Suppression of Combustion Instability using an Aerodynamically Exited Atomizer

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ABSTRACT

The paper is concerned with the suppression of combustion instability in jet engine and gas turbine combustors. This is done by the optimization of a combined atomizer and flameholder assembly that is able to suppress the instabilities of the main combustor by generating an additional (controlled) oscillating liquid fueled heat source. The principal idea was to adopt a specially designed effervescent atomizer, driven by the energy of the oscillatory motion of the gas in the unstable combustor for the atomization and distribution of the additional control fuel. The ability of an atomizer to produce oscillating spray and the consequently heat release at a wide frequency range as well as its high sensitivity to small pressure perturbation was demonstrated. At some frequencies, 100%-modulated heat was achieved. In order to test the ability of the atomizer to suppress flame oscillations in a practical combustor, an experimental axisymmetric combustor was assembled that includes two sequential burners. The first (main), located upstream is fed with steady state air and fuel supply. The second (control) one was incorporated into flameholder assembly and located further down stream. Excitation of the combustor was accomplished by adding an oscillating airflow to host combustor airflow far upstream to the both atomizers. During the study, the main combustor was operated at wide range of frequencies (8- 1100Hz). During the study, the main combustor was operated at wide range of frequencies (8- 1100Hz). Thereafter the control atomizer was activated to act at the same frequency as the main combustor, however with different phases between the combustor pressure pulsations and the control atomizer triggering. The phase between the fuel injection and the pressure pulsations were varied continuously using a telescopic air tube.

Results clearly showed the effect of the control atomizer and its dependence on the phase. It is seen that at the appropriate phase, significant suppression was achieved. In practical combustion systems that suffer from severe pressure oscillations at a distinct frequency due to combustion instability, the control atomizer can be mounted at the appropriate location within the flameholder section of the combustor. The exact location and orientation should be so that the pressure difference between the stagnation and static pressures in that section will equal to the required pressure for the spray modulation. For typical flow velocities in the ramjet combustor, such a difference is much larger than the minimum required for the formation of spray and the associated heat modulation. This means that the effervescent type atomizer has the potential to suppress combustion instability almost completely in a practical combustor.

INTRODUCTION

Combustion instabilities were encountered in most propulsion system development programs. In liquid fueled ramjet combustors, the most dangerous oscillations are within the 80-500 Hz frequency range. This low-frequency "rumble" is generally characterized by longitudinal acoustic oscillations. Although considerable effort was invested in understanding and controlling this undesirable phenomenon over the last 60 years, it continues to present significant challenges in the design of reliable engines design. To date, the only way to overcome this problem in real ramjets and afterburners of jet engines is by experimental development of the fuel injection and flameholder assembly, which required hundreds of expensive ground testing of the full-scale combustor. Such an experimental development is based primarily on trial-and-error and is relevant only to the specific design.

One of the most advanced and promising techniques for suppression of the longitudinal combustion instability, is the active control principal. It has been shown that combustion oscillations can be stabilized by periodic addition of secondary fuel, usually in the form of premixed gaseous fuel. Typically, control is applied by active modulation of the additional fuel flow rate in synchronization with the signals of the pressure transducers located in the combustor with the required phase shift. The simulation of the instability suppression process predicted that only a small portion (0.1-0.3%) of the total fuel is needed to be injected in the oscillating manner for successful suppression [1]. In experiments with active controlled oscillating gas fuel injection, successful results were achieved with 3-4% of additional fuel injection [2]. However in an experimental design of a flameholder/injector combination within an actual kerosene fueled ramjet combustor, the suppression of longitudinal pressure oscillations was achieved only with a minimum of about 10% additional fuel injection [2, 3]. This means that significant amount of the additional fuel must be injected in an oscillating manner to stabilize practical combustor. Thus, in spite of progress in the modeling of control systems under laboratory conditions, the large amount of control fuel that is required limits the applications of these methods in real liquid fueled combustors.

An alternative concept was proposed at Refs. 4 and 5. The principal idea was to use a specially designed atomizer, driven by the energy of the oscillatory motion of the gas in the unstable combustor for the atomization and distribution of the additional control fuel (without external controllers). The additional fuel is part of the main liquid fuel of the combustor. The oscillating airflow in the unstable combustor enters the atomizer of the control fuel and consequently the atomizer produces an oscillating spray. As a result, additional oscillating heat is released at a certain time delay relative to the pressure oscillations. Hence the atomizer senses the pressure oscillations of the main flow and produces phase-shifted oscillating heat release as a response to these oscillations. Therefore, it can be considered simultaneously as a sensor, phase-shift controller, and actuator. It seems that proper atomizer design may result in spray and heat release modulation, at the frequency of the pressure oscillations and with phase shift, in accordance with Rayleigh's criterion, and lead to suppression of combustion instability.

An effervescent type atomizer was chosen as a prototype for this type of control. One of the main advantages of the effervescent atomization is that it can achieve good atomization even when operating at low air injection pressures (of the order of the dynamic pressure available in typical ramjet engines) [6, 7]. For typical flow velocities in the ramjet combustor (M = 0.25 - 0.35), the difference between stagnation and static pressures may be $\Delta P = 0.15 - 0.25\ kg/cm^2$. Such values were found to be sufficient for the formation of spray (and heat) modulation. This advantage highlight the need for guidance on the efficient usage of the available atomizing air in terms of pressure and flow rate to achieve optimum atomization performance. Unfortunately, all literature on effervescent atomization has focused almost entirely completely on the effects of liquid properties and operation conditions upon the drop-size distribution, and very little attention was given to the atomizer design. Information on effervescent atomization by oscillating air pressure is absent in the literature.

The ability of the flameholder assembly to suppress combustion instability by producing 100% modulated heat release in accordance with interchamber pressure oscillations was demonstrated in the past [5]. This was done through parametric investigation of the effect of atomizer dimensions and flameholder geometry, as well as the atomizing air supply pressure (AC and DC component) and fuel supply pressure, on the spray atomization and the consequent flame modulation. The present study make use of the same atomizer design and investigates the effect of the phase between the oscillating pressure wave driving the control heat source and the wave of the oscillating pressure within the combustor. Namely, the effect of the phase on the resulting pressure within the combustor.

METHOD

The principal idea of the present study was to adopt a specially designed effervescent atomizer, driven by the energy of the oscillatory motion of the gas in the unstable combustor for the atomization and distribution of the additional control fuel. The secondary (control) fuel source is situated inside the core of the main flame region and is supposed to counter-balance the pressure oscillations of the main (unstable) combustor.

For analyzing the ability of the flameholder assembly to suppress combustion instability, we modified and tested its ability to produce 100% modulated heat release in accordance with interchamber pressure oscillations. This is done through the parametric investigation of the effect of atomizer dimensions and flameholder geometry, as well as the atomizing air supply pressure (*AC* and *DC* component) and fuel supply pressure, on the spray atomization and the consequent flame modulation.

EXPERIMENTAL SYSTEM

The study makes use of a sophisticated and highly equipped laboratory scale combustion system. It is designed to operate under oscillating conditions using oscillating air supply and constant fuel source. The system includes an atomizer centrally mounted within a cylindrical tube and a flame holder in the form of a hollow cone, situated at further distance down stream. The air to the combustor could be supplied at constant condition or in an oscillating manner at different frequencies and at different *AC* (oscillating amplitudes) to *DC* (mean pressure) values. The combustor was capable to maintain high frequency flames over long period with frequencies as high as 1100 Hz. An additional fuel source was mounted at the core of the conical bluff body stabilizer of the combustor. This is an effervescent atomizer with separate fuel line and separate driving air supply. It has the capability to produce an oscillating spray (and heat source) at frequencies in the range of 7-1100 Hz [4]. Consequently, the secondary fuel source has the potential to counter balance the oscillation of the main combustor. At the present study the secondary fuel source was driven by air, oscillating at the same frequency as the main combustor. Its air is supplied through a variable length tube that allows changing the phase of its driving pressure wave relative to the oscillating pressure inside the combustor.

