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Journal

Symposium (International) on Combustion, 25(1)

ISSN

0082-0784

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Publication Date

1994

DOI

10.1016/S0082-0784(06)80657-0

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ACTIVE, OPTIMAL CONTROL OF A MODEL INDUSTRIAL, NATURAL GAS-FIRED BURNER

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Optimal, active control of a model industrial, swirl-stabilized, natural gas-fired burner is considered as a strategy to attain and maintain low flue-gas NO_x concentration ($[\text{NO}_x]$) and high combustion efficiency (η_c), simultaneously. A performance index, J , has been defined such that the maximization of J correlates to optimal burner performance, with respect to $[\text{NO}_x]$ and η_c . Two parameters, swirl intensity (S') and excess air (EA), known to affect the value of J , are made amenable to control and incorporated as variable burner inputs. The two measurable burner outputs, $[\text{NO}_x]$ and η_c , are continuously monitored via a bank of extractive probe emission analyzers, similar to those proposed for industry as continuous emission monitoring systems (CEMS). The settings of EA and S' are automatically adjusted by a specialized search algorithm in order to maximize the performance index, thereby optimizing η_c and $[\text{NO}_x]$. Two fundamentally differing search algorithms are explored. The first is a variation of Powell's direction-set method and incorporates a simple hill-climbing, line-maximization technique. The second technique uses the genetic algorithm analogy, which works in parallel from a population (set) of burner inputs and associated fitness (performance index) values in order to generate more highly fit (better performing) populations. The control scheme is shown, in both cases, to increase overall burner performance. Advantages and disadvantages to each of these algorithms are identified and discussed. While promising, a robust practical application of optimal, active control will benefit from a refined and more mature search technique, possibly including a hybridized combination of one or more methods.

Introduction

In the combustion of natural gas for heat generation in industrial and commercial applications, a major consideration is the flue-gas minimization of nitric oxide (NO) and nitrogen dioxide (NO_2), collectively referred to as NO_x . The current driving force in the United States is the Clean Air Act of 1990, which limits the amount of NO_x allowed to be released into the atmosphere annually [1]. The concern with these pollutants is their role as precursors in urban photochemical oxidant ("smog") formation [2]. Indeed, in the Los Angeles Air Basin (where geography and a remarkable population of both people and automobiles make air quality a special concern), local regulations are even more strict than the national standard [3].

In addition to the reduction of NO_x emissions, another goal in commercial and industrial heat generation is the maximization of combustion efficiency. The driving force in this case is the association of higher combustion efficiency with overall thermal efficiency and, therefore, lower operating costs. Even a fraction of a percent in overall thermal efficiency can equate to substantial savings in fuel costs.

Optimally, then, a natural gas burner would operate at conditions that produce the lowest NO_x

emission and yield the highest combustion efficiency. Typically, however, conditions for which the highest efficiency is obtained are not the same conditions where low NO_x emission can be found, and vice versa [4]. Also, the control of a practical burner is usually in the hands of an expert, human operator who adjusts the burner according to his or her notion of how a "good" reaction should look. Further, optimal burner operating conditions can be subject to both changes initiated by an operator or process control system (e.g., modifications in fuel load, fuel type, or burner geometry), as well as subtler changes in fuel composition or changes caused by degradation of equipment. Even assuming an expert operator *could* find the optimum operating conditions for any *sensed* change in boundary conditions, it is conceivable that there could be changes *unsensed* by the operator (thereby shifting the optimum operating condition) for which no action would be taken.

A continuous, active, optimal control scheme would, in principle, address this issue. The objectives of the present work explore the application of such a scheme to minimize NO_x formation with the concomitant attainment and maintenance of high combustion efficiency in a model, industrial, natural gas-fired burner. The first objective is to identify

parameters that (1) are amenable to control, and (2) affect NO_x formation and combustion efficiency. The second objective is to develop a methodology, including a strategy for measuring combustion efficiency and NO_x concentration in the exhaust gases and the ability to actively articulate the parameters identified as control inputs. The final objective is the integration and comparison of appropriate search and optimization techniques.

