An active control mechanism to enhance and parametrically study a multi-fuel, Rijke-type, pulse combustor

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An active control mechanism has been developed to study the effect of an actively controlled acoustic field on the characteristic parameters of a practical combustion system. This mechanism has been used to attenuate and enhance the combustion instabilities in a multi-fuel, Rijke-tube combustor. The main parameters for this control are discussed in both theory and application on the combustion process. Performance characterization as a function of important reactor and control system parameters for the control schemes developed, using either external loudspeakers or inline fuel modulation, are presented. The effect of the control mechanisms on the combustion process is studied by investigation of the changes in flame structure and heat transfer to the reactor walls. The results show that the burner position inside the Rijke-tube combustor is an important parameter for development and implementation of an effective control mechanism. Implementation of the control mechanism on a two-phase combustion system showed that the heat transfer to the wall of the combustor increased as much as 26% for oscillating conditions with a sound-pressure level of 150 dB (re: 20 μPa) over the non-oscillating value, along with an increase of temperature and mixing. The results from the implementation of the control mechanism on gaseous and liquid fuel showed a changed flame structure. The effects of controllable pressure modes on the flame structure are significant. In general the flame height decreased with oscillation and increased sound-pressure level indicating a more compact and efficient combustion process. © *1997 Institute of Noise Control Engineering.* [S0736-2501(97)00404-9]

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1. INTRODUCTION

Standing acoustic pressure waves have been observed in many practical combustion processes. These pressure oscillations, generally coupled with unsteady heat release, are known as combustion instabilities. Depending on the application, combustion instabilities can yield beneficial results, such as increased heat transfer for residential heating purposes, or catastrophic failure of the combustor, as in jet or rocket engines. Some benefits of pulsating combustion include enhanced mixing of fuel and oxidizer, increased heat transfer to the surroundings, higher temperature reactions, and more efficient combustion which leads to lower emissions and significant fuel savings.[1] In order to systematically study the effect of pressure oscillation amplitude and frequency on the combustion process to quantify these benefits, it becomes necessary to control the acoustic oscillations. This is particularly true in a Rijke-type combustor because the characteristics of the acoustic field are very sensitive to parameters such as overall stoichiometry, burner position, and fuel type. Furthermore, this sensitivity is such that repeated tests with the same operating conditions often result in significantly different acoustic conditions; therefore the need for active control.[2]

An active control mechanism implemented on a Rijke-tube combustor enables enhancement or attenuation of combustion instabilities. The Rijke-tube demonstrates one of the simplest manifestations of thermally driven acoustic oscillations. It consists of a straight open-ended pipe in which a heat source is placed in the lower half of the tube. The transfer of heat energy from the source to the air can become unsteady and can build up acoustic oscillations in the tube under the proper conditions, a phenomenon discovered and described by Pieter Leonard Rijke in 1859.[3] A Rijke-tube combustor was used for the present study to provide an environment in which the controllability of the frequency and amplitude of the acoustic field could be studied. The objective of this control was to isolate and study the effect of the acoustic mode amplitude on the characteristic parameters of spray and gaseous flames.

The control of the acoustic oscillations in the Rijke-tube is obtained using direct control of the acoustic field by loudspeakers and also by fuel modulation during gaseous combustion. Variables that have been observed to affect the controllability include sample rate of the controller, position of the flame in the combustor, combustor power, actuator power, geometry of the combustor, and actuator position. The effect of acoustic control has been linked to several combustion parameters including mixing, temperature profile, heat transfer, droplet evaporation and structure of the flame.

The objective of the present study was to demonstrate how an active control system can be used to enhance or attenuate combustion instabilities using direct control by loudspeakers and indirect control by fuel modulation. The present study was undertaken to develop an active control mechanism, to study the limitations of a controller in a combustion system, and to observe the effects this control

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has on the combustion process. The implementation of the control mechanism is important for two reasons: (1) fundamentally, the study of important phenomena not presently understood (such as the interaction of an acoustic field with reacting droplets) will be possible in a controlled environment; (2) practically the operating range of Rijke-type combustors is stabilized and extended making them more attractive for industrial applications.

A. Past research

Past research in the application of active control to combustion has focused on attenuation of combustion instabilities. In order to attenuate these instabilities several control schemes have been developed. In a review paper by McManus, Poinsot and Candel,[4] several studies using open-loop, closed-loop and adaptive-loop control mechanisms to control combustion instabilities by attenuation of the acoustic wave have been noted. The most practical and successful control schemes have been based on the principles of a feedback loop to produce the control signal. Control is accomplished by generating a secondary pressure wave exactly 180 degrees out of phase with the primary pressure wave. In order to implement this control approach it is necessary to monitor the primary pressure field and to use that pressure as an input to the controller in a feedback loop. A control algorithm based on this approach has been developed for a Rijke-tube combustor by Heckl,[5] who studied the stability of a feedback loop system. The results for a Rijke tube show a decrease in the flame-driven oscillations by over 40 dB. Poinsot, Bourienne, Candel, Esposito, and Lang[6] have also used the concept of destructive interference and feedback to suppress combustion instabilities. They have tested their active instability control theory in a 250-kW turbulent combustor and found that the sound-pressure level can be reduced by more than 20 dB.

In these studies stabilization of the pulsation has been the objective, but little is found in the literature for situations in which active control has been used to study practical combustion systems. Thus, the present study was undertaken to better understand the behavior of a combustion system under the influence of an actively controlled acoustic field of varying amplitude, and to understand the main parameters that affect the controllers performance.

2. THEORETICAL BACKGROUND

A. Control theory

Acoustic pressure fluctuations in a Rijke tube are the product of static conditions, such as the geometry of the tube, and also dynamic conditions, such as the temperature of the gas pulsating in the combustor which affects the speed of sound in the medium.[7] Standing pressure waves build up as a result of pressure reflections at the open ends of the Rijke tube.

