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Effects of Electric Fields on the Blowoff Limits of a Methane-Air Flame

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Introduction

THE influence of electric fields applied to flames on extinction limits and flame stability have been reported by a number of researchers.[1-5] It is extremely difficult to draw precise conclusions concerning the effects of an electric field on flames due to the variety of experimental conditions and procedures employed by the various investigators; however, evaluation of the data indicates an increase in flame stability.

The main objective of this Note is to present the experimental results of the application of an electric field to the blowoff limits of a premixed methane-air flame. Methane-air flame is presently in worldwide use and is likely to become more important in energy economies based on fossil fuels in the near future. If the imposition of an electric field on a methane-air flame results in an increase in the extinction limits of a burner where extinction would normally occur were no field applied, burners could be operated at substantially leaner conditions—resulting in a potential increase in fuel efficiency.

In the present investigation, all experiments are performed with and without electric fields. The electric field was produced by a high-voltage dc power supply. The results of the investigation indicate that, under suitable electrode configuration, electric fields can be used as a suitable technique in controlling the combustion process.

Apparatus and Procedures

Tests on blowoff limits were carried out on two different geometries. Figure 1 represents the first geometry, consisting of a burner (Veriflow blowpipe, model 3A), a Pyrex glass tube of 11 cm diam, and a copper mesh electrode. The Pyrex tube was placed over the burner port in order to maintain an undisturbed flame. The mesh electrode was put on the top of the glass tube. A longitudinal electric field was obtained by connecting the copper mesh to the positive terminal of the dc power supply and the burner tube to the ground terminal.

Methane (99.7% purity) and air were fed into the burner through flowmeters attached to the gas and air cylinders, the air being of breathing quality.

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The flame was always ignited at low velocities (approximately 33 cm^3/s) with an alcohol burner. The field was then turned on and the methane and air flow rates increased simultaneously up to the total velocity at which the blowoff limits were to be determined. Blowoff points were obtained by maintaining a constant flow of either the methane or air, while varying the other flow until the flame left the burner port.

By decreasing the gas flow rates, the lower blowoff limits were obtained, with and without electric fields. The upper blowoff points could not be obtained by increasing the gas flow rates because the flame picked up more air from the open surroundings at higher rates. As a result, another set of lower blowoff limits were obtained by keeping the gas flow rate constant and increasing the airflow rate.

Figure 2 represents the configuration for the second geometry. A longitudinal electric field was obtained by placing an aluminum foil ring around the glass tube for one electrode and making the brass burner the other electrode. Following the procedures of the first geometry, lower blowoff limits were obtained, with and without electric fields.

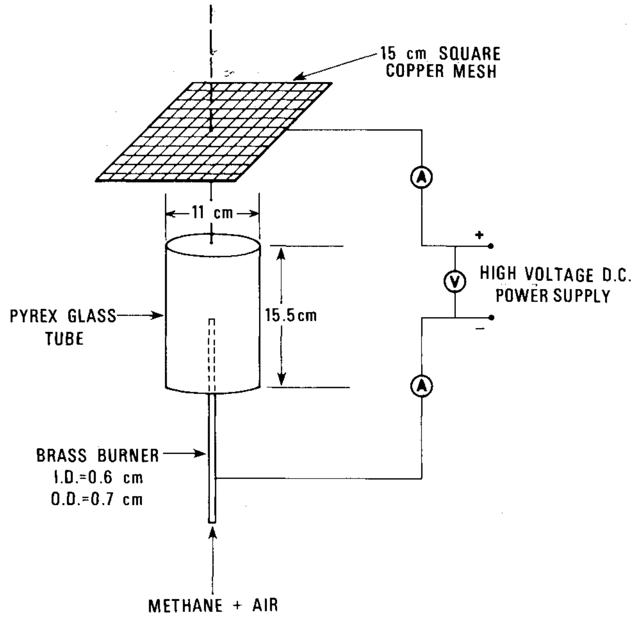

Fig. 1 Burner in longitudinal electric field with gage electrode.

