DOE FINAL REPORT

DOE/PC/50257- 4

DEVELOPMENT OF A COAL BURNING PULSATING COMBUSTOR FOR INDUSTRIAL POWER

By

Ben T. Zinn

Muh-Rong Wang

Brady R. Daniel

Prepared for

DEPARTMENT OF ENERGY

PITTSBURGH ENERGY TECHNOLOGY CENTER

Under

DOE Contract No. DE-FG22-82PC50257

November 1983

GEORGIA INSTITUTE OF TECHNOLOGY

A Unit of The University System of Georgia
School of Aerospace Engineering
Atlanta, Georgia 30332

DOE FINAL REPORT

DOE/PC/50257- 4

DEVELOPMENT OF A COAL BURNING PULSATING COMBUSTOR FOR INDUSTRIAL POWER

Prepared for

Department of Energy

Pittsburgh Energy Technology Center

by

Ben T. Zinn

Muh-Rong Wang

Brady R. Daniel

School of Aerospace Engineering

Georgia Institute of Technology

Atlanta, Ga. 30332

DOE Contract No. DE-FG22-82PC 50257

November 1983

ABSTRACT

This report describes the results obtained during a twelve months period under DOE contract DE-FG22-82PC50257 which terminated on June 21, 1983. The research conducted under this program investigated the performance characteristics of a previously developed coal burning pulsating combustor whose design is based upon the Rijke tube principles. The combustor consists of a vertical tube opened at both ends with a fuel burning bed located in the middle of its lower half. Coal is supplied to the bed by a rotating auger-type feed system located 1 ft above the bed. Following ignition, the interaction between the combustion process and the combustor flow results in the excitation of high amplitude (up to 165 dB) fundamental, longitudinal acoustic mode oscillations with frequencies in the range 75-90 Hz in the combustor. Maximum amplitudes occurred near stoichiometric air/fuel ratio operation, suggesting that systems utilizing the developed combustor should possess high thermal efficiencies, as they could operate with relatively little excess air. Both bituminous and subbituminous coals with sizes in the range 1/4" - 1/2" were burned in the developed pulsating combustor. The CO, CO_2, NO_x, SO_2, O_2 and particulates concentrations in the exhaust flow were measured to evaluate the combustor performance. In tests with bituminous coal, combustion efficiencies higher than 95% for coal feed rates in the range 42-60 lb/ft^{2}hr were achieved with only 13% excess air while NO_x and SO_2 concentrations were comparable to those obtained with other steady state combustors. A higher performance was attained in initial tests with subbituminous coal. Finally, pulsating operation was possible under fuel rich conditions suggesting that the developed pulsating combustor could be possibly used as a gasifier.

I. INTRODUCTION

This report describes the results obtained under a research program entitled "Development of a Coal Burning Pulsating Combustor for Industrial Power" which was supported under DOE Contract No. DE-FG22-82PC50257 during the period June 27, 1982 to July 26, 1983. The research conducted under this program was concerned with the determination of the performance characteristics of a Rijke-type, coal (or any other solid fuel) burning pulsating combustor which had been developed earlier under this program[1,2].

As its name implies, the burning in a pulsating combustor takes place under oscillatory conditions. The excitation of acoustic velocity oscillations in the combustor is expected to enhance mixing processes which, in turn, intensify the combustion process. Keeping this in mind, the present study had been undertaken with the hope that the developed pulsating combustor would possess high thermal and combustion efficiencies, high combustion intensity and be capable of burning unpulverized coal. In addition, it had been expected that the developed combustor will exhibit improved convective heat transfer characteristics which are known[3] to occur when pulsations are present in a flow. Finally, it was of interest to determine whether benefits such as reduced slagging, ability to maintain heat transfer surfaces clean by the scrubbing action of the pulsating flow and reduced NO_x formation[4], which were observed in other pulsating combustors, would be also present in the developed pulsating combustor.

The reasons for expecting the above mentioned benefits are discussed in detail in Refs. 1 and 2 and, consequently, they are not to be repeated herein. Instead, this report discusses the results obtained in a series of tests in which the performance of the developed pulsating combustor under various operating conditions was investigated.

II. DEVELOPED EXPERIMENTAL SETUP

The developed combustor is based upon the principles of the acoustic Rijke Tube[5,6] which consists of a vertical pipe of length L containing a heated metal gauze at a distance L/4 from the bottom of the tube. The pipe is open at both ends and heat transfer from the gauze to the surrounding air results in an upward flow of air (due to buoyancy) and the excitation of the fundamental, longitudinal acosutic mode of the tube. The Rijke type, coal burning pulsating combustor developed under this program is shown in Fig. 1. A coal burning bed located at a distance of L/4 from the bottom of the tube serves as the Rijke tube heat source which excites the fundamental acoustic mode of the combustor whose wave structure is also shown in Fig. 1. The combustion bed is located in a region where both the acoustic pressure and velocity are nonzero and the interaction between these oscillations and the combustion process establishes a positive feedback loop which provides the energy required for maintaining the oscillations.

Coal is fed into the bed at a preselected rate by an auger-type feed system that is attached to the combustor wall just above the combustion bed. A preselected flow rate of combustion air enters the combustor through the bottom decoupling chamber. Combustion occurs when this air moves through the bed and reacts with the combustible volatiles and coal. The presence of acoustic velocity oscillations in the bed increases the coal burn rate by improving the efficiencies of the gas phase mixing processes and the transport of oxygen to the coal surface.[7,8,9]

Two auger-type feed systems have been developed under this program to date, see Fig. 2. The auger shown in the right of Fig. 2 was developed later on in the program after it had been found that the auger on the left of Fig. 2 produced an undersirable periodic coal feed rate which, in turn, resulted in periodic variation of the air/fuel ratio in the combustion zone. The desired coal feed rate is established by controlling the rate of rotation of the auger. Thus, by controlling the coal and air supply rates, testing at different air/fuel ratios can be performed.

The measurements performed during a given test are described in Fig. 1. A pressure transducer at the midpoint of the combustor, where the acoustic pressure antinode is located, measures the amplitude of the pulsations. The gas temperatures near the entrance to the combustor, above the combustion bed and below the exit plane are measured with thermocouples as shown. Probes for sampling gas and particulates from the exhaust flow are located just below the combustor exit plane, see Fig. 3. A schematic of the exhaust gas and particulate sampling trains is presented in Fig. 4. The exhaust gas is sampled continuously and analyzed to determine the CO, CO_2, NO_x, SO_2 and O_2 concentrations in the exhaust flow. Not shown in the figure is an O_2 analyzer which was recently added to the gas analysis system. Particulate sampling is performed isokinetically to determine the exhaust flow particulates concentration during selected time periods of a test. A mini computer based data acquisition and storage system which digitizes the analog test data and stores it for post test analysis and plotting was developed. Consequently, the performance of the combustor throughout the duration of a test can be continuously recorded and analyzed. More details about the developed instrumentation system can be found in a recently completed Ph.D. thesis[2] which was performed as part of this research program.

III. RESULTS

Todate, the performance of the combustor was evaluated using bituminous and subbituminous coals whose properties are described in Table I below. However, since most of the testing was conducted with the bituminous coal, only results obtained with this coal will be considered in detail herein. These data will be supplemented with a qualitative discussion of the results obtained to date with the subbituminous whose testing is still in progress.

The stoichiometric air/fuel ratios for these coals were determined under the assumption that all carbon reacts to form carbon dioxide, all sulphur reacts to form sulphur dioxide, and all hydrogen reacts to form water vapor.

Tests conducted under this study to date have demonstrated that unpulverized coal can be burned continuously under a pulsating mode of combustion in the developed Rijke type combustor. Pulsating operating is

Table I

Properties of the Bituminous and Subbituminous Coals Tested Under This Program

		Bituminous Coal	Subbituminous Coal
Proximate Analysis	Fixed C	55.38%	34.53%
	Volatile	35.13%	36.82%
	S	1.55%	0.88%
	A	7.39%	8.86%
	M	2.10%	19.79%
	Heating Value	13,801 Btu/lb	9,402 Btu/lb
Ultimate Analysis	C	76.46%	54.47%
	H	4.88%	3.82%
	N	1.39%	0.64%
	O	6.09%	11.18%
Stoichiometric Air/Fuel Ratio		10.35	7.18

achieved consistently within minutes after igniting the fuel in the bed.* Completely different characteristics of burning under pulsating and non pulsating conditions were observed.

Under the pulsating mode of operation, the flames above the combustion bed were relatively short and exhibited an intense agitation. The coal in the bed was totally immersed in the flames and "dancing", downward pointing flamelets were anchored to the bottom of the combustion bed. In addition, the exhaust flow appeared clear and smoke free. Finally, the combustor wall in the region of the combustion bed heated up very rapidly after ignition to a glowing red condition.

During the course of this investigation it has been noted that opening one or more half inch holes in the combustor wall approximately one foot above the combustion bed caused a transition to nonpulsating burning. When the pulsations stopped the flames became relatively long, sometimes reaching the top of the 9 foot combustor, and the base of the flames appeared to be attached to the coal at some distance above the metal grid which supported the bed. Also, the flames lacked the agitation observed during pulsating operation and rapid accumulation of unburned coal occurred

---

* It should be pointed out that the characteristics of the pulsating combustion operation depend upon the ignition method in such a system without mechanical coal distribution mechanism . "Good" start up which required following a developed ignition procedure, assured proper, "steady state" pulsating combustion operation while poor ignition often resulted in "unsteady" pulsating operation which was characterized by amplitude variations and rapid ash accumulation.

in the bed. The exhaust gases were smoky and the wall surrounding the burning bed was not red hot as it was during operations with pulsations.

The observed qualitative differences between the pulsating and nonpulsating modes of operation support arguments in the literature which claim that the presence of pulsations improves the efficiencies of the combustion and heat transfer processes. The oscillatory flow in the combustion zone improves the mixing between the oxidizer and the fuel, which results in a higher reaction rate and a more complete combustion process. The latter is responsible for the observed short flames and the clear and apparently smoke free exhaust gases. The back-and-forth velocity oscillations in the combustion zone are also responsible for the presence of the highly agitated flames which engulf the coal in the bed and for the flamelets that extend downward from the bottom of the metal grid which supports the bed. Finally, support for the intensification of heat transfer under pulsating conditions is provided by the observed rapid heat-up of the combustor wall surrounding the reaction zone.

A typical set of test data measured during a test is presented in Figs. 5 through 10. The pressure amplitude shown in Fig. 5, remains relatively constant with time. However, the data exhibits step-function changes because of round-off errors in the data reduction program. The program is currently being modified to reduce the round-off errors and provide a more representative output of the pressure data. Figures 6, 7, 8 and 9 show the time variations of the exhaust flow concentrations of CO, CO_2, NO_x and SO_2, respectively. The fluctuations in the measured concentrations have been correlated with the periodic discharges of coal from the rotating auger feed system. Modifications to the coal feed system have recently been completed resulting in a more uniform coal feed rate which, in turn, decreased the fluctuations in the measured concentrations.

Figure 10 shows the time variations of the temperatures at different combustor locations. Temperature T_2 was measured 1.5 ft. above the combustion bed and the remaining temperatures were measured 1 ft below the combustor exit plane, at the radial locations shown in Fig. 11. The temperature data indicate that temperatures inside the combustor are relatively low. For example, note that T_2, the temperature 1.5 ft above the burning bed, is only around $1400^{\circ}F$, which is considerably lower than the $3000^{\circ}F$ temperatures which are expected in coal combustors.[10,11] The reasons for the measured low temperatures is that the developed steel combustor was not insulated and the presence of acoustic velocity oscillations resulted in high heat losses through the combustor walls.

