Experimental Transfer Function of Acoustically Perturbed Bunsen-type Flame


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Abstract
The measurement results of the Transfer Function (TF) of the flame heat release rate (OH* chemiluminescence) response to acoustic velocity excitation are presented. Influence of flow rate and equivalence ratio as well as burner tube diameter, wall thickness, wall material and tube opening geometry on flame TF behaviour is discussed. A function for an empirical TF representation is proposed. Correlations between the parameters of the TF and flame/flow/burner parameters are derived. The physical mechanisms of TF formation are analyzed.

Introduction
Acoustical instability of combustion in practical devices up to now is difficult for a-priori predicting phenomena. The general scheme of the instability development is well known. It includes a source of energy (heat release of reactions), oscillating unit (gas in vessels which compose combustor), mechanism of energy transfer from the source to acoustic mode (known as Rayleigh criterion), and a feedback mechanism. This feedback unit is a stumbling block of the scheme because a large variety of physically different phenomena can lead to heat release rate oscillation in response to the system (combustor) on the acoustic parameters (pressure, temperature, gas velocity, etc.) perturbation. Which of the possible mechanisms will be dominating depends strongly on combustor and/or burner design, fuel/oxidizer composition, burner load, etc.

An overview of the results received up to the nineties of last century can be found in a book [1]. The results of the last decade are presented in a review [2].

The object of our study is a premixed flame interacting with acoustic perturbations of the mixture flow. A review [3] summarizes the results in this area up to 2003.

One of the simplest and well-studied methods of gas combustion organization is a conical Bunsen-type laminar flame of premixed fuel. Studies of this flame response on acoustic perturbation of flow were started more then 50 years ago [4,5,6]. In the last ~15 years significant progress in understanding the interaction of acoustics with Bunsen flames was achieved due to investigations in EM²C laboratory, Georgia Institute of Technology, Cambridge university and several other groups. Good correspondence between measured and modelled perturbed forms of the flame front has been achieved (see citation in [3]).

For instability prediction the important information is the flame (burner) Transfer Function (TF) which reflects the relation between the flame response (oscillating part of the heat release rate \( Q' \)) and the perturbation (acoustic velocity \( V' \)). The knowledge of the TF gain \( G(f, \alpha) = (Q'/Q_0)/(V'/V_0) \) and the phase delay \( \phi(f, \alpha) \) as function of the excitation frequency \( f \) and of the vector of flame and burner parameters \( \alpha = (V_0, \alpha, d, \ldots) \) as well as the acoustic model for combustor vessels is sufficient for the prediction of the instability area of the burner, combustor and fuel mixture parameters [7]. Here \( V_0 \) and \( Q_0 \) are the mean fuel flow velocity and the mean heat release rate; \( \alpha \)– the equivalence ration of the fuel/air mixture, \( d \) – the burner tube diameter.

In this paper, the results of a systematic parametric study of the TF are presented. The fuel mixture and burner parameters varied are:
- mean (volume averaged) velocity \( V_0 \) and the fuel (methane/air) equivalence ratio \( \alpha \);
- burner neck diameter \( d \), burner tube wall thickness, tube material, burner opening geometry.

At least three physically different mechanisms, which are able to provoke the variation of heat release rate of the flame under flow velocity oscillation, can be expected: first, a variation of flame surface area; second, a variation of the normal flame propagation velocity due to oscillation of the flame curvature and flow strain rate, and third, a possible source of energy release variation is the interaction of the flame with the burner rim. It can be expected that these mechanisms will be reflected in the behaviour of the flame TF.

Specific Objectives
The aim of the research is to study the behaviour of the TF of Bunsen-type premixed laminar flames of fuel-lean methane/air mixtures and to clarify the role of different physical phenomena of flame-acoustic interaction in the TF formation.

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Experimental method and setup

Experimental set-up

The parametric study of the TF requires a facility to apply acoustic excitation of flow velocity with controlled amplitude and frequency. The method to monitor the perturbation as well as the flame response should be also developed. As a heat release rate indicator the chemoluminescence intensity of \( \text{OH}^* \) was chosen [8]. The tests with \( \text{CH}^* \) and \( \text{C}_2^* \) chemoluminescence measurements show the same results for the TF as the \( \text{OH}^* \) signal provides. For the velocity oscillation monitoring a hot-wire anemometer was used. A probe wire was installed across the burner tube with a distance \( \sim 2\text{cm} \) from the burner rim. The burner tube was long enough for a Poiseuille velocity profile to develop. The main parts of experiments were conducted with glass burner tubes. To test the influence of burner neck material on the TF a brass muzzle on the burner was installed. To impose the flow velocity perturbation a loudspeaker operated by a pure tone generator was installed upstream in the mixture supply tube. Gas flow rate \( V_0 \) and composition \( \alpha \) were operated by mass-flow controllers installed far enough from the burner to allow perfect mixing and to avoid possible acoustic influence on \( \alpha \) and/or \( V_0 \). A photomultiplier with appropriate UV light filter (UG11) detects the \( \text{OH}^* \) luminescence from the whole flame. The signals from the photomultiplier (\( I_{\text{OH}^*} \)) and anemometer were collected by a data acquisition system and post-processed for the TF gain \( G \) and phase delay \( \phi \) restoration.

