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PEAK FREQUENCY SCALING OF COMBUSTION NOISE FROM PREMIXED FLAMES

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Abstract
An experimental investigation of the noise emission of turbulent premixed flames is presented. Since the beginning of combustion noise research, the precise forecast of the peak frequency has been a point of major uncertainty and discussion. The main problem for the precise forecast of the peak frequency is the existence of multiple time scales in turbulent combustion. In the past, predictions were either based on flame chemistry or on turbulence, depending on the particular view of the investigator. As the consequence, fundamental inconsistencies were generated, which prevented the development of a suitable theoretical model. The paper attempts to resolve the existing discrepancies and shows that turbulence as well as chemistry are both of fundamental importance for the forecast of the peak frequency. As the result of the analysis of the experimental data a model is presented, which covers both effects. Most remarkably, this theory does not require any free parameter to predict the measured peak frequencies properly.

INTRODUCTION

Lean premixed turbulent flames exhibit the advantage of low levels of oxide emissions. However, noise emissions from turbulent flames are a general issue and noise reduction requires a better understanding of the underlying physical mechanisms.

Several authors suggest that mainly the turbulence length- and time-scales determine the spectra of the heat release and for this reason also the peak frequency of the noise emission [9]. In the literature, the burner diameter [5] [8] was often proposed as the characteristic length scale, because it is linked to the integral length scale of the flow. An other group of authors attempted to cover the influence of the chemical kinetics in addition to turbulence [1] [7], e. g. via the laminar flame thickness or laminar flame speed. More recent studies revealed that the flame length, which is also influenced by turbulence as well as chemical kinetics, can be taken as a more adequate length scale than the burner diameter. Most of the existing studies resulted in empirical formulas. Unfortunately, the general validity of such formulae is highly questionable due to a lack of theoretical foundation and the quality of their prediction may be restricted to the investigated test cases.

The main reason for the diverging conclusions in the open literature is that they were derived from the analysis of microphone measurements alone and that the heat release in the flame was not studied in parallel in sufficient depth. Dynamic heat release measurements require sophisticated experimental techniques, which were not available in the past. It was mainly this deficit, which prevented the development of a better understanding of combustion generated noise in the past.

In the presented study, the flow field as well as the heat release distribution were acquired in parallel to the acoustic data. On this basis the peak frequencies were calculated from the characteristic time scales including both, the local turbulence as well as the chemical kinetics. A space time mapping procedure finally yields the desired peak frequency. Since this model is deducted from optical measurement techniques, also errors arising from room acoustics are minimized. It will be shown that the peak frequency can be predicted if the turbulent as well as the chemical time scale are precisely known. Finally, the predicted peak frequencies are compared to acoustic data.

THEORETICAL BACKGROUND

The noise emission of turbulent premixed flames is dominated by local heat release fluctuations. These are generated by turbulent velocity fluctuations v'. According to turbulence theory the turbulence energy cascade exhibits its maximum close to the integral length scale. Within the inertial subrange, the turbulent kinetic energy $E_{v'v'}$ depends on the wave number κ and scales as [10]

$$E_{v'v'}(\kappa) \sim \alpha \varepsilon^{2/3} \kappa^{-5/3} \tag{1}$$

with the dissipation rate ε and the constant factor α. For calculating the heat release spectra, the progress variable c [4] will now be introduced. It describes a normalised temperature T which is equivalent to the combustion process in adiabatic premixed flames. Since the heat release q in turbulent flames is controlled by the mixing of the hot exhaust and the cold fresh gas, it is common practice to assume

$$q \propto \overline{\frac{\partial c'}{\partial x}\frac{\partial c'}{\partial x}} \propto \overline{c'^2} \quad . \tag{2}$$

The latter approximation holds if c' was a passive scalar of the flow However, the same approximation is often used for the combustion progress variable, too. This is still a fair approach [4]. Near the integral length scale l_t, which determines the peak emission frequency, the passive scalars behave similar to the flow turbulence [4]. Thus, l_t also governs the maximum of the scalar spectrum $E_{c'c'}(\kappa)$, i.e. heat release spectrum.

