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Abstract

An experimental and analytical study of the combustion of "partially" vaporized fuel/air mixtures was performed to assess the impact of the degree of fuel vaporization upon emissions for a premixing-prevaporizing flametube combustor. Data collected in this study showed near linear increases in NO_x emissions with decreasing vaporization at equivalence ratios of 0.6. For equivalence ratios of 0.72, the degree of vaporization had very little impact on NO_x emissions. A simple mechanism which accounts for the combustion of liquid droplets in partially vaporized mixtures was found to agree with the measured results with fair accuracy with respect to both trends and magnitudes.

Introduction

This paper presents analysis and test results from a study of the effect of the degree of fuel vaporization upon emissions from a flametube combustor burning premixed, "partially" vaporized Jet A fuel.

Increased demands are being placed upon combustion systems as a result of escalating costs for fuel and maintenance as well as regulations governing the permissible levels of exhaust gas pollutants. Several studies[1-4] have explored methods of advancing combustor technology to meet these demands. A combustion technique which has been identified as a potential method of obtaining superior performance, high durability, and low pollutant emissions is premixed-prevaporized combustion at lean equivalence ratios.

Numerous flametube studies[5-10] have demonstrated the low emissions potential of the lean premixed, prevaporized (LPP) approach, particularly, with respect to oxides of nitrogen. In general, these studies have utilized fully premixed, prevaporized mixtures in which the fuel is completely vaporized and well mixed with air prior to combustion. In the application of the LPP concept to aircraft gas turbines, it may not be feasible to obtain this ideal condition because, at some operating points, the fuel-air mixture may become chemically reactive and autoignite prior to achieving complete vaporization.

The objective of the research presented herein, was to study the combustion of "partially" vaporized fuel-air mixtures to assess the impact of the degree of fuel vaporization upon emissions. An analysis of the combustion of partially vaporized mixtures was developed to predict nitrogen oxide emissions. The results of the analysis are compared to the experimental data obtained from tests conducted in a flametube rig using a water cooled perforated plate flameholder. The spatial fuel distribution and degree of fuel vaporization were measured upstream of the flameholder and pollutant emissions measurements were obtained by probing the combustor. Tests were conducted at an inlet air pressure of 0.3 MPa, inlet air temperatures of 600 and 700 K, a reference velocity of 35 meters per second, and equivalence ratios of 0.60 and 0.72 using Jet A fuel. The degree of vaporization was varied from 72 to 100 percent vaporized.

Analysis

The application of lean premixed-prevaporized combustion to aircraft gas turbines may entail the burning, at certain times, of fuel and air mixtures in which the fuel is only partially vaporized. The mechanism, which is herein proposed to account for the effect of partially vaporized mixtures upon emissions of oxides of nitrogen (NO_x), is based upon the observations of several investigators[11-14] of droplets being consumed by diffusion flames in partially vaporized mixtures and the rationale that the combustion of liquid droplets, as well as phase burning, will contribute to the total NO_x emissions.

For mixtures which are comprised of mostly vapor, the impact that droplets have upon the combustion process can be viewed as a perturbation to the main vapor burning mechanism. The total NO_x produced by the liquid droplets burning can then be considered an addition to vapor contribution. Thus, total NO_x emissions for a partially vaporized mixture can be separated as

$$(NO_x)_{total} = E_V \cdot (NO_x)_{vapor\ burning} + (1 - E_V) \cdot (NO_x)_{droplet\ burning}$$

where E_V is the fraction of the fuel in the vapor state and $(1 - E_V)$ the fraction of fuel in the liquid droplet state.

Emissions of oxides of nitrogen (NO_x) have been found to be strongly influenced by both the equivalence ratio and the combustor entrance conditions. The adiabatic flame temperature, which is itself a function of these quantities, has been found to be a useful correlation parameter for NO_x.[8,15]

For partially vaporized mixtures, the vapor phase adiabatic flame temperature, T_V, is a function of the vapor phase equivalence ratio, φ_V, which is a function of the fuel vapor fraction, E_V, and the overall equivalence ratio, φ.

$$\varphi_V = E_V \cdot \varphi$$

From a knowledge of these quantities, it is possible to determine the vapor phase adiabatic flame temperature, T_V, and the corresponding NO_x emissions by using an analytic model[16,17] for combustion in a stirred reactor or published experimental data.[6,8,15]

Droplet combustion has been found to be a diffusion flame mechanism with stoichiometric conditions and correspondingly high temperatures which produce large quantities of NO_x. Thus, it may be assumed that NO_x produced by droplet combustion can be estimated from the adiabatic flame temperature, T_1, which corresponds to stoichiometric conditions at the combustor inlet conditions.

Based upon this analysis, the effect of fuel vapor fraction, E_v, on the total NO_x emissions over a range of inlet temperatures and overall equivalence ratios has been calculated. The results are shown in Fig. 1 and tabulated in Table I.

Figure 1(a) shows the effect of fuel vapor fraction upon the total NO_x emissions for fixed residence time, inlet pressure, and overall equivalence ratio over a range of inlet temperatures. The total NO_x emissions decrease with decreasing inlet temperature. This would be expected since NO_x correlates with adiabatic flame temperature which itself decreases with decreasing inlet temperature.

Figure 1(b) shows the effect of fuel vapor fraction upon the total NO_x emissions for fixed residence time, inlet pressure, and temperature over a range of overall equivalence ratios. The total NO_x emissions decrease with decreasing overall equivalence ratio, a result expected since the adiabatic flame temperature decreases with decreasing overall equivalence ratio.

In Fig. 1(b), note that a minimum exists in the total NO_x emissions for overall equivalence ratios of 0.7 and 0.9. The reason for this minimum is the tradeoff which exists between reductions in the vapor phase equivalence ratio to reduce the vapor phase NO_x contribution and a corresponding increase in the liquid fraction which increases the NO_x contribution for liquid droplet burning. The NO_x emissions initially decrease with decreasing fuel vapor fraction, E_v. The reduction in the vapor phase equivalence ratio dominates since the liquid droplet fraction contribution is initially small. A balance point between the vapor phase and droplet contributions is reached at a minimum NO_x emission. The liquid droplet fraction contribution then dominates with the NO_x increasing with decreasing vapor fraction (increasing liquid droplet fraction).

Based upon the results tabulated in Table I, the following behavior may be noted in terms of the vapor phase adiabatic flame temperature, T_v. For a given inlet temperature and overall equivalence ratio -

1. When the vapor phase adiabatic flame temperature, T_v, falls below 2050 K, decreases in the fuel vapor fraction will result in an increase in the total NO_x emissions. (Liquid droplet fraction contribution dominates).

