# Burning Characteristics of Heptane in 2.7m Square Dike Fires

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ABSTRACT

An experimental study was made to explore the burning characteristics of heptane in 2.7m square dike fires, through measuring burning rate, flame temperature, thermal radiation, hot gas velocity and gas composition of flames. Two types of dike fire experiments were performed; one was a dike fire with four open top tank fires and another was a dike fire without tank.

The results show that there is little difference between both types regarding total mass burning rate and thermal radiation, but it was noted that burning in the dike fire with open tanks was accelerated in spite of poorer air entrainment than that of the dike fire without tank based on the gas composition data and the ratio of air entrainments A/Ao. (A: Mass air entrainment, $A_0$: Mass air for stoichiometric combustion of heptane).

key word: dike fire, radiation, burning rate, isotherms, air entrainment, flame merging, gas composition

## INTRODUCTION

Oil dike fires are one of the most dangerous types of accident in oil storage tank facilities, because the fire area becomes very wide, and not only one tank but other tanks within the same oil dike may be ignited due to radiation or direct contact with the oil dike fire. It may happen when, for example, an oil tank is damaged by earthquake, or oil is leaking from a tank or piping for any reason. Fortunately, there have been very few oil dike fires in Japan, but some terrible oil dike fires have occurred in other countries.

In spite of the dangerous nature of oil dike fires, very few experimental reports can be found except for the author's earlier work [1]. In this paper, the burning characteristics of heptane in 2.7m square dike fires were explored, through measuring the burning rate of heptane, flame temperature, vertical hot gas velocity, gas composition in the flame, and thermal radiation to surroundings.

To see the influence of existence of tanks in oil dike fires, two sorts of dike fires tests were conducted, that is;

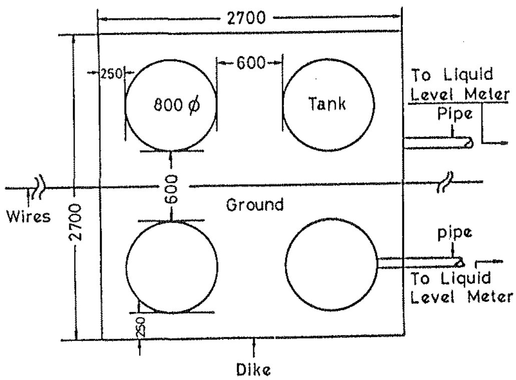



FIGURE 1. Arrangement of a dike and four tanks. unit:mm

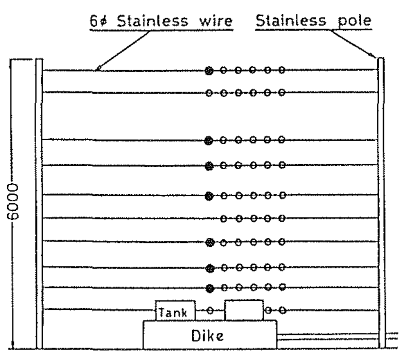



FIGURE 2. Position of thermocouples (Open & solid circles) and bidirectional tubes (Solid circle). unit:mm

(1) Dike fire with four open-top tanks fires
(2) Dike fire without tank

EXPERIMENTAL

The test was conducted at the Fire Research Institute's large test facilities (main test room is 24m x 24m wide, and 20m high). Figure 1 shows a schematic illustration of the arrangement of a dike and four tanks. A 2.7m square steel pan was used as a model oil dike. This size of oil fire is the maximum which can be conducted in the test facilities. Four tanks each of which has a diameter of 0.8m were set in the dike under the following conditions: 0.6m tank-to-tank space, 0.25m tank to dike space, and 0.4m tank height (above dike rim). Initial free board, distance between tank or dike edge and fuel surface, were 7 cm for oil dike, and 3 cm for tanks. Fuel level was left to go down during the test.

Burning Rate

About 3-6 cm of heptane floating on water was burned in the oil dike and each tank. The burning rates (liquid surface regression rates) were measured by float type level meters which were connected with the piping of the oil dike and a tank as shown in Figure 1. The outputs of the level meters were recorded on a pen chart type recorder.

