Analysis on the Fluctuation of the Light Emission from Methane-Air Premixed Flames

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1 Abstract

This paper deals with the analysis on the fluctuation of the light emission from methane-air premixed flames. Planar flames formed on a flat burner at the equivalence ratio of unity; cellular flames formed at low equivalence ratios, because diffusive-thermal effects have a destabilizing influence in this range. We measured the light emission to get the time series of intensity, and obtained the root mean square (RMS) and power spectrum density of the emission intensity normalized by its average value. The RMS increased as the equivalence ratio decreased, which is due to the increase in the instability level. The power spectrum density had a sharp peak at the frequency corresponding to the typical oscillation of premixed flames, and the $1/f$ spectrum appeared in low frequency range. The characteristics of the dynamic behavior of flame fronts depended strongly on the equivalence ratio, i.e. on intrinsic instability. Thus, the obtained results suggest that the present analysis on the fluctuation of the light emission is applicable to the diagnostics of the instability of premixed flames.

Key Words: Fluctuation, Light Emission, Time Series Analysis, Flame Instability

2 Introduction

Recently, we focus on the lean combustion of methane-air mixtures to reduce emissions of carbon dioxide and nitrogen oxide, and this type of combustion is often adopted in most plants. Methane is lighter than air, i.e. the mass diffusion of the deficient reactant is in excess of the heat diffusion, so that methane-air lean premixed flames are usually unstable. The instability phenomena of premixed flames is observed in experiments as the formation of cellular flames and the dynamic behavior of flame fronts [1-2]. The intrinsic instability of premixed flames consists principally of hydrodynamic effects, induced by the thermal expansion through the flame front, and of diffusive-thermal effects, induced by the preferential diffusion of mass versus heat [3]. Through experimental and theoretical investigations, it was found that the shape and behavior of flame fronts are strongly affected by intrinsic instability [4-8]. Moreover, the characteristics of cellular flames were numerically investigated in detail by several researchers [9-12], based on the diffusive-thermal model equation with constant-density approximation and on the compressible Navier-Stokes equation. Hydrodynamic and diffusive-thermal effects control the dynamic behavior of cellular flames.

Intrinsic instability has a great influence on the dynamic behavior of premixed flames, so that it is closely related with the fluctuation of the emission of light. Thus, we can estimate the level of intrinsic instability

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through the time series analysis on the light emission. This indicates that we can diagnose the characteristics of combustion phenomena by means of the time series analysis. When the technique of the time series analysis for the combustion diagnostics is established, we can consider the flame instability from the other point of view.

In our investigation, we measured the emission of light from methane-air premixed flames to obtain the root mean square (RMS) and power spectrum density. The target of the present investigation is to diagnose the flame instability through the time series analysis on the fluctuation of the light emission.

3 Experimental Design

Methane-air premixtures flowed into the flat burner, and premixed flames formed on a porous board with 60 mm in diameter. The flow rate of premixtures Q ranged from 25 to 40 ℓ/min, and the equivalence ratio ϕ was 0.62 through 1.00.

To measure the emission of light from premixed flames, the photodiode and the interference filter were used. The output current from the photodiode was converted to the voltage, and its time series signal was digitally recorded with the resolution of 14 bits. The sampling frequency and sampling time were 500 Hz and 262.144 sec, respectively.

The measured emission intensity $x(t)$, varying with time t, was normalized by its average value $< x(t) >$. As to the normalized emission intensity $y(t)$, the RMS and power spectrum density were obtained. In the present experiments, the characteristics of the emission intensity are independent of the setting position of the photodiode. Through the time series analysis, the characteristics of the instability of premixed flames were investigated.

4 Fluctuation of Light Emission

The emission intensity is strongly affected by the shape of flame fronts. Figure 1 shows the range of two kinds of flame shapes, planar and cellular shapes, depending on the flow rate and equivalence ratio. Planar flames were observed under stoichiometric conditions, and cellular flames were observed at low equivalence ratios. This is because diffusive-thermal effects have a destabilizing influence at low equivalence ratios in methane-air premixed flames. In addition, the cellular-flame range became wider as the flow rate increased. The reason is that the instability level becomes higher owing to the increase in the burning velocity.

The power spectrum densities at Q = 25 and 40 ℓ/min, and ϕ = 0.66 and 1.00 are shown in Fig. 2. In all cases, the power spectrum density P was inversely proportional to the frequency f, i.e. the $1/f$ spectrum was observed in low frequency range. In addition, two sharp peaks were found at $f = f_1$ and f_2. The first sharp peak at $f = f_1$ corresponds to the typical oscillation of premixed flames, which is generated mainly by the shear flow between the hot burned gas and the atmospheric gas. The second sharp peak at $f = f_2$ is weaker than the first one, and f_2 is double f_1. Thus, f_2 is the harmonic frequency of f_1.