2. If the vapor phase adiabatic flame temperature, T_v, is between 2050 and 2200 K, decreases in the fuel vapor fraction will have little effect on total NO_x. (Liquid droplet fraction and vapor phase contributions balanced).

3. If the vapor phase adiabatic flame temperature, T_v, is above 2200 K, decreases in the fuel vapor fraction will result in a decrease in NO_x emissions. (Vapor phase contribution dominates).

The minimum NO_x emissions occur at the fuel vapor fraction which corresponds to a vapor phase adiabatic flame temperature of approximately 2100 K. Mixtures for which the vapor phase adiabatic flame temperature is always below 2100 K have their minimum at complete fuel vaporization.

For given inlet conditions and combustor geometry, the lean stability limit is the lowest overall equivalence ratio which will support combustion. As shown in Table I and marked on Fig. 1, the lean stability limit has been assumed to be the point when the vapor phase adiabatic flame temperature falls below 1700 K. This value is based upon the results[9] of flametube studies of prevaporized fuels. Lean stability limits for partially vaporized mixtures tend to be lower than those of fully vaporized mixtures and depend upon droplet size number and distribution.[11-14] These factors are dependent upon the particular combustion system being studied. For the purposes of this paper, it is assumed that the lean stability limit is conservatively determined to be the point when the vapor phase adiabatic flame temperature falls below 1700 K.

Apparatus and Procedure

The tests reported herein were conducted in a closed duct test facility as shown in Fig. 2. Incoming air to the test section was preheated to temperatures from 600 to 700 K by a nonvitiating preheater. Jet A fuel was injected into the airstream through two different fuel injectors which were mounted in series 18 to 44 cm upstream of a water-cooled perforated plate flameholder. The mixture burned in a water-cooled combustor section. Samples of the fuel-air mixture upstream of the flameholder were obtained for analysis to determine the degree of fuel vaporization and fuel-air ratio. Samples of combustion products were analyzed to determine gaseous emissions.

Fuel Injectors

Two different fuel injectors were utilized in this study. The injector shown in Fig. 3 is denoted as the multiple conical tube injector. Seventeen conical tubes form a tube bundle through which the air flows. Each conical tube had an upstream diameter of 1.3 cm and a half angle of 7°. The length of the tubes was 10.2 cm. Fuel was injected at the upstream end of each conical tube through a 0.5 mm i.d. open ended tube. Each fuel tube had a length of 25.4 cm. This injector was located 44 cm upstream of the flameholder for all tests and was designed to produce complete fuel vaporization at the flameholder plane.

The injector shown in Fig. 4 is the multiple jet injector. Fuel was injected cross stream through 48 orifices which were 0.05 cm diameter. The orifices were located so that each of the orifices injected fuel into a space of approximately equal area. This injector was located 18 cm upstream of the perforated plate flameholder. This injector was designed to produce incomplete fuel vaporization at the flameholder plane.

Flameholder

The water-cooled flameholder was made by welding 61 tubes of 0.6 cm i.d. between two 0.6 cm thick stainless steel plates, as shown in Fig. 5. This arrangement resulted in an open area of 25 percent of the inlet duct cross-sectional area. Several thermocouples were mounted on the upstream surface of the flameholder to detect burning upstream of flameholder. An automatic fuel shut off control was connected to these thermocouples to minimize hardware damage in the event of autoignition or flashback.

Combustor

The water-cooled combustor was 10.2 cm in diameter, the same as the inlet duct, and 80 cm in length (see Fig. 2). At the downstream end, quench water was sprayed into the gas stream to cool the exhaust to about 370 K. This mixture of combustion products and water passed through a remotely operated back-pressure valve for control of rig pressure.

Gas Sampling

Gas sampling of the combustion gases was accomplished by two sets of multipoint gas sampling probes. Each set consisted of four water-cooled probes spaced 90° apart around the combustor. The two sets were located 48 and 79 cm downstream from the flameholder plane. The downstream set was rotated 45° with respect to the upstream set, in order to minimize wake interference effects. Each probe was 1.27 cm in diameter and had three ports of 0.165 cm diameter located at centers of equal area in the circular combustor section. Stainless steel tubing (0.95 cm diameter) connected the gas sample probes to the gas analysis instrumentation. The gas sample line was heated with superheated steam to prevent condensation of unburned hydrocarbons. The sample line was approximately 18 meters long.

Gas analysis equipment included a flame ionization detector for measuring unburned hydrocarbons, nondispersive infrared analyzer for measuring concentrations of carbon monoxide and carbon dioxide, and a chemiluminescence instrument for total NO_x concentration. Calibration of the instruments with standard calibration gases was performed at the beginning of each day's testing and whenever a range change was made.

A local fuel-air ratio and degree of vaporization were determined from gas samples obtained from a traversing, single port sample probe located immediately upstream of the flameholder. The fuel and air mixture was passed over a catalyst heated in an oven to 1030 K and the reaction products were analyzed for carbon dioxide, carbon monoxide, and unburned hydrocarbons. The amounts of carbon monoxide and unburned hydrocarbons measured were negligible (<100 ppm) because the mixture ratios were lean and nearly complete reaction occurred in the catalyst bed.

Measurement and Computation

Tests were conducted at inlet air temperatures of 600 and 700 K, a pressure of 0.3 MPa, a reference velocity of 35 meters per second, and equivalence ratios of 0.60 and 0.72 using Jet A fuel. Reference conditions were based upon the total airflow, the inlet air density using total temperature and pressure at the inlet plenum, and the reference area (82.13 cm^2) which is the cross-sectional flow area in the combustor.

The combustor residence time was computed by dividing the distance of the emission probes from the flameholder by the plug flow velocity of the combustion gases.

Emissions were measured as concentrations in ppm by volume and converted to emission indices (EI) using the expressions suggested in Ref. 18.

Sample validity was checked by comparing the fuel-air ratio based on metered fuel and airflow rates to the fuel-air ratio based on a carbon balance from the measured concentrations of CO, CO_2, and unburned hydrocarbons. Only those points whose metered and calculated ratios varied by less than 15 percent are included in this paper.