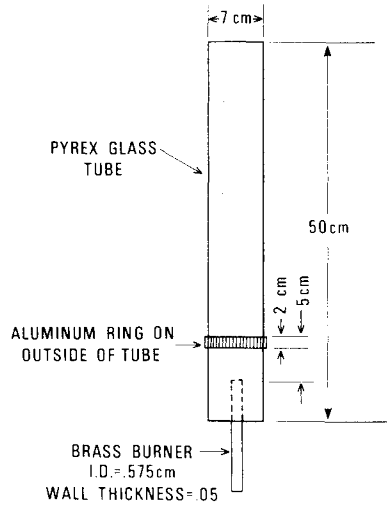

Fig. 2 Burner in longitudinal electric field.

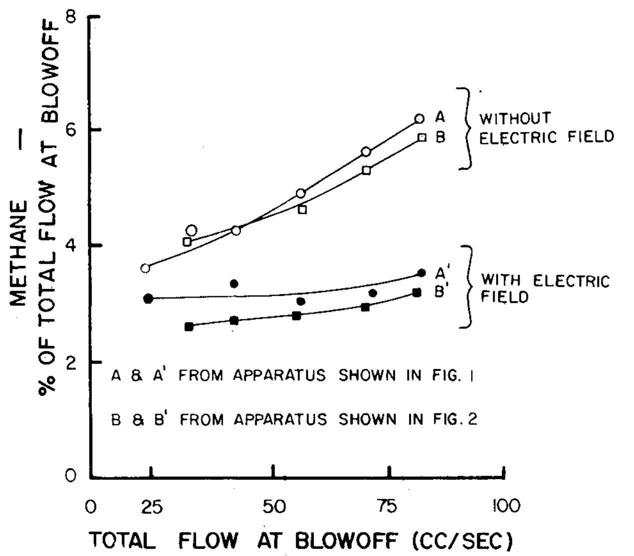

Fig. 3 Lower blowoff limits of methane-air flame, with and without 10 kV electric field.

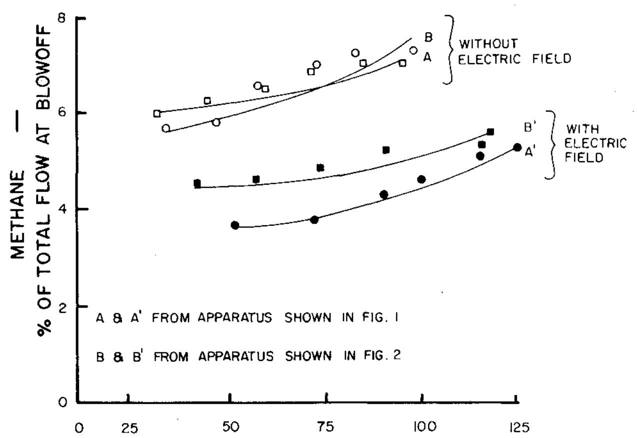

Fig. 4 Lower blowoff limits of methane-air flame, with and without 10 kV electric field.

Results and Discussion

When the ring was positive with respect to the burner, the most striking deviation in the burning characteristics was the change in blowoff limits. For example, at a total flow rate of 75 cm^3/s, the normal lower limit of flame stability was 5.5% methane of the total flow rate, whereas with a field of 10,000 V the limit was lowered to about 3.0% methane. This represents an increase of 83% in the limit over which a stable flame can be maintained under these particular experimental conditions. The limit increases with the increase in flow rate.

Figure 3 shows the methane percentage as a function of the total flow rate at blowoff, without and with an electric field of 10 kV. The flow rate was varied from 25 to 85 cm^3/s. In this figure, curves A and B were obtained from experiments corresponding to Figs. 1 and 2 without electric fields. A′ and B′ represent blowoff points with 10 kV electric fields.

