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Daniel L. Bulzan
National Aeronautics and Space Administration
Lewis Research Center

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CORRELATIONS OF CATALYTIC COMBUSTOR PERFORMANCE PARAMETERS

by Daniel L. Bulzan

National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

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SUMMARY

Data from a 12-cm-diameter catalytic combustor test rig using propane fuel at an inlet temperature of 800 K, a pressure of 3×10^5 Pa, and reference velocities from 10 to 20 m/s was analyzed. Correlations were obtained for combustion efficiency, percentage pressure drop, and the minimum required adiabatic reaction temperature to meet emissions goals.

Combustion efficiency at the test conditions was found to be a function of the catalyst bed cell density, cell circumference, reactor length, and the reference velocity. Combustion efficiency was also dependent upon the adiabatic reaction temperature to the tenth power.

The percentage pressure drop was found to be proportional to the reference velocity to the 1.5 power. The percentage pressure drop was also proportional to the reactor length, and inversely proportional to the cell hydraulic diameter, fractional open area, and the pressure.

The minimum adiabatic reaction temperature required to meet the emissions goals of 13.6 g CO/kg fuel and 1.64 g HC/kg fuel was found to be proportional to the reference velocity to the 0.1 power and inversely proportional to the cell circumference, cell density, and reactor length to the 0.1 power.

A catalyst factor was included in the correlations to account for differences between catalysts. Combustion efficiency, the percentage pressure drop, and the minimum required adiabatic reaction temperature were found to be a function of the catalyst factor. The catalyst factor ranged from 0.12 to 1.52. A reactor with a larger catalyst factor achieves a higher combustion efficiency for a given adiabatic reaction temperature. It also, however, has a higher pressure drop. Thus, there is a tradeoff between combustion efficiency and pressure drop. The catalyst factor decreased from 0.46 to 0.12 for one reactor after approximately 20 hours of testing.

INTRODUCTION

The purpose of this paper is to present three correlations based on previous catalytic combustion data (refs. 1 to 3). The first correlates combustion efficiency. The second is a correlation of the percentage pressure drop at an adiabatic reaction temperature of 1450 K. The third is a correlation of the minimum adiabatic reaction temperature required to meet the steady state emissions goals set for the DOE supported Gas Turbine Highway Vehicle Systems Project (the goals are described in ref. 2).

The correlations can be used in the design of a catalytic combustor to operate at a given combustion efficiency and meet emissions goals. With given constraints such as operating temperature or pressure drop a catalytic reactor could be designed with a specific geometry, length, and catalyst type that is necessary to meet the efficiency and/or emissions goals. Descriptions of some of the various types of catalysts available can be found in the references.

The correlations are based on an inlet temperature of 800 K, a pressure of 3×10^5 Pa, and reference velocities from 10 to 20 m/s for operation with propane fuel. All catalysts used were noble metal.

The performance of the catalytic reactors on which the correlations are based should be viewed as conservative. Heat losses from the 12-cm-diameter test rig were fairly large, about 10 percent of the total heat available. The adiabatic reaction temperature necessary for a given combustion efficiency would be expected to decrease for test conditions closer to adiabatic.

RESULTS AND DISCUSSION

Combustion Efficiency

Combustion efficiency for 12-cm-diameter catalytic reactors using propane fuel at an inlet temperature of 800 K, a pressure of 3×10^5 Pa, and reference velocities from 10 to 20 m/s is correlated in figure 1. At these conditions, combustion efficiency is found to be a function of

$$C_f\left(\frac{T_{AD}}{1000}\right)^{10}\left(\frac{C_c \cdot C_d \cdot L}{V_{REF}}\right) \qquad (1)$$

where

T_{AD} adiabatic reaction temperature, K

C_c cell circumference, cm

C_d cell density, $cells/cm^2$

L reactor length, cm

V_{REF} reference velocity, m/s

C_f catalyst factor

The catalyst factor is a measure of the relative performance of a catalytic reactor. It was used to account for differences between reactors.

There is considerable scatter in the correlation, especially at lower combustion efficiencies. At combustion efficiencies where the curve is steep, there is a range of ±7 percent in the correlation. At a combustion efficiency of 99 percent, which is probably a normal operating point, there is a range of ±1 percent in the correlation.

The reactors considered and their respective catalyst factors are listed in Table I. Reactors were chosen which used the same substrate for all elements. A description of the elements comprising each reactor is given in Table II. A six-digit code is used for each element. The first digit gives the manufacturer and the second digit names the catalyst. The third and fourth represent the catalyst loading. The last two digits give the cell density for the element. Average cell circumferences, cell hydraulic diameters, and fractional open areas were estimated for some of the reactors. The values used for each element are given in Table II.

