Soot 배출 확산 화염에 대한 음향 가진 효과 연구

An Investigation of Acoustic Excitation on Sooting Diffusion Flame

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ABSTRACT

본 논문에서는 soot을 배출하는 층류 확산 화염에 대한 음향 가진(acoustic excitation) 효과에 대해 연구하였다. 최근의 연구결과는 soot 배출 화염에 음향 가진을 작용시키면 radiation은 증가하고 soot 배출은 감소한다는 사실을 밝혀주었다. 음향 속도(acoustic velocity)는 음향 압력(acoustic pressure)과 900 상(phase) 차이가 있기 때문에 acoustic driver를 장착한 유리 튜브 내부의 축방향으로 soot을 배출하는 아세틸렌 확산 화염을 이동시킴으로서 soot 배출 감소에 대한 음향 속도와 음향 압력의 상대적인 중요도를 밝혀낼 수 있다. Soot을 배출하는 아세틸렌 화염에 soot 배출이 멈출 때까지 음향 가진을 작용시키고 유리 튜브 안의 최대 압력 위치에서 음향 압력을 측정하며, 화염 위치의 음향 속도와 음향 압력은 운동량 방정식과 파동 방정식을 통해 계산된다. 실험 결과 음향 속도가 최대이고 음향 압력이 최소인 위치에서 보다 음향 속도가 최소이고 음향 압력이 최대인 위치에서 훨씬 더 큰 acoustic power가 필요함을 보여주었다. Soot 배출을 멈추는데 필요한 음향 속도의 크기는 유리 튜브의 축방향에 대해 거의 일정한 반면 음향 압력의 크기는 상당한 변화가 있었다. 이러한 결과는 Soot 배출의 감소가 주로 음향 속도에 의한 것임을 강하게 시사한다고 할 수 있다. 또한 연료의 유량이 증가함에 따라 soot 배출을 억제하는데 필요한 acoustic power도 증가한다는 사실을 확인 할 수 있었다.

주요기술용어 : Soot, Diffusion Flame(확산 화염), Acoustic Wave(음향파), Acoustic Excitation(음향 가진)

1. Introduction

The ideal combustion of hydrocarbons(C_xH_y) leads to mainly carbon dioxide(CO_2) and water(H_2O). However, in practical combustion devices such as industrial furnaces, gas turbines, or combustion engines, there exist other products of incomplete combustion such as carbon monoxide(CO), hydrogen(H), hydrocarbons(C_xH_y) and soot. The intermediate formation of soot can be desired to enhance heat transfer by radiation in some devices.

On the other hand, soot emitting from the flame causes many problems in terms of environmental pollution, damage to machinery, and combustion efficiency.

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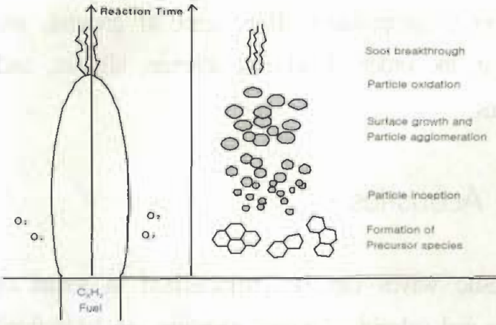
In many applications, the heat from the combustion must be transferred out of the flame. This requires the presence of soot within the flame, since solid particles have much higher emissivities than gaseous combustion products. For example, in oil lamp the incandescent soot within the flame is the primary source of the diffusion flame's luminosity. Therefore, an ideal combustor for a boiler, for example, would generate soot early in the combustion process, which would then be consumed in the downstream regions of the flame.

1.1 Soot Background

The formation and destruction of soot occurs in both premixed and non-premixed(diffusion) hydrocarbon/ air flames. In premixed flames, the tendency to soot is correlated with the equivalence ratio at which noticeable sooting just begins. When the equivalence ratio is defined as the actual fuel-air ratio to the stoichiometric value, the smaller the equivalence ratio the greater the tendency to soot. In diffusion flames, the tendency to soot is measured by the height of the flame or the mass flow rate at which the luminous diffusion flame breaks open at its apex and emits a stream of soot. The smaller the flame height at the breakthrough (called sooting height or smoke point) or the smaller the mass flow rate the greater the tendency to soot.