The degree of vaporization was determined with the spillover technique as described in Ref. 19. This method consists of varying the sample flow through a single port probe, above and below the isokinetic value. Then from the variation in the carbon balance fuel-air ratio of different flows through the probe, the degree of vaporization can be determined. The reported vaporization data was taken in the center of the duct. Spot checks of the degree of vaporization at other locations showed less than 3 percent variation across the duct.

Two different fuel injectors were used in this study as a convenient method to alter the degree of vaporization. The multiple conical tube injector was located 44 cm upstream of the flameholder for all tests. When fuel was injected at this location, complete vaporization was obtained. The multiple jet injector was mounted 18 cm upstream of the flameholder. When fuel was injected through it, only partial vaporization of the fuel was obtained. The degree of vaporization could thus be easily altered by varying the fuel flow split between the two injectors. It varied from complete vaporization when all the fuel was passed through the multiple conical tube injector to a minimum level of vaporization when all the fuel was passed through the multiple jet cross stream injector.

Results and Observations

An experimental study of the combustion of "partially" vaporized fuel-air mixtures was performed to assess the impact of the degree of fuel vaporization upon emissions and to provide data for comparison to NO_x emissions predicted by the application of the mechanism presented in the Analysis section. As described in the section Measurements and Computation, the degree of fuel vaporization was altered by varying the fuel flow split between two different fuel injectors mounted in series and manifolded together. Data for spatial fuel distributions and degree of vaporization at the flameholder are presented. Emission indices for NO_x are shown for measurements 79 cm from the flameholder. Carbon monoxide emission indices for measurements at 48 and 79 cm from the flameholder are also given.

Baseline Test Results

Spatial fuel distribution. - Fuel-air ratio distributions are shown in Fig. 6 for baseline configurations, those for which all the fuel was passed through a single fuel injector. With an injector to flameholder distance of 18 cm, the multiple jet injector produced fuel-air ratio distributions which were within ±15 percent of the mean values. The distributions for the multiple conical tube injector were measured to be within ±5 percent of the mean values.

Vaporization. - Degree of vaporization data at the flameholder for the baseline configurations is presented in Table II. Injection of the fuel through the multiple jet injector resulted in various amounts of fuel vaporization. Increasing the inlet temperature produced increases in the degree of vaporization.

Fuel injection through the multiple conical tube injector was found to produce complete fuel vaporization for all test conditions.

NO_x emissions. - Parametric tests of the multiple conical tube injector were performed to obtain data comparable to other experiments of premixed-prevaporized combustion. In Fig. 7, NO_x emissions for this injector are presented. The emission index is seen to be an exponential function of equivalence ratio and to also vary with combustor inlet temperatures, results found by numerous previous investigators. These baseline data are replotted versus the adiabatic flame temperature in Fig. 8. Comparison of the results of this study with those of Ref. 20 and analytic predictions based upon the model of Ref. 16 shows good agreement.

NO_x emissions data for the multiple jet injector and the multiple conical tube injector are summarized in Table III. These data are for the probes located 79 cm downstream of the flameholder. NO_x data for the 48 cm location is not presented because the results are similar to those of the 79 cm location. Due to the residence time differences in the probe locations, the NO_x emissions were somewhat lower at the 48 cm location.

Parametric Test Results

Parametric tests on the effect of fuel vaporization upon NO_x emissions were conducted by simultaneously flowing fuel through the multiple conical tube and multiple jet injectors. Since these injectors produced different baseline levels of vaporization, the degree of vaporization was easily manipulated by varying the fuel flow split between the two injectors. The emissions corresponding to the particular level of vaporization were then obtained.

Spatial fuel distribution. - Fuel-air ratio distributions were measured at several conditions for which the fuel was injected through both injectors. These distributions showed the same general patterns established by the baseline configuration tests and fell within the established bounds.

Vaporization and emissions. - Results of the effects of vaporization on NO_x emissions are presented in Fig. 9. The data displays an effect of vaporization on NO_x which differs with the equivalence ratio. For an equivalence ratio of 0.60, decreasing the degree of fuel vaporization leads to a nearly linear increase in NO_x. However, for equivalence ratios of 0.72, changes in vaporization had very little impact on the NO_x emissions. Both slight increases and decreases were found.

Results on the effect of vaporization on CO emissions are shown in Fig. 10(a) for the 48 cm probe location. The data displays uniform declines in CO level with increasing degrees of vaporization. This indicates that the combustion of the fuel droplets lags that of the fuel vapor. Therefore, the primary zone residence time needs to be longer for partially vaporized mixtures in order to obtain levels of CO emissions equivalent to those of fully prevaporized mixtures.

Data for the 79 cm probe position is shown in Fig. 10(b) and shows the combustion of CO to be essentially complete and the degree of vaporization having little effect on the final levels of CO obtained.

Discussion

The NO_x data collected in this experimental study show that NO_x increases linearly with decreasing degree of vaporization for an overall equivalence ratio of 0.60, and that, for an overall equivalence ratio of 0.72, the NO_x emissions are only slightly affected by changes in the degree of vaporization. These trends are in agreement (see Fig. 1) with the results predicted by the mechanism proposed in the Analysis section. Recall that the proposed mechanism consists of both a vapor phase contribution to the NO_x as well as a contribution due to the stoichiometric combustion of liquid droplets.

In order to determine if the experimental data supports the proposed mechanism for NO_x emissions, the fuel vapor fraction, E_v, must first be determined from the degree of vaporization, E. These quantities are not identical since the degree of vaporization was measured upstream of the flameholder and as such is not an accurate measure of the relative liquid droplet-vapor phase fuel distribution which ultimately undergoes combustion. A sizeable fraction of the droplets would be expected to impact upon the flameholder. A liquid sheet would be formed which would undergo both vaporization and be drawn to the holes in the flameholder by differences in the local static pressure. This liquid sheet would then be carried through the flameholder and reatomized into the combustion zone by the high velocity air streams. The calculated droplet size range for the reatomized liquid is 10 to 15 microns Sauter Mean Diameter. Investigators[12,22] have found that droplets in this size range burn as would a completely vaporized mixture, a "pseudo vapor." Thus droplets which impact the perforated plate flameholder ultimately burn and produce NO_x as would a vaporized mixture.

This observation on the NO_x contribution from small droplets was confirmed by placing the multiple conical tube injector 18 cm upstream of the flameholder. It was observed that only 85 percent vaporization was achieved. However, the NO_x emissions were nearly equivalent to those of completely vaporized mixtures. The calculated initial dropsize for this injector was 15 microns Sauter Mean Diameter, and as in the case of the reatomized liquid, falls within the size range where droplets burn as would vapor.