Changing the phase altered the structure of the global flame and heat release characteristics and optimal phases range was searched.

In order to test the ability of the atomizer to suppress flame oscillations in a practical combustor, an experimental axisymmetric combustor was assembled that includes two sequential burners, see figure 1. The first (main), located upstream is fed with pulsating air supply and constant fuel source. It has a high frequency response and can trigger high pulsations of flames. The second (control) fuel source was located further down stream (see Fig. 2). During the study, the main combustor (see Fig. 3) was operated at high frequency (about 600Hz). Thereafter the control atomizer was activated to act at exactly the same frequency as the main combustor, however with different phases between the air pressure pulsations and fuel pulsation.

Phase Doppler Anemometry (PDA) was used for time-dependent measurements of the diameters and velocities of droplets in the oscillating spray (cold flow experiments), see figure 4. The determination of flame oscillations, resulting from spray modulation, was based on the measurement of chemilluminescence of CH*-radicals (λ=431.5nm), which indicated the reaction intensities and location (see Figs. 4 and 5). The measurement system consisted of a photomultiplier (with data acquisition equipment), mounted on a vertical computer-controlled traversing mechanism, appropriate interference band pass filter, lens and 2x30 mm slit aperture for limiting the photomultiplier field of view to the flame cross section.

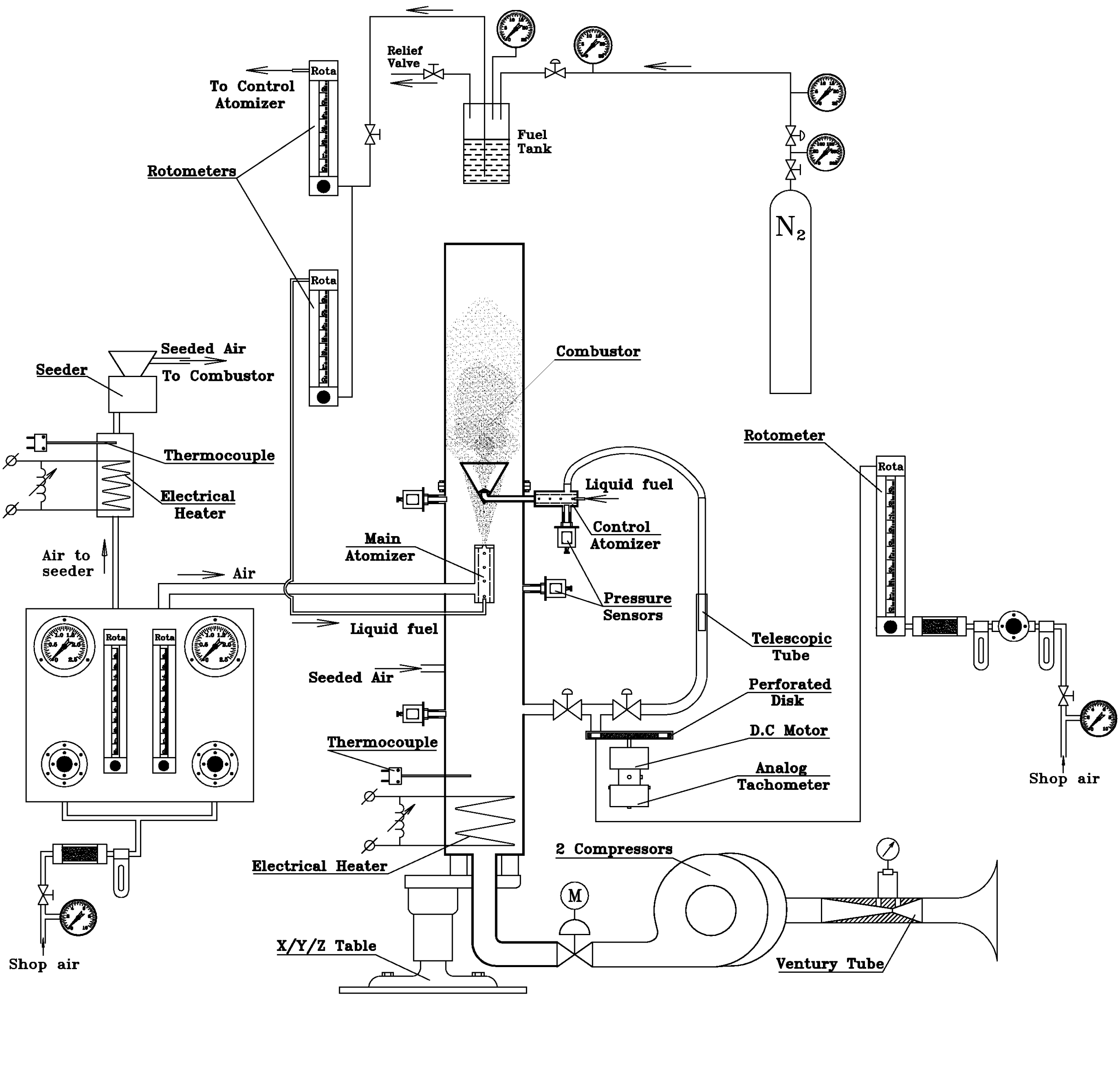
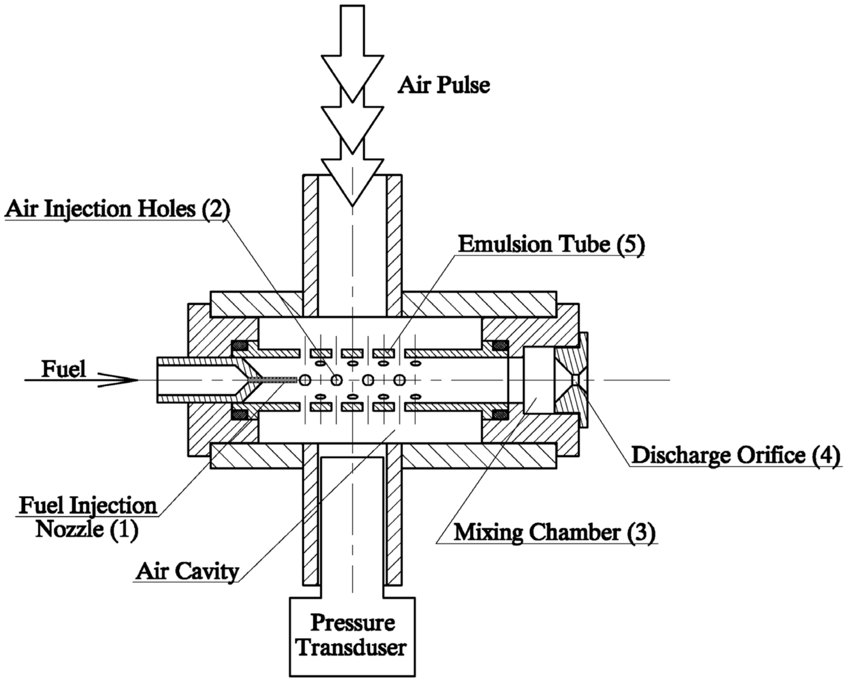
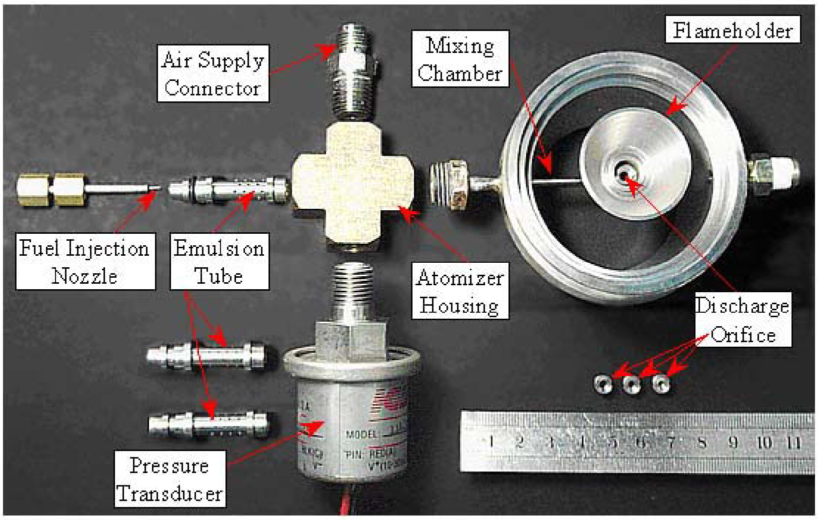


Fig. 1: The experimental system



a.



b.