By using active control algorithms a certain frequency, and thus a certain pressure mode, can be isolated via two different control methods. In this study, control is achieved by using a fast response feedback controller to induce a pressure wave through loudspeakers or a fuel modulator to induce fluctuations of heat release. Although several control schemes could be appropriate for this application and have been the subject of past research,[8,9] the fast-response feedback controller described by Poinsot, Bourienne, Candel, Esposito, and Lang[6] and Lang, Poinsot, and Candel[10] is used with slight modification because of the simplicity and robustness of the controller for attenuation. A block diagram showing the setup of the controller is shown in Fig. 1. For attenuation the controller monitors the primary pressure at a specified pressure transducer and changes the phase by 180 degrees. This phase-shifted input is then amplified and sent to the actuators, closing the control loop.

Enhancement of the primary pressure field is also possible using the same control scheme without phase shifting the input wave. This approach increases the amplitude of the primary standing wave in the tube. For enhancement, where the standing wave amplitude may be nonexistent or very small, it is necessary to induce a pressure field at the desired frequency. This reference field, which can be the output of a function generator, is compared to the primary pressure field in the tube and the difference between the two fields is sent to the actuator(s). In this manner a specific pressure field frequency and amplitude can be obtained in the combustor.

B. Indirect control

The sound field can also be controlled by modifying the source of oscillation, which in this case is the burning of fuel inside the combustor. It has been shown that the burner position has a direct effect on the acoustic mode(s) which naturally occur in the combustor.[11] However, this is not the only way of controlling the acoustic mode with the flame. Past studies have demonstrated that combustion instabilities can be attenuated by fuel modulation.[12] The present study has investigated how control by fuel modulation is affected by the burner position. This fuel modulation method will be referred to as *indirect control* of the sound field.

The sinusoidal compression and rarefaction of the gas allows coupling with the heat release and expansion of the burning fuel which can intensify or attenuate the primary

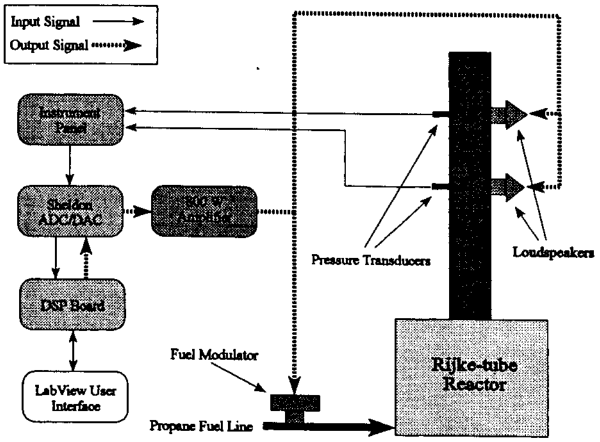

Fig. 1 – Block diagram of the control schematic developed at BYU to actively control the Rijke-tube combustor.

standing acoustic wave as dictated by the Rayleigh criterion for pulsating combustion. This criterion is that heat addition at the maximum compression will increase acoustic oscillations and heat subtraction at the point of maximum rarefaction will have a similar effect.[3] Practical limitations of control in this manner are dictated by the power limitations of the actuator as well as the expansion per unit volume of the gaseous fuel. With a gas of low expansion per unit volume, one does not expect high controllability by fuel modulation because the expansion of the gas is linked directly to the flow mode inside the reactor. Burner position also plays a vital part in this control of the standing acoustic wave by the flow mode. Another practical limitation of fuel modulation is burner design. Burner design determines controllability in that the burner assembly can act as an acoustic filter, which may decrease the controller effectiveness at certain frequencies. Acoustic filtering characteristics change with different burner geometry. Changes in burner design may take place as a result of natural burning phenomena, such as sooting or slagging. For this reason, direct control of the sound field by loudspeakers may be a more desirable option.

C. Direct control

The pressure modes associated with the frequency of oscillation can be actively controlled (enhancement or attenuation) by inducing secondary pressure waves via an external loudspeaker(s) mounted in the wall of the Rijke reactor. This method of using loudspeakers to control the sound field will be referred to as *direct control.*

In direct control by loudspeakers, the power limitations of the actuators still dictates the controllability. This limit of power can be partially solved by arranging actuators in a manner in which multiple actuators influence the same axial position in the tube. In this way several actuators can be used to influence the acoustic pressure in the tube. The loudspeaker position in the tube is also of vital importance because pressure modes cannot be controlled by a loudspeaker operating at the nodal position of oscillation. Acoustic wave forms associated with the first three acoustic modes in a Rijke tube for both acoustic velocity and pressure are shown in Figs. 2(a) and 2(b), respectively. These plots were obtained from the simplified equations for the standing wave amplitude as developed by Carvalho, M. Ferreira, Bressan, and J. Ferreira.[11]

Implementation of control through loudspeakers also requires the design of a proper speaker enclosure to direct the controlled pressure to the region of the tube of interest for control. This enclosure is often a gradually necked-down tube with acoustic properties of its own and, like the burner with indirect control, it may act as an acoustic filter. The enclosure can also be further complicated by the requirement of cooling and shielding the actuator from the intense heat associated with the combustion process. These requirements of cooling and thermal shielding further complicate the acoustic properties by elongating and curving the enclosure.