Figure 4 shows another set of blowoff points that were obtained by increasing the airflow rate while keeping the gas flow rate constant. The results of this set of experiments were similar to those of the previous set because, by increasing the airflow rate, the mixture was becoming leaner. The same effect was obtained in the previous experiments by reducing the gas flow rate. However, the results of Figs. 3 and 4 are not identical because, while taking data for Fig. 4, the air flowmeter could not record the additional air that was picked up by the flame from the open atmosphere.

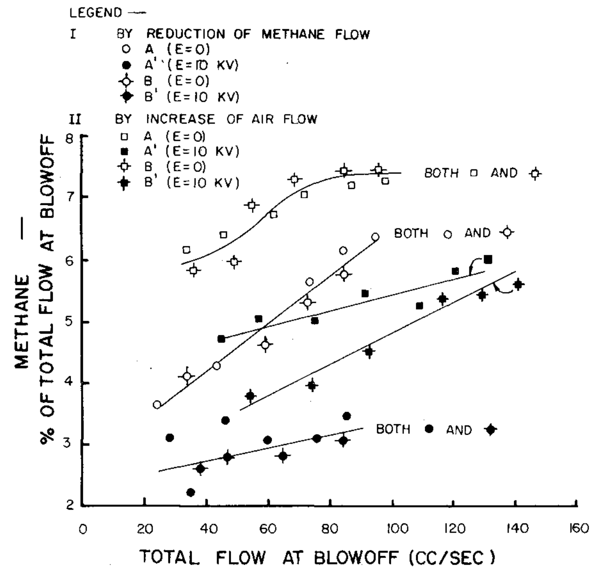

Fig. 5 Lower blowoff limits of methane-air flame, with and without 10 kV electric field.

The experimental data of Figs. 3 and 4 have been used to plot the comprehensive graph of Fig. 5. This graph shows the lower blowoff limits of a methane-air flame, with and without electric fields. It is also clear from this graph that the "leaning out" of an industrial burner should be accomplished by reducing the gas flow rather than by increasing the airflow rate.

The change in flame stability due to electric fields may be accounted for by assuming that the electric field ensures a sufficient supply of energy to the bulk of the cold reactants, either from the discharge directly or from the hot products. The electric field also helps to bring the reactants into direct contact with the discharge.

Experiments were also conducted on a geometry with transverse electric fields. Such fields decreased the stability of the flame. Even with a longitudinal electric field in which the polarity of the field was changed to negative, no positive result was obtained.

Conclusions

In experiments with longitudinal and transverse electric fields on the blowoff limits of a methane-air flame, the following conclusions may be summarized:

1) Longitudinal electric fields have marked effects on the stability of methane gas flames. Under suitable electrode configurations, they can sustain combustion with an electric field at velocities and mixture compositions with which, without the field, there would be no combustion.

2) Transverse electric fields do not contribute to the stability of the gas flames, because the transverse pull of the electric field distorts the flame significantly. Nor do negative electric fields contribute to the stability.

3) The results of the investigation indicate that the lower extinction limits of a burner can be extended several times into regions where extinction would normally occur if there were no electric field. As a result, burners can be operated at substantially leaner conditions, resulting in a potential increase in fuel utilization efficiency.

4) Before applying electric fields to the combustion of methane gas in commercial applications, questions of whether these results can be extrapolated to systems of larger dimensions, higher flow velocities, etc., must be answered.

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An Efficient Method for Dynamic Response Optimization

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Introduction

OPTIMIZATION in mechanical and structural systems under dynamic loads has been of interest since the mid 1960's, not long after optimization under static loads was treated. A review of the literature on the subject is presented in Ref. 1 and several references cited therein. Methods of design sensitivity analysis for dynamic response (point-wise state variable) constraints have been studied recently.[1-5] In one approach, each such constraint is replaced by several constraints imposed at the local maximum point. This type of treatment is called the worst-case design formulation.[2-5] Numerical results show the formulation to be very effective as optimal solutions satisfying precise optimality conditions are obtained. The formulation alleviates difficulties with the equivalent functional constraint formulation of Refs. 5 and 6. Another treatment, called the hybrid formulation, is presented in Refs. 1 and 4. This treatment is to divide the domain of the constraint into several subdomains, each containing one local maximum point. An equivalent functional constraint is then formulated over certain subdomains around the local maximum point. The numerical results show that the hybrid formulation takes more iterations to converge and the optimum cost function is slightly higher as compared with the worst-case design formulation. However, the computer time is substantially reduced.

