

Field-scale rotary kiln incineration of batch loaded toluene/sorbent. I. Data analysis and bed motion considerations

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Abstract

In this study, a field-scale rotary kiln incinerator was used for experiments on the processing of toluene contaminated sorbent contained in plastic packs. The incinerator was probed with instruments in several different locations. The results obtained in this study agree in many ways with previous studies on xylene and dichloromethane in the same incinerator. The species and temperature stratification observed near the kiln exit is consistent with previous observations. The moderate mixing induced by turbulence air addition is similar to that observed during the xylene and dichloromethane studies. The bed motion was different from that of previous experiments, and this difference affected the measured responses. Additional instrumentation has provided a clearer view of the processes occurring within the incinerator and through the entire system. The second paper in this series will expand upon the analysis of this data. Mass balances will be performed on the system, the evolution rates of toluene will be calculated, and the characteristic times for the toluene evolution will be determined.

Introduction

The study of hazardous waste incineration in rotary kilns is receiving increased attention in the U.S. and abroad, especially as landfill restrictions are expanding to an ever broader range of solid waste materials. Also, as the regulations on hazardous waste incinerators in the U.S. become increasingly stringent, predictive ability for the performance of these systems, even in a rudimentary sense, is needed. Because of the considerable complexity of the process, however, much remains to be learned. As part of our comprehensive

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study of this process at Louisiana State University, we have recently emphasized the need to broaden the full-scale experimental data base. Such data are needed to provide insight into this complicated process, for use in both model development and validation, and in scaling analyses [1]. Initially, our field-scale efforts focused on obtaining species and temperatures at the exit of an industrial rotary kiln during quasi-steady processing of liquid carbon tetrachloride [2-4]. Subsequent work focused on obtaining continuous gas and temperature measurements during transient processing of polyethylene packs containing clay sorbent charged with toluene [5], xylene [6], and dichloromethane [7]. These studies were performed on the rotary kiln incinerator operated by the Louisiana Division of The Dow Chemical Company at their facility in Plaquemine, Louisiana.

The studies of transient behavior have focused on characterizing the incinerability of an aromatic and a chlorinated hydrocarbon in a rotary kiln environment. Toluene was selected as the aromatic test liquid because it is commonly used as a surrogate waste during trial burns in the permitting process, and because we have used it extensively in bench- and pilot-scale work [8-10]. Unfortunately, Federal regulations precluded our use of toluene at the Dow facility after the first experiment; thereafter xylene was substituted. Recent facility additions, however, have allowed us to complete our study using toluene. With the experience gained from previous full-scale transient experiments, we have, in this most recent study, been able to perform a much more detailed study of the Dow incinerator system. The experimental variables and conditions have remained largely the same for comparison purposes. The experimental procedures have been improved, and the number of continuous measurements has been greatly increased. The details of this most recent study, including descriptions of the instrumentation and the operating conditions studied as well as some preliminary results, were presented by Leger et al. [11]. Therefore, only a brief summary of the experimental methods will be presented here.

Materials and methods

Facility

The rotary kiln at the Louisiana Division of Dow Chemical USA is 3.2 m in diameter and 10.7 m long, with a design firing capacity of 17 MW and 800 °C outlet temperature. Gases flow through the kiln exit plane into a transition section and then into the afterburner. The afterburner has a design firing capacity of 7 MW, a design outlet temperature of 1000 °C, and a minimum residence time of 2 seconds. Gases exiting the afterburner pass through a quench chamber, a series of wet scrubbers and wet electrostatic precipitators, through an induced draft fan, and up a stack. A simplified schematic of the system is shown in Fig. 1.

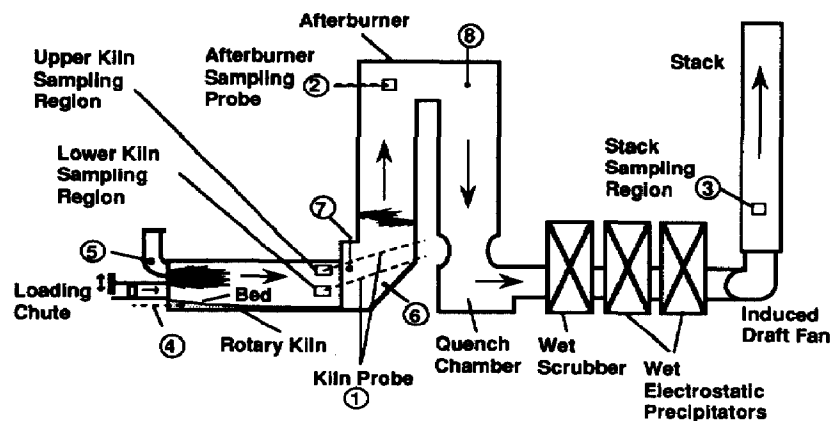


Fig. 1. Schematic of the Dow rotary kiln incinerator facility showing the measurements taken at each location. (1) Kiln sampling probe O_2 , CO_2 , CO , THC concentrations, gas temperature, (2) afterburner probe O_2 , CO_2 , CO , THC concentrations, gas temperature, (3) stack sampling O_2^* , CO concentrations (2)*, (4) bed thermocouple temperature, (5) kiln feed end pressure*, (6) kiln exit pressure*, (7) kiln exit temperature*, and (8) afterburner temperature*. (* Indicates measurements from instruments that are a permanent part of the facility.)

Experimental conditions

Polyethylene packs, each containing 18.9 l of toluene on 22.7 kg of sorbent (montmorillonite granules of approximately 6 mm diameter), were prepared by Dow personnel before the experiments. Blank packs (sorbent only) were also prepared. One pack was fed into the kiln every 10 minutes throughout the experiment; blank packs were fed while changing operating conditions to maintain bed thickness in the kiln. Two nozzles, located on the stationary kiln face, allow the injection of compressed air (at ambient temperature) into the kiln to promote turbulence, bulk mixing, and combustion; we further shall refer to this as turbulence air (TA). Continuous gas measurements and gas temperatures were obtained during four different test modes: operation with and without the addition of turbulence air and operation at two kiln rotation rates, 0.1 and 0.25 rpm. Table 1 gives the experimental test matrix that was used on the two consecutive days of testing.

To the greatest extent possible, all operational parameters were held constant during each test mode. These parameters included: kiln rotation rate, natural gas and air feed rates to the kiln burners, and the turbulence air injection rate. Stack measurements, taken by Dow personnel using EPA approved methods, verified that incinerator emissions remained well within regulatory limits during the entire test period.

Sampling and instrumentation

As in previous studies [2, 6, 7], two water-cooled probes were used to obtain gas samples and gas temperature measurements within the kiln and

TABLE 1

Experimental test matrix for each day

No. of packs	Contents	Sampling	Rotation rate ^a	Turbulence air
4	Blank	None	Fast	Off
6	Toluene	Continuous	Fast	Off
3	Blank	None	Fast	Changing
6	Toluene	Continuous	Fast	On
3	Blank	None	Changing	On
6	Toluene	Continuous	Slow	On
3	Blank	None	Slow	Changing
6	Toluene	Continuous	Slow	Off
2	Toluene	Sample bomb	Slow	Off

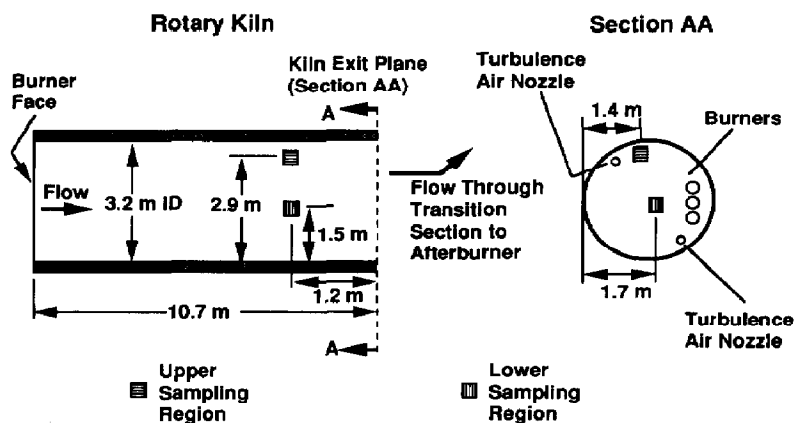
^a Fast = 0.25 rpm, slow = 0.1 rpm.

Fig. 2. Location of the two sampling regions near the kiln exit plane. The locations are estimated to within ± 0.15 m (see Ref. [12]). This diagram is not to scale.

afterburner. Figure 1 shows the probe sampling locations and the measurements taken at each location. Each probe is equipped with a radiation-shielded type K thermocouple at its tip. The kiln probe, 7.8 m in length, was inserted through the transition section and drew samples from near the kiln exit. Only two access ports were available; one allowed the probe to reach a point in the upper half of the kiln, while the other allowed the probe to reach a point in the lower half of the kiln. The locations of these two sampling points are shown in Fig. 2. The kiln probe was inserted into the upper access port on the first day of experiments (3 October 1990) and it remained there for the entire day. On the second day (4 October 1990), the probe was inserted into the lower access port and the experiments were replicated. The afterburner probe, 3.8 m in length, was inserted in a different location from previous studies in an effort to sample from a better-mixed region of the afterburner. Sample gases were drawn

through each probe using an air-driven jet pump. These gases were cooled by passage through the probe and any condensate was removed using a cyclone separator. The sample gases were next drawn through a teflon sample tube to a rotary sample pump, then passed through a particulate filter, a chiller, and another condensate trap. The dried sample gas was metered through a flow controller into a series of gas analyzers. All continuous data were recorded using Omega® data acquisition packages on Macintosh SE® computers, at a frequency of 1 Hz. A more detailed discussion of the instruments and sample treatment is given by Leger et al. [11].

Along with these measurements, the readings of several facility instruments were continuously recorded during these experiments. Oxygen and CO concentrations in the stack, temperatures in the kiln and afterburner, and pressures in the kiln feed end and transition section were recorded. These locations are also indicated in Fig. 1.