3. EXPERIMENTAL FACILITY

Figure 3 is a schematic of the Rijke-tube combustor used in the present investigation. This variable-length combustor has a maximum length of 3.0 m and a diameter of 0.2 m, and has water-cooled walls. Acoustically, the tube is open

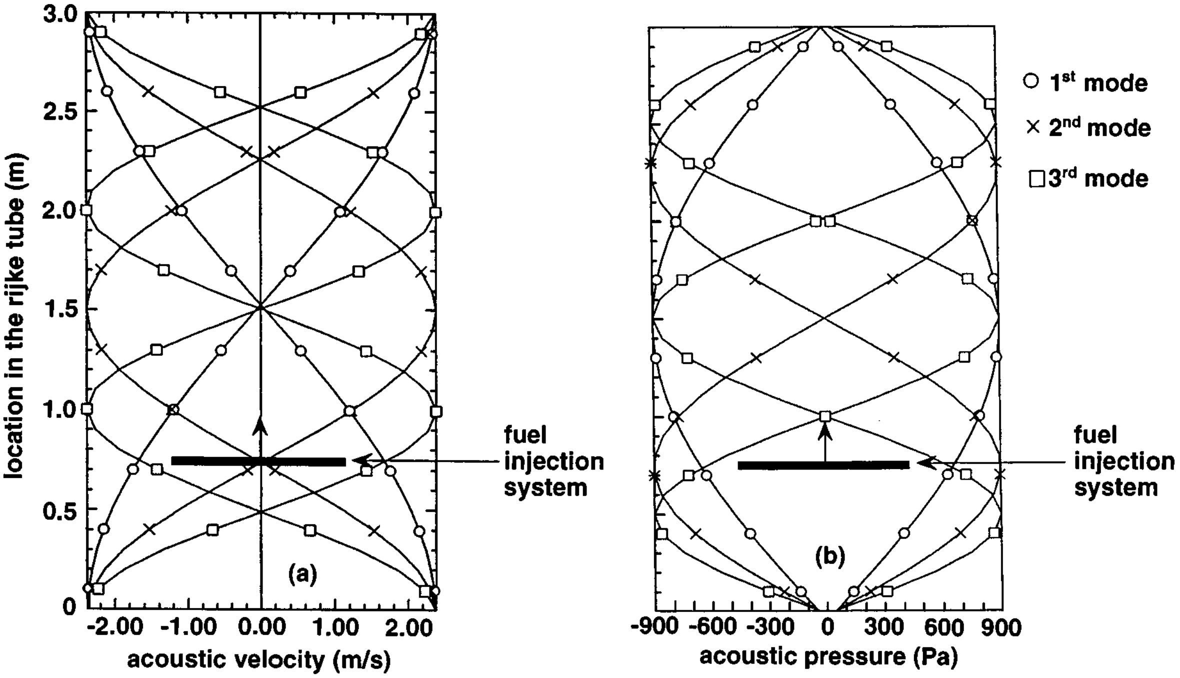

Fig. 2 – (a) The velocity flow field for first, second, and third mode of oscillations inside the Rijke-tube combustor. (b) The pressure field for first, second, and third mode of oscillations inside the Rijke-tube combustor.

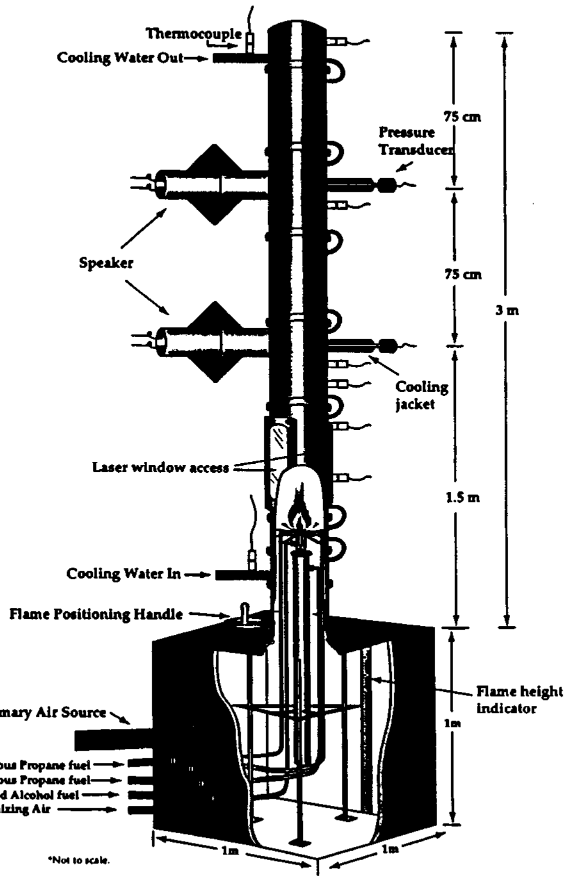

Fig. 3 – Artistic rendition (not drawn to scale) of the Rijke-tube combustor used in the present study.

on both ends. The Rijke combustor is open to the atmosphere at the top and is mounted on top of a 1-m^3 cubical decoupling chamber. The frequency and sound pressure of the acoustic wave is measured at $L/2$ and $3L/4$, using factory-calibrated pressure transducers with a sensitivity of 0.022 pC/Pa. Two 350-W Clarion loudspeakers can be mounted at $L/2$ or $3L/4$ (where L is the total length of the reactor) to directly control the acoustic field inside the combustor. Indirect control is implemented by compression and rarefaction of the gaseous fuel using a Sanming SG-100 driver on the gaseous fuel line. As noted earlier, the control scheme used is a fast-response feedback controller. Amplification of the output signal is accomplished by an 800-W dual channel amplifier. The controller is digital signal processor (DSP) based so that the processing time and the phase lag between output and input waves are minimal. The control scheme was implemented using a Sheldon Instruments SI-100 with a user interface of LabVIEW for Windows.

Several sets of experimental data were taken so that the controller performance and the effect of this control on the combustion process could be studied. With the oscillating pressure waves being actively controlled, several sets of variables were monitored. Temperature profiles along the center line of the combustor were measured, along with the heat transfer to the water-cooled walls of the reactor. Average temperature measurements were made at six positions above the burner along the central axis of the Rijke combustor using K-type thermocouples. The two significant locations were near $L/4$ and at the exit plane of the combustor where the maximum and minimum temperatures were measured, respectively. K-type thermocouples were also used for measuring the temperature of the inlet and exit of the cooling water. Flow rate of the water was measured using an Omega rotameter.

Laser and visual access windows are 80 mm wide and 460 mm high and are positioned at 150 degrees from each other in the reactor. The reactor can be configured so that these windows are available near the desired burner position. Axial profiles of droplet diameter, velocity, and data rate were measured for an ethanol spray flame through these windows along the nozzle axis using a phase Doppler particle analyzer (PDPA). Photographs of the flame were taken to see the changes in flame structure due to the acoustic field. These measurements provide insight into the mixing, and overall combustion efficiency under the various acoustic situations that were controllable.

