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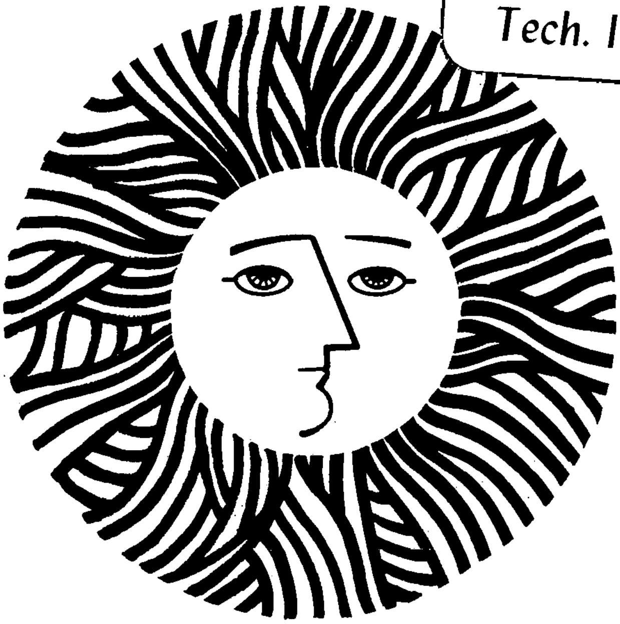

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FLOW AND COMBUSTION CHARACTERISTICS OF A TWO DIMENSIONAL SPOUTED BED

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ABSTRACT

A two dimensional spouted bed laboratory combustor has been designed and constructed with the objective of studying the interaction among the gas flow, particle flow, and combustion. The facility, designed for a maximum thermal power of 20 kW, has a quartz front wall providing full optical access to particle flows and combustion processes. The combustor was characterized in terms of pressure, temperature, gas velocity, and particle velocity profiles and operating limits. Initial studies employed premixed propane and air and a fixed bed height, bed material, injector slot width, and combustor geometry.

As in previous invetigations of axisymmetric spouted beds, the ratio of particle mass circulation rate to jet mass flow rate was observed to be about ten. Combustion increased this ratio by about ten percent. A pulsating mode of operation was noted with a characteristic frequency of about ten Hz, controlled by the interaction of the particle and gas flows. In the present configuration internal heat recirculation is approximately balanced by heat losses so that lean and rich flammability limits are extended only slightly beyond those of premixed laminar flames.

INTRODUCTION

Spouted beds have been used as solids-gas contacting devices for three decades in such applications as drying grains, solids blending, and for the cooling, coating and granulation of solids. Other applications, as chemical reactors, include coal carbonization, coal gasification, shale pyrolysis, ore roasting, and petroleum cracking (Mathur and Epstein, 1974). A spouted bed typically consists of a coarse solid material of a diameter of about one mm with a fluid jet moving vertically upward through the bed, Figure 1. The jet, either liquid or gaseous and possibly itself containing a solid, entrains the bed material within a "spout" which is followed by a particle "fountain" region in which the bed material rains back onto the bed. Combustion may occur if premixed reactants comprise the spouting fluid or if a solid fuel is added to the bed in combination with an oxidizing spouting fluid.

In comparison with fluidized bed combustors, spouted bed combustors can exhibit improved heat and mass transfer characteristics because of the spout driven circulation of the bed material. The stirring induced by the spout can prevent the caking of solid fuels in the combustor, as in coal gasification applications. Some of the gas flows countercurrently through the particles. Combustion occurs primarily in a Bunsen-type flame at the top of the spout.

Weinberg and his co-workers were the first to report systematic studies of the behavior of spouted bed combustors. Their interests were primarily for the heat recirculation characteristics of spouted beds and the opportunity thereby provided for the burning of low calorific fuels or fuel/air mixtures beyond normal lean flammability limits (Khoshnoodi and

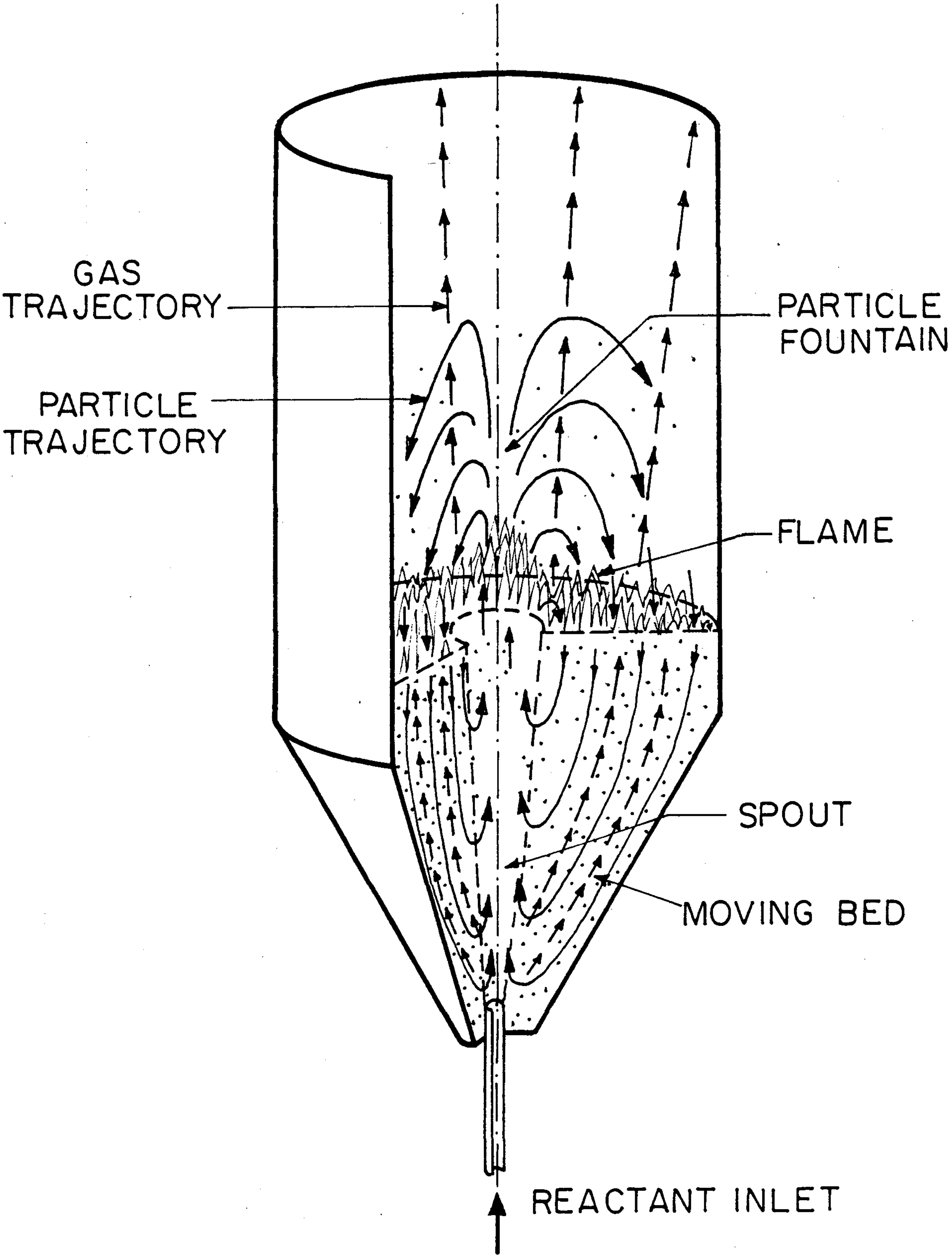

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Figure 1. Flow and combustion schematic of an Axisymmetric Spouted Bed Combustor with an Inclined Base.

Weinberg, 1978 and Arbib et al., 1981). Weinberg cites earlier work by Desty of British Petroleum and Mathur and Epstein (1974) mention a spouted coal fired combustor by Syromyathnikov, but in neither case is documentation readily available. More recently, Arbib and Levy (1981) have explored the potential application of spouted bed combustors to waste incineration.