Measurement of the temperature of the solids bed in the kiln was attempted using a 19 mm diameter heavy wall stainless steel pipe supporting a 3.175 mm diameter stainless steel sheathed type K thermocouple. This probe was not cooled and was inserted 1 m into the kiln, where the thermocouple tip was immersed in the bed of solids. Figure 1 shows the location of this probe.

The sample gas from the kiln and afterburner probes could also be diverted into one-liter glass sample bottles for later analysis using GC and GC/MS techniques. To simplify the sampling procedure, these grab samples were not taken simultaneously with the continuous measurements. Instead, during the incineration of a single pack at the end of each day, the continuous analyzers were disconnected and a series of grab samples was taken from both the kiln and afterburner probes at predetermined intervals.

Leger et al. [11] and Leger [12] presents the details of this experimental study and the continuous record of the oxygen concentration measured in the kiln, afterburner, and stack. These data show the variation of the transient oxygen concentration as a function of operating condition at different locations within the system. Because the data were for individual packs, differences from pack to pack under the same operating conditions could be observed. These differences were seen to persist through the entire system. Comparison between operating conditions was somewhat obscured by the variation of individual pack responses. Vertical stratification of the oxygen concentration at the kiln exit, however, was readily observed and agreed well with previous transient studies [6,7]. Although the baseline levels of oxygen were affected by the addition of turbulence air to the system, it was unclear if the oxygen response of individual packs was influenced by the turbulence air. Whether kiln rotation rate had any effect on the oxygen response was also unclear.

In this paper, the data from all monitored channels are considered. The data are averaged over several packs during each experimental condition to reduce the effects of individual pack variations. These averaged data characterize the conditions at each sampling location and demonstrate the influence of the kiln rotation rate and turbulence air addition. In a companion paper [13], mass

balances will be performed on the data, the evolution rates of toluene will be characterized, and the influence of bed motion on the evolution rates will be discussed.

Data reduction

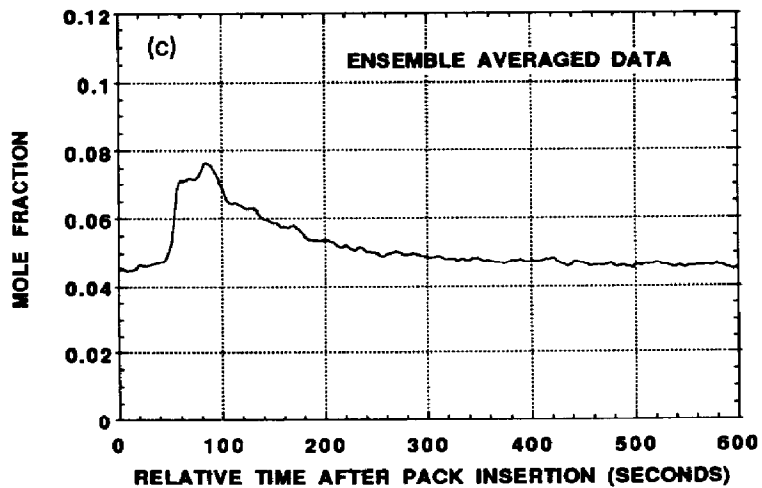
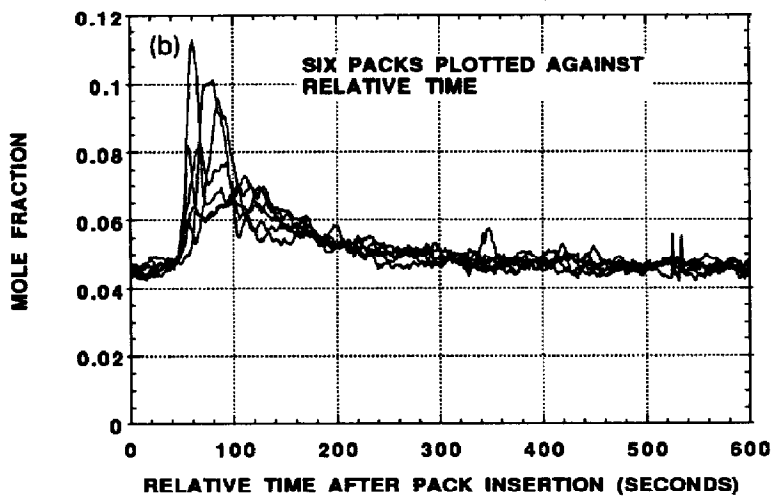
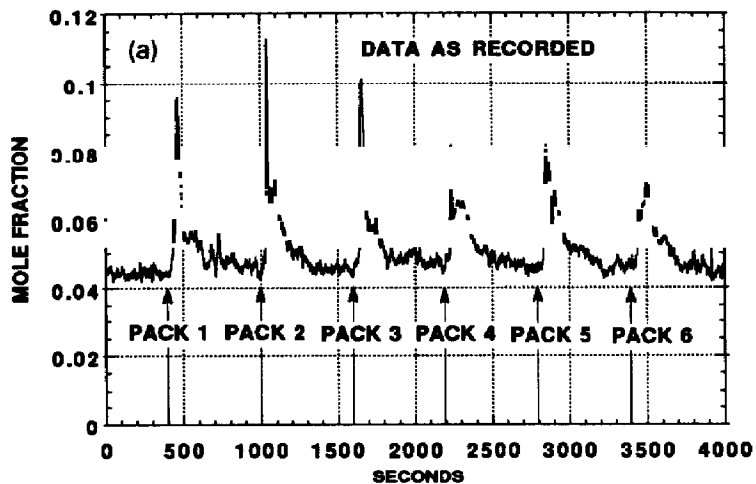
For these experiments, the independent variables were kiln rotation rate (0.25 rpm or 0.1 rpm), and turbulence air addition (on or off). An additional variable is the location of the sampling probe near the kiln exit (upper or lower sampling region). For each combination of independent variables, the system was allowed to equilibrate for at least 30 minutes while blank packs containing only sorbent were fed into the kiln. Then a series of 6 toluene-charged packs were fed into the system, one every 10 minutes, providing one hour of data at that condition. The experimental test matrix, shown in Table 1, was duplicated on two consecutive days with the kiln sampling probe in the upper kiln location on the first day and in the lower kiln location on the second day. All other measurement locations remained the same; therefore, for all measurements other than those from the kiln probe, the experiment was replicated on the second day.

In the unaveraged oxygen data presented by Leger et al. [11], the effects of the independent variables were difficult to discern from the variation of individual packs. The same is true of the other continuous variables in their unaveraged form. Thus, an average response to a pack during each experimental condition is more useful for comparisons because the variation between individual packs is averaged out while the primary features of the data are retained. Also, since the ultimate goals of this work include performing mass balances and characterizing toluene evolution rates for each experimental condition, the use of averaged data reduces the individual pack variation in these calculations as well.

Results

The procedure for ensemble averaging the data is discussed here and illustrated in Fig. 3. To generate an average transient response of a given data channel to a single pack, an appropriate time base must first be generated. The time at which each pack dropped into the kiln was recorded during the experiment. This time provides the reference for the transient response of that pack, i.e. for each data point, the time relative to the most recent pack insertion is calculated. Then the ensemble average of the data for each pack at the same relative time is calculated. Figure 3 shows examples of the CO₂ data in the unaveraged form, the relative time based form, and

Fig. 3. Carbon dioxide data as (a) recorded, (b) in the time-based form, and (c) in the averaged form.



the ensemble averaged form. The ensemble averaging process tends to smooth the data, yielding a result that is easier to compare between experimental conditions.

Data presentation

The averaged data are shown in Figs. 4 through 8. In general, the graphs show continuous measurements taken during fast kiln rotation rate with turbulence air off, fast rotation rate with turbulence air on, slow rotation rate with turbulence air on, and slow rotation rate with turbulence air off. Figure 4 shows the O_2 , CO_2 , gas temperature, CO, and total hydrocarbon measurements obtained from the upper and lower kiln exit locations. In Fig. 5, graphs of similar afterburner data are shown for each day of experiments. The graphs for both days should replicate each other since the afterburner probe remained in the same location. Figure 6 shows the stack data, which should also replicate over the two-day period. Figure 7 presents the bed temperatures, and typical facility temperatures and pressures are shown in Fig. 8.

Each of the figures is discussed next. One general observation common to all figures is that there was no clearly discernible effect of kiln rotation rate on any of the measured parameters.

Kiln O_2 — Fig. 4(a) and (b)

In the upper kiln, the magnitude of the oxygen response to the waste containing packs is roughly the same regardless of operating conditions. In the lower kiln, however, the response is considerably increased when the turbulence air (TA) is on, Fig. 4(b). The baseline oxygen values are very low in the upper kiln when the turbulence air is off, Fig. 4(a). The oxygen values are quite high in the lower kiln regardless of operating conditions.

Kiln CO_2 — Fig. 4(c) and (d)

The addition of turbulence air, Fig. 4(d), lowers the overall levels of CO_2 in the upper kiln and increases the magnitude of the CO_2 response in the lower kiln. The levels of CO_2 observed in the lower kiln are substantially lower than those in the upper kiln, particularly with the turbulence air turned off, Fig. 4(c).

Kiln gas temperature — Fig. 4(e) and (f)

The addition of turbulence air lowers the overall gas temperature levels in the upper kiln and increases the magnitude of the temperature response (compare Fig. 4f with 4e). In the lower kiln, the turbulence air does not clearly change the overall temperature levels, but it does increase the magnitude of the temperature response. The gas temperatures in the upper kiln are much higher than those in the lower kiln.

