A MECHANISM TO EXPLAIN THE ORIGINS OF SPRAY COMBUSTION INSTABILITY

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ABSTRACT

This paper proposes a new mechanism that explains the origins of spray combustion instability in a chamber. The mechanism relates the origins of oscillations to the frequency of droplet free oscillation and to droplet size. A tubular combustion chamber and an alcohol atomizer were constructed and used in experiments that checked the validity of the model. By varying the alcohol and the primary air flow rates, it was possible to change the average size of the droplets and, consequently, their frequency of free oscillation. It was found that acoustic instabilities occurred only when the spray contained droplets that oscillated in one of the natural frequencies of the combustion enclosure.

INTRODUCTION

The basic principle that determines the condition for occurrence of a combustion driven acoustic oscillation in a chamber is known as the Rayleigh criterion (Lord Rayleigh, 1945). It states that if heat is periodically transferred to an acoustically oscillatory mass of a gas, the amplitude of oscillation will increase if the heat addition takes place during compression. The same will occur if heat is removed during rarefaction. Putnam and Dennis (1954) proposed a mathematical formulation for the criterion which proved to be useful in a number of cases. The Rayleigh criterion is a necessary but not sufficient condition since it does not reveal the origins of oscillations in a chamber.

Several mechanisms have been proposed to explain how oscillations are generated. Pflaum (Feldman, 1968), in 1909, stated that the origins of the sound were related to friction tones such as those occurring when wind blows across a wire. If oscillations were caused only by friction, the sound intensity would increase as the gas flow velocity along a combustion chamber increased and the heat source would have practically no effect on instability.

In the case of premixed flames, several investigators agree that the oscillatory heat release occurs by either a variation of the flame area or a variation of normal burning velocity, or both (Jost, 1946; Lewis and von Elbe, 1951; Blackshear, 1952). Tau-Yi et alii (1965) showed evidence that Tollmien-Schlichting waves (Schlichting, 1960) were the cause of oscillations in chambers. The origins of instability are regarded by Jones (1977) as being linked to the flame interior dynamics and by Pol'shin (1982) as being associated with a relaxation mechanism. In most references on the subject, the researchers explain how the vibrations occur in a combustion chamber enclosure but do not show conclusively their primary origins.

This paper proposes a new mechanism that can explain the origins of acoustic oscillations in a combustion chamber in which atomized liquid fuel is burned. The mechanism is supported by experimental results obtained with a Rijke tube (Lord Rayleigh, 1945) in which the heat source was an ethyl alcohol burner. It is shown that the origins of oscillations are related to the frequency of free droplet oscillation of the spray droplets.

PROPOSED MECHANISM

The droplets of liquid fuel do not at once assume and retain a spherical geometry as they are separated from a jet. Instead, they execute a series of vibrations, being alternately compressed and elongated in relation to their axes of symmetry. The frequency of free oscillation of a liquid droplet in air was first derived by Lord Rayleigh (1945) as being

$$f = \frac{1}{\pi}\left[\frac{2n\,(n-1)\,(n+2)\,\sigma}{\rho D^3}\right]^{1/2}, \tag{1}$$

where n is an integer, σ the surface tension, ρ the density, and D the droplet diameter. The first mode of oscillation occurs for $n = 2$ and the corresponding frequency is

$$f = \frac{4}{\pi}\left[\frac{\sigma}{\rho D^3}\right]^{1/2} \tag{2}$$

This formula agreed well with results of experiments with free falling droplets (Daimon and Kimura, 1982). For experiments with a jet, however, probably due to the occurrence of excessive amplitudes, the frequency of droplet oscillation was observed to be 20% lower than that predicted by the formula (Lord Rayleigh, 1945).

In the case of sprays, there will be droplets in a broad range of sizes oscillating in a broad range of frequencies. It is proposed that the combustion chamber act as a tuning element coupling those frequencies of droplet free oscillation that match with a natural frequency of the enclosure.

EXPERIMENTAL APPARATUS AND PROCEDURE

Two combustion chambers were used for the investigation. The first, shown in Figure 1, was modular, 320cm long by 20cm internal diameter, with a bottom decoupling chamber to allow control of the secondary air flow rate without alteration of the open end boundary condition at the entrance section. The second chamber was a 295cm long by 15.5cm internal diameter tube and also possessed a decoupling chamber.

