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Study on catalytically ignited premixed combustion

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Abstract

This paper describes some of the major issues related to catalytically ignited premixed combustion and the effect of pressure and velocity on the mass transfer of the catalytic reaction. The first issue is concerned with partial burning of the fuel air mixture on the catalyst surface prompting gas phase combustion to take place downstream of the catalyst layer. The latter part of this paper deals with the potential for reduced combustion efficiency from a mass transfer perspective, when going from atmospheric testing conditions to actual high pressure gas turbine operating conditions.

Keywords: Combustion; NO_x; Fuels; Premixed combustion

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1. Introduction

Water injection, steam injection, lean diffusion combustion, and lean premixed combustion can be utilized to reduce the NO_x emissions from gas turbines. However, none of these methods will yield NO_x levels low enough to the stringent Japanese local NO_x regulations [1]. Therefore, in addition to these methods, a selective catalytic reactor is always used as a NO_x reduction system.

Catalytic combustion, on the other hand, has the potential to reduce NO_x to as low as 10 ppm while maintaining stable combustion with a flame temperature less than 1780 K. There are many complexities, however, involved with applying this method to actual gas turbines: high temperature resistance, durability, etc. To overcome these obstacles, a full understanding of the phenomena is essential. Some of the results shown in this paper are from a combustion viewpoint rather than from a catalytic perspective.

2. Catalytically ignited premixed combustion

2.1. Combustion test

The combustion test rig consists of air heater, fuel air mixer, catalyst, temperature measuring section, gas sampling section and cooler as shown in Fig. 1. The gas temperature is measured by Pt–Pt/Rh (1.6 mm) sheathed thermocouples. After setting the air flow and temperature, the fuel flow is increased gradually to the design point. Measurements are taken after confirming that all of the operating conditions are steady. Natural gas, consisting of 98.9% methane, is used for the fuel and tests are conducted at atmospheric pressure.

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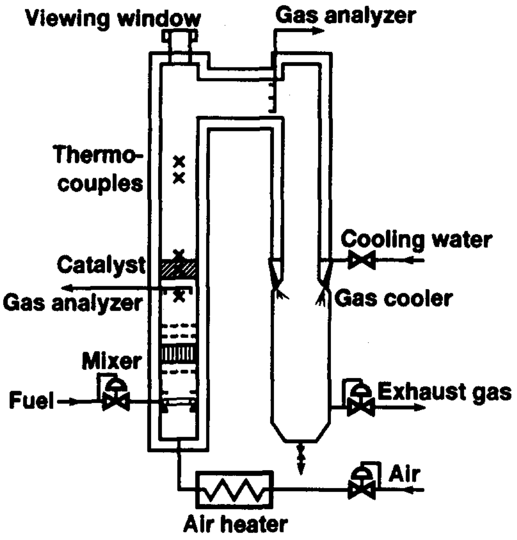

Fig. 1. Combustion test rig.

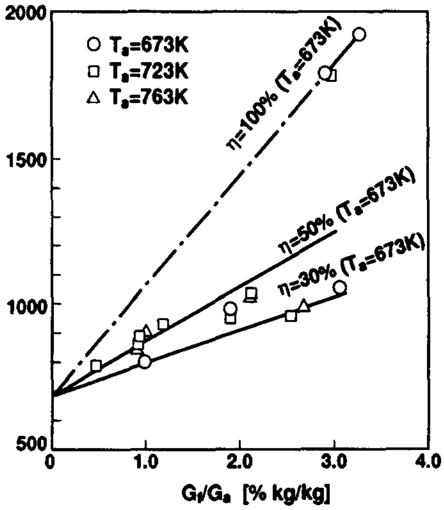

Fig. 2. Fuel/air ratio vs. gas temperature.

2.2. Catalytic combustion

The relationship between gas temperature and fuel/air ratio for a 400 cpi, 80 mm catalyst is shown in Fig. 2. Combustion efficiency was observed to be fairly steady (ranging from 30–50%) and the gas temperature was found to be proportional to the fuel/air ratio for values less than 0.028 kg/kg. These observations are consistent with typical mass transfer controlled regions. For fuel/air ratios greater than 0.028 kg/kg, the combustion efficiency discontinuously rose to 100%. The temperature for this condition is about 1000 K which is the auto ignition temperature. In addition, the fuel/air ratio satisfies the flammable limit. As such, the combustion process is considered to be 'flame type' combustion.

2.3. Catalytically ignited premixed combustion

The gas temperature distribution along the centerline for a 200 cpi, 50 mm catalyst is shown in Fig. 3. Gas temperatures at the catalyst core were approximately 1000 K which is almost the same as that at the catalyst exit. Gas temperatures increased to 1400 K at 300 mm downstream of the catalyst exit, indicative of 'flame type' combustion.