Approach

Methods for the control of NO_x emission can be separated into two groups according to whether they are performed during or after the combustion process. Technologies in the first group aim to prevent the formation of NO_x , while postcombustion controls seek to destroy or remove oxides of nitrogen from the exhaust gases [5]. The definition of "control," in this context, is simply the reduction or prevention of NO_x emission into the atmosphere. In the context of the present investigation, "control" is expanded to include the slightly broader notion of manipulating burner inlet parameters in order to optimize overall performance of a burner, with respect to NO_x emission and combustion efficiency.

Currently, practical control of NO_x in natural gas-fired burners is limited to either modifying equipment (e.g., retrofit with low- NO_x burners, flue-gas recirculation, overfire air, staged combustion) or modifying operating conditions (e.g., low excess air, off-stoichiometric combustion, burners-out-of-service, biased burner firing). While each of these techniques has been shown to be effective in reducing the emission of nitrogen oxides, none is designed to react to changes in combustion operating conditions [6]. In other words, these methods are passive.

The present approach involves modification of combustion operating conditions and is of an active nature. The controller responds to a set of input variables (i.e., NO_x concentration in the flue gas and combustion efficiency) by adjusting a set of some output variables (i.e., parameters known to affect the input variables) in order to optimize the input set.

Active control of combustion processes is only recently beginning to be explored. In combustion-based propulsion systems, studies are addressing the control of pressure oscillation (an indication of instability and performance degradation) [7]. An optimizing, active control strategy has been performed with some success using pressure oscillations and volumetric heat release of a dump combustor as controller inputs [8]. In the area of active control of natural gas burners, very little has been done, especially with respect to optimizing pollutant emission. Closed-loop control of the fuel-to-air ratio has been performed on a natural gas-fired boiler using an infrared-radiation-based sensor [9], and an effort has

been made to maximize combustion efficiency of a model gas turbine combustor with an active control approach [10], but never has the optimization of both efficiency and pollutant emission been attempted with anything but passive control strategies.

Parametric studies were performed on the model, industrial burner [4]. NO_x concentration corrected to 3% O_2 by volume in the flue gas (hereafter noted as " $[\text{NO}_x]$ ") and combustion efficiency (η_c) were determined across a range of stable excess air (EA) and swirl intensity (S') values, for several different nozzle geometries. Swirl intensity is given by

$$S' = \frac{2 \cdot S_g \cdot A_t}{\pi \cdot r_0 \cdot d_a \cdot R} = \left(\frac{\dot{m}_\phi}{\dot{m}_\phi + \dot{m}_a} \right)^2 \quad (1)$$

where $\dot{m}$ is mass flow rate. The subscripts ϕ and a refer to the swirl air stream and the axial air stream, respectively. The term S_g is the geometric swirl number, as defined by Feikema et al. [11], where A_t is the total area of the tangential (swirl) inlets, r_0 is the radius to the tangential inlets, and d_a is the throat diameter. Both EA and S' are calculated from knowledge of the inlet air and fuel flow rates.

A database of burner performance was established for a variety of nozzle geometries across the range of lean excess air and swirl intensity values, where each nozzle could be operated with a stable reaction. Figure 1 is a plot of selected $[\text{NO}_x]$ and η_c results as a function of excess air and swirl intensity for a typical nozzle geometry. As this figure shows, NO_x concentration tends to increase along with combustion efficiency. Conditions do exist, however, where $[\text{NO}_x]$ is relatively low and η_c remains relatively high [4].

The qualitative idea of "peak" burner performance must be defined in quantitative terms, based on a tradeoff between $[\text{NO}_x]$ and η_c , in the form of a performance index, J . This performance index then becomes the variable that is maximized by the controller, indirectly optimizing NO_x concentration and combustion efficiency.