## Temperature

Temperatures both within and near the flame were measured with 60 K-type, stainless sheathed, thermocouples of 0.3 mm diameter wire. The locations of the thermocouples are illustrated in Figure 2. The signals from the thermocouples were recorded on a computer data logger at intervals of 10 seconds.

## Radiation to Surroundings

Radiation from the whole flame to surroundings was measured by thermopile type radiometers, which time constant is 2.3 seconds, were located at the position of L/W=5. Where L was the radial distance from dike center to the radiometer, and W was a side length of the dike.

Radiations from horizontal slices of the flame were measured by five narrow angle radiometers. Each of them has a different opening size hood to get the different view angle. All radiometers were installed at L/W=5 and an elevation equal to that of the top edge of the oil dike.

## Vertical Velocity and Air Entrainment

Vertical hot gas velocities on the axis of the oil dike were measured by 7 stainless steel bidirectional pressure probes. The locations of the pressure probes are illustrated in Figure 2. The amplified signals from the differential pressure transducers (maximum range of

TABLE 1. Burning rate of Heptane and heat radiation from the flame in two sorts of dike fires.

| Type of dike fires | Total mass burning rate* (kg/min) | Burning rate (mm/min) | | Radiation*** ($kW/m^2$) |
|---|---|---|---|---|
| | | Dike** | Tank | |
| Dike fire with 4 open-top tank fires | 39.2 (24.1) (15.1) | 6.7 | 10.8 | 3.40 |
| Dike fire without tank | 37.2 | 7.1 | | 3.55 |

* Total of mass burning rate of Heptane on the ground and in 4 tanks. Numeral in upper parentheses in second row shows mass burning rate of Heptane on the ground and that in lower one shows total mass burning rate of 4 tanks.

** Burning rate of Heptane on ground in a dike.

*** Irradiance at a point of 13.5m from center of a dike.

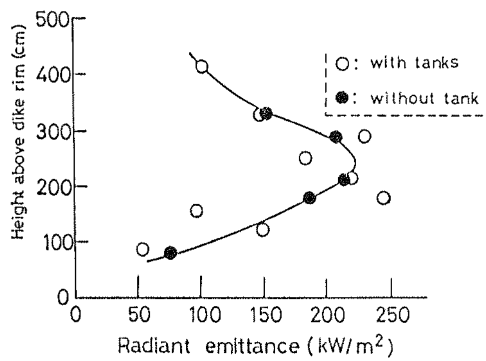



FIGURE 3. Radiant emittance measured by narrow angle radiometers.

measurement 70 mm $H_2O$) were recorded on a digital data recorder.

The amount of air entrainment into the flame at any height was clculated by using time averaged velocity and temperature, which were taken for at least five minutes after few minutes from ignition. The flame was straight vertically during the measurement.

## Gas Compositions

Gas samples along the flame axis were withdrawn by means of a batch sampling system and system and were analyzed $O_2$, $N_2$, $CO_2$, CO and hydrocarbons ($C_1$ - $C_7$) with four gas chromatographs. Concentration of $H_2O$ was calculated with these data by the method of Alger [3]. To avoid soot choking at the tip of the sampling probe, six 8 mm i.d. stainless steel pipes were used themselves as the sampling probes. The samples were drawn into six syringe type 100 ml glass sampling tubes. The data obtained were both space- and time-averaged values. To prevent condensation of water and fuel vapors, the lines to the sampling tubes were all heated to about 100°C with ribbon heaters.

## RESULTS AND DISCUSSIONS

Following results and discussions are based on the data obtained from under steady state burning.

## Burning Rate and Radiation

A summary of the burning rate and radiation test results from the flame are shown in Table 1. In this table, total mass burning rate means sum of both mass burning rate of ground fire and that of tank fires. The results show that, on the total mass burning rate and thermal radiation, there is little difference between two oil dike fire. From dozens of photographs for each flame, the averaged, visible flame heights are 7.6m for the oil dike fire without tank, and 7.0m for the oil dike fire with tank fire. There is relatively little difference between the two cases, but it is apparent that combustibility of dike fire with 4 tanks is better than that of fire without them since the flame height as lower in spite of a higher burning rate.

