Combustion and Emission Phenomena in Incinerators

Studies on Combustion Behavior
and
Extinction Limits of Smoke Flames

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NOMENCLATURE

\( \bar{c}_p \)  mean specific heat for reactants and products (cal/g°C)
\( C_0 \)  fuel concentration (g/g)
\( E \)  activation energy (cal/mol)
\( F_s \)  smoke flow rate (g/sec)
\( f \)  gasification products rate from the cards clippings (g/sec)
\( \dot{G} \)  total mass rate of air (g/sec)
\( \dot{g} \)  mass of rate of air to the smoke generator (g/sec)
\( \Delta H \)  heat of combustion (cal/g)
\( H_w \)  total wall loss to the water cooled jacket (cal/sec)
\( k_0 \)  frequency factor for pseudo first order reaction of smoke disappearance (sec\(^{-1}\))
\( M \)  feed rate of card clippings (g/sec)
\( Q_I \)  heat-generation rate (kcal/kg)
\( Q_{II} \)  heat-loss rate (kcal/kg)
\( Q_a \)  heat-generation rate (cal/sec)
\( Q_L \)  heat loss rate (cal/sec)
\( T \)  reactor temperature (K)
\( T_o \)  effective input temperature (K)
\( U \)  volume flow rate at \( T \) K (cc/sec)
\( U_o \)  volume flow rate at \( T_o \) K (cc/sec)
\( V_c \)  volume of well-stirred section of reactor (cc)
\( \rho \)  material density in reactor at \( T \) K (g/cc)
\( \rho_o \)  material density in reactor at \( T_o \) K (g/cc)
\( \tau_o \)  holding or residence time of reactor at \( T_o \) K (sec)
\( \phi \)  completeness of combustion (dimensionless)

INTRODUCTION

Smoke emission from incinerators is a result of failure of overbed burnup of carbon-bearing volatiles. The failure can be complete, meaning that there is no overbed flame at all, or it can be partial, meaning either that the smoke reaction is quenched before completion or else that there is inadequate mixing so that some of the smoke-bearing gases bypass the overbed flame and escape.

It has been argued elsewhere [1], as well as in an associated paper of this set [2], that we should be able to eliminate the problem, without necessarily knowing the detailed mechanisms and kinetics of smoke formation and combustion, so long as we can guarantee ignition and flame holding (see also Ref. [3]). The mixing problem by itself is discussed in an associated paper of this set [4], which describes the construction and determination of mixing factors...
for a method of stirring using opposed vortices. The model experiments themselves, of course, directly demonstrate adequacy of mixing, with only implications for flame holding. Testing of the mixing method, however, using smoke as a fuel, established that the countervortex does also operate as an effective flame holder [5], and in further qualitative experiments, flames ranging in color from smoky-yellow to blue, with yellow inner cones, were obtained [6].

The device used to obtain these results is described in greater detail in this paper. In further substantiation of the mixing method, the countervortex has also been found effective for oil flames using No. 2 oil at rates up to 15 gal/h and in gas flames to produce combustion intensities up to \(10^6\) Btu/ft\(^3\)/h, which is approaching the intensity developed in the Longwell bomb [7]. This, therefore, has provided a basis for adoption of the countervortex method of mixing on the test incinerator [8]. There is, of course, no guarantee that the countervortex flow generates the optimal mixing pattern, but it is clearly adequate, and possibilities for further improvement are being investigated separately in the cold-model studies [4].

The qualitative demonstration of effectiveness has therefore encouraged us to extend the experiments quantitatively. This has proved to be particularly difficult because of the variability of smoke and the problems of specifying it. However, initial measurements have now been completed, and reporting these is the purpose of this paper. This paper has two objectives. The first objective is to determine operational kinetic constants for equations governing the burnout so that the overbed combustion volume can be correctly sized using the equations developed earlier [2]; the second objective is to use the kinetic constants to predict extinction limits of the smoke flames. If these are known and within our control, there is hope of so maintaining operating conditions in the incinerator that a fully adequate overbed flame never extinguishes and the unit never smokes.