The typical-oscillation frequency f_1 depends on the flow rate and equivalence ratio. Figure 3 shows the relationships between the typical-oscillation frequency and the equivalence ratio at Q = 25, 30, 35, and 40 ℓ/min. When planar flames were observed, the typical-oscillation frequency became higher as the flow rate increased. This is because the velocity of the hot burned gas increases with an increase in the flow rate. When cellular flames were observed, the typical-oscillation frequency became lower with a decrease in the equivalence ratio. The results indicate that the appearance of cellular-flame fronts causes the lowness of the typical-oscillation frequency. At ϕ = 0.66, cellular flames were observed in all cases, and the typical-oscillation frequency became "lower" with an increase in the flow rate. This tendency is opposite to the results at ϕ = 1.00. We can understand the mechanism of the interesting results as follows: The cellular-flame range at Q = 40 ℓ/min is wide (ϕ = 0.66 through 0.80), so the decrease in the typical-oscillation frequency is drastically. On the other hand, the former at Q = 25 ℓ/min is narrow (ϕ = 0.62 through 0.66), so the latter is slightly. Thus, the typical-oscillation frequency at ϕ = 0.66 (ϕ = 1.00) becomes lower (higher) as the flow rate increases.

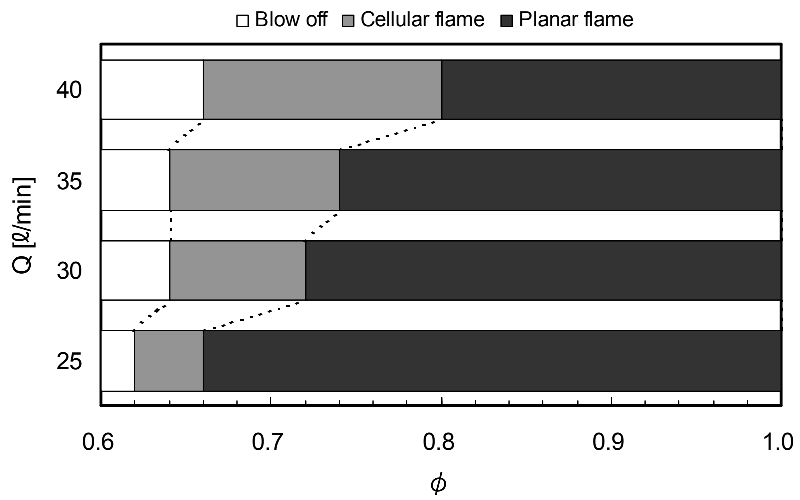

Fig. 1. Range of two kinds of flame shapes, planar and cellular shapes, depending on the flow rate and equivalence ratio.

