Penerbit Akademia Baru

Journal of Advanced Research in Fluid Mechanics and Thermal Sciences

Journal homepage: www.akademiabaru.com/arfmts.html
ISSN: 2289-7879

A Brief Review of Acoustic Excitation Toward Jet Flame Characteristics

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ARTICLE INFO

Article history:
Received 16 March 2020
Received in revised form 2 June 2020
Accepted 5 June 2020
Available online 15 August 2020

ABSTRACT

Acoustic interaction toward jet flame in a combustion system is essential to understand the characteristic of combustion instability. Combustion device such as turbine, ramjets, industrial processor, jet rocket and other mostly occurrence for self-excited due to mechanical part and coupling. The combustion driven oscillation can affect the combustion system life and performance. This paper is mainly focused on the characteristic of the flame, which having interacted with the acoustic excitation. This paper is organized into three parts. First part is the introduction, follows by the literature review, which mainly focused on the physical characteristic of the flame, the structure, the length, the shape, and the color of the flame. Then the last part consists of the subject goes toward the application of acoustic perturbation – utilizing acoustic excitation toward good intention, the formation of soot and nitride oxide reduction.

Keywords:
Acoustic excitation; Diffusion flame; Jet flame; Combustion instability; Lift-off; Jet branching; Flame structure; Flame behavior; Flame length; Flame shape; NOx reduction; Soot formation

1. Introduction

There are a lot of problems arise in a combustion system that affect the combustion process, mainly known as the combustion instability. Study on combustion instability are important due to under certain circumstances, it can become extremely detrimental that will eventually affect the combustion system process [1–5]. It exists in a wide range of applications such as the rocket propulsion engines, industrial burner, industrial processing, ramjets, afterburners and gas turbine [6–10].

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https://doi.org/10.37934/arfmts.74.1.151164

Advances combustion system have a low emission characteristic without undermined it operational advantages [11–15]. There are many sources and conditions that affect the stability of a combustion system [16–18]. Moreover, there are some researchers that focus on controlling the blending of fuel ratio to influence the effect of instability in a combustion system [19-24]. This paper reviews focus on to the primary interaction of acoustic perturbation that affect the stability of a combustion system.

For an acoustic perturbation that interact with a premixed combustion, the issues related are the interaction between acoustic and flames. Those two interactions have an important role in influencing the behavior of combustion systems stated earlier. Interaction between both arise instabilities, for an instance. The unsteady heat release that produced due to the disturbances add energy to the acoustic field when both fields are in phase. It will lead to enhance of vibration thus affecting the whole combustion process.

Not all interaction between acoustic and flame is bad for the combustion process. It is noted that, by utilizing these effects, there are possibilities to improve combustion control of such phenomena as high-load combustion [25–28], soot suppression, NOx reduction [29–34] and noise control [35-36].

The objective of this paper is mainly focused on reviewing the behavior of a premix flame subjected to an acoustic propagation; effect of the behavior on the characteristic and behavior, then the discussion describes the destruction and importance on understanding the relationship between acoustic and flame.

2. Effect of Acoustic Excitation on Flame Characteristics

Interaction between acoustic and flame in a combustion system can be classified into two categories, called as direct interaction and indirect interaction. Both categories are differentiated by the position or the direction of the wave contact [37].

For direct interaction, it occurs in the flame zone where the incident scatters the flame zone and amplifies it due to the steep gradients in a gas property at the flame front. Further information about the effect of this direct interaction has been discussed for both premixed and diffusion flames [38–40]. The indirect interaction, on the other hand, is occurred in the flow field, regardless of the flame characteristics. It has been discovered that the acoustic forcing on a non-reacting jet or flow induces velocity fluctuations [41–43], sinuous oscillations [44–49], or steady streaming [50–52] has major effect on the change of behavior of jet flames under acoustic perturbation. Further discussion onto the effect of acoustic perturbation whether direct or indirect interaction toward the jet flame behavior are discuss in this paper.

2.1 Flame Structure

Figure 1 shows the interaction between acoustic responses and flame [53]. This interaction provides linear change with the increasing of number of frequency (f) detest to the flame. When no acoustic perturbation f = 0 Hz, the flame has a single-layer structure for all values of volume concentration, ΩE.

Double layer of flame structure can be observed when the frequencies start to be increased. The change of the structure concerning the outer flame part can been seen by the increase of brightness and the size become wider than the burner exit. However, the change difference concerning the inner flame core where the color become luminous and the size is much smaller than the burner exit.