If one is interested in the peak frequency instead of peak wave number, a space time mapping is necessary. Therefore it is assumed that the energy of the wave number spectrum $E(\kappa)$ is conserved, when it is converted into the frequency spectrum $\chi(\omega)$ [10]. This assumption yields

$$\kappa E_{c'c'}(\kappa)=\omega\chi(\omega) \quad . \tag{3}$$

For the precise determination of the noise emission the observer must move with the source, i.e. heat release fluctuations generated by vortices. Therefore, the authors propose the lagrangian spectrum $\chi(\omega)$ [10] to be taken to describe the frequency content. As the result, a relation between the (Eulerian) wavenumber and the (Lagrangian) frequency is obtained [10]:

$$\omega=\alpha^{1/2}\varepsilon^{1/3}\kappa^{2/3} \quad . \tag{4}$$

In eq. (4), the dissipation rate ε is

$$\varepsilon=\frac{v'^3}{l_t}\approx l_t^2\left(\frac{1}{\tau_c}\right)^3 \quad . \tag{5}$$

In [10] a model spectrum of the turbulent kinetic energy was introduced that exhibits its maximum near κl_t=1.8. Thus, the peak frequency is found near

$$f_{peak}\approx\frac{0{,}3}{\tau_c} \tag{6}$$

The integral length scale is transferred to the peak frequency f_{peak}, which must be scaled with a characteristic time scale τ_c. As the noise emission is dominated by heat release fluctuations, the authors propose the time scale being represented by the turbulent burning velocity s_t and the flame brush thickness δ_t. According to [6], the turbulent flame speed is given by

$$\frac{s_t}{s_l}=1+\frac{v'}{s_l}\left(1+Da^{-2}\right)^{-\frac{1}{4}} \tag{7}$$

while the flame brush thickness is

$$\frac{\delta_t}{l_t}=\frac{\delta_l}{l_t}+\left(1+Da^{-2}\right)^{\frac{1}{4}} \tag{8}$$

with the Damköhler number Da. Finally, the characteristic time scale is given by

$$\tau_c \approx C_\tau \frac{\delta_t}{S_t} \tag{9}$$

Since τ_c should be half the turbulence time scale l_t/u' for infinite Damköhler numbers [4], the constant must be of order unity and is set to $C_\tau \approx 0,5$. An important charcter of this model is that it incorporated effects from chemical kinetics as well as from turbulence. The relative contribution of both effects depends on the character of the premixed flame, i.e. the Damköhler number), which is governed by the operating point of the combustion system,.

It can be shown analytically that the acoustic behavior of the flame can be derived from its heat release spectrum [11]. This analysis reveals that the maximum of the noise emission spectrum is identical with the peak frequency of the heat release.

TEST RIG

For the experiments a modular and flexible swirl burner (see figure 1) was used. Natural gas and hydrogen were used as fuel. For premixed combustion, a static mixer was implemented upstream. The thermal output was kept constant at $P_{th} = 60$ kW, while the swirl number was set to $S = 0.5$. The outer diameter of the nozzle is $D = 40$ mm and the diameter of the center body is $d = 16$ mm.

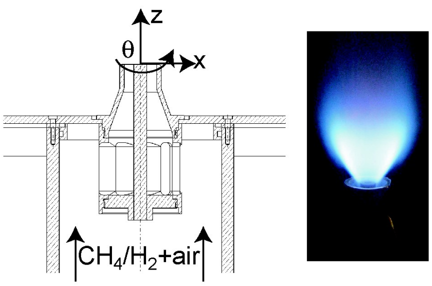

Figure 1 – Modular swirl burner with radial coordinate x, axial coordinate z and tangential coordinate θ.

The mean axial velocity v_{bulk} at the burner exit ranges from 16.9 m/s to 23.0 m/s. The Reynolds number at the burner exit ranges from $Re \approx 27000$ to 37000 for a hydraulic diameter of $d = 24$ mm of the annular gap. For the acoustic measurements, the burner was operated in an combustion lab with acoustically damped walls.

MEASUREMENT TECHNIQUES

The turbulent velocity fluctuations were measured with PIV. From this velocity data spatially resolved length scales and finally characteristic time scale distributions were calculated. In the next step, the resulting peak frequencies were weighted with the local heat release. The distribution of the local heat release was acquired using chemiluminescence probes in combination with laser induced fluorescence (LIF).

