Proceedings Combustion Fundamentals and Applications, Combustion Institute/ Central and Western States, Mexican National Section, and American Flame Research Committee

MEASUREMENTS OF POOL-FIRE TEMPERATURE USING IR TECHNIQUE

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ABSTRACT

We made an attempt to measure the flame temperature of four different diameter hexane-pool-fires using an IR technique. Emissivities for these four flames were estimated based on measurements of transmitted energy from a blackbody radiant source. The average flame temperature half way to the flame tip was 700 - 800°C, which was in good agreement with thermocouple-temperature measurements by others for a 3 m diameter hexane pool fire.

INTRODUCTION

Combustion, as a tool to mitigate spilled oils on the ocean surface, turned out to be more feasible compared to other possible means by converting rapidly large quantities of oil into their primary combustion products, carbon dioxide and water, with a small percentage of other unburned and residue byproducts [1]. According to Evans et al., "*In-situ burning of spilled oil has distinct advantage over other counter measures. It requires minimal equipment and less labor than other techniques. It can be applied in areas where many other methods can't due to lack of response infra-structure and/or lack of alternatives* [1]." However, it is difficult to establish an effective combustion method which has a high burning rate and emits only environmentally acceptable products mainly, because the structure of large crude oil fires is not well understood.

To understand the nature of the large scale pool fires, therefore, the Building and Fire Research Laboratory at the National Institute of Standards and Technology (NIST) conducted a series of pool fire experiments in order to characterize radiation and smoke emissions from large scale crude-oil pool-fires [2]. A series of pool fire experiments were performed using different diameter pools with the aim to establish effective correlations among these different pool fires. The main difficulty in this approach is that radiant energy emitted to surrounding changes as a function of the pool diameter affecting chemical and physical structures of pool fires.

As early as 1957, Blinov and Khudiakov [3] reported the first results of a series of pool fire experiments using four different liquid fuels. They changed the diameter of the pool from less than 1 cm to 22 m. They showed that the regression rate of fuel does not depend on the pool size, and two different scale lengths were used. One was associated with convective motion of fuel vapor, hot products and air, and the other was associated with the thickness of the hot layer formed on the fuel surface. In 1959, two years after the report of Blinov and Khudiakov [3], Hottel, by analyzing Blinov and Khudiakov data, concluded that in the turbulent pool fires, the dominant heat input to the fuel surface occurs by radiation [4].

The data by Blinov and Khudiakov [3] had been widely used by many fire researchers until the Japan Society for Safety Engineers conducted a series of larger scale pool-fire experiments [5,6]. In their 1979 experiments [5], three different diameter (6.5m, 10.9m, and 30.8m) tanks were used with light crude oil as fuel. In their 1981 experiments [6], three further larger diameter (30m, 50m, and 80m) tanks were used with kerosene as fuel. JSSE obtained very interesting data except in the 80m pool fire test in which the flame spread over the entire fuel surface because of the wind effect. Analyzing these data, Akita and Kashio [7] reported that radiation received at geometrically similar locations outside the pool decreased with the increase of the pool diameter, the regression rate of fuel remained approximately constant regardless of the pool diameter, and smoke production increased by increasing the pool diameter. The smoke effect was for the first time recognized as "smoke blockage effect" in which relatively cold smoke encloses the luminous flame zone, thus irradiance decreased with increasing the tank diameter [8].

Because little data is available on radiation from large pool fires, Koseki and Yumoto [8] measured radiation using a narrow angle radiometer to characterize the smoke blockage effect. Hayasaka et al [9] applied a high-speed thermography to measure radiation from a large scale pool fire. Recently, Koseki, Evans and Walton [10] applied a high-speed thermography to measure flame characteristics in a 15 m square crude oil fire which was conducted by NIST at the US Coast Guard Fire and Safety Test Detachment in Mobile, Alabama, March, 1994. In that experiment, the University of Kentucky team participated in measurement of a series of IR image maps for the pool fire. Our main objective was to measure the flame temperature (hopefully the maximum flame temperature in a luminous zone) by penetrating cold smoke and combustion by-product layers which surround the flame. We reported a 35mm direct photograph of two pool-fire flames, a schematic of the IR camera set up, the IR images corresponding to these two flames obtained with and without filters [11]. We found that the IR image for the flame with the 10.6 μm filter was designed to eliminate emissions from smoke and combustion by-product layers [12,13], while no-filtering IR images likely correspond to the highest temperature. These test results indicate that if we can come up with the correct understanding of the filtering technique, the IR technique with an appropriate filter can measure flame temperatures by penetrating smoke and combustion by-product layers enveloping the luminous flame.