A schematic diagram of the burner is shown in Fig. 4. The entire burner assembly is mounted on a positioning device whose location can be adjusted from outside the combustor to vary the location of the burner from $L/8$ to $L/2$ within the Rijke tube. This burner has the capability of burning both liquid and gaseous fuels. The burner consists of an annular cavity that has ten burner arms to distribute gaseous fuel at the burner plane. A Delavan AIRO, model 30615, solid cone air atomizing nozzle was located at the center of the burner. This nozzle uses high-pressure air to

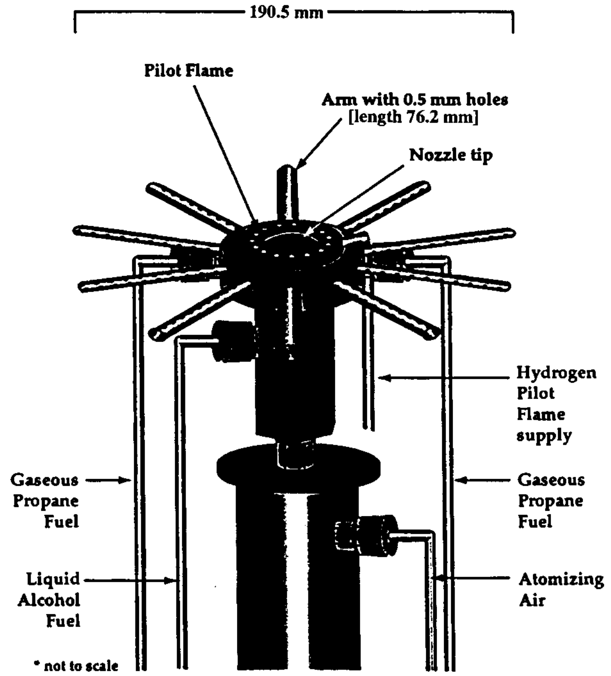

Fig. 4 – Artistic rendition (not drawn to scale) of the burner assembly used in the present study.

atomize the liquid ethanol into a solid cone spray and produces droplets in the range of 3 to 150 μm.

The main parameter studied for the controller performance was the sound-pressure level for varying burner positions using both direct and indirect control on the Rijke-tube reactor. The sample rate of the digital control was also studied. The effect of combustor length and total combustor power was investigated for controller performance, using loudspeakers and fuel modulation. The effect of changing fuels was also studied. The first three acoustic modes were studied under the influence of the controller. From these main parameters that were investigated, several trends are identifiable and provide a reference for the practical implementation of active control on a pulse combustor.

4. RESULTS AND DISCUSSION

The results and discussion are divided into two sections. The controllability and the variables affecting the controller performance are discussed, followed by a discussion of the effect of the control mechanism on the combustion process.

A. Controllability

Attenuation of the combustion instabilities has been demonstrated on the combustor under various conditions. Burner position in the combustor was found to have the most noticeable effect on the attenuation when using indirect and direct control. Figures 5(a) through 5(c) show how the attenuation is affected by the burner position. Propane was used as the fuel in these cases with the burner position as the controlled variable. Stoichiometry was held at an excess air of 700%. In all cases, the controller had to overcome natural oscillations in the tube. Natural oscillations were dominated by the first mode and thus monitored by the pressure transducer located at $L/2$. This pressure transducer was used to generate the feedback signal. A transitional region was noted for the control using direct as well as indirect control. This transitional region is defined as the area where a stable reactor could be maintained and an oscillating reactor would remain in oscillation. As Heckl[5] noted, maintenance of a stable combustor required negligible power to the actuators. As a result, if the burner was moved up from the area below the transition region, there was relatively little attenuation observed until the upper edge of the transitional region was reached. On the other hand, if the burner was moved down from the area above the transitional region, significant attenuation was observed until the lower edge of the transitional region was reached. Below this transitional region, the natural oscillations built up despite the control effort which acted in opposition to the oscillations. It is noted that while natural oscillations did build up in the combustor, the amplitude of the standing wave was lower than under uncontrolled conditions.

For all cases, as the height increased, controllability also increased. This increased control for attenuation is a result of the heating region moving into the upper half of the tube, which has been found to suppress the first mode natural oscillations as noted by Carvalho, M. Ferreira, Bressan, and J. Ferreira[11] and also as suggested in the Rayleigh criterion.[3] Controller performance in regard to attenuation was notably lower for the direct control from $3L/4$ [see Fig. 5(c)]. This is expected, since the first mode is the dominant mode in the tube, and an actuator positioned at $3L/4$ is not as effective as one placed at $L/2$ for this mode. There is also significant acoustic delay from an actuator at $3L/4$ to the feedback pressure transducer at $L/2$; this delay leads to decreased controller performance as the phase discrepancy increases.