Data processing and presentation

Raw experimental data consist of 0.5s samples of \( V' \) and \( I_{\text{OH}^*} \) time history digitized with a sampling rate of 20KHz. The gain of the TF was calculated as the relation of the amplitude of the Fourier transform of the \( I_{\text{OH}^*}(t) \) signal (integrated over the peak on excitation frequency) to the amplitude of the Fourier transform of acoustic velocity signal \( V'(t) \). The phase difference between \( I_{\text{OH}^*}(t) \) and \( V'(t) \) was restored by cross-correlation analysis of these signals.

The TF can be presented either in the form of a frequency dependent gain \( G(f) \) and phase delay \( \phi(f) \), or in a polar plot where \( G(f) \) presents the radial length and \( \phi(f) \) presents the angle, or in the form of real \( \text{Re}(f)=G(f)\cos(\phi(f)) \) and imaginary \( \text{Im}(f)=G(f)\sin(\phi(f)) \) parts of the TF.

Results

The typical curves of the TF for a conical flame are presented in Figure 1. Three meaningful peculiarities of the TF should be mentioned. The gain of the TF decreases non-monotonically with increasing frequency. Several minima and maxima can be recognized. However, a general trend of damping of the gain is evident and resembles a low-pass filter behaviour. The phase of the TF increases with frequency and, for some flame conditions, a phase delay of several times \( 2\pi \) is measured. This behaviour of the phase clearly leads to a spiral form of the TF in the polar plot form – Figure 1c. A “revolution” of the TF curve is typical for
the system with a “time delay”. Such a system generates a response time $\tau$ after the perturbation is applied.

The third significant feature of the TF is that the gain does not drop to zero with frequency increase up to the experimental limit ~400Hz. After several oscillations of $G(f)$ some limit level of gain that is significantly bigger than the noise level is reached. After a region of near linear growth, the TF phase reaches a constant level, which is not far from value of $2\pi N+1/2\pi$. This behaviour leads to convergence of the TF curve in the polar plot (Figure 1c) to a point that is located in the upper half-plane of a polar plane. Such a peculiarity of the TF indicates the presence of relatively small remaining of flame response (on the level 5-8% from quasi-stationary ($f=0$) case), but this part has a weak frequency dependence. Therefore, for high enough frequencies, when low-pass behaviour damps the TF gains significantly, the role of this “constant” item starts to be dominating.

Above-mentioned features of the TF, the spiral form of the TF in a polar plot, as well as curves of Re and Im parts of TF in the form of an “attenuated oscillation” – Figure 1d, were measured for all flames and burner parameters studied. Therefore, there is the prospect to describe (or to fit) TF by a universal function with a few coefficients, which depend on flame/burner parameters.

The mean flow rate and mixture equivalence ratio influence on flame TF

Figure 2 presents the field of $(V_0, \alpha)$ parameters. The points indicate the parameter values for which the measurements of the TF were conducted. The right part of the figure presents the characteristic polar plots of the TF that correspond to parameters $V_0$ and $\alpha$ filled by appropriate grey level. The influence of $\alpha$ on the qualitative view of the TF is weaker than the influence of $V_0$. The larger flames (larger $V_0$) have a TF with more turns of the TF curve “revolution”, or weaker “damping” of the TF gain (higher cut-off frequency of the low-pass filter). The series of TF phase delay curves for fixed $\alpha=0.85$ and varied $V_0$ are presented in Figure 3. After several “steps” of monotone growth the TF phase saturates on levels $\pi/2+2\pi N$ ($N$ is integer). The number $N$ of phase delay “steps” or TF “revolutions” increases with gas velocity $V_0$.

