16th Australasian Fluid Mechanics Conference
Crown Plaza, Gold Coast, Australia
2-7 December 2007

An experimental study of the transfer function of a ducted, laminar premixed flame

N. Karimi, S. H. Jin and M. J. Brear

Department of Mechanical and Manufacturing Engineering
University of Melbourne, Victoria, 3000 AUSTRALIA

Abstract

This paper presents an experimental study of the transfer function of a ducted, laminar, premixed flame. This transfer function is defined as the ratio of the fluctuations in flame heat release to the flow velocity modulations at the base of the flame. A conical, laminar, propane/air premixed flame stabilised at the rim of the burner and confined in a glass tube is considered. The flame is excited by incident acoustic waves generated by a loud speaker over a range of forcing frequencies. The fluctuations of heat release due to corrugation of the flame by the acoustic wave is measured using a photo-multiplier tube (PMT) while the flow velocity fluctuation is determined by considering the loud speaker diaphragm motion and assuming conservation of classical acoustic energy within the burner. In keeping with other studies, the results clearly show qualitatively the low-pass filter nature of the flame. The decay of the amplitude of the flame transfer function by increase of forcing frequency is further supported by images of the excited flame.

Introduction

Lean, premixed combustion is now commonly used to reduce NO_x emissions from gas turbine power plants [1]. Lean, premixed combustion features a lower flame temperature which significantly decreases the formation of NO_x [1]. However, premixed combustors are rather susceptible to a form of 'combustion instability' [2, 3] which is due to the growth of pressure waves inside the combustor, causing unsteady combustion, very intense noise, mechanical vibration and even structural damage.

The essential mechanism responsible for this instability is usually a coupling between the combustion chamber acoustics and the flame's heat release. A pressure disturbance perturbs the flame heat release which then generates further pressure disturbance at a later time; constructive phasing between the two can then cause instability.

For more than half a century tremendous effort has been spent on understanding, predicting and suppressing combustion instabilities. Despite this the physics of the problem are not entirely understood and therefore modelling of combustion instability has not been completely successful [2, 3]. The problem at the very least requires a proper understanding of three elements; the nature of the propagating waves, the effect of boundaries and the flame response to the incident waves. While it is now commonly accepted that linear acoustics gives a reasonable representation of the wave propagation, the effect of combustor boundaries and flame dynamics are still being researched [2, 4]. Flame dynamics in particular continues to be challenging. This is mainly due to complex, non-linear dynamics of flames in practical situations. However, appropriate knowledge of the linear dynamics of flames is of primary interest in the modelling of linear instability of combustors [3].

The complexity of turbulent flames, found in most practical combustors, substantially increases the difficulty of a systematic study of interactions between flames and duct acoustics. Therefore, laminar flames are often examined since many consider that the essential mechanisms are the same. Such an analysis is typically performed by exciting a premixed laminar flame by acoustic waves generated by loud speakers. The response of the flame is characterised by the velocity modulations just upstream of the flame and the perturbation in the instantaneous flame heat release. In the linear limit, a transfer function is then defined as the ratio of the disturbances in heat release and upstream mixture velocity respectively normalised by the mean heat release and mixture velocity. Such a transfer function serves as the dynamic model of the flame in combustor models.

Several attempts for both directly measuring the flame transfer function and theoretically calculating it in different configurations have been reported in the literature. Open conical flames have been investigated experimentally in [4, 5], with the amplitude flame transfer function measured in these studies show a low pass filter behaviour. Karimi et al [6] showed similar qualitative behaviour in a theoretical analysis of a laminar flame stabilised by a bluff body in a duct, based on the earlier work of Dowling [7]. The phase of the transfer function was shown to represent a constant time lag between the forcing velocity and flame heat release. In the present study the dynamics of a conical, laminar premixed ducted flame is investigated experimentally. The flame is excited acoustically from upstream over a range of frequencies and the flame transfer function is measured revealing the low pass filter amplitude characteristic and time lag nature of the phase. The former is further confirmed by the series of photographs of the flame excited at different frequencies.

Experimental setup

Fig. 1a shows a schematic view of the experimental setup. Two streams of compressed air and gaseous fuel (vaporised propane) are controlled by means of MKS mass flow controllers. The capacity of air and fuel mass flow controllers are respectively 100 and 4 standard litres per minute with accuracy of 1% full scale. The measured streams are then mixed together, with care taken to provide a number of bends and junctions as well as a manifold to ensure the complete mixing of air and fuel. The mixture then enters the rig through 3 equally spaced injection ports. The rig consists of a plenum, a contraction and a flame holder which allows different flame configurations. There are several layers of honeycomb and mesh inside the plenum which provide a laminar flow.

