Thermography Research for Radiation Measurement on an Oil Spill Fire

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Abstract

Research activity on the oil spill fire by the Fire Research Institute in Japan was introduced. Thermography, a high-speed radiation measurement with a IR camera using the computer for crude oil spill fire was focussed. This study started with the Hokkaido University and has been applied into the collaboration with NIST/BFRL of the US. That is, smaller scale experiments up to 2.7 m square fire tests were done in the FRI large scale test facilities, and the applications into Mobile 15 m square fire tests of NIST also were done. Through the analysis of both results, the scale dependency on radiant emittance of oil flame was obtained.

1 Introduction

To understand the combustion properties of oil fire is one of the most important items for fire science and fire fighting. The radiation from fire is especially one of the keys for fire fighting. Therefore many groups have been doing research in this field [For example, 1,2,3]. Recent accidents of large oil fires and oil spill fires have made this study more important. The Fire Research Institute, Japan (FRI) have been studying oil fires experimentally for a long time. Research on oil spill fires were also done as part of research of oil fires. Nii[4] reported about a huge oil spill fire tests which were done in 1969 on the Pacific Ocean near Tokyo. Yumoto did a large scale oil spill fire tests on water[5]. In most cases they were concerned about radiation from flame to surroundings, burning rates of fuel and flame spread rate in the case of unconfined fire. Currently we have focussed on the following topics regarding oil spill fire. That is, (1) Radiation from flame to surroundings, (2) Flame spread rate on oil on water. and (3) Boilover phenomenon.

In this paper, our recent radiation research with high-speed thermography using IR camera was introduced, which was done in FRI large test facilities[6], and at the US Coast Guard Field Test Facilities in Mobile, AL. Through the collaboration with NIST/BFRL, Dep. of Commerce, US, radiation measurements with the IR camera and wide angle radiometers were applied in these tests. The burning rate of fuel smoke emission were also measured.

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2 Experimental

2.1 High speed thermography

Thermography technique is not so novel, Hagglund and Persson[7] measured radiation from JP-4, 2 m fire using a IR camera and gave an averaged radiant emittance distribution of flame. Recent advanced technology made this measurement more precise, faster and easier. Mostly this has been used for measuring temperature of solid surface, and to measure gas temperature is difficult because we do not know emissivity of gas. A few groups already have been using this technology in fire science. That is, Oka and Sugawa used it for flame shape and height[8]. Saito and Ishida also used in their flame spread research [9]. We have started to use the measurement of radiation distribution of the pool flame surface[6]. Table 1 shows our equipment specification. It gives us 25,600 data about radiation and temperature in each picture which is able to be taken at maximum every 0.05 seconds. Temperature data and radiation one are able to be changed easily following the Steffan-Boltzmann's law (1).

$$q_a = k \cdot \epsilon \cdot \Phi \cdot \sigma \cdot T_a^4 \qquad (1)$$

Here, T_a is the flame surface or smoke temperature of each data point, q_a is the radiation from each flame part, s, at the target of outside flame, σ is the Stefan-Boltzmann constant. ϵ is the emissivity of flame surface or smoke which was not known exactly, but in such huge fires, emissivity of flame should be 1 or very close to 1, so we assumed $\varepsilon = 1$. Φ is the view factor, and k is a factor.

After receiving IR energy, thermography converted IR energy to temperature and shows 16 steps from 0 °C to 2,000 °C. In the FRI tests we selected temperature between 300 °C and 1300 °C, therefore each step had 62.5 K in width. This information was stored in the computer and dealt with easily.

Total radiation which a IR camera received, q, was expressed by the following equation (2)

$$q = \Sigma\, q_a \qquad (2)$$

For references, we also used wide angle radiometers which specifications are shown in Table 2. q should be similar value to which radiometer received from flame, q_{rad}.