The above statements and observations indicate that only droplets not impacting the flameholder could contribute to NO_x by a diffusion flame mechanism. Investigators[12,22] have found that fuel droplets greater than 50 microns are consumed by the diffusion flame mechanism. Based upon calculations of the initial dropsize distribution for the multiple jet injector and analysis of droplet heat up and vaporization times, it is estimated that greater than 95 percent of the fuel droplets at the flameholder plane are larger than the 50 micron diameter. Thus for purposes of computing the fractions of fuel in vapor and liquid phase, it will be assumed that all droplets not impacting the flameholder are consumed by a diffusion flame mechanism and that the remaining fuel may be treated as "pseudo vapor." The liquid fraction, E_d, is then

$$E_d = (1 - B) \cdot (1 - E)$$

where B is the flameholder blockage, (1 - B), the flameholder fractional open area, E, the measured degree of vaporization, and (1 - E), the computed fraction of fuel in liquid droplet phase. The fuel vapor fraction, E_v, would then be $(1 - E_d)$.

For the experimental conditions studied in this program Table IV presents the computed fuel vapor fraction and NO_x emission indices for various degrees of vaporization. As discussed in the Analysis section, the total NO_x emissions are computed from

$$(NO_x)_{total} = E_v \cdot (NO_x)_{\varphi_v} + (1 - E_v) \cdot (NO_x)_{\varphi=1}$$

where $(NO_x)_{\varphi=1}$ is the value for stoichiometric burning and $(NO_x)_{\varphi_v}$ is the value for burning at a "pseudo vapor" fraction equivalence ratio φv. The values of NO_x which correspond to a pseudo vapor phase equivalence ratio, φ_v, were determined from the experimental data shown in Fig. 7. The NO_x emission index for burning at stoichiometric conditions were determined from stirred reactor predictions.[16] Values of 30 and 45 were used for inlet temperatures of 600 and 700 K, respectively. The total NO_x values are shown in Fig. 11 with the data collected in this study. Note again that the degree of vaporization, E, was measured upstream of the flameholder.

The NO_x emission indices predicted by the proposed mechanism are in fair agreement with the measured values. Application of the mechanism accurately predicts the effect of decreasing vaporization on NO_x, that is, a linear increase in NO_x for equivalence ratios of 0.60 and very little change for equivalence ratios of 0.72.

Concluding Remarks

An experimental and analytical study of the combustion of "partially" vaporized fuel-air mixtures was performed to assess the impact of the degree of fuel vaporization upon emissions for a premixing-prevaporizing flametube combustor. Tests were conducted at an inlet air pressure of 0.3 MPa, inlet air temperatures of 600 and 700 K, a reference velocity of 35 meters per second and equivalence ratios of 0.60 and 0.72 using Jet A fuel. The degree of vaporization was varied from 72 to 100 percent vaporized.

The data collected in this study displays an effect of vaporization upon NO_x emissions which differs with equivalence ratio. For an equivalence ratio of 0.60, decreasing the degree of vaporization increases the NO_x emission index. (From 1.5 at 100 percent vaporization to 2.8 at 72 percent vaporized and from 2.3 at 100 percent vaporization to 4.3 at 75 percent vaporized for inlet temperatures of 600 and 700 K, respectively.) The increases were nearly linear functions of the degree of vaporization. For equivalence ratios of 0.72, the degree of vaporization had very little impact on the NO_x emissions. (From 4.5 at 100 percent vaporized to 4.1 at 72 percent vaporized and from 8.3 at 100 percent vaporized to 8.3 at 75 percent vaporized for inlet temperatures of 600 and 700 K, respectively.)

A simple mechanism which accounts for the combustion of liquid droplets in the partially vaporized mixtures was found to predict the measured NO_x levels with fair accuracy. Both the trends and magnitudes at various degrees of vaporization, equivalence ratio and temperature are found to agree with measurements.

The effect of the degree of vaporization upon CO emissions varied with combustion residence time. Uniform decreases in the CO level with increasing vaporization were found for residence times of 3 to 4 milliseconds. Measurements at longer residence times showed the combustion of CO to be essentially complete and the degree of vaporization having little effect on the CO emissions.

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TABLE I. - EFFECT OF FUEL VAPOR FRACTION UPON NITROGEN OXIDES EMISSION INDEX OVER A RANGE OF INLET TEMPERATURES AND EQUIVALENCE RATIOS

[Inlet pressure, 10 atm; residence time, 2 msec.]

Overall equivalence ratio, φ	Fuel vapor fraction, E_v	Vapor phase equivalence ratio, φ_v	Inlet temperature, K					
			600		800		1000	
			Vapor phase flame temperature, T_v, K	NO_x emission index, gNO_2/kg fuel	Vapor phase flame temperature, T_v, K	NO_x emission index, gNO_2/kg fuel	Vapor phase flame temperature, T_v, K	NO_x emission index, gNO_2/kg fuel
0.5	0.70	0.35	-----	---	[a]1630	-----	----	----
	.80	.40	-----	---	1700	7.40	----	----
	.90	.45	-----	---	1785	4.25	----	----
	1.00	.50	-----	---	1910	1.40	----	----
0.6	0.60	0.36	[a]1420	---	[a]1620	-----	1750	20.0
	.70	.42	[a]1590	---	1750	11.0	1895	16.0
	.80	.48	1700	4.4	1870	8.0	2005	12.0
	.90	.54	1810	2.9	1980	5.3	2115	9.0
	1.00	.60	1920	1.6	2090	4.25	2225	10.0
0.7	0.60	0.42	-----	---	1750	14.4	----	----
	.70	.49	-----	---	1865	11.4	----	----
	.80	.56	-----	---	2010	9.1	----	----
	.90	.63	-----	---	2115	8.0	----	----
	1.00	.70	-----	---	2285	11.0	----	----
0.9	0.50	0.45	-----	---	1810	19.0	----	----
	.60	.54	-----	---	1965	15.2	----	----
	.70	.63	-----	---	2130	14.4	----	----
	1.80	.72	-----	---	2255	15.8	----	----
	1.90	.81	-----	---	2370	21.5	----	----
	1.00	.90	-----	---	2480	30.0	----	----

[a] Below lean blowout limit of 1700 K.[9]

TABLE II. - DEGREE OF VAPORIZATION AT FLAMEHOLDER OVER A RANGE OF EQUIVALENCE RATIOS AND INLET TEMPERATURES

[Reference velocity, 35 m/sec; inlet pressure, 0.3 MPa.]