The performance under each test condition was determined from time averages, over the duration of the test, of data similar to that presented in Figs. 5 through 10. Typical results are presented herein and more data can be found in Ref. 2. The following set of data was obtained with the inclined auger on the left of Fig. 2. These tests were conducted with a nominal coal feed rate of 50 gr/min and different air/fuel ratios. The measured CO and CO_2 concentrations together with the air/fuel ratio were used to determine the combustor efficiency η. Typical dependence of η upon the nondimensional air/fuel ratio (i.e., α) is presented in Fig. 12. As expected,

η increases with α and it is larger than 96% for α = 1.15, which compares very favorably with coal burning stokers. The latter usually operate at 20-30% excess air and typically have a carbon loss of 4 to 8%, depending on the amount of reinjection.[11] No reinjection of unburned refuse was performed in any of the experiments of this investigation.

Figure 13 shows the dependence of the average dB level of oscillations upon the nondimensional air/fuel ratio. The data show that maximum amplitudes occur near stoichiometric air/fuel ratio. It is believed that this behavior is related to the magnitude of the temperature change, from cold air to hot combustion products, which occurs at the bed. This temperature jump is maximum near stoichiometric operation and it has been shown[12,13,14] that the efficiency of driving acoustic waves in tubes with a temperature jump (see Fig. 18) increases when the magnitude of the temperature jump increases. The results shown in Fig. 13 also indicate that a Rijke type combustor can be operated at high amplitudes of pulsation with little excess air. This result suggests that systems utilizing such a combustor should exhibit high <u>thermal</u> efficiencies. Furthermore, Fig. 13 shows that pulsating combustion of coal is possible in a Rijke type combustor over a wide range of air/fuel ratios. Since for $\alpha < 1$, the exhaust flow contains combustibles, these data suggest that the developed pulsating combustor could possibly be used as a coal gasifier.

For the following series of tests the inclined auger was replaced by the horizontal auger on the right of Fig. 2. The new auger provided a much more uniform coal feed rate into the combustion bed and it was used to investigate the dependence of the combustor performance upon the coal feed rate for fixed values of the normalized air/fuel ratio. Two normalized air/fuel ratios were tested; that is, α = 1.00 and α = 1.13. The coal feed rate was increased from 36 to 90 gr/min (28.9 to 72.2 lb/ft^2hr) in steps of approximately 8-10 gr/min (6.4 - 8.0 lb/ft^2hr).

Results obtained in this series of tests are presented in Figs. 14 through 17. Figure 14 describes the dependence of the combustion efficiency η upon the coal feed rate. It shows that for α = 1.00, the maximum efficiency is 92% and it is equal or larger than 90% for feed rates between 42.1 and 56.1 lb/ft^2hr. On the other hand, when x = 1.13, $\eta >$ 95% for coal feed rates in the range 42 - 60 lb/ft^2hr, with η reaching a maximum value of 97%. Again, these results compare very favorably with characteristic combustion efficiencies of stokers.[11]

The trends indicated by the data presented in Fig. 14 can be understood with the aid of the results presented in Fig. 15 which describe the dependence of the average dB level of pulsations on the coal feed rate. Figure 15 shows that the dB level of pulsations increases monotonically with an increase in the coal feed rate for a constant α. Furthermore, as expected (see Fig. 15), the amplitudes produced under stoichiometric conditions are, in general, larger than those for α = 1.13. The lower acoustic pressure amplitudes at the lower feed rates result in a reduction in the efficiency of mixing between the oxidizer and the fuel which is probably the reason for the decrease in the observed combustion efficiencies (see Fig. 14). As the fuel feed rate increases (for a fixed air/fuel ratio) both the dB level of pulsations and the steady air velocity increase. An analysis performed under this program has shown that an increase in the dB sound level would result in the expulsion of small particles out of the combustor. This effect together with the increase in the steady state velocity, which is required to keep constant when the fuel feed rate increases, would tend to cause an increase in the elutriation of small unburned coal particles from the combustor which, in turn, should result in a decrease in the combustion efficiency of the combustor. Indeed, the presence of coal particles in the exhaust flow was observed in tests conducted at the higher fuel feed rates. The presence of burning particles in the exhaust flow is believed to be the main cause of the observed decrease in combustion efficiencies at the higher coal feed rates.

The combustion efficiency data were used to determine the combustor heat release rate as function of the coal feed rate. These results are shown in Fig. 16. The heat release rates, Q, in Btu/ft^{2}hr, were computed from the following formula:

$$Q = \frac{Hv \times m_F \times \eta}{A} = 110.4\ m_F\ \eta$$

where m_F is the coal feed rate (in gr/min), η the combustion efficiency, Hv the heating value of the coal (Btu/lb) and A the cross sectional area of the combustor (ft^2). Figure 16 shows that a maximum heat release rate of approximately 0.87 MBtu/ft^{2}hr was attained; a value which is higher or comparable to heat release rates of other state-of-the-art combustors.[11]

The dependence of NO_x formation upon the coal feed rate is presented in Fig. 17 for different values of m_F. For comparison with the government's New Source Performance Standards (NSPS) of 1971 and 1979 the data are expressed in terms of lb NO_x per 10^6 Btu. Figure 17 shows that for α = 1.13 the NO_x production slightly exceeds the 1979 NSPS standard for feed rates up to, approximately, 48 lb/ft^{2}hr with a higher production of NO_x occuring at higher feed rates. Figure 17 also indicates that for a given coal feed rate, the NO_x production increases with increased excess air (i.e., α) and it is below the 1979 NSPS standard for stoichiometric operation (i.e., $\alpha = 1$).

In what follows, some recent results obtained when the subbituminous coal (see Table I) was burned under pulsating conditions are briefly discussed. First, it would be useful to consider some of the differences between the two coals which might also help to explain some of the observed trends. Contrary to the bituminous coal, the subbituminous coal does not tend to cake which would reduce the possibility of this coal agglomerating on the bed. Since the heating value of the subbituminous coal is lower, less energy was supplied and released into the combustor for a given coal feed rate. This would result in lower temperatures in the combustor when subbituminous coal is burned. Finally, since these coals have different stoichiometric fuel/air ratios, the burning of a given amount of subbituminous coal requires less air than would be required for the burning of a comparable amount of bituminous coal. Less air would imply lower air velocities in the combustor which, in turn, would reduce elutriation.

Differences in the pulsating combustor performance resulting from burning subbituminous and bituminous coals at a feed rate of 50 gr/min and α = 1.13 are presented in Table II below. One should note that when subbituminous coal is burned the percentages of particulate matter, carbon monoxide and nitrogen oxides in the exhaust flow are lower. In addition, the temperature in the combustor is lower, the dB level is higher and the combustion efficiency is higher. The tests with the subbituminous coal are currently in progress.

In summary, the results presented in this section demonstrate that coal can be burned efficiently in a Rijke type pulsating combustor. High combustion efficiencies were obtained in spite of the fact that the combustor was uninsulated, which resulted in high heat losses (which are recoverable) through the combustor walls and relatively low temperatures is the combustion zone. Furthermore, these high combustion efficiencies were achieved with the combustor operated with relatively little excess air (i.e., 13%). The NO_x production only slightly exceeded the 1979 NSPS standards for coal feed rates up to 48 lb/ft^2 hr and it decreased when the excess air was decreased. Finally, it has been demonstrated that both bituminous and subbituminous coals can be burned in the developed pulsating combustor and preliminary data indicate that better performance can be attained when burning subbituminous coals.

Table II

Comparison of the Performance of the Pulsating Combustor when burning Bituminous and Subbituminous Coals with m_F = 50 gr/min and α = 1.13.

	Bituminous Coal	Subbituminous Coal
Particulates in the exhaust flow, percent of carbon in feed rate	1.2	0.1
Exhaust flow carbon monoxide concentration, percent	0.8	.0353
Exhaust flow NO_x concentration, ppm	460	350
Exhaust flow SO_2 concentraction, ppm	900	870
Temperature 1½ ft above the combustion bed, ^oF	1500^oF	1400^oF
Combustion efficiency, percent	94	96.1
Sound pressure level, dB	156.0	157.1

REFERENCES

1. Zinn, B. T., Miller, N., Carvalho, Jr., J. A. and Wang, M.R., "Development of Coal Burning Pulsating Combustor for Power Generation," DOE Final Report Contract No. DE-AS05-79ER 10068, December 1982.

2. Carvalho, Jr., J. A., "Investigation of the Characteristics of a Coal Burning Rijke Type Pulsating Combustor," Thesis, Georgia Institute of Technology, March 1983.

3. Hanby, V. I., "Convective Heat Transfer in a Gas-Fired Pulsating Combustor," Published ASME January 1969, pp. 1-5.

4. Vedikhin, S. V., Gafarov, A. S., Dolgikh, E. B. and Kandalintseva, M. V., "Burning of Fuels in the Pulsating Combustion Regime," Izvestiya VUZ. Aviatsionnaya Teknika, Vol. 22, No. 3, pp. 75-77, 1979.

5. Feldman, Jr., K. T., Jr. Sound & Vibration, 7, pp. 83-89, 1968.

6. Malling, Jr., G. C., Jr. Acoustical Society America, 35, p. 1058, 1963.

7. Lyman, F. A., "Enhanced Combustion of Fossil Fuel Particles and Droplets in Oscillating Flow," Progress Report, DOE Grant No. ET-78-G-01-3303, 1980.

8. Sabnis, J. S. and Lyman, F. A., Combustion and Flame, Vol. 47, pp. 157-172, 1982.

9. Hanby, V. I., Jr. of the Fuel Society, Vol. 18, pp. 44-49, 1976.

10. Faeser, R., "Combustion Enhancement and Pollutant Control with Acoustically Induced Mixing," Presentation made in DOE Contractors' Review Meeting on Pulverized Coal Combustion, Pittsburgh, PA, 1982.

11. Singer, J. G. (ed.), "Combustion-Fossil Power Systems," 3rd ed., Combustion Engineering, Inc., Windsor, Connecticut, 1981.