The shape of a particular performance index is a design decision and is defined based on the relative importance assigned to each measured parameter. In the case of the present experiment, performance is defined in terms of combustion efficiency and NO_x concentration and is assigned the following form:

$$J = w_{\eta_c} g(\eta_c) + w_{[\text{NO}_x]} f([\text{NO}_x]) \quad (2a)$$

$$f([\text{NO}_x]) = \begin{cases} 1 - 0.75 \cdot \left(\frac{[\text{NO}_x]}{[\text{NO}_x]_{\text{limit}}} \right)^4; & [\text{NO}_x] \leq [\text{NO}_x]_{\text{limit}} \\ (1 - 0.75) \cdot \frac{[\text{NO}_x]_{\text{max}} - [\text{NO}_x]}{[\text{NO}_x]_{\text{max}} - [\text{NO}_x]_{\text{limit}}}; & [\text{NO}_x] > [\text{NO}_x]_{\text{limit}} \end{cases} \quad (2b)$$

FIG. 1. NO_x concentration and combustion efficiency for a co-swirl nozzle at low and high swirl values for various excess air conditions. Combustion efficiency is listed above each bar [4].

FIG. 2. Performance index, J , as a function of excess air, EA , and swirl intensity, S' , for indicated stability range. Shaded area is interpolated from a grid of 93 points. White area is band of "good" performance.

$$g(\eta_c) = \left(\frac{\eta_c - \eta_{c,\min}}{100\% - \eta_{c,\min}} \right)^{1/2} \quad (2c)$$

where w_{η_c} and $w_{[NO_x]}$ are positive weighting factors that sum to one. The terms $[NO_x]_{\max}$ and $\eta_{c,\min}$ are set according to the ranges expected for a particular burner geometry. The definition of the efficiency function term is such that an increasing reward (i.e., an increase in J) is applied as combustion efficiency increases. The $[NO_x]$ function is slightly more complex, with the performance index decreasing until $[NO_x]$ surpasses a user-defined limit, $[NO_x]_{\text{limit}}$, beyond which J decreases linearly to $[NO_x]_{\max}$. The purpose of this piecewise definition of $f([NO_x])$ is to impose a high penalty on J above $[NO_x]_{\text{limit}}$ and a rapidly decreasing penalty for measurements below this limit. In other words, the contribution from $f([NO_x])$ to J is high as long as the measured NO_x concentration is below the specified limit. The value of $[NO_x]_{\text{limit}}$ can have practical significance, such as the

permitted NO_x emission limit for a particular burner application.

The performance index, thus defined, is shown graphically in Fig. 2 for one of the nozzles across the range of stable excess air and swirl intensity values. Note from Eq. (2) that the performance index, J , is bound between 0 and 1 and increases monotonically with both a decrease in NO_x concentration and an increase in combustion efficiency. Optimal performance of the burner would correspond to $J = 1$, where η_c is 100% (1.00) and $[NO_x]$ is zero. As combustion efficiency approaches $\eta_{c,\min}$ and NO_x concentration approaches $[NO_x]_{\max}$, J approaches 0. Hence, the responsibility of the controller (which has no knowledge regarding the shape of the performance index surface) is to evaluate J at the current EA and S' setpoint, compare this value with past performance, and determine a new setpoint such that the performance index, J , approaches a maximum. This region of maximum J is indicated on Fig. 2 in a clear band and

FIG. 3. Figurative representation of components in the active control loop. Fuel and air mix and react in the *burner*, the object under control. The *sensor* samples species concentrations in the exhaust and calculates combustion efficiency (η_c), and NO_x concentration corrected to 3% O_2 ($[\text{NO}_x]$). These values are sent to the *controller*, which evaluates burner performance, J , and determines the excess air (EA) and swirl intensity (S') setpoint, which are then sent to the *air flow generator*.

is defined as the region of desired, or "good," performance.