The present work was undertaken to provide a better understanding of the fluid and particle flows within spouted bed combustors and to explore the interaction of combustion and bed fluid mechanics. In contrast to previous investigations (Khoshnoodi and Weinberg, 1978; Arbib, et al., 1981; Arbib and Levy, 1981), a planar two dimensional geometry was chosen to provide optical access to particle motion at the front wall which, hopefully, would be characteristic of the entire bed flow field.

Spouted bed experimental geometries are compared in Table 1. While no fixed rules govern spouted bed combustor design, some general considerations lead to similar characteristics among configurations so far employed. A ratio of the bed cross-section area to the spout area of less than about 300 insures that the majority of the bed material circulates. Sloping sides also insure full circulation of the bed material. Our configuration differs in this respect from the other investigations, having a flat bottom and therefore a packed bed region with little or no particle motion. Bed heights are limited by the ability to blow a spout through the bed and pressure drop considerations. Particle diameters on the order of one mm or greater minimize particle elutriation from the bed. Note that the linear and areal ratios for the planar bed are equal while they are related by the second power for axisymmetric geometries. The depth of our combustor (corresponding to the length of the slot injector) was chosen to provide uniform flow from the front to the back walls. As this dimension is increased, flow tends to channel up either the front or back wall.

EXPERIMENTAL FACILITY AND METHODS

The spouted bed is a rectangular, two-dimensional combustor of dimensions 12.7 mm x 100 mm (cross-section) x 300 mm (height), Figure 2. The spouted combustor is another configuration of a modular, general fluidized combustion facility which, in a staged fluidized bed configuration, was described earlier (LaFond, et al., 1981). In the present configuration the depth of the flow channel was decreased by 75% to improve two dimensionality, thereby reducing the thermal power rating from about 20 kw to 5 kw based on the propane input flow rate. The slot width is 1.6 mm.

The combustor is constructed of 304 stainless steel with the exception of the front wall which is a GE124 quartz window. In these experiments the combustor is fired with premixed, room temperature propane and air. All experiments are at one atmosphere pressure. The bed material is nominally one mm diameter silica, obtained by sifting between 0.833 and 1.168 mm. Some reduction in particle size was observed during use, especially under combustion conditions. The effect is minimized through small particle elutriation and through periodic changing of the

Table 1. Spouted bed combustion studies

Researcher(s)	Fuel	Geometry	A_b/A_i	h_b/D_b	d_p	D_b/D_i
			-	-	mm	-
Syromyatnikov (1951)*	coal	?	?	?	?	?
Desty (1968)**	?	?	?	?	?	?
Knoshnoodi & Weinberg (1978)	methane	axisym.	178	2-1	1	13
Arbib, Sawyer, & Weinberg (1981)	methane	axisym.	312 261	.15 .13	3 2.4	17 16
Arbib & Levy (1981)	methane	axisym.	256	.58	1	16
present work	propane	planar	63	.38	1	63

*Referenced by Mathur and Epstein, 1974
**Referenced by Khoshnoodi and Weinberg, 1978

A_b	bed cross-section area
A_i	injector area
h_b	bed height
D_b	bed diameter (width)
D_i	injector diameter (width)
d_p	particle diameter, mm

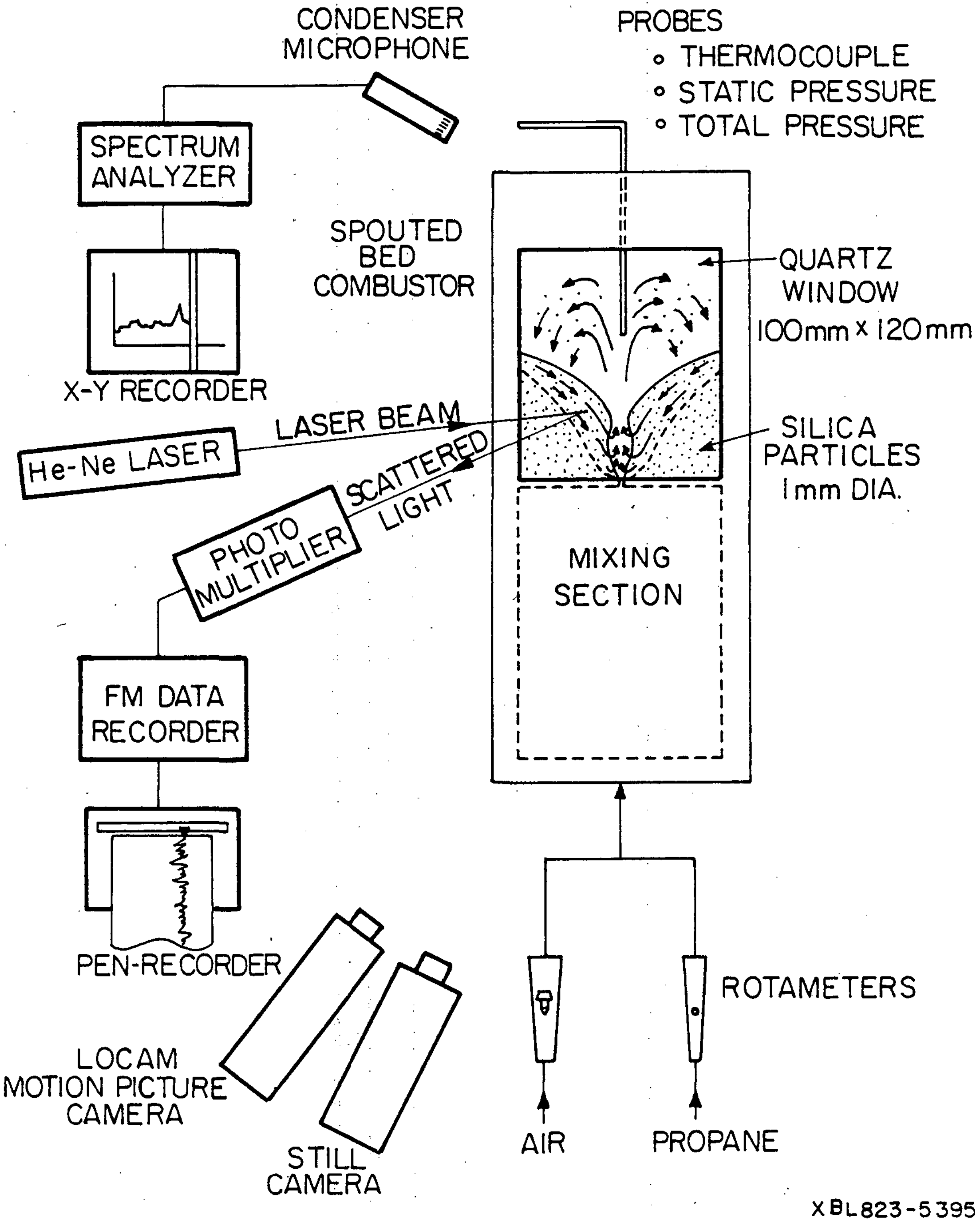

Figure 2. Schematic of Planar Two Dimensional Spouted Bed Combustor and Diagnostics.

particles. The back and side walls contain instrumentation ports which in these experiments were used primarily for monitoring temperatures for operating purposes. In these studies combustor temperatures were measured using bare chromel-alumel thermocouple probes and pressures were measured with (separate) static and stagnation probes.

Several types of photographic recordings were made for different purposes. Flow visulization was obtained using a Locam motion picture camera with speeds of from 20 to 200 frames per second. The lower speeds were appropriate to observing the particle motion in the moving bed region of the combustor and the higher speeds for the particle motion in the spout and fountain regions. A timing light was used to mark the film accurately. A xenon discharge lamp was used to illuminate the bed. Still photographs were taken with a 35mm camera with a calibrated shutter speed and the resulting streak protographs of individual particles used to determine particle velocity in the moving bed. Stoboscopic and chopped lighting also were used to produce particle multiple exposure photographs for particle velocity measurement.