It is obvious that the formation of soot, i.e. conversion of a hydrocarbon fuel to a particle containing some millions of carbon atoms, is an extremely complicated process. It is a kind of gaseous-solid phase transition where the solid phase exhibits no unique chemical and physical structure.



(Figure 1) A Rough Picture of Soot Formation in Diffusion Flame

Therefore, soot formation encompasses chemically and physically different process, the formation and growth of large aromatic hydrocarbons and their transition to particles, the coagulation of primary particles to larger aggregates, and the growth of solid particles by picking up growth components from the gas phase.

Figure 1 shows a rough picture of soot formation in a diffusion flame. In premixed flames, there exist a competition between the pyrolysis rate of the soot precursors and the rate of attack of these precursors by oxidizing radicals, particularly hydroxyl(OH). In the range of temperatures of concern in flames, an increase in temperature favors a higher rate of attack on the precursors more than a pyrolysis rate to soot. The flame temperature is important in that it strongly affects the hydroxyl radical concentrations. In diffusion flames the opposite is true; the precursor growth process take place in the absence of any oxidizing radicals and an increase in temperature increase the rates of pyrolysis and thus the tendency to soot. Therefore, the sooting behavior is more dominant in diffusion flames than in premixed flames. The parent-fuel molecular structure is very important in determining the fuel's sooting propensity.

Fuel sooting propensities, from least to greatest, are known in the order of alkanes, alkenes, alkynes, and aromatics.

1.2 Acoustics

Acoustic waves can be characterized in terms of pressure and velocity. Acoustic pressure can be defined as a pressure disturbance that is small in amplitude relative to the ambient pressure. The pressure disturbance travels with speed c given by the relationship,

$$c=\sqrt{\gamma \cdot RT} \tag{1}$$

where γ is the specific heat ratio, R is the gas constant and T is the absolute temperature.

The generation of resonances in the tube with a closed and an open end can be described as following. If the disturbance is generated by a harmonic oscillator, the pressure oscillations will be harmonic in time. If one were to observe the pressure oscillations at a point in space, the wave would pass that point as a series of compressions and rarefactions, and the pressure at that point would be given by the relationship,

$$P=\mathrm{Re}(\overline{P}e^{iwt}) \tag{2}$$

where w is the angular frequency given by

$$w=2\cdot\pi\cdot f \tag{3}$$

$\overline{P}$ is the maximum acoustic pressure amplitude, t is the time and f is the frequency. Therefore, the pressure is observed to oscillate harmonically in time.

If this resonator is a cylinder with one open end and one closed end, the wave will propagate at speed C toward the closed end. When the wave reaches the closed end, the wave will be reflected in such a way that the sum of the incident and reflected waves result in a pressure amplitude maximum. At the open end, the waves will be reflected in such a way that the incident and reflected waves result in a pressure amplitude minimum.

If the pressure disturbance is harmonic in time for the entire time under consideration, the pressure in the pipe will be the sum of all such reflected and incident waves that have been generated in the pipe during that time.

The result is that the pressure amplitude would rise without bound in a perfect resonator if the frequency of the harmonic oscillation is a harmonic of the natural frequency of the resonator. Since all resonators have some losses, the amplitude of the standing wave is finite. The pressure distribution measured throughout the length of the pipe is such the pressure amplitude varies in space and time according to,

$$P=\mathrm{Re}(\overline{P}e^{i(wt-kx)}) \tag{4}$$

where k is the wave number.

Therefore at any given point in the pipe, the pressure is observed to oscillate with fixed amplitude harmonically in time. However, the maximum amplitude of the oscillation varies with position in the pipe. The point of maximum pressure amplitude is called the pressure anti-node. The location of the minimum pressure amplitude is called the pressure node. Such a wave is called a standing wave.

In this investigation, the standing wave is applied to the sooting diffusion flame with acoustic excitation and the resonant tube has the open ends on both sides.

1.3 Soot Studies in Forced Flames

A few investigators have reported on the effects of flow forcing on combustion-generated soot.

