equipped with a band pass filter. For \( \text{OH}^+ \) this is a UG11 filter, and for \( \text{CH}^+ \) it is a 432 nm bandpass filter with a FWHM of 10 nm. The photon multiplier is positioned perpendicular above the flame front and focussed on the center of the flame. Only the center of the flame is measured to avoid measurement of quenched radicals on the side near the flame holder.

Results

From the measurements and simulations the following results were made. In figure 1 the transfer function of the acoustic velocity for the tested flame and Stettner burner deck is displayed. It can be seen that there is agreement between the measurements and the simulation. This agreement has already been shown in previous work by Schreel [3, 2] and the burner properties as described in table 1 were not changed.

The transfer function of the heat release in figure 2 shows surprisingly a good correspondence with the transfer function of the velocity. Similarity can be noticed while the amplitude of both transfer functions decreases by 75% from 40 to 800 Hz. The phase of both transfer functions is similar. Therefore it can be said that the response of the acoustic velocity fluctuations is representative for the heat release response under the tested conditions.

The measurement and simulation of the transfer function of the emission of \( \text{OH}^+ \) in figure 3 shows the same trend for the amplitude but no coherence for the behavior. The simulated transfer function gives a similar result as the transfer function for the velocity except that the amplitude of transfer function of the emission of \( \text{OH}^+ \) drops faster than for velocity. The experimental and numerical results disagree strongly with respect to the phase. This might be caused by the fact that the layer in which the excited radicals are present is positioned partly within the porous ceramic. This adds extra quenching that is not taken into account by the model. More work on this is needed.

The calculated transfer function of the \( \text{CH}^+ \) emission in figure 4 shows also a strong similarity with the transfer function of the velocity response in figure 1. Similarity can be noticed while the amplitude of both transfer functions decreases by 75% as the frequency increases from 40 to 800 Hz. The phase of both transfer functions is similar. But also in this case should these results be interpreted with care, since burner surface quenching was not taken into account.

The response of the temperature is evaluated at different positions varying from directly above the flame front up to 1 cm height. The response of the amplitude and the phase show a strong position dependence and no similarity with the transfer function of the velocity or heat release.

Conclusions

For a burner stabilised flame, the transfer function between the upstream velocity and a number of downstream variables has been modeled with Chem1d. The downstream velocity fluctuations have been validated by means of LDV and show a good correspondence. The chemoluminescence can be modeled, but its correspondence to the measurements is not good. The main cause for this is probably that the region containing excited radicals is partly within the ceramic material. This can cause ad-
ditional quenching that is not taken into account in the model. The temperature shows a strong position dependence (as is to be expected), and has not been validated experimentally. The relation of all abovementioned observables with the heat release can in this way be understood.

Acknowledgements
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References


[5] See http://www.me.berkeley.edu/gri_mech/

Figure 3: Transfer function for emission of excited OH, $\phi=0.8$, $v=18$ cm/s

Figure 4: Transfer function for emission of excited CH, $\phi=0.8$, $v=18$ cm/s


[13] L.C. Haber, U Vandsburger, *A global reaction model for OH* chemiluminescence applied to a laminar flat-
Figure 5: Transfer function for flame temperature at different positions, \( \phi=0.8, \, v=18 \) cm/s