Light scattering employing a He-Ne laser and photomultiplier was used to count particles as they moved passed the point of view providing a second method of determining particle number fluxes and thereby to infer particle mass flow rates. Measurment of spout particle velocities was attempted from the time delay between light scattered from two points a few millimeters apart, aligned with the flow velocity. This technique has not yet proven completely satisfactory. Light scattering signals were also used to provide information on the unsteady characteristics of the flow. Finally, a microphone and spectrum analyzer were used to obtain frequency characteristics of the flow and combustion processes.

SPOUTED BED CHARACTERISTICS

The general characteristics of the spouted bed under cold flow (without combustion) conditions are described in Figure 3. Flow regimes are mapped with spout inlet velocity and bed height as parameters. As inlet velocity is increased at a fixed bed height, the first particle motion noted is as an internal spout. This spout then breaks through the surface of the bed producing a small spout which is initially stable but then, as it grows, begins to wander (laterally) in a non-period fashion. With a further increase in velocity the oscillation becomes periodic and, finally, at high velocities a stable spout results. The spouted bed is characterized by four regions: the spout, the fountain above the spout in which the particles rain back to the bed, a moving bed region, and a packed bed region. Other investigators have used sloping walls, thereby eliminating the packed bed region.

Under combustion conditions similar behavior is observed, except that the regions of operation occur at lower spout inlet velocities due to a flow expansion by a factor of about four and the effects of increased fluid viscosity at the higher temperatures. The fountain size is increased and particles are dispersed further from the combustor centerline than without combustion. With combustion a new parameter, the mixture ratio (expressed as the propane/air equivalence ratio) is

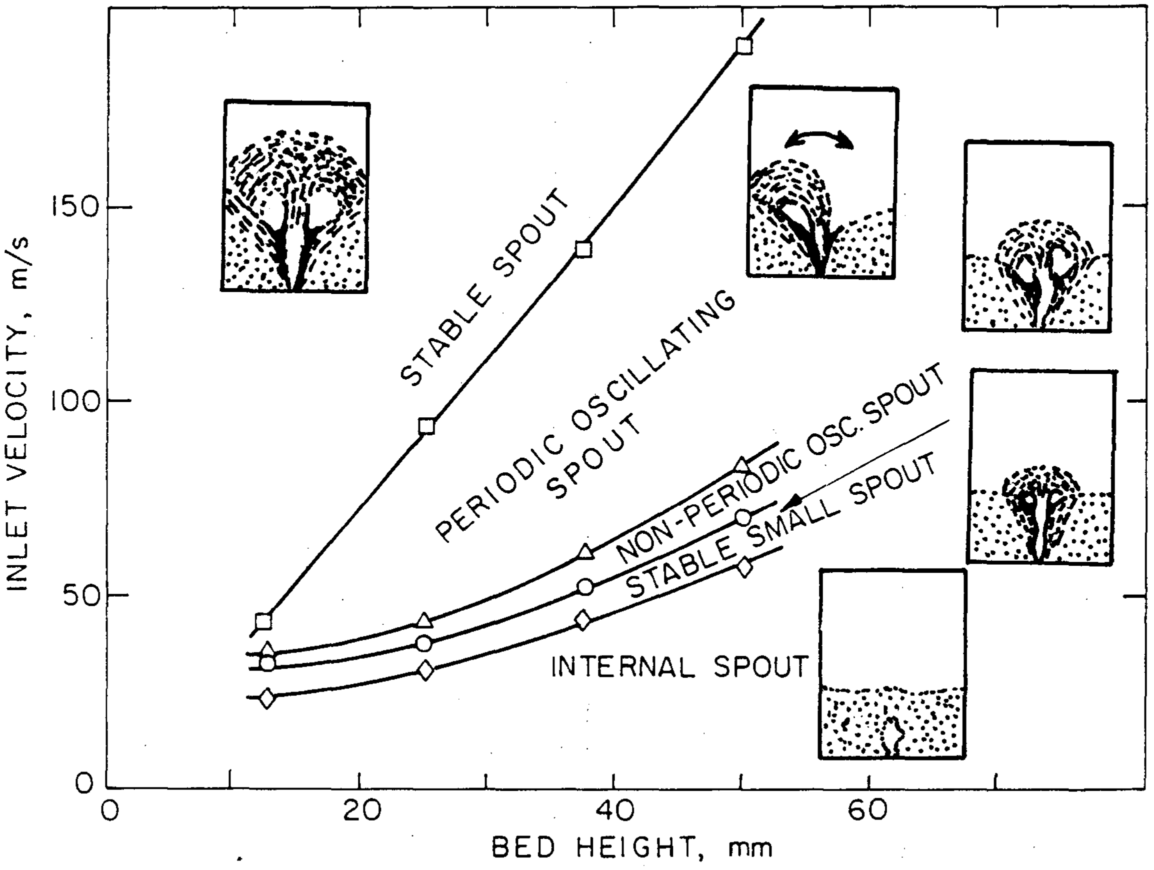

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Figure 3. Stability Diagram for Two Dimensional Spouted Bed without Combustion (Cold Flow).

available. Lean and rich operating limits are presented in Figure 4, for a fixed bed height of 38 mm (measured with a level surface under zero flow conditions). Also identified on this figure are the six combustion operating points of this study (1-6) and two non-combustion cases (7-8). Operating conditions for the eight cases are summarized in Table 2.

EXPERIMENTAL RESULTS

The combustion process observed is unsteady, usually periodic, with a frequency of about ten Hz. The steady behavior, specifically, the time-averaged temperature, pressure, apparent gas velocity, particle, and cold and hot mass circulation rates of the spouted bed are presented first. The unsteady characteristics of the bed are then examined.

The temperature profile within the bed for a stoichiometric mixture and inlet jet velocity of 38 m/sec, Case 2, is presented in Figure 5. Temperatures were measured by a thermocouple probe lowered from above the bed. The probe produces some local disturbance in the particle flow in the fountain and spout regions but does not affect the general behavior of the bed. The temperature so measured should fall between the temperature of the gas and the temperature of the particles. In the moving and packed bed regions, the thermocouple temperature should be close to the particle temperature. In the spout region and fountain regions, where the void fractions are much larger, about .99, the temperature will be further from the particle temperature. Temperatures are not corrected for radiation losses or gains.

The maximum temperature is found on the centerline, close to the apparent (time-averaged) location of the top of the visible flame. The reactant gases are preheated within the spout by convection from the heated particles and by conduction from the moving bed and flame. The particles are heated by conduction as they flow through the bed. In the central fountain the measured temperatures fall as heat is transfered by the combustion products to the cocurrently flowing particles. At the edge of the fountain the gas and particles are flowing countercurrently. The rise in the measured temperature as the thermocouple enters the bed from above in the outer regions is probably the combined effect of better particle temperature measurement and the unsteady deposition of particles on the bed surface.

Centerline temperatures for Cases 1,2,3 and 5 are shown in Figure 6. The effect of increasing the inlet velocity at stoichiometric conditions is seen, by comparing Cases 2 and 5, to be small. As the velocity is increased the peak temperature, and therefore the flame, moves slightly deeper into the bed. This is a result of the greater heat release and higher combustion temperature. The equivalence ratio effects the peak centerline temperature in both magnitude and location. That the peak temperature continues to rise and the flame moves deeper into the bed as the mixture becomes fuel rich is somewhat surprising and probably the result of the complex interactions between heat transfer and combustion in this device.