EXPERIMENTAL METHODS

The IR Technique

We developed the IR temperature measurement technique which can penetrate smoke and flame in a room fire and identify the active pyrolysis location in burning materials [11]. It was found that the IR image through a 10.6 ± 0.5 μm band-pass filter had no flame interference effects, and accurately represents the wall temperature. Theoretical considerations confirmed that the technique is applicable for the spread rate measurement for commonly used building materials [11]. The significant advantages of the IR technique compared to the conventional thermocouple are:

* No sample preparation is required prior to the measurement
* The technique is non-intrusive (the system can be controlled in a remote location away from the fire)
* Nearly simultaneous temperature mapping in a relatively large area (easily, 20m x 20m) is available with high spatial and temperature resolution.

The IR image technique is an effective tool for studying large structure fires and could be applied to measuring the flame temperatures in large scale pool fires, where the conventional thermocouple technique has limitations because of unknown radiation-heat loss effect from the TC beads and thermophoretic effect of soot on the TC beads.

To investigate this possibility, we conducted a series of hexane-pool fire-experiments using four different diameter (5 cm, 9 cm, 14 cm and 20 cm) open-top containers and in the future we are planning to conduct pool fire experiments of

30 cm and 60 cm diameter. The 5 cm diameter pool fire is in a laminar regime, the 9 cm to 30 cm pool fires are in a transition regime, and the 60 cm pool fire is in a turbulent regime.

Emissivity Measurements

It is well known that emissivity of the pool fires changes as a function of the flame width (or diameter) and fuel type. We need to determine emissivity of the flame prior to the application of the IR technique to measure the flame temperature. Emissivity can be determined by: (1) comparing the pool fire with a target whose emissivity is known and temperature is the same as the pool fire, and (2) measuring τ and ρ, then using an equation,

$$\epsilon = \alpha = 1 - (\tau+\rho),$$

where, ϵ = emissivity of the flame, α = absorptivity of the flame, τ = transmissivity of the flame, and ρ = reflectivity of the flame. We assumed $\rho = 0$ and measured the transmission of the flame, τ. A schematic of the experiment for measuring transmission of the flame is shown in Fig. 1. The IR incident radiation level was measured with one point-measurement mode. Two different radiant sources, A and B were used. The radiant source A: $\epsilon_A = 1$ and the radiant intensity = I_A (Case 1). The radiant source B: $\epsilon_B = 1$ and the radiant intensity = I_B (Case 2). The radiant intensity of the flame, I_f can be measured by the IR camera. Then, placing a pool fire whose transmissivity is un-known between the radiant sources A and B and the IR camera (Cases 3 and 4), transmission energies $I_{AF} + I_f$ and $I_{BF} + I_f$ can be measured by the IR camera. Using the following equation,

$$\tau = [(I_f+I_{AF}) - (I_f+I_{Bf})]/(I_A-I_B),$$

transmissivity of the flame can be calculated. We conducted the transmission measurements for four different diameter hexane-pool-fires. We found the emissivitiy of the flame was approximately constant along the centerline and varied significantly in the radial direction. Figure 2 shows ϵ as a function of pool diameter.

Flame Temperature

Using the emissivities determined from the above measurement, the IR camera's isothermal mode was selected to measure flame temperatures. Increment of each isothermal contour was fixed at 50°C. Pool fires pulsate because of unsteady fire-induced buoyancy-driven flow [14] and when the flame pulsates, flame shape changes significantly. To characterize the pool fires, therefore, a time averaged emissivity is better than an instantaneous one. Figure 3 shows five different IR images for four different diameter pool fires. Interestingly, for these pool fires, the average flame temperature was approximately in the neighborhood of 700 and 800°C which is in good agreement with the thermocouple temperature measurement for a 3 m diameter hexane-pool-fire. The maximum centerline temperature was recorded approximately half way to the visible flame tip, while the flame temperature is relatively low in the lower half of the flame. This observation is consistent with the thermo-couple temperature measurement data for a 3 m pool fire reported by Koseki et al [8].