Using excess air and swirl intensity as the two input parameters, a control scheme having four distinct components was developed, as figuratively depicted in Fig. 3. The *burner* component is the object under control, the performance of which is the subject of this study. The *sensor* must convert information in the exhaust gases into $[\text{NO}_x]$ and η_c signals for input to the controller. The *air flow generator* is responsible for reading EA and S' signals output by the controller and adjusting the axial and swirl air mass flow rates accordingly. The final, and most important, component in the current approach is the *controller*, which consists of an algorithm having the general responsibility of continuously searching the space of EA and S' in order to optimize the output variables, $[\text{NO}_x]$ and η_c .

Experiment

This study makes use of facilities already in place at the UCI Combustion Laboratory [4], as well as additional equipment incorporated into the test stand specifically for the present work on active control. The experiment performed is best described with respect to the four components introduced in the previous section and figuratively represented in Fig. 3.

Burner:

Figure 4 provides a cutaway view of the model, natural gas-fired burner. The reaction is up fired and swirl stabilized, and the nominal fuel load rating is 30 kW (100,000 Btu/h). Features making this burner valuable as a research tool include a variable quarl

FIG. 4. Model industrial burner.

angle and fuel nozzle, and the ability to alter the aerodynamic characteristics by varying the amounts of axial air, swirl air, and secondary (dilution) air.

The burner exhausts into an octagonal furnace enclosure, the walls of which may be configured to impose variable exit boundary conditions including heat loading and downstream flow-field geometry. These walls may also be replaced with transparent windows to facilitate laser diagnostic techniques being performed in parallel with the experiment presented in this paper.

For the current experiment, the nozzle geometry, furnace geometry, fuel load, quarl angle, and secondary air flow rate are held constant. The only parameters varied for the purpose of active control are axial air flow rate and swirl air flow rate.

Sensor:

In the present study, an extractive probe technique, similar to the type used as continuous emission monitoring systems (CEMS) in the burner industry, is employed to measure the concentrations of carbon monoxide ($[\text{CO}]$), carbon dioxide ($[\text{CO}_2]$), hydrocarbon species ($[\text{HC}]$), oxygen ($[\text{O}_2]$), and nitrogen oxides (the uncorrected sum of $[\text{NO}]$ and $[\text{NO}_2]$, $[\text{NO}_x]_{\text{measured}}$) in the flue gas. A fraction of the exhaust gas is continuously removed from a well-mixed portion of the stack. The sample stream is then divided and fed to each of five species concentration analyzers. One hundred samples are taken over a period of 20 s at each setpoint. The average absolute NO_x signal, $[\text{NO}_x]_{\text{measured}}$, is converted to a value that

is corrected to 3% oxygen by volume in the exhaust gases, $[\text{NO}_x]$. Combustion efficiency is calculated as well, using the heat and carbon contents of the fuel, along with averaged $[\text{CO}]$, $[\text{CO}_2]$, and $[\text{HC}]$ values. Care is taken to preserve the integrity of the sample between extraction and analysis points.

$[\text{NO}_x]$ and η_c are measured by the sensor and sent to the controller. The controller, in turn, uses these values, along with previous performance index values and its specific search algorithm, to determine changes in EA and S' values, which are then sent to the air flow generator.

Air Flow Generator:

The heart of the air flow generator involves a magnetic actuator valve and a mass flow sensor in each of the two combustion air paths (swirl and axial). Each valve and sensor package is referred to collectively as a mass flow controller (MFC). Each MFC reads a setpoint in the form of a DC voltage, linearly proportional to the desired mass flow. Internal to each MFC is a closed-loop controller that adjusts the valve such that the sensor output voltage agrees with the setpoint voltage.

The software aspect of the air flow generator consists of a simple conversion from excess air and swirl intensity values (received from the controller) to voltage setpoints. The total air flow required, $\dot{m}_{\text{tot}}$, is determined using the theoretical fuel to air ratio of natural gas, the fuel load, and the desired excess air value (EA). Given $\dot{m}_{\text{tot}}$ and swirl intensity (S'), the swirl air flow ($\dot{m}_\phi$) and axial air flow ($\dot{m}_a$) values are extracted and converted to voltage setpoints.