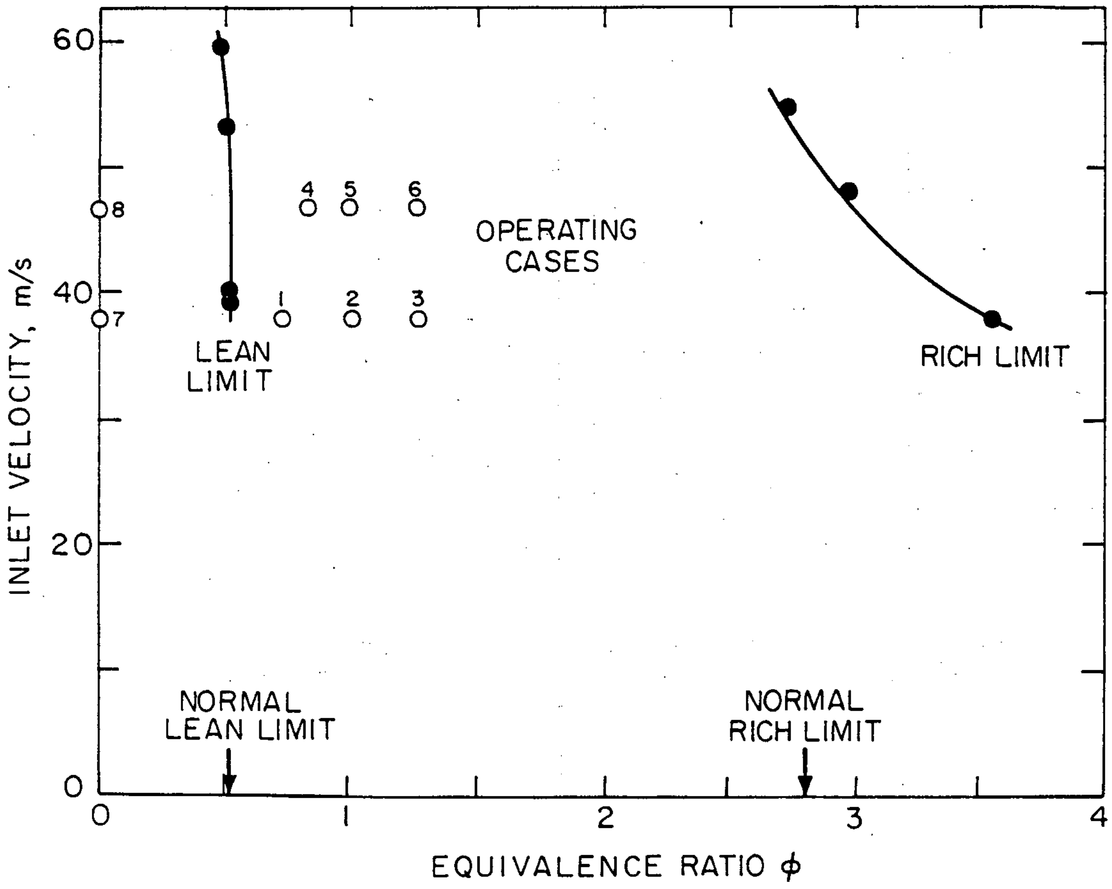

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Figure 4. Stability Diagram for Two Dimensional Spouted Bed Combustor Fired with Propane and Air.

Table 2. Operating conditions

Case	Ø	Velocity m/s	$\dot{m}_r$ g/s	$\dot{m}_f$ g/s	Power* kW
1	0.73	38	.94	.038	1.8
2	1.01	38	.95	.052	2.4
3	1.28	38	.97	.066	2.2
4	0.81	47	1.18	.052	2.4
5	1.00	47	1.19	.064	3.0
6	1.27	47	1.21	.082	2.7
7	0	38	0.90	0	0
8	0	47	1.12	0	0

$\dot{m}_r$ reactant mass flow rate

$\dot{m}_f$ fuel mass flow rate

*Based on complete conversion of C_3H_8 to CO_2 and H_2O for $Ø < 1$ and conversion to CO_2, H_2O, CO, and H_2 where $H_2/CO = .5$ for $Ø > 1$.

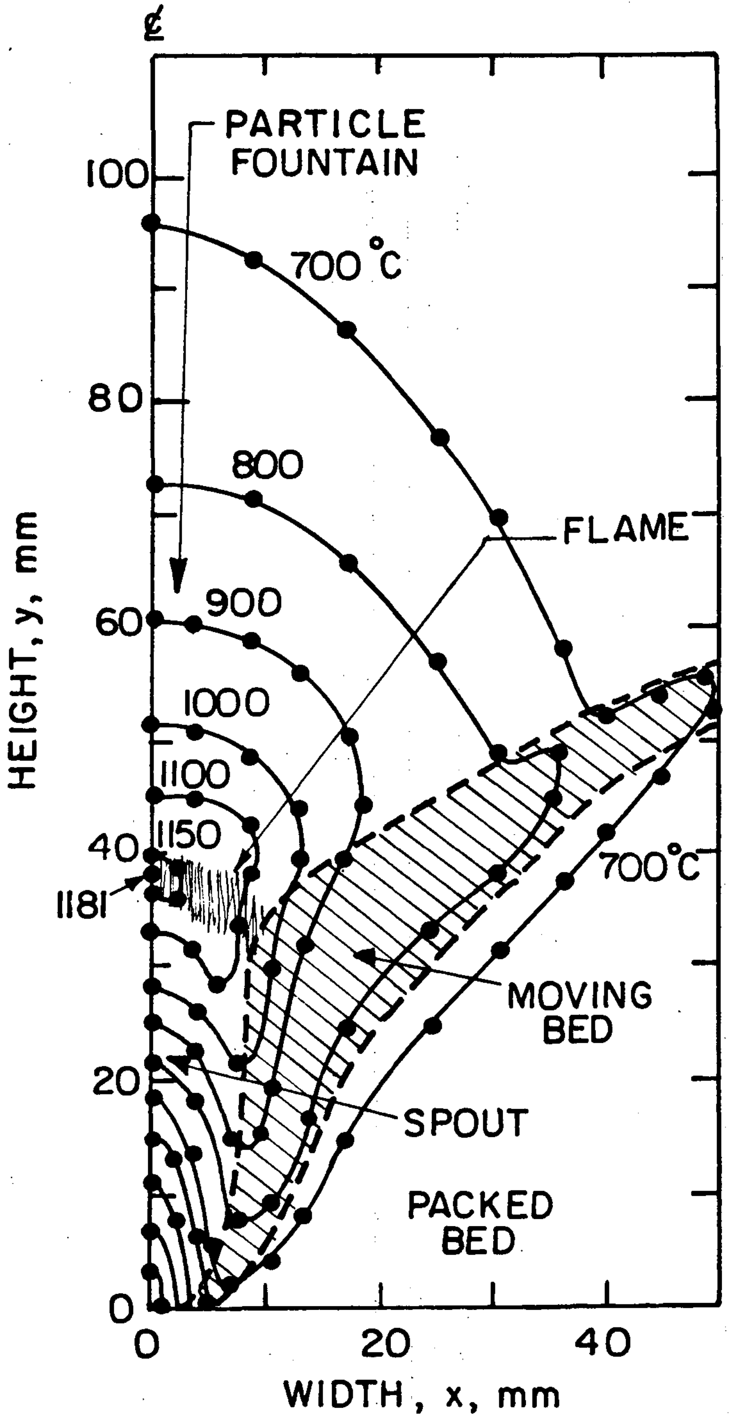

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Figure 5. Time Averaged Temperature Profiles for the Right Half of the Two Dimensional Spouted Bed Combustor. Case 2, Stoichiometric Mixture, 38 m/sec.