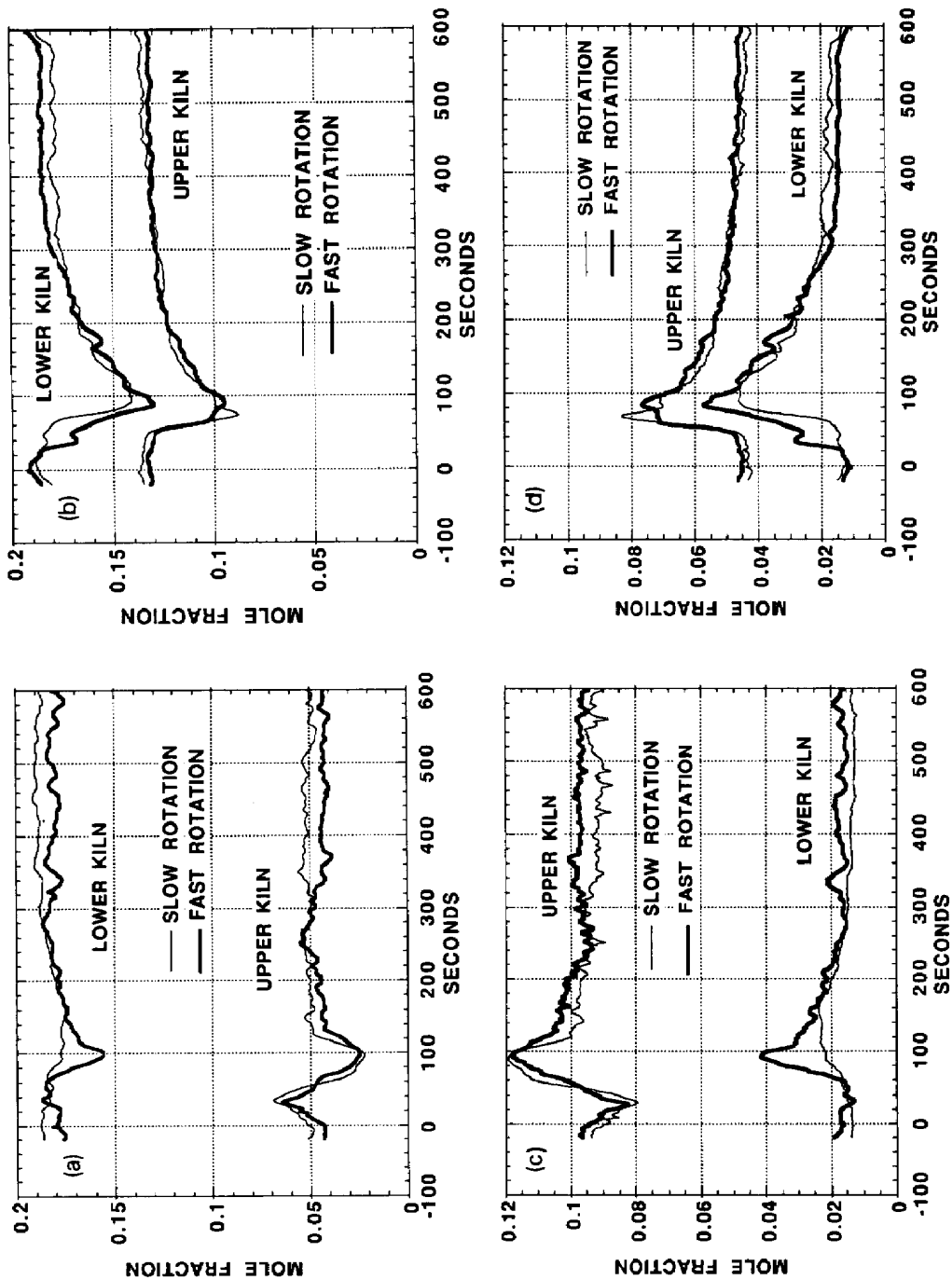


Fig. 4. Parameters measured by the kiln probe, with and without turbulence air (TA). Oxygen dry mole fraction (a) without, and (b) with TA; carbon dioxide dry mole fraction (c) without, and (d) with TA; gas temperature (e) without, and (f) with TA; and carbon monoxide (g) and total hydrocarbon (h).

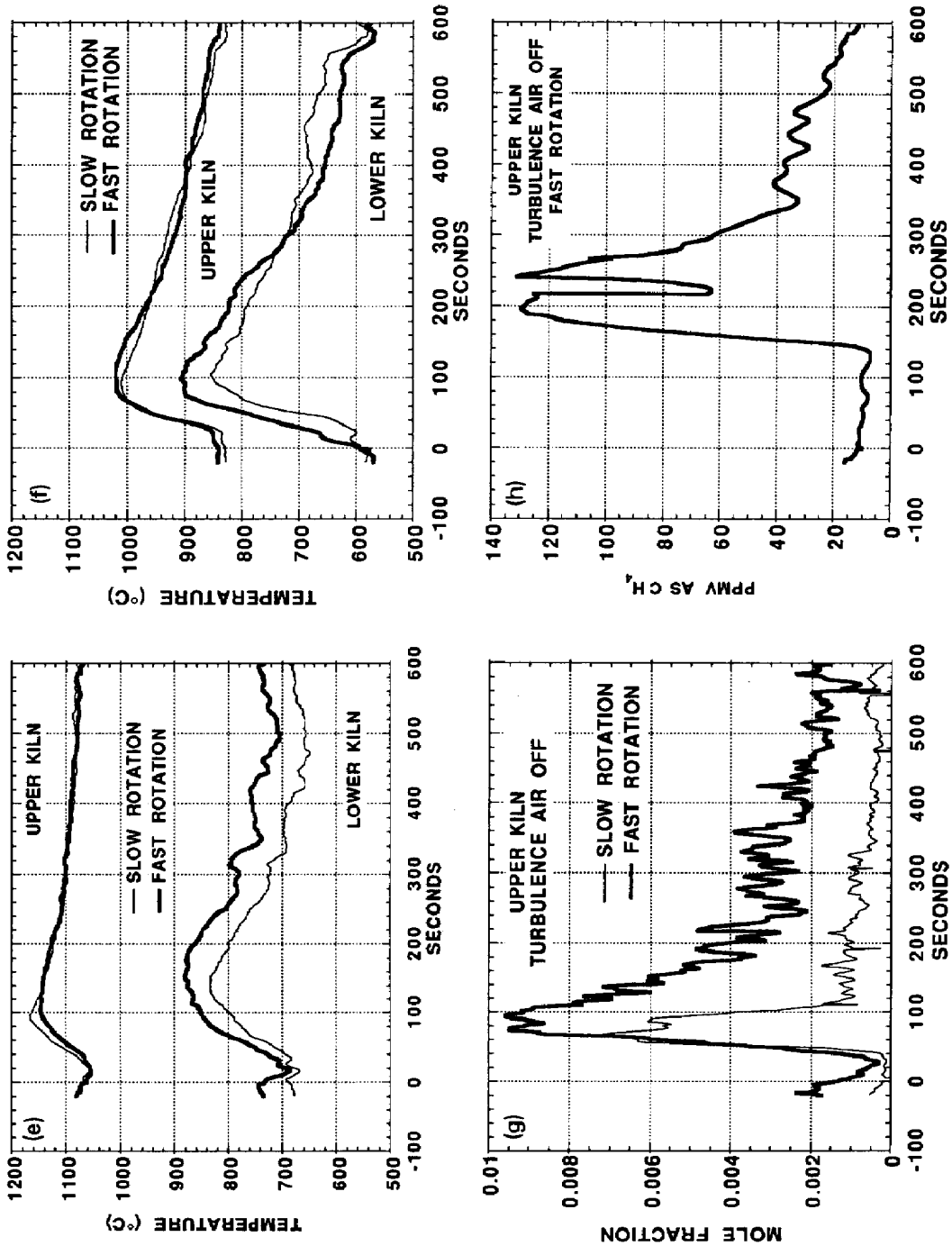


Fig. 4. Continued.

Kiln CO and THC — Fig. 4(g) and (h)

In the upper kiln, relatively large amounts of CO were observed only during operation with turbulence air off. The addition of turbulence air reduced the observed CO values to near zero so these data were not plotted in the figure. Very little CO was observed in the lower kiln under any conditions; hence, these data also were not plotted. In the upper kiln with turbulence air off, it appears that the fast rotation rate caused a greater CO response than did the slow rotation rate. However, it should be noted that the CO concentration should be rather sensitive to oxygen levels, and the baseline oxygen level was almost one percent higher during the slow rotation rate conditions. Since the baseline conditions are not a result of the waste combustion and should be independent of rotation rate, this difference in CO response may result from slightly different support flame feed settings.