A rim stabilised flame holder was used having 25 mm rim diameter, Fig. 1b. This flame holder produces a conical laminar flame (e.g. Fig. 4). The flame is in a quartz tube which allows optical access to the flame and which also makes the flame confined. The total length of the rig was intentionally chosen to be short enough such that the duct acoustics are of a much higher frequency than the expected response of the flame. A similar

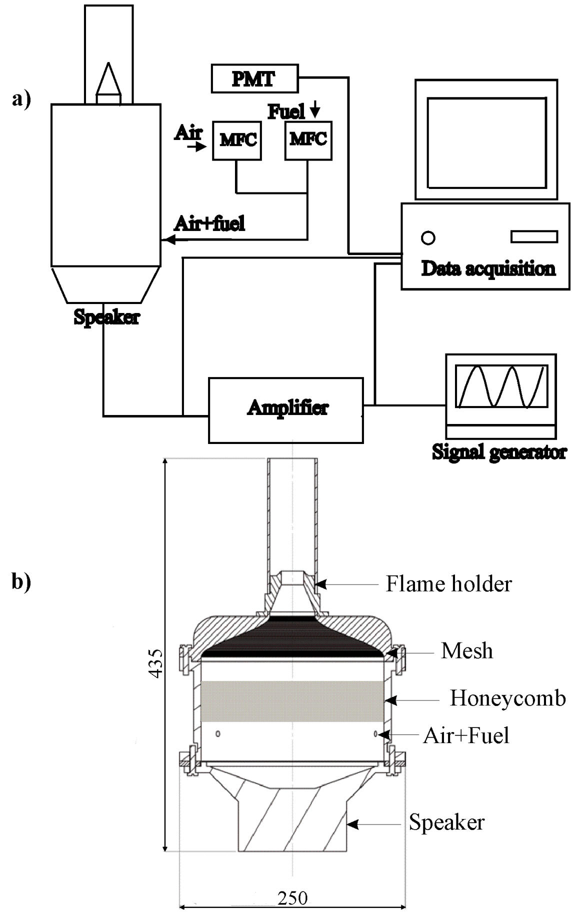

Figure 1: Experimental rig a) schematic of the setup b) cross sectional view of the rig.

approach has been taken in the work by [8] for the study of the forced response of a turbulent flame.

Underneath the burner a 'woofer' loud speaker, RCF model L8S800, with sensitivity of 93 dB/W has been installed. This speaker is driven at fixed voltage of 0.2 V with a sine wave voltage signal generated by a signal generator and amplified by an amplifier (Fig. 1a). The frequency of the driving signal was varied from 20 Hz up to 250 Hz in increments of 10 Hz for the measurement of the flame transfer function.

The instantaneous heat release of the flame was inferred by a photomultiplier tube (PMT) installed 50 cm away from the flame in the darkened test cell. This distance was enough to capture the light emitted by the total flame. A CH^* filter with FWHM of 10 nm was put in front of the PMT to establish the correlation between the flame heat release and PMT generated voltage [5]. It is commonly accepted that for laminar flames the chemiluminescence is proportional to the heat release of the flame, i.e. $V'_{PMT}/\bar{V}_{PMT} = q'/\bar{q}$. In this relation V_{PMT} is the PMT generated voltage and q is the flame heat release while the dash and bar refer to perturbation and time averaged quantities.

The voltages generated by the PMT, signal generator and the amplifier were acquired simultaneously at the sampling rate of 40 kHz by using a data acquisition card, NI-PCI-6040E, with a resolution of 12 bits and maximum sampling rate of 500 kHz. Labview software, version 8.1, was used for the measurements. Also the excited flame was filmed using a simple digital camera, SONY IXUS60, with frame rate of 30 per second. Equally

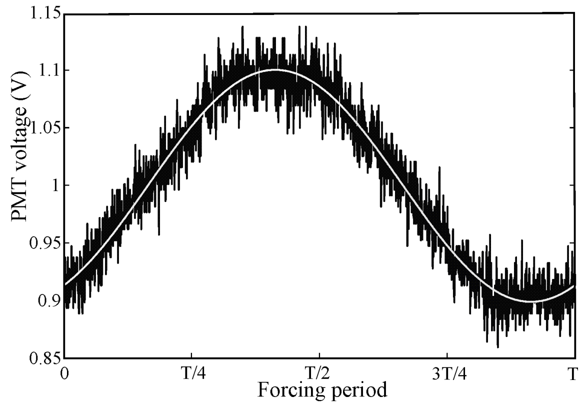

Figure 2: The raw signal generated by PMT and the fundamental component (white) during one forcing period

spaced snapshots were then chosen during one forcing period.