12. Rott, N., In "Advances in Applied Mechanics," (C. S. Yih, ed.) Academic Press, New York, pp. 135-175, 1980.

13. Katto, Y. and Sajiki, A., Bulletin of the JSME, Vol. 20, No. 147, pp. 1161-1168, 1977.

14. Katsnel'son, B. D., Marone, I. Ya. and Tarakanovskii, A. A., Thermal Engineering, Vol. 16, No. 1, pp. 3-6, 1969.

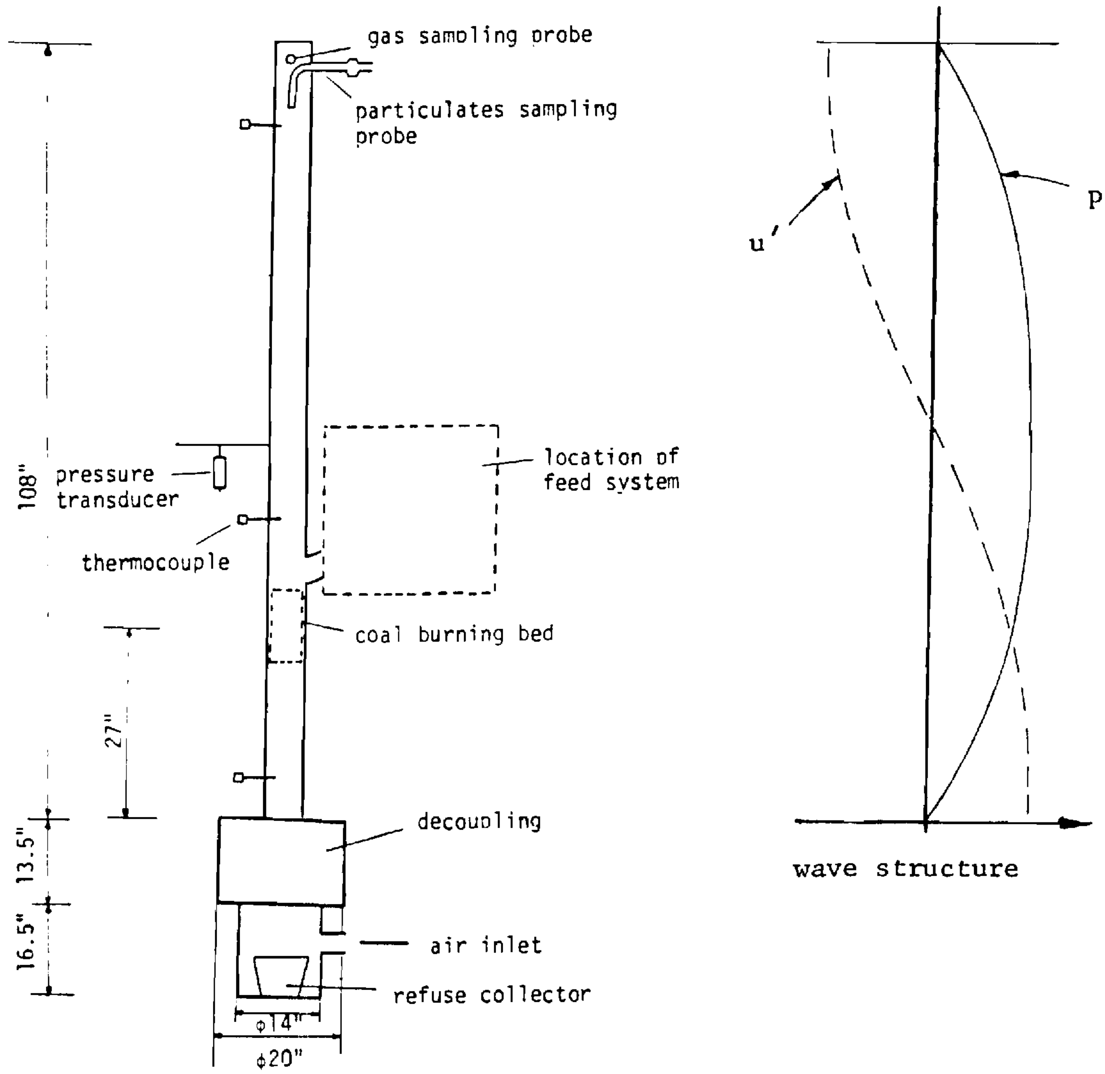
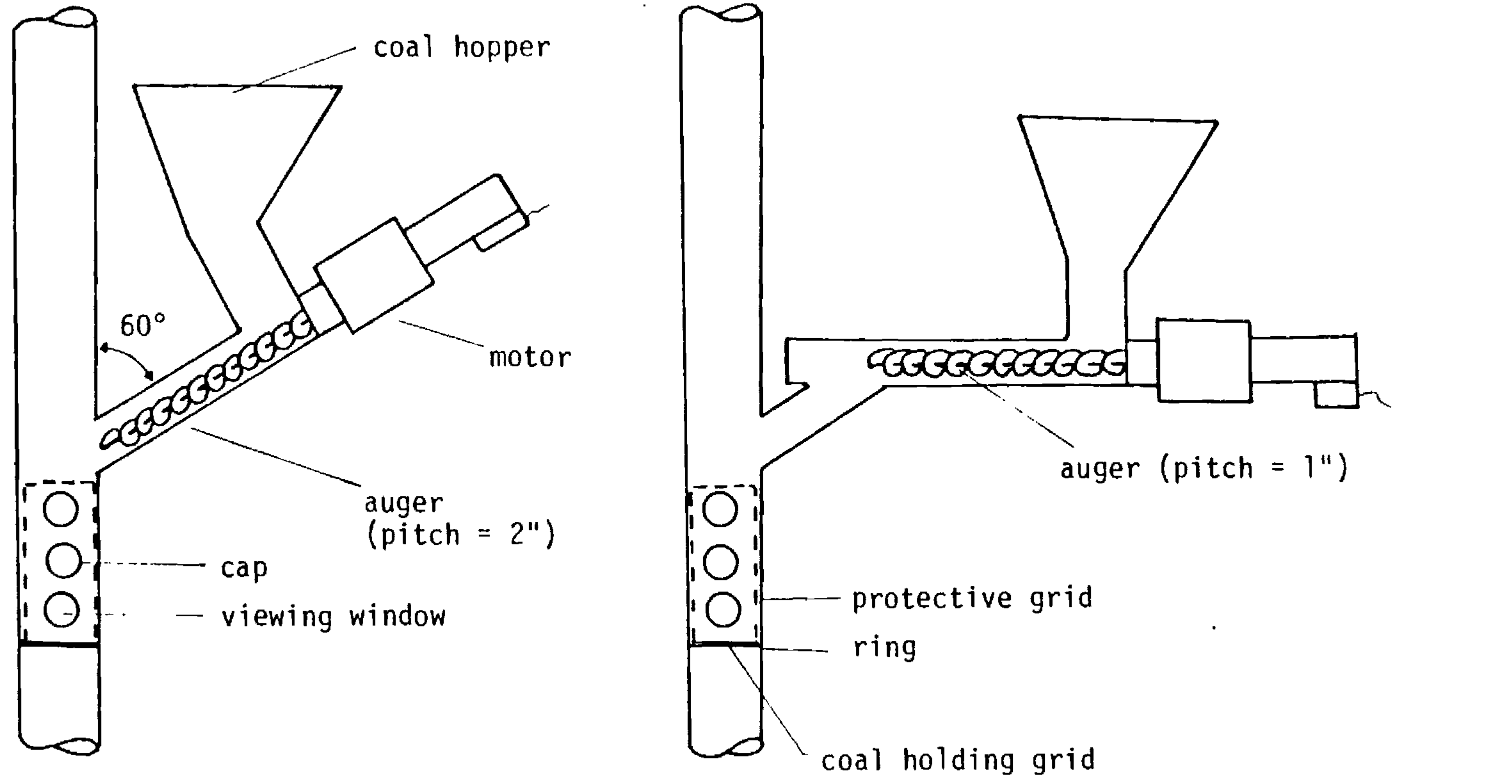


Figure 1. Schematic of the Rijke Tube Pulsating Combustor and Wave Structure.



Inclined Auger

Horizontal Auger

Figure 2. Schematic of the Auger Type Feed System (Inclined and Horizontal Auger).

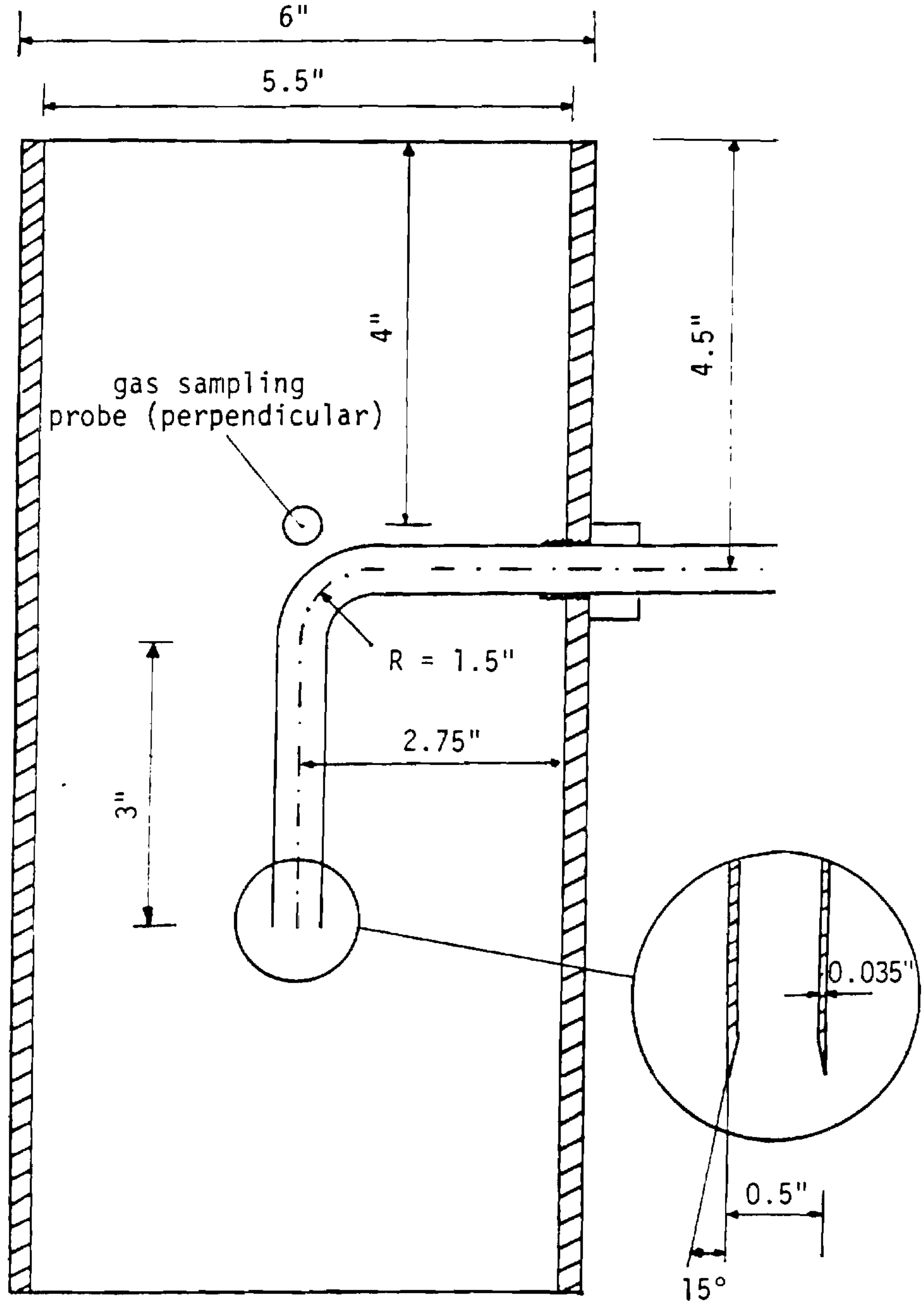


Figure 3. Particulates Sampling Probe and its Dimensions.