Controller:

In general, the controller is designed to continuously receive inputs in the form of $[\text{NO}_x]$ and η_c , and determine new EA and S' outputs, improving performance of the burner over time.

NO_x concentration and combustion efficiency values are time-averaged at steady-state conditions for a given excess air and swirl intensity setpoint. The steady-state values of $[\text{NO}_x]$ and η_c are used by the controller to evaluate performance at the present EA and S' setpoint based on the value of the performance index, defined above, which defines a trade-off between the real values of concern.

An important note is that the controller component in this experiment does not perform *control* in the classical sense. Classical control presupposes some form of analytical or numerical model of the process under control. The failure of classical control techniques to be applied to the control and optimization of practical combustion processes lies in the lack of any sort of practical, computationally simple model defining a relationship between inputs and outputs.

In this study, the controller is more aptly described as a specialized search and optimization algorithm, the description of which has thus far been kept intentionally general. The purpose of this generality is to allow flexibility in implementation of a search algorithm, of which there are many to choose. In this way, different optimization algorithms can be incorporated into the controller, and the efficiency of one can be compared with the performance of another.

Several techniques have been identified as holding promise in this approach, two of which are explored in this work: a direction-set algorithm and a genetic algorithm [12,13,14]. Search techniques were selected based on their satisfaction of several requirements for application to a combustion system. These include the following: (1) applicability in multiple dimensions; (2) lack of dependency on an underlying model describing the process; (3) concern for performance values at a given point (or set of points) only, without requiring a database or look-up table of performance index values; and (4) the ability to function within a constrained search domain. Specifically, the search domain is constrained by the line $EA = 0$ (fuel-rich operation is not permitted) and by empirically determined stability limits.

Direction-set method

The first technique implemented in this study, and the simpler of the two, is a direction-set method. The algorithm is based on and adapted from Powell's method in two dimensions [13]. The basic procedure is described as follows: Given an initial starting point ($S'_i, EA_i, i = 0$), maximize J along some initial direction, a_i . Call that point (S'_{i+1}, EA_{i+1}). From there, search along a direction perpendicular to the initial direction ($a_{i+1} = a_i + \pi/2$) for the maximum J . Call that point (S'_{i+2}, EA_{i+2}). Now, maximize J along the line passing through the two points (S'_i, EA_i) and (S'_{i+2}, EA_{i+2}). Call the new point (S'_{i+3}, EA_{i+3}), let $a_{i+3} = a_i + \pi/6$, increment i by 3 and repeat.

In this way, the third line search is always in the direction of the greatest increase in J achieved by the first two line searches. The reinitialization of the search direction every three iterations ensures that convergence to a single path does not occur. Each time J is maximized along a particular direction, a separate, line-maximization routine is followed. This subalgorithm uses a simple *hill-climbing* search, where the search variables, S' and EA , step along the search direction until the performance index, J , ceases to increase. A hill-climbing technique is employed in this initial approach for one reason: By examining the character of the J surface (Fig. 2), it appears to be essentially unimodal with respect to swirl intensity and excess air, therefore ensuring that the first maximum along any line is the global maximum on that line. However, this technique has a drawback in that it will always converge to the first

FIG. 5. Direction-set search results. Symbols along search path (a) correspond with symbols on plot of performance history (b).

maximum encountered and therefore will most likely not reach the global maximum in a multimodal response surface.

Genetic algorithm

The genetic analogy can be a powerful search technique [14]. Based on natural selection mechanics, the description of this method requires language borrowed from that field of study. The algorithm starts with a population of individuals. An individual consists of a binary string coded so as to represent a single point in EA and S' space. The fitness of each individual (its scaled performance index value) is evaluated, and a new population is produced based on the previous generation's fitness. Individuals are selected for reproduction according to each one's fitness: Individuals with higher fitness have a better chance of reproduction. Each binary string individual selected for reproduction functions as a chromosome and may undergo crossover with its mate based on a finite probability that crossover will occur. In addition, each allele, or character in the binary string, has a small probability of mutating (changing from a 1 to a 0 or vice versa).