2.2 Experiments in the FRI large test facilities

Smaller scale experiments were done at the center of the main test room of the FRI large indoor test facilities, which is 24 m times 24 m wide and 20 m height, so all the tests were done in a quiescent atmosphere. We used several size steel vessels, that is,

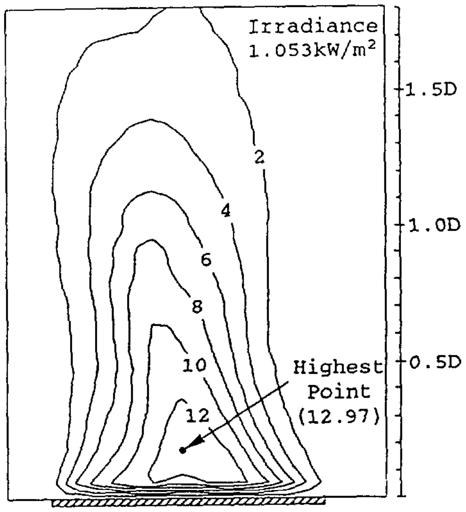

Figure 1 Radiant emittance distribution in 2.7m square crude oil fire (Unit ; $kW/m^2/Sr$)

Table 1 Thermography specifications

Type, Manufacture	TVS 3,000, Nippon Avionics Co.LTD
Detector	InSb (Indium - Antimonide)
Detector Coolant	Argon Gas
Spectral Range	3.0 to 5.4 μm
Scanning Method	Roating Mirror Wheel
Focus Range	254 mm to Infinity
Field of view	15° Horizontal x 1° vertical
Accuracy	0.4 % (Full scale)
Emissivity Compensation	1.00 to 0.10, 0.01 Step
Spatial Resolution	2.18 m rad (0.128°)
Display	10-inches RGB Color Monitor
Display level	16 colors
Display resolution	200 lines vertical
(Interpolation)	(100 x 256 = 25,600 Dots)
Time Constant	1 μ sec.

Table 2 Radiometer Specifications

Type, Manufacture	Re-2, Tokyo Seiko Industry Co. Ltd.
Detector	Thermopile Coated with Platinum Black
Solid angle	119° 41′
Heating surface area	100 mm^2
Time constant	0.30 sec

0.3 m, 0.6 m, 1 m in diameters and 2.7 m square vessels. Heptane, kerosene and Arabian light crude oil were used as fuels. Fuel was fed on the water for burning as steady state condition for at least 5 minutes.Initial lip height (vertical distance between vessel top and fuel surface) was 3 cm except 0.1 m for the largest one. Fuel level was not controlled during the test. IR camera was set at L/D=7.6 for 2.7 m square vessel, and L/D = 5 ~ 10 for the other vessels, here L is the distance between vessel center and IR camera and D is the effective vessel diameter, here D = 3 m was adopted for 2.7 m square vessel. Therefore most part of the flame was within the range of camera view. Radiometers were set at similar position, L/D = 5 ~ 10. Burning rate was measured by fuel level meter. Smoke yield was measured through the collaboration with the NIST group, which results were reported in another paper[10].

2.3 Large experiments at Mobile, AL

In order to measure smoke emission a series of experiments using 15 m square vessel were done at the US Coast Guard Mobile Test Facilities by NIST and other US organizations. The IR-camera which is portable, and similar to what was used at the FRI, was applied in the tests. Detector cooling type is different from stirring cooling with Helium gas. The distance between vessel center and IR camera was 129 m (L/D = 7.6), and height of the IR camera was 7.2 m. In this case, the area of each data point s was 707.6 cm^2. Louisiana crude oil was used, which density is 0.845 and heavier than Arabian light oil (0.830). The average initial lip height was 10 cm and the initial fuel depth was 5.5 cm. Details of this test will be reported by Walton et al.[11] in this Seminar.

3 Experiment results

Table 3 shows the summary of test results of using crude oil (Arabian light and Louisiana), heptane and kerosene.

