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Project Summary

Mixing Phenomena in Industrial Fume Afterburner Systems

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This report reviews the physical mixing phenomena involved in the reactions that occur in afterburners or fume incinerators. Mixing the afterburners is considered from three points of view. First, the typical designs of afterburner components that are involved in the mixing phenomena are covered. With the paucity of information available on performance, there is no clear-cut indication of the superiority of any particular design. Second, consideration is given to the possible application of mathematical modeling principles developed for studies of conventional furnaces to afterburner design. Although the problem for the afterburner is basically simpler, practical application of mathematical modeling still seems some time off. Third, empirical relations available in the literature for describing the performance of jet flow systems similar to various afterburner components are presented. Use of these relations permits an estimate of time-temperature histories of various flow paths through different afterburner designs. Overall, the design of adequate afterburners from the mixing point of view seems well within the current state of the art.

This Project Summary was developed by EPA's Industrial Environmental Research Laboratory, Research Triangle Park, NC, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

The aim in an industrial afterburner is to consume a pollutant down to a safe lower level while balancing the economics of auxiliary fuel requirements, afterburner size and complexity, operating and maintenance costs, and meeting any other specific requirement, such as turndown capabilities. While the kinetics of the specific reactions that are desired will control minimum time-temperature-concentration requirements, the mixing patterns in the afterburners will be critical in providing these conditions. Furthermore, the complexities of providing mixing patterns of a desired size will control the size of the afterburner, the amount of auxiliary fuel actually required, and the pressure drop through the afterburner. It is therefore clear that a detailed consideration of the various mixing phenomena that occur in industrial afterburners could result in significant advances in their design.

One might designate three characteristic times in an afterburner system, namely:

1. Chemical time, τ_c. For a first-order reaction, τ_c is proportional to l/k where k is the rate constant. For other orders, the rate constant is multiplied by an appropriate average concentration.
2. Mixing time, τ_d. The mixing time is proportional to L^2D_v where L is a characteristic linear dimension and D_v is the effective diffusion coefficient.

3. Residence time, τ_r. The residence time is proportional to L/V where V is an average gas velocity.

One notes that the ratio of the mixing time to residence time is proportional to the Reynolds number, which is expected to be high in the usual afterburner. This means that mixing across the combustor must be examined critically. While the procedure for computing the flow and mixing in nonreacting systems can be quite satisfactory, where reaction systems are considered, the problem of "unmixedness" enters. Unmixedness was first analyzed in some depth by using a Gaussian distribution as a basis for computational procedure. A turbulent diffusion flame is made of pockets of unreacted fuel, air, unreacted mixture, reacting mixture, and products of combustion. A similar situation occurs for a turbulent premixed flame. As a result, a sampling at one point may show both reaction products, and fuel, oxygen, and nitrogen. In dealing through mathematical modeling with the physical (as contrasted to the chemical) aspects of combustion in a combustion system, the phenomenon of unmixedness must be added to the other flow considerations. However, it is well known that the jets and vortex flow systems that make up the usual combustion system do not show a Gaussian-type distribution on the scale of interest. Quite common in the literature are pictures and sketches of the rolling-up vortices at the region of highest velocity gradient, which normally is in the highest reaction rate region.

The ratio of the chemical time to the residence time is V/kL, the reciprocal first Damkohler group. If the rate constant is very high, or V/kL is low, the reaction can be inhibited by lack of proper mixing but not the chemistry. This is the usual case in combustion systems. However, in fume incinerators, it is possible that the rate constant for the fumes [not the fuel for the gas burner(s)] is low and the performance will be limited by both the reaction time and the mixing time. As a result, an optimum fume incinerator must be designed for a particular class of fumes.

To complicate these chemical aspects further, the presence of a flame is important for contaminant removal. Evidence indicates that, when using electric heat energy, much higher temperatures are required—1088 to 1255 K—to obtain the same efficiency achieved with a direct-flame system at 810 to 1033 K. If satisfactory incineration is to be achieved at the lowest possible temperature, the type of flame and the design of the combustor are also important factors to be considered. In 1980, studies of the self-ignition temperature of kerosene sprays downstream of a gas turbine combustor can were reported in the literature. The temperatures varied from about 500 K to 1300 K, with an inverse correlation of the self-ignition temperature with a measure of the nonequilibrium ionization of the igniting gas from the turbine. This would indicate that the more intimately and quickly the primary products of combustion in a fume incinerator mixed with the polluted secondary air, the lower the temperature or the shorter the time could be for complete combustion of the fumes.

Estimates of the chemical reaction time for various fumes are covered in Reference 1, a parallel study to the present one. In the present study, the factors entering into the estimate of the mixing time are reviewed. The review covers three aspects of the mixing problem, namely, a consideration of the various direct flame afterburner systems that are in present use, a consideration of the possible mathematical modeling of fume incineration systems, and a review of the performance parameters associated with the various components of an afterburner.

