Acoustic response of multiple flame perforated burners

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ACOUSTIC RESPONSE OF MULTIPLE FLAME PERFORATED BURNERS

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The acoustic response of multiple conical-type flames is experimentally studied. The flames are stabilized on uniformly perforated burner decks. The flame transfer function (TF) method is used to characterize the acoustic response. The change in the TF with changing the burner perforation (hole diameter $d$ and pitch $l$) and flame (bulk flow velocity $\bar{u}$ and equivalence ratio $\Phi$) parameters is investigated and presented. The key characteristics of the measured TF such as maximum value of gain, the corresponding frequency at which it occurs and time delay of the TF phase are extracted. The correlations of the TF characteristics with variations in mixture/perforation parameters are presented and discussed.

1. Introduction

The development of condensing boilers encounter the problem of combustion instabilities. These instabilities may result in loud tonal noises (such as humming, buzzing or screech) or for large oscillation amplitudes it may result in flame extinction. It is possible to predict and to suppress/avoid these instabilities a-priori in a combustion system using different available thermo-acoustic evaluation methods/tools (see references [1]). However, this requires the knowledge of the flame response to the acoustic fluctuations. The flame response (heat release rate) to the acoustics fluctuations (upstream velocity fluctuations) can be characterized by frequency dependent Flame Transfer Function (TF). The TF is defined as: $TF(f) = \frac{q'(f)/\bar{q}}{u'(f)/\bar{u}}$, where $u'$ and $q'$ are the oscillating and $\bar{u}$ and $\bar{q}$ are the mean component of the velocity and the heat release rate respectively.

The phenomenon of flame interaction with acoustics is known for more then two-centuries [2]. This interaction between flame and acoustics depends upon the energy feedback mechanisms which may differ for different types of flames and combustion systems. An overview of the progress and understanding of the thermo-acoustics interaction phenomenon for different types of flames is highlighted by Candel [3], Lieuwen [4] and De Goey et. al. [5]. From the studies of the thermo-acoustic behaviour of single Bunsen type flames (see references in [6, 7]) it may be deduced that:

- These flames have a typical time delay ($\tau_0$) behaviour i.e. the flames respond to the acoustic fluctuations some time $\tau_0$ after they have been applied at the flame base.

- These types of flames show a global low-pass filter behaviour to the incident acoustic fluctuations.

- The gain of the TF decreases non-monotonically from the quasi stationary condition ($|TF| = 1$ at $f = 0$) having several recognizable local maxima and minima as function of frequency.

- For higher frequencies the TF saturates to a small offset value for the TF gain.
Household boilers consists of perforated burner decks where the stabilized flame is of multiple conical type. The knowledge of the thermo-acoustic response of a single Bunsen type flame is typically used for combustion stability analysis of such devices with multiple conical type flames. However, recent studies [8–12] show that the TF of burner deck stabilized multiple conical type flames differs from that of the constituent single flames. It was anticipated that the difference in the TF occurs due to the mutual interaction between the adjacent flames. This interaction will be stronger if the flames are closer. Recent numerical investigations [10, 11] report that the resonance behavior (i.e. overshoot of gain above unity) of the TF could be due to the heat exchange between the flame foot and the burner deck. It is also possible that the inter-flame spacing restricts the flame foot motion due to the fact that gases have less space to expand. As a result, a modification of the flame foot as well as flame height compared to single flames is expected. This modification of flame geometry has an influence on the phase of the TF [6]. In a study of laminar multiple tent type flames [10], the effect of changing slit width and distance between two slits (pitch) on the TF was characterized. It was shown that due to the change in pitch of the multi-slit burner, the flame height $H$ and standoff distance $\delta$ increases which leads to changes in the TF phase. Such a systematic study of the acoustic response of multiple conical flames stabilized on a perforated plate with varying flame/burner parameters, to the best of our knowledge, was never reported.

In this paper, a systematic study of the acoustic response of multiple conical flames stabilized on perforated plates having uni-size holes in hexagonal perforation pattern is performed. The effect of varying perforation (pitch and hole diameter) and mixture (velocity and equivalence ratio) parameters on the measured TF is studied. The key characteristics of the TF such as linear time delay, low frequency gain peak and the frequency corresponding to the gain peak are extracted. The variations of the TF key parameters with perforation and mixture parameters are obtained and will be discussed. This work may therefore lead to a more accurate prediction of the TF due to changes in burner perforation patterns.