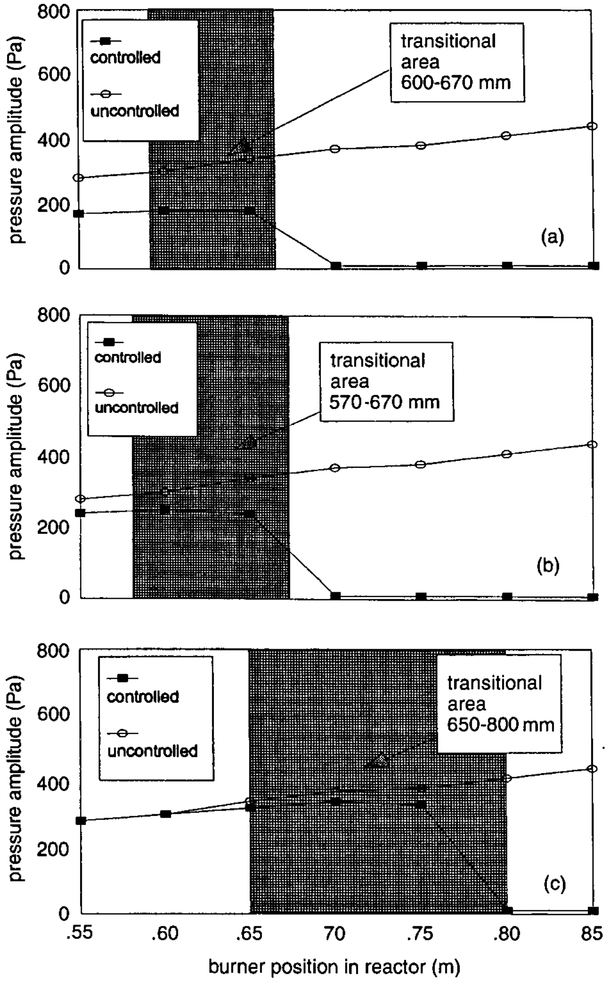

Fig. 5 – (a) Variation in pressure amplitude as a function of burner position inside the combustor under attenuation by indirect control using fuel modulator. (b) Variation in pressure amplitude as a function of burner position inside the combustor under attenuation by direct control using external speakers at L/2 position. (c) Variation in pressure amplitude as a function of burner position inside the combustor under attenuation by direct control using external speakers at 3L/4 position.

Direct control at $L/2$ [see Fig. 5(b)] and indirect control [see Fig. 5(a)] showed an increased effect for attenuation of the first mode. The direct control of $L/2$ has the greatest effect on the attenuation of the first mode because it has the lowest transitional region. Examination of the pressure modes in Fig. 2(b) reveals that direct control should have the greatest effect on the first mode from the $L/2$ position.

Like attenuation, enhancement is also affected by actuator and burner position. Figures 6(a) through 6(c), show that the enhancement of the first three modes is affected by burner position for the control methods. As expected, direct control from $L/2$ loudspeakers [see Fig. 6(b)] has limitations during enhancement of the second mode. This is a result of the attempt to control a mode at its nodal point. Enhancement of the second mode is facilitated by moving the actuator to $3L/4$, as seen in Fig. 6(c). Figure 6(a) shows that indirect control enhancement capability of the second and third modes is notably less than that observed for the first mode (significantly more so for the third mode, where no enhancement is observed). This is a result of low-pass acoustic filtering of the burner associated with its geometry. The burner acts as a low-pass acoustic filter because of the larger annular cavity connected to the smaller burner arms that spread the flame at the burner plane.

Carvalho, M. Ferreira, Bressan, and J. Ferreira[11] have studied in depth the influence of the burner position on natural oscillations. They have found that the position of the burner correlates directly with the acoustic mode in Rijke-type combustors. From their analysis it is known that for burners located at velocity nodes, natural oscillations will not occur for the corresponding mode. Results of enhancement from the present study, also confirm their findings. As Figs. 6(a)–6(c) show, enhancement is high at certain burner positions in the combustor. These positions correspond to velocity antinodes which demonstrates the coupling between pressure control and the velocity mode due to expansion of the gaseous fuel burning and heating.

Coupling between the velocity mode for the burner position and pressure mode for the actuator position is evident in the results found for enhancement by direct control from the $L/2$ position in Fig. 6(b). As previously noted, the second mode is not highly controllable from this actuator position for the current actuator and setup. For the third mode, $L/2$ is positioned at a pressure antinode, thus it is expected that the control from this position should have a significant effect on the third mode. Coupling between velocity and pressure is evidenced by the lack of enhancement when the burner position passes through the third mode velocity node near 500 mm. This coupling effect can be minimized by controlling the mode from a position near to but not exactly on the pressure antinode for the desired mode. This is evidenced by careful analysis of the third mode enhancement by direct control from $3L/4$ in Fig. 6(c). Examining the third mode enhancement reveals that little change in pressure amplitude is noted for various burner positions. It is also noted that the maximum level of enhancement is not as high as that of direct control from $L/2$. Because $3L/4$ is slightly below an antinode of the third mode, the actuator can also couple with other acoustic modes. This distorts the acoustic field so that it is not necessarily a single dominant mode, and this allows a consistent pressure amplitude as the burner moves through the third mode velocity node, thus minimizing the coupling effect between burner position and pressure amplitude.

The sampling rate of the controller was also investigated to study its effect on both enhancement and attenuation inside the combustor. Table 1(a) and (b) shows how the sample rate affects the attenuation and enhancement for indirect control and direct control from $L/2$, respectively.