Assuming isotropy, the total radiative power output, Qrad, is simply the flux times the spherical surface area:

$$Qrad = 4\pi L^2 E$$

Total heat release rate Qtot is:

$$Qtot = \pi R^2 V \rho Hc$$

So the radiative fraction X, ratio of radiative output to total nominal heat release rate, is

$$X = Qrad/Qtot = 4\pi L^2 E/\pi R^2 V \rho Hc$$

where V is burning rate (linear regression rate), $\rho$ the density of fuel, Hc the heat of combustion, and E the irradiance at distance L, and R the vessel diameter. The results of these calculations give radiative fractions of 0.280 for the fire with tanks, and 0.309 for the fire without tanks. These results indicate that radiative fraction is smaller, and the convective fraction for upwards in larger for the fire with tanks.

Radiant emittance measured by narrow angle radiometers is shown in Figure 3. In both fires the peak radiation is at about H/D=0.75, at the same height as maximum temperature in the flame. In this figure, based on limited data, the existence of second radiative peak is not clear, but we would expect to find one corresponding to the second flame temperature peak at H/D=0.8.

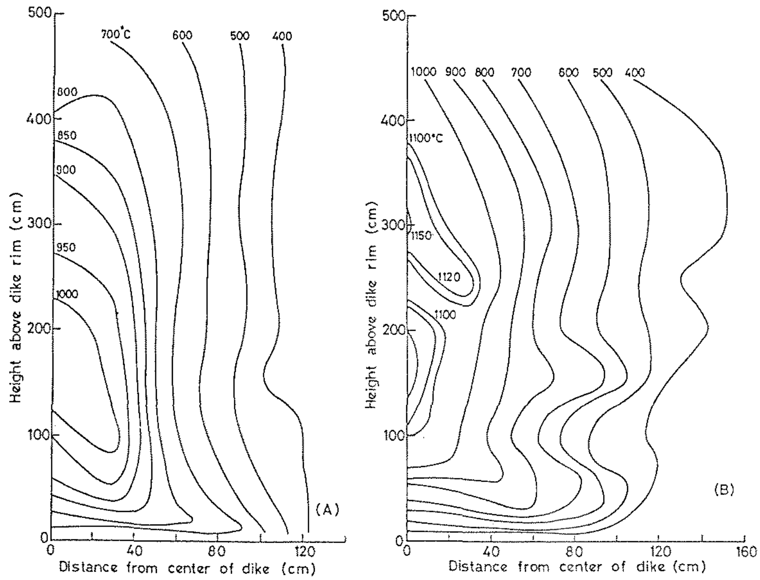
## Isotherms

Since the flame was a turbulent one, isotherms varied with time although the burning rate was constant. The isotherms were shown in Figure 4 (A)-(C) are samples taken at random from several tests. Temperature along rhe flame axis, in the fire with tanks is higher than that in the fire without tank, that is, maximum temperature in the dike fire with tanks was about 1160°C, and that in another fire was about 1050°C.

Isotherms in the dike fire without tanks (Figure 4(A)) are very similar to those of ordinary oil tank fires [4]. In the dike fire with 4 open top tank fires, there are two types of isotherms, one showing two peaks (Figure 4(B)) and another showing is one peak (Figure 4(C)). We supposed that the reason for the peak in down-stream may be flame merging from the 4 open top tank fires in the dike. Unfortunately, we could not distinguish visually flame merging with both dike and tanks burning, but we found flame merging when the 4 open top tank fires in the dike were continued just after the ground dike fire in the dike burned out.

To clear up this problem, we conducted a test on flame merging using 4 open 0.8m diameter tanks. Figure 5 shows this test briefly. Here, S is tank-to-tank space, V is burning rate of heptane. In one tank fire, the burning rate was 2.9mm/min, but in 4 combined tanks (S=0), burning rate was 5.5mm/min because of flame merging.

In four tanks fires having certain spaces between tanks, the burning rate was 4.7mm/min (S=0.3m), and was 4.6mm/min (S=0.6m). From these data and observations we saw that flame merging caused increases in burning rate and flame size. When S=0.6m, it was just transitional with frequent flame merging.