This Note continues to investigate the treatment of point-wise state variable constraints for the dynamic response optimization problems. A suggested alternate treatment is to impose constraints at the two grid points that bracket a local max-point. The main advantage of this formulation is that the points of local maxima for the constraint function need not be located very accurately. Much computational effort is expended in accurately locating the max-points, as in the worst case design formulation.[2] Therefore, the present formulation could result in an optimization algorithm that would be more efficient and effective than previous algorithms. The purpose of this Note is to study the performance of this procedure.

The general optimization problem for dynamic response considered here is defined in Eqs. (2.1)-(2.6) of Ref. 2. The ith dynamic response constraint is written as $\psi_i(z,b,t) \le 0$, $0 \le t \le T$ [Eq. (2.4) of Ref. 2], where b is a design parameter vector, z a state variable vector, and T the total time of interest. It is proposed to replace each such constraint by several constraints imposed at the time grid points bracketing a local max-point:

$$\psi_i(z,b,t_j) \le 0; \quad j=1, \quad 2m(i) \tag{1}$$

where t_j is a grid point neighboring the local maximum and $m(i)$ is the total number of max-points for ψ_i. Note that the number of constraints is twice the number of max-points. Therefore, the number of constraints to be imposed during the optimization process is twice that of the max-value or hybrid formulations. The proposed treatment contains all of the advantages of previous max-value[2] and hybrid treatments.[4] That is, it does not assume constant Lagrange function over the time domain, does not require precise location of local max-points, and does not require interpolation of certain (adjoint) variables during sensitivity analysis. It is therefore expected to be more efficient and effective than the previous treatments.

To compare the proposed treatment with equivalent functional max-value and hybrid treatments,[5,6] let us consider a constraint function ψ_i plotted in Fig. 1. The constraint is violated over three subdomains. The equivalent functional treatment would add areas I, II, and III to define a constraint. The max-value treatment would locate the max-point for each of the three subdomains and impose the constraint only at those points (i.e., points A, B, and C). A separate functional constraint for each of areas I, II, and III would be imposed in the hybrid treatment. In the proposed treatment, the constraint will be imposed at the time grid points neighboring each local max-point (i.e., points A_1, A_2, B_1, B_2, C_1, and C_2).

Design Sensitivity Analysis and Optimization Algorithm

To implement the proposed treatment in a numerical optimization method, we need to compute the design gradient of a constraint imposed at a particular time t_j. Two methods for calculating these gradients recently have been published[2]: direct differentiation and adjoint variable. Both methods require solution of additional differential equations. The direct differentiation method is such that sensitivity of a constraint function can be obtained at any time. With the adjoint variable method, a differential equation for each constraint in Eq. (1) must be defined and integrated. There are two different adjoint variable procedures. Depending on the numbers of design variables, constraints, and loading conditions, one method will be preferred over the other. The differential equation during sensitivity analysis can be linear with constant coefficients for a large class of nonlinear problems. The advantage of this fact is realized in computations.[1,2]

The computational optimization algorithm to implement the suggested treatment of dynamic constraints is very similar to that presented in Ref. 2. The only difference is in the number of constraints and the grid points at which they are imposed. All the numerical details given there also apply to the present treatment.

Sample Problems

To study the effectiveness of the proposed treatment of constraints, two design problems are optimized: a linear two-degree-of-freedom vibration isolator and a five-degree-of-freedom vehicle suspension system. The results are compared

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