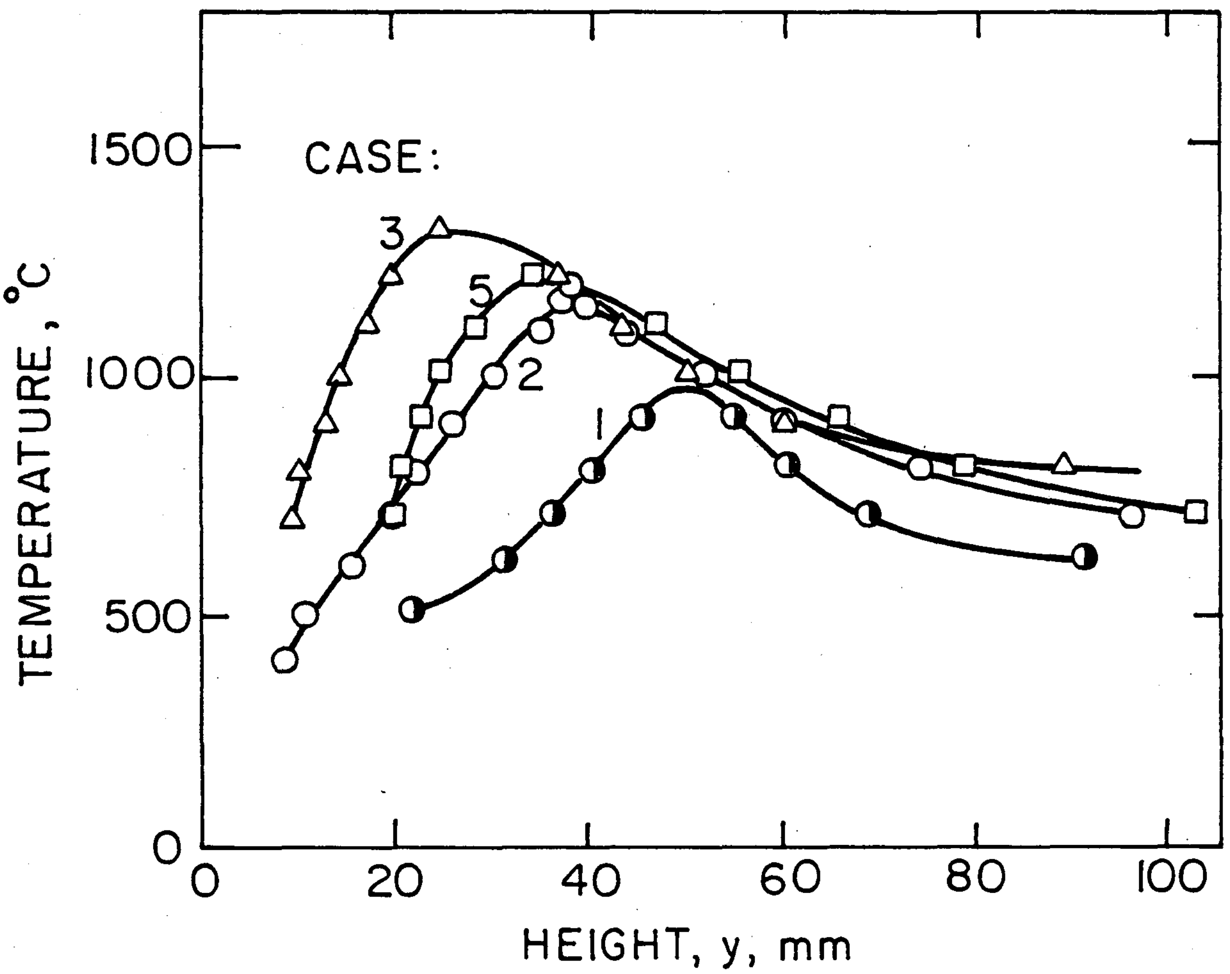

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Figure 6. Time Averaged Centerline Temperature Profiles for Cases 1, 2, 3, and 5.

Measurements of static pressure for Case 2, shown in Figure 7, are evidence of gas flow within both the packed and moving bed regions, as well as the spout itself. Stagnation pressures were also measured although the interpretation of these pressures in the two phase flow region is not straightforward. The static and stagnation pressures were used to calculate an "apparent" gas velocity with the qualification indicating uncertainties regarding the meaning of the stagnation in two phase flow and the effect of the pulsating flow on both the pressure and temperature measurements. This velocity, Figure 8, is therefore the velocity which would exist if the gas temperature were that measured by the thermocouple probe and if the measured pressures were true properties of the gas flow. Expansion of the gas upon combustion is countered by the increasing flow channel area. In the region of the flame the flow area has increased by a factor of about 5 while the combustion process has resulted in an expansion of the gases by a factor of about 4, based on the measured temperature. A velocity of about 30 m/sec would therefore be expected, in reasonable agreement with the measured "apparent" velocity of 28 m/sec.

Particle velocities in the moving bed region were made by the light scattering technique along the path described in Figure 9. Comparison of the particle velocities for cold flow and for flow with combustion show that the particle velocities near the top of the moving bed are always greater for the hot flow. The particle path is almost parallel to the boundary line between the moving and packed beds. Since the angle of the boundary line is steeper in the cold cases, flat particle velocity profiles appear near the surface of the moving bed. In the combustion cases, a small size eddy-like motion of particle recirculation appears near the top of the spout region causing a reduction of particle velocity near the surface of the moving bed. Stoichiometric mixtures produce the highest particle velocities in the moving bed.

Since all of the circulating particles cross this path, knowledge of their velocity at the location can be translated into mass flow rate. The mass of a particle was determined by weighing and assuming all particles to be of equal size and mass. The resulting mass circulation rates are given in Table 3. Particle mass circulation rates are about ten times greater than the reactant mass flow rates, in agreement with the cold flow weighing measurements of Khoshnoodi and Weinberg (1978). Combustion increases the particle mass circulation rate by about ten percent. Note that while the momentum of the incoming flow is unaffected by combustion, the effectiveness of momentum transfer between the gas and particles in increased by both the flow acceleration and increasing viscosity resulting from the gas temperature increase.

From the data obtained above, a rough estimation of heat circulation has been carried out. Heat transfer from the flame to the particles passing through the flame zone was estimated by convective heat transfer. Radiation and natural convective heat transfer were considered in calculating a heat loss from the combustor. In Case 2, about 8% of the heat input may be transfered to the particles. Heat loss is evaluated as almost 20%, corresponding to a decrease in the flame temperature of about 300 degrees centigrade.

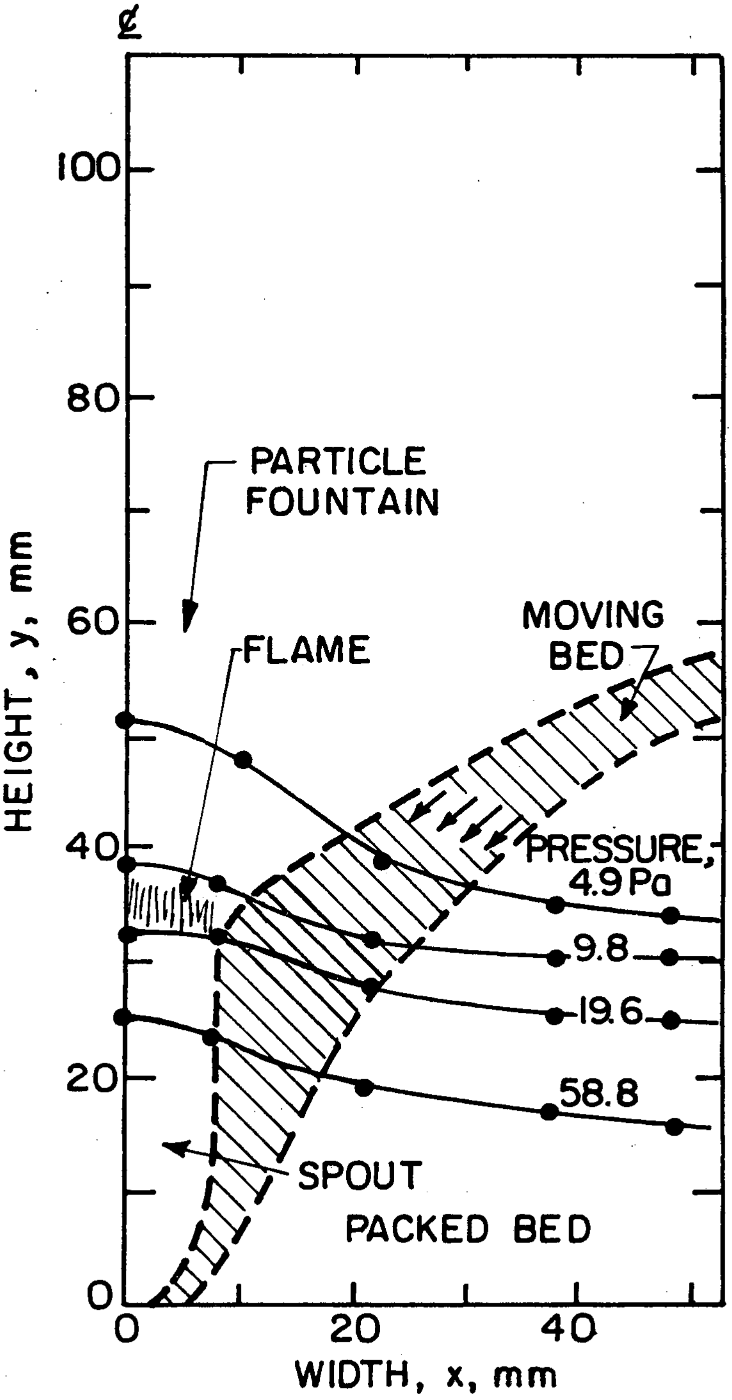

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Figure 7. Time Averaged Static Pressure Profiles for Case 2.