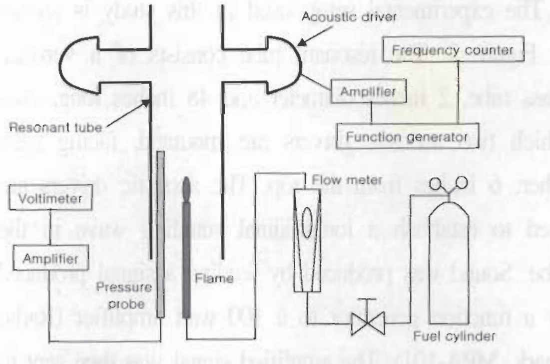
Smyth et al.[1] observed that flickering methane /air diffusion flames have a four-fold increase in the time-averaged, volume -integrated soot volume fraction over their steady counterparts. In these studies, the fuel flow was pulsed and no external acoustic field was imposed.

Gutmark et al.[2] acoustically forced both the fuel and air flow in a diffusion injection system found that by judicious timing of the reactant injection soot could be reduced by nearly three orders of magnitude. This research concerned forcing the inlets of both fuel and air, not acoustic forcing the downstream. Regarding the flame shape change under acoustic excitation, Durox et al[3] showed that a conical flame, in the presence of high -frequency and high-amplitude acoustic modulation of the cold gases, deforms to a shape that is approximately hemispherical. It was shown that the acoustic level required to produce a hemispherical flame is such that the ratio of acoustic velocity to laminar combustion velocity is about 3.

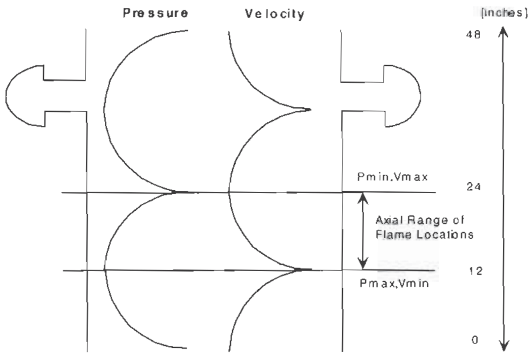
Chen et al.[4] found out that the interaction between the acoustic field and the flame produces a space -dependent, oscillatory normal velocity component in the flame region, and oscillatory reaction-and heat-release rates, which depend upon the excited acoustic field. Test carried out at the EPA laboratories in Research Triangle Park, NC have shown that the presence of pulsation in an experimental incinerator significantly decrease the soot emitted through the stack.

These studies suggest that acoustics can be used to control soot formation, burnout and thus soot emissions. The objective of this study is to determine what effects acoustics pulsations have on soot formation and burnout in diffusion flames.

In the longer term, this information can be used to investigate whether properly tailored acoustics can be used to design a burner with high radiative heat transfer and low soot emissions. In this investigation, a diffusion flame is positioned at various locations in an externally generated acoustic field and the effects of acoustic oscillations on sooting flame are studied.



(Figure 2) Experimental Setup



(Figure 3) Acoustic Field in the Resonant Tube

2. Experiments

The tendency of diffusion flames to soot is commonly compared using the concept of sooting height by comparing the height that a diffusion flame can reach before soot breaks through its tip, i.e., the flame produces smoke. At higher volumetric fuel flow rates, more smoke is produced. Acetylene was chosen as the fuel for the tests reported here because of its strong tendency to soot.

The experimental setup used in this study is shown in Figure 2. The resonant tube consists of a vertical, glass tube, 2 inches diameter and 48 inches long, onto which two acoustic drivers are mounted, facing each other, 6 inches from the top. The acoustic drivers are used to establish a longitudinal standing wave in the tube. Sound was produced by feeding a signal produced by a function generator to a 100 watt amplifier (Radio Shark, MPA-101). The amplified signal was then sent to an 8 ohm 100 watt sound drivers (University Sound, 10-75-8).

Resonant frequency was calculated by following formula,

$$f=\frac{\lambda}{c}=\frac{\lambda}{\gamma \cdot RT} \quad (5)$$

where γ is the specific heat ratio, λ is the wavelength and R is the specific gas constant. The wavelength was set to be one half of the tube length, thus the second harmonic of the tubes longitudinal mode was excited. The calculated resonant frequency was 283 Hz.

