Flame detection on EV burner using process tomography and OH_PLIF data fusion

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Abstract. With increasingly urgent requirements for pollution control and energy saving, the study of low-emission and high-efficiency burners has been proposed worldwide. Among all these new technologies, swirl-induced environmental (EV) burners are outstanding with notable features, such as low emissions, particularly NOx, while maintaining a good combustion stability. In this study, an EV burner is investigated by both an ECT system and an OH-PLIF system. The aim is to detect the structure of a flame and obtain more information, for instance, OH radicals distributions about the combustion process in an EV burner. The experimental images of a flame by ECT are in good agreement with the OH radical distribution pictures captured by OH-PLIF. Visualizing flame distributions in combustion chambers would be the first and necessary step to more difficult tasks such as detecting the locations of poor combustion zones in a combustion chamber that tend to reduce the combustion efficiency, and the locations with excessively high temperature that would generate high concentration of nitric oxides (NOx) gases

1. Introduction

As the requirements for pollution control and energy saving have become increasingly stringent in recent years, the study of low-emission and high-efficiency burners has prospered worldwide. Among these new technologies, swirl-induced environmental (EV) burners have notable features such as low emission generation while maintaining good combustion stability [1]. As a relatively new type of burner, investigations are still greatly needed.

ECT is a type of process tomography (PT) based on capacitance sensing. As a promising technique, ECT has been applied in the parametric measurement in multiphase systems. Waterfall et al. [2], He et al. [3], Liu et al. [4] apply the ECT method to the visualization of the spatial distribution of a combustion flame which provides an effective approach for understanding the underlying physical and chemical mechanisms of the combustion process. Some particular advantages of ECT, such as being capable of measuring very high temperatures, providing cross sectional and even 3D temperature profiles without disturbing the flame by placing probes into it, make it a perfect candidate for flame detecting.

According to flame ionization theory, in a methane flame, the positive ions in a high concentration might be C3H3+, bH3O+ etc., while the negative particles are mainly electrons and a few negative ions. The variation of the permittivity distribution in a flame will cause a corresponding capacitance variation measured by each pair of the electrodes. Therefore, the distribution of permittivity in a flame can be detected. Previous work of our study [5] found that the geometry of a planar circular sensor

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would serve best for the purpose of 3D flame imaging. It also revealed the structure, e.g. different zones, in a flame by the reconstructed images of different cross sections.

As for the OH-PLIF technique, PE Dimotakis first used PLIF to measure the mixing transition state and found that this phenomena is universal to turbulent flow [6]. After that, lots of works have focused on analysing the instantaneous flame structure.

2. Experimental Procedure

The experimental apparatus and measuring system used in the experiments are shown in figure 1. Three parts, including the EV burner system (1 Methane cylinder, 2 Air cylinder, 3 Pressure gauge, 4 Pressure regulator, 5 Flow rate valve, 6 Float meters and 7 Combustion chamber), the OH-PLIF system (15 Dye lasers, 16 Laser optical components, 17 ICCD Cameral and 18 Computer), and the ECT system (8 Shielding, 9 ECT sensor, 10 ECT data logging device and 11 Imaging system) comprise this fire detecting system, as detailed below.

2.1. The EV burner system

Swirl-induced environmental burner, short for EV burner, is a conical burner with two air slits on opposite sides of the cone’s wall, basically. The combustion air flows tangentially from the two slits into the burner. Small holes in the middle part of the slits serve as the inlet of the gaseous fuel. The fuel and combustion air should mix well for complete combustion. The swirling gas emitted from the slits and holes will form a stable recirculation zone inside the conical burner which stabilizes the combustion flame. The geometrical model of the conical burner is shown in figure 2.

2.2. The OH-PLIF system

The OH-PLIF system, short for hydroxyacetic planar laser-induced fluorescence, is divided into three parts - the laser excitation part, the optical system part, and the signal receiving part. The principle of the OH-PLIF is as follows: the laser, generated by the YAG laser; is tuned by the grating in the dye laser; and then the laser doubled or tripled the frequency by the BBO frequency multiplier, and sheeted by the optical lens group, which will dye the OH free radicals in a flame. Simultaneously, the OH fluorescence signals are captured by the ICCD. The supporting operation software, Davis 8.0, is installed on the imaging computer, and synchronizes the laser pulse signals with the ICCD captured signals. The speed of the shutter in this experiment is set to 200ns, and the delay time for the shutter is 100 ns. The resolution of ICCD images is 0.198 mm.
2.3. The ECT System
A typical ECT system usually contains three parts: a sensor with a well-arranged electrode array, a data acquisition device which collects data from the sensor and a PC which analyses the signals from the data acquisition device and reconstructs images applying certain algorithms.

In this paper, a planar circular sensor with eight electrodes was designed to detect the 3D material distribution in the EV burner mentioned above. To avoid signal saturation during measurements, proper calibration should be conducted before the experiments. Based on our former study [7,8], sand with a permittivity of above 8 for the high range calibration was suitable for the experimental combustion conditions and are sufficiently high to prevent signal saturation.

For a more in-depth study of the characteristics of the EV burner, the ECT system was combined with the OH-PLIF system, as depicted in figure 3(a). The laser sheet from the dye laser went exactly through the gap between electrodes 6 and 7 to the gap of electrodes 2 and 3, which coincides with the central vertical section of the sensor and separates the electrodes array into two parts with four electrodes in each, as is shown in figure 3(b).

![Figure 3](image)

**Figure 3.** The sketch picture of the combined system and the ECT sensor.

3. Results and discussions
Sets of OH radical distribution pictures captured by OH-PLIF are presented below, when the feed rate of methane $Q_{CH4}$ increased from 0.6 L/min to 2.4L/min by 0.6L/min each step. To ensure the accuracy of experiments, 500 instantaneous OH radical distribution pictures under each flow rate were averaged and compared with the instantaneous images.

| $Q_{CH4}$ | Averaged images | Instantaneous images |
|-----------|-----------------|---------------------|
| 0.6 L/min | ![Image](image)  | ![Image](image)     |
| 1.2 L/min | ![Image](image)  | ![Image](image)     |
| 1.8 L/min | ![Image](image)  | ![Image](image)     |
| 2.4 L/min | ![Image](image)  | ![Image](image)     |

**Figure 4.** OH radical distributions of flames under different cases.

It can be seen from the instantaneous images that the distribution of OH radicals is basically in an “M” shape, which is mainly due to the reflux effect caused by the swirling action of the EV burner. Also, an increase of concentration of OH radicals can be observed by both the averaged images and the instantaneous images with the raising flow rate of methane.

For better comparison, a series of flame images in the experimental condition are captured simultaneously by ECT and OH-PLIF system. Representative images of the tomographic data from 500 frames for an experimental run when the feed rate of methane was 2 L/min are displayed in figure...
5. Figure 5(a) is the reconstructed image using the sensitivity calculated above. Figure 5(b) presents the distribution of OH radicals in a flame on the central vertical section. These two images exhibit a good consistency in shape, which again proves the feasibility of using ECT measurements and also shows a strong correlation between the permittivity and OH radicals in a flame.

4. Conclusions and Discussions
As a development of a measurement technique for EV burners, this study is an extension of our previous work on the 3D visualization of the structure of flames using a newly developed planar circular ECT sensor. The OH-PLIF system was employed for better understanding the measurement results of ECT and thereby to improve the final measurement results. Good agreement was found with the OH-PLIF image, which indicates a new way to study the characteristics of a flame.

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