2. Experimental setup and measurement techniques

To quantify the flame transfer function it was necessary, firstly, to build an experimental setup where multiple conical flames can be organized, then it is needed to measure the velocity fluctuations $(u')$ and the heat release rate $(q')$ response to the forced velocity fluctuations. Finally, we need to post-process the acquired data to obtain the TF.

The experimental setup used is illustrated in Figure 1a. The burner decks (Figure 1b) are made from a 65mm diameter and 0.5mm thick brass disc having a hexagonal pattern of holes in the central 50mm diameter portion. The experimental setup consists of a plenum tube of 50mm uniform internal diameter having 10mm thick PVC plastic walls. At one end of the plenum the burner deck is mounted with a water cooled head whereas the other end is connected to the loudspeaker housing. The flow enters the setup through a dump chamber which is connected to the loudspeaker housing. To measure the velocity fluctuation, a velocity probe (CTA) is mounted at a distance of 25mm upstream from the burner deck.

The bulk velocity $\bar{u}$ and the equivalence ratio $\Phi$ of the methane-air mixture was controlled with Bronkhorst mass flow controllers (MFC). The flame transfer function is measured at discreet frequencies keeping the flow oscillations amplitude in the linear regime $(u'/{\bar{u}}) \sim (10 \pm 2\%)$ for the complete measured frequency range [6, 9]. The OH* chemiluminescence emitted by the whole flame was used as instant heat release rate indicator [13] and is detected with a photo-multiplier tube (PMT) equipped with a 309nm narrow band optical filter. A LabView programme with national instrument NI-6225 card was used to generate and control the input voltage to the loudspeaker and to acquire the signals. The data file contains time series of velocity $(\bar{u} + u')$ and heat release rate $(\bar{q} + q')$ recorded at 25kHz sampling rate for 0.6 seconds. For smaller frequencies $< 170$Hz a total 100 of waveforms was recorded. The fast Fourier transformation (FFT) gives the respective amplitude of oscillation $(u', q')$
Figure 1: a) Experimental setup to measure the TF, b) sample burner deck made from machined holes in hexagonal pattern

at the forcing frequencies. The phase of the TF is obtained by cross correlating the velocity and heat release rate signals. To avoid calibration of PMT and CTA, the virtue of quasi-static condition \((|TF| = 1 \text{ at } f = 0 Hz)\) was used. Using this, the gain of the TF is smoothly extrapolated to zero frequency which is used as scaling factor for the gain [6, 7].

3. Discussion of results

For the parameterization of multiple conical type flames, in total 10 perforated plates were produced by varying the perforation hole diameter and the pitch (See Table 1). The study was performed by varying one flame/burner parameter \((\bar{u}, \Phi, d, l)\) at a time while keeping the other parameters constant.

Table 1: Burner deck perforation details

<table>
<thead>
<tr>
<th>(d [\text{mm}])</th>
<th>2</th>
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<tbody>
<tr>
<td>(l [\text{mm}])</td>
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<td>4</td>
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<td>5</td>
<td>5.5</td>
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<tr>
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<td>1.33</td>
<td>1.5</td>
<td>1.67</td>
<td>1.83</td>
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3.1 Effect of mixture parameters \((\bar{u}, \Phi)\)

To investigate the effect of the mixture parameters on the multiple flame TF, a burner deck with perforation \(d = 3 \text{mm}, l = 4.5 \text{mm}\) is used. The TF was measured for different mean flow velocities \(\bar{u}\) keeping \(\Phi (=0.85)\) constant and for different equivalence ratios \(\Phi\) keeping the \(\bar{u} = 125 \text{ cm/s}\) constant (see Figure 2). It is observed that for multiple flames the gain of the transfer function first increases to a value higher than the quasi stationary value \((|TF| = 1 \text{ at } f = 0)\) before it non-monotonically decreases for higher frequencies of acoustic excitation. An increase in \(\bar{u}\) or a decrease in flame burning speed \(S_L\) (decreasing \(\Phi\)) results in an increased value of the maximum of the TF gain \((G_{max})\). The TF gain attains its highest value for the largest measured \(\bar{u}/S_L\) indicating a reduction in the damping of the acoustic fluctuations for longer flames. The TF phase for different \(\bar{u}\) coincides mostly with a single curve indicating a constant time delay \(\tau_o\) (see Figure 2a). With increasing \(\Phi\) the TF phase decreases which changes \(\tau_o\) (see Figure 2b). For stability calculation an increased gain of TF at higher flow
rates might lead to wider unstable frequency ranges whereas a \( \sim \pi \) phase shift (between \( \Phi = 0.75 \) and 0.95 at 300Hz) can switch the system stability.