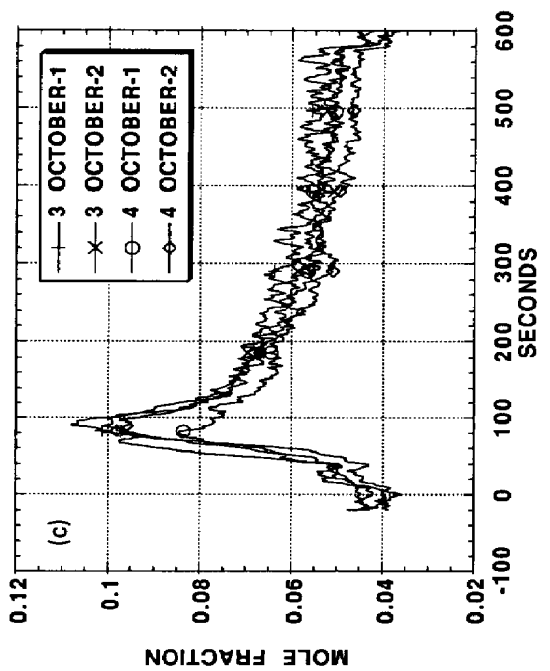
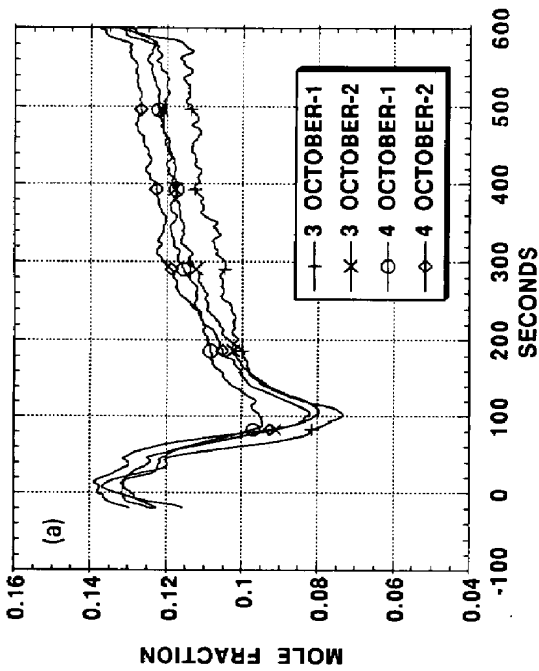
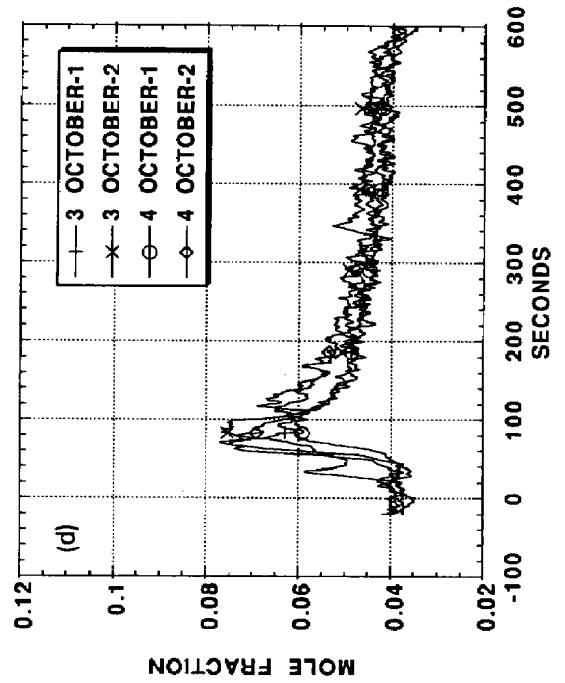
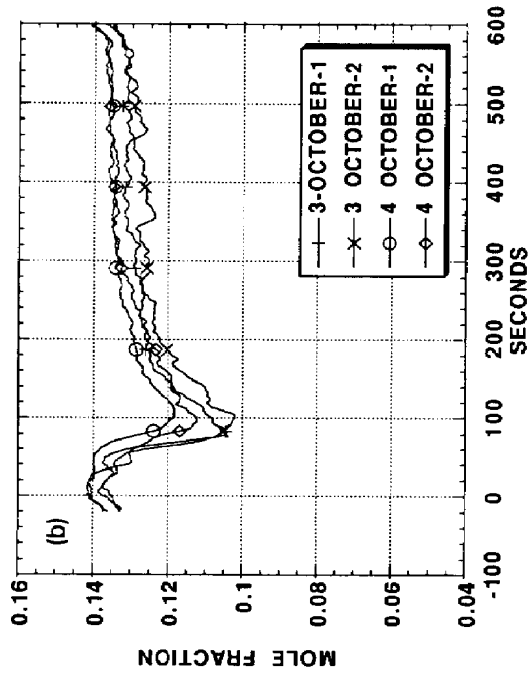
Before discussing the total hydrocarbon (THC) data, an operational aspect must be considered. To prevent the loss of hydrocarbons from the sample gas, the THC sample stream was split from the main sample stream before passing through the sample chiller, secondary condensate trap, and desiccant dryers. Unfortunately, excessive condensation in the sample line extinguished the flame ionization detector on a few occasions and greatly reduced the sample flow rate at other times. As a result, the kiln THC data are generally suspect. The THC analyzer appeared to be operating properly during the first set of data obtained in the upper kiln with turbulence air off and fast kiln rotation rate as shown in the figure. A substantial THC response was observed during that operating condition, corresponding with high CO levels observed at the same time. For slow rotation rate with turbulence air off in the upper kiln, the THC response was suspiciously flat even though high CO levels were observed. We attribute this behavior to the THC sampling problems discussed above. All the other operating conditions showed low THC levels corresponding to low CO levels. Although this seems reasonable, the sampling problems preclude confirmation of this observation.

Afterburner O₂ — Fig. 5(a) and (b)

For the afterburner data, one sees good reproducibility from one day to the next, although the overall oxygen levels are about 1% higher on the second day. On both days, the addition of turbulence air reduced the magnitude of the oxygen response, Fig. 5(b). Since turbulence air addition is accompanied by an increase in overall gas flow rate while the amount of toluene burned remains the same, the response to pack combustion is diluted by the increased flow.

Afterburner CO₂ — Fig. 5(c) and (d)

The reproducibility of the CO₂ data appears very good. Again, the addition of turbulence air, Fig. 5(d), appears to decrease the response from a pack due to dilution.



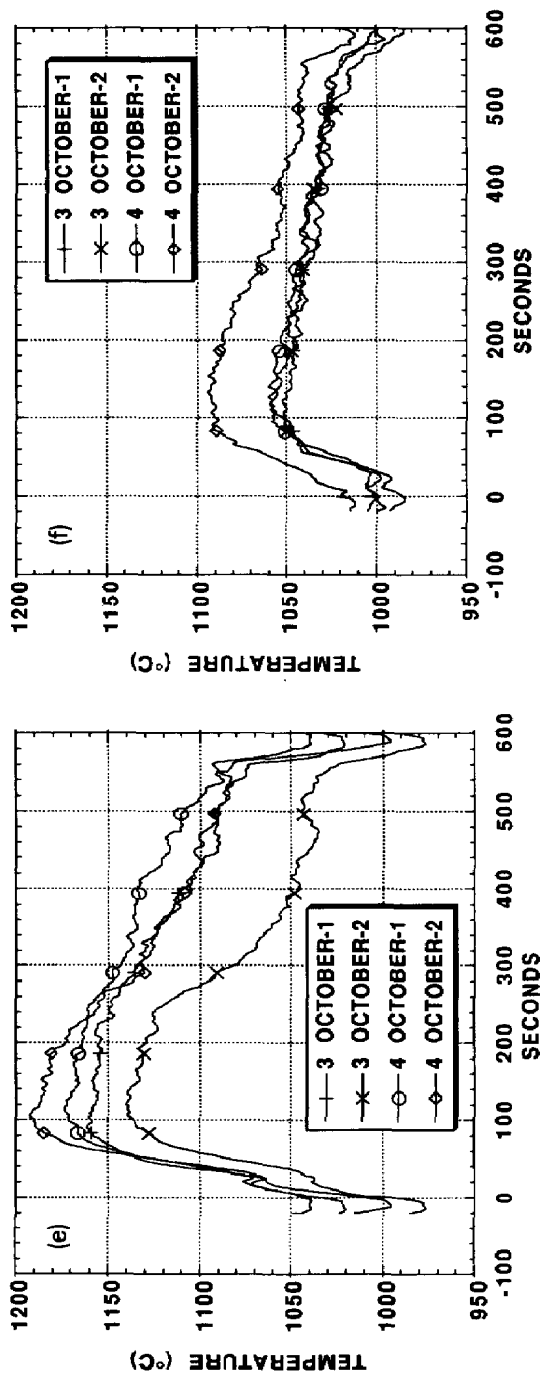


Fig. 5. Parameters measured by the afterburner probe. Plot symbols are used intermittently to identify data sets only. Key symbols - 1 and - 2 refer to slow and fast kiln rotation rates, respectively. Oxygen dry mole fraction (a) without, and (b) with TA; carbon dioxide dry mole fraction (c) without, and (d) with TA; and gas temperature measured (e) without, and (f) with TA.

Afterburner gas temperature — Fig. 5(e) and (f)

Overall, the afterburner gas temperature response appears to be quite reproducible. It clearly shows the effect of opening the loading chute door for pack insertion into the kiln. This is seen as the sudden drop in temperature at the end of each curve, which results from additional air entering through the kiln loading chute door during pack loading. Sometimes, the temperature level is seen to return momentarily to the baseline value after the door closes but before the pack begins to burn. Notice that the magnitude of the effect due to the loading chute door is reduced when turbulence air is added, Fig. 5(f). This is also true of the peak temperature response due to pack combustion. This is, in both cases, thought to be due to dilution by the higher gas flow under turbulence air addition.

Afterburner CO and THC

In contrast to what was observed in the kiln, very little CO is seen in the afterburner under any conditions. In fact, for discussion purposes, the afterburner CO never rose above baseline. The THC analyzer used with the afterburner probe suffered from the same operational problems as the THC analyzer for the kiln probe. In addition, problems with the sample flow rate caused a very long lag in the instrument response. The observed THC levels were low (<15 ppmv), which corresponds to the low levels of CO observed in the afterburner on both days. In general, both the CO and THC measurements taken from the afterburner never rose appreciably above baseline.

Stack O₂ — Fig. 6

The stack oxygen response tends to be very smooth, with the minimum occurring later than for kiln or afterburner measurements, as expected. The delay may be due to stack oxygen analyzer response or to the time required for the combustion gases to flow through the pollution control equipment. The data are quite repeatable, showing only a slight dilution effect with turbulence air turned on, Fig. 6(b). One should note that the oxygen levels measured in the stack generally match those measured in the afterburner, indicating little or no air infiltration downstream of the afterburners in the pollution control equipment. Measurements with turbulence air off on the first day are an exception, showing stack oxygen levels approximately 1% higher than those measured in the afterburner.

Stack CO

We were able to monitor two redundant facility CO analyzers in the stack. For the operating conditions in these experiments, the CO levels in the stack were so low that all we could observe was instrument noise.