Fig. 2. Schematic diagram (a) and photo (b) of the effervescent (control) atomizer.

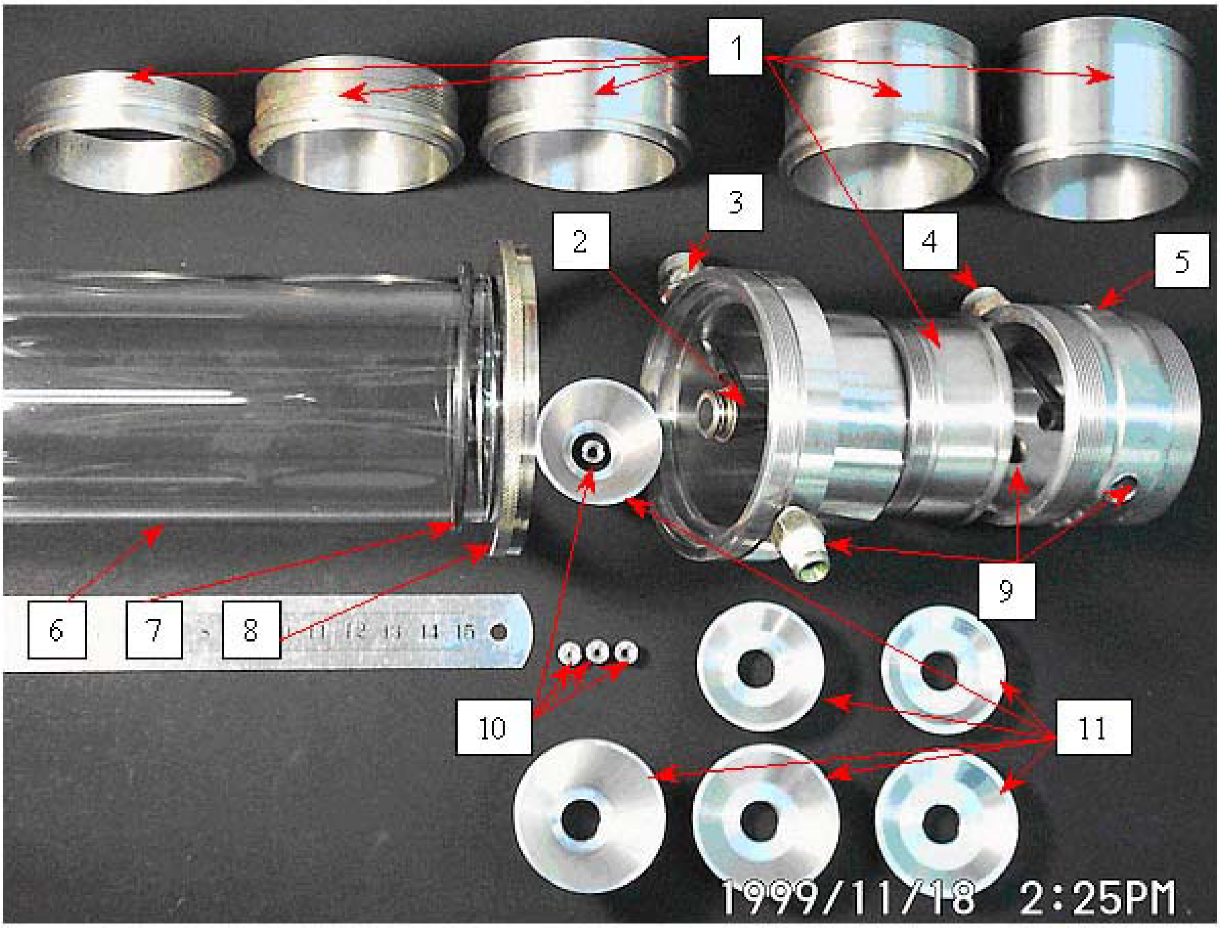


Fig. 3: The combustor assembly (cone-cone flameholder configuration). 1.- spacer; 2.-first cone of flameholder; 3. – control atomizer connector; 4. - main atomizer connector; 5. – thermocouple connector; 6. – quartz tube (the main combustion zone); 7.- O-ring; 8. – sleeve nut; 9. – pressure transducer connectors; 10. – discharge orifices of control atomizer; 11. – second cones of flameholder.