Post-processing

Raw experimental data saved as text files were post-processed using a MATLAB script. This script establishes a transfer function between any of the two measured or calculated signals. This is done by selecting a number of excitation periods on a given signal and Fourier transforming it. A new signal is constructed which has the amplitude and phase of the fundamental component of the Fourier series of the original signal. The amplitude of the desired transfer function between any chosen two original signals is the ratio of the amplitudes of the fundamental signals and the phase is simply the difference between the phases of the fundamentals. Fig. 2 shows the raw and fundamental signals of the PMT generated voltage signal.

By applying the above method, two transfer functions are calculated as will be explained further in detail. As defined earlier, the flame transfer function is the ratio of the normalised heat release to the velocity modulations at the tip of the flame holder (just upstream of the flame), i.e. $(q'/\bar{q})/(u'/\bar{u})$. Typically, fluctuations in the these quantities are measured simultaneously and the transfer function is then a directly measured one. However, in the present work, while the heat release fluctuations are measured the velocity disturbances will be determined in a way described later. This method requires calculation of two transfer functions, defined as the ratio of the PMT voltage signal and speaker input voltage (V'_{PMT}/V'_{spk}) and also the ratio of the velocity fluctuations at the flame base and the speaker input voltage (u'/V'_{spk}). The first of these transfer functions is directly measured by employing the procedure explained in the last paragraph. The second one, however, is approximated as the exact value of u' is unknown. The flame transfer function is then readily derived by multiplying the first transfer function with the inverse of the second one.

Approximation of u' is performed based on the following energy arguments. The sensitivity of the speaker is the sound pressure level (SPL) produced by the speaker 1 m away from it at 1 W of input power, and is available by the speaker manufacturer for a wide range of driving frequencies. We use this frequency response to establish a relation between the speaker input voltage and the velocity modulations at the tip of the flame holder. Toward this aim a number of assumptions are made:

- the speaker acoustic energy efficiency, defined as the ratio of the acoustic energy produced to the electrical energy consumed by the speaker, is fixed for all frequencies,

- the dissipation of acoustic energy within the rig is negligible,
- sound generation and reflection by the flame is negligible.

By knowing the sensitivity, the acoustic energy intensity (W/m^2), defined as the product of acoustic pressure and velocity perturbations and the total acoustic energy radiation (W), can be easily calculated. According to our first assumption, this energy is proportional to the speaker electrical power, which is itself a function of speaker voltage. This results in the following relation for the acoustic intensity AI at any position along the rig

$$AI\left(V_{spk,\omega}\right) = 8\pi\sqrt{\frac{3}{2}\frac{|V_{spk}|^2}{R.\rho.c.A}}10^{(SPL(\omega)/10-10)}, \qquad (1)$$

where R is the speaker electrical impedance (Ω), and A, ρ, c and ω are respectively the rig cross sectional area, the fluid density, the sound speed at the position where A is measured and the speaker radial frequency. Consider now two upstream and downstream travelling characteristics at the flame holder and also include the effect of the reflection of the acoustic wave from the open end of the glass tube. The velocity modulation at the flame holder, in the absence of the flame, can be expressed as

$$u'\left(V_{spk,\omega}\right) = \frac{1}{\rho c}\sqrt{\frac{1+\exp\left(2i\omega l/c\right)}{1-\exp\left(2i\omega l/c\right)}AI\left(V_{spk,\omega}\right)}. \qquad (2)$$

Here l is the distance between the tip of the flame holder and the open end of the glass tube.

Non-linearity measurement

As mentioned before, interactions between the flame and acoustics can be complex and non-linear. The linear limit in the response of the flame to acoustic perturbations is not generally known. Thus, a measure of non-linearity is required. Following Moase et al [9], we assume the time series g denotes the flame response over the full forcing period. The discrete Fourier transform and the inverse discrete Fourier transform can then be used to isolate g_ω, defined as the component of g occurring at the excitation frequency ω. We define the measure of non-linearity for g as

$$\kappa = \frac{|g - g_\omega|}{|g|}. \qquad (3)$$

By this definition a signal containing no spectral component other than at the forcing frequency will have a $\kappa = 0$, whereas a signal with no component at the forcing frequency will result in $\kappa = 1$.