Equivalence ratio, φ	Injector type	Injector to flameholder spacing, cm	Inlet temperature, K	
			600	700
			Degree of vaporization at flameholder ×100%, percent	
0.60	Multiple conical tube	44	100	100
0.60	Multiple jet	18	72	75
0.72	Multiple conical tube	44	100	100
0.72	Multiple jet	18	72	75

TABLE III. - NITROGEN OXIDES EMISSION INDEX OVER A RANGE OF EQUIVALENCE RATIOS, INLET TEMPERATURES, AND DEGREE OF VAPORIZATION

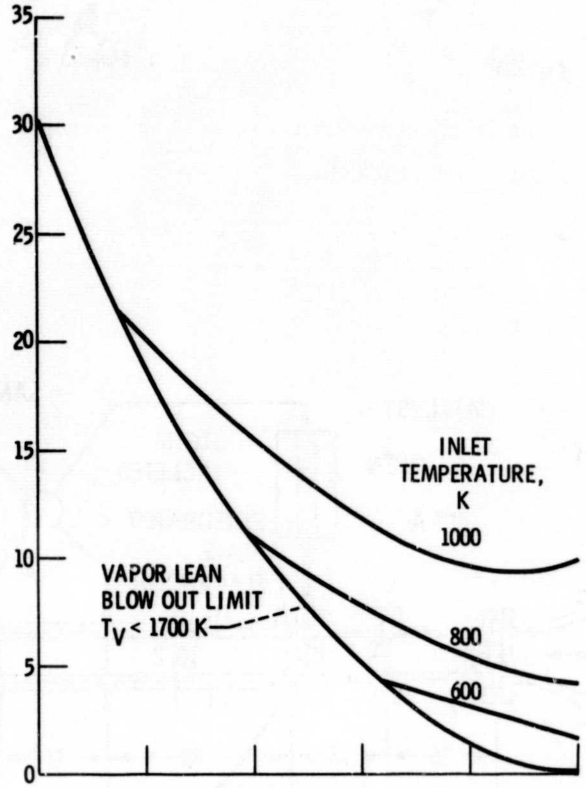
[Sample probe position, 79 cm; reference velocity, 35 m/sec; inlet pressure, 0.3 MPa.]

Equivalence ratio, φ	Injector type	Injector to flameholder spacing, cm	Inlet temperature, K	
			600	700
			Average NO_x emission index, gNO_2/kg fuel, at percent vaporization	
0.60	Multiple conical tube	44	1.5 at 100%	2.3 at 100%
0.60	Multiple jet	18	2.8 at 72%	4.3 at 75%
0.72	Multiple conical tube	44	4.5 at 100%	8.3 at 100%
0.72	Multiple jet	18	4.1 at 72%	8.3 at 75%

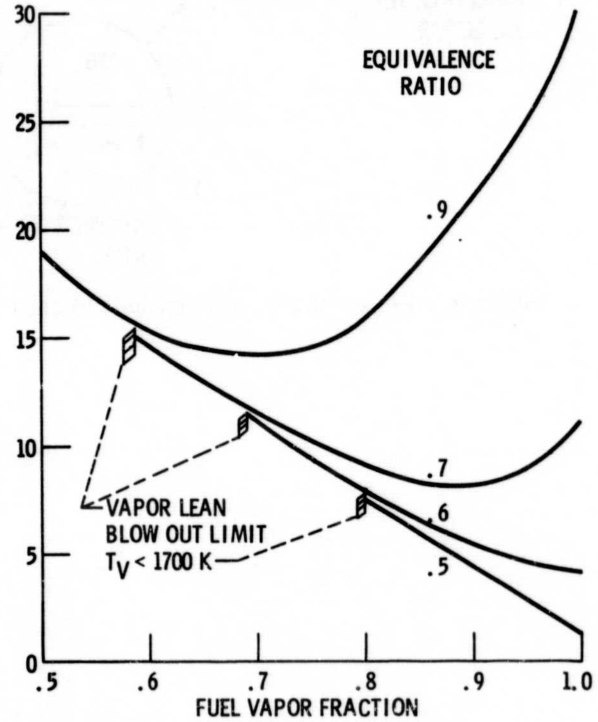
TABLE IV. - PREDICTED NITROGEN OXIDES EMISSION INDEX FOR PARTIALLY VAPORIZED MIXTURES OVER A RANGE OF EQUIVALENCE RATIOS, INLET TEMPERATURES, AND DEGREE OF VAPORIZATION

[Flameholder blockage, 75%; residence time, 6 msec.]

Degree of vaporization, E	Fuel vapor fraction, E_v	Overall φ					
		0.60	0.72	0.60	0.72	0.60	0.72
		Pseudo vapor fraction equivalence ratio, φ_v		Inlet temperature, K			
				600		700	
				Total NO_x emission index, gNO_2/kg fuel			
0.70	0.9250	0.555	0.666	3.22	4.84	4.61	7.71
.75	.9375	.563	.675	2.88	4.73	4.27	7.69
.80	.9500	.570	.684	2.64	4.65	3.91	7.67
.85	.9625	.577	.693	2.35	4.56	3.47	7.75
.90	.9750	.585	.702	2.09	4.50	3.08	7.84
.95	.9875	.593	.711	1.81	4.45	2.68	8.00
1.00	1.0000	.600	.720	1.55	4.50	2.3	8.25



(a) CONSTANT EQUIVALENCE RATIO, $\varphi = 0.6$.



(b) CONSTANT INLET TEMPERATURE, 800 K.

Figure 1. - Effect of fuel vapor fraction upon nitrogen oxide emission index over a range of inlet temperatures and equivalence ratios. Inlet pressure 1 MPa residence time, 2 milliseconds.