**EXPERIMENTAL**

**Equipment**

The equipment is illustrated in Fig. 1. It consists essentially of a "smoke tube" of steel about 3-ft long and 3-in. i.d., erected vertically with a smoke generator at the bottom and air injection ports at the top. The air injection ports are 1/16-in. i.d. and are arranged to produce two vortex flows rotating in opposite senses. They consist of a total of eight horizontal jets through the tube wall, set in two sets of four each, each set being arranged on a horizontal plane, with the two planes about 3 in. apart and the top plane being about 3 in. below the top of the smoke tube. On each plane, the four nozzles are aimed tangential to an imaginary circle of 2-in. dia. These generate the vortices, and the relatively small vertical displacement of one from the other, coupled with the opposed rotation, generates such shear between the flows that adequate horizontal and backmixing are produced. This was initially investigated in water models as described elsewhere [4].

The smoke generator is a separate pyrolysis/gasifier consisting of a refractory box of circular cross section about 4-in. i.d. and 18-in. high internally. The bottom is a steel screen, as a grate, on which there is a 4-in. deep bed of punch clippings from computer cards. Incomplete combustion of these clippings, by air supplied through the perforated plate, generates copious quantities of white or white/grey smoke. Blacker smoke could be produced by adding an appropriate quantity of fuel oil. The offtake from the generator, of 3-in. i.d., is on one side and connected to the smoke tube through a butterfly valve. On the top is a 4-in. aperture for supply of fresh clippings either through a screw feeder or by batch feeding every few minutes. This new feeder can keep the smoke generation reasonably constant. With the batch feeding, initial pyrolysis is relatively fast compared with gasification so that the initial product is rich in volatiles but the end product can be mainly CO. For ease of initial operation, batch feeding was used first since a satisfactory continuous feed has taken some development. The consequence has been, as expected, that the smoke composition (monitored by the analysis of the exit gas) has changed through the runs, but advantage has been taken of this to obtain typical data for indicating the probable variability of behavior as the production of volatiles rises and falls. This will partly correspond to behavior resulting from feeding four times in an hour, as required, for example, in the testing schedule proposed by the I I A [9].

The separation of the smoke generator from the flame section of the smoke tube is to decouple the processes of generation and burnup. The effect of coupling between the two processes is under investigation in the test incinerator [10]. To assist the steady flow of smoke from the generator up the smoke tube,
there is a nitrogen jet on the axis of the smoke tube about 6 in. below the feed pipe from the generator to the smoke tube. Air to the smoke generator and the combustion air jets is metered separately by calibrated venturi meters. Temperatures up the smoke tube and in the reactor section are measured by suction pyrometer. There are five of these pyrometers located at 5, 9, 13, 24, and 28 in. from the top of the smoke tube. These temperatures are required in establishing a heat balance in the system. Part of this heat balance requires knowledge of the wall loss, which is determined by measuring the heat rise in a water jacket around the stirred section. The jacket starts 2 to 5 in. from the top of the smoke tube and extends 4 in. down it. It does not necessarily correspond precisely with the length of the stirred section (determinable by tracer experiments as shown in the model studies [4]); but, since it is largely a correction, high accuracy is not necessary here. The actual dimensions of the stirred section have been checked during the flame experiments by thermocouple surveys using Chromel-Alumel wires to determine the dimensions of the uniform temperature region. This is taken to be the stirred volume. The
volume changes with flow conditions and ranged from 600 to 1100 cc. Residence times in the stirred section are based on these volumes.

Fuel Measurement

Metering the smoke presents a problem. The method used, however, has been adequate for initial results, although it will have to be improved if accuracy is to be improved. The figure we require for the theory, as will be shown in the next section, is the mass fraction of smoke, as the "fuel" or reactant, in the total mass flow in the reactor. If the mass rate of air flow is \( G \) g/sec. and that of the smoke flow is \( F_s \) g/sec, then the input fuel concentration \( C_0 \) is given by

\[
C_0 = \frac{F_s}{(F_s + G)} \quad \text{g/g}
\]  

(1)

The problem is to determine \( F_s \). The first and most direct method used is as follows: the mass low rate of air to the smoke generator is \( g \) g/sec. If we assume that the mass flow rate of pyrolysis and gasification products derived from the card clippings is \( l \) g/sec, then the "smoke or mass flow rate discharged from the generator is \((l + g)\) g/sec. To determine \( l \), the rate of feed into the smoke generator was measured, and after a period of time the weight of char accumulated in the generator was also measured. In the collecting and measuring of some tar that dripped through the base of the unit, the net balance between the quantity fed in and the quantity retained or lost as tar gave \( l \). These measurements showed that about 80 percent of the material fed in was pyrolyzed or gasified. For a rate of feed \( M \) g/sec, the mass loss rate into the smoke \( l \) is equal to about 0.8 \( M \). In most of the experiments, this ranged from about 1 to 5 g/sec. With the air rate in the region of 0.3 g/sec, the mass flow rate of smoke is predominantly derived from the solids pyrolysis and gasification. The composition of this smoke is predominantly some "tarry matter" that from Martin's analyses [12] we may assume is his tentatively identified laevoglucosan. \( \text{CO}_2 \) and \( \text{N}_2 \) are, of course, also present.