Review of Direct Flame Afterburner Systems

An effective direct flame afterburner provides (a) contact between the contaminants in the air and the burner flame, (b) time for the combustion process to be completed, (c) sufficiently high temperature for the complete oxidation of the combustibles, and (d) flow patterns that ensure adequate mixing while preventing excessive quenching. (It is common for legislation or regulations to prescribe a pair of fixed values, such as 0.3 sec for "b" and 1300°F for "c," without regard to type of pollutant. The analysis in Reference 1 shows this is not an adequate approach.) To do this, the contaminated gases are delivered to the afterburner where they are mixed with the burner flame or flames in the upstream part of the unit, normally a refractory-lines chamber. They then pass through the remainder of the chamber, where the combustion process is completed prior to discharge to the atmosphere. A typical fume afterburner uses a mixing plate or grid burner. An array of line burners, multijet burner, a nozzle-mix burner, or a premix burner could be used in the same general configuration. Variations on the recuperator from no recuperator to more extensive ones can also be made. A catalytic afterburner would have the catalyst section inserted at the downstream end of the combustion chamber, and the combustion chamber would not run as hot, thus saving on the required amount of supplemental fuel.

Mathematical Modeling of Turbulent Combustion

At present there are three main types of mathematical models available for predicting the performance of furnaces. These can be classified according to the dimensionality of the model. The simplest model is the zero-dimensional, well-stirred single-zone model. This model has the great advantages of simplicity and computer economy, and is capable of predicting the overall performance of a conventional furnace surprisingly accurately. Thus, despite various shortcomings, the well-stirred model with well-established empirical correction factors is used as the basis for routine design of radiant sections of boilers and fired heaters. Limitations of the well-stirred model lie in the fact that it does not predict spatial variations in temperature and heat flux along a furnace and it cannot predict the effect of changes in flow pattern and flame length. These limitations are critical to any use in fume reactor design.

The second class of models are one-dimensional, such as the long furnace model in which the gas velocity and temperature transverse to the flow direction are assumed to be uniform and axial radiation is neglected. This model is economical and is capable of predicting axial variations of temperature and heat flux. It can deal with changes in flame length but not recirculation of gases within the furnace. When the recirculation zone is of limited extent, a combination of well-stirred and plug flow models can be used successfully. This modeling approach is applicable to certain fume reactor designs.

The third class of models are multidimensional. Zone and multiflux methods are available for solving that part of the calculation concerned with radiative heat transfer. However, these must be coupled with some method for calculating the flow and heat release. In principle, this can be done by solving the governing equations for conservation of mass, momentum, and energy using (say) a finite-difference solution procedure. However, these methods require considerable expertise and computer time, and often produce unreliable predictions. The unreliable results probably arise from the need for various turbulent mixing coefficients which must be evaluated by trial and error comparison with data on a similar system. For these reasons they are used rarely (if at all) for design of industrial furnaces.

In time (about 1985) these methods are expected to become more reliable and gain wider acceptance in furnace design. Because of some simplifying factors, practical application of this approach may be even sooner in the fume incinerator field.

Jetlike Components of Afterburners

Examination of afterburner components reveals that many of them can be classified as resulting in jetlike action in the flow field. Looking at the components as regions in the flow field, one could consider the regions as jet flow regions. For instance, discrete source burners can be treated as hot gas jets interacting with surrounding fume laden air. While the simple jet in an infinite environment of identical properties to the jet has been discussed in many reports, some consideration of the jetlike flames in an afterburner shows that many variations in the jet and environmental flow patterns can lead to significant differences in results. On the other hand, the smaller variations in temperature and reaction rate in the combustion chamber section of an afterburner, as contrasted to normally expected combustor rates in the combustion region of a furnace, permit the use of the simpler nonreacting jet results in analysis. In this report, emphasis is placed on "cold jet" results that are applicable to afterburner design.

For orientation, Table 1 lists several sets of type variations that one might encounter in a combustion system. For a given jet, a type must be specified from each set; this leads to a large number of variations in jets even without consideration of details. For the present study, several examples in the literature that are pertinent to afterburners are cited.