Choice of the function for the phenomenological description of the flame TF

The unsmooth behaviour of the TF gains and strong dependence of the phase delays on the flame parameters make it difficult to fit these curves by a universal function with a few parameters. Fortunately, the Re and Im parts of the TF are smooth curves with a regular change of their shape as a function of flame parameters. The guess function for the TF fitting should take into account the above-mentioned characteristic behaviours: the time delay, the low-pass filter and the additional weakly frequency dependent component.

From the theory of system control it is well known that “time delay” behaviour is described by a factor $\exp(i\pi \tau f)$. Because the information about the weakly frequency dependent component is quite limited now, a zero order approach for its description will be a constant $A=|A|\exp(\arg(A))$.

Many functional forms could be proposed to include the low-pass behaviour into the TF guess function. The compromise between the need to keep a minimal quantity of fitting parameters and to reach a good matching of experimental points and the fit curve should be found.

In this paper, we chose the following formula for the TF:

$$G(\text{i}f) = \frac{\exp(-i\pi \alpha_0 f)}{(i\tau_i f + i)} + A$$  \hspace{1cm} (1)
A power of 2 in denominator is chosen because it leads to a better fitting accuracy than a power 1 or 3 provide. Of course, a polynomial function with several parameters in denominator of (1) allows to get an even better fitting accuracy, but here the minimal possible number of parameters is chosen to the detriment of perfect fitting.

The 4 parameters \((\tau_0, \tau_1, |A|, \text{arg}(A))\) are fitted for all experimental TF's in Figure 2 and for experiments with other burner diameters.

The main correlation that was found is that the non-dimensional combination \((\tau_0 V_0)/(2\pi H)\) of time delay \(\tau_0\), velocity \(V_0\) and flame height \(H\) is equal to a constant 4 with a deviation of only \(\pm 5\%\) for all TF.

For the relaxation time parameter \(\tau_1\), which is responsible for low-pas filtering behaviour, such an accurate correlation with flame or flow parameters could not be derived, but the general tendency is observed that the absolute value of \(\tau_1\) (\(\tau_1\) is negative in (1)) decreases with \(V_0\) (and \(H\)). It reflects the fact that the TF for larger flames is less “damped”.

Absolute values of parameter \(A\) in (1) do not have a drift as function of \(V_0\), \(H\), or \(\alpha\), and values of \(|A|\) are scattered between 0.06 and 0.09. The \(\text{arg}(A)\) have a drift as function of \(V_0\) or/and \(H\), and varies from \(-40^\circ\) for the shortest flames (\(V_0\) is close to flash-back limit) to \(-110^\circ\) for the largest flames (\(V_0\) close to blow-off limit).

**Burner tube diameter influence on TF**

Figure 4 presents the gain and phase of the TF for the same \(V_0\) and \(\alpha\), but 4 different burner diameters. The main correlation found is that the phase delay curves can be scaled linearly with tube diameters and then it collapses to one line. In other words, the tube diameter influence on the phase of the TF is equivalent to a frequency axis stretching with a factor proportional to the diameter. In Figures 4c,d the frequency axis was scaled for each curve from figures 4a,d by a factor \(d/d_0\) where \(d_0\) can be any tube diameter (in Figure 4c \(d_0=1\text{cm}\) is chosen). The correspondence is nearly perfect, especially in the frequency domain, which is far from the phase delay saturation. The TF gains also can be scaled with the burner diameter (Figure 4c). The reason for the worse correspondence for high frequency for phase and gain close to the minima is, probably, connected with the nature of the mechanism which is responsible for a constant A in the TF.

**Influence of burner tube wall thickness, material and opening geometry on the flame TF**

A reduction of burner diameter leads to a relative increase of the part of the flame close to the burner neck where the heat transfer between the oscillating flame and the tube wall can play a significant role. Therefore it can be expected that a variation of burner wall thickness or tube material will lead to a change of the TF, especially for short flames (low \(V_0\) and \(H\)).

In Figure 5a the comparison of the TF gain and phase for glass and brass burner are presented. The difference is not significant (same type of curves received), but the phase difference for a given frequency can be quite large (especially in frequency ranges that correspond to the minima of the TF gain). For a smaller flame, (low gas flow rate) the burner material influence on the TF is larger than for the longer one.

The influence of the burner wall thickness on the TF is also only quantitative. The change of the tube wall thickness from 0.5mm to 1mm leads to a weak change of

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*Fig. 4 TF for flames with \(V_0=125\text{cm/s}\), \(\alpha=0.95\), and \(d\) from 0.5 to 1cm*
the TF gain and phase (Figure 5b). The modification of the TF phase can be described as a “stretch” of phase delay axis. The phase delay value for the 1mm wall thickness burner is 20-50% less than the one measured on the burner with 0.5mm wall thickness, depending on the excitation frequency and flow parameters.