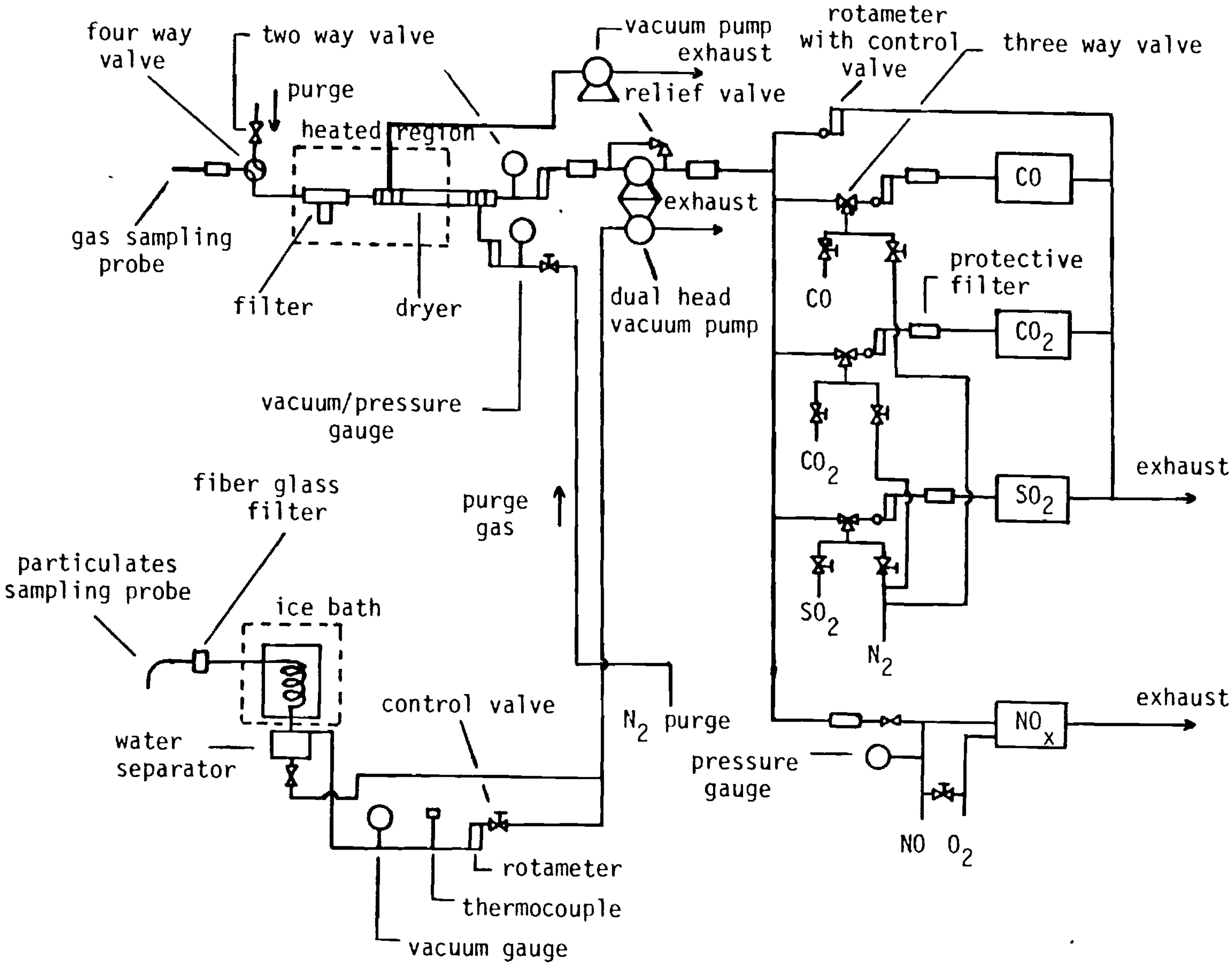


Figure 4. Schematic of the Modified Gas - Particulates Sampling Train.

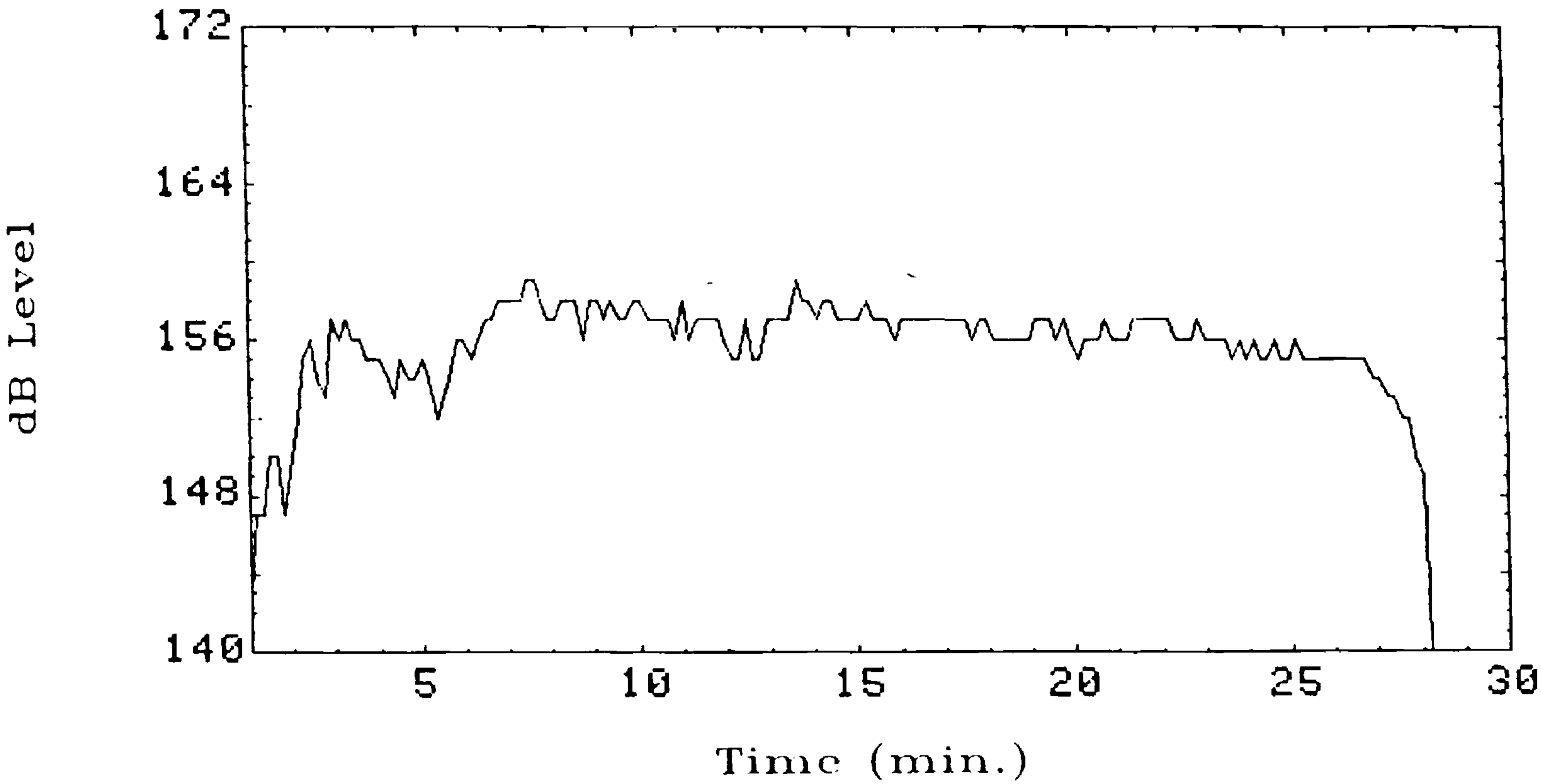


Figure 5. Time Variation of the dB Level of Oscillations (m_F = 29.9 lb/sqft. hr., Alpha = 1.13).

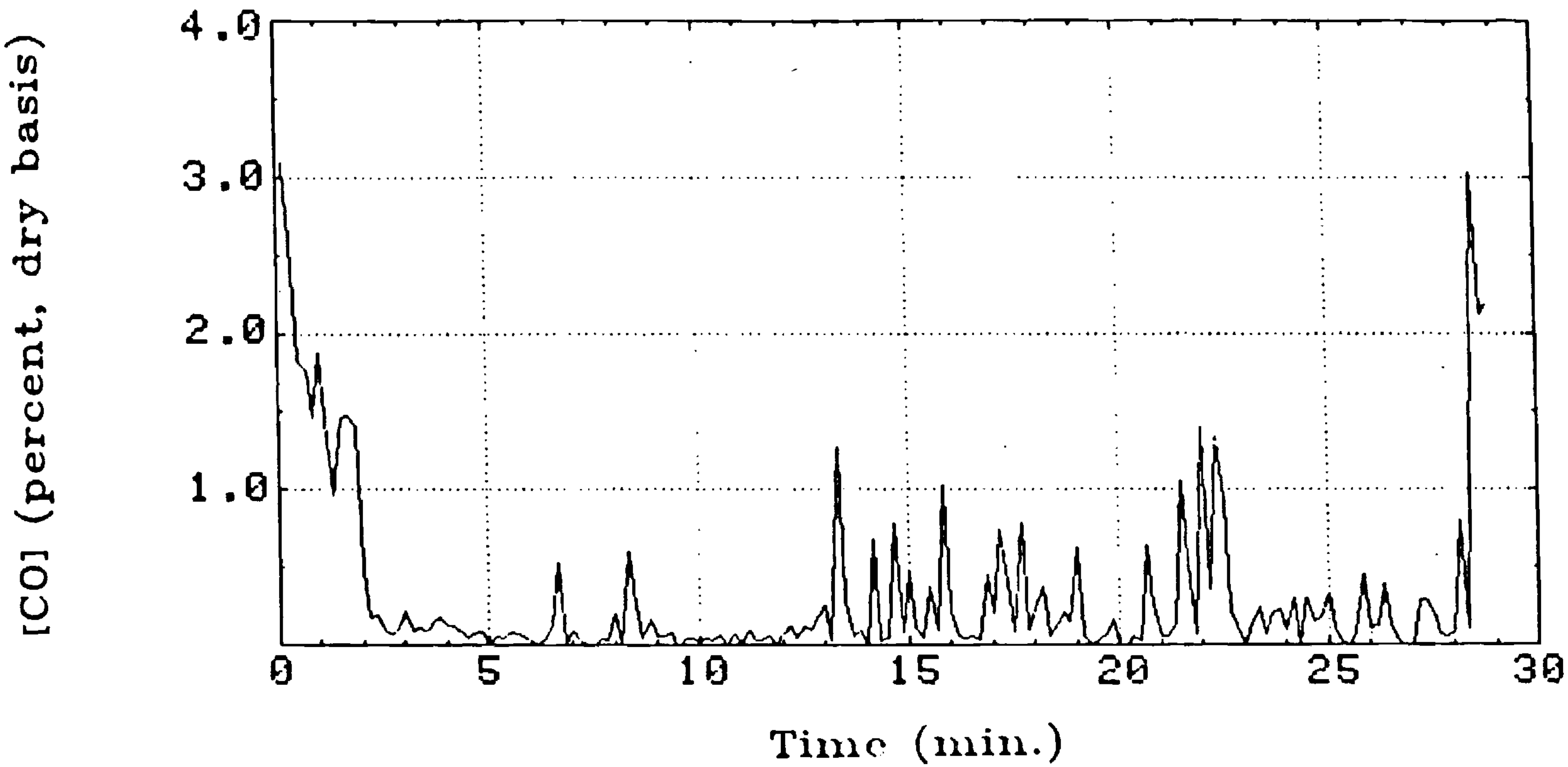


Figure 6. Time Variation of the CO Concentration (m_F = 29.9 lb/sqft. hr., (Alpha = 1.13).