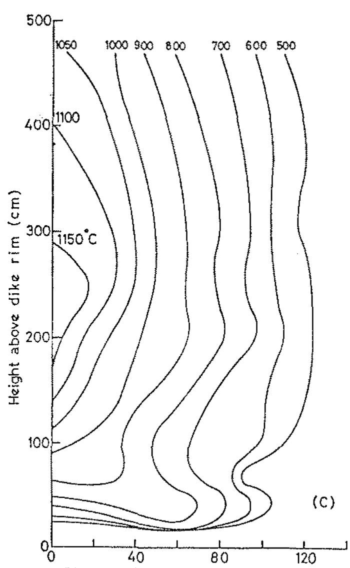




FIGURE 4. Isotherms in flames.
(A) Dike fire without tank.
(B) Dike fire with 4 open top tank fires. (Two peaks type)
(C) Dike fire with 4 open top tank fires. (One peak type)

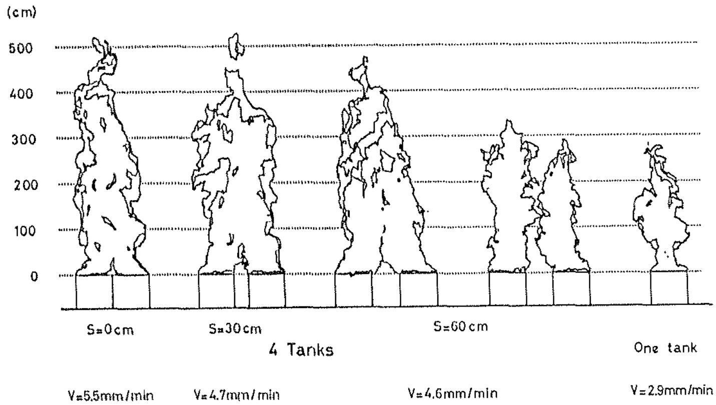



FIGURE 5. Flame merging of four 0.8 m open top tank fire (S: Tank-tank space, V: Burning rate of Heptane). Four tanks are not in a dike.

## Air Entrainment

In Figure 6 (A)-(B), the relationship between dimensionless air entrainment $A/A_0$ and height above top of dike was shown. Here, A is mass air entrainment at a given height, and $A_0$ is mass air for stoichiometric combustion of heptane. For this calculation, we adopted two assumptions: one was based on the top hat profile, that is, velocity, density, temperature are uniform across the section. 'Top hat profile model' is not the best way to discuss flame dynamics, but we use this model because it is easy to compare two type dike fires with this model. Another is that the flame is rectangle with the same cross-section as the oil dike.

From these figures, air entrainment in the fire with tanks, is slightly less at any height. Probably the reason for this phenomenon is prevention of air entrainment by tanks.

## Gas Composition Profiles

Figures 7,8 and 9 show gas composition profiles along the flame axis. These profiles were drawn from the data obtained in several tests, Figure 7 shows $O_2$ concentration along the flame axis. In the fire with tanks, $O_2$ concentration is slightly higher, but we did not find a large difference between two cases.

Figure 8 shows $CO_2$ concentration along the flame axis. There is a peak of $CO_2$ at about H/D=0.7. This height is about same as the peak radiant emittance of the flame, and peak temperature. In the fire with tanks, we don't find a peak in the $CO_2$ level between 0.4 and 1.5 of H/D. Concentration of $CO_2$ is 0 at the fuel surface, so the peak must be at between 0 and 0.4 of H/D. From the figure we can deduce that most combustion reaction occurs at a lower position than in the fire without tanks. To clarify this relationship, the dimensionless carbon dioxide