Kiln bed temperature — Fig. 7

The kiln bed temperature measurements presented here were measured by a thermocouple probe inserted axially through the kiln's front rotary seal and

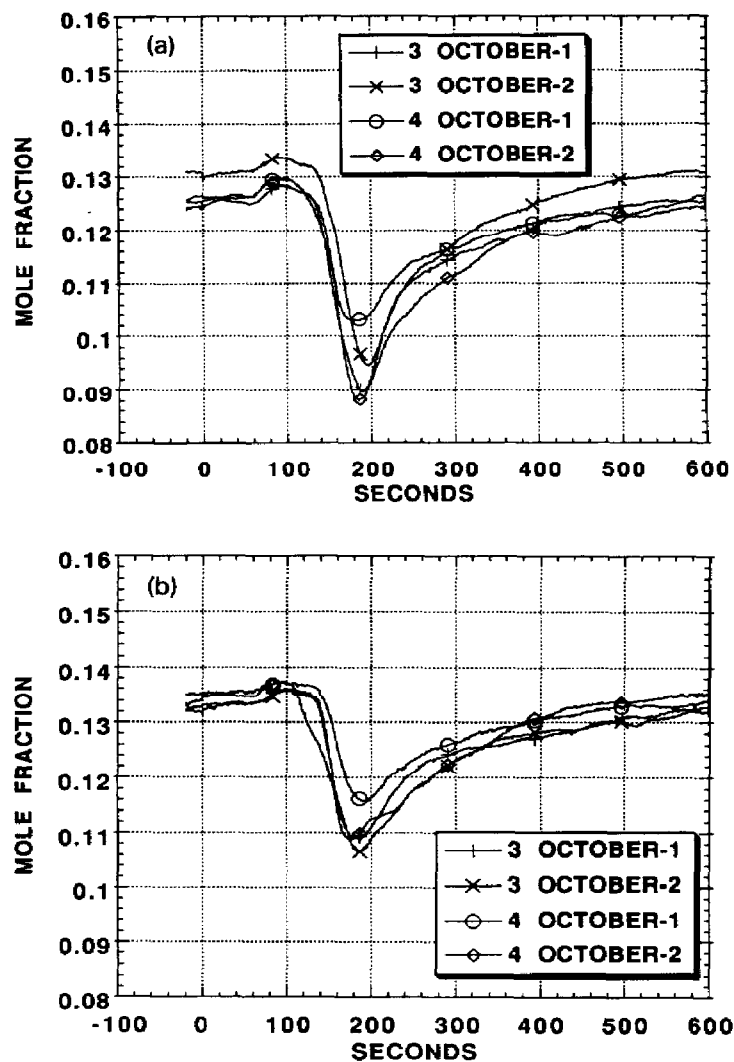


Fig. 6. Oxygen dry mole fraction measured in the stack. Plot symbols are used intermittently to identify data sets only. Key symbols -1 and -2 refer to slow and fast kiln rotation rates, respectively. (a) Without, and (b) with TA.

into the solids bed. Unfortunately, even though the probe consisted of a 19 mm diameter heavy wall stainless steel tube, it was bent substantially during the experiments each day. When one considers the forces acting on the probe due to the drag of the sorbent bed and the occasional pack bumping into it, together with the high temperatures, it is not too surprising that the probe was bent. The data obtained, although somewhat erratic, bear a strong resemblance to the gas temperature data obtained by the kiln probe. The "bed" temperature is seen to drop off before a pack is loaded, as if it were measuring

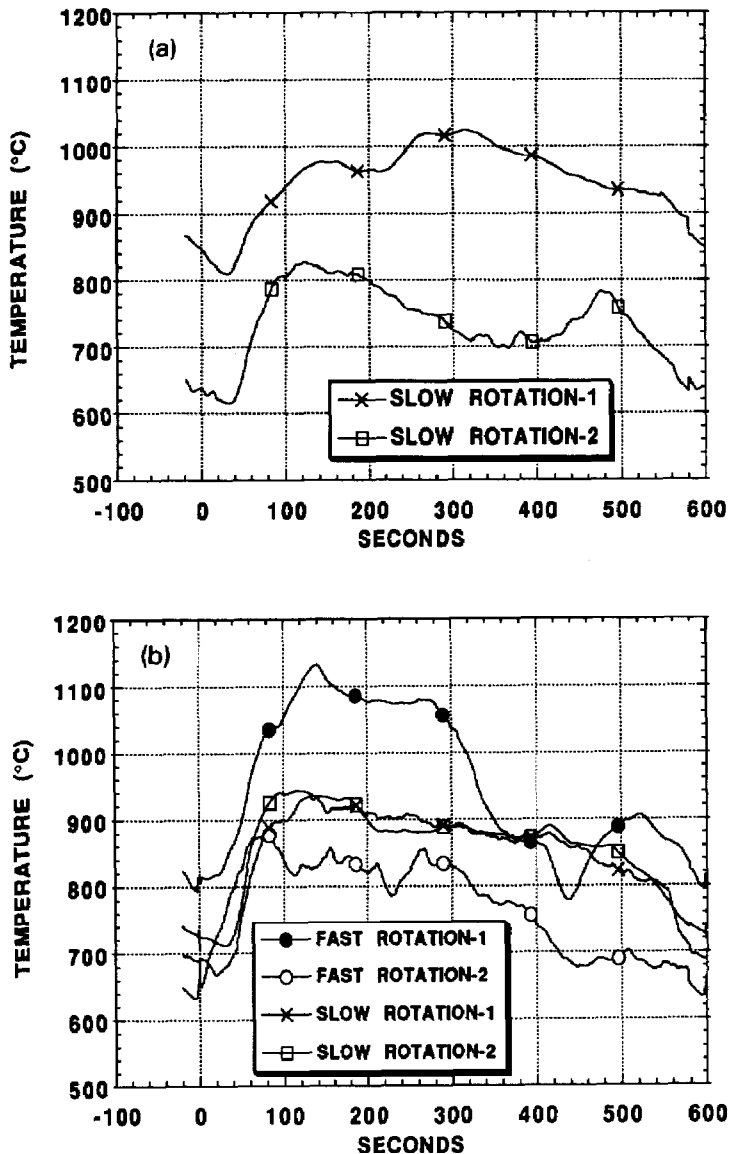


Fig. 7. Temperature measured by the bed thermocouple probe. Plot symbols are used intermittently to identify data sets only. Key symbols -1 and -2 refer to operation on 3 and 4 October, respectively. (a) Without, and (b) with TA.

the effect of cold leak air entering from the loading chute door. As a result, we believe that the thermocouple tip was protruding from the solids. This could not be verified visually because a number of steel lid-retaining rings from the plastic packs collected where the end of the probe should have been, as if they were hung on the probe tip. They may have contributed to the bending of the probe. No clear observations can be drawn from these data, except that the

temperatures measured with this probe may represent a very rough measure of the bed and kiln wall surface temperatures in this general location.

Facility temperatures and pressures — Fig. 8(a) and (b)

Two facility thermocouples were monitored during these experiments. One was located near the top of the kiln exit in the transition section, while the other one was located in the afterburner. Under all conditions, the afterburner thermocouple gave the higher reading of the two. Typical traces for the experiments are shown in Fig. 8(a). Notice the smooth, gentle response of each facility thermocouple compared to the gas temperature responses measured by the kiln and afterburner probes (Figure 4e and f, and 5e and f). One explanation for this smooth response is that each facility thermocouple is inside a heavy wall 19 mm Monel thermowell, resulting in fairly long thermal time constants. A second explanation is that neither thermowell is radiation shielded. At the temperatures indicated, radiation heat transfer between the refractory walls and the thermowell may be the dominant mode of heat transfer. If this is the case, then the thermocouples are indicating the rise and fall of the refractory surface temperature in the region around the thermocouple. The refractory itself has a long thermal time constant, thus the measured response will be slow and gradual, as was observed. In the afterburner, where the temperatures are higher, the refractory to thermowell radiation exchange should be even more dominant. Indeed, the afterburner temperature response is very small in magnitude and it lags the pack insertion considerably more than does the kiln exit temperature response. The temperature measured by the afterburner thermocouple is always substantially lower than the gas temperature measured by the afterburner probe, again consistent with radiation heat exchange with the refractory walls. The temperature measured by the kiln-exit thermocouple is substantially lower than the gas temperature measured by the kiln probe in the upper kiln exit region. This may be due to the radiatively cool ash quench area below the facility thermocouple acting as a radiant heat sink, or it may be due to a non-homogeneous temperature field at the kiln exit. Overall, the temperatures measured by the facility thermocouples are remarkably repeatable and the overall temperature levels do not vary in response to experimental conditions. This is expected because the input air and gas flow rates were set to provide the same facility temperature for each operating condition.

The facility pressure transducers at the feed end of the kiln and in the transition section were monitored, and typical traces are presented in Fig. 8. The transition section pressure (Fig. 8b) is always the higher of the two. The data appear noisy compared to the other monitored variables, even though they have been ensemble averaged like all the other data. The responses measured at each end of the kiln by different pressure transducers, even after averaging, show almost exactly the same "noise" down to the smallest fluctuation. This would be unlikely if the fluctuations were originating in the

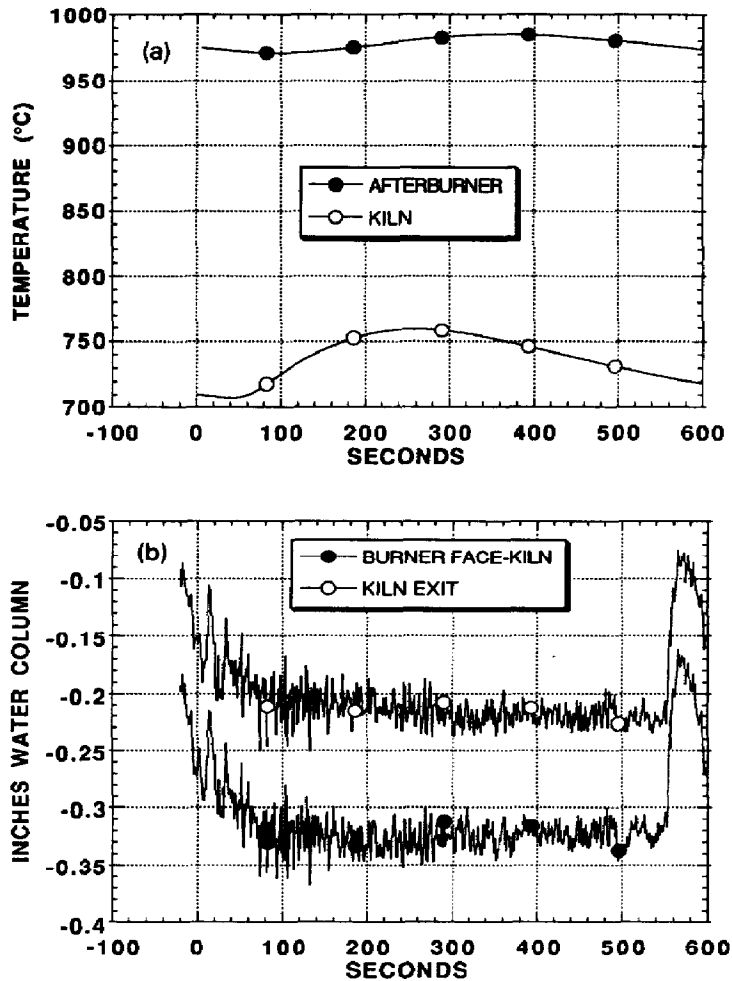


Fig. 8. (a) Temperature and (b) pressure measured by the facility probes. Plot symbols are used intermittently to identify data sets only. For temperature, the higher reading is from the top of the afterburner and the lower reading is from above the kiln exit. For pressure, the higher reading is from the exit end of the kiln and the lower reading is from the burner end of the kiln.

instruments, so these rapid fluctuations in pressure are evidently present in the kiln and are not instrument noise.