The tube thickness variation leads to a change of heat exchange between flame and burner as to a change of boundary condition for the flow. To separate these factors an experiment with a different burner opening geometry was conducted. A Teflon ring of large external diameter was plugged to the burner rim. The change of the TF for the burner with such an added ring was ~10% for the phase delay of the TF. The differences for the TF gain were somewhat bigger but are not qualitative.

The burner tube material, the wall thickness and the geometry of the burner opening affect the TF stronger in the frequency ranges where the TF gain has minima. In these ranges the “constant” part of the TF dominates. Therefore, it can be surmised that the action of the mechanism, which is responsible for the constant A, is localized in the flame foot zone. To verify this hypothesis a measurement of the response of different parts of the flame cone was conducted. For this purpose, an additional lens between the flame and photomultiplier was installed. The lens forms an image of the flame on a screen with an appropriate window. Only the interesting part of flame radiation comes through the window to the light detector. In such a way the TF for the whole cone (as reference), an upper ~2/3 of the flame cone, an upper half of the cone and a bottom 1/3 of the cone (foot zone) were measured. For comparable scales of the measured TF gain the values for the flame foot zone presented in Figure 6a are in arbitrary scale. The TF for a flame without the foot zone has significantly smaller values in the high frequency limit and less pronounced minima. The TF gain and phase delay of the foot part of the flame cone are weakly frequency dependent and the value of phase delay is not far from $\pi/2$.

**Discussion**

The three possible response mechanisms (flame area and flame stretch rate oscillations, and heat transfer in the flame foot zone) and the three components of TF (time delay, relaxation time and “constant” item) are discussed.

The low-pass filtering behaviour (relaxation time) of the TF is the most well studied question and it is
associated with the kinematics of flame surface area response to flow excitation. This problem was intensively studied [9,10,11]. A good physical understanding of this phenomenon, analytic results as well as successful modelling was achieved.

Experimental investigation of the oscillating curvature contribution to the flame response requires phase-resolved flame front form capturing simultaneously with heat release rate measurement. This research is in progress and will be reported elsewhere.

The results of burner tube rim properties influence on the TF as well as the TF measured for the flame foot zone shows that processes in this region are responsible for the weak frequency dependent and small value part in the TF. A more detailed understanding of these phenomena requires a research of the burner rim with the oscillating flame interaction. This item was not reported before, probably because its detection requires an accurate measurement technique and a low level of noise-to-signal ratio.

The availability of the time delay behaviour of the flame TF was measured and results are published in [12]. In this research, an experimental approach close to the one used here was applied. The TF was fitted by functions resembling (1), which also included time delay and low-pass filter factors. Recent measurements [9] also give for the TF gain and phase delay qualitative resemblance to the ones presented here.

The known attempts to explain time delay behaviour are based on ideas of some convectively transported perturbation, which has to cover a distance from the burner rim section to the flame front. This perturbation begins to affect the flame after some travelling time, which is the origin of the delay time. Schuller et al. [9] developed a model for the flame front tracking and flame surface oscillation analysis under a flow velocity perturbation, which include a convective travelling wave item. This model was also analyzed by Pretham and Lieuwen [11]. The flow-transported perturbation induces the TF with a time delay, which is proportional to the flame height and inversely proportional to the mean flow velocity. The concept of a convectively transported perturbation allows one to explain the time delay behaviour of the flame TF but in this case, the problem is shifted towards the understanding of the mechanism of this travelling wave (convective perturbation) origin and development.

**Conclusion**

The heat release transfer function has a particular dependence on frequency. It exhibits a behaviour typical for a system with time delay and for a system with a low-pass filter. Some additional effects lead to the small but weakly frequency dependent part of the TF.

Not only the quantitative, but also qualitative behaviour of the TF gain and phase depend on the flame parameters ($\alpha$ and $V_0$).

However, the TF can be presented in a universal form with few fitting parameters.

A TF has a response “time delay” part and there is a universal relation between the time delay, the gas velocity and the flame height.

A variation of burner tube diameter leads to significant change of TF, but in many cases, the variation of the diameter results in apparent “stretch” of the frequency axis proportional to the diameter.

A variation of burner neck material, wall thickness and geometry of burner opening lead to a qualitatively small change in TF, but the quantitative change for particular frequency ranges can be significant.

The weakly frequency dependent part of the TF is mainly determined by the processes in the foot zone of flame cone. The influence of heat exchange between flame and burner rim can have a significant role for this part.

**References**