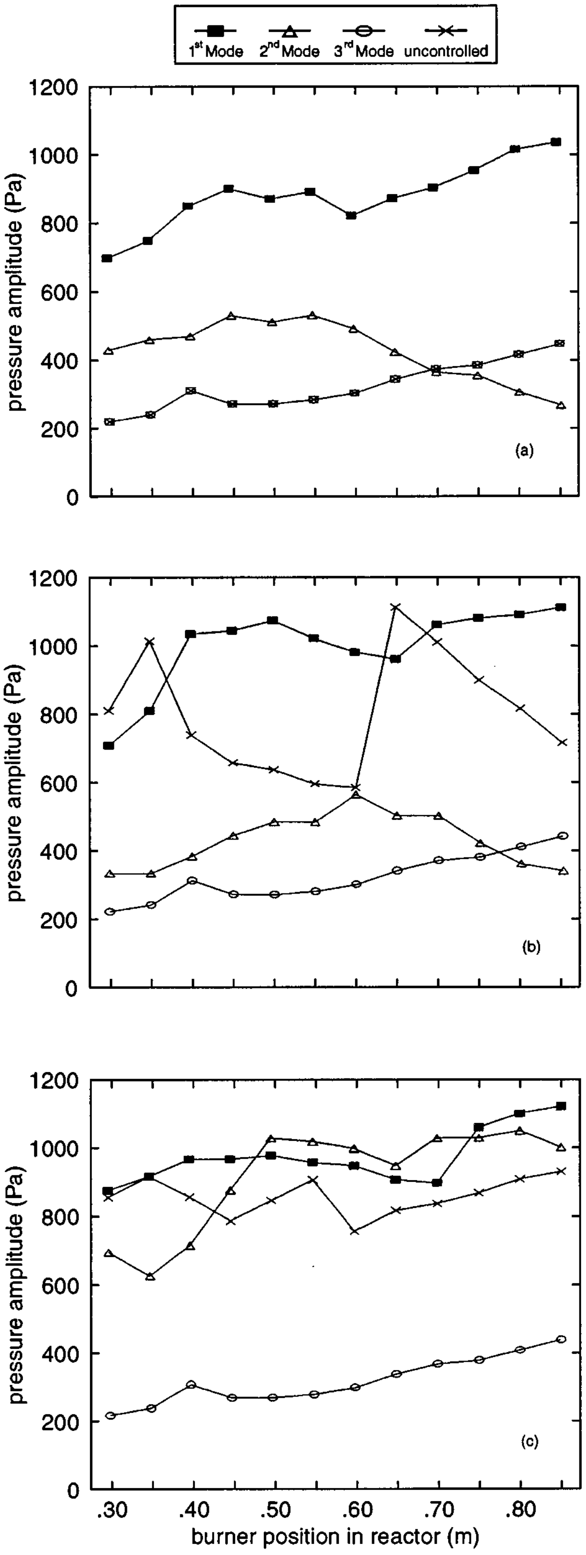

Fig. 6 – (a) Variation in pressure amplitude as a function of burner position inside the combustor under enhancement by indirect control using fuel modulator. (b) Variation in pressure amplitude as a function of burner position inside the combustor under enhancement by direct control using external speakers at L/2 position. (c) Variation in pressure amplitude as a function of burner position inside the combustor under enhancement by direct control using external speakers at 3L/4 position.

TABLE 1 – The effect of sample rates on the attenuation and enhancement control of the gaseous propane flame using (a) indirect control by a fuel modulator and (b) direct control by loudspeaker at $L/2$.

Sampling rate (Hz)	Attenuation pressure at $L/2$ (Pa)	First mode enhancement $L/2$ pressure (Pa)	Second mode enhancement $3L/4$ pressure (Pa)	Third mode enhancement $L/2$ pressure (Pa)
(a)				
1000	910	900	310	360
2500	320	940	320	350
5000	250	940	340	360
7500	10	950	320	340
10000	10	940	310	340
15000	10	950	330	340
20000	10	950	330	340
25000	10	950	320	350
30000	10	980	330	350
(b)				
1000	570	107	430	810
2500	560	1080	410	800
5000	360	107	420	810
7500	320	1060	430	830
10000	280	1070	420	820
15000	10	1060	410	810
20000	10	1050	420	810
25000	10	1070	440	820
30000	10	1070	420	810

TABLE 2 – The effect of active control on the enhanced sound-pressure levels for various fuels in the Rijke combustor using direct control by loudspeakers at $3L/4$ and indirect control by gaseous fuel modulation.

Fuel	Power (kW)	First mode enhancement by $3L/4$ speakers $L/2$ pressure (Pa)	Second mode enhancement by $3L/4$ speakers $3L/4$ pressure (Pa)	Third mode enhancement by $3L/4$ speakers $L/2$ pressure (Pa)	First mode enhancement by indirect control $L/2$ pressure (Pa)
Propane	15	1050	980	820	1010
Acetylene	25	790	500	490	380
Ethanol	25	1030	830	680	10
Ethanol + Propane	25 + 15	1070	500	560	950

As the tables show, enhancement did not seem to be affected by the change in sample rate. Attenuation was sensitive to sample rate changes, as shown by the amplitude drop with an increase in sample rate until the natural oscillations were canceled. Acoustic delay contributed to diminished effect for attenuation. Indirect control by fuel modulation [see Table 1(a)] was able to attenuate at a relatively low sample rate of 7500 Hz. It is suggested that this increased effect for attenuation is a result of using the power of the burning fuel as it is modulated prior to the burning process.

The pulsating combustor was also studied with various fuels. Propane was the principal fuel for the study, but the control using gaseous acetylene and liquid alcohol was also investigated. For the liquid alcohol, natural oscillations would not build up and this necessitated the use of direct control by loudspeakers. The acoustic pressure was controlled from $3L/4$ and $L/2$. Because the spray flame was elongated through the combustor, the heat release was spatially distributed. As a result the acoustic mode was not closely coupled with the burner position. Table 2 shows the oscillating pressure amplitudes for various modal enhancements for acetylene, propane, and ethanol fuels. Acetylene fuel was also used in the study to show how different gaseous fuels affect the control. Little difference is noted for direct control yet indirect control is affected by this fuel. Although the heat release of acetylene is higher than that of propane, indirect control had a reduced effect with this fuel. Sooting and fouling problems also contribute to the diminished indirect control by changing the acoustic properties of the burner. It is suggested that the lower expansion per unit volume of acetylene fuel may also contribute to the diminished effect for indirect control. Because the molecular structure of acetylene produces only one molecule of water for one molecule of acetylene burned the expansion of the reactants is much lower than that of its ethane counterpart or of propane. The expansion of the gas allows for control of the acoustics through the velocity mode. Thus for acetylene, the acoustics could not be controlled to the same degree as propane through modulation of the fuel supply. A combination of all these effects was manifest as a drop in controller enhancement capabilities with the acetylene fuel.

For enhancement with various burner positions, direct control from $3L/4$ tends to have a flat response for the three modes investigated. The high amplitude of these waves allows for the effect of the control to be seen at an established sound-pressure level range for all three modes. Direct control from $L/2$ yields good control for enhancement of the first and third mode, yet is more sensitive to burner position because of the coupling between pressure and velocity modes. Indirect control is also sensitive to burner position because of the use of the velocity mode through heating and expansion to control the pressure mode. For spray flames, the use of indirect control was not implemented in the present study. In the present study, indirect control is also complicated by the burner design, which acts as a low-pass filter. Sooting and fouling of the burner may also become a complication, because small changes in the burner geometry have drastic effects on the acoustic properties of the indirect control. Understanding the main parameters of the controllability makes it possible to investigate the effects of the controlled acoustic field on the combustion process.