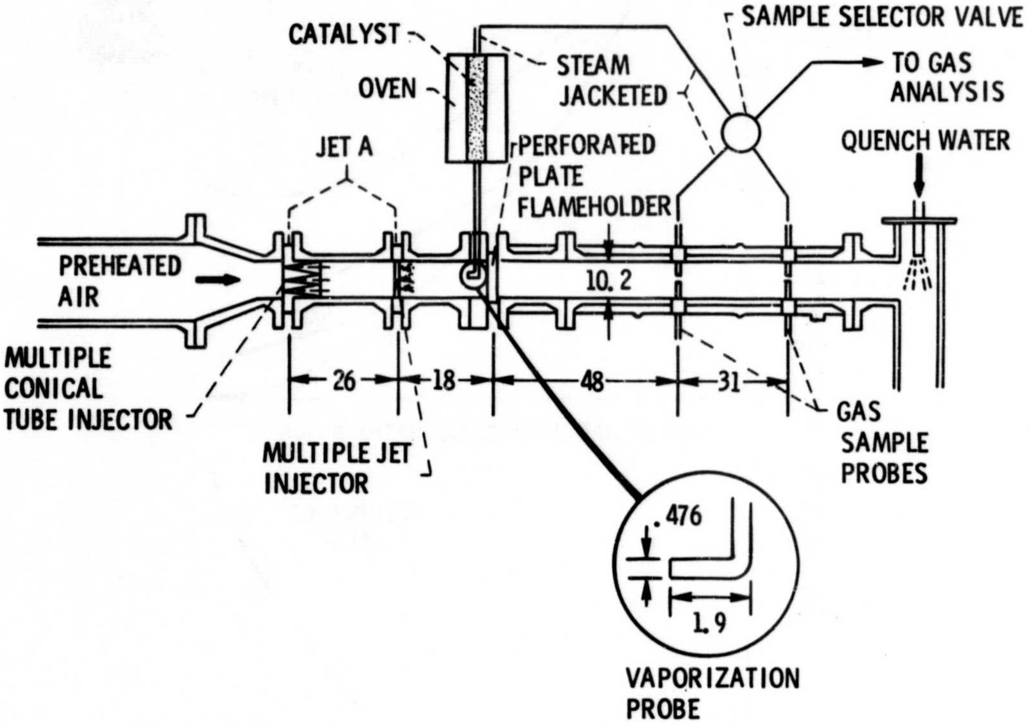
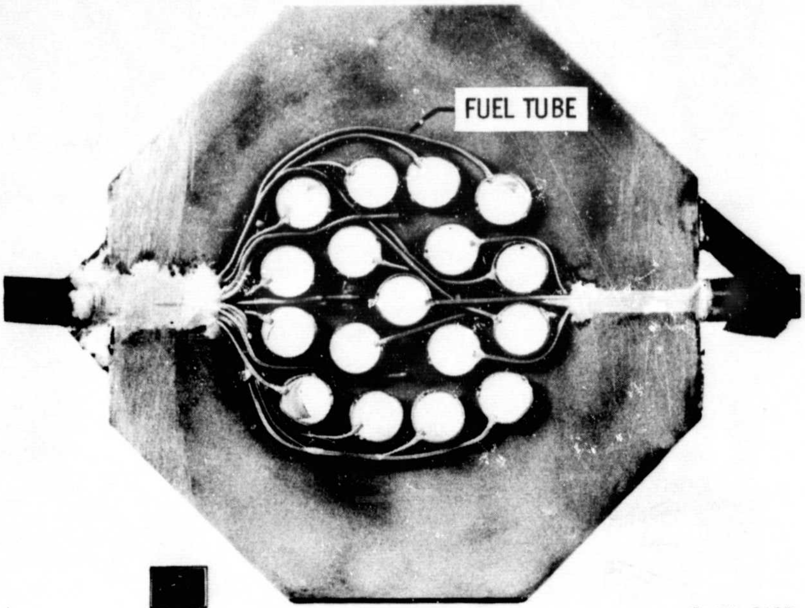


Figure 2. - Rig schematic. (Dimensions in cm.)



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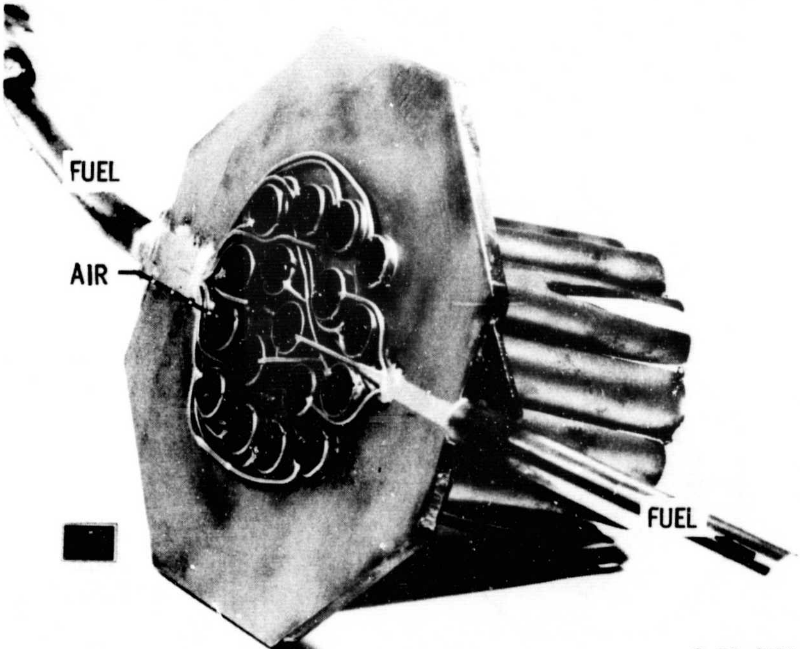

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Figure 3.- Multiple conical tube injector.

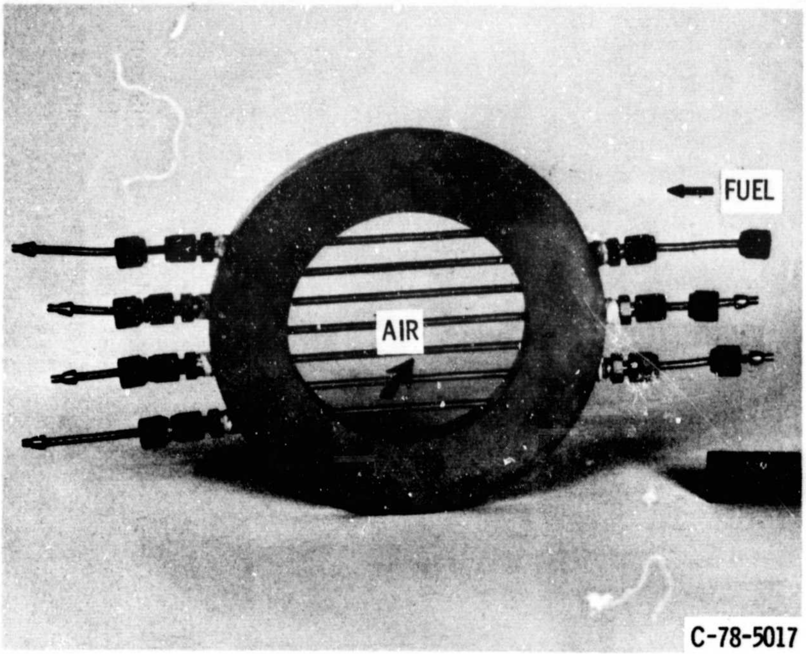


Figure 4.- Multiple jet injector.