![TF measured for different, a) mean flow velocities \( \bar{u} \) through perforation holes for \( \Phi = 0.85 \), b) equivalence ratio \( \Phi \) for \( \bar{u} = 125cm/s \), with respect to the excitation frequency, for burner perforation parameters \( d = 3mm, l = 4.5mm \).](image)

### 3.2 Effect of burner perforation parameter \((d, l)\)

The effect of changing the perforation pattern on TF is characterized by changing perforation hole diameter \( d = 2, 3 \) and 4mm keeping pitch to diameter ratio \( l/d = 1.5 \) constant (Figure 3a) and changing perforation pitch \( l = 4, 5, 6 \) and 8mm keeping \( d = 3mm \) (Figure 3b). The mixture parameters were kept constant (\( \bar{u} = 125cm/s \) and \( \Phi = 0.85 \)). The TF gain attenuation rate as well as the time delay \( \tau_o \) increases with increasing the perforation parameters \((d \text{ or } l)\). In addition the \( G_{\text{max}} \) value decreases with increasing \( d \) whereas it increases with increasing \( l \). However, the frequency \( f_{\text{max}} \) corresponding to the \( G_{\text{max}} \) decreases with an increase in any of the perforation parameter \((d, l)\).

From the above analysis it can be summarized that the effect of the mixture parameters \((\bar{u}, \Phi)\)

![TF measured for different, a) perforation hole diameters \( d \) for \( l/d = 1.5 \), b) perforation pitch to diameter ratios \( l/d \) for \( d = 3mm \), with respect to the excitation frequency. The flow parameters are \( \bar{u} = 125cm/s, \Phi = 0.85 \).](image)
on the TF is similar to that of single Bunsen type flames [6], except for the “resonance” behavior or the overshooting of the TF gain above unity. The dependence on the perforation hole diameter \(d\) in case of multiple flames is qualitatively similar to that of a single Bunsen type flame with some quantitative differences. The differences are, probably, due to the interaction between adjacent flames. This interaction will depend on the perforation pitch \(l\) which eventually determines the flame height, stand-off distance, flame width, etc. These flame geometrical parameters have effect on the acoustic response of the flame. Therefore, the pitch of the perforation pattern becomes an important parameter in order to understand the resonance behavior of the TF.

The modification of the TF of the multiple Bunsen type flames due to a change in perforation/mixture parameters is clearly visible. In order to quantify this, it is worth to analyze the typical characteristics of the TF (e.g. the linear time delay \(\tau_o\) of the TF phase, the maximum of the gain \(G_{max}\), the frequency at which it occurs \(f_{max}\), etc.).

### 3.3 Linear time lag (\(\tau_o\))

The dependence of the mean system time lag \(\tau_o\) on different perforation/mixture parameters is shown in Figure 4. It is known that for single laminar flames the \(\tau_o\) is proportional to the convective time of flame \((H/\bar{u})\) [6, 9, 14]. If we assume that such a proportionality between \(\tau_o\) and convective time exists for multiple flames as well, then the effect of mixture/perforation parameters on \(\tau_o\) can be analyzed on the basis of the convective time.

Figure 4a shows that \(\tau_o\) decreases with increasing \(\Phi\). This observation is inline with single Bunsen type flames as the flame height is inversaly proportional to the burning speed \(S_L\). However, for multiple flames, the \(\tau_o\) decreases with increasing \(\bar{u}\) (Figure 4b). Two possible reasons for this

![Figure 4](image-url)

**Figure 4:** The linear acoustic time delay \((\tau_o)\) dependence on, a) mixture equivalence ratio \(\Phi\) \((l/d = 1.5)\), b) mean flow velocity \(\bar{u}\) through perforation holes \((l/d = 1.5)\), c) perforation hole diameter \(d\) \((l/d = 1.5)\) and, d) perforation pitch \(l\) \((d = 3mm)\)
behavior can be given: 1) the flame height for multiple flames is not proportional to $\bar{u}$ due to the influence of the surrounding flames which results in a reduced flame height, 2) the flame stand-off distance adds a relatively large part to the convective time for smaller $\bar{u}$ which decreases as $\bar{u}$ increases. The latter argument supports the saturation of $\tau_o$ with increasing $\bar{u}$.