Figure 3 shows the acoustic field in the resonant tube. The acoustic velocity is 900 out of phase with the acoustic pressure. Therefore, the location of a pressure maximum is a velocity minimum.

The burner consists of a 3/16 inch i.d. (1/4 inch o.d.) glass tube, which can be translated within the acoustic enclosure, so that flame can be positioned at different locations with respect to the longitudinal standing waves. As can be seen in Figure 3, a flame was positioned in a range of locations between the pressure anti-node (or V_{min}) and the pressure node (or V_{max}). This permits study of the relative importance of acoustic pressure and velocity fluctuations.

To characterize the acoustic field, oscillatory pressures were measured at the pressure maximum. The sooting acetylene diffusion flame was placed at a given axial position and acoustic excitation was applied to stop soot breakthrough from the flame. At that condition, Pmax was measured by positioning a pressure probe at the expected pressure maximum point under second mode resonant frequency. Pressure probe consists of a 10 inch long, 3/16 inch i.d. (1/4 inch o.d.) steel tube with pressure transducer (Kistler, SN C45275) connected at the bottom in a tee to which long coiled tube (3/16 i.d., 1/4 o.d.) is connected. Signal from pressure transducer was magnified by the pressure amplifier (Kistler, SN C18806). Then, local pressure and velocity corresponding to the actual flame height was calculated by the combination of momentum equation and wave equation as following.

The equation describing such disturbances is known as the wave equation in one dimension and has the following general form,

$$\frac{\partial^2 \zeta}{\partial x^2} = \frac{1}{c^2}\frac{\partial^2 \zeta}{\partial t^2} \tag{6}$$

Here, C is the velocity of propagation of the wave and ζ can be taken to represent any desired quantity such as pressure, i.e.,

$$\frac{\partial^2 P}{\partial x^2} = \frac{1}{c^2}\frac{\partial^2 P}{\partial t^2} \tag{7}$$

and the momentum equation in one dimension is given by,

$$\frac{\partial u}{\partial t} = -\frac{1}{\rho}\frac{\partial P}{\partial x} \tag{8}$$

The acoustic velocity associated with a one-dimensional simple harmonic wave travelling in the x direction can be calculated by substituting the following general solution of the wave equation into the momentum equation,

$$P = a_1 \cos(wt - kx) + a_2 \sin(wt - kx) \tag{9}$$

then

$$\int \frac{\partial P}{\partial x} = ka_1 \sin(wt - kx) - ka_2 \cos(wt - kx) \tag{10}$$

$$\int \frac{\partial P}{\partial x}\partial t = -\frac{k}{w} a_1 \cos(wt - kx) - \frac{k}{w} a_2 \sin(wt - kx) = -\frac{p}{w} k \tag{11}$$

and

$$u = \frac{k}{wp} P = \frac{P}{wc} \tag{12}$$

So once we measure Pmax, Vmax is calculated from,

$$V_{max} = \frac{P_{mar}}{Pc} \tag{13}$$

Because we know the waveform of acoustic pressure and velocity in the resonant tube, local pressure and velocity can be obtained through following,

$$P' = P_{max} \sin(kx) = P_{max} \sin\left(\frac{w}{c} x\right) = P_{max} \sin\left(\frac{2\pi f}{c} x\right) \tag{14}$$

$$V' = V_{max} \cos(kx) = V_{max} \cos\left(\frac{w}{c} x\right) = V_{max} \cos\left(\frac{2\pi f}{c} x\right) \tag{15}$$

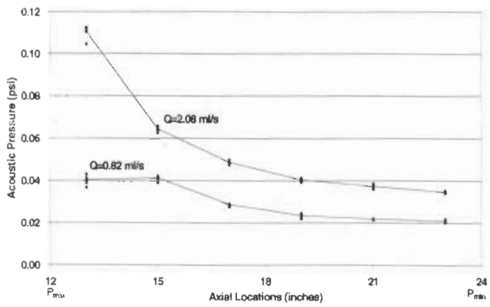
Fuel flow rates are measured using a calibrated rotameter (Matheson 600). Rotameter calibration was performed with a bubble meter. By recording the travel time of a bubble caused by the flowing gas at each rotameter scale, the calibration table could be obtained.