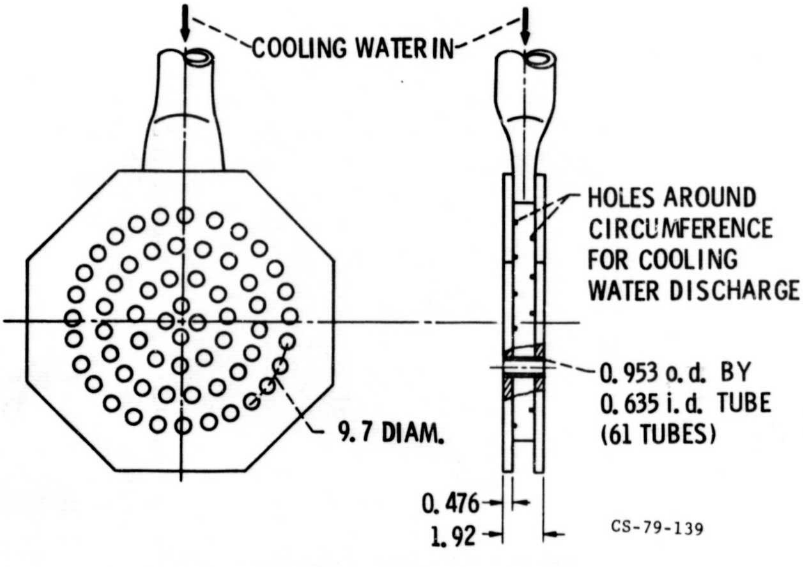
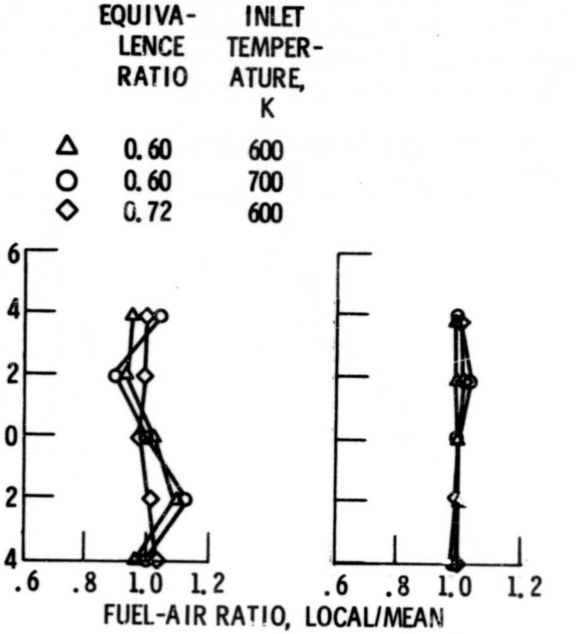


Figure 5. - Flameholder (dimensions in cm) blockage of 75 percent.



(a) MULTIPLE JET INJECTOR - INJECTOR TO FLAMEHOLDER SPACING-18 cm.

(b) MULTIPLE CONICAL TUBE INJECTOR - INJECTOR TO FLAMEHOLDER SPACING-44 cm.

Figure 6. - Spatial fuel distribution at flameholder over a range of equivalence ratios and inlet temperatures. Reference velocity, 35 meters per second. Inlet pressure, 0.3 MPa.

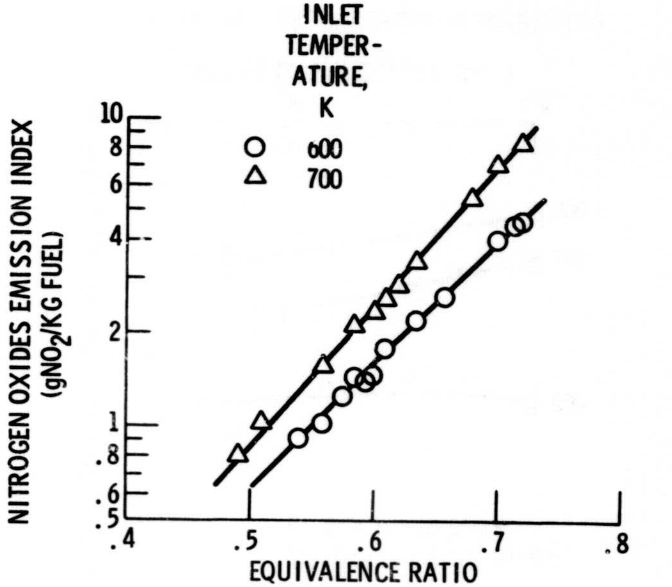


Figure 7. - Effect of equivalence ratio on nitrogen oxides emission index. Multiple conical tube injector; degree of vaporization, 1.0. Combustor residence time, 6 to 8 milliseconds. Reference velocity, 35 meters per second. Inlet pressure, 0.3 MPa.

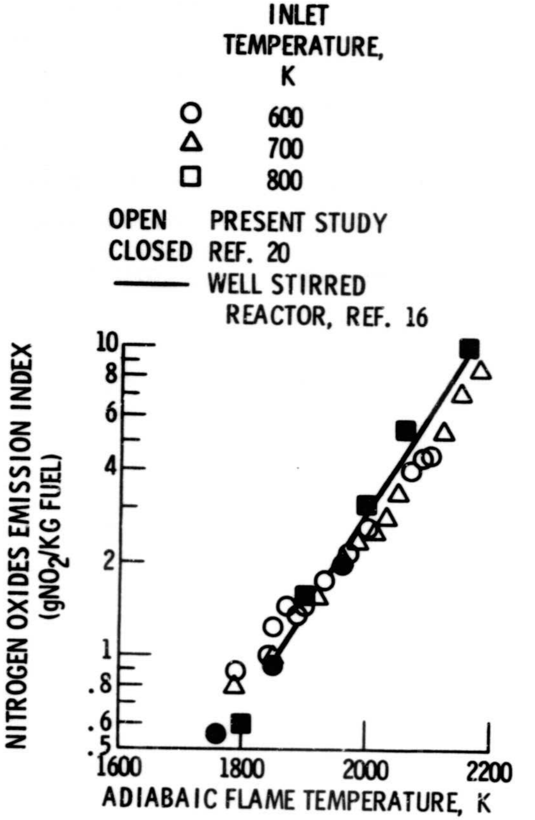


Figure 8. - Comparison of analytic and experimental results of nitrogen oxides emission index over a range of inlet temperatures. Reference velocity, 35 meters per second. Inlet pressure, 0.3 MPa.

