Study on A Novel Approach for Boilover Prediction in Liquid Pool Fires with Water Sublayer

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Abstract

Experimental examination on the process of boilover, especially on the thermal process in the oil-water layers during oil burning, demonstrated that boilover happens only after the oil-water interfacial temperature reaches water's boiling point. And water's seething on the interface results in the emission of micro-explosion noise, which is certainly the premonitory phenomenon of boilover and supplies the fundamental of a new boilover predicting method, i.e., the occurrence of boilover could be predicted by the micro-explosion noise using noise recognition technique. For this purpose, some characteristics of micro-explosion noise was studied during boilover process, and analyzed in relation with the thermal process on the oil-water interface. In real fire fields, the micro-explosion noise is always contaminated by environment noise. A set of features and a practical noise identification model were submitted to identify the micro-explosion noise from background noise and predict the occurrence of boilover.

Key Words: Boilover, Noise Recognition, Prediction

1. Introduction

Generally, boilover is considered as one of the most dangerous behaviour in oil tank fires for its special combustion features. For example, it always happens suddenly after a long time quasi-steady burning of oil, which brings great difficulty for fire fighting. Additionally, once boilover happens on an oil tank, the flame goes up quickly, the flame radiation is enhanced strongly, a lot of burning oil is erupted out of the oil tank, and etc. All these disastrous behaviours not only could destroy the suppression apparatus and ignite other nearby oil tanks, but also could burn fire fighters, who may take suppression measurements nearby the oil tank. Unfortunately, the mechanism of boilover is still not clearly known, and there is no most efficient fighting strategy for boilover yet. Under this situation, boilover fire is somewhat unavoidable. So, either now or in the future, to monitor and predict the occurrence of boilover may be an important strategy to decrease the fire loss as possible and an effective supplementary strategy for active suppression measurements.

Based on experimental study on the boilover process, it could be concluded that a typical boilover process consists of three necessary periods: quasi-

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steady combustion period, premonitory period and boilover period. In the quasi-steady combustion period, oil's burning is stable, and hot zone is formed gradually in the oil layer and spreads along the depth of oil-tank[1]. When the bottom of hot-zone reaches the oil-water interface, the boilover process comes into its premonitory period and exhibits some special phenomena, such as the emission of micro-explosion[2,3], the fluctuation of flame height and etc. As the combustion process goes on, the oil-water interface is heated further and the water's seething becomes stronger. At last, boilover will happen as described previously. To predict and monitor the occurrence of boilover, our attention was mainly focused on the emission of micro-explosion noise. The mechanism of noise emission and the characteristic of micro-explosion noise were studied experimentally.

In actual fire fields, the premonitory micro-explosion noise is always contaminated by the background noise, such as speech noise, automobile noise, siren noise and etc. Consequently, one of the key technical points of this approach is to extract a set of features and create a practical model to identify the premonitory noise from the environment noise. Some preliminary works on this aspect were conducted, and the experimental results demonstrated the effectiveness of this approach. Practically, this approach also has its special advantages, i.e., sound signal could transmit to a far location from oil tank and boilover could be monitored and predicted remotely and safely.

2. Experimental Method

Experimental work can be mainly divided into two parts: one of them was designed to study the mechanism of the emission of micro-explosion noise. And the other part was designed to extract features of micro-explosion noise, and to build a recognition model and check its effectiveness. The experimental apparatus used may be schematically shown in Fig.1.

To study the noise emission mechanism and its relationship with the water's seething process on the interface, a special rectangular-shaped tank with three wall mounted with quartz glass was designed. The water's boiling process could be observed and recorded by a camera. And a set of sound recording system was used to record the micro-explosion noise on tapes during the entire oil burning process, so that the micro-explosion noise could be replayed and processed repeatedly, and the features most suitable for noise identification could be chosen from so many acoustic parameters.