3. Results and Discussions

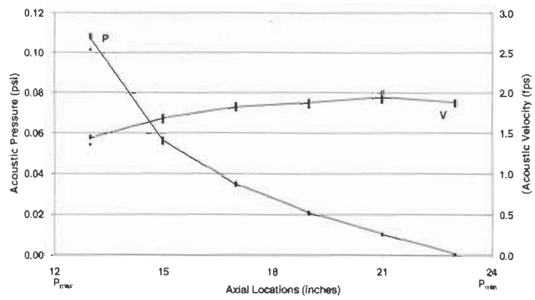
The results show that acoustic excitation reduces sooting of a laminar diffusion flame greatly.

Measurements were carried out to determine whether acoustic velocity or pressure oscillations are primarily responsible for the observed reduction in soot. In the standing wave used in this investigation, acoustic velocity and pressure oscillations are 90^0 out of phase. Thus, the relative effect of pressure and velocity oscillations could be observed by positioning the flame at different locations with respect to the standing wave.

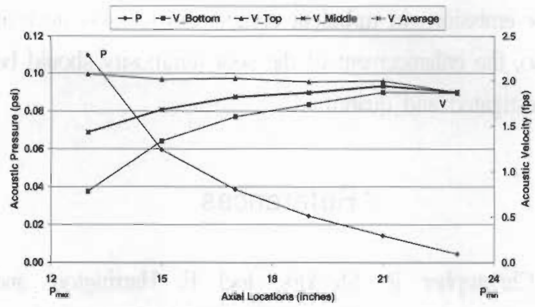
For this purpose, the measurements and calculations were carried out for two flow rates. One was just enough flow rate for acetylene to start soot breakthrough and the other was a relatively high flow rate for acetylene to emit soot much more than the low case. With a flow rate 0.82 ml/s (Re=7), the acetylene flame starts to emit smoke, and the flame height is 0.8 inches. For the higher smoke case, 2.08 ml/s (Re=26) was chosen and the flame height is 2 inches. As described previously in Figure 3, and Ⅱ.Experiments, after positioning a 3/16 inch glass fuel tube in the resonant tube, acoustic wave was applied to sooting flame until the flame stopped soot breakthrough. The P_{max} position was considered to be fixed which is reasonable because the gas temperature gradient in the resonant tube was not so large. Gas temperature over the flame 4 inches below the top of the resonant tube with Q=2.08 ml/s was 65 C. V is a function of location, but the flame exists over a finite length of the acoustic period. Thus, it is difficult to describe the velocity fluctuations with a single number. So the calculation was done at 4 conditions : V at the top, bottom, middle of the flame and the average value of V top and V bottom. Figure 4 shows P_{max} required to stop soot breakthrough for the two flow rates at different axial locations. Figures 5-6 shows the results for the relatively high flow rate case and Figures 7-8 are for the low flow rate case. The resonant frequency of oscillations was calculated to be 273 Hz and the experiments were repeated 5 times. On the figures, we can observe some strange result near the P_{max}, V_{min} region deviating from the other locations. That may be because approaching the V_{min} region, the acoustic velocity is very small and as can be seen in Figure 3, around this region the slope of acoustic velocity is very steep, so small error from eithercalculation or measurement can cause relatively big difference.



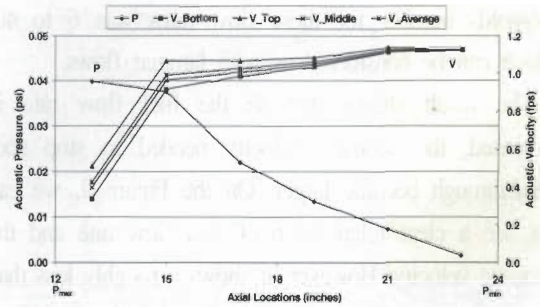
[Figure 4] Maximum Acoustic Pressure Needed to Stop Soot Breakthrough with Flame at Different Axial Locations



[Figure 5] Local Acoustic Pressure and Velocity (Q=2.08 ml/s)