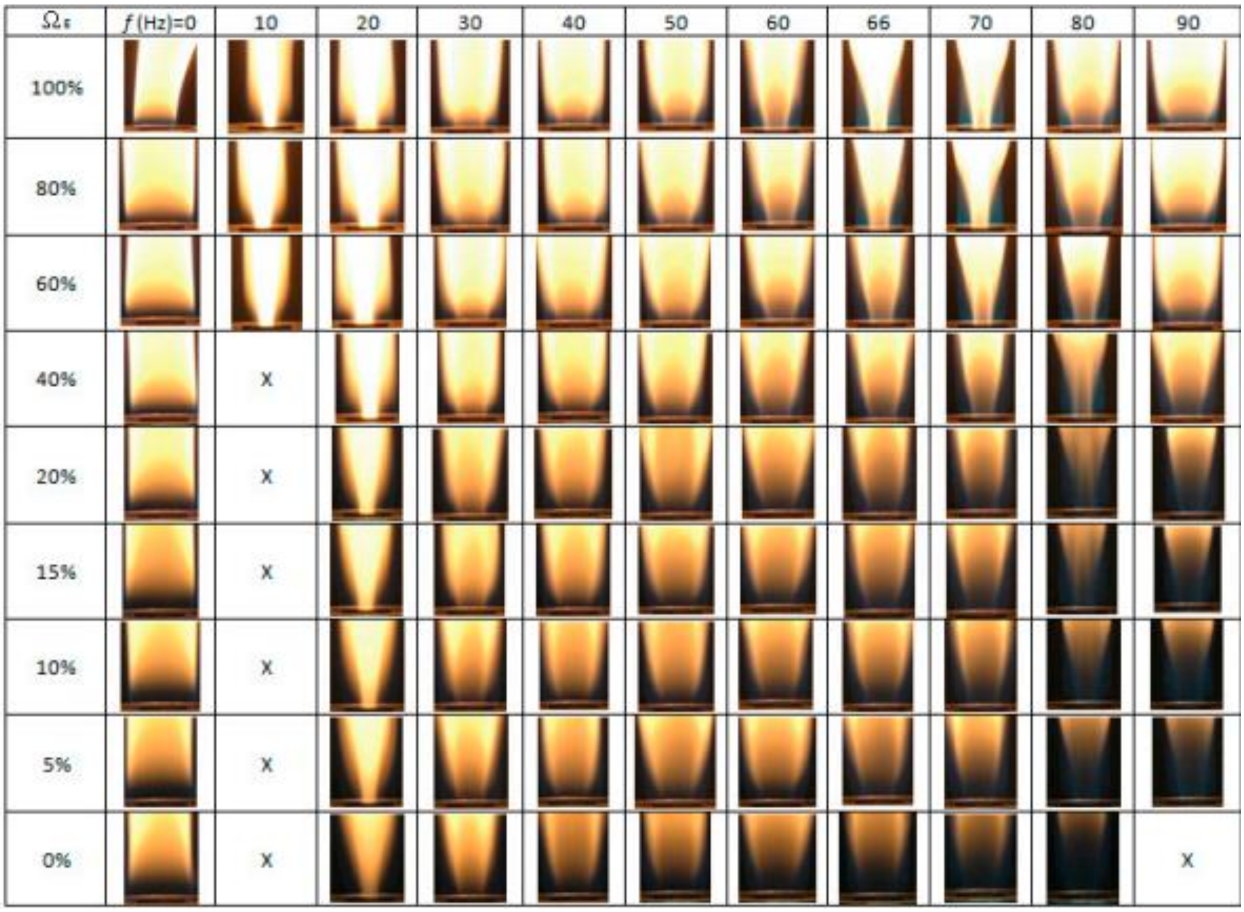


Fig. 1. Flame interaction with frequency [52]

Result shows that the flame during lower range of frequencies experience acoustic excitation near the natural flickering frequency or been called as acoustically resonant. The linear change of flame structure with the increase of frequencies has also been analyze by Camacho and Ahsan [54], Chung and Ta-Hui [55] and Lakshminarasimhan *et al.,* [56] thus the effect of flame structure also influence the flame spread behavior [57-61]. All results have been in agreement that at certain frequencies, flame will have natural flickering frequency that creates the flame to wave and change of its color intensity.