B. Effect on combustion parameters

To investigate the effect of the active control mechanism on combustion parameters, experiments were performed on gaseous propane, gaseous acetylene, and liquid ethanol fuel in the Rijke-tube reactor. Measurements of total heat exchange with the wall of the combustor, Sauter-mean diameter of the ethanol spray droplets, and power spectral density of the droplets' axial velocity are presented. Photographs of the gaseous propane flame structure under steady (no oscillations), first mode, second mode, and third mode oscillations are also presented. Even though extensive data sets were taken to study the effect of the control mechanism on combustion, only limited representative results will be presented here due to space limitations.

Figure 7 presents the photographs of the gaseous propane structure under steady conditions (no oscillations), as well as for the first, second, and third modes of oscillation. Shutter speed was 1/15 s and the photographs were taken through the visual and laser access windows. The burner location is at 750 mm for all cases with 700% excess air. As can be seen from these photographs, there is a remarkable difference in the flame structure with and without the acoustic field. Under non-oscillating conditions, the gaseous flame is long and yellow in color and is smooth without small scale wrinkles. With the onset of the first mode of oscillation, the flame structure becomes shorter and wrinkled, is blue in color, and is pulled downward, indicating negative flow velocities at the burner arms associated with the acoustic oscillations for this mode. Compared to the first mode, the second mode of oscillation does not have a pronounced effect due to the location of the burner at the node of the acoustic velocity field, although enhanced mixing is evidenced by a bluish color near the burner. Here the flame is longer and bluish yellow in color, and is not as compact as the first mode. The effect of the third mode of oscillation is similar to that of the first mode with a compact flame, which is blue in color. This flame has wrinkles pulled towards the side, characteristic of the third mode acoustic velocity field at the burner position [see Fig. 2(a)]. Similar behavior in the flame structure was also seen for the liquid ethanol spray combustion.[13]

The heat transferred to the walls of the Rijke-tube combustor, under non-oscillating conditions and for the first mode of oscillation with sound pressure levels of 140 dB (re: 20 μPa) and 150 dB (re: 20 μPa), is shown in Table 3. As seen in this table, heat transfer to the wall of the combustor increased significantly with the sound-pressure level of the acoustic field. Based on the total energy supplied to the combustor (40 kW), the heat transfer for the steady condition was 14 kW, or 34% of the total; 15 kW, or 37% for the first mode with a sound-pressure level of 140 dB; and 17 kW or 43% for the first mode with a sound-

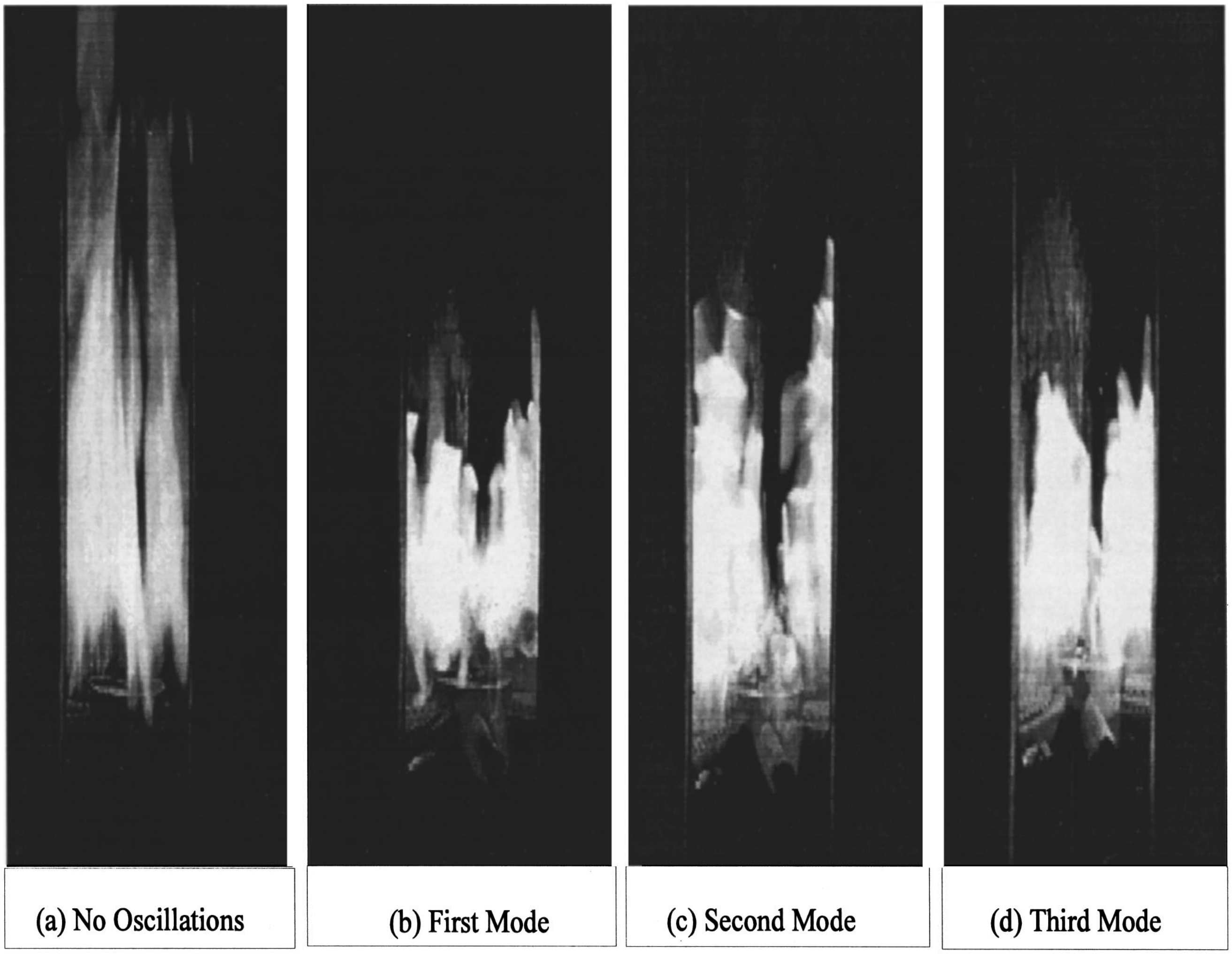

Fig. 7 – Photographs of the flame in the Rijke-tube combustor. (a) Steady, (b) first mode, (c) second mode, (d) third mode of oscillation for gaseous propane flame inside the Rijke-tube combustor.