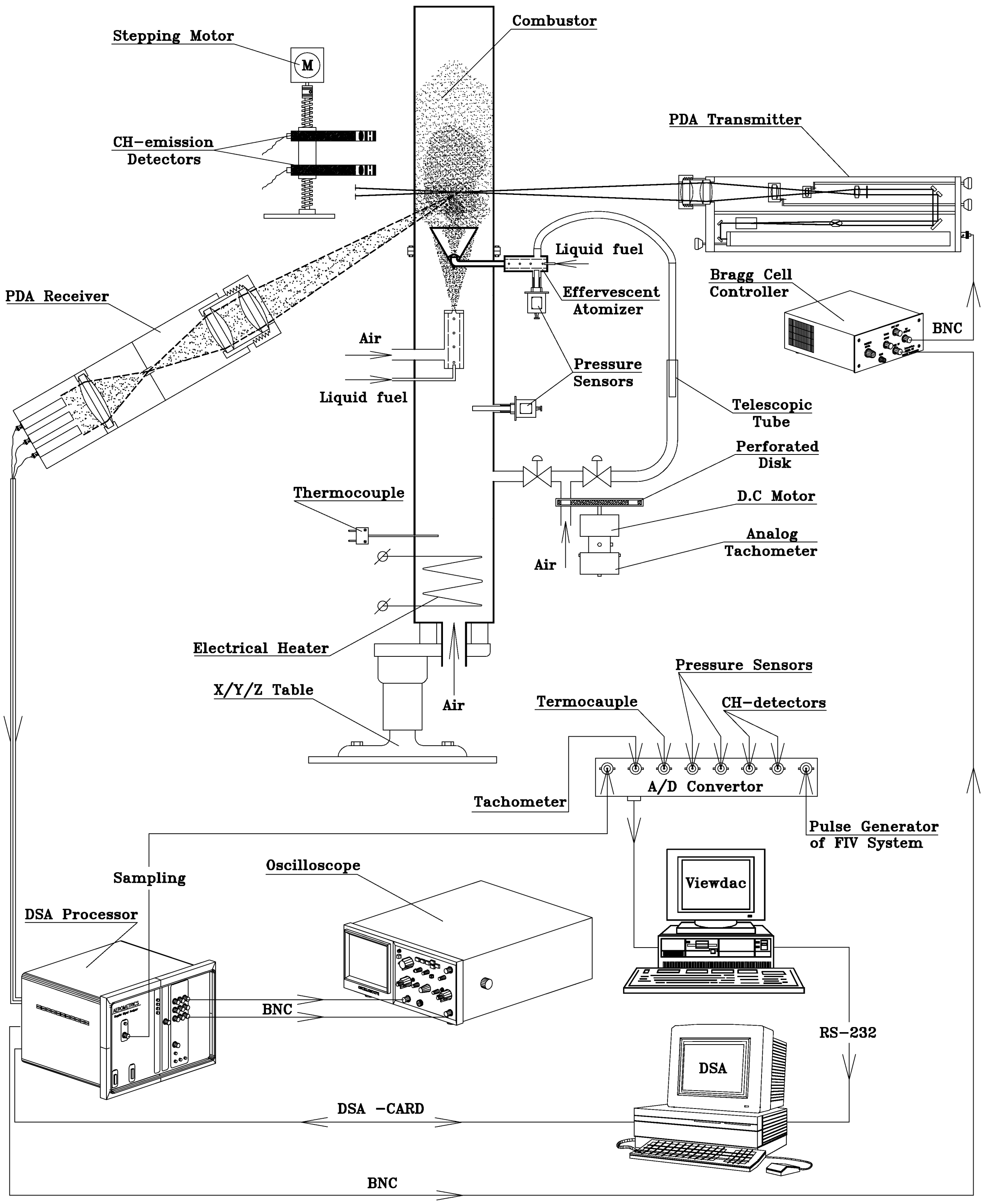
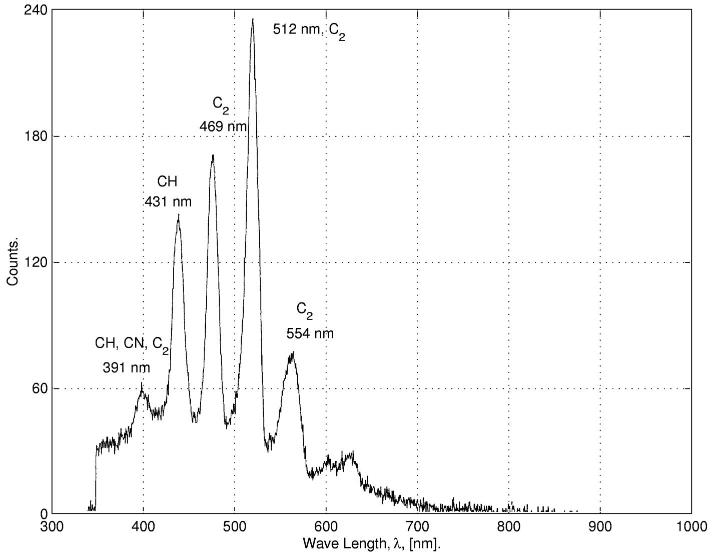
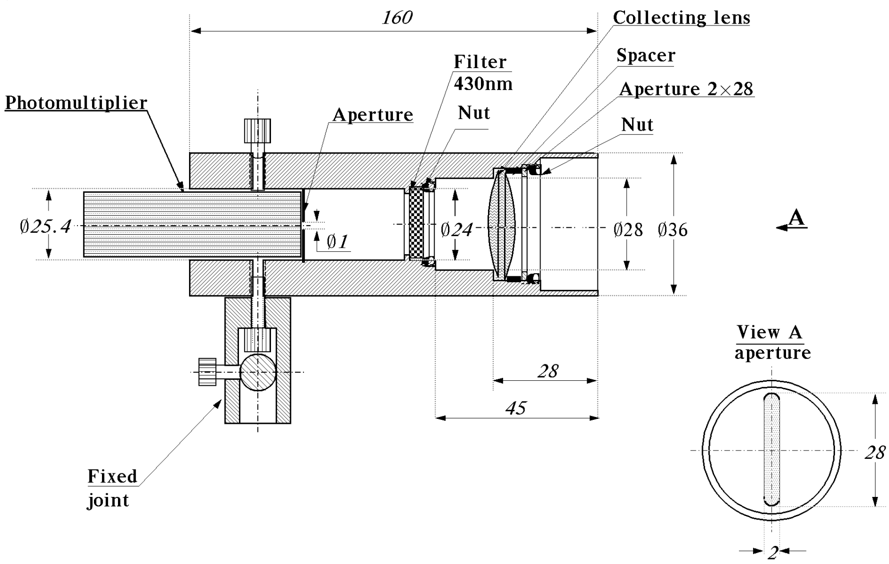


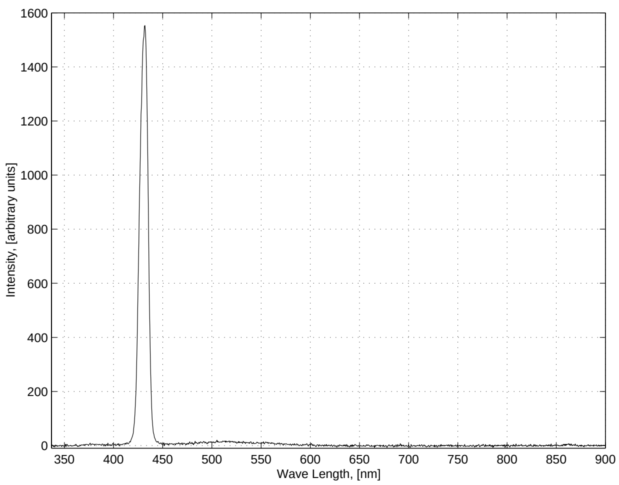
Fig. 4. Experimental and Optical Diagnostic System.



(a) Typical chemiluminescence spectra of Kerosene/Air mixture acquired by PCD-1000 spectrometer (Ocean Optics Inc.).



(b) Schematic drawing of the measurement instrument for the detection of heat release oscillations.



(c). Narrow band-pass filter characteristic for the recording of the CH emission (sun light acquired though the filter by PCD-1000 spectrometer, Ocean Optics Inc.).

Fig. 5: The measurement system

RESULTS

The present study has demonstrated the ability of the atomizer to produce oscillating spray and the consequently heat release at a wide frequency range as well as its high sensitivity to small pressure perturbation. The results clearly showed the effect of the control atomizer and its dependence on the phase.

Figure 6 demonstrates the atomizer response to air pressure oscillations - droplet diameter and velocity measurements of oscillating spray for operating frequency of 12 Hz, 16 mm downstream from the atomizer nozzle. The data rate of signals from the PDA system was sufficient to show the response of the atomizer to the pressure oscillation. This is seen by the coupled fluctuation of the spray velocity and droplet generation. Higher air supply frequencies also produced high frequency sprays however the present measurement system was not capable to demonstrate the phenomenon in a representable way. The mean droplets diameter vs. frequency of atomizing air is seen in figure 7 (Flame holder: cone-cone. Mixing tube with oval cross section). The mean droplet velocity vs. frequency of atomizing air for similar conditions is seen in figure 8. The time variation of the chemiluminescence emission of the CH* radical and pressure oscillations of the atomizer's driving air is seen in figure 9 (frequency = 9 Hz, 30 mm downstream of the flame holder). The measured flame characteristics is presented along the combustor axis: a) chemiluminescence b) chemiluminescence oscillation intensity at driving frequency. Figure 10 demonstrates an example of low amplitude flame modulation (a) and high amplitude flame modulation with variouse defenitions of the oscillating characteristics.