2.2 Flame Length and Liftoff Height

A liftoff height is a point measured from the centerline distance of the duct exit to the plane of flame stabilization [52–65]. Oh *et al.,* [30] proved the correlation of interaction between flame length and liftoff height during acoustic excitation. The result shows liftoff height increases as the flame height decreases by increasing amount of acoustic excitation, as shown in Figure 2.

The phenomenon shows an increased amount of coaxial air velocity. However, different phenomenon is occurred during resonance frequency; when the flame length seems to be prominent [66]. This is due to the larger amplitude during resonance frequency compare with non-resonance frequency.

The fluctuation is occurred due to the flame surface distortion at the fuel and air reaction zone. The distortion is caused by a large coherent vortex produce during acoustic forcing, making the flame base move upstream as vortices become larger [67]. Vortices or vorticity plays a major role in flame lift off stabilization due to its ability to induce a premixing layer between fuel and air [18,68].

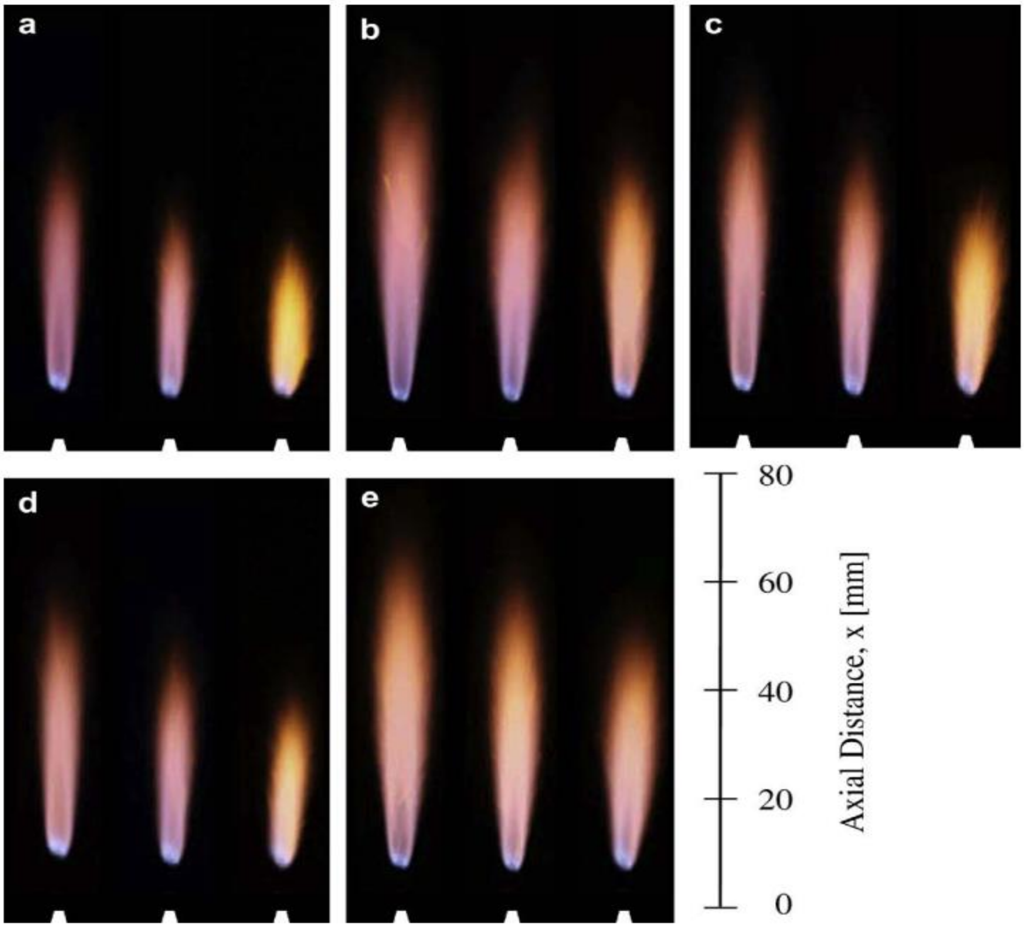


Fig. 2. Visible flame appearance (left image for non-excitation, center for f= 340 Hz, and right for f = 490 Hz) [30]

2.3 Flame Shape

During acoustic excitation, it has been observed that the flame changes its shape with the increased level of excitation. As seen in Figure 3, the flame shape is categorized to five stages of region [69]. By examining the correlation of flame to the length mode for the unforced flame, the outer vortex motion is owed to a flame flickering; which is caused by a buoyancy motion [70]. The shape is typical for most jet flame shape [71–73].