The adiabatic reaction temperature used for the correlation ranged from 1100 to 1600 K. Reference velocities ranged from 10 to 20 m/s. The catalyst factor ranged from 0.46 to 1.52 for reactors with a maximum of 3 hours testing. All reactors except J4 were tested using a batch of propane which was 98.5 percent pure (ref. 2). Reactor J4 used this batch of propane and also a second batch which was 99.8 percent pure (ref. 2). Reactor J4 was initially tested with the 98.5 percent propane, aged for approximately 20 hours with propane, diesel, and Jet A fuels, and then retested with the 99.8 percent propane. The shaded symbols refer to the aged J4 reactor.

Pressure Drop

The percentage pressure drop for the reactors listed in Table I at an adiabatic reaction temperature of 1450 K is correlated in figure 2. It is found to be proportional to

$$C_f\left[\left(\frac{L}{D_H \cdot P \cdot F}\right) V_{REF}^{1.5}\right] \tag{2}$$

where

D_H cell hydraulic diameter, cm

P pressure, Pa

F fractional open area

and C_f, L, and V_{REF} are defined in the discussion of combustion efficiency.

The data upon which the correlation is based was taken at a pressure of 3×10^5 Pa, the effect of pressure was obtained from reference 3. The percentage pressure drop is correlated generally within ±0.5 percent. Element lengths, cell hydraulic diameters, and fractional open areas used for the correlation can be found in Table II.

The measured percentage pressure drop included the pressure drop due to inlet and catalyst bed thermocouples, and also an exit instrumentation section containing 12 thermocouples and a 1.27-cm-diameter gas sampling rake. The exit plane blockage was approximately 18.5 percent. Recent tests found the pressure drop due to the instrumentation to be fairly small. Reference 3, however, reported a pressure drop of about half that used for this correlation for reactor J4 without the instrumentation. The pressure drop correlation should, therefore, be regarded as an estimate of the pressure drop expected for a reactor.

Temperature Required to Meet Emissions Goals

The minimum adiabatic reaction temperatures, $T_{AD}(min)$ required to meet the emissions goals set for the automotive gas turbine programs was correlated from the data as

$$T_{AD}(min) = C_f^{-0.1}\left[\left(\frac{V_{REF}}{C_c \cdot C_d \cdot L}\right)^{0.1} 1814\right] \tag{3}$$

and is plotted in figure 3 for all reactors listed in Table I. The symbols were defined previously. The emissions goals are 13.6 g CO/kg fuel, 1.64 g HC/kg fuel and 1.60 g NO_2/kg fuel. NO_x emissions with propane fuel were negligible (ref. 1). The goals correspond to a combustion efficiency of approximately 99.5 percent. Equation (3) correlates the minimum required adiabatic reaction temperature within ±5 percent.

Catalyst Factor

The catalyst factor was used to account for reactor differences due to catalytic materials and loading, manufacturing techniques, effects due to the wash coat, etc. It provides a measure of the relative performance of a catalytic reactor. Combustion efficiency, the percentage pressure drop and the minimum required adiabatic reaction temperature are a function of the catalyst factor. Thus, there is a tradeoff between combustion efficiency and pressure drop.

The type of catalyst for reactors G1, G3, and G8 as shown in Tables I and II, was 1Pt:1Pd. Catalyst loadings ranged from 3.5 to 9.4 kg/m^3. Since performance differences due to catalyst loadings are reflected in the catalyst factor, the constant factor of 1.0 for these reactors indicates this range of loadings had no effect on the performance at these conditions for this type of catalyst. The catalyst type for reactors 01 through 07 was 1Pt:1Pd. A comparison of catalyst factors from Table I for reactors 03 and 05 shows no effect of catalyst loading. however, comparing reactors 02 and 04 shows an increase in the catalyst factor from 0.68 to 1.00 with an increase in catalyst loading from 1.8 to 3.6 kg/m^3. The effect of catalyst loading has yet to be fully determined.

Reactor J4

The combustion efficiency, percentage pressure drop, and the minimum required adiabatic reaction temperature correlations are based only on data obtained for reactors tested for a maximum of 3 hours except for reactor J4. Reactor J4 was tested for approximately 20 hours with propane, diesel, and Jet A fuels. Degradation in performance was obtained for operation with propane fuel only, not diesel or Jet A. The catalyst factor decreased from 0.46 to 0.12. The effect of aging was primarily reflected in the combustion efficiency and the minimum required adiabatic reaction temperature. The pressure drop decrease was small. The initial tests were made with the 98.5 percent purity propane, while 99.8 percent purity propane was used after aging. The small increase in purity may have contributed somewhat to the decrease in the catalyst factor, however, unpublished data indicate that the decrease probably was caused mainly by aging.

