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Flickering characteristics and temperature field of premixed methane/air flame under the influence of co-flow

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The flickering characteristics and the temperature field of an axisymmetric premixed methane/air flame under the influence of co-flow are studied experimentally using the image analysis and the flame reaction technique. The premixed flame is visualized by the alkali metal solution of sodium (Na) for characterizing the flickering characteristics. The temperature measurement of the flame is carried out using the flame reaction technique combined with the relationship between the local intensity of the flame and the temperature from the sodium D-line reversal method, and the influence of the number density distribution of Na on the measured temperature field is corrected by the measurement integrated analysis of the flame with the iterative procedure. This technique is validated by the local temperature measurement in the steady flame under the influence of co-flow using the thermocouple calibrated by the sodium D-line reversal method. The flame visualization and temperature measurement in the flickering flame of the premixed methane/air flame indicates that the flame contour and the temperature field oscillate periodically with the flickering frequency due to the Kelvin–Helmholtz instability of the flame. The oscillation amplitude decreases and the frequency increases gradually with the co-flow velocity increases similar to the observation in the diffusion flame in literature, while the oscillation amplitude grows with the equivalence ratio increases. These changes in the flickering characteristics of the flame are caused by the variations of the temperature field in the premixed flame.

1. Introduction

Recent advances in the measurement technique of temperature and combustion products contributed greatly to the improvement in the performance of energy conversion systems, such as the boiler, the gas turbine and the internal combustion engine [1,2]. Although there exits several experimental techniques for measuring the combustion temperatures, most of the practical techniques are limited to the thermocouple and the resistance thermometer, which are intrusive and point-wise technique of temperature measurement, so that it is not efficient to measure the whole temperature field in the target volume of interests.

In order to overcome such difficulties, optical measurement techniques have been developed, such as laser-induced fluorescence, Rayleigh scattering and spontaneous Raman scattering [3,4]. These techniques are reliable in the accuracy of temperature measurement, though they are expensive due to the necessity of high power lasers and the image intensified sensors for measurement. Other optical techniques, such as rainbow Schlieren [5,6], interferometry [7] and laser speckle [8,9] are other options with less expensive measurement techniques, though they require rather complex image analysis software to determine the temperature field from the multiple images of line-of-sight illumination. In addition, there are two/three color pyrometry methods available for practical non-intrusive temperature measurements, though they are limited to point-wise measurements and with particles [10].

In recent years, the visualization of the flame has been carried out by the flame reaction technique, which requires only small amount of spray mists of alkali metals, such as sodium (Na), potassium (K), and lithium (Li) [11,12]. The introduction of such mists to the flame allows the observation of flame structure, which is well visible by the standard digital camera without any image enhancement device. When the flame reaction technique is applied to the flame, the metal atoms are excited by the thermal energy in the flame and results in the shift in the electron energy to the excited state. Then, the flame reveals a beautiful color of distinct wavelength characterized by the electron energy of the metal atoms. According to the Maxwell–Boltzmann statistics of thermodynamics, the intensity of the light emitted from the visualized flame is a function of the temperature. Therefore, the flame temperature can be measured by evaluating the light intensity distribution, once the light intensity is calibrated against the true temperature using the other reliable temperature sensors. Our preliminary

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Nomenclature

a_1	constant defined by Eq. (3)
C	number density of metal atoms
C_0	number density of metal atoms at burner exit
C_r	relative number density of metal atoms
C_{ref}	number density of metal atoms at reference position
c	speed of the light (=2.998 × 10^8 m/s)
c_1	constant in Eq. (1)
c_2	constant in Eq. (2)
D	diffusion coefficient
d	burner diameter
E_i	electron energy in excited state
E_0	electron energy in ground state
Fr	Froude number ($=U_f^2/gd$)
f	frequency
H_0	height of steady flame
H_m	mean flame height
H_{rms}	rms oscillation amplitude of flame height
h	Plank constant (=6.626 × 10^{-34})
I	line-of-sight intensity
i	local intensity
k	Boltzmann constant (=1.3806 × 10^{-23})
L	optical path length
p	pressure
R	universal gas constant
r	radial distance
T	temperature
t	time
St	Strouhal number ($=fd/U_f$)
U_c	co-flow velocity
U_f	fuel velocity
U_r	co-flow velocity ratio ($=U_c/U_f$)
u	velocity
V_{rms}	rms value of output signals of photo detector
x, y, z	coordinate (see Fig. 1)
Greek letters	
α	absorption coefficient
μ	viscosity
ρ	density
φ	equivalence ratio
λ	wavelength
Subscripts	
i, j	tensor components