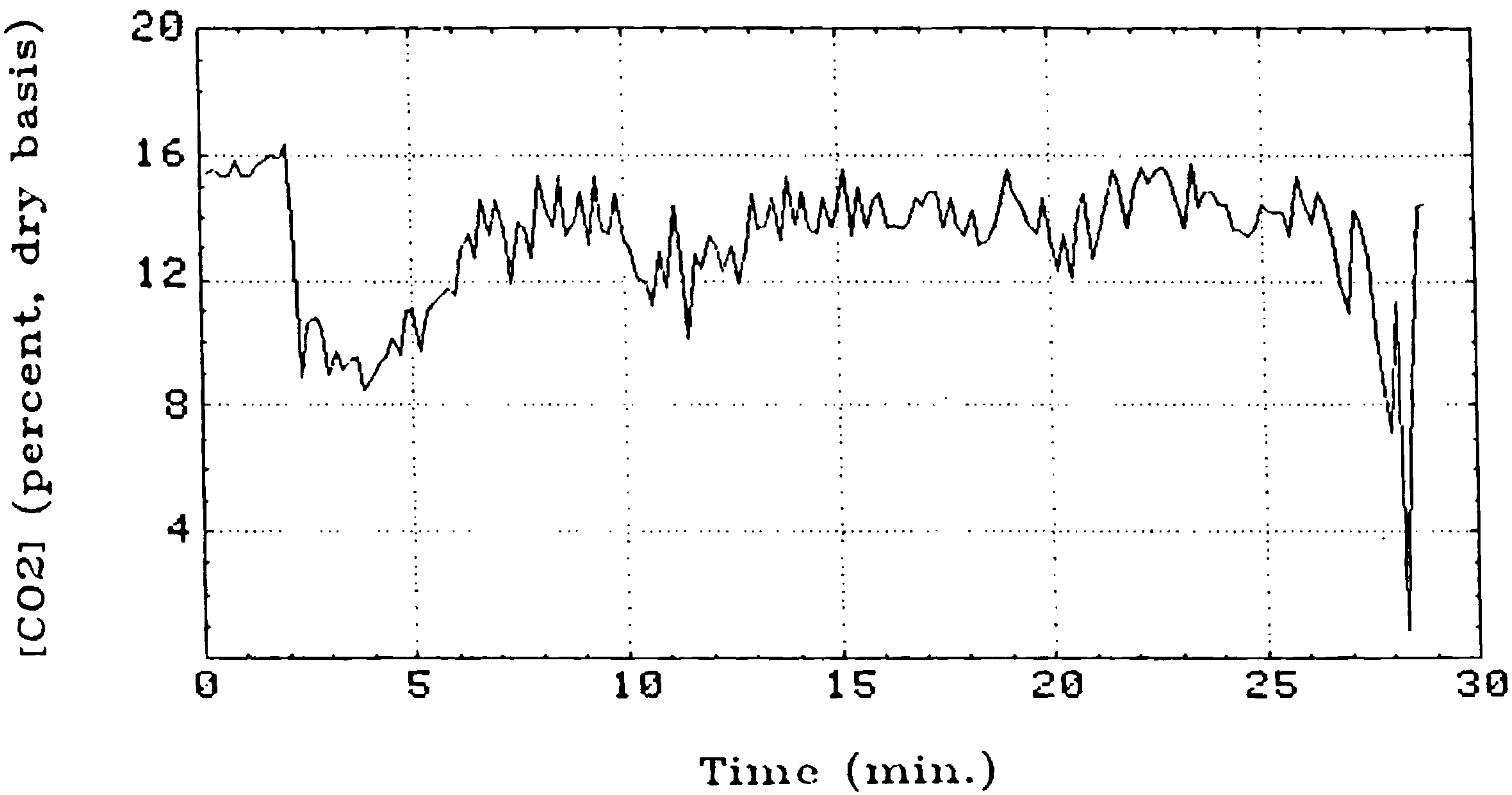


Figure 7. Time Variation of the CO_2 Concentration (m_F = 29.9 lb/sqft. hr., Alpha = 1.13).

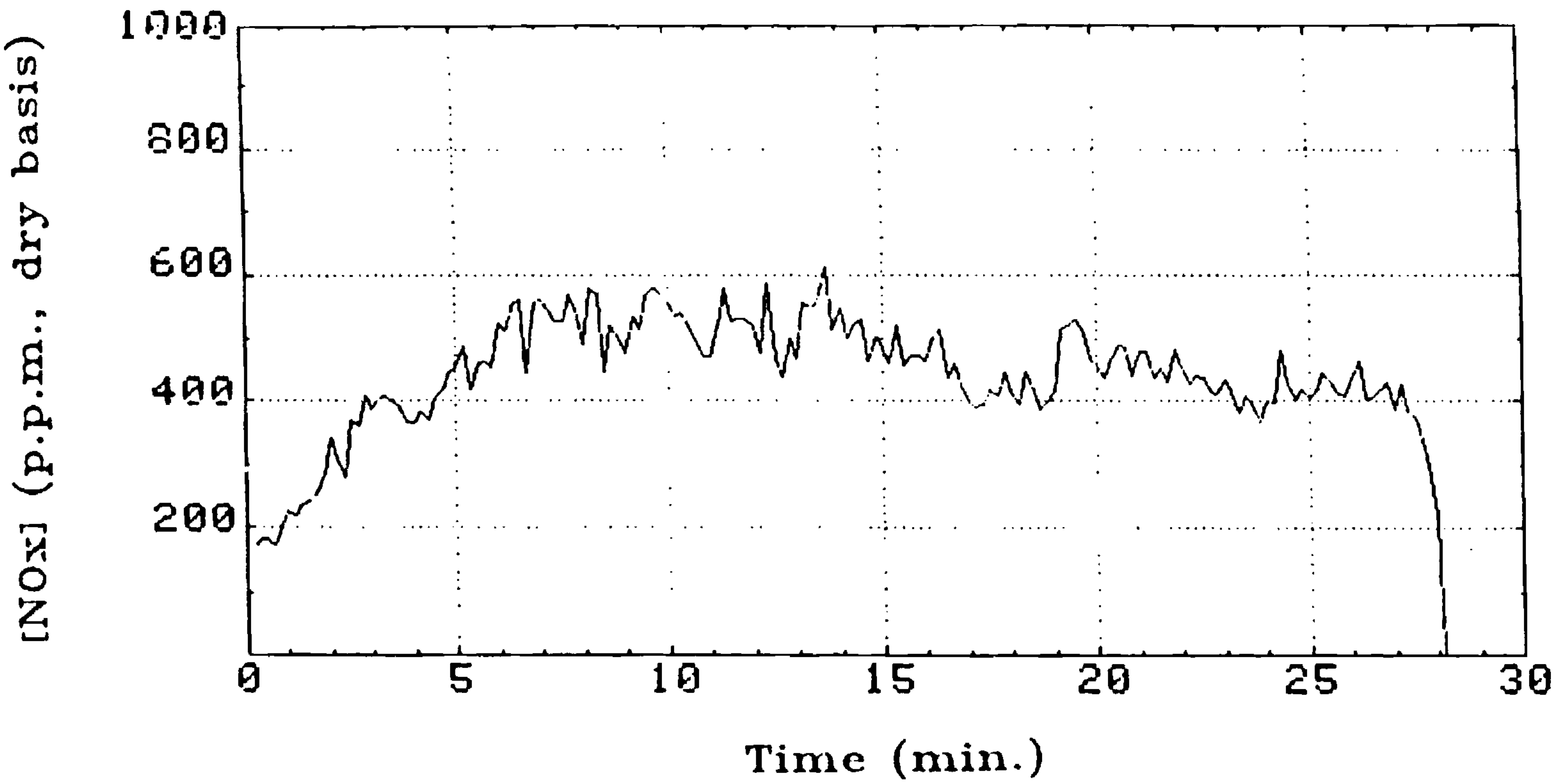


Figure 8. Time Variation of the NO_x Concentration (m_F = 29.9 lb/sqft. hr., (Alpha = 1.13).

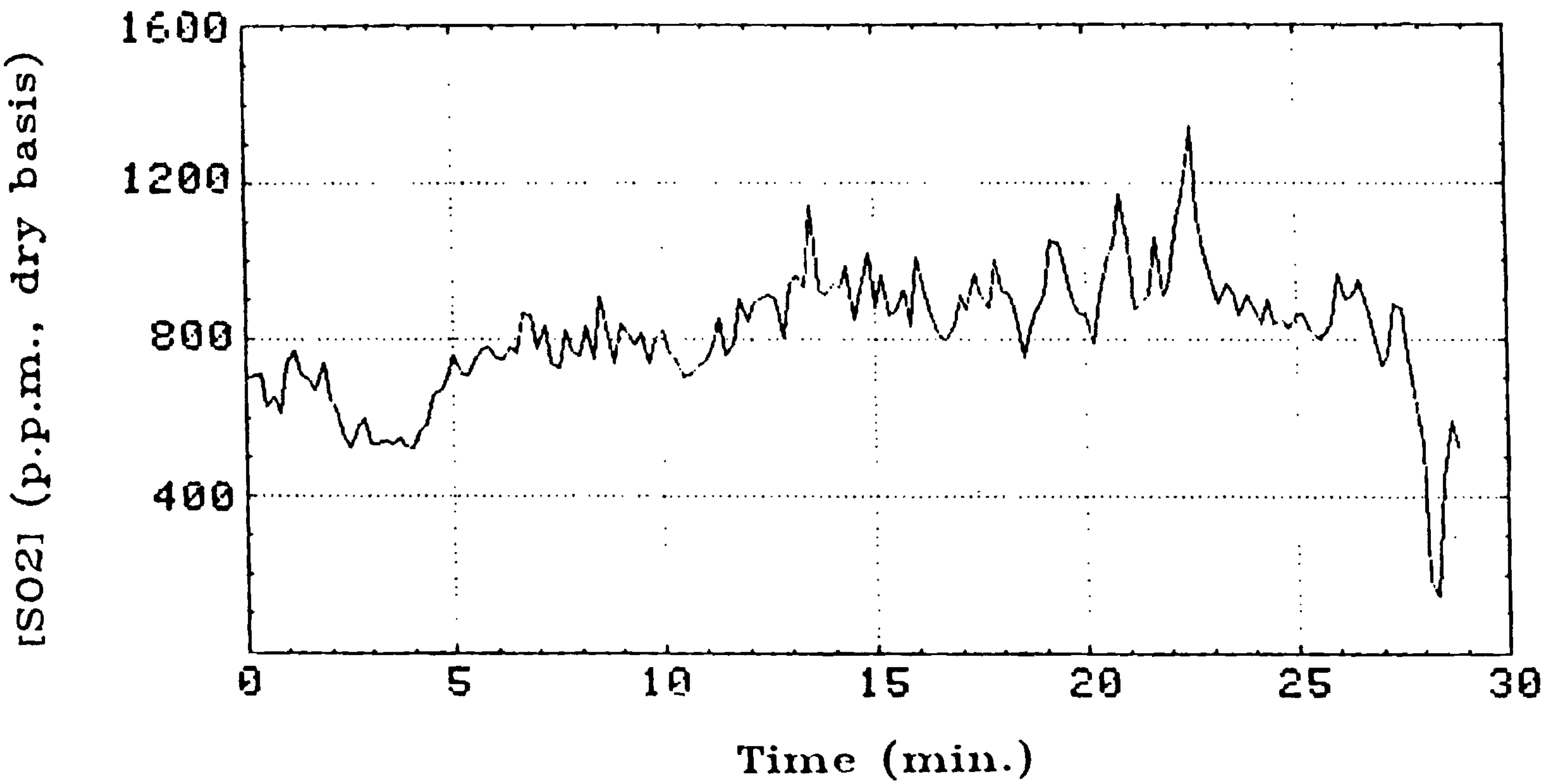


Figure 9. Time Variation of the SO_2 Concentration (m_F = 29.9 lb/sqft. hr., Alpha = 1.13).