A schematic of the ethyl alcohol burner is shown in Figure 2. The depth of the burner inside the chamber could be varied by means of a simple sliding rod mechanism. The alcohol, the atomization or primary air, and the secondary air flow rates were measured with rotameters.

The amplitude and frequency of acoustic pressure were measured at a half and at a quarter length from the bottom of the tube using Kistler type 7261 piezoelectric pressure transducers, Kistler type 5006 amplifiers, and an Analog model F8100A frequency meter. The indicated measurement positions correspond, respectively, to the acoustic pressure maximum amplitude of the fundamental and second harmonic modes od oscillation. The signals from the pressure transducers were displayed in a Tektronix model 7633 oscilloscope screen.An Euromicro acquisition system was used to record and reduce the experimental data.

The burner was designed to generate sprays that contained droplets in sizes required to check the proposed mechanism. The droplet size distribution could be varied by changing either the primary air or the alcohol flow rate. The atomization was not affected by the secondary air flow rate.

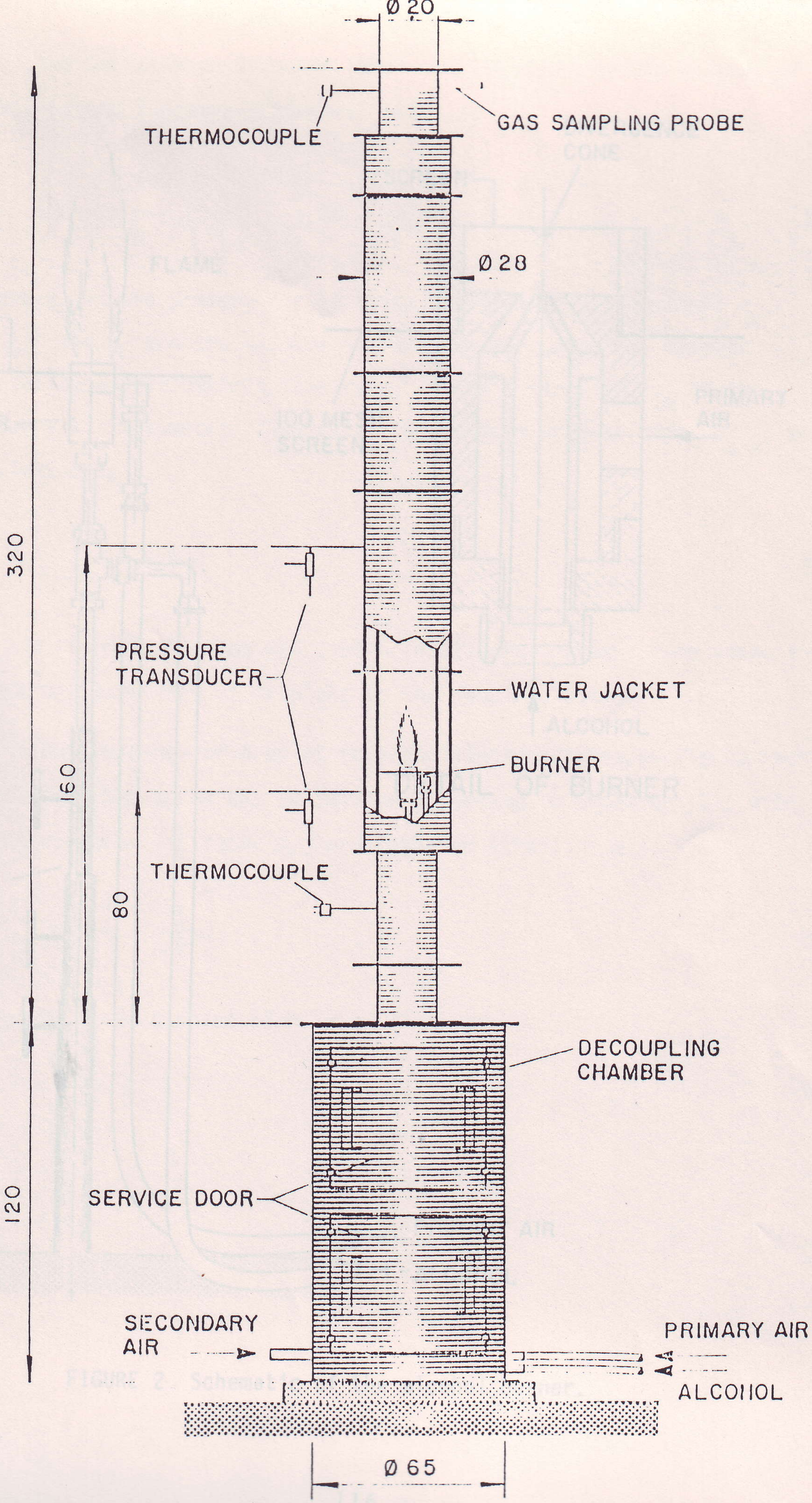

FIGURE 1 Schematic of the experimental apparatus.