TABLE 3 – Total heat transfer to the wall of the Rijke-tube combustor for an ethanol spray flame for the non-oscillating condition, and first mode of oscillation with sound-pressure levels of 140 and 150 dB, in the Rijke-tube combustor.

	Non-oscillating	First mode at 140 dB (re: 20 μPa)	First mode at 150 dB (re: 20 μPa)
Acoustic pressure amplitude (PA)	10	320	1020
Reactor power (kW)	40	40	40
Heat transfer to cooling water (kW)	13.7	14.9	17.3
Percent of total energy transferred	34.25	37.25	43.25
Percent increase over stable case	N/A	8.76	26.28

pressure level of 150 dB. This increase is due to the enhanced transport of heat and mass from the combustion zone with the presence of the acoustic field, which increases with the sound-pressure level.

The effect of acoustics on the combustion of fuel droplets is illustrated in Fig. 8 by axial profiles of the Sauter-mean diameter (D_{32}) for non-oscillating conditions, and for the first mode with sound pressure levels of 140 and 150 dB. The results show that the presence of the acoustic field causes a distinct decrease in droplet diameter of the spray. This decrease, negatively correlated with sound-pressure level, indicates higher evaporation and combustion rates under oscillating conditions. The average decrease, over the steady value, in these axial profiles was 8 μm for a sound-pressure level of 140 dB, and 12 μm for a sound-pressure level of 150 dB. Figure 9 shows the power spectral density (PSD) of the time-resolved axial droplet velocity of the liquid ethanol spray for the three conditions considered here. These PSD plots show that the acoustic field affects the time-resolved velocities of the droplets. For a higher sound-pressure level, this effect is also increased.

5. CONCLUSIONS

An active control mechanism has been developed and applied to a Rijke-tube combustor. The active control allows for the study of the effect of multimode oscillation field and sound-pressure level on the controllability, geometric parameters, and combustion characteristics of reacting gaseous and liquid fuels. The conclusions based on the present investigation are as follows:

(1) The location of the fuel injection relative to the combustor is a very important parameter for the performance of the control mechanism. This is because at different locations, the magnitude of the acoustic velocity flow field varies, and this in turn affects the coupling of the pressure and expansion waves necessary for development of acoustic oscillations.

(2) The type of fuel used is also a very important parameter for control due to differences in expansion and burning characteristics. Liquid fuel is harder to control because the heat release is extended over a long section of the combustor as compared to the gaseous fuel, which is shorter in length and is better for the control mechanism.

(3) Acoustic oscillation has a significant effect on the flame structure of both liquid and gaseous flames. In general, the length of the flame shortens with the onset of oscillation and is affected by the location of the burner inside the combustor.

(4) An increase in the heat transferred to the walls of the combustor, under the influence of the acoustic field, is observed. This is due to better transport of heat and mass within the reactor, which indicates higher combustion efficiencies for oscillating conditions.

(5) The results of the study on the droplet characteristics of the ethanol spray show a decrease in Sauter-mean diam-

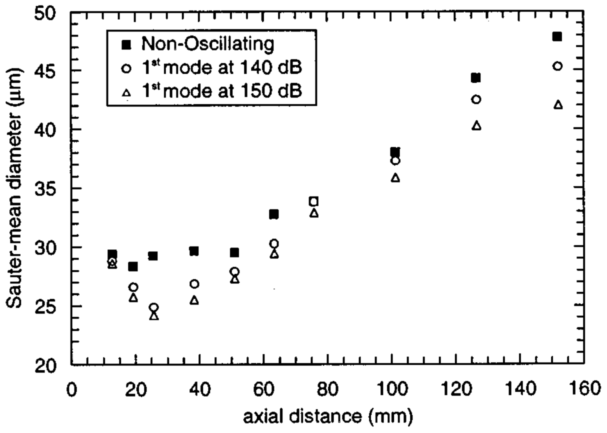

Fig. 8 – Axial profiles of Sauter-mean diameter for the ethanol spray flame at steady, and first mode of oscillation with sound-pressure levels of 140 and 150 dB, in the Rijke-tube combustor.

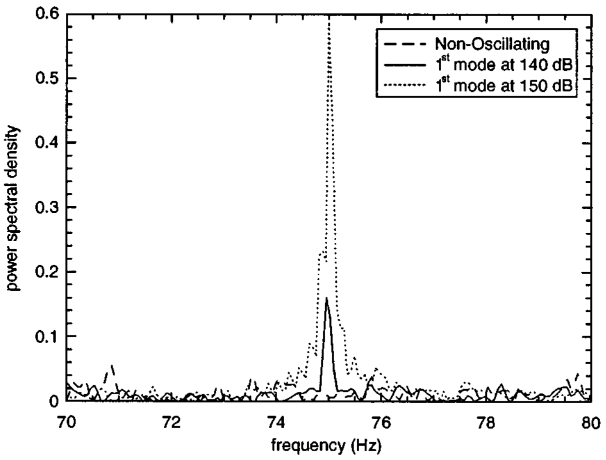

Fig. 9 – PSD of the time-dependent droplet axial velocity for the ethanol spray flame at steady, and first mode of oscillation with sound-pressure levels of 140 and 150 dB, in the Rijke-tube combustor.

eter due to increased mixing, and also that was proportional to the sound-pressure level. Also, the oscillating flow has a strong effect on the time-resolved droplet velocities, which are proportional to the sound-pressure level of the acoustic field.

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