The next region, the length of flame increases and decreases substantially with the increased amount of excitation; this mode of shape is called fat flame [74] moreover the excitation disturbs the gas mixture influencing the thermophoretic parameter of the flame [75-77]. Further increasing of the amplitude, the flame length starts to decrease after reaching its maximum height at an elongated flame and the shape start passing through an in-burning flame.

By exciting the flame, an inner vortex appears irrespective of the outer structure related with the in-burning flame mode shape. The flame is believed to be in a threshold phenomenon, respectively its collapsible mixing [78,79]. This is referred to the entrainment of air caused by an acoustic cycle under the influence of a strong positive pressure gradient [80]. By increasing the amount of excitation, the negative part of the acoustic starts to influence the flame and induce the entrained air [81].

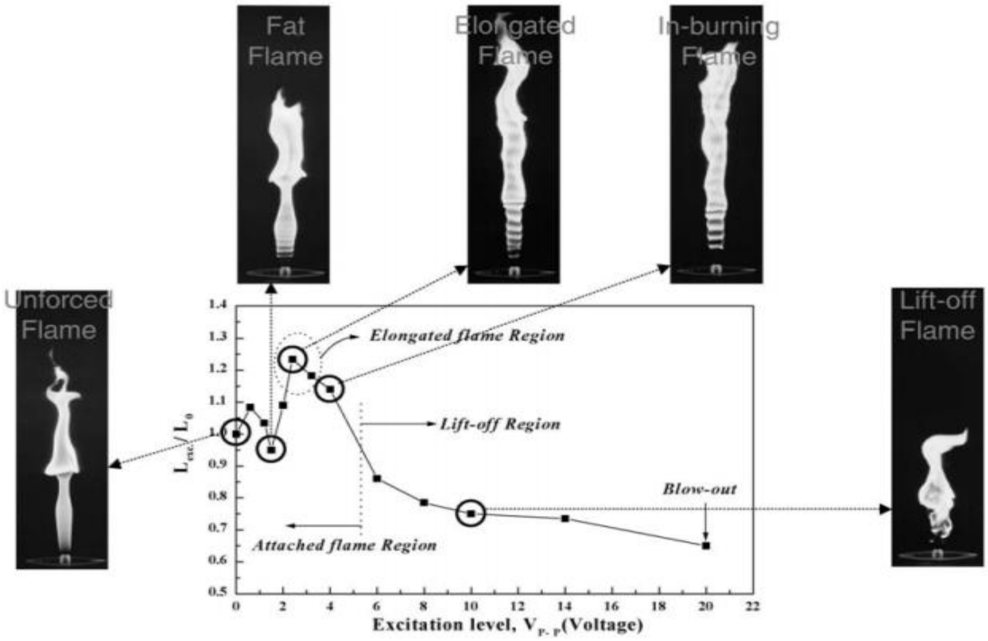
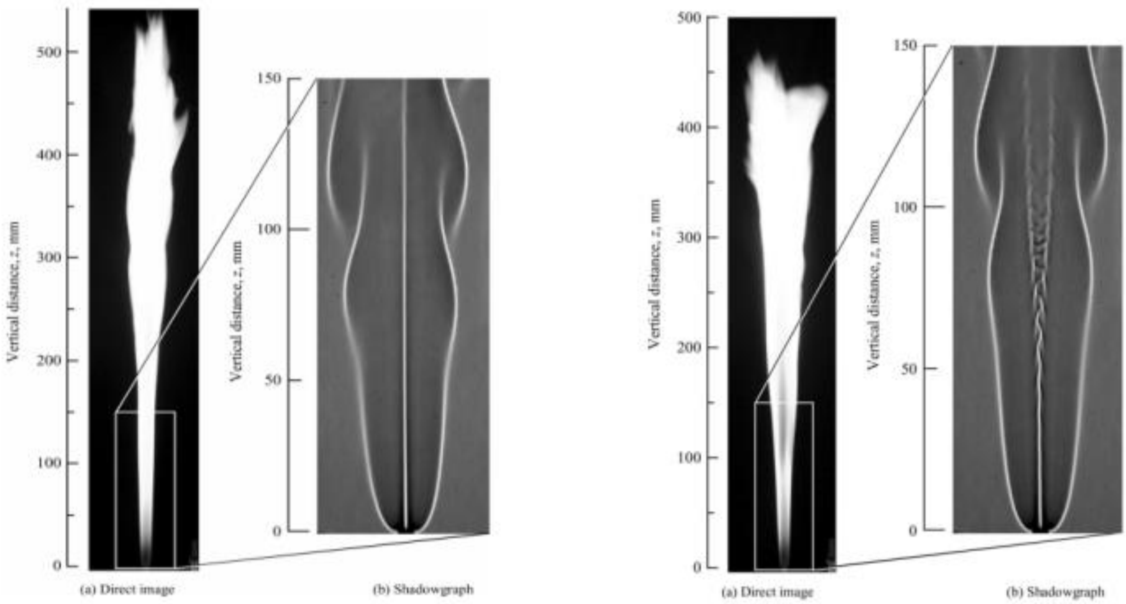