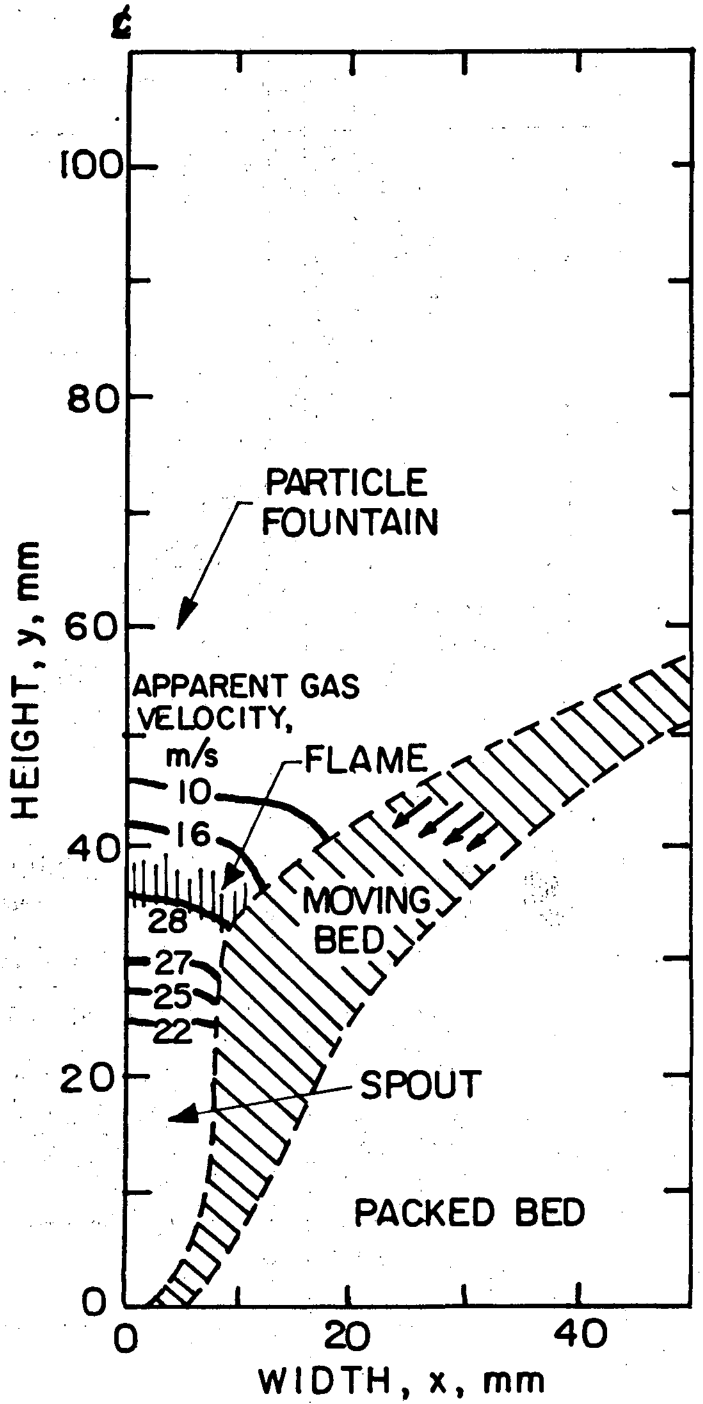

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Figure 8. Apparent Time Averaged Gas Velocity Profiles for Case 2.

A second determination of particle velocities in the moving bed was made from particle streaks on still photographs. This method gives an instantaneous particle velocity which was also transformed into a total particle mass flow rate, Figure 10. The photographs correspond to a "typical" series of events as identified in the high speed movies (but the photographs were selected from still shots). The particle mass flow is seen to be periodic. The characteristic periodicity is about 100 ms, or the frequency, about ten Hz. These results may be compared with the previous time-averaged results. The agreement and trends are consistent. Highest particle circulation rates occur for stoichiometric mixtures and higher inlet flow velocities.

The downward particle movement which covers the gas jet above the slot and is periodically carried up is clearly observed in the cold cases. The characteristic ten Hz oscillation is probably produced by this process. With combustion the downward movement still exists near the slot, but another particle flow appears above the middle part of the spout region. Ignition then produces a rapid expansion of the gases which blows particles upward. Moving bed particles then rush in to fill the gap and cause another single or two stage bubble to form. The frequency of these events is controlled by the particle motion. With combustion the process becomes more violent with the particles probably serving as the ignition source for the incoming gas.

The periodic nature of these processes was studied using high speed motion pictures, light scattering from particles, and audio frequency analysis. Bubble bursting events were counted from 200 frame per second motion pictures. These data are pesented as histograms in Figure 11. The histograms give an indication of the randomness of these events but also confirm a dominant frequency of about ten Hz.

Continous light scattering signals taken on the spout centerline just below the combustion zone are recorded in Figure 12 for cases 7, 2, and 5. Every peak corresponds to a particle passing through the observed point. A clearly defined frequency of ten Hz is observed for the cold flow while the combustion cases are better characterized by the first overtone at 20 Hz. In Cases 2 and 5, a characteristic pattern is observed consiting of a large peak followed by a time duration of no signal, which may correspond to the breakthrough of an ignited bubble. This set of signals may be produced from a large expansion which will then form a two stage bubble inside the spout region and produce this overtone. The characteristic frequency associated with particle motion would be expected to be affected by bed dimensions, particle size, particle material, and bed height. However, the effects of these parameters have not yet been investigated.

Frequency analyzed audio data collected from a microphone placed near the combustor are shown in Figure 13. Well identified peaks occur at about 10 Hz for Cases 1,2,3, and 4 but not for Cases 5 and 6. The bubble igniton and bursting events become quite random for Cases 5 and 6 and no characteristic frequency is discernible.