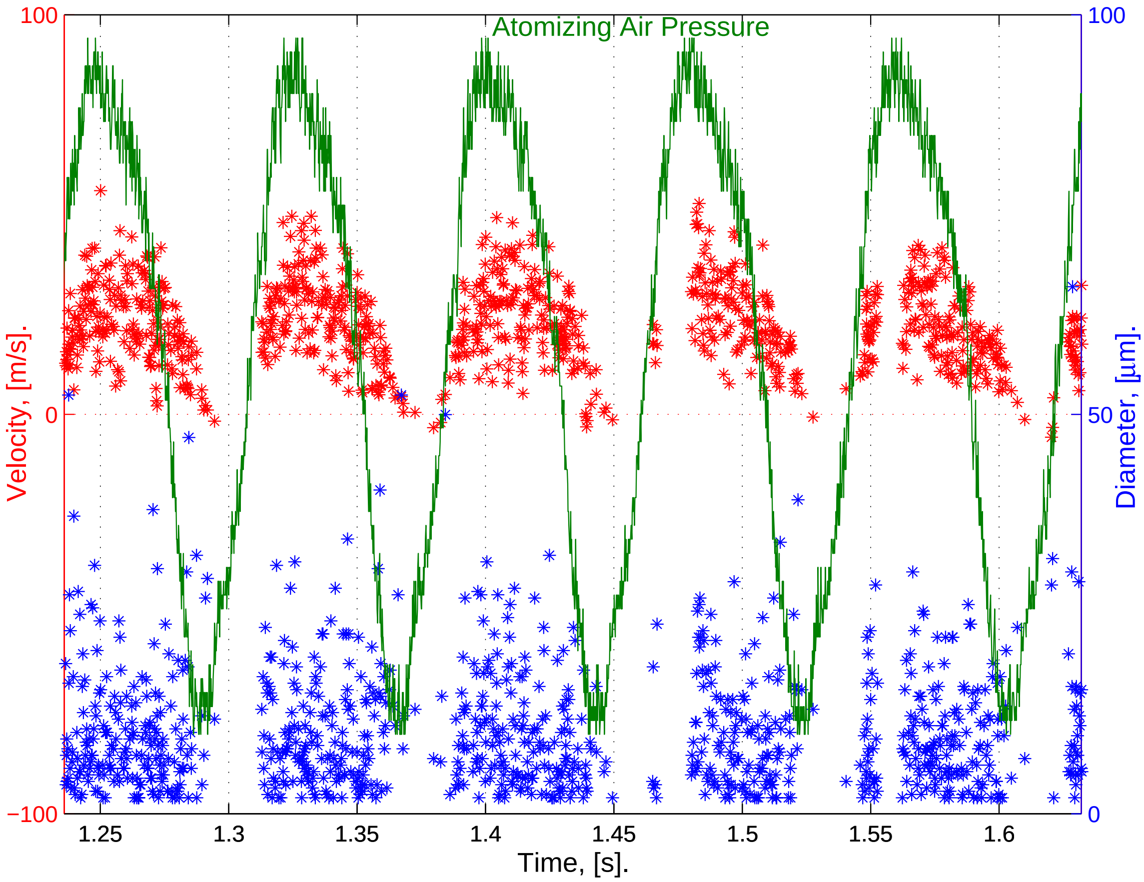


Fig.6. Atomizer response to air pressure oscillations - droplet Diameter and Velocity Measurements of Oscillating Spray, frequency = 12 Hz, 16 mm downstream from the Atomizer Nozzle.

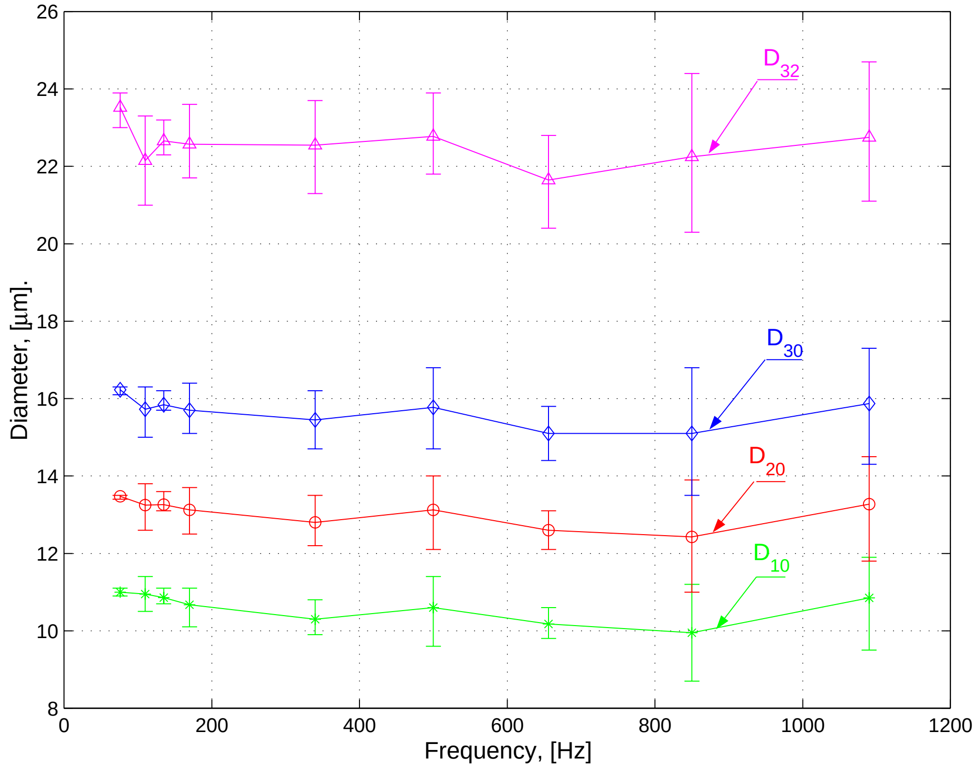


Fig. 7. Mean droplets diameter vs. frequency of atomizing air. Flame holder: cone-cone, mixing tube with oval cross section.

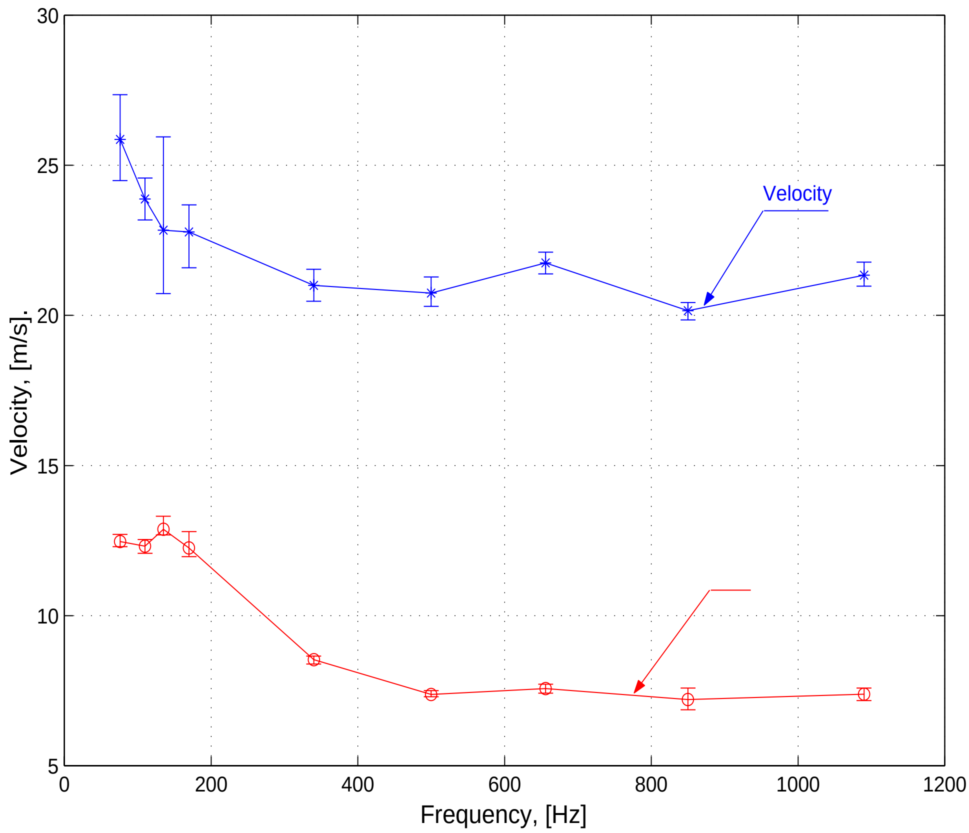


Fig. 8. Mean droplet velocity vs. frequency of atomizing air. Flame holder: cone-cone. Mixing tube with oval cross section.