The particular coding utilized, the number of individuals per population, and the probabilities selected for crossover and mutation all can have an effect on the efficiency of this algorithm. Selection of these parameters was based on engineering judgment and rules of thumb developed in the field of genetic algorithm research [14]. Excess air and swirl

intensity are coded as 10-bit binary strings, with the first five bits representing swirl intensity, and the last five bits representing excess air. Population size is limited by the time required to measure performance for a single individual, and is set to 12 in this study. A crossover probability of 50% was chosen to ensure vigorous reproduction, and the mutation probability was set at 10%.

Results

Figure 5 illustrates a representative performance history from the direction-set method. Beginning at 3.0% excess air and a swirl intensity of 0.44, J is maximized along the initial direction, $a_0 = 11\pi/6$. Search continues along $a_1 = \pi/3 (a_0 + \pi/2)$, where J is maximized in the region of "good" performance. At this point, after 15 iterations, J reaches a value of 0.893. The search proceeds and converges around $S' = 0.53$, $EA = 17\%$.

Figure 6 displays a typical performance history generated by the genetic algorithm technique. The distribution of the individuals in the first generation is initialized uniformly across the search domain. Following fitness (performance) evaluation of the first generation, reproduction and crossover produce the second generation, which is more fit than its predecessor. Indeed, as Fig. 6 shows, both the minimum and the average performance index values increase with each successive generation. By the fourth generation, most of the individuals lie clustered about the point $S' = 0.53$, $EA = 17\%$.

FIG. 6. Representative genetic algorithm search results. Each graph represents a single population of 12 individuals (points). Successive generations converge to the region defined as "good" performance. Number of individuals in a cluster is indicated where markers overlap. Average, minimum, and maximum performance index values are listed as well.

Several interesting observations may be drawn from these results. First, they demonstrate that an active, optimal control scheme can lead to improvement in overall burner performance with respect to combustion efficiency and NO_x emission. The time between performance evaluations is essentially the same for both techniques, so that a comparison of

the two techniques is appropriate, pointing out the strengths and weaknesses inherent to each.

The direction-set method attains operation in the region of "good" performance in 15 iterations. Once a peak is reached, the controller does not deviate from this location, and performance flattens out. The algorithm is shown to maintain operation in a region of "good" performance. However, there is no guarantee that the peak reached is the global peak. This region happens to be the only peak across the surface, but every system is not guaranteed to be as unimodal.

The genetic algorithm, by virtue of its initialization across the entire stable region, visits areas of "good" performance relatively early, but does not converge significantly until the fourth generation, which is relatively late compared to the direction-set results. However, confidence that this final point is a global maximum is higher, because the algorithm effectively searches the entire surface, while the direction-set technique only searches along a narrow line. A primary drawback to the genetic algorithm method of search is in the area of maintenance. Even after the fourth generation, excursions far from the region of "good" performance occur, as individuals continue to mutate.

In this particular demonstration, the direction-set algorithm seems to be a better method of optimizing performance. However, for a general system, where multiple extrema may exist, the genetic algorithm would seem to have a clear advantage. An even better solution may lie in the hybridization of these two techniques, where, for instance, a genetic algorithm locates the area of the global maximum, and hands over control to the direction-set method, which seeks out and maintains operation on the local peak.

The time between performance evaluation iterations is limited, in the present case, by the time required to obtain a stable extractive probe measurement. While the controller has a response time on the order of milliseconds, the extractive probe sensor has a response on the order of 1 min. The extractive probe would be suitable for boiler and furnace applications where (1) load changes occur on the order of hours, and (2) continuous emission monitoring systems (CEMS) are installed by regulatory mandate. However, a more rapid response sensor technology, if available (e.g., laser-based detection of CO and NO), would reduce the time between iterations by two orders of magnitude.