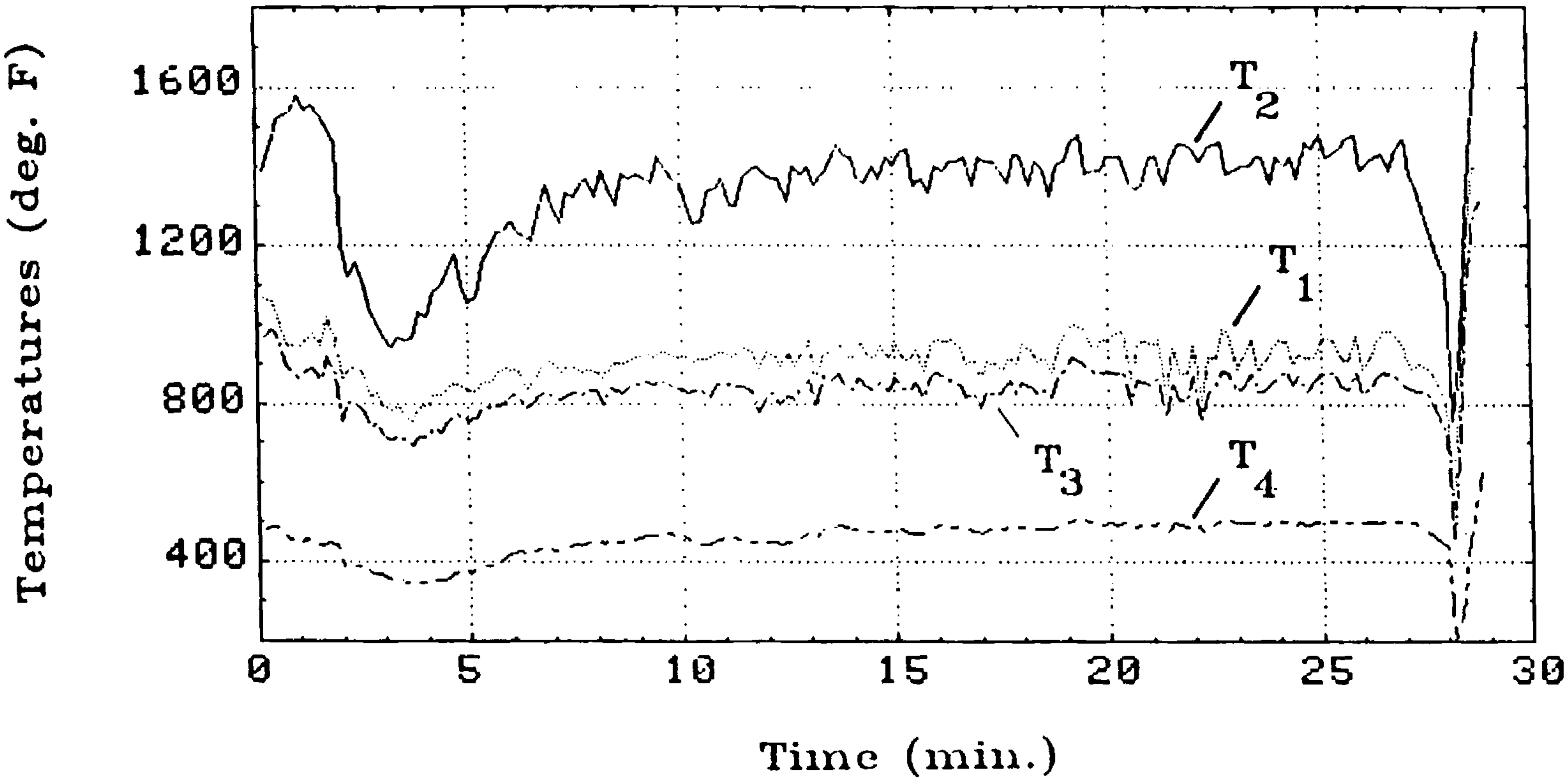


Figure 10. Time Variation of Temperatures (m_F = 29.9 lb/sqft. hr., Alpha = 1.13).

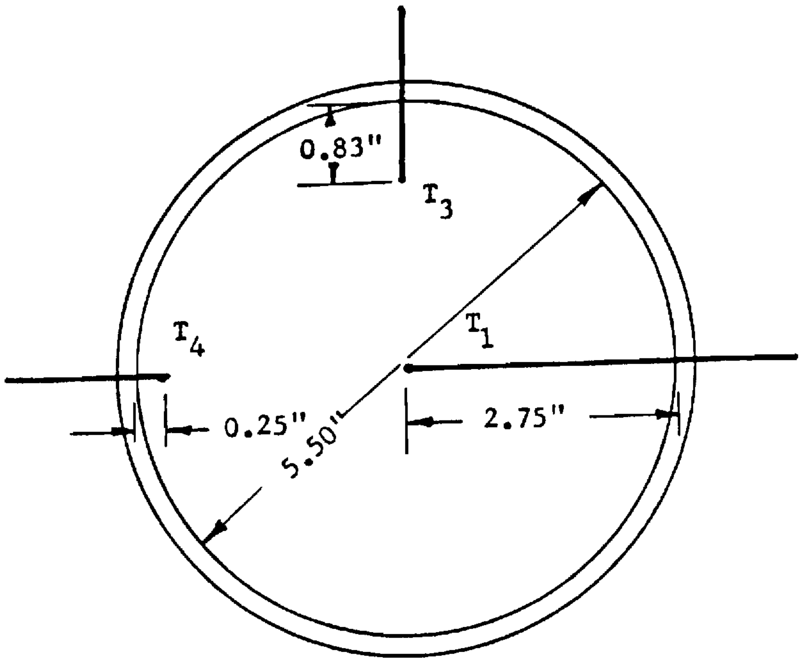


Figure 11. Locations of Thermocouples T_1, T_3, and T_4.

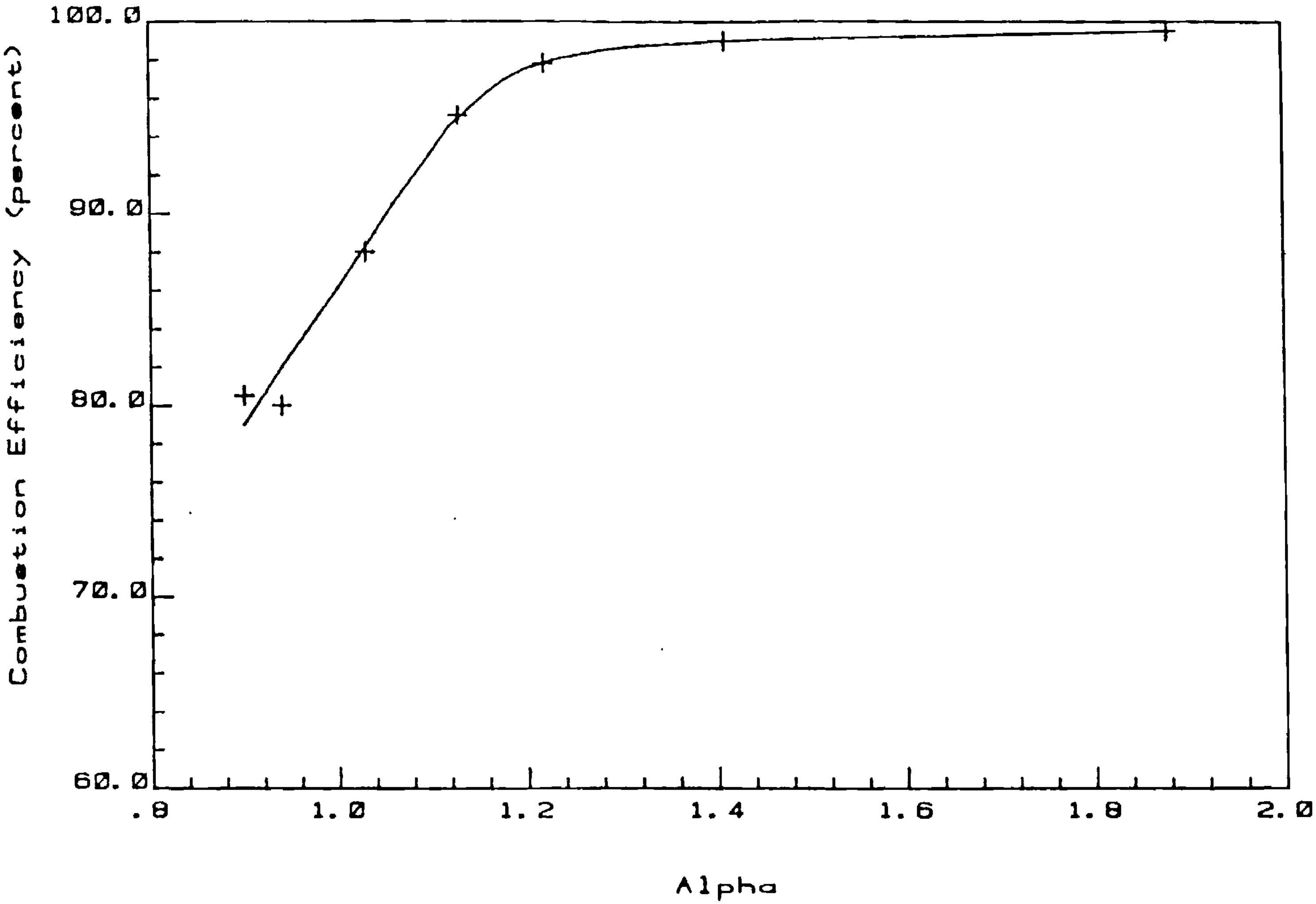


Figure 12. Dependence of the Average Combustion Efficiency upon the Normalized Air/Fuel Ratio (m_F = 40.1 lb/sqft. hr.).