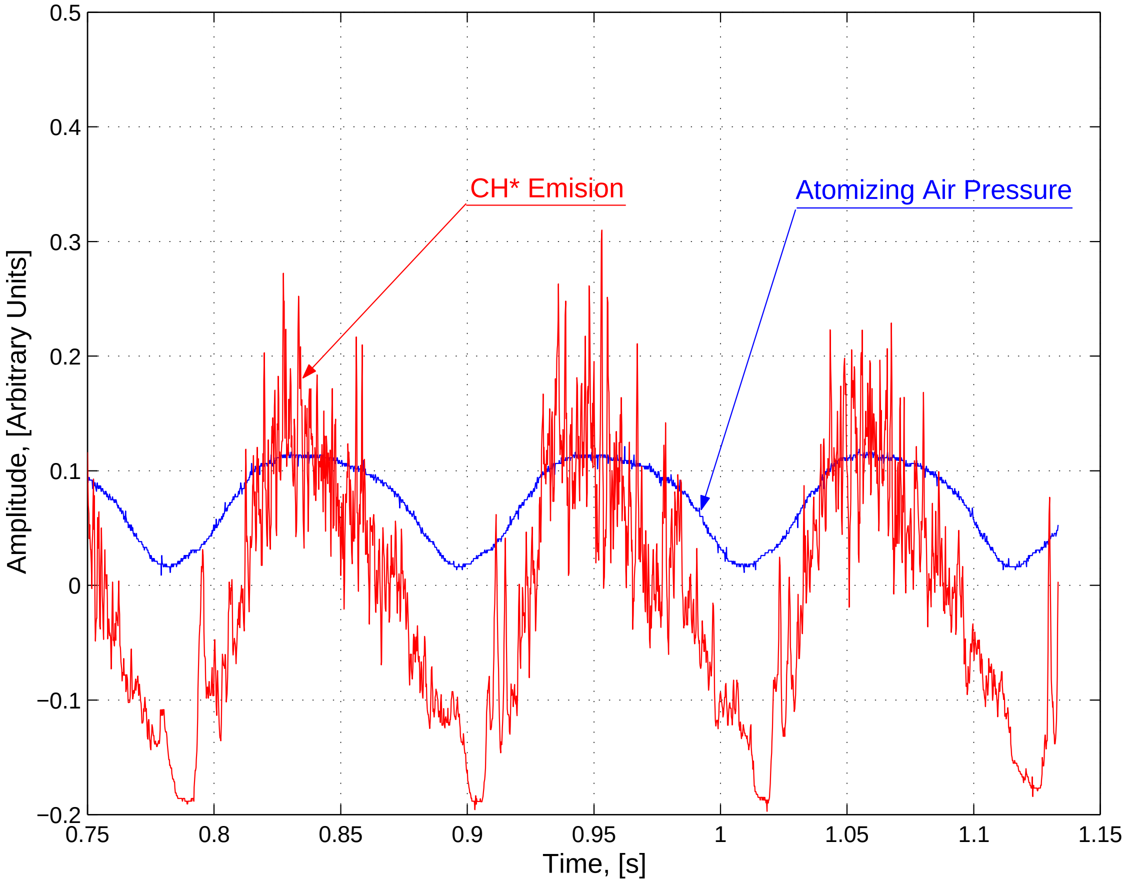


Fig. 9. Time variation of the chemiluminescence emission of the CH radical and pressure oscillations of the atomizer's, driving air, frequency = 9 Hz, 30 mm downstream of the flame holder.*

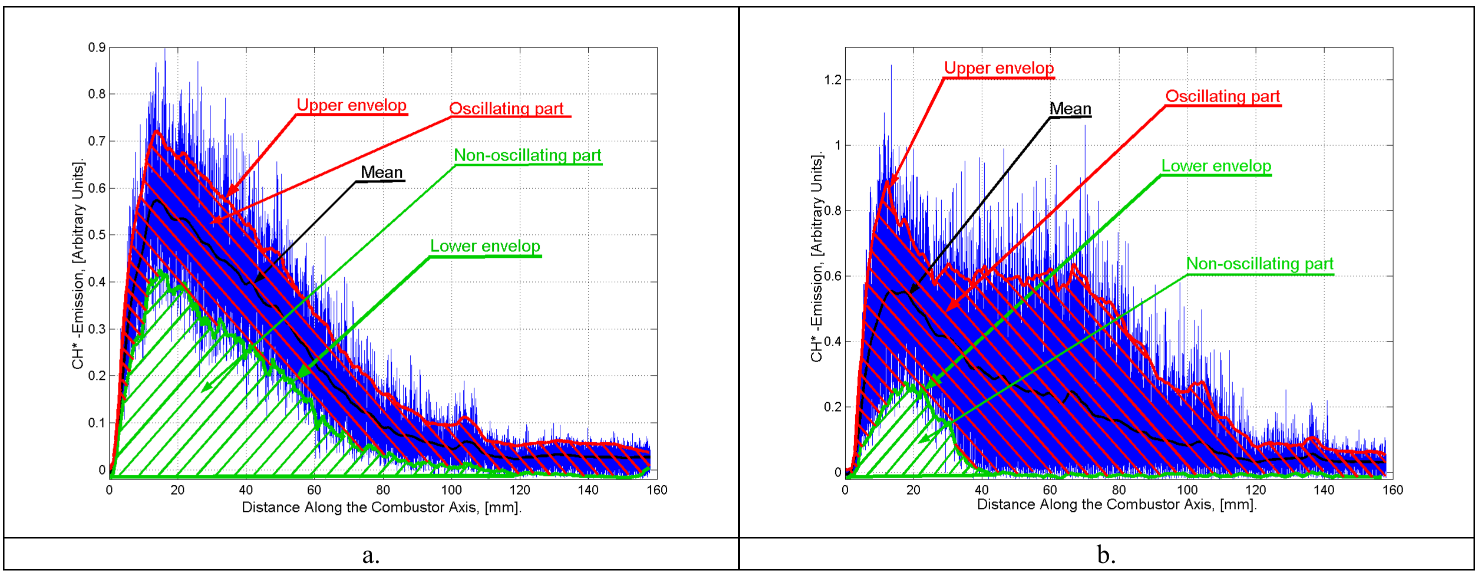


Fig. 10. An example of low amplitude flame modulation (a) and high amplitude flame modulation (b) conditions.

The combustor characteristics are demonstrated in figure 11 and figure 12. Figure 11 demonstrates the variation of CH* emission along the combustor axis. Figure 12 analyzes the frequency response of the combustion system: a)

Power spectra of combustor pressure oscillation at 4 mm upstream the flame holder (see Fig. 1), b) power spectra of oscillating driving air for control atomizer (inside the atomizer), c) power spectra of CH* at 22 mm downstream of the flame holder (the frequency spectra was obtained from the marked zone in Fig. 11). Figure 13 demonstrates the axial variation of heat release intensity at the driving frequency and at a certain phase between the pressure fluctuations inside the combustor and the fluctuations in the driving air of the control fuel atomizer. The variation of heat release modulation amplitudes at the driving frequency (570.9 Hz) and at different phases between the driving pressure of the control atomizer and the pressure fluctuations inside the combustor is seen in figure 14. The figure demonstrates maximum power spectra intensities, of the pressure oscillations inside the combustor, at about 110 degrees (phase difference). Figure 15 and figure 16 demonstrate the variation of the maximum local visibility and the area visibility with fluctuating frequencies for two geometrical designs, the cone-cone configuration 60^0 35 mm with "sharp" lip (Fig. 15) and with "normal" lip (Fig. 16).