There are other considerable vapors and also small quantities of \( \text{CO}, \ \text{CH}_4 \), and \( \text{H}_2 \) (and a little \( \text{O}_2 \)). These gases were measured by chromatography after removing the tar and vapors by suitable traps and condensers. In terms of proportions by weight, after making allowance for the mass supplied from the air, the tarry matter and condensibles were present in somewhat similar quantities to those reported by Martin [12]. If we can assume that pyrolysis occurs before combustion in the smoke generator, the composition may well be similar. On this assumption, a calorific value of the smoke was calculated that was in the region of 2500 cal/g, varying somewhat, of course, with the \((l/g)\) ratio. The smoke will, of course, have more \( \text{CO}_2 \) and also contain \( \text{N}_2 \) because of the combustion air, but, as explained previously the mass contribution from the air is small.

These direct estimates were indicative but were not considered good enough for kinetic calculations, particularly inasmuch as it was found later that significant condensation of tars occurred in the horizontal cross link from the smoke generator to the smoke tube. Instead, dry-gas analyses of the combustion products were used to determine the carbon flow rate. More details of this are given in the discussion of the basic measurements later in the paper. At the same time, the excess air was calculated and was found to range very widely, from under 40 to nearly 200 percent, in spite of only small changes in primary- and secondary-air quantities. This finding is evidently a consequence of the batch feeding every few minutes, and it illustrates the importance of maintaining uniform feed to the bed or else of rapid monitoring of the gas analysis with feedback to adjust the air as the flush of volatiles produced by batch feeding dies away.

THEORY

In this analysis our prime concern is with the stirred section of the smoke tube. We can, therefore, adopt existing stirred-reactor equations, suitably modified to fit the conditions involved under discussion here. The modifications involved, however, can be nominal. Although reaction is between "smoke" and oxygen, with the smoke a complex mixture of components, the very complexity requires us to take an admittedly somewhat simplistic view of the process. We do this by assuming that the smoke can be treated as a single component, at input concentration \( C_0 \), as given by Eq. (1) from the smoke and air rate. We also assume that the system can be treated by application of phenomenological kinetics based on the assumption in the Law of Mass Action: that the rate of disappearance (reaction of smoke) is proportional to the product of the smoke and oxidant concentrations. This is an assumption subject to direct experimental testing. Finally, we assume that, if the air is in
sufficient excess, the reaction becomes substantially independent of oxygen concentration and the reaction rate can be treated as pseudo first order in smoke concentration.

Given these assumptions, we can now give directly the equations for heat generation and heat loss, \( Q_I \) and \( Q_{II} \), respectively (see Ref. [2]), inasmuch as these have been obtained by Vulis [13] for the first-order condition. Vulis gives the equations in dimensionless form. Here we give them with the dimensionless groups written out in full and converted from the units used by Vulis (kcal/kg of material in the reactor) to total quantities (cal/sec generated in or lost from the reactor). For these latter units we write \( Q_I \) for the heat-generation rate and \( Q_L \) for the heat-loss rate, giving

\[
Q_I = \left( \rho V_c C_0 \right) \frac{(k_0 \tau_s) \Delta H}{k_0 \tau_s + \exp \left( E/RT \right)} \text{cal/sec} \quad (2)
\]

and

\[
Q_L = \left( \rho V_c \tau_s \right) \bar{c}_p \left( T - T_0 \right) + H_w \text{cal/sec} \quad (3)
\]

where: \( \rho \) is the materials density in the reactor at temperature \( T \); \( k_0 \) is the frequency factor for the pseudo first order reaction of smoke disappearance; \( \Delta H \) is the heat of combustion for the reaction; \( E \) is the operational activation energy; \( \bar{c}_p \) is the mean specific heat (cal/g °C) for the reactants and products; \( T \) is the system temperature; \( T_0 \) is the effective input temperature (taking into account any thermal energy in the smoke); and \( H_w \) is the total wall loss to the water-cooled jacket. We can also relate some of these quantities to the smoke generation rate \( F_s \), since

\[
F_s = \rho V_c C_0 / \tau_s = \rho U C_0 = \rho U C_0 \quad (4)
\]

where \( \rho \) and \( U \) are the density and volume flow rates, respectively, at temperature \( T \), with subscripts zero for the input rates at \( T = T_0 \).