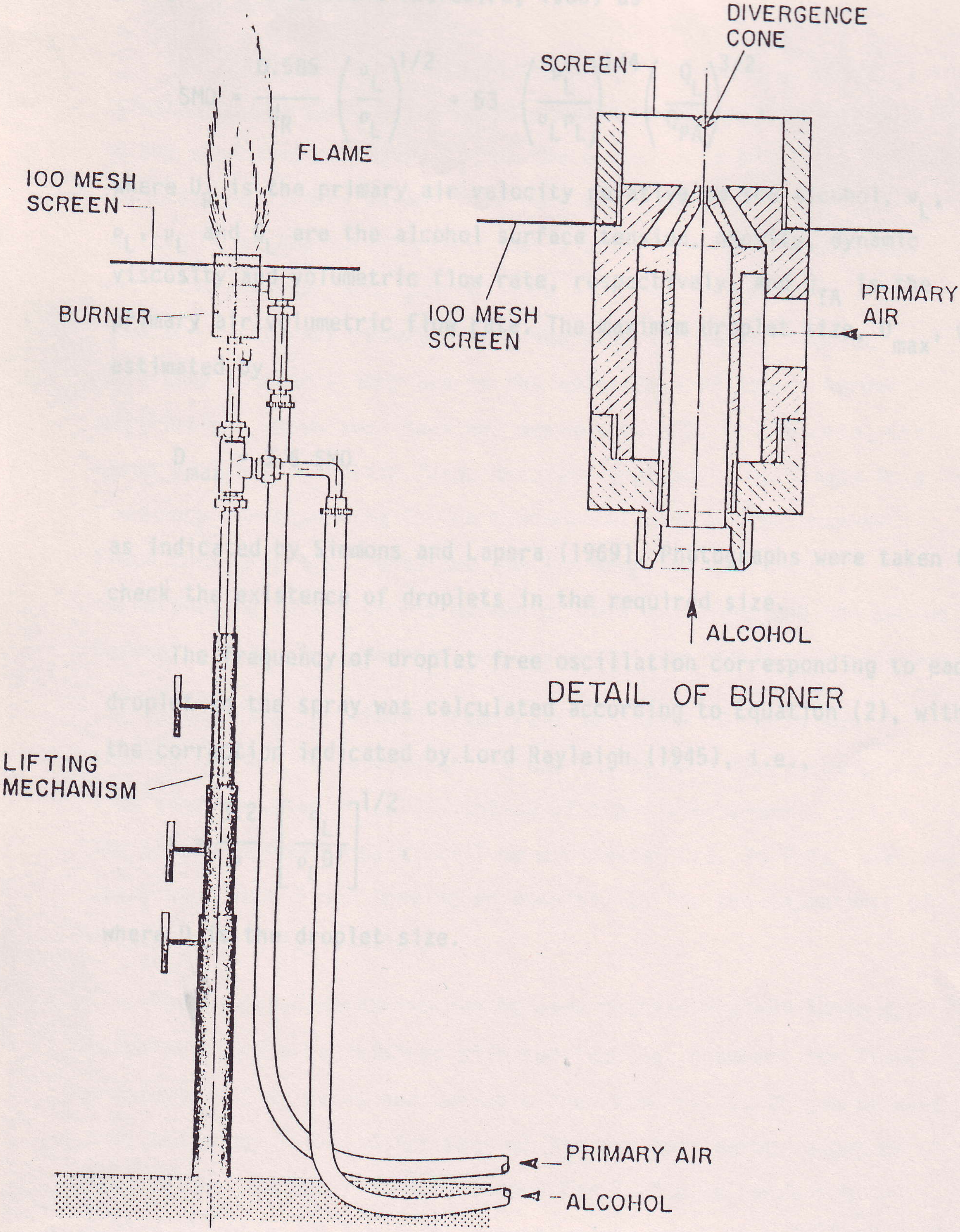

FIGURE 2 Schematic of the alcohol burner.