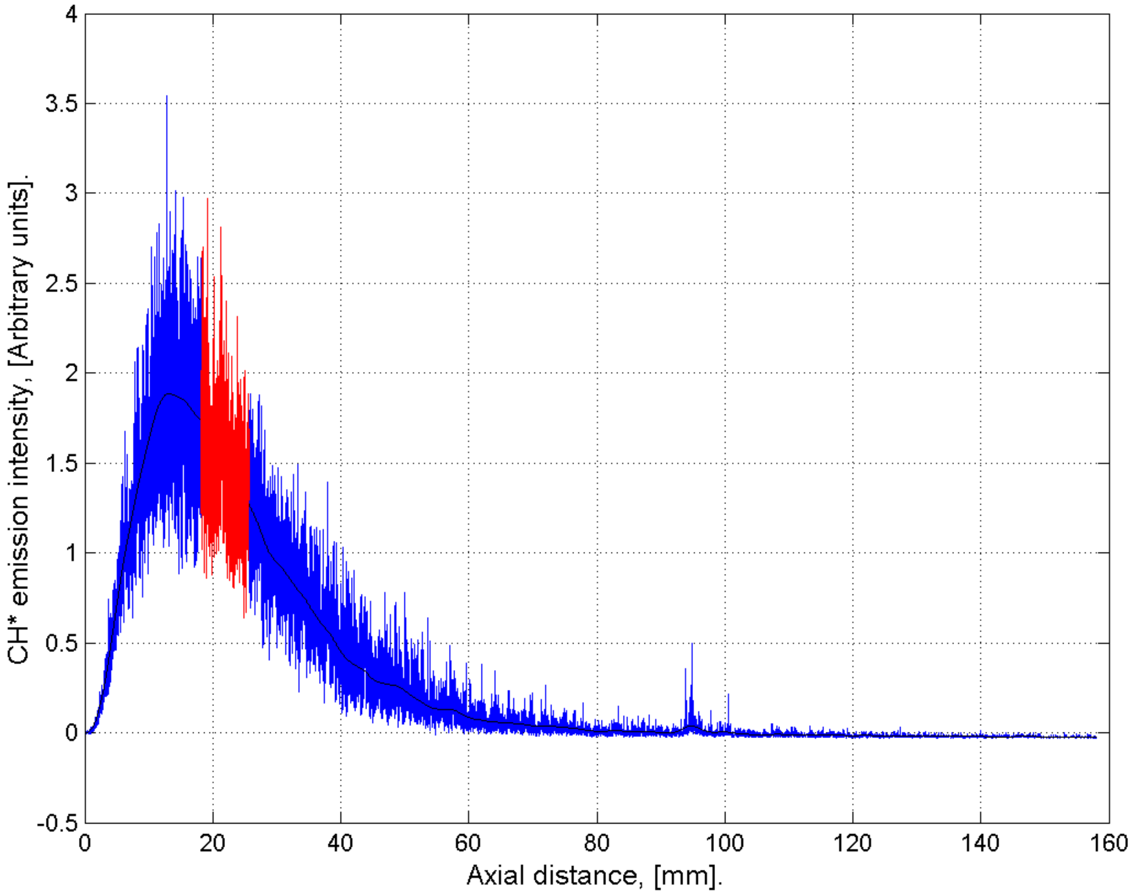
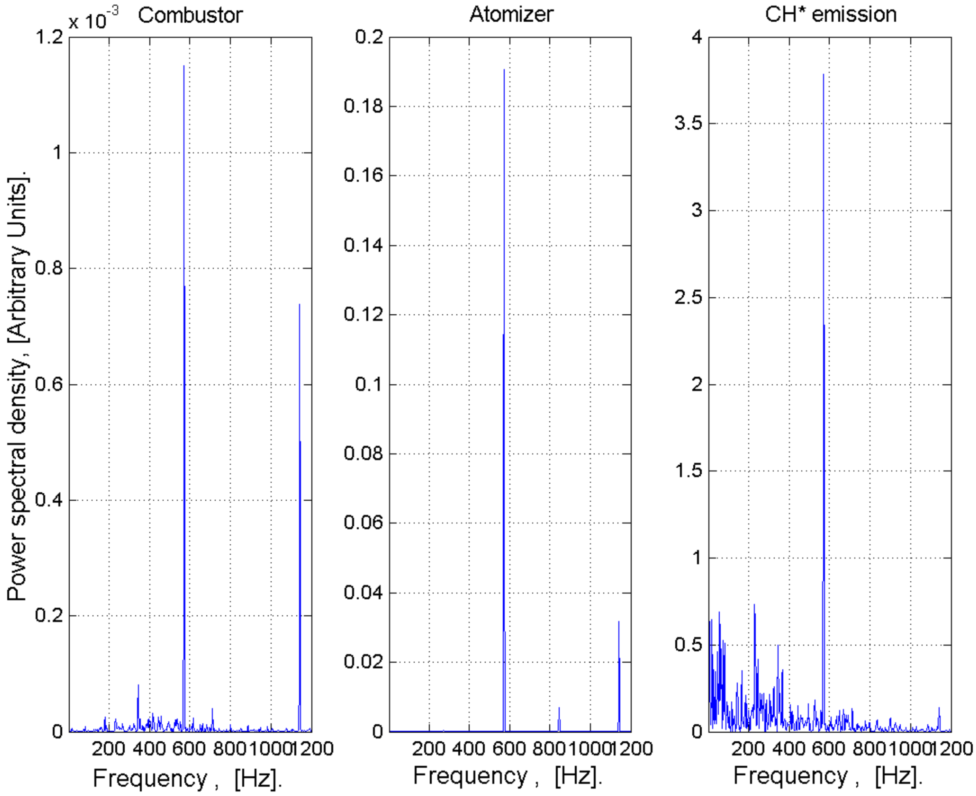


Fig. 11. Variation of CH emission along the combustor axis, the frequency spectra was obtained from the marked zone, driving frequency=570.9 Hz.*



a b c

Fig. 12. Frequency response of the combustion system: a) Power spectra of combustor pressure oscillation at 4 mm upstream the flame holder (see Fig. 1), b) power spectra of oscillating driving air for control atomizer (inside the atomizer), c) power spectra of CH at 22 mm downstream of the flame holder (frequency spectra obtained from the marked zone in Fig. 9).*

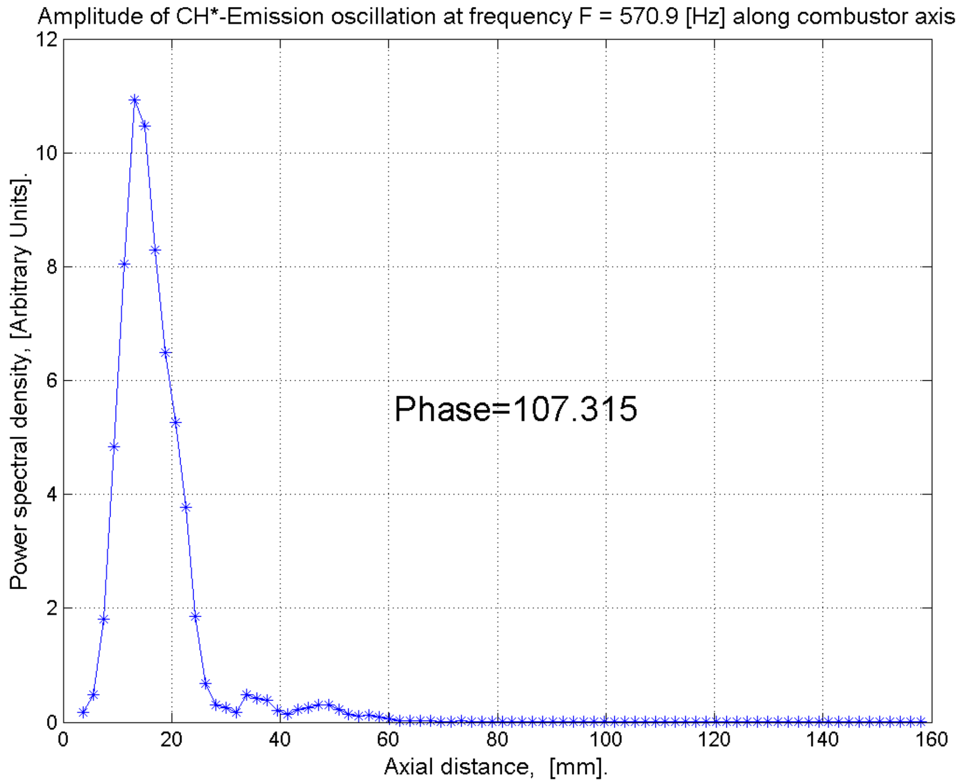


Fig. 13. The axial variation of heat release intensity at the driving frequency (570.9 Hz).

