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Full Length Article

Prediction of equivalence ratio in pulse combustor from ion current amplitude spectrum

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ABSTRACT

This study presents a method for the prediction of equivalence ratio in pulse combustor from the ion current amplitude spectrum measured by a multi-frequency ion current sensor supplemented with principal component analysis (PCA) and support vector machine (SVM) technologies. An experimental study was conducted on a Helmholtz-type combustor to validate the proposed method. During the experiment, a multi-frequency excitation source whose crest factor was pre-optimized was applied on the ion current sensor to obtain ion current signals with high SNR. The excitation source has ten frequency components from 500 Hz to 5 kHz. The multi-frequency ion current signals were acquired under six different operation conditions. Under each condition, three typical positions with different distances from the gas inlet of the combustor were selected. The amplitudes of all frequency components in the multi-frequency ion current signals were extracted and projected into two subspaces via PCA to reduce the data dimensions and attenuate the noise corruption. An SVM model was built based on the amplitude spectrum features in the first two principle components subspace to predict the equivalence ratio. Experimental results show that the ion current amplitude spectrum relies on the equivalence ratio and the position where the sensor is installed. The equivalence ratio can be predicted with the PCA-SVM model with an average determination coefficient higher than 98%. This study validates the feasibility of the amplitude spectrum obtained by the ion current sensor for prediction of the equivalence ratio in the pulse combustor.

1. Introduction

Pulse combustors are unsteady, resonant thermo-acoustic devices in which heat release couples with the acoustic field. Properly designed combustors have simple mechanical structures as well as improved thermal and emission characteristics. These characteristics make pulse combustors attract increasing attentions and find potential applications in propulsion devices [1]. However, the performance and stability of a pulse combustor is prone to the operation condition that is directly related to the equivalence ratio in the combustor. A proper range of equivalence ratio allows high stability and conversion efficiencies of the combustor, thus permits low pollutant emissions. For the pulse combustor, prediction of the equivalence ratio is still challenging due to the measurement difficulties caused by its self-excited combustion process.

Currently, two approaches are mainly used to obtain the equivalence ratio. The most basic one is calculating the equivalence ratio from the inlet fuel and air flows measured by a flowmeter installed in the system inlet [2]. However, the fuel gas analysis method is limited when the inlet flows are time-varying. Another way is using chemical balance equations to calculate the equivalence ratio from the measured CO, CO_2, and O_2 concentrations [3]. Various advanced laser based techniques, such as the laser-induced breakdown spectroscopy (LIB), laser-induced fluorescence (LIF), and infrared absorption techniques, are applied to measure the concentration of the needed species [4–8]. However, the laser based techniques have limited application in a practical burner due to the requirement of transparent optical access and the existence of uncertainties [9]. Currently, the most popular way is to use an oxygen sensor which is installed in the exhaust stream and responds to the oxygen concentration. Two examples are the heated exhaust gas oxygen (HEGO) sensor and the commercial universal exhaust gas oxygen (UEGO) sensor [10]. However, the HEGO sensor fails to provide the exact value of equivalence ratio. The UEGO sensor provides an accurate equivalence ratio value, while it is expensive and mostly limited to laboratory applications [11,12]. To address problems associated with the above mentioned approaches, researchers proposed various methods to estimate the equivalence ratio using combustion parameters measured by pressure sensors, optical chemiluminescence sensors and CCD camera, etc. [13–16]. Meanwhile, intelligent

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Nomenclature

A	amplitude
c	specific heat
C_{va}	discharge coefficient of air valve
C_{vg}	discharge coefficient of gas valve
d	distance from the gas nozzle
D	diameter
f	frequency
h	enthalpy per unit mass
I	current
L_t	length of tailpipe
m_a	mass flow rate of air
m_g	mass flow rate of fuel
P_a	gauge pressure at air inlet valve
P_g	gauge pressure at gas inlet valve
P_s	gas supply pressure
R_{ion}	resistor of ion current sensor
R_g	perfect gas constant
S_A	amplitude spectrum
s	stoichiometric mass ratio
Q_a	flow area of air valve
Q_c	cross-sectional area of the combustor
Q_g	flow area of gas valve
t	time
v	velocity
V_c	volume of the combustor
U	voltage
ΔH	heat of combustion per unit mass of fuel
ΔP	pressure difference
β	constant in mass flow model
Φ	equivalence ratio
φ	phase
ρ_a	density of air
ρ_g	density of gas

algorithms including principal component analysis (PCA), artificial neural network (ANN) and support vector machine (SVM) are adopted to extract the features and estimate the equivalence ratio [17–20]. The spark plugs served as ion current sensors have also been widely investigated to determine the equivalence ratio in various engines. These investigations have revealed a strong relation between the equivalence ratio and the features of the ion current signal, such as the maximum value, the integral value, the maximum derivative in the front flame, or the area ionic current across under the post flame [21–23]. For the pulse combustor whose combustion process is periodic and highly dynamic, an ion current sensor that can be easily installed in the combustor for continuous periodic measurement is a promising method for the equivalence ratio determination.