Results and discussion

Fig. 3 shows the flame transfer function calculated by the procedure explained in the previous sections. The measure of non-linearity for the presented results (Fig. 3c) always remains less than 2% indicating that the system under investigation can be considered linear. A reduced frequency is defined as fa/S_l where f is the excitation frequency while a is the rim radius and S_l is the laminar flame speed. The qualitative 'low pass filter' behaviour of the flame is clearly represented in the gain

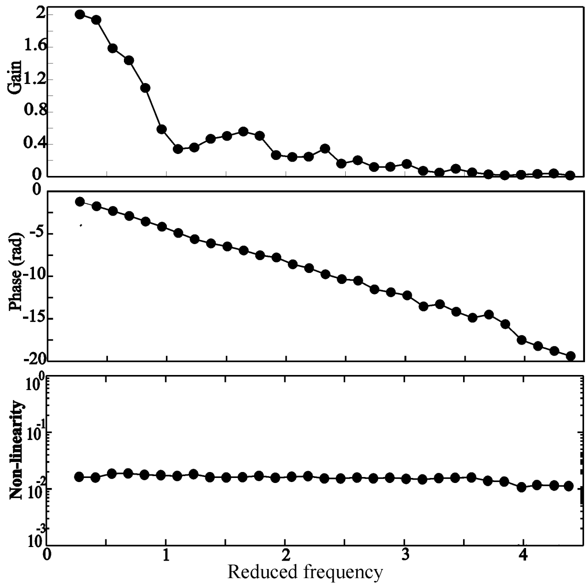

Figure 3: Flame transfer function: gain, phase and non-linearity (κ). $\bar{u}_g = 1.83m/s$ and $\phi = 0.98$.

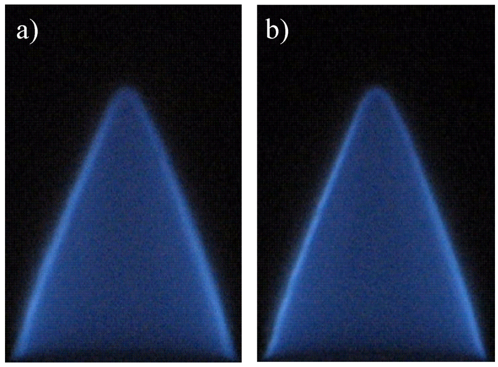

Figure 4: View of the flame a) excitation frequency of 100 Hz b) no excitation

of this transfer function. Low frequencies of excitation result in significant amplitude response. However, this ratio quickly decays with the increase in the excitation frequency such that beyond a certain frequency the flame becomes essentially insensitive to the acoustic forcing. This behaviour of the gain of the flame transfer function is in agreement with several other theoretical and experimental flame transfer function measurements and calculations [7, 5]. Fig. 3b shows a transport lag nature of the phase which indicates there is a constant time delay between the speaker voltage change and response of the flame. The total time delay in this case is approximately 0.02 s. Such behaviour is also consistent with other published studies [7, 5]. A simple calculation shows that this time is mainly due to the convection of the velocity disturbance along the flame. It is therefore inferred that this convection is the main parameter characterising the phase of the flame transfer function.

The qualitative trend in Fig. 3 can be also observed in the series of photographs taken from the excited flame. Fig. 4 shows the unexcited flame and the flame under 100 Hz excitation (a reduced frequency of roughly 2.8). Clearly the difference between the two images is very small, which is not surprising since Fig. 3 suggests negligible response at these frequencies.

Fig. 5 presents a series of flame pictures during one forcing period at different frequencies. Very pronounced flame response to low frequency excitation is associated with significant flame distortion and elongation (Fig. 5a). At higher frequencies the corrugation of the flame can be seen as a convective wave forming at the flame base and propagating toward the flame tip (Fig. 5b). The amplitude of such a wave diminishes as the excitation frequency increases (Fig. 5c) and eventually approaches zero at high enough frequencies (Fig. 4).

Conclusion

The transfer function of a ducted, laminar premixed flame was calculated using experimentally measured heat release modulations and determined values of the velocity perturbations at the tip of the flame holder. The results clearly indicated the low pass filter nature of the amplitude of the flame transfer function as well as the transport lag character of the phase. The former was further supported by the photographs taken from the excited flame under different forcing frequencies. Such behaviour was found to be consistent with several other reported studies. Further, a measure of non-linearity was introduced and used to confirm that the observed response was strongly linear. Such an approach does not appear to have been reported elsewhere.

References

[1] H. C. Mongia, T. J. Held, GC Hsiao, and R. P. Pandalai. Challenges and progress in controlling dynamics in gas turbine combustors. *Journal of Propulsion and Power*, 19(5):822–829, 2003.

[2] S. Candel. Combustion dynamics and control: Progress and challenges. *Proceedings of the combustion institute*, 29:1–28, 2002.