The Sauter Mean Diameter (SMD) was estimated by the formula of Nukiyama and Tanasawa (Lefebvre, 1980) as

$$SMD = \frac{0.585}{U_R}\left(\frac{\sigma_L}{\rho_L}\right)^{1/2} + 53\left(\frac{\mu_L^2}{\sigma_L \rho_L}\right)^{1/4}\left(\frac{Q_L}{Q_{PA}}\right)^{3/2}, \quad (3)$$

where U_R is the primary air velocity relative to the alcohol, σ_L, ρ_L, μ_L and Q_L are the alcohol surface tension, density, dynamic viscosity and volumetric flow rate, respectively, and Q_{TA} is the primary air volumetric flow rate. The maximum droplet size, D_{max}, was estimated by

$$D_{max} = 3.6\ SMD \quad (4)$$

as indicated by Simmons and Lapera (1969). Photographs were taken to check the existence of droplets in the required size.

The frequency of droplet free oscillation corresponding to each droplet in the spray was calculated according to Equation (2), with the correction indicated by Lord Rayleigh (1945), i.e.,

$$f = \frac{3.2}{\pi}\left[\frac{\sigma_L}{\rho_L D^3}\right]^{1/2}, \quad (5)$$

where D is the droplet size.

RESULTS AND DISCUSSION

The first set of results is presented in Figure 3, which illustrates the time variation of acoustic pressure measured at L/4, in the apparatus of Figure 1, for the burner located at (a) L/4 and (b) L/8. The alcohol volume flow rate was $8.86 \times 10^{-6} m^3/s$. The excitation of the first mode of oscillation was readily obtained when the burner was positioned at L/4. Slowly lowering the burner resulted in a decrease of the oscillation amplitude to nearly zero and in the appearance of second harmonic oscillations whose amplitude was maximum at L/8. In the case, the spray was set to contain large droplets that would oscillate in a frequency corresponding to the fundamental mode of the chamber. Since the spray also contained smaller droplets with sizes corresponding to the second harmonic, both the first and the second harmonics could be generated, depending only on the burner position.

Decreasing the alcohol feed rate to $3.80 \times 10^{-6} m^3/s$ and keeping the O/F ratio constant by decreasing only the secondary air flow rate resulted in no excitation of the first harmonic at L/4. The second harmonic could still be excited at L/8. In this case, the spray was much finer leaving no possibility for the appearance of first harmonic oscillations.

The proposed mechanism can be also checked against Table I, which shows results obtained with the two test chambers for fixed primary air flow rates and variable fuel feed rates. It can be seen that the model is valid for most of the two considered ranges of feed rates. The observed discrepancy for $7.27 \times 10^{-6} m^3/s > Q_L > 6.33 \times 10^{-6} m^3/s$ in the first apparatus and for $5.51 \times 10^{-6} m^3/s > Q_L > 4.50 \times 10^{-6} m^3/s$ in the second happens because of the existence of larger than theoretically predicted droplets in the spray. These droplets were caused by a non symmetry of the jet and

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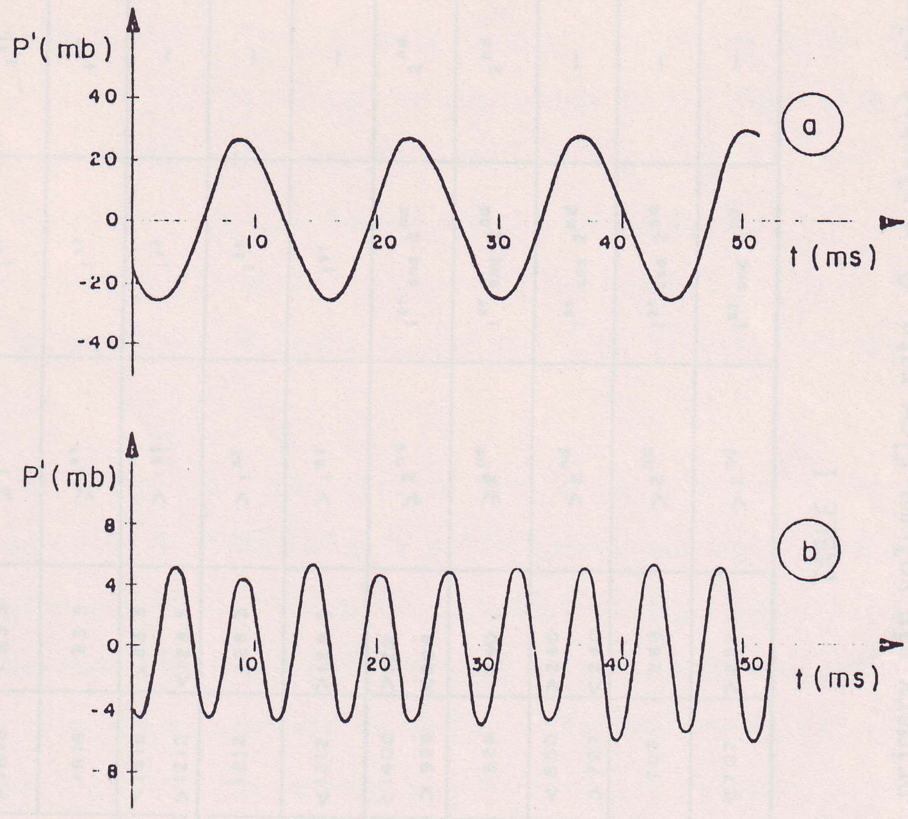