It can be seen in Fig. 4 that a gas composed of premixed fuel and air, shown by point A, burns to point B by catalytic combustion. The temperature at point B is higher than ignition temperature and within the flammable limit. Therefore, gas phase combustion must take place from point B to point C. This process can be described as catalytically ignited premixed combustion. This type of combustion has the potential to reduce catalyst temperature and length as well as reduce the gas flow pressure drop.

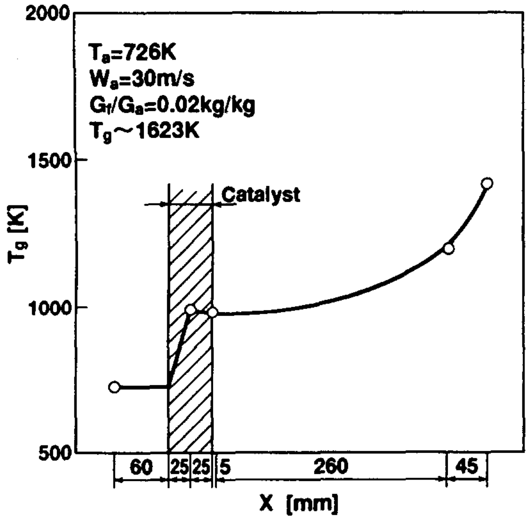

Fig. 3. Gas temperature distribution on gas path centerline.

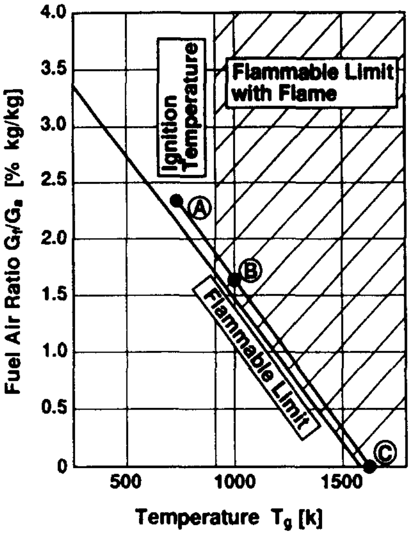

Fig. 4. Flammable limit.

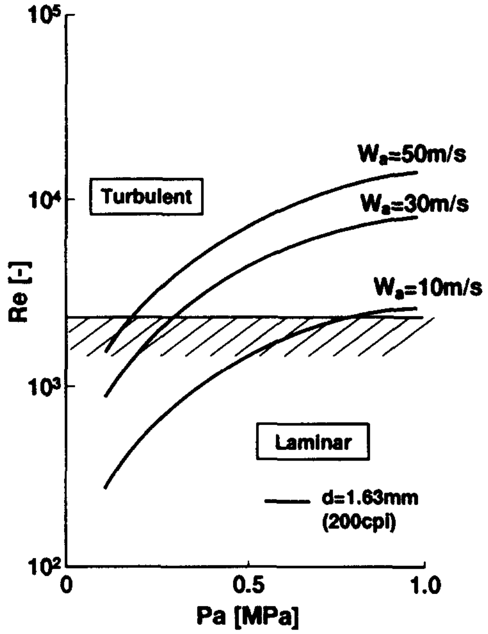

Fig. 5. Reynolds number.

3. Role of mass transfer

3.1. Flow condition

A study has been conducted on the theoretical analysis of catalytic combustion [2]. The results reported in this paper showed that the reaction rate is higher at the downstream portion of the catalyst when subjected to higher gas temperatures. These observations apparently conflict with the results shown in Fig. 3. Hence, the flow conditions and resulting mass transfer properties were further studied in attempt to understand the underlying reasons for these differences. Some parametric calculations were completed assuming a constant temperature of 288 K.

The Reynolds number for the 200 cpi catalyst is shown in Fig. 5. Since the cell of the catalyst is small, the flow is laminar for a velocity of 30 m/s and 0.1 MPa. The flow is turbulent, however, for actual gas turbine operating conditions ($P_a = 1$ MPa, $W_a = 30$ m/s).

The length of the hydrodynamic entrance region is shown in Fig. 6. This length increases with increasing velocity and pressure for laminar flow whereas it is constant for turbulent flow [3].

3.2. Mass transfer coefficient

The length of the hydrodynamic entrance region and the mass transfer coefficient are calculated for laminar and turbulent flow by the following Eqs. [3].

Laminar flow

Hydrodynamic entrance region

$X_e = 0.05 R_e \cdot d$

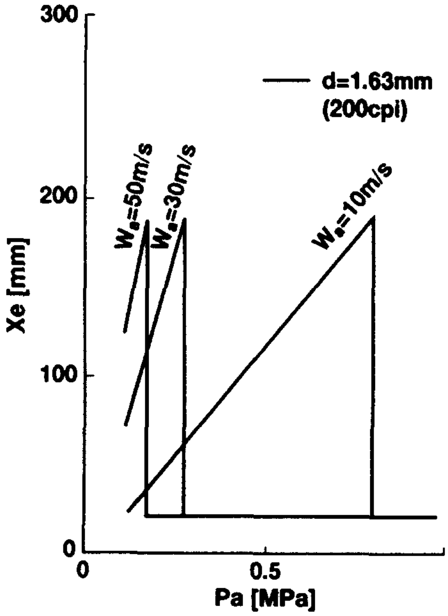

Fig. 6. Hydrodynamic entrance region length.