Conclusions

Industrial sources of air pollutants in urban areas will be required in the future (1) to attain and maintain low NO_x emission, and (2) to do so without sacrificing high combustion efficiency. The present study addresses these needs with an optimal, active

control approach. The investigation of active control leads to several conclusions:

1. Optimal, active control is a viable method for attaining and maintaining low-emission, high-efficiency performance of a natural gas-fired burner.
2. Active control methods have the advantage of adapting to changing load, particular burner idiosyncrasies, and changes in system performance over time.
3. A trade-off can be defined between combustion efficiency and NO_x concentration in the form of a performance index. This index can then be used as a viable search criterion.
4. The two search techniques explored in this study have advantages and disadvantages, and a generically applicable, robust approach will likely involve a combination of two or more optimization methods.
5. The sensor technology adopted for the present application is readily adaptable to the CEMS requirements evolving for impacted urban areas. The control inputs are also easily implemented.

Acknowledgments

This program is supported by the California Institute of Energy Efficiency (CIEE) and the Southern California Gas Company (SoCalGas). We are grateful for the continued guidance and interest provided by Dr. Diane Fisher, the Program Monitor at CIEE, and Mr. Cherif Youssef, the Program Monitor at SoCalGas. Also, special thanks go to Mr. Matt Miyasato, without whom this effort would not have been possible, and to Mr. Kevin Trout and Mr. Stephen Dunn for their assistance.

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COMMENTS

Roman Weber, *International Flame Research Foundation, The Netherlands*. Your experimental burner incorporates both inlet swirl and excess air ratio as two variables to control NO_x emissions. In the industry, NO_x emissions are controlled by either air or fuel staging, recirculation of flue gas from the furnace exhaust back to the burner, or by enhancing on entrainment of combustion products into the flame. Do you have plans to develop and test NO_x control strategies for these techniques?

Author's Reply. We recognize that swirl intensity and excess air may not always be practical as inputs to a combustion control scheme. Likewise, $[\text{NO}_x]$ and η_c may not always be the output parameters of concern in all systems. However, we feel the approach presented in this paper can be applied to any system, simply by changing the performance index to reflect the output quantities that are of interest and by incorporating inputs that can be controlled in a particular system. The key is that the input parameters

on which a control algorithm searches must have some effect on the output parameters that are under control.

As an example, consider a scheme to control NO_x emissions and overall thermal efficiency, η_{th} , on a system that incorporates flue gas recirculation. The same approach to control as that presented in the paper could be taken. In this case, the performance index would be a function of $[\text{NO}_x]$ and η_{th} and the search variables would be related to recirculation of the flue gas (percentage recirculated, etc.). The point is that this optimization scheme may be applied to any system where there are system variables that can stand some adjustment, as long as those system variables have an effect on the performance index (output variables).

We are currently investigating the incorporation of other burner parameters (inputs and outputs) into the control strategy introduced in this paper.

R. T. Waibel, John Zink Co., USA. It is important to include the effect of excess air when considering efficiency. This could be done by minimizing excess oxygen as well as NO_x , CO, and unburned hydrocarbons. In addition, the measurement and control might be simplified by eliminating the measurement of unburned hydrocarbons. Practical experience shows that minimizing CO also minimizes unburned hydrocarbon emissions.

Author's Reply. We agree that the effect of excess air is important. Excess air affects many output parameters in a combustion system. In this paper, the effect of excess air on NO_x concentration ($[\text{NO}_x]$) and combustion efficiency (η_c) has been shown. Excess air certainly has an effect on other output parameters, including volumetric heat loading (which may be measured as the spatial temperature distribution of a reaction). This will be directly related to the thermal efficiency of a system. For a given system, measurement of excess oxygen can be an indirect measurement of the system's thermal efficiency. In a system where a compact, high-temperature reaction is desired, it may then be desirable to minimize excess oxygen. In such a system, this would be equivalent to optimizing thermal efficiency.