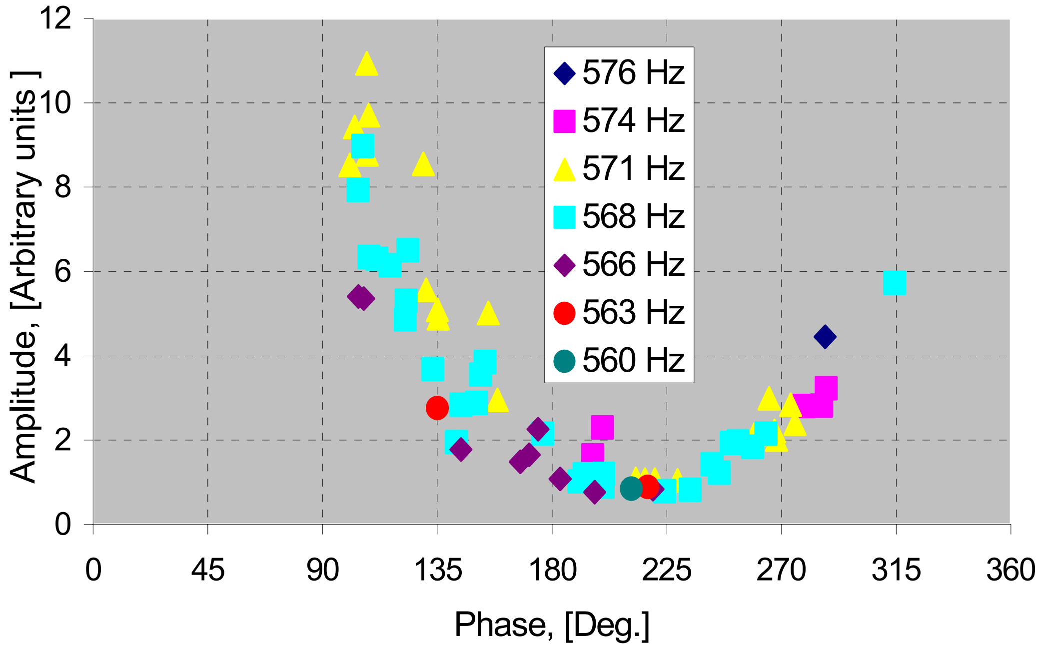


Fig. 14. The variation of heat release modulation amplitudes at the driving frequency (568.3 Hz) and at different phases between the driving pressure of the control atomizer and the pressure fluctuations inside the combustor.

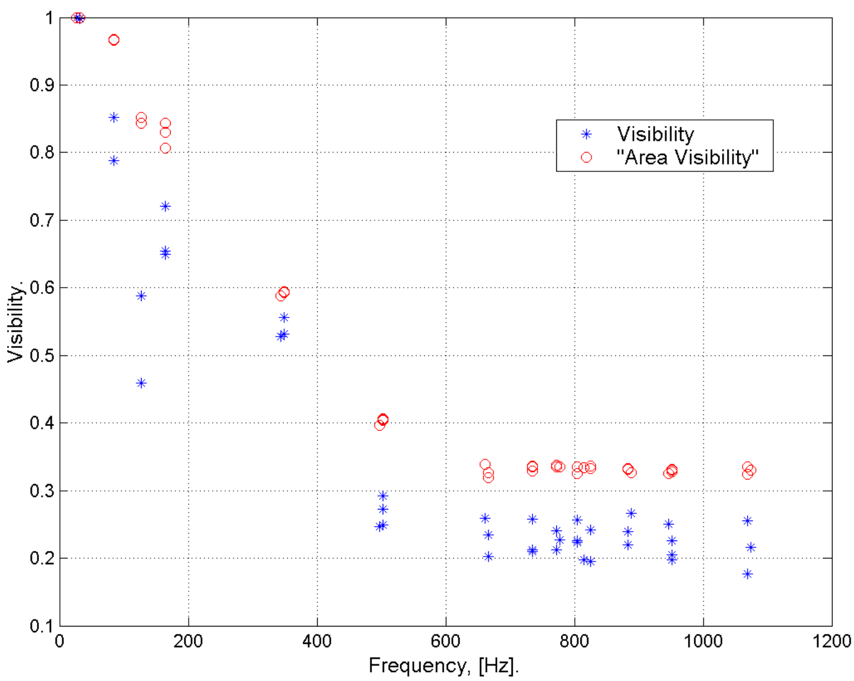


Fig. 15. The variation of the maximum local visibility and the area visibility with fluctuating frequencies for the cone-cone configuration 60^0 35 mm with "sharp" lip.

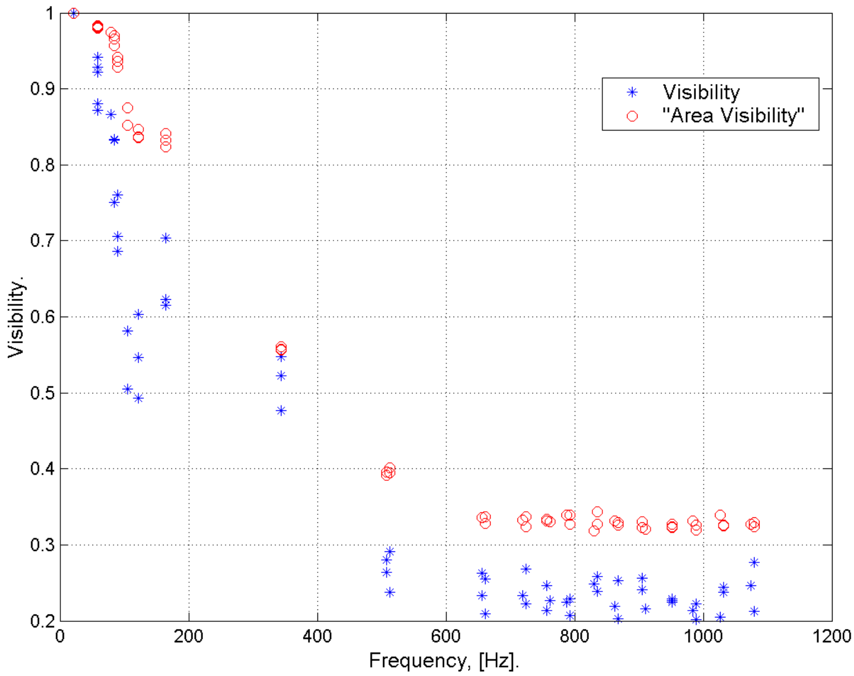


Fig. 16. The variation of the maximum local visibility and the area visibility with fluctuating frequencies for the cone-cone configuration 60^0 35 mm with "normal" lip.

CONCLUSION

The phase between the pressure fluctuations inside the combustor and the fluctuations of the driving air of the controlled fuel atomizer seems to have a significant influence. The pressure oscillations inside the combustor reduced by a factor of 6 while changing the phase from about 100 degrees to 260 degrees.
This phenomenon is in accordance with the basic Raleigh theory and demonstrates that with proper design, if the appropriate phase is maintained, a significant reduction in the pressure oscillations inside the combustor can be achieved.

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