Fig. 3. Flame shape based on flame region curve [69]

Another flame shape visualizing from the acoustic excitation is "Y" shape flame [82]. The "Y" shape flame, as shown in Figure 4, is seen under certain condition of acoustic excitation. Figure 4(a) and Figure 4(b) represent the flame without and with acoustic excitation, respectively. The shape of flame meanders without acoustic excitation and starts to separate when an acoustic being excite to the flame. This result agrees with the experiment conduct by Monkewitz *et al.,* [83] and Yoshida *et al.,* [84].

This branching behavior inside the flame is the key to the notable change in the shape of the flame. Reynolds *et al.,* [85] has found similar bifurcating behavior that allows the merging of axial and circumferential excitations at the nozzle exit. This bifurcation occurs due to mutual induction between the consecutive vortices induced by the axial disturbances.



(a) (b)

Fig. 4. Formation of Y- Flame Shape [72]; (a) without an acoustic excitation, (b) with an acoustic excitation

2.4 Flame Color Characterization

Color of flame plays significant role in understanding the change of behaviour under acoustic excitation. Method used to characterize the color spectrum using RGB and HSV color model [86]. Flame, during acoustic excitation and non-excitation releases various discontinuous spectra that emitted radiant energy and distributed it around the narrow wavelength, an attribute to the release of photon energy [87]. The discontinuous spectra or signal is used as 'fingerprints' because of its unique characterization [88–92].

Figure 5 shows the variety of color diffusion in a premixed methane flame. Each set of flame is characterized using digital image processing. It has been found that the hue distribution obtained from the flame chemiluminescence allow us to identify any radical emission change from the flame [91,92].

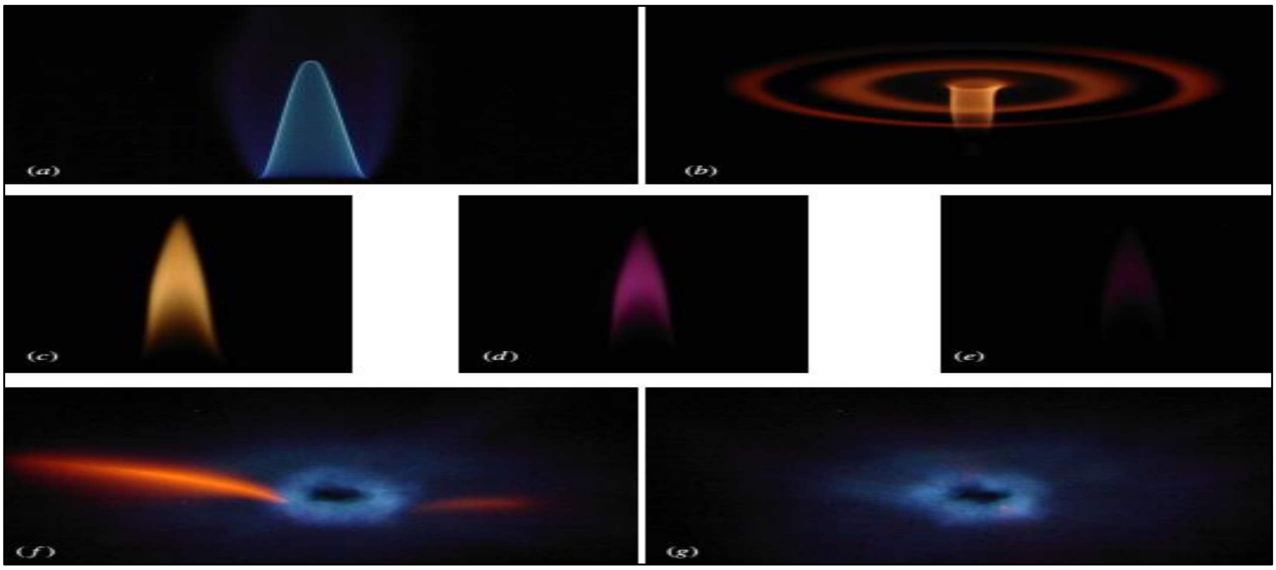


Fig. 5. Characterizing flame using RGB and HSV [86]