One prominent feature of the pressure response is the dramatic rise before pack insertion associated with air entering through the loading chute. One may notice that the pressure is somewhat more erratic during the first 100 to 200 seconds after pack insertion. This may be the result of toluene combustion in the kiln. It is important to note that the toluene combustion did not cause a net pressure rise of the sort that could lead to a positive pressure excursion. Finally, since the pressure was a controlled parameter, it shows little variation across operating conditions.

Gas chromatographic data

The gas chromatographic (GC) methods used in these experiments are identical to those used in previous experiments [7, 14]. The sampling procedure is slightly modified. The gas stream from the sampling probe in the kiln is drawn through a one liter glass sampling bomb with teflon stopcocks. The bomb is purged with the sample gas for approximately 30 s, then the stopcocks are closed, isolating the sample. A second sample bomb is then purged and filled, and so on for a total of six samples all obtained in series during the combustion of a single pack. The sample bombs are contained in boxes of three bombs each, so between the third and fourth samples the lines are disconnected from one box and connected to the next. Samples were taken in the same fashion from the afterburner probe simultaneously with the kiln samples. The continuous monitors were used for the first six packs during the operating condition and then were disconnected. The grab samples were taken immediately afterward, during the seventh pack under the same operating condition. Because of time constraints, grab samples were obtained only during slow rotation rate with no turbulence air addition. The samples were obtained at the end of the experiment on both days and were immediately transported to the laboratory and analyzed within several hours.

The results of the GC sample analyses are shown in Figs. 9 through 12. The GC methods quantified N_2 , O_2 , CO_2 , CO , CH_4 , C_2H_2 , C_2H_4 , C_2H_6 , C_6H_6 , and C_7H_8 . The hydrocarbon concentrations measured by the GC were multiplied by the number of carbon atoms in each species and then summed to give a total hydrocarbon measurement in methane equivalents (only for comparative purposes). The GC data are plotted as a function of sample time together with the averaged continuous data (heavy line in the figures) obtained on the same day for the same operating condition. In these figures, the 95% confidence intervals (the lighter lines) are included for the continuous data to show the relative variability of the continuous data for each pack. The confidence interval is defined as:

$$\text{Confidence interval} = \bar{y}_i \pm t_{n-1} \sqrt{\frac{\sum y_i^2 - (\sum y_i)^2}{n(n-1)}} \quad (1)$$

where \bar{y}_i denotes the mean value of the samples at time "i"; t_{n-1} is the two-tailed student t statistic for $n-1$ degrees of freedom, $\alpha=0.025$; y_i is the value of a sample at time "i"; and n is the number of samples to be averaged at time "i". The sample size, n , in each case was 6, one for each pack, at a given relative time.

Upper kiln GC data — Fig. 9

The graph of oxygen in the upper kiln (Fig. 9a) shows good agreement between continuous data and the GC data points. The same behavior is seen for the CO_2 data (Fig. 9b). Other questionable GC samples taken from the second box of three sample bombs are not shown on the graph. It appears likely that an

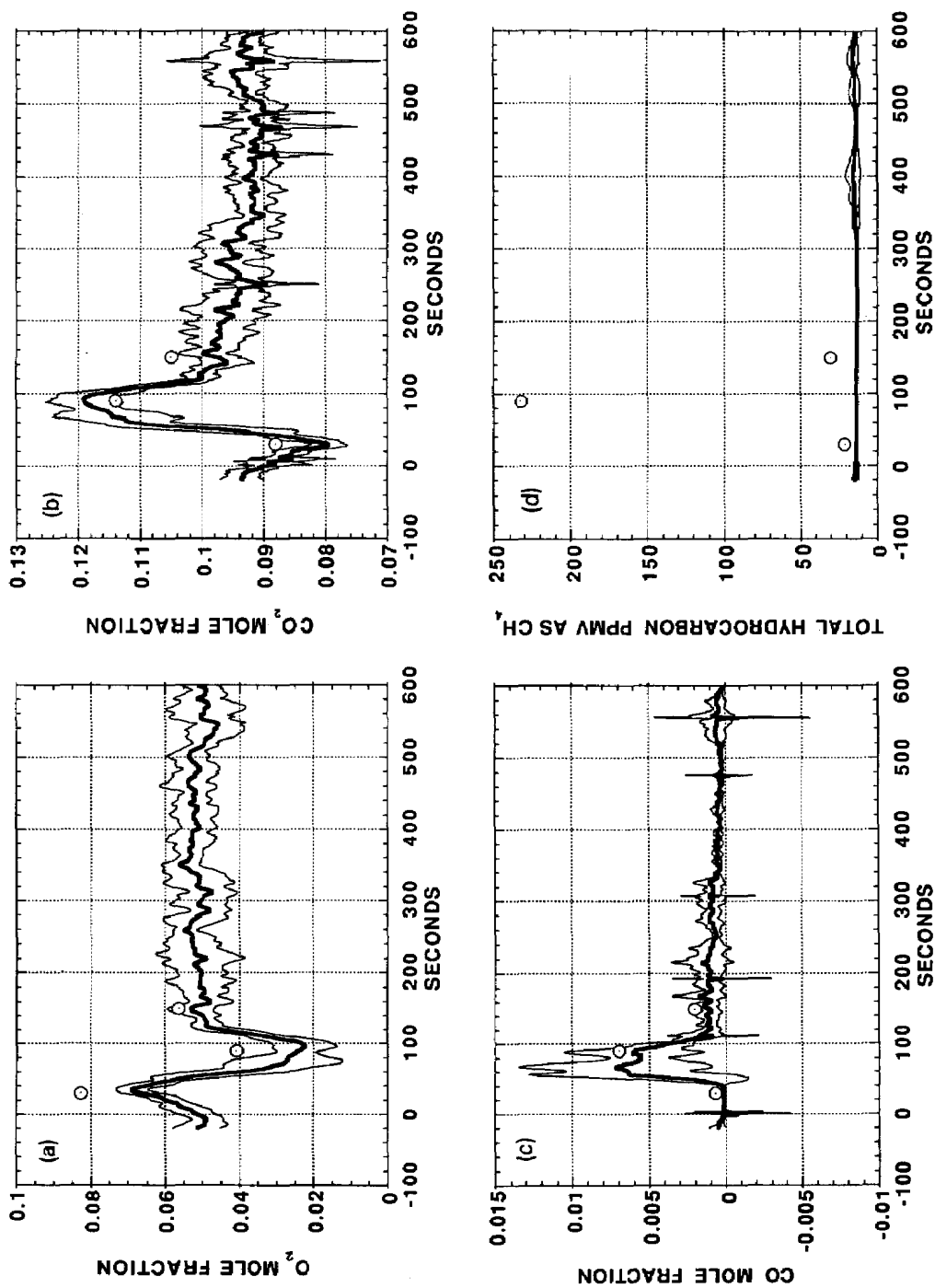


Fig. 9. GC data (circles) and average continuous data (heavy line) obtained from the upper sampling location in the kiln during slow rotation rate and operation without turbulence air addition. The 95% confidence interval on the continuous data is shown by the two light bracketing lines. (a) Oxygen and (b) carbon dioxide measurements, (c) carbon monoxide and (d) THC measurements.

air leak occurred somewhere in the connection of the second sample box, causing the last three samples to be diluted with air. Figure 9(c) shows the CO data and again there is very good agreement with the continuous data. While the continuous THC analyzer showed little or no response, the GC samples (Fig. 9d) clearly show a large response. From this we conclude that the kiln THC analyzer was in fact malfunctioning during that operating condition. This means that large amounts of hydrocarbons were present in the upper kiln during both fast and slow kiln rotation rates when the turbulence air was turned off. This corresponds with the high CO levels that were present during these operating conditions. The hydrocarbon species measured in the upper kiln showed that methane was predominant, and no toluene was detected. This is consistent with results obtained during processing of xylene [6].

Lower kiln GC data — Fig. 10

In the lower kiln, the oxygen data points (Fig. 10a) agree fairly well with the continuous O₂ data, although the second data point is below the continuous data. Since the low value is backed up by a correspondingly high CO₂ data point and no likely mechanism exists to cause this type of error in the GC samples, we accept it as a valid measurement. The CO₂ data (Fig. 10b) show reasonable agreement for the three data points shown. The CO data of Fig. 10(c) agree well, all registering low levels. The GC THC data points (Fig. 10d) indicate a small spike in the hydrocarbon concentration that was not registered by the continuous THC analyzer. Again one may conclude that the continuous analyzer was not functioning at that time. The GC analyses showed small quantities of toluene in these samples, and relatively low concentrations of methane. Again these measurements are consistent with those obtained during xylene experiments [6].