CONCLUDING REMARKS

Catalytic reactor data from a 12-cm-diameter test rig using propane fuel at an inlet temperature of 800 K, a pressure of 3×10^5 Pa, and reference velocities from 10 to 20 m/s has been correlated for combustion efficiency, pressure drop and the minimum required adiabatic reaction temperature. Combustion efficiency was found to be a function of

$$C_f \left(\frac{T_{AD}}{1000}\right)^{10} \left(\frac{C_c \cdot C_d \cdot L}{V_{REF}}\right)$$

At a combustion efficiency of 99 percent, the data correlates within ±1 percent. The percentage pressure drop was found to be proportional to

$$C_f \left(\frac{L}{D_H \cdot P \cdot F}\right) V_{REF}^{1.5}$$

at an adiabatic reaction temperature of 1450 K. The percentage pressure drop generally correlates within ±0.5 percent. The minimum adiabatic reaction temperature required to meet the emissions goals of 13.6 g CO/kg fuel and 1.64 g HC/kg fuel can be found from the expression

$$T_{AD}(min) = C_f^{-0.1} \left(\frac{V_{REF}}{C_c \cdot C_d \cdot L}\right)^{0.1} 1814$$

This expression correlates the minimum required adiabatic reaction temperature within approximately ±5 percent.

Catalyst durability is an important consideration for a catalytic reactor. The decrease of the catalyst factor from 0.46 to 0.12 for one reactor after approximately 20 hours of testing was probably mainly due to aging. The change in the catalyst factor with aging could be used as a measure of the durability of a catalytic reactor.

The correlations are based on data obtained at one inlet temperature and except for the pressure drop correlation, they are based on one pressure. A more general correlation is needed to cover a range of inlet temperatures and pressures.

REFERENCES

1. Anderson, D. N.: Effect of Catalytic Reactor Length and Cell Density on Performance. Presented at the 2nd Workshop on Catalytic Combustion (Raleigh, North Carolina), June 21-22, 1977. Sponsored by Environmental Protection Agency.

2. Anderson, D. N.: Performance and Emissions of a Catalytic Reactor with Propane, Diesel, and Jet A Fuels. NASA TM-73786, 1977. Also CONS/1011-20.

3. Anderson, D. N.: Effect of Inlet Temperature on the Performance of a Catalytic Reactor. DOE/NASA/1040-78/3, NASA TM-78977, 1978.

TABLE I

Reactor	Elements						Symbol	Catalyst factor, C_f
	1	2	3	4	5	6		
E1	--------	--------	E1-00-35	E1-00-35	E1-00-35	E1-00-35		0.87
E2	--------	--------	E2-00-35	E2-00-35	E2-00-35	E2-00-35		1.10
E3	--------	--------	E1-00-35	E2-00-35	E2-00-35	E2-00-35		1.52
E7	--------	--------	--------	E1-00-35	E1-00-35	E1-00-35		1.26
G1	--------	--------	G3-53-30	G3-53-30	G3-53-30	G3-53-30		1.00
G3	--------	--------	G3-35-45	G3-35-45	G3-35-45	G3-35-45		1.00
G8	--------	--------	G3-94-34	G3-94-34	G3-94-34	G3-94-34		1.00
J1	--------	--------	--------	←	J1-53-62	→		.51
J2	--------	--------	--------	←	J2-53-62	→		.35
J4	←	J1-53-62	→	←	J2-53-62	→		.46
J4 (aged)	←	J1-53-62	→	←	J2-53-62	→		.12
01	--------	--------	05-18-10	05-18-10	05-18-10	05-18-10		.68
02	--------	--------	05-18-11	05-18-11	05-18-11	05-18-11		.68
03	--------	--------	05-18-34	05-18-34	05-18-34	05-18-34		.68
04	--------	--------	05-36-11	05-36-11	05-36-11	05-36-11		1.00
05	--------	--------	05-36-34	05-36-34	05-36-34	05-36-34		.68
06	05-36-11	05-36-11	05-36-11	05-36-11	05-36-11	05-36-11		.68
07	05-36-34	05-36-34	05-36-34	05-36-34	05-36-34	05-36-34		.68