The unsteady behavior of the spouted bed can lead to a second type of extinction which was observed to fall within the flammability limits of Figure 4. Under some circumstances, which are not yet fully

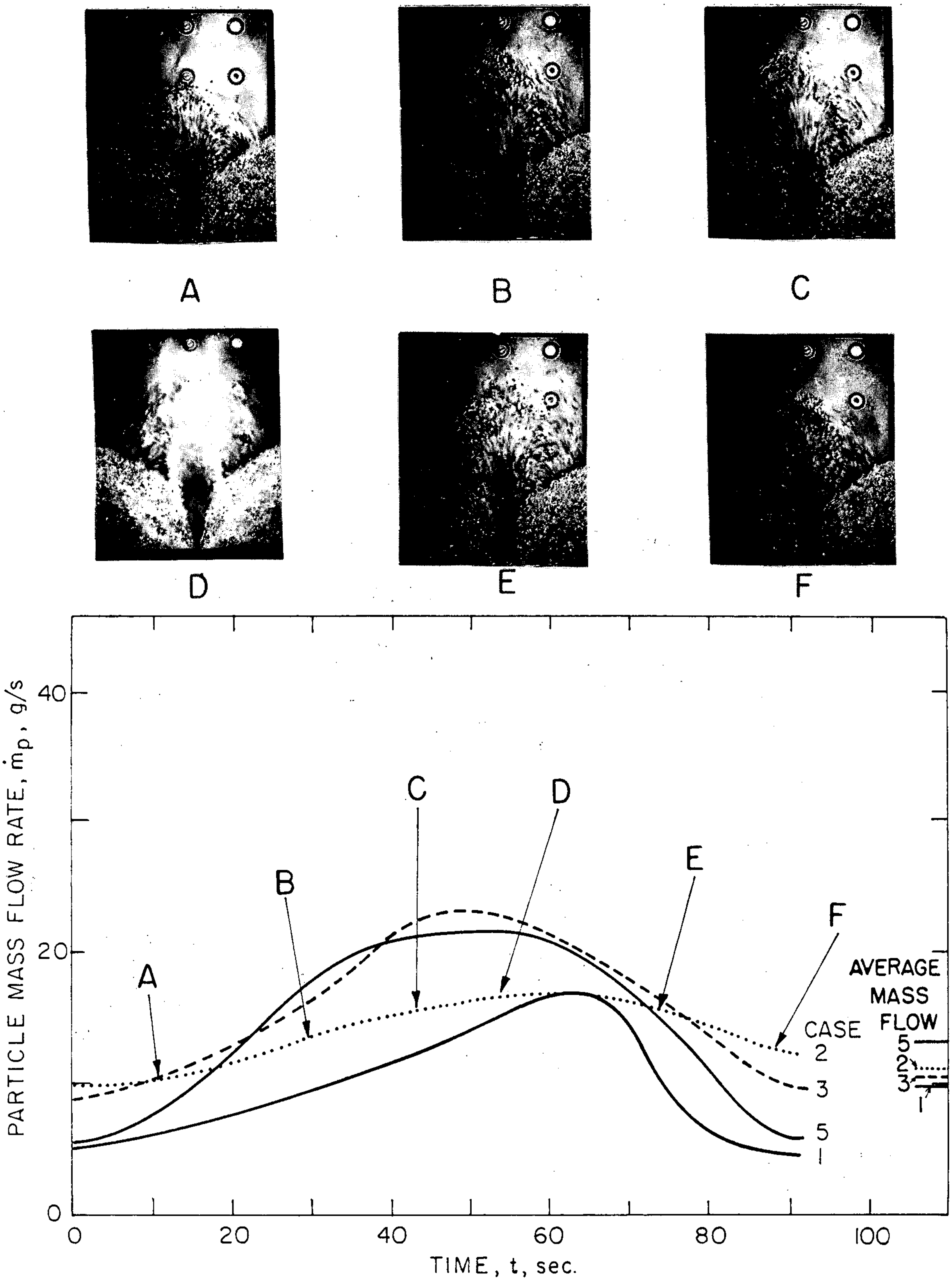

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Figure 10. Instantaneous Particle Mass Flow Rates for Cases 1, 2, 3, and 5.

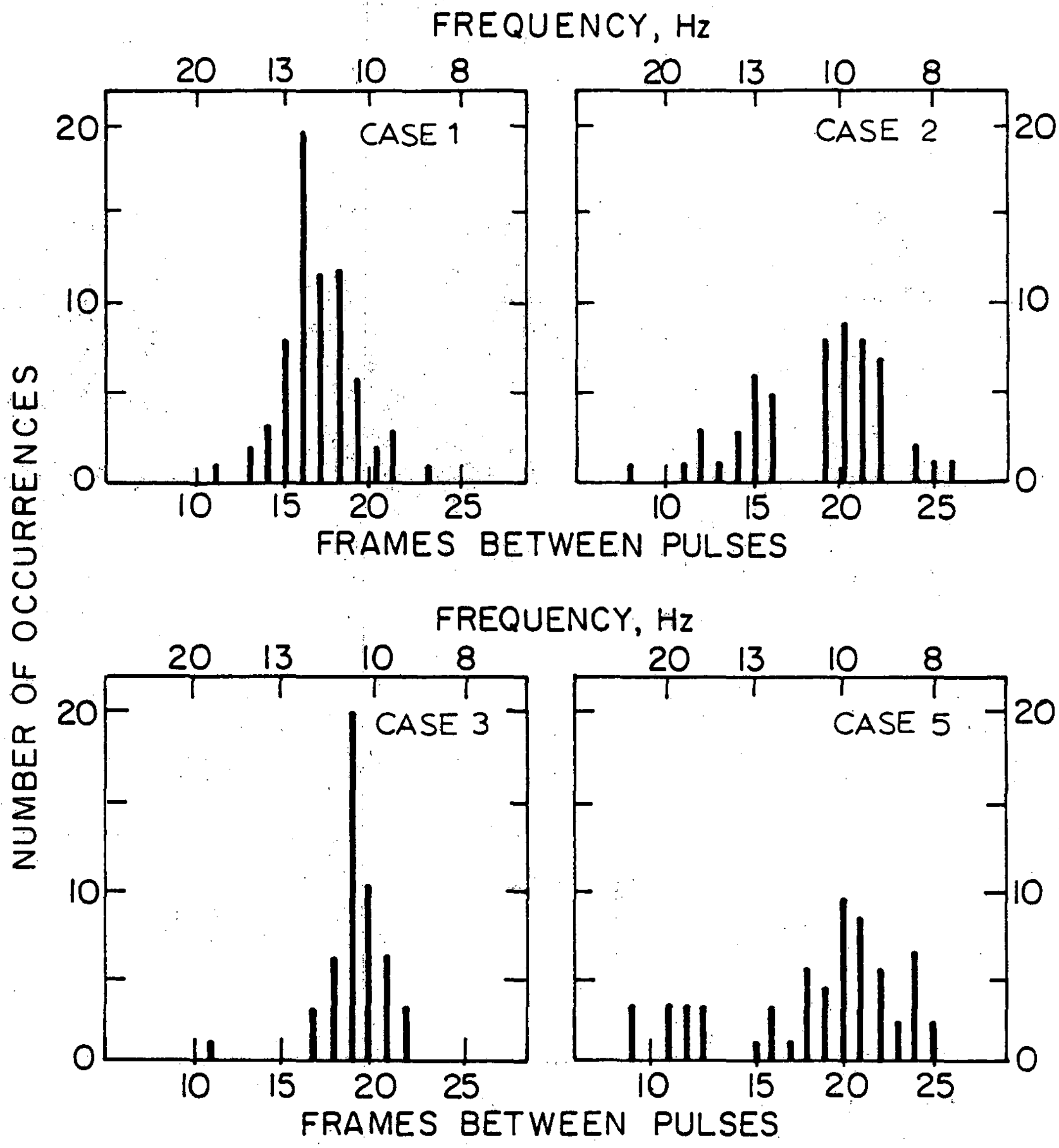

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Figure 11. Frequency of Combustion Pulses for Cases 1, 2, 3, and 5.