These are the equations on which analysis, of the results to follow, is based, and from them values of the two unknown quantities, \( k_0 \) and \( E \), can in principle be obtained. At the same time, the completeness of reaction, \( \phi \), can be calculated, since, from Vulis, \( \phi = (Q_I \tau_s / C_0 \Delta H) \): Hence,

\[
\phi = \frac{Q_I \tau_s}{\rho V_c C_0 \Delta H} \quad (5)
\]

With the kinetic constants established, the burnout distance or time can be estimated, thus allowing the total overbed combustion volume to be sized, although this extension is not performed in this paper.

**RESULTS**

**General Behavior**

Since the general behavior of the smoke flames has been described elsewhere [7,8], it will only be summarized here. Further details may be obtained from the publications cited. In establishing the flame, the smoke generator is first started. When smoke is flowing smoothly out of the top of the smoke tube, the secondary-air supply is started, and the mixture is lit with a torch. If the air supply is low for the quantity of smoke (fuel rich), the mixture burns above the top of the tube, remaining stabilized by velocity balancing. The fuel then generally burns smokily with a yellow flame. As the air supply is increased, the flame is finally drawn back into the reactor section of the smoke tube. The color turns redder, but the flame starts to burn clean without transmission of smoke through it. As the air is increased further, the flame becomes hard, turning yellow white with blue tinges around the outside, though with a yellowish inner cone. Finally, at a high enough air/fuel ratio, the flame burns fairly clear blue (nonluminous), although the yellowish inner cone remains.

**Basic Measurements**

To determine the kinetic constants \( k_0 \) and \( E \) in Eq. (2), we need to be able to determine all the other parameters. We can calculate \( \tau_s \) if we know the volume of the stirred section \( V_c \), the total input volume flow rate (mainly the secondary air), and the reactor temperature. As explained in the previous section, \( V_c \) was determined directly by thermocouple traverses and varied in these experiments by a factor of two with variation in air rate. The cold volume flow rate was measured directly by calibrated venturi. The reactor temperature was measured by the suction pyrometer (the thermocouple giving only relative values), and \( \tau_s \) was calculated for the different air flow rates.

With these quantities known, \( Q_L \) in Eq. (3) was calculated by using the value of \( H_w \) determined directly by the calorimeter shell around the reactor section (substantially insensitive to variable conditions) and by taking average values of \( c_p \) from tables [14]. The density was taken as approximating air at the reactor temperature with a correction for the
smoke addition. The values for this heat flow rate were found to lie in the range 6000 to 10,000 cal/sec (about 85,000 to 150,000 Btu/h).

Comparison of $Q_L$ with the quantity $(F_s \Delta H)$ showed that they were comparable. Since $(F_s \Delta H)$ is the maximum potential thermal input to the system and is developed by complete combustion ($\phi$ in Eq. (5) equals unity), this implied that combustion was near completion. When this is the case, random errors of measurement conceal any small departures of $\phi$ from unity since this depends on calculating small differences from large numbers. In particular, the method of estimating both the smoke flow rate $F_s$ and its heat of combustion $\Delta H$ were simply too inaccurate for this very sensitive measurement. The kinetic constants were therefore estimated by other means, as discussed in the following section.

As a direct check on the conclusion that combustion was nearly complete, gas samples were taken just inside the stirred section. These yielded condensate samples and gas analyses. The condensate samples were rather discolored but so far have tested as mildly contaminated water, indicating little or no residual combustible in the condensibles. Similarly, the gas analyses showed no traces of CO, H2, or other gaseous combustibles at levels detectable by the gas chromatograph. One conclusion is that the smokes so far tested are highly reactive.