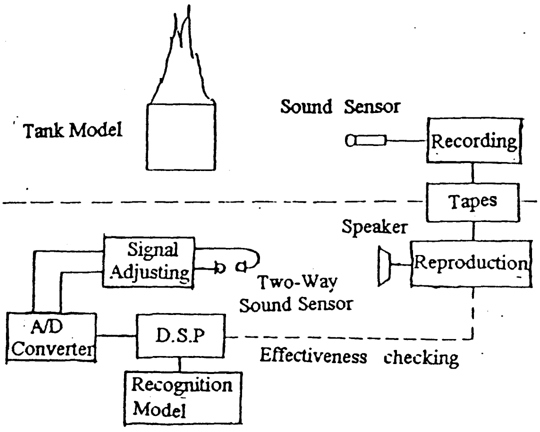

Fig.1 The schematic diagram of experimental apparatus

The second part comprises sound reproduction system, sound detection system and signal process system. To simulate the real situation, the micro-explosion noise and typical background noise are firstly retrieved from tapes. And then, they were detected by a two-may-sound sensor, which located several meters away from the speaker. After the sound signal was amplified and digitalized, it was processed and analyzed using digital signal processing technique. The recognition model gave the prediction results, which was checked with the actual situation to modify the model parameters. To check the effectiveness of this approach, the simulation of boilover was conducted under various experimental conditions and some good prediction results were obtained by the recognition system.

3. Features Extraction

Based on experimental studies, some features, which were suitable for noise recognition, were empirically defined as following.

3.1 Spectrum Form of the Micro-Explosion Noise

The spectrum structure, as we know, is the basic acoustic features of micro-explosion noise. Although the micro-explosion noise is a time varying signal during the entire boilover process, it could be regarded as stationary signal in a short time period. So the signal may be truncated by a short time window function and the transient spectrum structure may be estimated by FFT algorithm. To get more reliable data, the spectrum structure need to be averaged statistically over a short interval. Therefore, the averaged transient spectrum of micro-explosion noise could be obtained as following,

$$X(t,f) = \int_{-\infty}^{+\infty} x(t')\, W(t-t')\, e^{-j\,2\pi f t'} dt' \qquad (1)$$

$$S'(t,f) = \frac{1}{\Delta T} \int_{t}^{t+\Delta T} X(t,f) \cdot X^{*}(t,f)\, dt \qquad (2)$$

where $x(t)$ is noise signal series at time t ; $W(t)$ is the short time window function; $X(t,f)$ is the DFT transfer of noise signal at time t ; $S'(t,f)$ is the averaged power spectrum of noise at time t ; ΔT is the length of averaging interval.

Actually, the magnitude of the micro-explosion noise signal detected by the sound sensors not only may be affected by many factors such as the sensitivity of sound sensor, the distance between the sensor and oil tank and etc, but also varies with the burning time in the premonitory period. Under this situation, the absolute magnitude of the micro-explosion noise is not very important for noise identification. However, the power spectrum form, which denotes the sound energy distribution in frequency domain, is an important discriminant between the micro-explosion noise and the environment noise. To obtain the noise spectrum form, the short-time averaged noise spectrum given by Eq.2 was normalized by the total sound energy as following,

$$S(t,f) = \frac{S'(t,f)}{\int_{0\,khz}^{5\,khz} S'(t,f)\, df} \qquad (3)$$

3.2 Spectral Matching and Spectral Distance Calculation.

Template Matching is one of the most effective technique in patterns identification. Here, several groups of the micro-explosion noise samples collected from experimental simulation or in real fire field were used as the matching model. If the group $\{Sa(t,f)\}$ represents the spectrum form series during a typical boilover process, the template of the micro-explosion may be given by the following formula:

$$M(f) = \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} Sa(t,f)\,dt \qquad (4)$$

where, t_1, t_2 represents the beginning and the ending time of the premonitory period respectively.

The idea of template matching is to create a mathematic model to calculate the similarity between the detected signal and the sample model. Here, the formula shown following was used to calculate the spectral distance(SD), i.e., the similarity:

$$SD(t) = \sqrt{\int_{0\,khz}^{5\,khz} \frac{[\,s(t,f) - M(f)\,]^2}{W(f)}\,df} \qquad (5)$$

$$W(f) = \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} [\,Sa(t,f) - M(f)\,]^2 dt \qquad (6)$$

where $W(f)$ is the weight factor function calculated from the sample group.

3.3 Spectral Ratio

The spectral distribution of sound energy is a significant discriminant for noise recognition. Normally, the high frequency part (1.0-2.6khz) denotes the acoustic aspects of the micro-explosion noise, and the low frequency part (0.5-1.0khz) denotes the occurring rate of bubbles' explosion. So, in the premonitory period, two frequency parts coexist, but, in the quasi-steady combustion period and boilover period, main frequency domain is concentrated on the low frequency part. Here, spectral ratio(SR), a feature of the micro-explosion noise, was defined as,