3.1 FRI experimental results

Figure 1 shows an example of averaged emissivity distribution from 70 thermography pictures in a flame of 2.7 m sq. The figure unit of radiant emittance was in kW/m^2Sr. Arabian crude oil fire. The highest area of emissivity was around H/D=0.18, and the maximum value was about 163 kW/m^2, H was height from fuel surface. This height and maximum value were lower than other fuels, 0.50 and 185 kW/m^2 for heptane and 0.30 and 175 kW/m^2 for kerosene. This result for heptane is in good agreement with and more precise than our previous results using covered wide angle radiometer in heptane fire[3]. In smaller flames, smoke emission effects was relatively so small that emissivities of flame were less than that of 2.7 m square flame because emissivity was given the following equation;

$$\epsilon = 1-\exp(-\kappa \cdot D) \qquad (3)$$

Table 3 Summary of test

Place	Vessel Size (m)	Fuel	Burning rate (mm/min)	Radiation by radiometer at L/D=5 (kW/m^2)	Maximum Irradiance (kW/m^2)
FRI	0.3 0.6 1 2.7sq	Arabian	0.65 1.40 1.95 2.30	- 1.4 - 2.0 2.20 1.05	60.0 84.0 120.0 163.0
	2.7sq	Heptane	4.80	2.88	185.0
	1 2.7sq	Kerosene	2.50 4.20	2.30 1.27	144.0 175.0
Mobile	17	Louisiana	3.72	0.45	127.0

Absorption coefficient, κ for crude oil flame was given 2.8 m^{-1} by Babrauskas[12]. As radiant emittance, q_a was proportional to ε, the results were acceptable because we was able to ignore the smoke blockage effect in these size fire.

3.2 Mobile experimental results

In such a large scale fire using sooty fuel like crude oil, huge amounts of smoke were emitted, ie., smoke yield was around 10-15 %[11]. Therefore most parts of the flame were covered with black smoke. Figure 2 shows a series of thermography pictures which were obtained every 0.2 seconds. The temperatures shown in the figure were obtained assuming $\varepsilon = 1$. Only the part of a very near to fuel surface was always seen as a red flame. Its temperature was lower than 950 °C which was correspond to about 127 kW/m^2. Every few seconds a red flame ball type flame appeared and rose up. At H/D = 0.7 its size and temperature was maximum, and was able to be seen through the black smoke plume. This pulsation was around 0.45 Hz. This maximum temperature was 900 to 930 °C and was lower than the maximum one of flame base. These values were very low compared with the value which thermocouples gave within the flame, 1200 ~ 1400 °C in our previous data[10]. Most radiation, more than 80 % of total radiation from flame, was from the flame base at H/D < 0.2. The temperature of smoke was very low, that is, averaged temperature was about 400 °C, sometimes its temperature was below 100 °C even H/D < 1. These temperatures of smoke was correspond to the radiation of 4~20 kW/m^2.

3.3 Scale effect of radiant emittance

The radiant emittance of flame was obtained in each test. In the smaller flame, most of the flame was seen and maximum and averaged