In the experiment presented in this paper, two parameters have been optimized, $[\text{NO}_x]$ and η_c . The thermal efficiency, η_{th} , of our system could be defined, and this parameter could be included in the definition of the performance index. In this way, thermal efficiency could be optimized as well. If low excess oxygen correlated with high thermal efficiency in our definition, then an excess air term would effectively be incorporated into the performance index.

Our experience also agrees with the statement that "minimizing CO also minimizes UHC emissions." During our testing, UHC emissions are monitored routinely to ensure that the furnace is free of fuel just prior to lighting the burner. We include a measurement of unburned hydrocarbons in our calculation of combustion efficiency simply because the measurement is readily available and it gives us a more accurate reflection of the percent to which com-

bustion is complete. In a practical system, however, it might be more reasonable to simply monitor CO emissions, as an indirect measurement of combustion efficiency. Indeed, it is [CO] in the exhaust that typically falls under government regulation, as opposed to combustion efficiency. Again, the control scheme presented here could incorporate any parameters that were deemed important into the performance index.

Anthony Hamins, National Institute of Standards and Technology, USA. The careful measurements that were presented showed that the combustion efficiency (η_c) has values ranging from near unity to approximately 80%. Determination of η_c requires independent measurements of CO, CO_2 , hydrocarbons, and O_2 . What was the total uncertainty in the η_c measurement? Were the measurements normalized to obtain near unity η_c ? Did the calibration scheme somehow insure a near unity η_c value under certain conditions?

Author's Reply. Combustion efficiency, η_c , was calculated based on the concentrations of CO, CO_2 , and hydrocarbons in the stack, and with knowledge of the composition of the fuel (carbon content, higher heating value). The actual equation used is adapted from an equation presented by Goodger [1]:

$$\eta_c = 1 - \frac{C_f}{C_m} \left[\frac{[\text{CO}] \cdot \Delta h}{\text{HHV}} - [\text{HC}] \right]$$

where C_f is the fraction of fuel-bound carbon, C_m is the total measured fraction of carbon in the exhaust products, and [CO] and [HC] are the measured fractions of carbon monoxide and hydrocarbon species, respectively. The Δh term is the difference in the enthalpies of converting C to CO_2 and C to CO (the energy lost due to the incomplete conversion of CO to CO_2). Finally, the term HHV is the measured higher heating value of the natural gas.

The total uncertainty in the calculation of η_c is a function of the uncertainty in each term's measurement. This ranged from 0.40 to 0.66%. The calculated values of η_c are absolute values (i.e., the measurements were not normalized). A value of unity was not insured under any conditions, and combustion efficiency was simply a function of the actual measurements taken at a given condition.

REFERENCE

1. Goodger, E. M., *Combustion Calculations*, MacMillan Press, Ltd., 1977, pp. 74-75.

R. V. Serauskas, Gas Research Institute, USA. In considering applying this strategy to a practical control system,

say via microprocessor-actuated feedback, would you recommend a system based on algorithms (such as direction sets or genetic algorithms) which appear either to take long times to converge or show erratic values along their trajectory to convergence?

Author's Reply. In any practical system, three options are available for application to a control scheme: (1) classical feedforward or feedback control, (2) some sort of look-up table or empirical fit of the data to a function, and (3) some kind of search and optimization algorithm.

The first option requires the knowledge of a mathematical relationship between burner outputs and inputs. For

the case of practical, turbulent combustion processes, this option must be eliminated since a simple, reliable model does not yet exist. The second option requires an empirical mapping of burner inputs to outputs. While not entirely impractical, a control scheme based on this idea will be neither robust nor adaptable. That is, the look-up table must be updated as changes in the system occur (due to changing fuel compositions, degradation of equipment, etc.).

With the above information, and for reasons stated in the paper (lack of a need for a priori information, etc.), in applying a control strategy to a practical combustion system we recommend a scheme based on algorithms.