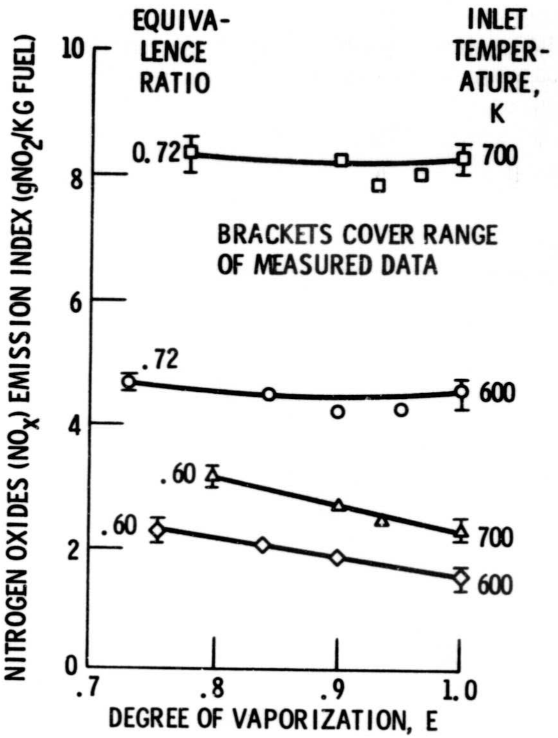
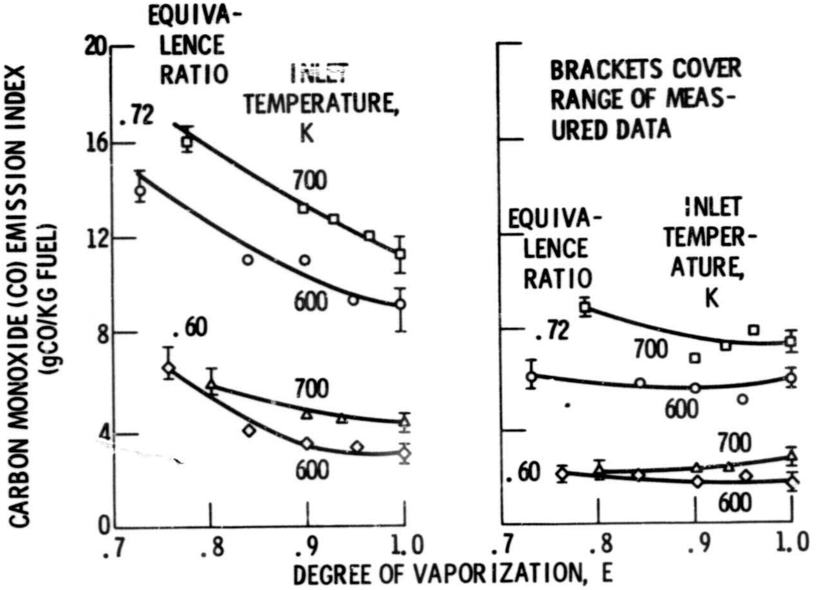


Figure 9. - Effect of degree of vaporization on nitrogen oxide emission index over a range of equivalence ratios and inlet temperatures.



(a) PROBE POSITION, 48 cm.

(b) PROBE POSITION, 79 cm.

Figure 10. - Effect of degree of vaporization on carbon monoxide emission index over a range of equivalence ratios and inlet temperatures at two sample probe locations. Reference velocity, 35 meters per second. Inlet pressure, 0.3 MPa.

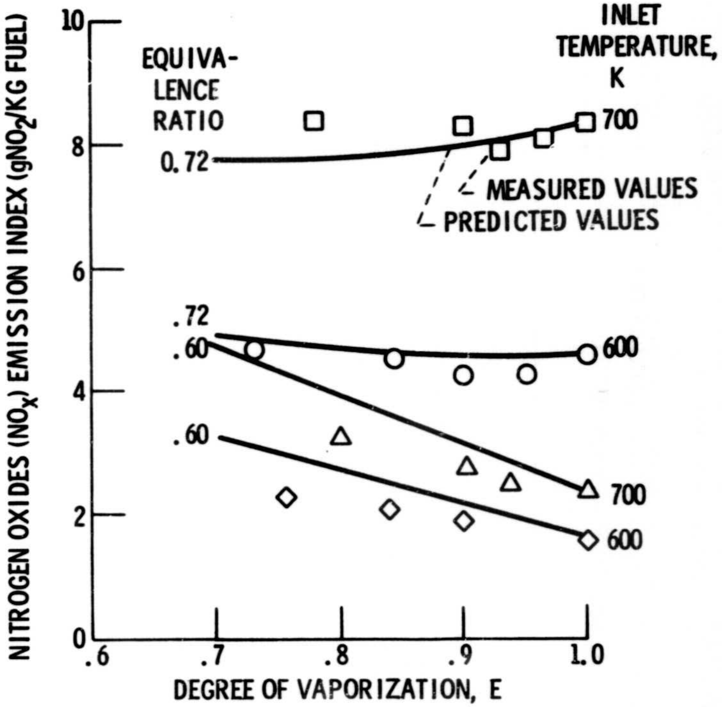


Figure 11. - Comparison of predicted and measured nitrogen oxides emissions index over a range of equivalence ratios, inlet temperatures, and degree of vaporization. Reference velocity, 35 meters per second. Inlet pressure, 0.3 MPa.

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16. Abstract

An experimental and analytical study of the combustion of "partially" vaporized fuel/air mixtures was performed to assess the impact of the degree of fuel vaporization upon emissions for a premixing-prevaporizing flametube combustor. Data collected in this study showed near linear increases in NO_x emissions with decreasing vaporization at equivalence ratios of 0.6. For equivalence ratios of 0.72, the degree of vaporization had very little impact on NO_x emissions. A simple mechanism which accounts for the combustion of liquid droplets in partially vaporized mixtures was found to agree with the measured results with fair accuracy with respect to both trends and magnitudes.

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