Study of flame characteristics using electric capacitance tomography

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Abstract

With increasing awareness of energy savings and environmental protection in recent years, more emphasis on the monitoring of the intensity distribution in a flame and its stability have been raised in connection with the improvement of combustion efficiency and pollutant control. Albeit there are different opinions, it is generally recognized that Electrical Capacitance Tomography (ECT) measurement is directly related to the ionization of the flame, which in turn is closely related to the intensity of combustion.

In this paper, a novel ECT sensor has been designed to withstand high temperatures and a series of experiments based on ECT system have successfully imaged diffusion flame of methane. Also, simulations on three dimensional sensitivity maps are generated to reconstruct images of 3D flame. Experiments and simulation results based on permittivity characteristics of a flame have successfully been used to image the flame, which in turn proves the assumptions raised in the study.

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1. Introduction

Electrical capacitance tomography (ECT) is a type of process tomography (PT) based on capacitance sensing. It features are fast response, low cost, easy implementation, non-intrusiveness, non-radiation and has the capability of acquiring 2D or 3D process parameter information. As a promising technique, ECT is widely applied in many aspects and is becoming one of the key topics in PT research [1-3].

Researchers pursuing visual measurements have obtained the in-cylinder distribution information, such as position, size and pulsation, of a premixed flame and free space using an ECT sensor [4-7]. Shi Liu has studied the relationship between ECT images and flame properties and deduced the effective permittivity of flame [8]. All the research above made it clear that is feasible to monitoring the flame characteristics by ECT system.

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2. **Theoretical analysis**

The basic principle of ECT is described as follows: the measured capacitance of each electrode pair changes in accordance with the permittivity of the working medium inside a sensor pipe or process container and varies with time. The values of the corresponding sensing areas between each electrode pair, which reflect the distribution information of the cross sections of the whole sensor pipe, are detected by a data acquisition system. All the data acquired is fed into a computer which then calculates an image using certain image reconstruction algorithms. In this way, the distribution images of the working medium in the sensor pipe are obtained.

![Figure 1. The cross section of a circle sensor pipe](image)

According to flame ionization theory, flame ionization consists of thermal ionization and chemical ionization. The high temperature area of a flame excites flame particle, which generate electrons and ions. Thermal ionization is determined by flame temperature and ionization Potential (V). On the other hand, chemical ionization is the process that closely related to endothermic and exothermic reactions of combustion. As for methane flame, the positive ions in high concentration are $\text{C}_3\text{H}_3^+\!,\, \text{H}_3\text{O}^+\!,\, \text{CHO}^+\!,\, \text{H}_5\text{O}_2^+\!,\, \text{NO}^+\!,\, \text{C}_2\text{O}_2\text{H}^+\!,\, \text{H}_2\text{O}^+\!,\, \text{H}_3\text{O}_2^+\!$, etc., however, the negative particles in the flame mainly are electrons with a few negative ions.

Shi Liu validated that the inner flame space has a changing magnetic and electric field, along with a large quantity of free electrons and ions, due to thermal and chemical ionization [8]. In this way, flame is viewed as weakly ionized plasma, which is electrically neutral on the whole. The speed of electrons is nearly a hundred times than that of ions, so the current of electrons is much larger than that of ions. The expression of efficiency permittivity of flame is also acquired in his study [8].

3. **Experiment and simulation**

Ordinary insulating materials and materials for the manufacture of the sensor, for example solder, whose upper temperature limit is only about 300ºC, could not meet the need of actual work condition due to high temperature of the flame. Corundum was therefore chosen as the material of the insulating pipe. The electrodes are electroplated with nickel, which significantly enhances the features of this novel sensor. The sensor is specified to withstand at most 1500ºC.

Based on the designed sensor, the detecting area in this experiment is circular, with a radius of 40mm. The thickness of the corundum insulating pipe is 50mm. There are eight electroplated measuring electrodes outside the insulating pipe, and the width of each electrode is 26.3mm. Between two measuring electrodes is a shield electrode to separate the measuring electrode, so there are also eight guard electrodes. The width of the guard electrode is 0.3mm. Surrounding the electrodes is a shielding layer. Asbestos are put inside the gap that separates the measuring electrodes and the shielding layer. The guard electrodes and the shielding layer are linked together and are connected to ground. The speed of the data acquisition is 10 frames per second. A schematic diagram and a photograph of the experimental device are shown below:
Before the experiment, we need to obtain a low and high permittivity level calibration. As for flame monitoring, please note that the calibration should be done at a high temperature that is close to the combustion environment. The permittivity for high calibration is mainly determined by the combustion intensity. As there is no reference, we choose 80-120 mesh quartz sand, whose relative permittivity is 2.3, as the raw material. As was tested, very small variations in the humidity of the sand will cause a significant change in permittivity. Therefore, the needed permittivity, ranging from 4 to 20, could be obtained by adjusting humidity of the sand. Comparing the measured capacitance, we may safely assert that the upper permittivity value of the sand can meet the need for imaging the diffusion flame of methane.

The exact permittivity of the working medium is measured by an LCR meter. Pixel values of each working medium, whose permittivity ranges from 1 to 17, is obtained under the condition that the detection area is filled. Therefore, the relationship between permittivity and pixel value can be acquired, which turns out to be a linear model polynomial.

A series of experiments, which are catalogued into two groups, the diffusion flame group and the premixed flame group, have been done to validate the theoretical model of the effective permittivity of flame. The following pictures below are the reconstructed images of a diffusion flame with different flows values (F) of methane as acquired by the imaging system.

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Based on experiment results above, another novel sensor for three dimensional detecting is designed to monitoring flame. Three dimensional sensitivity field maps show that differences indeed exist among each individual sensitivity image, for example, the closer height level to the electrode surface, the stronger sensitivity field would be. The results show for the first time that the height level indeed has a great impact on sensitivity and thereby influence the reconstruction images. Therefore, 3D sensitive field maps reconstructed in this paper are necessary and present as new model in ECT research area.

Learning from the 3D reconstruction images based 3D sensitivity field maps, we may draw the conclusion that with the increase in section radius of spherical working medium, reconstruction images in different height do report the changing, and the position information of working medium is also reflect in these images.

4. Conclusion and discussions

This paper has validated the theoretical model of effective permittivity of flame. An ECT sensor that can withstand high temperatures is manufactured and a series of experiments based on ECT system have successfully imaged diffusion flame of methane. With every known relationship between pixel point and permittivity, rules of effective permittivity of flame are concluded in accordance with the obtained ECT flame images. Furthermore, a novel 3D sensor was designed to image three dimensional flame images. Simulation results have successfully demonstrated the importance of 3D technique in ECT research area.

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