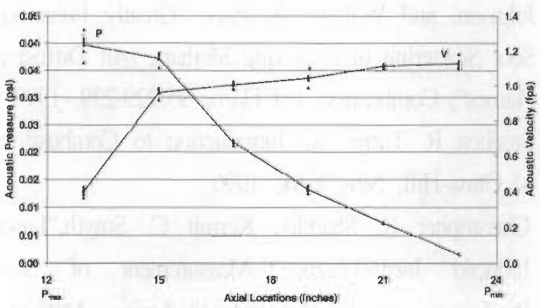


[Figure 6] Local Acoustic Velocity at Various Calculation Locations (Q=2.08 ml/s)

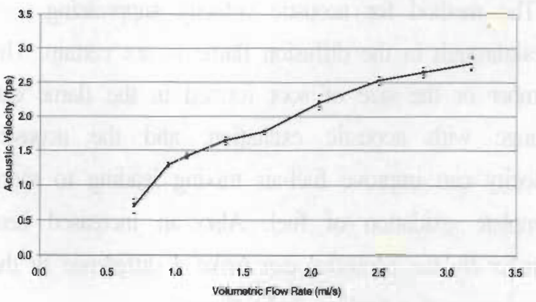


[Figure 8] Local Acoustic Velocity at Various Calculation Locations (Q=0.82 ml/s)

However, the general results show that a much higher acoustic power is needed when the flame is located at a pressure maximum, where acoustic velocities are small, than when it is near a pressure minimum, where acoustic velocities are largest. Most importantly, the magnitude of the local acoustic velocities required to suppress sooting is relatively constant over the entire length of the tube while the magnitude of the required acoustic pressures varies by more than an order of magnitude. This strongly suggests that the reduction of soot emission from the flame be mainly due to acoustic velocity oscillations. Figure 9 shows the effect of fuel flow rate on flow rate on the acoustic velocity required to stop soot breakthrough. The fuel tube was positioned at Vmax which is 24 inches up from the bottom of the resonant tube. Here, acoustic velocity is the average value of V calculated at bottom and V calculated at top of the flame. The flow rate was varied from the least value (just enough to start sooting) to the highest rate where we can not get a non-sooting flame. When the flow rate was increased pass to 3.2 ml/s, it was very difficult to get non-sooting flame with acoustic excitation. At this flow rate, the flame went down along the fuel tube and was very unsteady. Although much less smoke was observed, there existed still slight amount of smoke emitting from the flame. The range of



[Figure 7] Local Acoustic Pressure and Velocity (Q=0.82 ml/s)



[Figure 9] Acoustic Velocity Required to Stop Soot Breakthrough for Different Fuel Flow Rate

Reynolds number for these flow rates was 6 to 40, which can be considered as pure laminar flows.

The result shows that as the fuel flow rate is increased, the acoustic velocity needed to stop soot breakthrough become larger. On the Figure 9, we can not see a clear relationship of fuel flow rate and the acoustic velocity. However, it shows a roughly less than linear increase of acoustic velocity with the fuel flow rate increased. This implies that the sooting tendency of a diffusion flame decreases significantly in the presence of acoustic oscillations.

4. Conclusions

In conclusion, acoustic oscillations have been shown to reduce a soot emission for acetylene/air diffusion flames. The effect of acoustics on soot formation is mainly due to velocity oscillations and the acoustic velocity needed to soot breakthrough has a roughly linear increase with the fuel flow rate. Although radiation changes were not quantified here, an enhancement of the flame intensity was observed. Considering the soot as the primary source of flame radiation and brightness, this is related to the amount of soot formed inside the flame and the soot temperature.

The method for acoustic velocity suppressing soot breakthrough in the diffusion flame is not certain. The number or the size of soot formed in the flame can change with acoustic excitation, and the acoustic velocity can improve fuel-air mixing leading to more complete oxidation of fuel. Also an increased heat transfer by the acoustics can make a difference in the temperature distribution of the flame.

The current investigation concerned laminar diffusion flames. The ability of acoustic fluctuations suppressing soot emissions in turbulent combustors remains unclear. Also, the enhancement of the soot luminosity should be investigated and quantified.

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