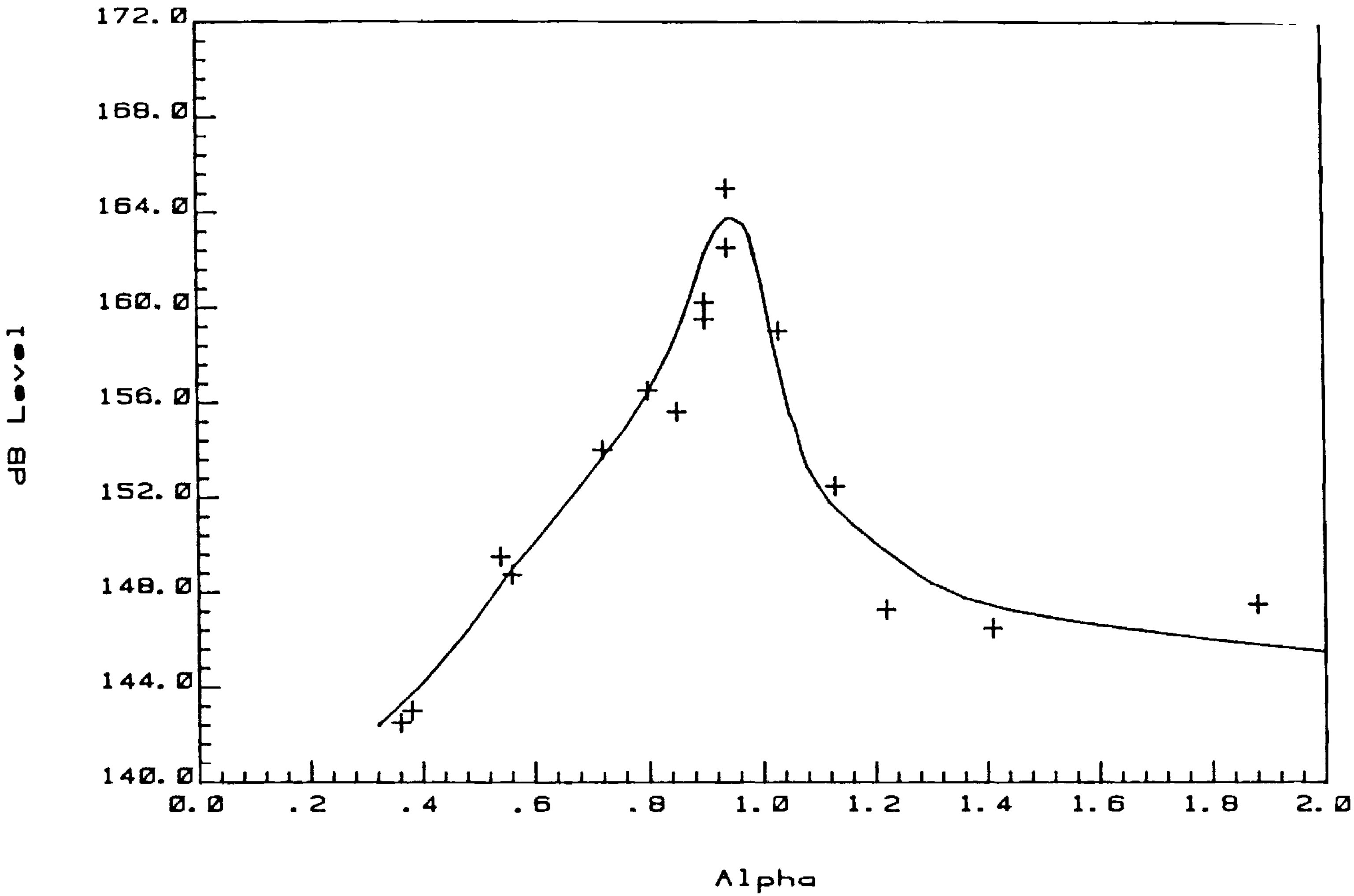


Figure 13. Dependence of the Average dB Level of Pulsations upon the Normalized Air/Fuel Ratio (m_F = 40.1 lb/sqft. hr).

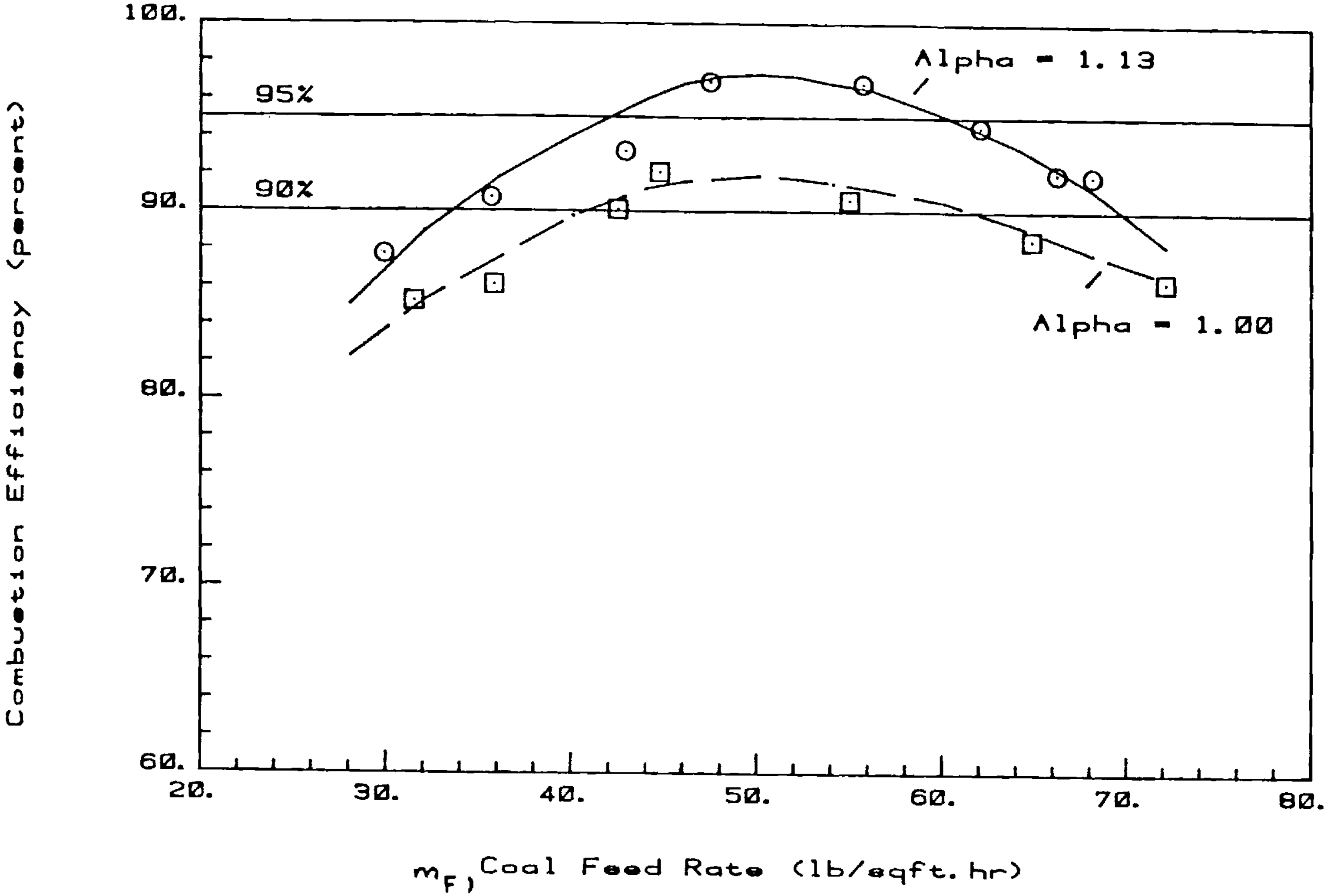


Figure 14. Dependence of the Average Combustion Efficiency upon the Coal Feed Rate.

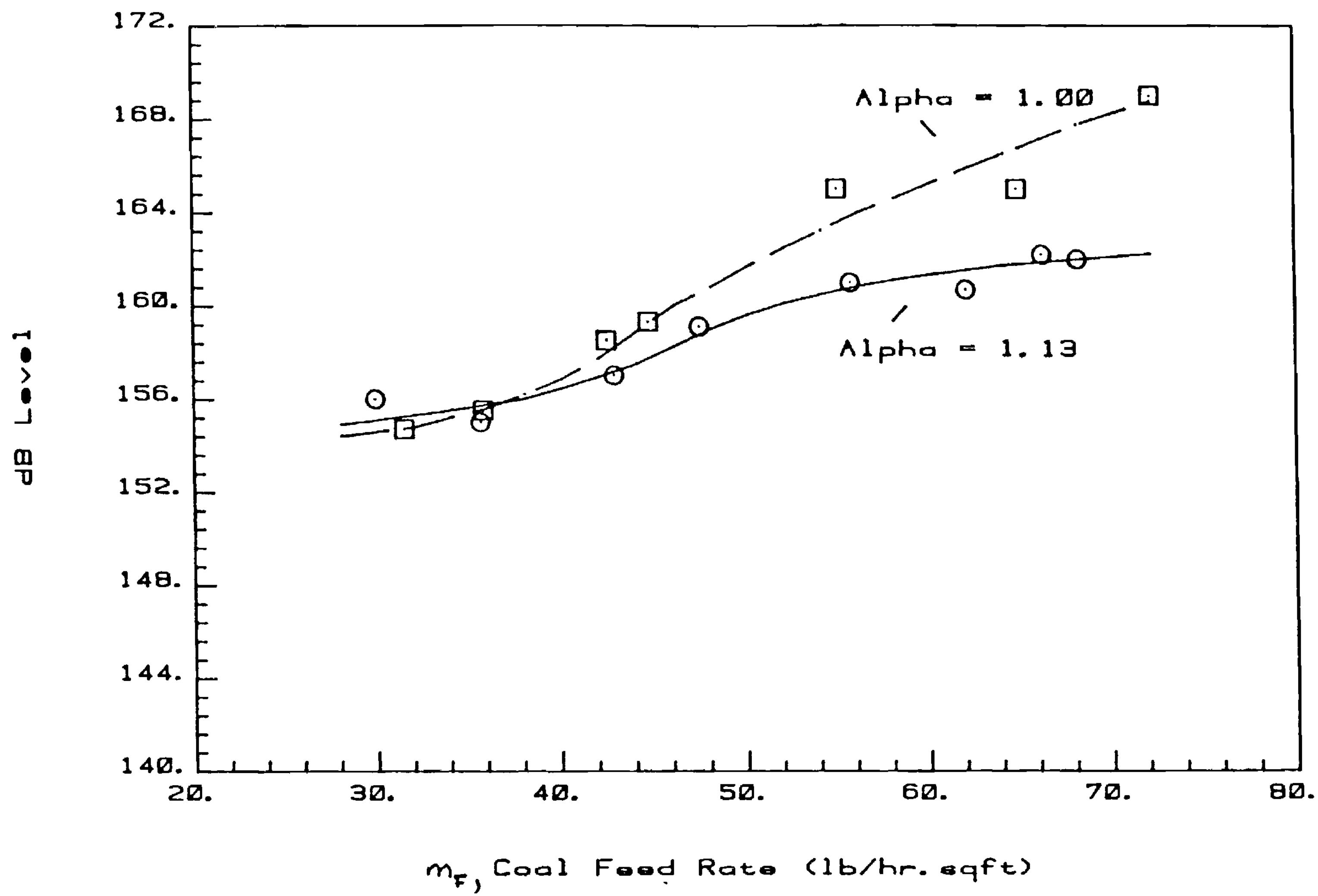


Figure 15. Dependence of the Average dB Level of Pulsations upon the Coal Feed Rate.