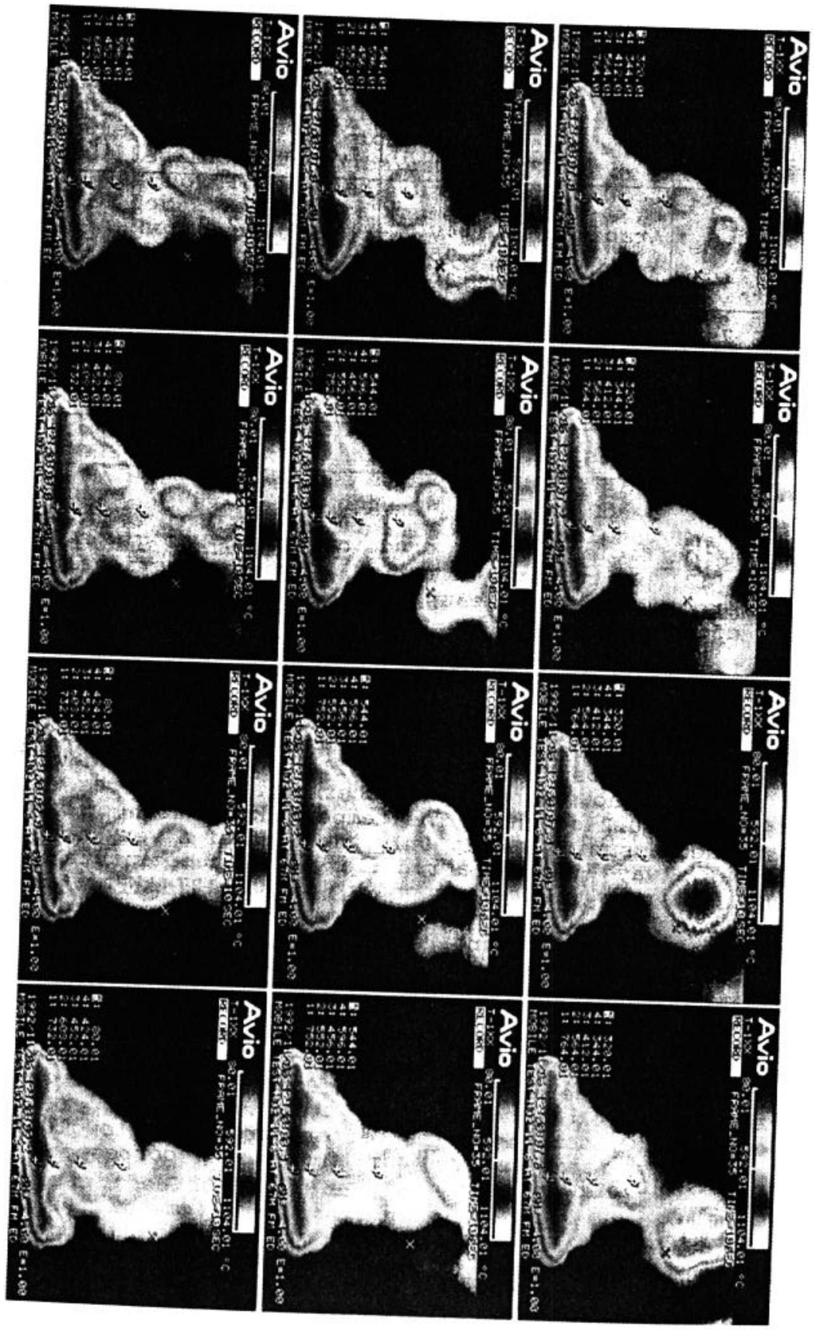

Figure 2 Thermograph picture taken by every 0.2 second
Numbers in this picture are temperature in each points assuming $\varepsilon = 1$.

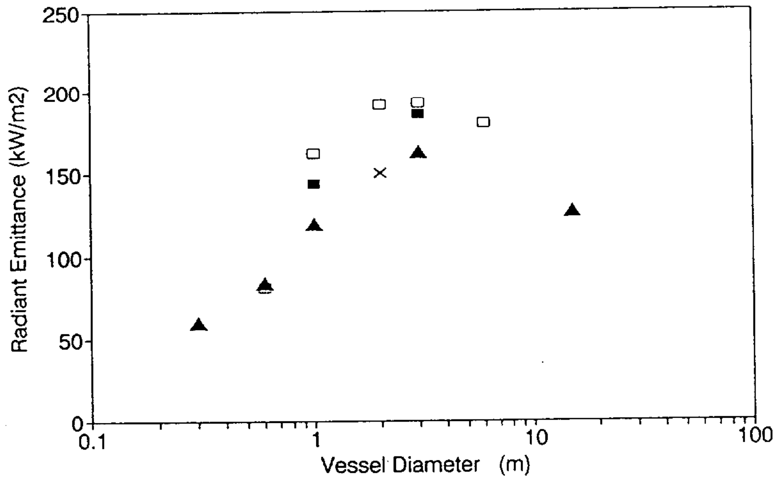

Figure 3 Relationship between radiant emittance of flame and vessel diameter
□: Heptane ■: Kerosene ▲: Crude oil ×: JP-4 [7]