SUMMARY AND CONCLUSIONS

(1) Transmission was measured using the IR camera for four different diameter hexane-pool-fires. Based on those data, emissivity was calculated for those four pool fires.

(2) Using the emissivity determined above, temperature distributions for those four different pool fires were measured by the IR camera. It was found that the average flame temperature was in the neighborhood of 700 to 800°C.

ACKNOWLEDGEMENTS

We wish to acknowledge Dave Evans and Doug Walton for their guidance in this research project. This study was supported by the Building and Fire Research Laboratory at the National Institute of Standards and Technology under Grant 60NANB4D1674.

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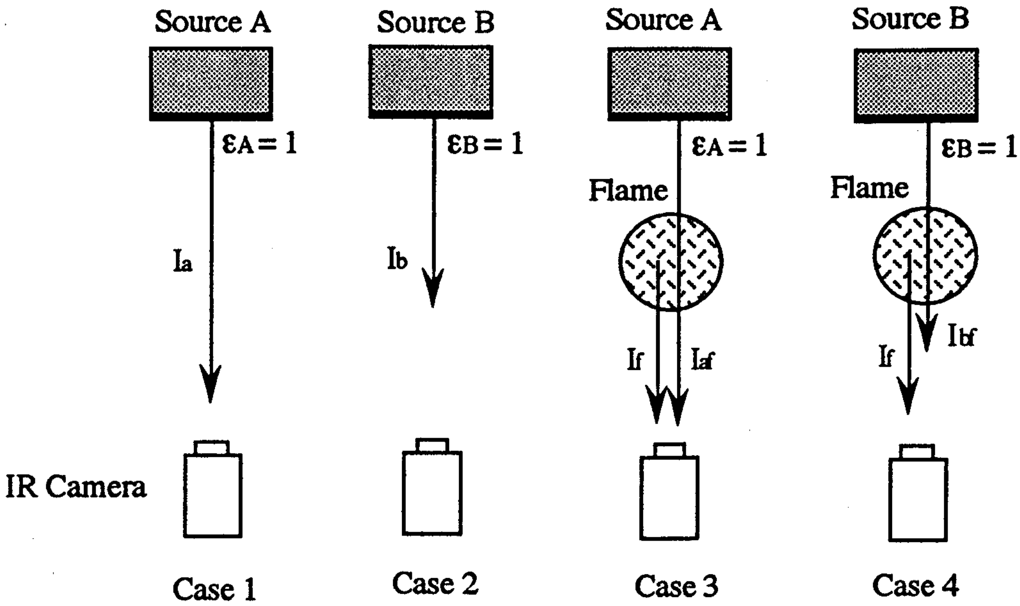

Figure 1 A schematic of the flame transmissivity measurement using two blackbody sources A and B.

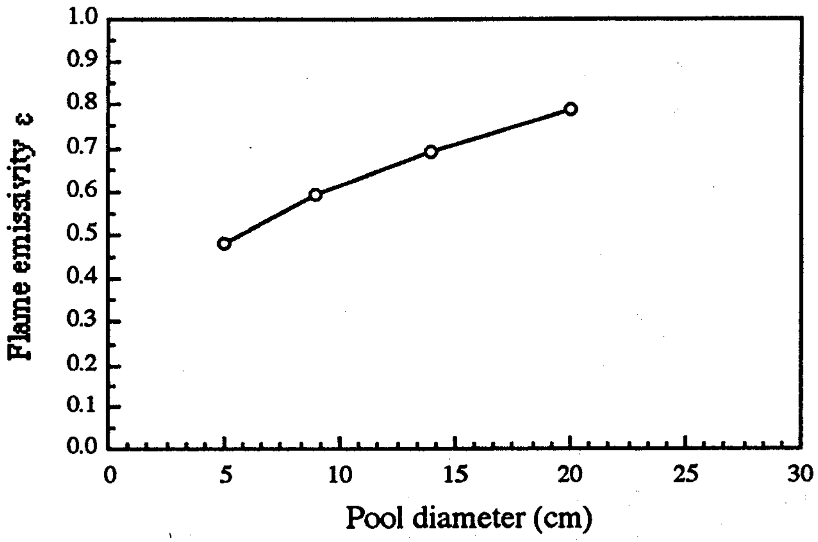

Figure 2 Hexane flame emissivity determined by the IR camera as a function of pool diameter