With combustion known to be complete, the gas analyses could then be used to determine the carbon-oxygen ratio, less water, in the smoke. Writing this as a “composite”: $CO_x(H_2O)_n$, $x$ was found to range from about zero to almost unity. As $x$ increased, there was some evidence that $n$ decreased. Quantitative measurements of the condensate (water) flow rate gave values ranging from about 0.1 to 1 g/sec, although they must have been substantially higher during the initial flush of volatiles. At the end of a period, just before recharging, the vapor flow rate was very low, and the gasifier must have been producing mainly CO. This agrees with the gas analysis indicating $x$ about unity, low $n$, and high excess air. The more genuine “smoke,” on the other hand, seemed to generate about equal weights of vapor to carbon in the CO2. The composite that was “smoke” in these experiments therefore corresponded approximately to the formula $C_3H_4O_2$, although this should be taken as being only indicative with rather wide margins of error.

Estimation of Kinetic Constants

Since the kinetic constants cannot be calculated directly from the experiments thus far carried out, they can only be estimated, with somewhat large margins of error. Nevertheless, this is still worthwhile in view of the almost total absence of kinetic data on such smokes. We use the following information:

1. The smokes, although of differing composition, would burn to completion at temperatures in the range 1000 to 1400°C (roughly, 1800 to 2500°F), with reactor times in the range 5 to 20 msec.
2. In one exploratory experiment to determine an extinction limit, this was obtained at very high air rates (beyond the capacity of the existing meters), but the temperature dropped to 400°C before extinction occurred.
3. Standard values of spontaneous ignition temperatures for a range of gases and volatile hydrocarbons [14] show these generally falling with increasing hydrogen content and/or degree of unsaturation. Untypically, hydrogen itself is quite high, at 550°C, and comparable to CO at 570°C. Ignition temperatures of components corresponding to the constitutional formula previously indicated ($C_3H_4O_2$) would otherwise seem to be in the range 250 to 350°C.

It is possible that spontaneous ignition and extinction correspond to different physical mechanisms since the latter involves failure of an operating system where plenty of intermediates for initiating fresh reaction already exist, whereas they do not in the spontaneous ignition case. This, however, does not seem to have been investigated; therefore, taking the data at their face values, which is the only possible way at present, we know that $\phi$ must rise from a value of 0.01 or less at about 300°C to a value of 0.7 or more at 400°C. This is consistent with a medium high activation energy at least of the order of 20 kcal or more. The value finally adopted as being consistent with the data given was 25 ± 5 kcal, and to satisfy the higher temperature data, the value adopted for the frequency factor $k_o$ was $4 \times 10^{10}$ g/g sec.

These values have been used to calculate $\phi$ from Eqs. (2) and (5) to plot against temperature, with a temperature correction for $\tau$ given elsewhere [15] included

$$\tau = \frac{T_0}{T}$$

Values of $\tau$ ranged from 25 to 100 msec. Values of $(k_o \tau)$ therefore ranged from $10^6$ to $10^{10}$. Figure 2 illustrates the Semenov plot for typical experimental runs based on these values. Strictly, we should not
expect the same kinetic constant values to apply to all the range of smokes thus far tested, but as yet the data obtained are insufficiently accurate for distinguishing between them. These results do suggest, however, that the values of the constants are likely to be of the same order-of-magnitude as those given here.

**Stability and Extinction Variations**

If we assume that $Q$ in Eq. (2) is known, by calculation from Eq. (3), then we can see from Fig. 2 that the prime parameter responsible for the variation in the stability or flame temperature of the reactor (other things being constant) is the residence time $r_s$. Of the other parameters, the important one is the input smoke concentration $C_o$ (or smoke feed rate $F_s$ or excess air). The result of such calculation is given in Fig. 3, which shows a plot of the reactor stability temperature against residence time ($r_s^0$), at several different levels of excess air, with some of the experimental determinations on the same plot. This has been calculated using the same kinetic constants already given.

This graph shows, first, the general trend to be expected of falling reactor temperature with increased residence time at any given excess air. This fall is due to the proportionately increasing wall loss (the
If, as is likely, the constants change significantly with smoke origin and composition, it will become a matter for reaction kinetics to determine the reasons. We do, of course, already have two activation energy values to compare: the value of 25,000 cal obtained in these experiments and the value of 11,000 obtained previously by analysis of the IIA data [16]. There are at least three possible reasons for the difference. First, doubt has been cast by others on the validity of the IIA data (see Sableski’s comments, for example, in Ref. [17], although it is our view that there is no real basis yet for assuming them to be invalid. Secondly, there are very likely important differences in composition. Third, the value of 11,000 is a gross average for the incinerator as a whole and, taking temperature variations and solid-bed contributions into account, they may be primarily responsible for the difference.