FIGURE 3 Time variation of acoustic pressure measured at L/4 for an alcohol volume flow rate of 8.86×10^{-6} m³/s and the burner located at (a) L/4 and (b) L/8.

APPARATUS	Q_{PA} (m^3/s)	Q_L (m^3/s)	U_R (m^3/s)	D_{max} (μm)	f_1 (Hz)	POSSIBLE HARMONICS, BY DROPLET SIZE DISTRIBUTION	POSSIBLE HARMONICS, BY RAYLEIGH CRITERION	HARMONICS PREDICTED BY PROPOSED THEORY	HARMONICS OBSERVED	f_2 (Hz)
	0.0184	$>7.27\times10^{-6}$	<7.09	>1616	<83.3	≥ 1st	1st	1st	1st	79
L = 320 cm;	0.0184	7.27×10^{-6}	7.09	1616	83.3	≥ 1st	1st	1st	1st	79
Ø = 20 cm;	0.0184	$<7.27\times10^{-6}$ $>6.33\times10^{-6}$	>7.09 <9.53	<1616 >1212	>83.3 <128.3	> 1st	1st	—	1st	79
BURNER AT L/4	0.0184	6.33×10^{-6}	9.53	1212	128.3	> 1st	1st	—	—	—
	0.0184	$<6.33\times10^{-6}$	>9.53	<1212	>128.3	> 1st	1st	—	—	—
	0.0184	$<6.93\times10^{-6}$ $>5.51\times10^{-6}$	>7.90 <11.71	<1400 >926	>129 <228	≥ 2nd	1st and 2nd	2nd	2nd	234
L = 295 cm;	0.0184	5.51×10^{-6}	11.71	926	240	≥ 2nd	1st and 2nd	2nd	2nd	234
Ø = 15.5 cm;	0.0184	$<5.51\times10^{-6}$ $>4.50\times10^{-6}$	>11.71 <14.34	<850 >707	>240 <240	> 2nd	1st and 2nd	—	2nd	234
BURNER AT L/8	0.0184	4.50×10^{-6}	14.34	707	288	> 2nd	1st and 2nd	—	—	—
	0.0184	$<4.50\times10^{-6}$	>14.34	<707	>288	> 2nd	1st and 2nd	—	—	—

TABLE I

Typical data from tests (Q_{pA} = primary air volume flow rate, Q_L = alcohol volume flow rate, U_R - relative velocity, D_{max} = maximum droplet size calculated by Equation (3), f_1 = frequency of free oscillation corresponding to D_{max} and calculated by Equation (5), f_2 = measured frequency).

they can be clearly observed in the photograph of Figure 4. In all cases, decreasing the alcohol feed rate for a fixed primary air flow rate resulted in a decrease in the number of larger droplets.

The above described tendencies were always observed and, in terms of frequency, did not depend on the O/F ratio. The amplitude of the generated oscillations, however, were strongly affected by the O/F ratio, as shown in Figure 5. The stoichiometric O/F ratio in this case is 8.95. The increase of oscillation amplitude as the excess of air increases can be explained by the fact that as more air is provided combustion is completed more rapidly and in a position closer to the burner which was located at L/4. As predicted by Rayleigh criterion, the energy fed to first harmonic oscillations will decrease as the position of heat release departs from L/4.