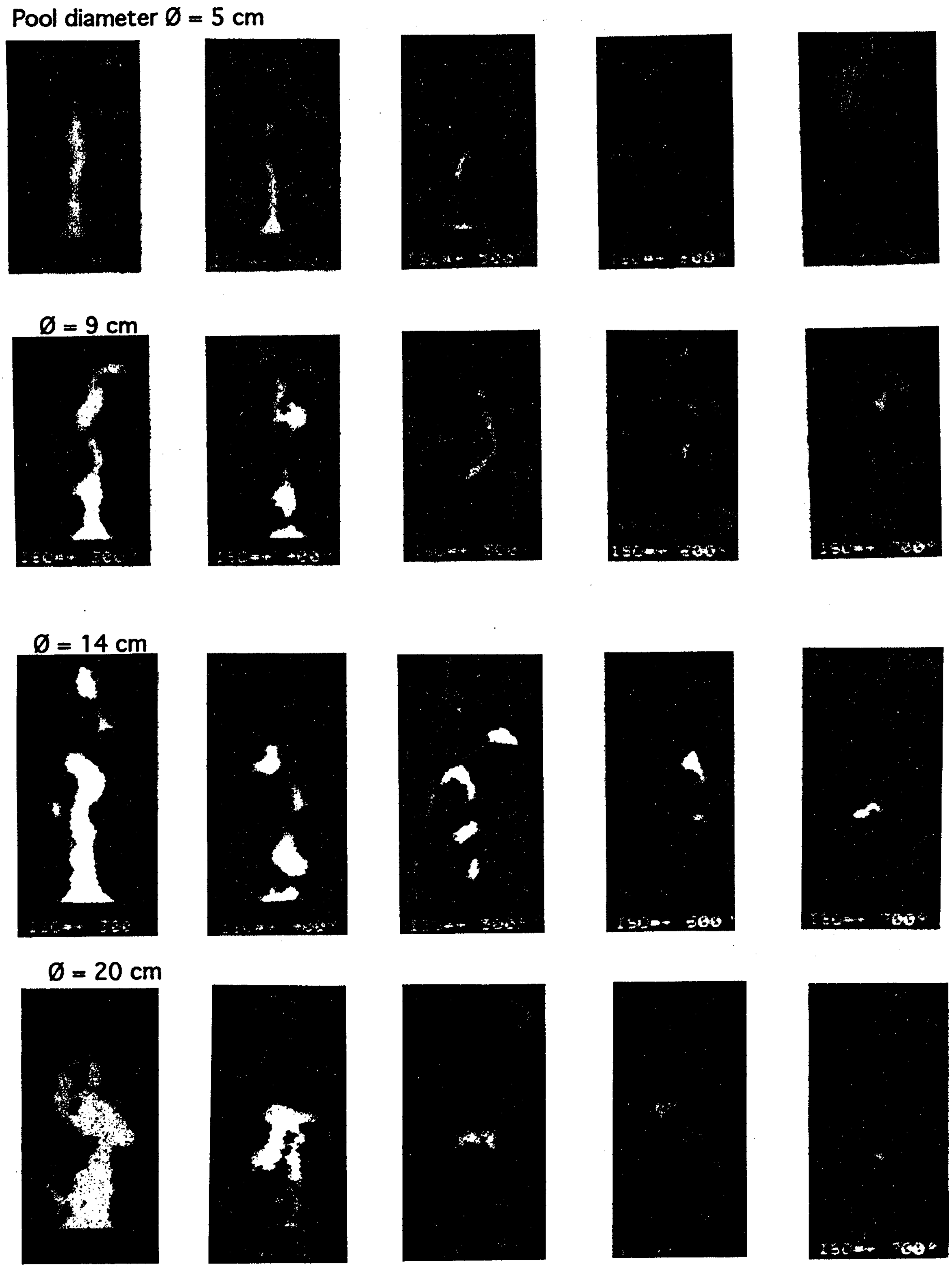

Figure 3 IR images of four different diameter pool fires. The ISO temperature is the temperature at the image boundary.