Mass transfer coefficient in the fully developed region

$$h_d = 4.36\frac{D}{d}$$

Mass transfer coefficient in the hydrodynamic entrance region

$$h_x = \frac{D}{X}S_h$$

$$S_h = 5.364\{1 + (220X^+/\pi)^{-10/9}\}^{3/10} - 1.0$$

$$X^+ = \frac{(x/d)}{(R_e \cdot S_c)}$$

Turbulent flow

Hydrodynamic entrance region

$$X_e = (10 \sim 20)d$$

Mass transfer coefficient in the fully developed region

$$h_D = \frac{D}{d}S_h$$

$$S_h = 0.022R_e^{0.8}S_c^{0.5}$$

Mass transfer coefficient in the hydrodynamic entrance region

$$\mathrm{h_x} = \frac{\mathrm{D}}{\mathrm{d}}\mathrm{S_{hx}}$$

$$S_{hx} = S_h \cdot \left\{1 + \frac{C}{X/d}\right\}$$

$$C = 0.8\left\{1 + \left(\frac{R_e}{1700}\right)^{-1.5}\right\}$$

Fig. 7 reveals the calculated mass transfer coefficient to be high in the hydrodynamic entrance region and low in the fully developed region at atmospheric pressure. This coefficient, on the other hand, is relatively constant for both regions at high pressure. Hence this relationship is dependent on the type of flow and the length of the hydrodynamic entrance region.

3.3. Comparison of gas temperature within the catalyst layer

A comparison between the experimental results and the analytical predictions of the gas temperature distribution within the catalyst layer is shown in Fig. 8. This figure is based on the same data as Fig. 3. Predictions were made using the calculation procedure outlined in the previous section. Good agreement between the analytical and experimental approaches was evident. Both methods indicated a large temperature increase in the inlet region even though an accurate prediction of the magnitude of the temperature rise would need to include additional factors such as catalyst effective area, surface roughness, etc.

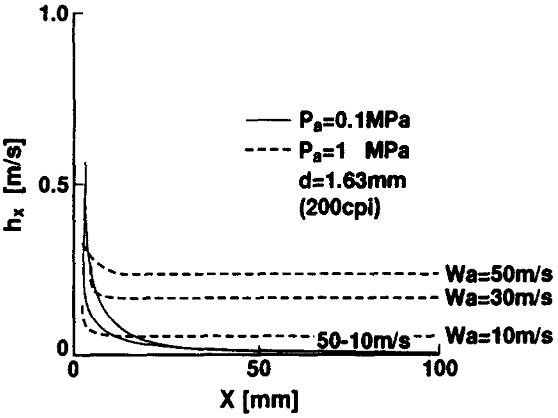

Fig. 7. Mass transfer coefficient.

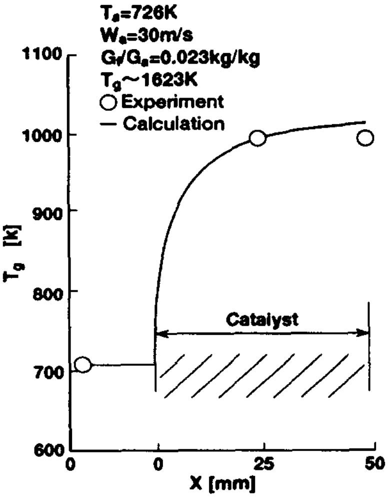

Fig. 8. Comparison of experimental and calculated results.

4. Conclusions

A combustion process consisting of burning a flammable fuel/air mixture up to 1000 K within a catalyst layer and 'flame type' combustion downstream of this region was proposed. This catalytically ignited premixed combustion method is effective in reducing both the catalyst temperature and the pressure drop. The flow type, laminar or turbulent, was found to be an important parameter for the evaluation of mass transfer and catalytic activity.

5. Nomenclature

D	Diffusivity of fuel in air (m^2/s)
d	Equivalent diameter of catalyst channel (m)
G_f/G_a	Fuel air ratio (kg/kg)
h	Mass transfer coefficient (m/s)
P_a	Pressure (MPa)
R_e	Reynolds number
S_c	Schmidt number
S_h	Sherwood number
T_a	Inlet temperature (K)
T_g	Gas temperature (K)
W_a	Air velocity (m/s)
X	Axial distance (m)
X_c	Hydrodynamic entrance region length (m)
η	Combustion efficiency (%)
Suffix	
d	Diameter
x	Axial distance

References

[1] S. Mandai, M. Inada, T. Gora and R. Araki, Trans. JSME, 56 (1990) 530.
[2] L.A. Kennedy, ASME Paper 79-HT-57.
[3] JSME Ed., Heat Transfer Data, 1986.