Afterburner GC data on 3 October 1990 — Fig. 11

In the afterburner on the first day of experiments, the O₂, CO₂, and CO data (Figs. 11a-c) show good agreement. The THC data (Fig. 11d) show an interesting behavior although the levels shown in the figure are quite small. The GC registered 14 ppmv of hydrocarbons at 30 s and the continuous analyzer registered essentially zero until the spike noted at 200 s. The maximum level registered by the continuous monitor was only approximately 12 ppmv which agrees quite well with the GC value at 30 s. We feel that the continuous analyzer was operating properly and registering the correct concentrations; however, the sample flow rate may have been reduced, causing a three minute delay before the sample reached the analyzer. This reduced flow rate could be attributed to the already long sample line and build up of condensate interfering with the flow control valve and rotameter.

Afterburner GC data on 4 October 1990 — Fig. 12

On the second day of experiments, the afterburner O₂ and CO₂ data again show very good agreement (Figs. 12a and b, respectively). The CO analyzer

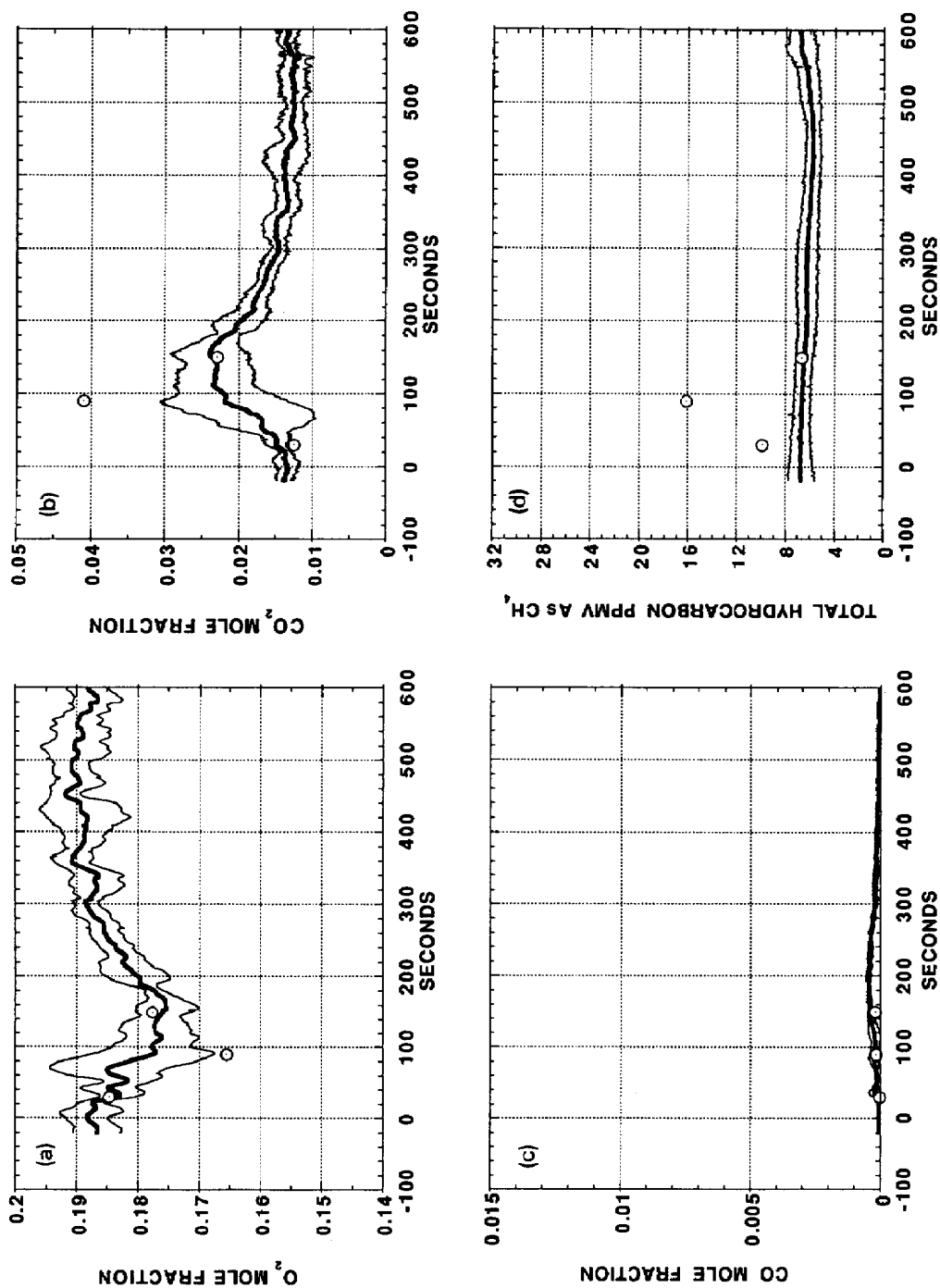


Fig. 10. GC data (circles) and average continuous data (heavy line) obtained from the lower sampling location in the kiln during slow rotation rate and operation without turbulence air addition. The 95% confidence interval on the continuous data is shown by the two light bracketing lines. (a) Oxygen and (b) carbon dioxide measurements, (c) carbon monoxide and (d) THC measurements.

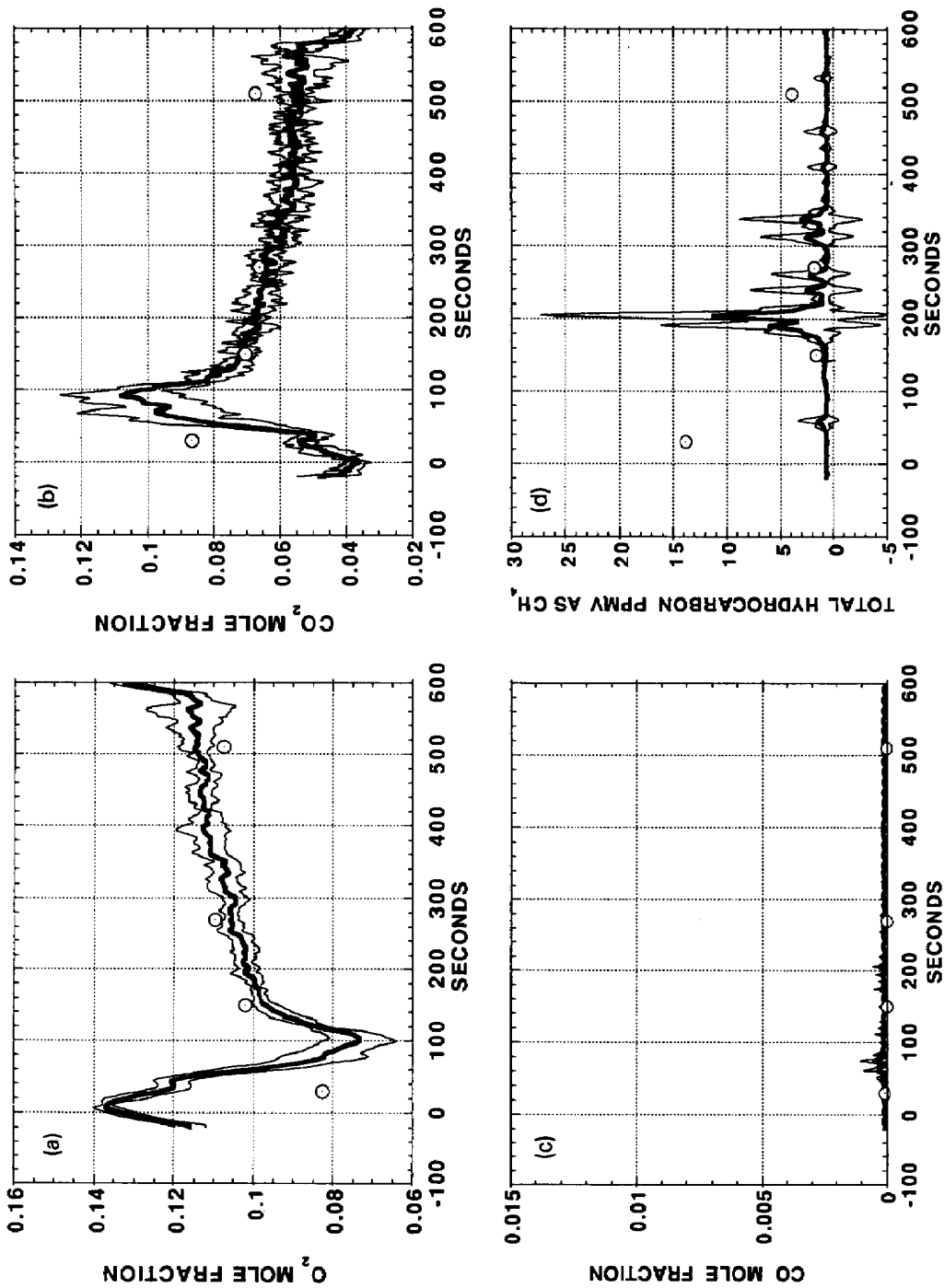


Fig. 11. GC data (circles) and average continuous data (heavy line) obtained from the afterburner on 3 October 1990 during slow rotation rate and operation without turbulence air addition. The 95% confidence interval on the continuous data is shown by the two light bracketing lines. (a) Oxygen and (b) carbon dioxide measurements, (c) carbon monoxide and (d) THC measurements.