These differences, however, are points that will be cleared up by further experiments. Of more immediate interest are the conditions to be drawn relevant to incinerator practice. The extinction temperatures given in Fig. 3 indicate that overbed flames can be maintained at unexpectedly low temperatures — 500°F — which is substantially below the temperatures of 1400 to 1500°F generally quoted as the low limit for destruction of odor. If there is appreciable carbon formation by cracking, these conclusions may hold for the ambient gases but fail for the solid particles. Of greater importance is the variation of temperature with excess air. Temperature can swing quite wildly for a given air rate if the smoke feed rate varies too much. This means that intermittent charging can easily cause trouble because of failure to destroy odor, at one extreme, or to gross overheating leading to slagging, at the other extreme. Flame retention, however, should be not too difficult as long as mixing is reasonably good.

Once again, therefore, we have results illustrating the need for reasonably accurate feed control, although an alternative would be control of secondary-air quantity based on gas analysis so that, as the oxygen rose or CO₂ fell, the air would be cut back to restore an adequate overbed air/fuel ratio. An alternative controller could be based on gas temperature measurement, which is, of course, a method now coming into increasing use as exemplified by the Miami County (Ohio) unit [18]. As the author of Ref. [18] points out, however, there are two pitfalls to be avoided with use and interpretation of thermocouple readings. These pitfalls can be partly eliminated by the use of suction pyrometers (sometimes known as high-velocity thermocouples) or venturi-pneumatic pyrometers. If conditions warrant the expense of installation, a combination of temperature measurements and gas analyses would be the best source of information for automatic control.

Since control of the air rate to maintain the gas temperature is evidently in use now in at least a few installations, we have, once again, a situation where empiricism based on operational experience has preceded the more fundamental research that might have led to the same result. This has been a large part of the history of combustion engineering. Nevertheless, these research findings are able to substantiate and amplify the empirical practice, and they may also be able to assist both in gaining wider acceptance of this practice and in optimizing it. What these research findings on the smoke kinetics are also able to do is to provide a basis for correct sizing of the overbed combustion volume, which otherwise has to be determined by further empirical studies. Extension of these results to predict this volume is the next task we must undertake.

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ABSTRACT

Smoke flames obtained by burning smoke from pyrolyzing computer cards in air in a section of a circular pipe have been found to burn at rates consistent with activation energies for the process being of the order of 25 ± 5 kcal. At high excess air (50 to 200 percent), the process was treated as being pseudo first order yielding a frequency factor of 4 x 10^{10} g/g sec. Flame temperatures were in the range 1200 to 1600 K (1800 to 2500°F). These are high for incinerator operation, but prediction of extinction limits from the kinetic constants indicate that the flames should be stable to temperatures as low as 500°F. Sensitivity of temperature to excess air, however, underlines the need for good feed control to avoid failure to destroy odor at one extreme and overheating with slag formation at the other.
$H_w$ term in Eq. (3)). The magnitude of this effect is very much dependent on the physical size of the system and is particularly high for the smoke tube because of its small dimensions. As the temperature falls, an extinction point is ultimately reached, with the extinction temperature rising with excess air.

At the other extreme of very high input (or short residence time), extinction again can occur, but Fig. 3 is not an appropriate type of plot for illustrating this clearly. To do this it has to be redrawn, with residence time on a logarithmic scale. The general pattern of behavior, however, can be described. With decreasing residence time, the reactor temperature rises steadily, as illustrated. Finally, at residence time, too short to be shown clearly on Fig. 3 (but not zero), the temperature peaks, and at a still shorter residence time close to the peak, extinction takes place. In contrast to the heat-loss extinction, this “adiabatic” extinction [13] should be at conditions that are independent of the experimental system. It should be noted that, if adiabatic extinction takes place at a temperature as low as 400°C, it corresponds to a very high level of excess air indeed.

**CONCLUSIONS**

The initial results described provide encouraging support both for the flame-holding concept of the countervortex flow pattern and for the view that the very complex “smoke” can be treated as a single reactive component with at least operationally valid kinetic constants that can be determined from the experiments. It is still, of course, a question of whether constants determined from experiments on this scale will be applicable on a larger scale; however, they should be, since the reactor is a zero-dimensional system and scale does not enter the equations (although it does affect some of the extinction behavior). More pertinently, the kinetic constants are more likely to change with smoke composition, but there is nothing to be gained in arguing this point until experimental data are available obtained from different smokes.
REFERENCES