$$SR(t) = \int_{f_1}^{f_2} S(t,f)\,df \qquad (7)$$

3.4 Occurring Frequency of the Micro-Explosion Noise

As stated above, the emission of micro-explosion noise is resulted from the water's seething on the oil-water's interface. Experiments demonstrated that, during a typical boilover process, the water's seething states occupied two phases, i.e., weekly seething stage and strongly seething stage. In the former period, there is only a small mount of bubbles generated on some regions of the interface and the micro-explosion noise is emitted now and then. As the burning process goes on, the interfacial temperature is increased further and more bubbles was generated on the entire interface. Consequently, the intervals between the emissions of the micro-explosion noise decrease. To describe this characteristic, a new notion named the occurring frequency of noise (OFN) is defined,

$$OFN(t) = \frac{1}{\Delta T}\int_{t}^{t+\Delta t} F(SD,\ SR)\ dt \qquad (8)$$

$$F(SD,\ SR) = \begin{cases} 1; & if\ SD, SR \in \{\ explosion\ noise\ \} \\ 0; & if\ SD, SR \notin \{\ explosion\ noise\ \} \end{cases}$$

4. Results And Discussions

4.1 Mechanism of Noise Emission

That the micro-explosion noise is emitted before boilover has been reported in [2,3] and observed in experiments. Normally, the oil which allows the occurrence of boilover has a higher boiling point than that of water, and smaller density. When oil burns, some of its combustion heat feeds back to the oil surface and heats the oil layer. Hot zone is gradually formed in the oil layer and spreads along the depth direction in the tank. When hot-zone reaches the oil-water interface, water near the interface is heated to its boiling point and water vapour begin to be generate on the interface. However, the hot oil layer prevents the water vapour from escaping from the interface. So, water vapour bubbles are formed and gathered on the interface. As the hot-zone spreads down further, the heat flux from the hot oil layer to the interface also increases. As a result, more water vapour is generated and the bubbles grow bigger. By the action of buoyancy force, vapour bubbles begin to leave the interface. When they pass through the hot zone, the vapour bubbles are heated, expand and are accelerated by larger buoyancy force. At last, enveloped by a thin oil-layer, the vapour bubbles escape from the oil surface and come into the flame zone. The violent combustion causes micro-explosion phenomena, which is accompanied by noise. A photograph shown in Fig.2 clearly illustrates the process described above. Measurement taken in [4] also show that the emission of micro-explosion noise in the premonitory is closely connected with the water's seething on interface. At the beginning, water seethes weekly, and the micro-explosion noise is emitted now and then. As combustion goes on, water's seething becomes stronger and the micro-explosion noise is emitted more frequently. When the water vapour's generating rate is so high that it can't escape from the interface in time, vapour explosion is caused on the interface and boilover fire will happen. Consequently, the emission of micro-explosion noise is certainly the premonitory phenomena of boilover.