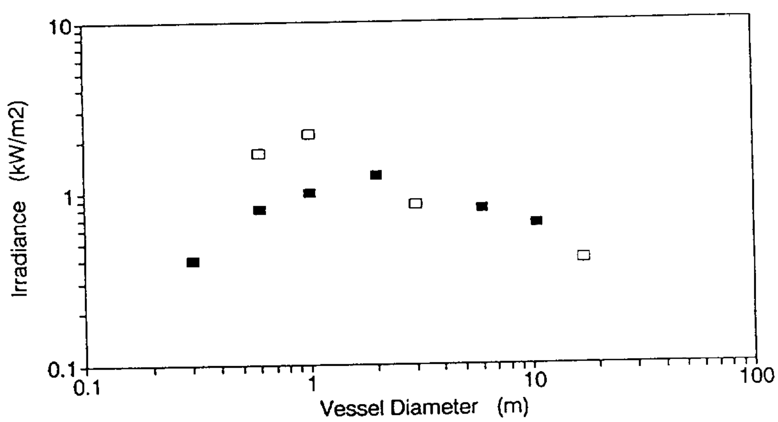

Figure 4 Relationship between irradiance at L/D = 5 and vessel diameter
□: Current data ■: Data from [10]

radiant emittance of flame were higher value. In the Mobile 15 m square fire most of the flame was covered with relative cold smoke when the temperature was lower than 300 ~ 500 °C. Therefore its radiant emittance was very low, around 20 kW/m^2. The relationship between maximum radiant emittance of flame and vessel diameter is shown in Figure 3. Our previous data of heptane and kerosene[3, 6] and averaged results of JP-4 fire given by Hagllund and Person[7] are shown too. They also gave 130 kW/m^2 for 1.5 m fire, 80 kW/m^2 for 5 m fire and 60 kW/m^2 for 10 m fire from spectra analysis as the average value. Their thermography results gave 90 kW/m^2 for maximum value and 20 kW/m^2 for smoke layer of 2 m square fire. Regarding the averaged value their results were good agreement with our crude oil data. Around 3 m in diameter fire, the radiant emittance of flame was maximum, 170 kW/m^2. Smaller than 3 m in diameter it followed with emissivity, and larger than 3 m, smoke blockage affected radiant emittance of flame. Compared 2.7 m square fire and 15 m square one, smoke yield were obtained at a similar value, about 10 to 15 %. Though most smoke existed above an upper flame in 2.7 m square fire, smoke emitted from near the base of flame too; and most of the flame was covered with smoke in 15 m square fire.

Irradiance at the target outside of the flame, q_{rad}, and burning rate also changed with the vessel diameter. Figure 4 shows the relationship between irradiance with radiometer at the place of L/D = 5 and the vessel diameter. Here our previous data were added[10]. These results were similar to the radiant emittance of flame, q, because q_{rad} can be given;

$$q_{rad} = q \cdot \Phi \qquad (4)$$

Φ did not change significantly because dimensionless flame height H/D, did not change when pan diameter changed. Therefore q_{rad} was affected mainly by q.

4 Conclusions

Thermography using the IR camera was used for oil spill fire test. This gave us radiation information which was more precise, faster and easier.

From the results, we understand that most of the radiation comes from a very low part of the flame in the case of crude oil fire. In larger flame, 15 m square fire, most of flame surface was covered with cold smoke and height of the maximum emissivity was very low. Average emissivity of flame was also very low.

The maximum radiant emittance of flame and irradiance at the outside target was maximum in 2 m or 3 m in the vessel diameter. In the smaller fire, it was smaller due to emissivity of flame which was less than 1. In the larger flame it became small with the vessel diameter increasing due to the smoke blockage effect.

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