Determination of the flow velocities

A high speed PIV system consisting of a CMOS camera and a Nd:YLF-laser was used for the experimental investigation. The PIV-system yields the instantaneous velocity of the flow field in the x-z-plane (figure 1). These data also allow to calculate the local length scales l_t by integrating the correlation coefficients of the velocity fluctuations in various directions [10].

Heat release detection

OH-molecules are supposed to be a key species in the hydrocarbon reaction mechanism and thus, are considered to be an indicator for flame fronts. Therefore, a planar LIF system was set up for their detection in the x-z-plane. The images show two zones, which reveal the hot burned exhaust gas (c=1) and the cold unburned mixture (c=0), respectively. The flame front is located in between and is assumed to be below 1 mm thick. Since in turbulent combustion the heat release is controlled by the mixing of the exhaust gas and the unburned mixture, it is assumed that the heat release scales with the scalar dissipation of the reactive scalar c (eq. (2)). As only information of the light sheet plane is acquired, the heat release zone deducted from LIF shows steeper gradients than line of sight techniques.

However, the main problem is the existence of OH-radicals in the hot exhaust gas. Therefore, the chemiluminescence of the CH*-radicals, which should also scale with the heat release, was recorded. The resulting intensity pictures were de-convoluted assuming axisymmetry using the robust algorithm developed by Dribinski et al. [2]. The chemiluminescence data was used to filter the scalar dissipation rate. As the result, the precision of the determination of the heat release zone is becoming substantially better than with either one or the other method alone.

Acoustic Measurements

Acoustic measurements were carried out with a G.R.A.S type 40AK 1⁄2" intensity microphone set mounted on a 25 mm microphone spacer. The intensity probe was located 0.7 m from the burner and 0.1 m above the nozzle exit. The microphone calibration and signal processing are reported in [11].

RESULTS

Since the model described above incorporates the influences of turbulence and chemical kinetics via the Damköhler number, experiments with different fuel compositions and the equivalence ratios are suitable to benchmark model thoroughly. The fuel composition was varied by adding hydrogen to the methane, which results in shorter chemical time scale and increasing Damköhler numbers. On the other hand, reducing the equivalence ratio decreases the Damköhler number substantially.

Influence of the equivalence ratio

For varying the equivalence ratio the thermal power was kept constant at P_{th}=60 kW. This results in an increase of the total mass flow rate for lower equivalence ratios ϕ, which is characterized by the bulk velocity v_{bulk}. The velocity profiles of the axial velocity only change slightly with increasing air ratio, if they are normalised with the bulk velocity (figure 2). Both show strong gradients in the axial components, resulting in shear layers which produce high turbulent fluctuations. In flames of the investigated type, the flame brush is always located in the zone of highest turbulent fluctuations. As the turbulent flame speed as well as the flame brush thickness both depend on the local value of the velocity fluctuation, a precise knowledge of the location of the heat release zone is crucial for the proper determination of the peak frequencies. At z/D=1 the length scale is in the range of 0.6-1 times the annular gap width and increases almost linearly in downstream direction. The peak frequencies derived from the data and the model presented above where weighted with the local scalar dissipation rate, the distance to the burner axis and the local coherence volume [11].

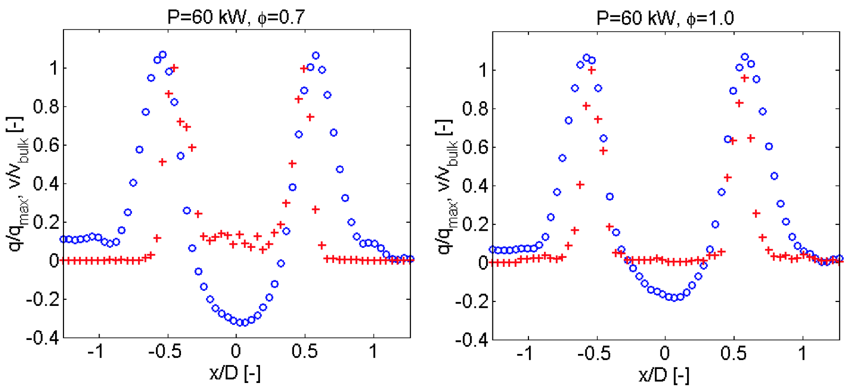

*Figure 2 – profiles of the mean axial velocities v (**o**) and the heat release q (+), normalised with the bulk velocity and the maximum of heat release, respectively. The radial coordinate x is normalised with the nozzle diameter D. The distance to the burner exit is z/D=1.*