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TABLE II

Element	Catalyst manufacturer	Manufacturer designation	Catalyst type	Loading, kg/m^3	Substrate manufacturer	Substrate composition	Cell density, cells/cm^2	Cell shape	Length, cm	Cell circum-ference, cm	Fraction open area	Hydraulic diameter, cm
E1-00-35	Englehard	EVD 1128	Pt	*	Corning	Cordierite	35	Sine	2.5	0.48	0.70	0.16
E2-00-35	Englehard	EVD 1412	Pd	*	Corning	Cordierite	35	Sine		.48	.70	.16
G3-53-30	W. R. Grace	DAVEX 512A	1Pt:1Pd	5.3	Pure Carbon	Silicon carbide	30	Sine		.48	.74	.21
G3-35-45	W. R. Grace	DAVEX 524A	1Pt:1Pd	3.5	W. R. Grace	Cordierite	45	Square		.47	.69	.14
G3-94-34	W. R. Grace	DAVEX 524A	1Pt:1Pd	9.4	General Refractories	Mullite	34	Circular		.50	.67	.16
J1-53-62	Johnson Matthey	------------	Pt	5.3	Johnson Matthey	Metal	62	Sine	7.6	.66	.93	.09
J2-53-62	Johnson Matthey	------------	Pd	5.3	Johnson Matthey	Metal	62	Sine	7.6	.66	.93	.09
05-18-10	Oxy-Catalyst	------------	1Pt:2Pd	1.8	General Refractories	Mullite	10	Circular	2.5	1.00	.78	.32
05-18-34		------------		1.8	Norton	Silicon carbide	11			.75	.70	.24
05-18-34		------------		1.8	General Refractories	Mullite	34			.5	.67	.16
05-36-11		------------		3.6	Norton	Silicon carbide	11			.75	.70	.24
05-36-34		------------		3.6	General Refractories	Mullite	34			.50	.67	.16

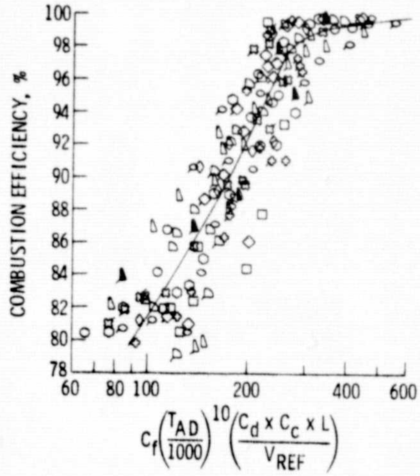

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Figure 1. - Combustion efficiency correlation Inlet temperature of 800 K. Pressure of 3×10^5 Pa. Propane fuel.

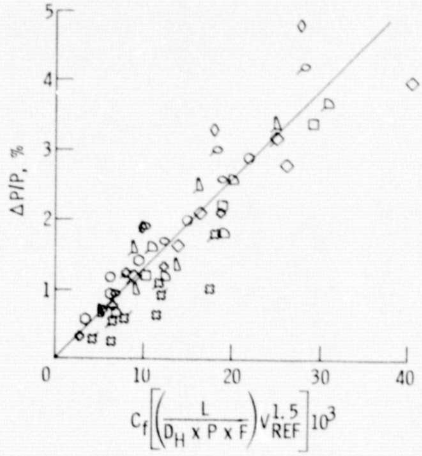

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Figure 2. - Pressure drop correlation. Inlet temperature of 800 K with propane fuel. Adiabatic reaction temperature of 1450 K.

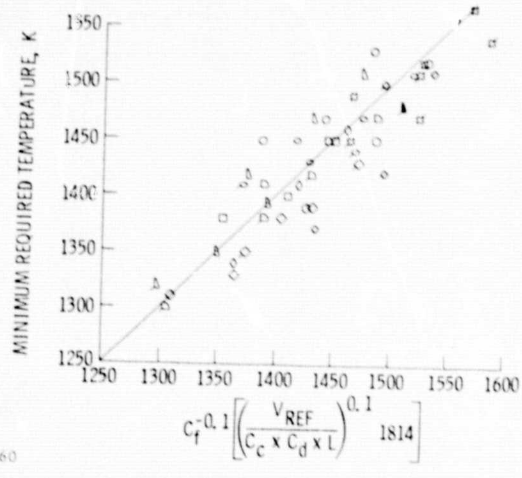

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Figure 3. - Minimum required adiabatic reaction temperature to meet emissions goals. Inlet temperature of 800 K and pressure of 3×10^5 Pa. Propane fuel