The objective of this investigation is to develop a method based on the ion current amplitude spectrum to predict the equivalence ratio in the pulse combustor. Experiments were conducted on a Helmholtz-type combustor. A multi-frequency ion current sensor was applied to measure the ion current signals. Pressure signals were simultaneously acquired to convert the gas supply pressure to equivalent ratio for verification purpose. Spectral analyses were conducted to extract the ion current amplitude spectrum from the multi-frequency ion current signals. Then the PCA was applied to reduce data dimensions and noises of the ion current amplitude spectrum. The SVM model was finally built based on the PCA features to predict the equivalence ratio.

2. Fundamentals on pulse combustion

2.1. Pulse combustion

The pulse combustor basically consists of a combustion chamber, a tailpipe, an air valve, a gas valve and a gas supply line. Fig. 1 shows the typical construction of the Helmholtz-type pulse combustor.

The pulse combustion operates in a sequence of the following four stages: ignition and combustion, flue gas expansion, purge and recharge, recharge and compression. In-depth descriptions of the mechanism for the pulse combustion have been given, for example, by Meng Xiangmei[24] and Minglong Du [25]. The most important parameter in the pulse combustor is the working frequency. Ali Kilicarslan proposed an estimation method for the working frequency of a gas-fired pulse combustor [26]. In this study, the air to fuel ratio in the equation was substituted by the equivalence ratio to facilitate the subsequent analyses. The working frequency of a gas-fired pulse combustor can be is expressed as:

$$f=\begin{cases}\frac{1}{2\pi}\left(\frac{R_g}{c_{pr}}\right)^{1/2}\left(\frac{S_t}{L_t v_c}\right)^{1/2}\left(\frac{\Phi\cdot\Delta H_f}{s+\Phi}+h_r\right)^{1/2}, & \Phi\leqslant 1\\ \frac{1}{2\pi}\left(\frac{R_g}{c_{pr}}\right)^{1/2}\left(\frac{S_t}{L_t v_c}\right)^{1/2}\left(\frac{\Delta H_f}{s+\Phi}+h_r\right)^{1/2}, & \Phi>1\end{cases}, \tag{1}$$

where, R_g is the ideal gas constant, ΔH_f is the combustion heat release per unit mass (kJ/kg), c_{pr} is the specific heat of the gases in the tailpipe at constant pressure, S_t is the cross-sectional area of the tailpipe, L_t is the length of the tailpipe, v_c is the volume of the combustion chamber, Q is the combustion heat release per unit mass (kJ/kg), h_r is the reactants' enthalpy per unit mass (kJ/kg), Φ is the equivalence ratio and s is the stoichiometric mass ratio. For propane and air applied in this study, s takes the value of 15.686.

As indicated by Eq. (1), the working frequency of pulse combustor is closely associated with the equivalence ratio. Generally, for a fixed combustor size, the closer the equivalence ratio is to 1, the higher the working frequency and the more stable the pulse combustor. However, recent studies have advised a lower equivalence ratio to improve the combustion efficiency and reduce the NO_X emissions. Therefore, the equivalence ratio must be controlled at a proper range to manage the trade-off between the combustion efficiency and the operation stability.

2.2. Relationship between equivalent ratio and gas supply pressure

For a pulse combustor, it is difficult to measure the equivalence ratio directly by the flowmeters installed in the inlet flows of gas and air for the self-excited combustion process and the flapper valve. In order to verify the proposed equivalence ratio prediction method, a simplified model based on Bernoulli equation was proposed to convert the gas supply pressure to the equivalent ratio. In the solving process, both air

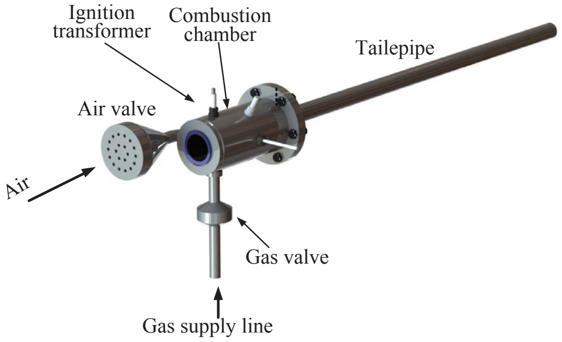

Fig. 1. Typical construction of the Helmholtz-type pulse combustor.