Basically, s_t and δ_t are local values. However, a global turbulent flame speed and a global flame brush thickness were calculated by setting v' = 0,2 v_{bulk} and l_t= 10 mm. Both values are chosen according to the real values acquired with the PIV-system in the area of maximum heat release. Although both, the length scale and the velocity fluctuations are not constant in the heat release zone, the resulting peak frequencies show an excellent agreement with the data acquired from the local information (figure 3, l.h.s.). Both evaluation methods constantly predict properly that higher equivalence ratios ϕ lead to a substantial increase of the peak frequency. The moderate deviations between the measured and calculated frequencies may at least to some extent stem from the limited acoustic damping characteristics of the combustion lab below 150-Hz. As the consequence, the peak frequencies determined from the microphone data may be slightly overestimated. Interestingly, peak frequencies calculated using the flame length or turbulence parameters only show a totally different behaviour and do not well match the experimental data.

Influence of the laminar burning velocity

The influence of the burning velocity was studied by changing the laminar burning velocity. This was achieved through H_2-addition to the fuel, which leads to an decreasing chemical time scale δ_l/s_l. In these tests the power (P = 60 kW) as well as the swirl number and the air ratio ($\phi = 0.8$) were held constant. Since the turbulence parameters remain almost equal under these conditions, the Damköhler number rises when hydrogen is added. This leads to a modification of the relative contribution of the influence of turbulence and chemistry. With hydrogen addition and with higher laminar burning velocities the peak frequency increases considerably and this effect is almost perfectly predicted by the theory presented above (Figure 3, r.h.s.).

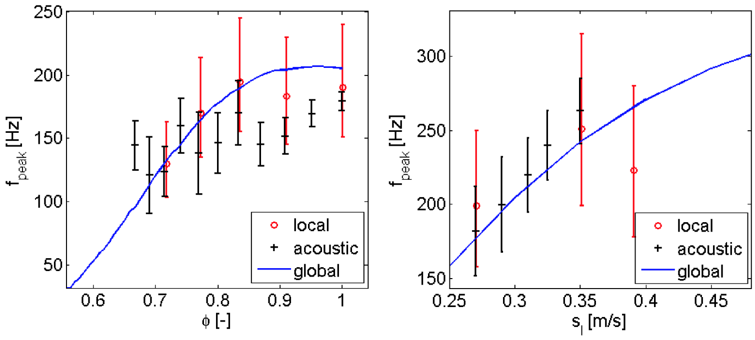

Figure 3 – peak frequencies calculated from local information (o), global estimations of velocity fluctuation and length scale (–) and extracted from microphone data (+).

The same model was also used to study the influence of the the turbulence intensity (figure 4). As expected, the peak frequency increases with the turbulence intensity. The model shows that a precise estimation of the integral length scale is required. If this information is not available a prediction of the peak frequency with good precision cannot be made. Furthermore, the turbulence intensity must be known with a precision of at least 5%. These requirements indicate that attempts to derive precise combustion noise models models based on global geometry, flow, and flame parameters alone will be facing serious difficulties.

SUMMARY

In the past either parameters characterising flame chemistry or flow turbulence have been used to predict the peak frequency. However, the presented paper shows that both effects are of fundamental importance. A model is presented, which incorporates both effects and does not need any free parameter for adjustment. Using this model the peak frequencies are precisely predicted but precise input data concerning the flow turbulence as well as the heat release distribution are required.

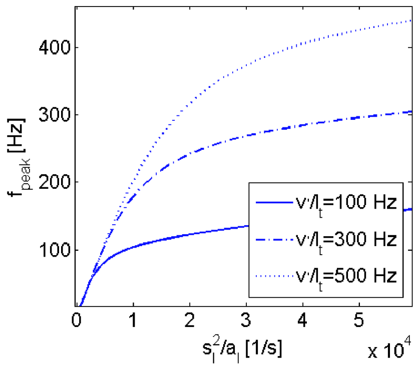

Figure 4 – Profiles of the peak frequencies for different chemical and turbulence time scales (l_t = 10 mm). The chemical time scale is calculated from s_l^2/a_l, where the molecular diffusivity a_l is kept constant.

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