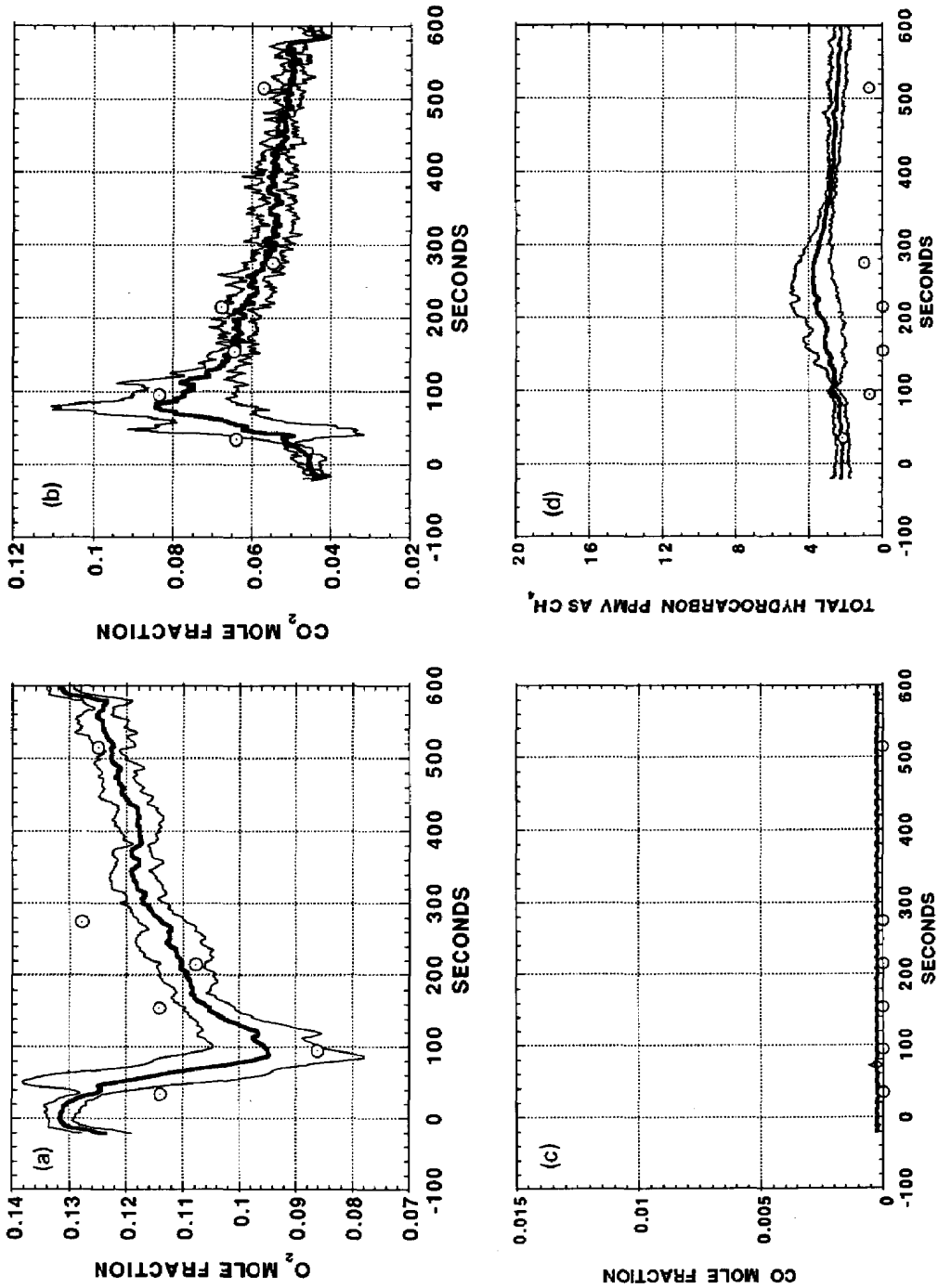


Fig. 12. GC data (circles) and average continuous data (heavy line) obtained from the afterburner on 4 October 1990 during slow rotation rate and operation without turbulence air addition. The 95% confidence interval on the continuous data is shown by the two light bracketing lines. (a) Oxygen and (b) carbon dioxide measurements, (c) carbon monoxide and (d) THC measurements.

shows no response due to pack combustion, nor do the GC samples (Fig. 12c). Both the GC and the continuous THC analyzer indicate low levels of hydrocarbons and little or no response from pack combustion (Fig. 12d).

Overall, although there were problems with some of the GC samples and with sample conditioning for the THC analyzers, the data agreement is generally very good. The confidence intervals show that the data, particularly the O₂ and CO₂ responses, were quite repeatable from pack to pack. Considering the difficulties inherent in this type of study in the field, the overall quality of the data is thought to be quite good.

Discussion

This set of experiments was designed to be experimentally similar to earlier experiments that were conducted using packs of xylene and dichloromethane [6, 7]. The only major differences were to be the use of toluene and the more extensive instrumentation and data acquisition in the latter experiments. Data taken during the xylene experiments and these toluene experiments should be similar because the two compounds are quite similar in their combustion properties. The stratification between the upper kiln exit and lower kiln exit is seen with both toluene and xylene, as well as during all other experimental studies on this system [2-4, 6, 7]. The changes associated with the introduction of turbulence air, particularly the dilution effect and the effect on CO and THC in the upper kiln, were also seen during the xylene experiments.

During the xylene experiments, rotation rate was seen to have a substantial effect on the response to a pack in the kiln. The faster rotation rate was associated with greater magnitude and shorter duration responses for all the measured variables. This effect was totally absent during the toluene experiments. In addition, the xylene experiments often yielded multiple-peaked responses from each pack. The toluene data showed no such tendency for multiple peaks and, in fact, tended to show a very repeatable response characterized by a rapid rise in the measured variable followed by a gradual decay.

Clearly some difference between the toluene and xylene experiments affected the way in which the waste evolved from the sorbent and thus affected the dependence of evolution rate on kiln rotation rate. Observations of the video taken during the experiments have pointed to differences in bed motion as the cause of the difference in evolution rates. The bed motion during the xylene experiments could be characterized as slumping motion. In this motion regime, solids intermittently tumble down the free surface of the bed, and then follow the wall in a layer below the surface before reemerging to tumble across the surface again. This motion causes the solids to mix, and each part of the bed is repeatedly exposed at the surface. During the toluene experiments, however, the bed exhibited a slipping motion. With this type of motion, the entire bed slips relative to the wall, and it moves as if it were a solid piece, with the same particles remaining on the surface. In this type of bed motion, the solids mix

very slowly. The reason for the different bed motions in the two sets of experiments is not entirely clear. The packs were identical except for the type of liquid contaminant added to each, they were fed at the same 10-minute intervals, and the kiln was rotated at the same rates. This should have resulted in the same type of bed motion.

The bed motion is, among other things, dependent upon the roughness of the kiln wall. Since the kiln wall refractory is usually coated with a layer of hardened slag of variable thickness and texture, it is quite possible that the surface was smoother during the toluene experiments, resulting in the slipping motion. Another possible influence is the presence of the bed thermocouple probe during the toluene experiments. Some of the steel lid retaining rings were observed collecting in the area of probe. If these rings were actually looped over the end of the probe, as we suspect, the probe could have held the conglomeration of barrel pack rings and sorbent together. This would have given the bed some structural integrity, causing it to slip as a whole rather than mixing and slumping. Even the drag of the thermocouple probe alone may have triggered slipping before the bed could rise high enough for a slump to occur.

The presence of slipping motion of the bed during the toluene experiments at first appears unfortunate. Our previous work has led to a scaling model for predicting waste evolution based upon measurements taken in a system of a different size [1]. The scaling model was lacking in the area of field-scale data; these toluene experiments were to provide additional field-scale data for use in testing the scaling analysis. Unfortunately, these data cannot be used because the scaling analysis requires similarity of bed motion. There may be a serendipitous side to this story, however. First, the bed motion was most likely influenced by the temperature probe, although unintentionally, even though all other parameters remained the same. This opens up the possibility that the bed motion may be intentionally modified by inserting fixed structures into the bed, allow one to control the bed motion and the resulting mixing and contaminant evolution characteristics. Second, we now have data obtained under similar experimental conditions with similar contaminant species (xylene and toluene), the only difference being the motion exhibited by the bed. This is an opportunity to make comparisons and determine the effects of bed motion on contaminant evolution in more detail. These comparisons will be made in the companion to this paper [13].

Summary and conclusions

A detailed study of unsteady conditions inside the field-scale rotary kiln incinerator operated by the Louisiana Division of Dow Chemical USA has been successfully accomplished. Experience gained during earlier studies and the use of more extensive instrumentation has provided a clearer picture of the processes occurring within the incinerator and through the entire system. In

this paper, the ensemble averaged data for each monitored variable are presented as a function of experimental conditions. A list of the conclusions that are drawn from this averaged data follows:

- The bed motion during these experiments was observed to be in the slipping regime, in contrast with slumping bed motion seen in earlier experiments under similar conditions.
- Vertical stratification at kiln exit is inferred through measurements of O₂, CO₂, and gas temperatures. The upper kiln is characterized by lower O₂, higher CO₂, and higher gas temperatures.
- The addition of turbulence air tends to reduce the magnitude of the stratification observed in the kiln.
- Substantial amounts of CO are observed only in the upper kiln and then only during operation with no turbulence air.
- Kiln rotation rate, over the range studied, appears to have no effect on any of the measured variables. This is thought to be a result of the slipping bed motion observed at both rotation rates during these experiments.
- The addition of turbulence air reduces the magnitude of responses to a pack measured in the afterburner and stack, apparently through dilution of the toluene combustion products by the higher gas flow rates.
- Reproducibility of data in the afterburner and stack are quite good. No replicate measurements were taken in the kiln on consecutive days.
- The continuous gas species measurements in the kiln and afterburner agree well with gas chromatographic analyses of grab samples from those locations.
- The measured bed temperatures presented here are probably not accurate because of uncertainty in the location of the thermocouple tip; however, they may be a rough measure of the bed and kiln wall surface temperatures in the front of the kiln.
- The temperature responses to pack combustion measured by the facility thermocouples are sinusoidal, and very smooth in contrast with the measured gas temperatures. Large thermowells and lack of radiation shielding on the facility thermocouples appear to explain the discrepancy.
- During these tests, the incinerator system met all state and federal regulations for each experimental condition.

The data presented in this paper will be used to calculate toluene evolution rates and mass balances in the companion paper [13] in this issue.

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