Table 1. *Jet-Type Variations Classified in Sets*

- *a. Geometry of jet exit*
  - *1. Axially symmetric*
  - *2. Two-dimensional*
  - *3. Rectangular*
  - *4. Wall*
  - *5. Radial*
  - *6. Annular*
  - *7. Other*
- *b. Environmental velocity*
  - *1. Zero*
  - *2. Coaxial positive*
  - *3. Coaxial negative*
  - *4. 90° cross flow*
  - *5. Non 90° cross flow*
- *c. Environmental properties*
  - *1. Temperature and composition same as in jet*
  - *2. Temperature different*
  - *3. Composition different*
  - *4. Temperature and composition different*
- *d. Number of jets*
  - *1. Single jet*
  - *2. Multiple parallel jets in line*
  - *3. Multiple parallel jets in pattern*
  - *4. Multiple nonparallel jets*
- *e. Relation of jet to wall*
  - *1. Nonimpinging jet*
  - *2. Jet impinging at 90°*
  - *3. Jet impinging at other than 90°*
- *f. Environmental geometry*
  - *1. Jet in open*
  - *2. Jet in enclosure without recirculation*
  - *3. Jet in enclosure with recirculation*
- *g. Swirl condition*
  - *1. Zero swirl*
  - *2. Low swirl*
  - *3. High swirl*
- *h. Buoyancy*
  - *1. No buoyancy effect*
  - *2. Positive buoyancy parallel to jet direction*
  - *3. Negative buoyancy parallel to jet direction*
  - *4. Nonparallel buoyancy effects*

Conclusions

This report on afterburner mixing phenomena is a companion to an earlier report, Reference 1, which discussed chemical aspects of afterburner systems. The report on chemical kinetics brought together information for estimating time-temperature-composition relations necessary to carry out the oxidation of various organic fumes. In the present report, sufficient information is given to permit the estimation of comparative values for various fluid dynamic systems that can be used as afterburners. These values can then be compared to the requirements based on Reference 1 to determine if a design is acceptable. The report is divided into three phases, namely, a review of direct flame afterburner systems, a consideration of the possibilities of using mathematical modeling in designing such systems, and a review of the empirical relations that can be used in the description of the mixing associated with various jet-like components of an afterburner.

Direct flame afterburner systems may be considered as composed of a fume polluted air source, a recuperator section (usually), an approach section to the burner section, a burner section, a combustion chamber section, possibly a catalytic section, the other side of the recuperator section (usually), and an exhaust. In this study, the sections involved in the mixing process related to the incineration of the fumes, namely, the approach section, the burner section, and the combustion chamber section, are considered. A large variety of designs in these three sections are found, with no clear-cut preference for any particular combination. This is

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because of conflicting requirements relative to capital cost, maintenance cost, size, complexity, fuel consumption, needed flexibility, and pollutant type, as well as variations in code restrictions and contract specifications. However, well-documented field studies of actual performance would undoubtedly eliminate many of the available fume afterburner systems as viable products.

Mathematical modeling of combustion systems is receiving great attention in the current literature. Therefore, the pertinence of these studies to the design of practical fume afterburners is considered in some detail. It is pointed out that mathematical modeling is only one of many possible design approaches. In the proper formulation of the pertinent equations, the character of the turbulence must be understood before suitable approximation can be made in mathematically specifying the turbulence at any point in a combustion system. Even then, the mathematical models contain arbitrary coefficients based on the fit of analytical results to experimental results for a particular experimental flow system. For best results, then, the particular system on which the coefficients are based should resemble the afterburner design of interest. Comparing the complexity of the typical afterburner with the simplicity of most experimental systems used in connection with specifying the parameters of a mathematical model, some pitfalls of this design approach become apparent. On the other hand, because the flow and reaction region of interest in the primary fume incineration process does not involve the high fuel concentration, high reaction rate, and high temperatures of the more usual types of combustion systems, simplifications are possible in the application of mathematical modeling to fume incinerator design. It is concluded that the practical use of mathematical modeling for fume afterburner designs is at least 5 years away.

For the same reason that there appears to be a possible simplification in the use of mathematical modeling, there also appears to be a possible simplification in using literature on various forms of jets to estimate the time-temperature-composition profiles as the hot combustion gases are mixed into the fume-laden secondary air flow. From such information, one can check whether the time-temperature-composition requirements predicted for a specific fume are met. Because of the low reaction rate, "cold jet" data may be used rather than having to invoke the complications of intense combustion process taking place in the jet flow. This opens up a wide range of applicable dat in the literature, with rather simpl relationships available for predictin the mixing features of a jet and it surroundings. Specifically, in this stud the following types of turbulent jets ar reviewed—circular free jet, plane fre jet, free compound jet, enclosed com pound jet, circular jet with swirl, jets i cross flow, and impinging jets. Th information in this literature is believe to be sufficient to permit the calculatio of adequate time-temperature-compc sition curves for most reasonable fum afterburner designs.

Reference

1. Barnes, R.H., M.J. Saxton, R.E Barrett, and A. Levy. Chemica Aspects of Afterburner System EPA-600/7-79-096 (NTIS PB 298465 April 1979.

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The complete report, entitled "Mixing Phenomena in Industrial Fume Afterburner Systems," (Order No. PB 81-222 259; Cost: $11.00, subject to change) will be available only from:

National Technical Information Service
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