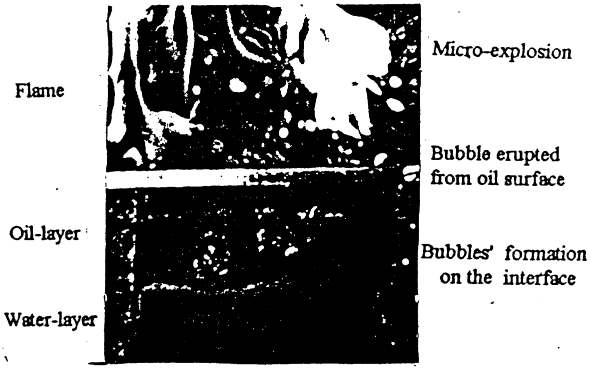

Fig.2 The emission mechanisms of micro-explosion noise

4.2 Specific Characteristics of the Micro-Explosion Noise

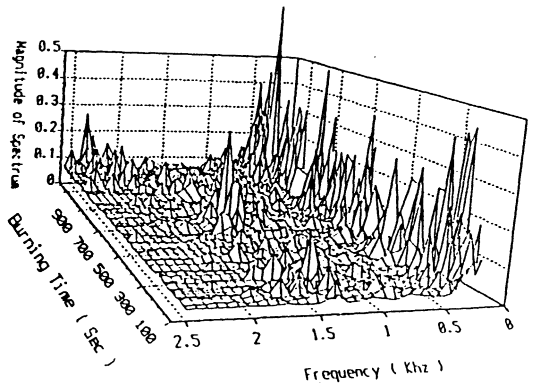

Fig.3 The variation of noise spectrum form with burning time

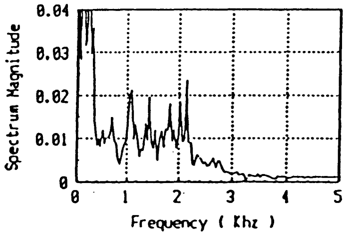

Fig.4 A typical spectrum form template of the micro-explosion noise

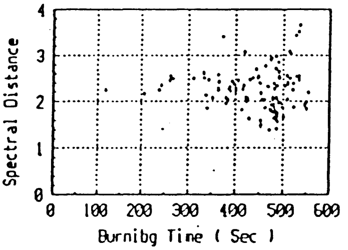

Fig.5 The variation of spectral distance with burning time

Fig.3 shows the variation of the normalized spectrum form during a typical boilover process. The environment noise occupied the low frequency domain during the entire process. In the quasi-steady period, there is also some noise emitted because of the existence of water in oil, but its main frequency is concentrated on the range of 1.0-1.6khz and its occurring frequency is lower. When boilover happens the main frequency shifted to higher range (1.6-2.6khz).

A typical template of micro-explosion noise and the variation of spectral distance (SD) during the entire boilover process was shown in Fig.4 and Fig.5 respectively. It could be clearly see that the template represented the basic spectral characteristics of the micro-explosion noise and the spectral distance reaches the smallest value in the premonitory period.

The variation of spectral ratio during a typical boilover process was shown in Fig.6. The spectral ratio reaches the largest value in the premonitory period.

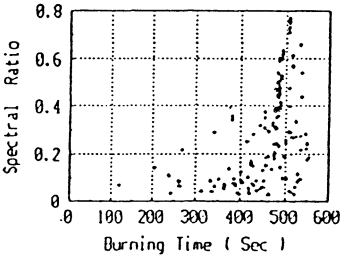

Fig.6 The variation of spectral ratio with burning time

4.3 Noise Recognition and Prediction

Fig.7 illustrated the distribution of one typical group of the micro-explosion noise and some groups of typical kinds of background noise in the space of features SD-SR. It tells us that the micro-explosion noise could be discerned from the environment noise.

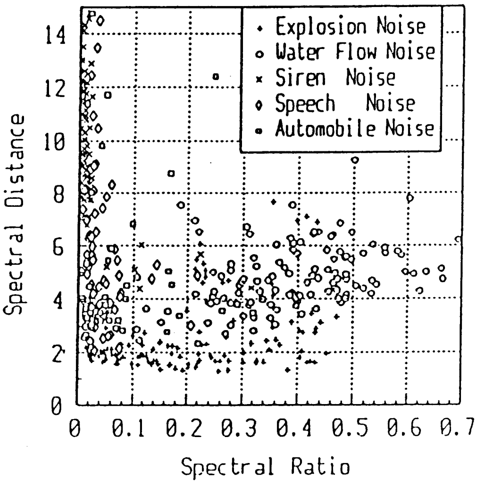

Fig.7 The distribution of micro-explosion noise and typical kinds of environment noise in the feature space

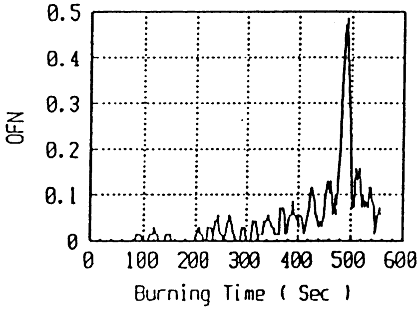

Fig.8 The variation of OFN with burning time

Based on the recognition of the micro-explosion noise, the occurring frequency of noise (OFN) could be obtained by Eq.3. Theoretically, the micro-explosion noise was emitted only after the interfacial temperature reaches water's boiling point. However, actually, because of the complexity of oil's component (e.g. existence of water), the noise is emitted during the entire oil burning process. The variation history of the feature OFN shown in Fig.8 illustrated that its value is lower in the quasi-steady period and boilover period, reaches its highest value in the premonitory period and ranges between 0.20-0.5.

5. Conclusion

Based on experimental studies on the thermal process of oil-water layer in the premonitory period of boilover, the emission mechanism of the micro-explosion noise was discussed and it was demonstrated that the emission of noise is the certain premonitory phenomena of boilover. As a result, a novel approach for boilover prediction, i.e. predicting the occurrence of boilover by the micro-explosion noise using noise recognition technique, was proposed and its effectiveness was demonstrated experimentally. Although the results given here are preliminary for they are obtained under lab condition on small scale oil-tank, they show us a successful prospect in practical situation.

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