3. Acoustic Excitation Application

3.1 NOx Reduction

Nitric Oxide (NOx) emission can cause serious environmental problems such as chemical smog, acid rain and ozone depletion [93–97]. It has been found that acoustic excitation with a proper frequency and amplitude is able to enhance entrainment by manipulating the coherent vortices produce by acoustic excitation [98]. Table 1 shows some of list researches that have been done.

Table 1
Research on NOx - Acoustic excitation application

Name	Amount of NOx Reduce	References
Oh *et al.,*	Up to 7% reduction	[30]
Delabroy *et al.,*	15% reduction	[31]
Kim *et al.,*	Up to 25% reduction	[33]
Keller and Hongo	Three times smaller compare to quiet burner	[99]
McManus *et al.,*	40% reduction	[100]

Based on the current research, the quantity of NOx reduction is caused by the large-structure vortices. This is due to the flame based that consists of laminar non-premixed flamelets. The stabilization point is believed to be affected by the local extinction and the reduction of local mixture concentration gradient [101,102]. The vortex generated by the acoustic excitation promotes air entrainment and enhances fuel-air mixing. Moreover, the large-structure vortices induce a large strain rate and curvature that lead to extinction and quenching of combustion reaction [103–106].

3.2 Soot Formation

Soot is a deep black powdery that consist of largely amorphous carbon produced by an incomplete burning in a combustion system [107]. Soot is one quarter of the total hazardous pollution in air [108]. Long term exposure of soot will increase the risk of coronary artery disease [109].

Previous study on examining the mechanism of soot formation discover that acoustic excitation will improve atomization characteristic thus making it possible to reduce the amount of soot produced [72]. Table 2 listed some of the work study in suppressing the soot formation in combustion system by using acoustic excitation technique.

Table 2
Soot Formation - Acoustic excitation application

Name	Frequencies Range	Findings	References
Dworkin *et al.*,	20 Hz	Maximum soot volume fraction increased with fuel flow modulation	[110]
Sapmaz and Ghenai	10 to 200 Hz using	Increase in total, volume averaged soot volume fraction when increasing the oscillation frequency	[111]
Shaddix *et al.*,	10 Hz	Decrease in total, volume averaged soot volume fraction when increasing the oscillation frequency	[112]
Jocher *et al.*,	20 to 40 Hz	Maximum soot volume fraction is overpredicted by 36% compared with the current measurements	[113]
Saito *et al.*,	Below 100 Hz	Laminar flow region ($Re^* < 2000$), the efficiency of soot suppression was less than 50%, while the efficiency exceeds 90% in the turbulent flow region ($Re^* > 3000$)	[114]

4. Conclusions

The problem of flame-acoustic interaction is a concern in the discipline of combustion. Based on the review presented in this paper, the following conclusions are made

i. The effect of the acoustic excitation towards flame shape is depending upon the amplitude and the value of frequency upon excitation. The shape of flame change and as the excitation become higher it may lead to flame extinction. The experiment done to study the change of shape flame is mostly transverse excitation, where the position for the source of excitation is located below the flame. Less work has been done to predict the change of shape with a different position for the source of acoustic excitation.
ii. The interaction of flame and acoustic largely been influenced by a vortex. However, less work is done to simplify the models of vortex-flame interaction. Most existing work is largely numeric and needed to be extended to further study the effect of the interaction.
iii. Flame-acoustic interaction in a combustion system in realistic environment occurs in a very hasty space. Any model that had been done to understand the effect of acoustic excitation in

laboratory usually has a control space. Fundamental issues, such as method of the model should response to the work must be address.

Acknowledgement
The authors would like to express his deepest gratitude to Universiti Tun Hussein Onn Malaysia (UTHM) and Ministry of Higher Education Malaysia (MOHE) for their financial support of the present work through Fundamental Research Grant Scheme (FRGS-1545) and GPPS Grant Scheme (U802).

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