[3] T. Lieuwen. Modeling premixed combustion-acoustic wave interaction: a review. *Journal of Propulsion and Power*, 19:765–781, 2003.

[4] S. Ducruix, T. Schuller, D. Durox, and S. Candel. Combustion dynamics and instabilities- Elementary coupling and driving mechanisms. *Journal of Propulsion and Power*, 19(5):722–734, 2003.

[5] T. Schuller, D. Durox, and S. Candel. Self-induced combustion oscillations of laminar premixed flames stabilized on annular burners. *Combustion and Flame*, 135(4):525–537, 2003.

[6] N. Karimi, M. J. Brear, and S. H. Jin. Nonlinear dynamics of thermoacoustic insability using a kinematic, premixed flame model. In *proceeding of the 15th Australasian Fluid Mechanics Conference, The university of Sydney, Sydney, Australia*, 2004.

[7] A. P. Dowling. A kinematic model of a ducted flame. *Journal of Fluid Mechanics*, 394:51–72, 1999.

[8] R. Balachandran, BO Ayoola, CF Kaminski, AP Dowling, and E. Mastorakos. Experimental Investigation of the Nonlinear Response of Turbulent Premixed Flames to Imposed Inlet Velocity Oscillations. *Comb. and Flame*, 143:1–2, 2005.

[9] W. H. Moase, M. J. Brear, and C. Manzie. The forced response of chocked nozzles and supersonic diffusers. *J. Fluid Mech.*, 585:281–304, 2007.

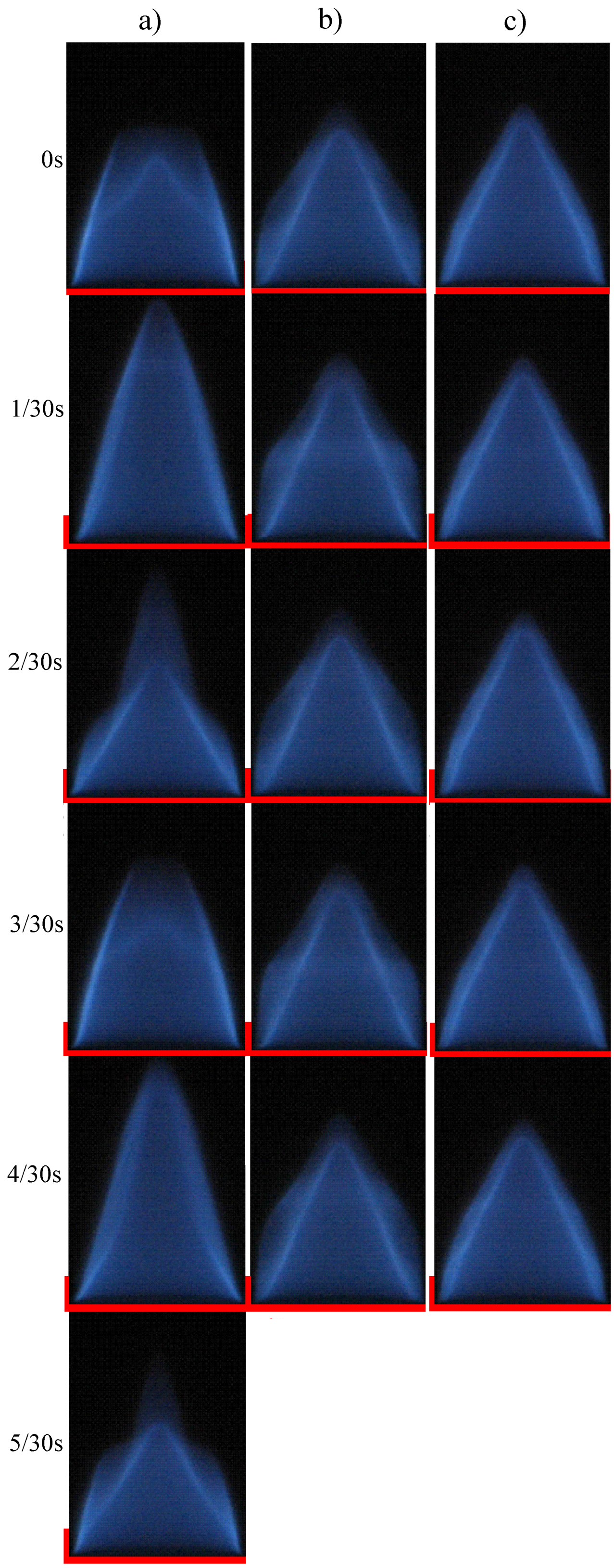

Figure 5: Series of flame pictures during one excitation period a) 10 Hz b) 40Hz and c) 70Hz.