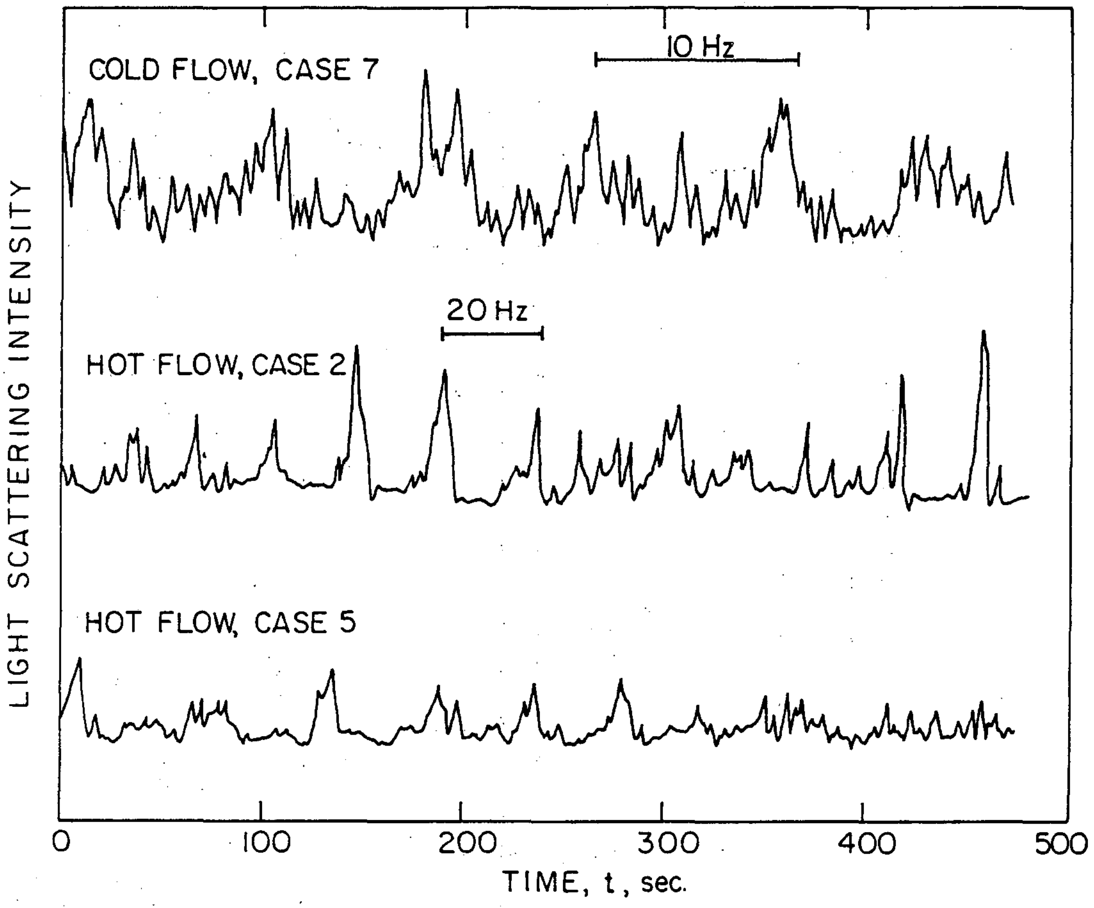

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Figure 12. Light Scattering Frequency for a Location on the Axis at the Top of the Spout for Cases 2, 5, and 7.

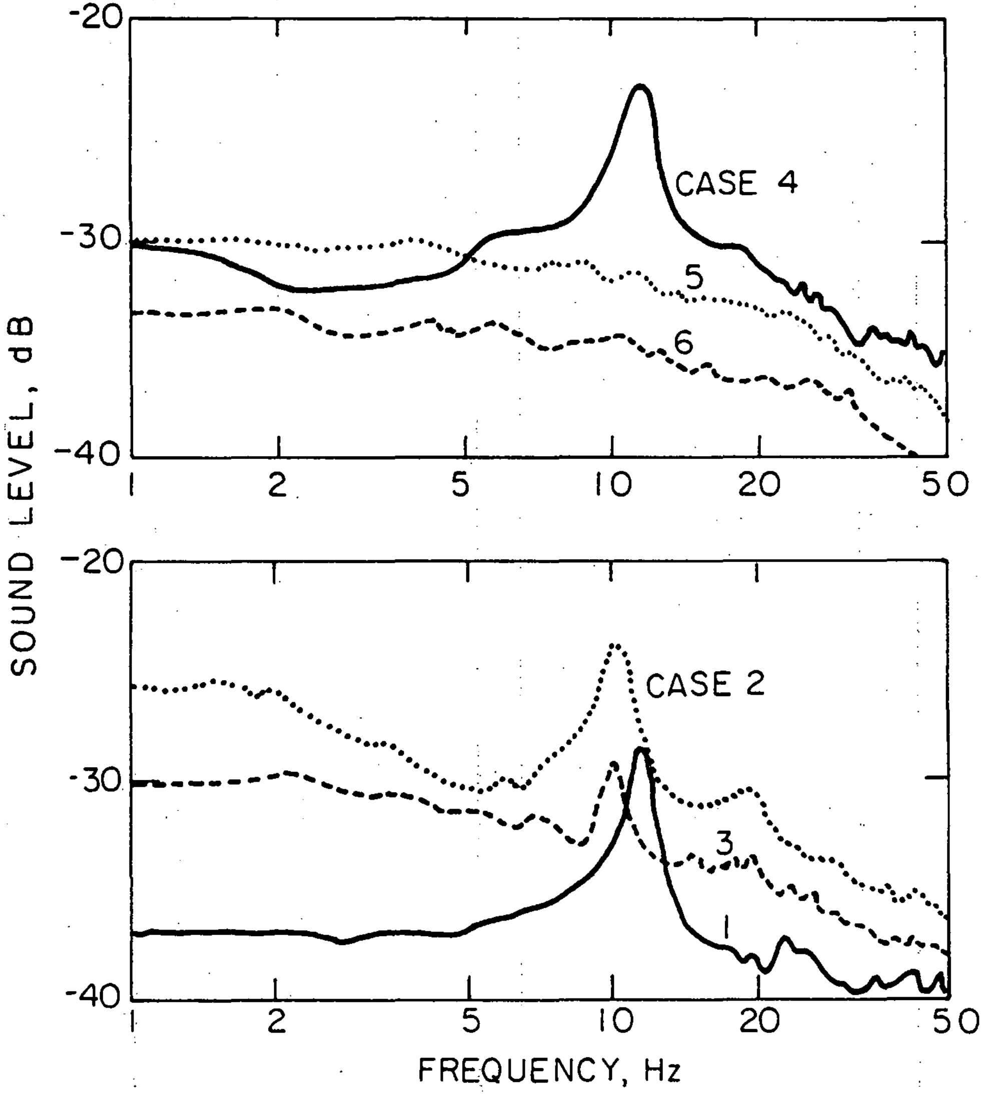

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Figure 13. Time Averaged Combustion Sound Level in the Frequency Range of 1 to 50 Hz.

characterized, extinction occured through a "blowout" process in which the flame was lifted above the bed and swept out of the combustor. The failure of the hot particles to re-ignite the incoming flow under these circumstances requires further investigation as the observation suggests that the combustion process may in this case not be stabilized by the hot bed but perhaps by a flame standing above the moving bed surface.

Understanding of the behavior of the spouted bed appears to require recognition and characterization of its unsteady characteristics. While studies of non-combusting spouted beds have explored their pulsating characteristics (Mathur and Epstein, 1974), previous investigations of spouted bed combustors have not included their periodic unsteady behavior.

CONCLUSIONS

A planar two-dimensional spouted bed combustor with a quartz front wall has been constructed which allows observation of particle flows. Important conclusions resulting from the initial phase of a study of the behavior of spouted bed combustion are:

1) The bed exhibits an unsteady, usually periodic behavior in both cold and combusting flow which is controlled by the particle flow in the moving bed region of the bed.

2) Temperature profiles suggest that the particles are heated both in the spout by convection from the hot combustion gases and in the moving bed region by conduction from the hot spout region. Total heat transfer from the combustion gases to the particles is estimated to be 8% of the energy released.

3) Pressure measurements give some qualitative understanding of gas flow within the combustor but do not allow determination of the fractions of the gas which pass through the spout, moving bed, and packed bed regions.

4) Measurements of particle velocities in the moving bed region provide particle circulation rates in the bed. Particle to gas mass flow ratios of about ten were observed. These were about ten percent greater with combustion than with cold flow.

5) A variety of techniques were used to observe and measure the unsteady behavior of the spouted bed combustor. Low frequency pulsations are controlled by particle flows in the moving bed region. Combustion amplifies these pulsations. Unsteady characteristics are important to both the time averaged behavior of the bed and such transient events as extinction.

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