The above described results are in contrast with those obtained by Zinn et alii (1982) with a solid fueled pulsating combustor of the same geometry of the combustion chamber of this paper. They observed that maximum amplitude oscillations occurred when combustion took place near stoichiometric conditions. In that case, the combustion bed was fixed and the energy was effectively released near L/4.

The decrease of oscillation amplitude as the primary air flow rate increases for the same O/F can be explained in the same line of thought. As the primary air flow rate increases, larger droplets are generated and their complete out burn occurs in a position further from the burner.

Other mechanisms were considered as the origins of oscillations. The occurrence of Tollmien - Schlichting waves was not possible since the Reynolds number of the flow was in all tests lower than the critical Reynolds number for generation of instabilities. The generation of vortices as the gas flow passes by the burner or by

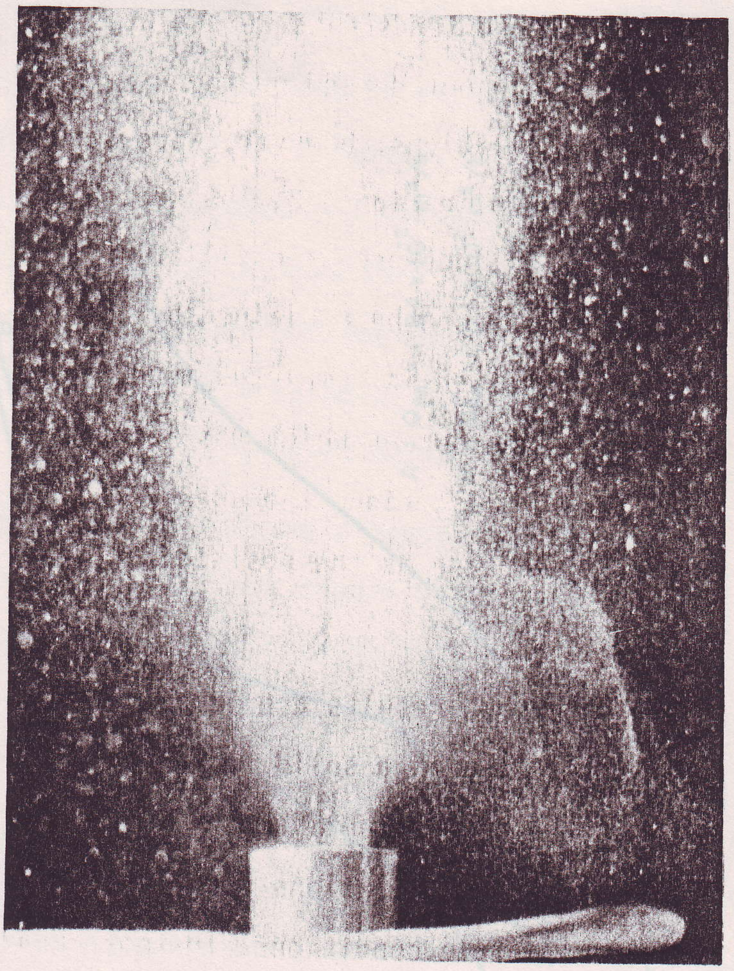

FIGURE 4 The spray.