study using a thermocouple for the temperature calibration [12] shows that the inverse temperature is proportional to the logarithmic intensity of the light, which is in agreement with the theoretical consideration of the Maxell–Boltzmann statistics. However, the measured temperature of the flame can be affected by the influence of the number density distribution of metal atoms, which has not been considered in the previous measurement.

The flame flickering occurs in a certain experimental condition of the flame due to the presence of Kelvin–Helmholtz instability in the shear layer between the flame and the surrounding fluid [13–15]. The flickering motion is governed by the buoyancy forces, so that the flickering frequency depends on the Froude number, which is the ratio of the inertia to the buoyancy forces of the flame, while the flickering frequency ranges 10–20 Hz in most of the burners, which is insensitive to the experimental details, such as the fuel type, the flow rate and the burner size [16]. Although there are experimental and numerical studies on the mechanism of flame flickering [17–20], the flame structure under the flickering motion has not been fully understood due to the limitation of the qualitative flow visualization technique used in the past studies [13–19]. According to the recent experimental studies, the flickering motion is strongly modified by the presence of the co-flow [21,22]. The flickering characteristics of the diffusion flame under the influence of co-flow are studied using the flow visualization and PIV measurement in the diffusion flame, and the results indicate that the flickering amplitude of the diffusion flame decreases and the flickering frequency increases gradually with the co-flow velocity, while the fully flickering suppression of the co-flow diffusion flame is observed by increasing the co-flow velocity to a certain level [21].

The purpose of this paper is to study the flickering characteristics of premixed methane/air flame under the influence of co-flow using the flame reaction technique combined with image analysis. Further, the measurement of temperature field of the flame is carried out by flame reaction method considering the influence of non-uniform spatial distribution of the metal atoms in the flame. The validation of this measurement technique is conducted using the steady flame under the influence of co-flow, and the result is compared with the thermocouple measurement calibrated by the sodium D-line reversal method. Further, the temperature field of flickering flame is characterized to understand the suppression mechanism of flame flickering in the premixed methane/air flame under the influence of co-flow.

2. Experimental method

2.1. Flame visualization

The flame visualization is carried out using the flame reaction of metal atoms Na, which are supplied to the flame in a form of spray mist [12]. The metal atoms Na in the flame emit the light having a distinct spectrum at 589 nm in wavelength. The experimental setup for the flame visualization is shown in Fig. 1. The premixed fuel of methane/air is supplied to the flame through a circular pipe of $d = 24$ mm in diameter. The methane and air are fully mixed in the mixing tank located upstream of the burner. The temperature of the premixed methane and air is about 290 K. It should be noted

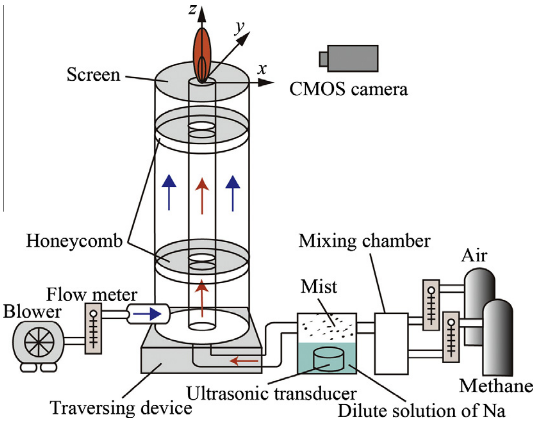

Fig. 1. Experimental setup for flame visualization.