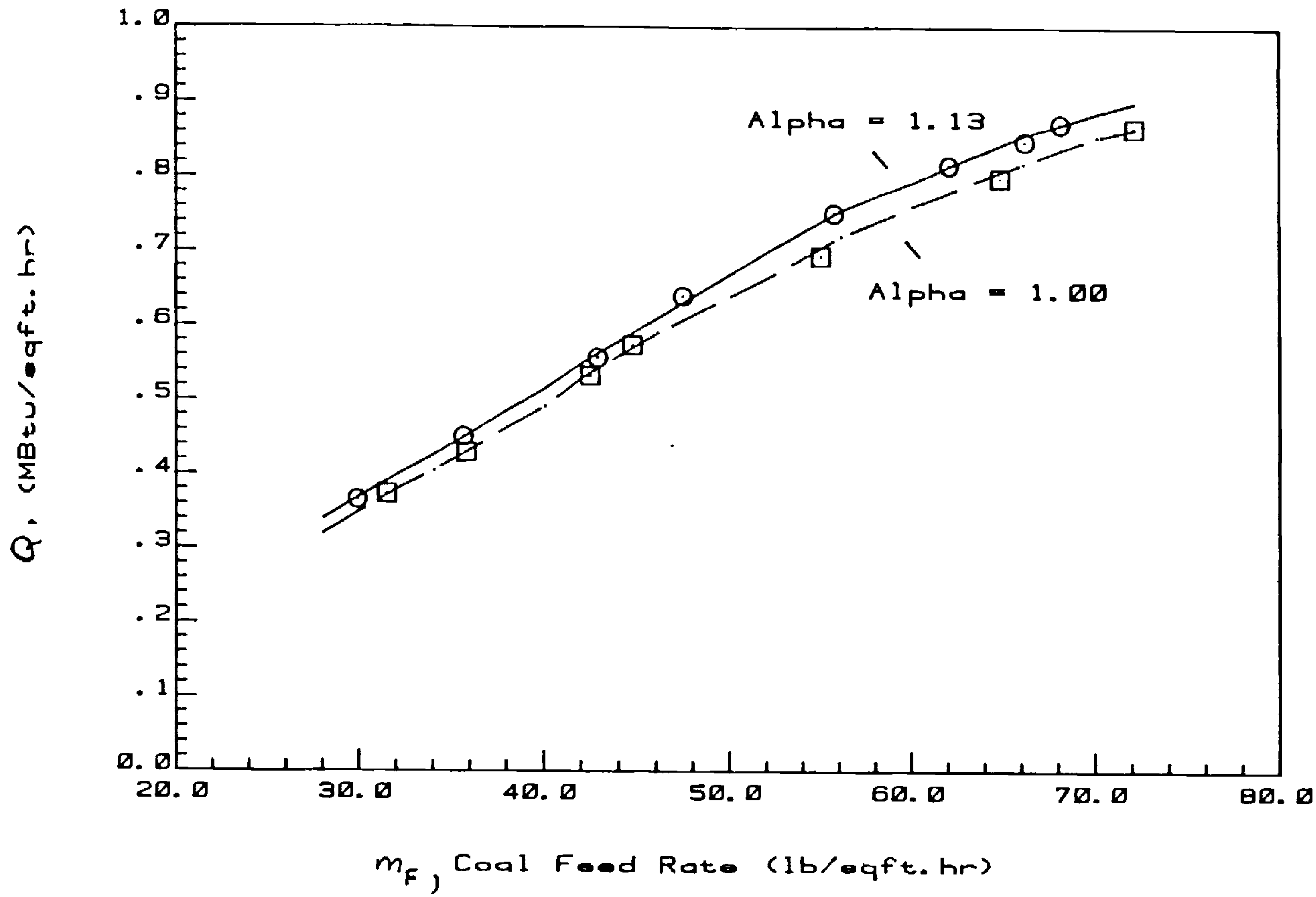


Figure 16. Dependence of the Average Heat Release Rate upon the Coal Feed Rate.

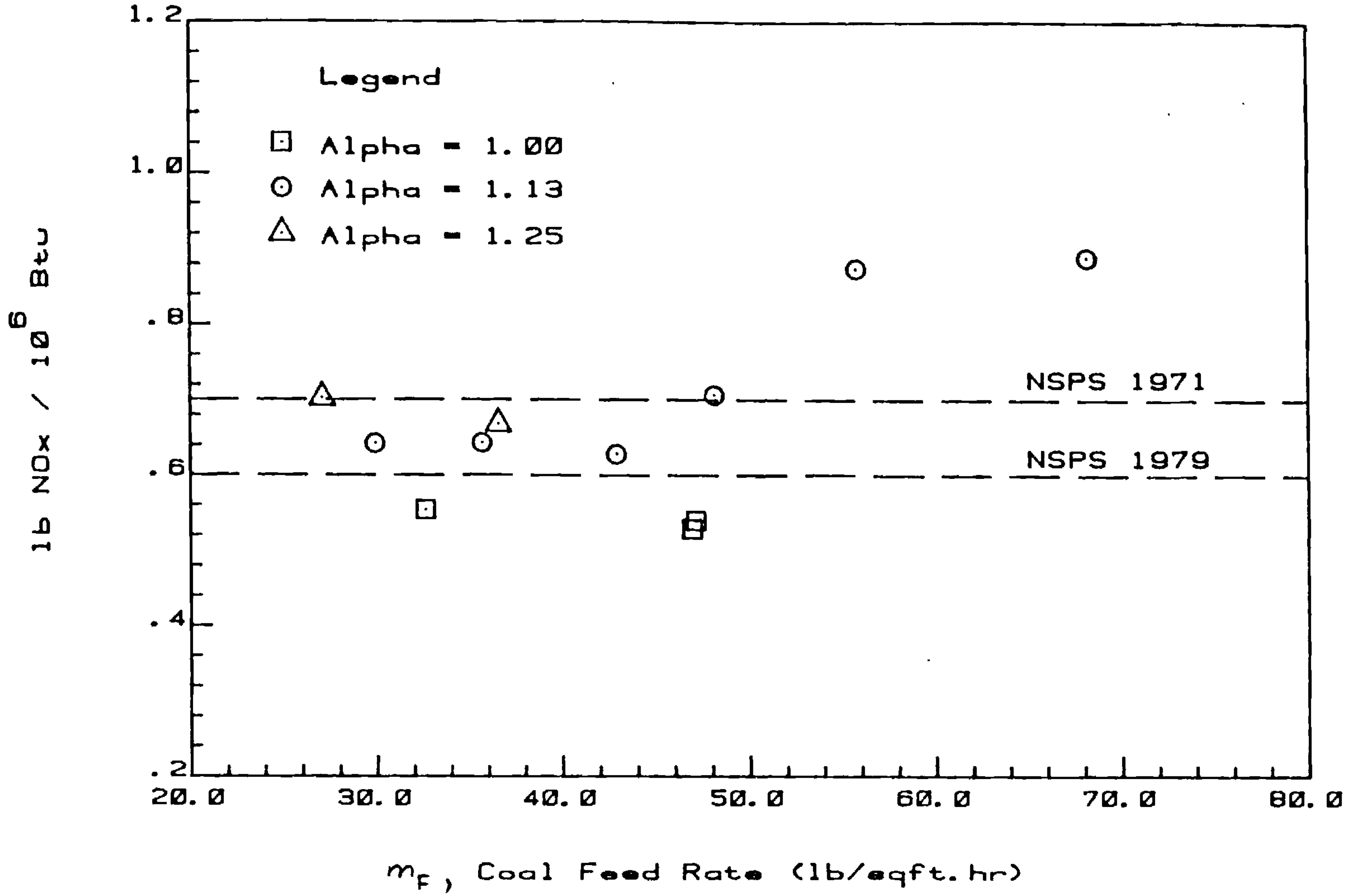


Figure 17. Dependence of the Average Amounts of Generated NO_x per 10^6 Btu upon the Coal Feed Rate.

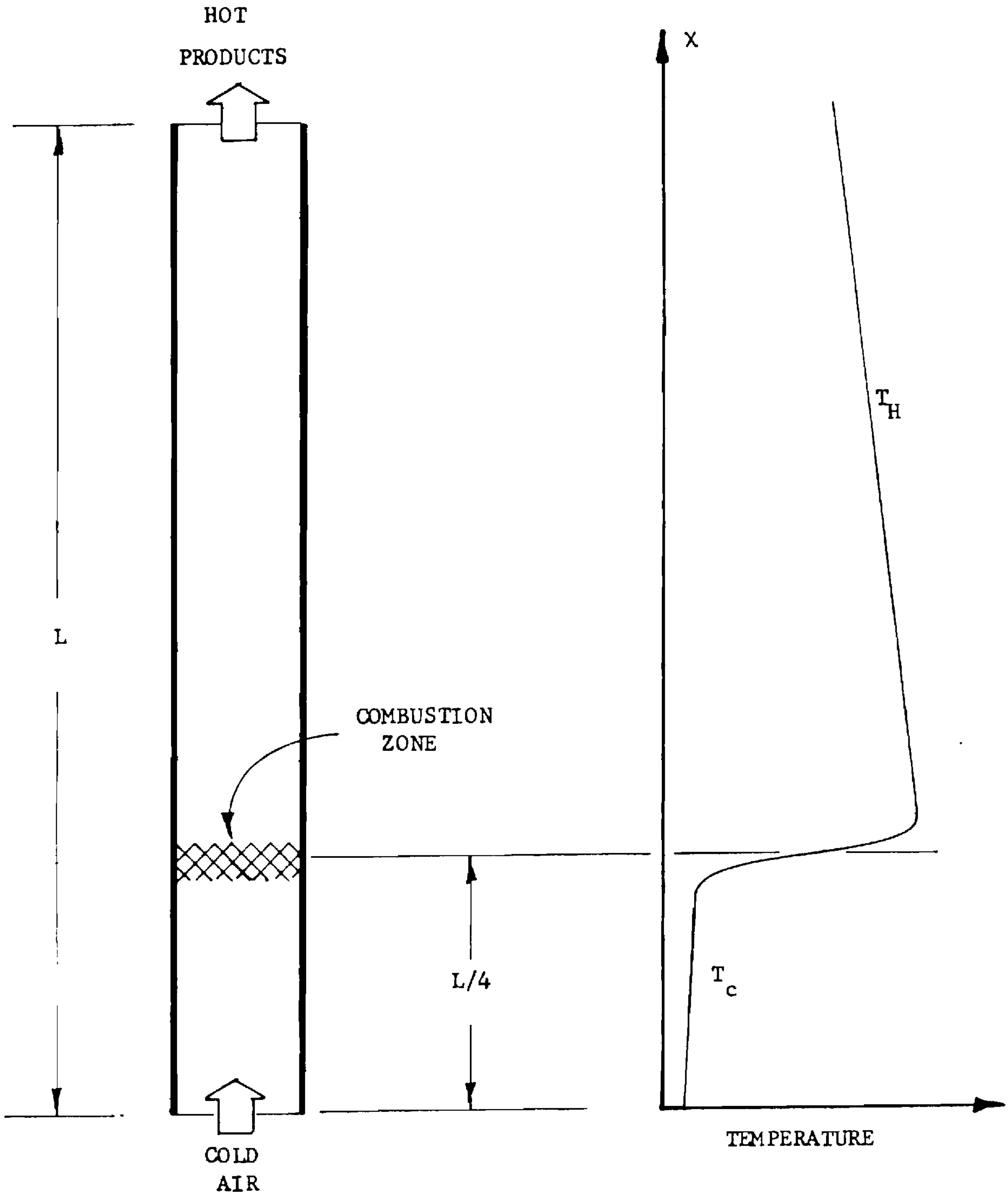


Figure 18. Dependence of Mean Flow Temperature upon Position (χ).