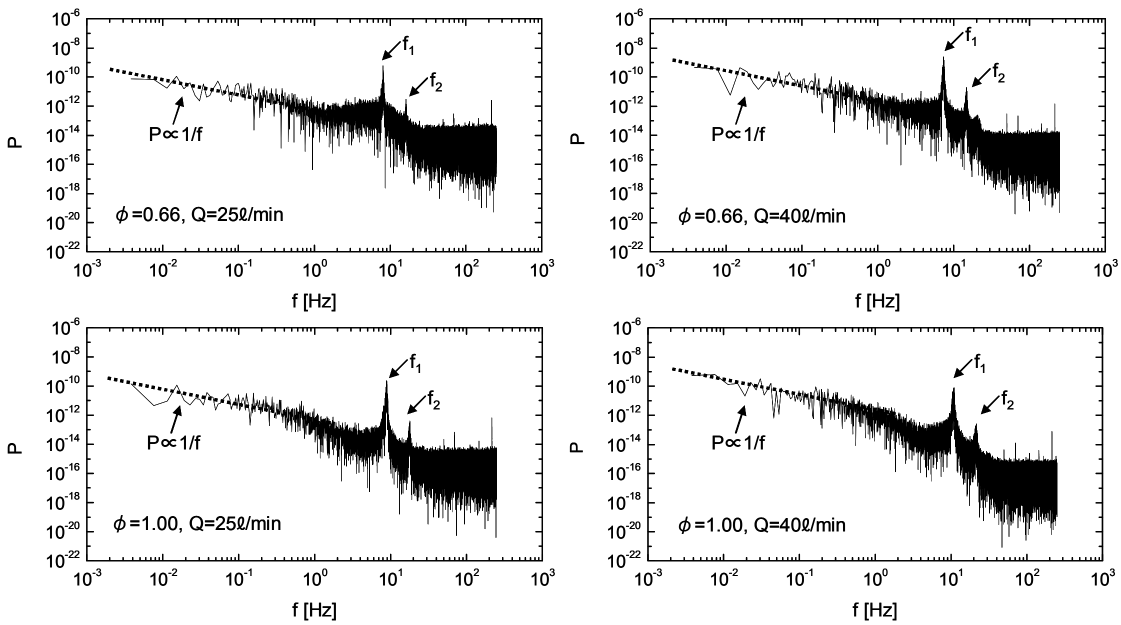

Fig. 2. Power spectrum densities of the normalized emission intensity at Q = 25 and 40 ℓ/min, and ϕ = 0.66 and 1.00.

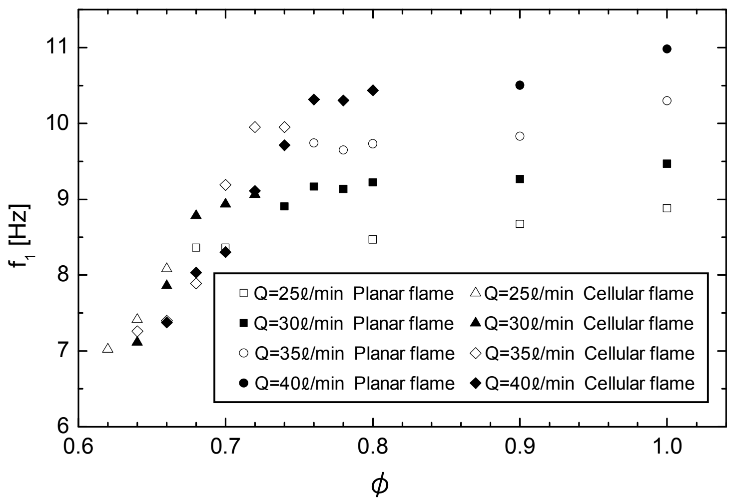

Fig. 3. Relationships between the typical-oscillation frequency and the equivalence ratio at Q = 25, 30, 35, and 40 ℓ/min.

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References

[1] Izumikawa, M., Mitani, T. and Niioka, T.: Experimental Study on Cellular Flame Propagation of Blend Fuels, *Combust. Flame*, **73** (1988), pp. 207-214.

[2] el-Hamdi, M., Gorman, M. and Robbins, K. A.: Deterministic Chaos in Laminar Premixed Flames: Experimental Classification of Chaotic Dynamics, *Combust. Sci. Technol.*, **94** (1993), pp. 87-101.

[3] Williams, F. A.: *Combustion Theory*, 2nd Ed., Addison-Wesley, Reading MA, 1985, pp. 294-372.

[4] Clanet, C. and Searby, G.: First Experimental Study of the Darrieus-Landau Instability, *Phys. Rev. Lett.*, **80** (1998), pp. 3867-3870.

[5] Qin, X., Kobayashi, H. and Niioka, T.: Laminar Burning Velocity of Hydrogen-Air Premixed Flames at Elevated Pressure, *Exper. Thermal Fluid Sci.*, **21** (2000), pp. 58-63.

[6] Sivashinsky, G. I.: Instabilities, Pattern Formation, and Turbulence in Flames, *Ann. Rev. Fluid Mech.*, **15** (1983), pp. 179-199.

[7] Clavin, P.: Dynamic Behavior of Premixed Flame Fronts in Laminar and Turbulent Flows, *Prog. Energy Combust. Sci.*, **11** (1985), pp. 1-59.

[8] Kadowaki, S.: Instability of a Deflagration Wave Propagating with Finite Mach Number, *Phys. Fluids*, **7** (1995), pp. 220-222.

[9] Matalon, M. and Matkowsky, B. J.: On the Stability of Plane and Curved Flames, *SIAM J. Appl. Math.*, **44** (1984), pp. 327-343.

[10] Denet, B. and Haldenwang, P. A.: Numerical Study of Premixed Flames Darrieus-Landau Instability, *Combust. Sci. Technol.*, **104** (1995), pp. 143-167.

[11] Bychkov, V. V., Golberg, S. M., Liberman, M. A., Kleev, A. I. and Eriksson, L. E., Numerical Simulation of Curved Flames in Cylindrical Tubes, *Combust. Sci. Technol.*, **129** (1997), pp. 217-242.

[12] Kadowaki, S. and Hasegawa, T.: Numerical Simulation of Dynamics of Premixed Flames: Flame Instability and Vortex-Flame Interaction, *Prog. Energy Combust. Sci.*, **31** (2005), pp. 193-241.