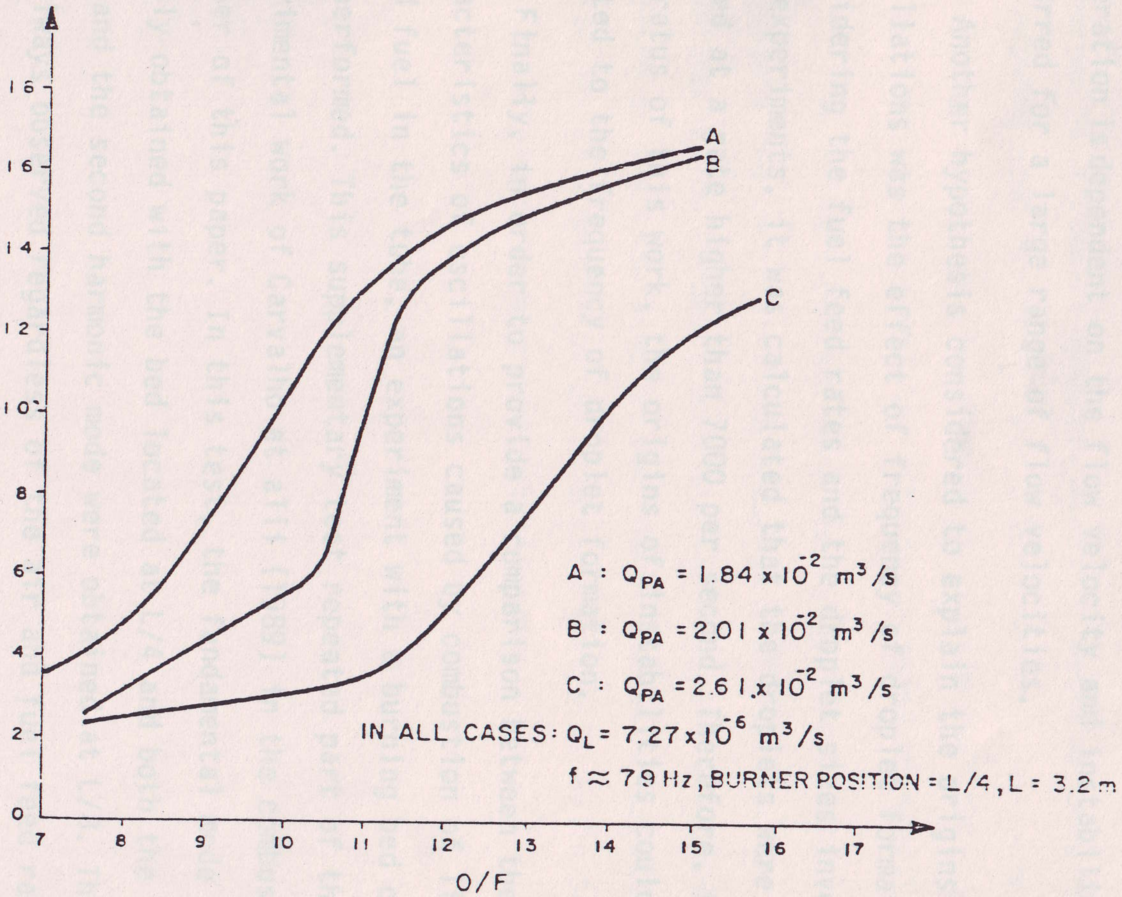

FIGURE 5 Dependence of the amplitude of acoustic pressure on the oxidizer to fuel ratio (Q_{pA}: primary air volume flow rate; Q_L: alcohol volume flow rate; f: frequency)

other parts of the combustion enclosure could also not be linked to the origins of oscillations. In this case, the frequency of vortex generation is dependent on the flow velocity and instabilities occurred for a large range of flow velocities.

Another hypothesis considered to explain the origins of oscillations was the effect of frequency of droplet formation. Considering the fuel feed rates and the droplet sizes involved in the experiments, it was calculated that the droplets were always formed at a rate higher than 7000 per second. Therefore, for the apparatus of this work, the origins of instabilities could not be related to the frequency of droplet formation.

Finally, in order to provide a comparison between the characteristics of oscillations caused by combustion of liquid and solid fuel in the tube, an experiment with a burning bed of wood was performed. This supplementary test repeated part of the experimental work of Carvalho et alii (1989) in the combustion chamber of this paper. In this test, the fundamental mode was readily obtained with the bed located at L/4 and both the fundamental mode and the second harmonic mode were obtained at L/8. This behavior was always observed regardless of the air and fuel feed rates. The gas flow through the heterogeneous pattern forced by the wood bed generates oscillations in a very broad range of frequencies which includes the natural frequencies of the tube. In this case, except for situations in which the gas flow rates are very low, the only condition establishing the location of the bed to produce oscillations is the Rayleigh criterion.

CONCLUSION

A mechanism that explains the origins of spray combustion instability was presented and checked experimentally with an alcohol burner in a tubular chamber. Acoustic oscillations, when excited, happened when the burner was placed in positions predicted by the Rayleigh criterion. The results indicated that the droplet free oscillation was associated with the origins of oscillations.

The authors believe that the results described in this work can be extended to predict the occurrence of oscillations in other types of combustion chambers such as, for example, a liquid rocket chamber. Based on the knowlwdge of the chamber acoustic characteristics, one can design a burner or an injection system to avoid instabilities that originate from droplet oscillation.

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