An increase in perforation diameter $d$ will increase the flame height for same $\bar{u}$ and $\Phi$. Therefore, an increase in $d$ will result in an increased time delay $\tau_o$ (see figure 4c). An increase in the perforation pitch has no direct effect on the flame height, still the time delay $\tau_o$ increases significantly. One of the possible mechanisms can be the change in heat transfer from the flame to the burner deck. An increase in $l/d$ will reduce the energy gained by the burner deck and as a result the flame stand-off distance increases. An increased flame stand-off distance $\delta$ will increase the flame height therefore an increase in $\tau_o$ (see Figure 4d).

3.4 The maximum value of TF gain ($G_{max}$)

Figure 5 shows the variation of $G_{max}$ with flame ($\Phi, \bar{u}$) and perforation ($d, l$) parameters. It is observed that the value of $G_{max}$ decreases with increasing $\Phi$ while it increases if the $\bar{u}$ is increased as shown in Figure 5a and 5b, respectively. At $\Phi = 0.95$ the TF maximum value $G_{max} = 1$ at $f = 0$. Therefore, these points are not present in the plot. Increasing the perforation diameter $d$ also results in a decreased $G_{max}$ (Figure 5c) which is similar to the effect of increasing $\Phi$. Due to an increase in the perforation pitch $l/d$, the value of $G_{max}$ first increases and attains its highest value at $l/d = 1.8$ and then decreases marginally with further increase of $l/d$ (see Figure 5d).

3.5 The resonance frequency ($f_{max}$)

Figure 6 shows the variation of frequency ($f_{max}$) corresponding to resonance peak ($G_{max}$) with flame ($\Phi, \bar{u}$) and perforation ($d, l$) parameters. It can be observed that $f_{max}$ increases with an increase in $\Phi$ and $\bar{u}$ as well as $d$ and $l$, respectively.
in the mixture parameters ($\Phi, \bar{u}$) whereas it decreases if the burner perforation dimensions ($d, l$) are increased. For some cases when the TF gain does not overshoot the quasi stationary condition i.e. $G_{max} \approx 1$, then the lowest measured frequency is obtained as $f_{max}$ (Figure 6a). For higher velocities or perforation pitch, the value of $f_{max}$ tends to saturate.

The maximum value in the TF gain could be due to “resonance” of the flames similar to that of flat flames where the TF gain peak is due to the heat transfer between the flame and the burner deck [15]. The resonance frequency depends on the stand-off distance of the flame so that $f_{max} \sim \bar{u}/\delta$. For multiple flames, the flame foot behaves as a flat flame which would produce the overshooting of the TF [11]. Therefore, the above results of $f_{max}$ can be discussed on the basis of the flame stand-off distances. For example, an increase in equivalence ratio will result in an increase in the flame temperature, i.e. an increase in the heat transfer to the burner deck. As a result, the flame foot will be closer or the stand-off distance $\delta$ will decrease i.e. an increase in the resonance frequency $f_{max}$.

Figure 6: The frequency corresponding to the $G_{max}$ ($f_{max}$) dependence on, a) mixture equivalence ratio $\Phi$ ($l/d = 1.5$), b) mean flow velocity $\bar{u}$ through perforation holes ($l/d = 1.5$), c) perforation hole diameter $d$ ($l/d = 1.5$) and, d) perforation pitch $l$ ($d = 3mm$)

4. Conclusions

This paper investigates the effect of the variations in the mixture/perforation parameters on the acoustic behavior of multiple conical flames. The effect of variations in equivalence ratio, mean flow velocity through perforation holes, perforation hole diameter and perforation pitch on the TF of laminar premixed methane-air flames is analyzed. The variations in the TF typical characteristics such as the linear time delay $\tau_o$, the maximum in the gain $G_{max}$ and the frequency at which it occurs $f_{max}$ are discussed. The differences between the acoustic response of multiple conical flame and the single Bunsen type flames are:

- The gain of the TF for multiple conical flames obtains a value higher than the quasi stationary response whereas in the case of a single Bunsen type flame it remains below unity.
The time delay $\tau_0$ and the TF gain for multiple conical type flames changes with a change in $\bar{u}$ whereas for single Bunsen type flames it remains unchanged.

Increasing the perforation diameter $d$ increases the damping of the TF similar to a single Bunsen type flames. However, the increase in damping is larger for multiple flames.

The effect of changing the perforation pitch $l$ is significant on the TF of multiple conical type flames.

On the basis of above effects it can be concluded that the transfer function of multiple flames differs from that of constituting elementary single Bunsen type flames [6]. Therefore, for the stability analysis of system with perforation burner decks, acoustic response of multiple conical flame should be used.

REFERENCES