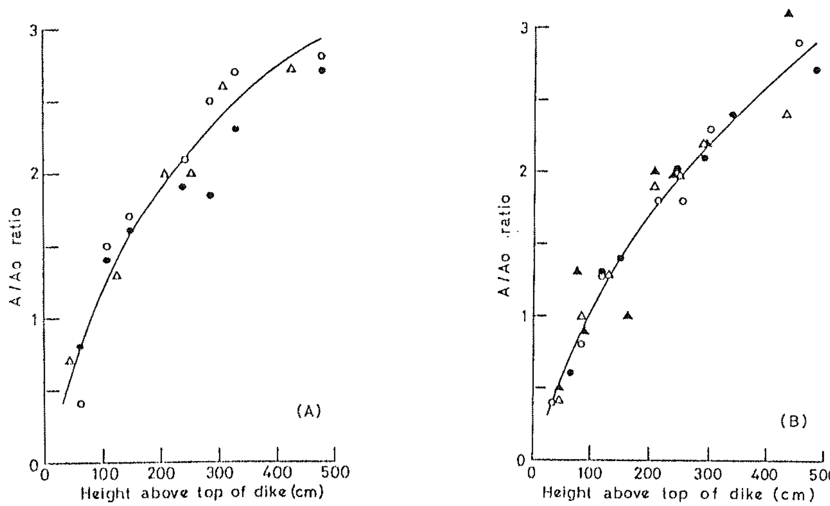



FIGURE 6. Dimensionless mass air entrainment based on Top hat profile assumption ($A_0$: Mass air entrainment, A: Mass air for stoichiometric combustion of Heptane).
(A) Dike fire without tank. Three different symbols show three tests in the same experimental condition.
(B) Dike fire with 4 open top tank fires. Four different symbols show four tests in the same experimental condition.

concentration ($CO_2$*) was calculated with the following equation.

$$CO_2{}^* = C_{CO_2}/(C_{CO_2} + C_{H_2O} + C_{CO} + C_{HC})$$

Here C denotes mass concentration of gas species, and HC stands for total hydrocarbons. By uging $CO_2$* we can cancel errors in sampling gases from fire, but there is a bit of error because of ignoring produced soot.

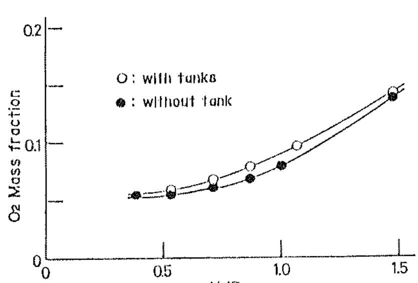



FIGURE 7. Oxygen concentration along the flame axis.

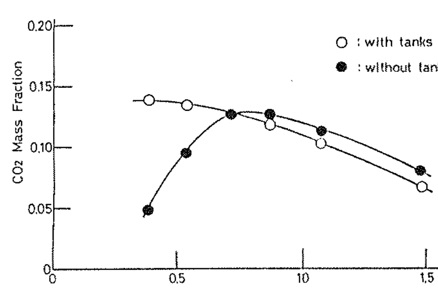



FIGURE 8. $CO_2$ concentration along the flame axis.

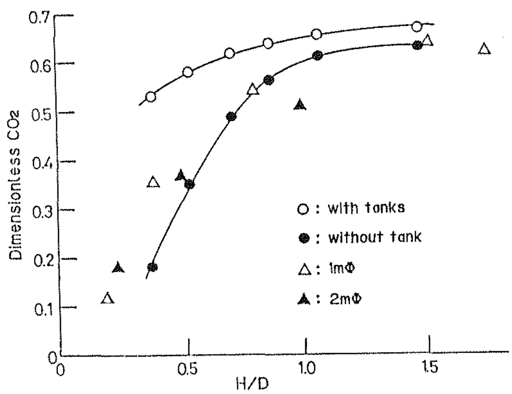



FIGURE 9. Dimensionless $CO_2$ concentrations along the flame axis.

Figure 9 shows dimensionless $CO_2$ along the flame axis. Data from a 1m diameter fire, and from a 2m diameter fire [5] are shown for reference. Except for the dike fire with tanks, $CO_2$* increased rapidly until 0.8 in H/D, but in the dike fire with tanks, most reaction finished below 0.4 in H/D. Finally, when heptane fuel was converted to $CO_2$ and $H_2O$ completely, with the equation:

$$C_7H_{16} + 11(O_2 + 3.76N_2) = 7CO_2 + 8H_2O + (3.76x11)N_2$$

So $CO_2$* must be 0.681 with this equation.

$$CO_2{}^* = C_{CO_2}/(C_{CO_2} + C_{H_2O}) = 7x44/(7x44+8x18)=0.681$$

The ratio of the value of $CO_2$* at each height to 0.681 gives a measure of completeness of reaction in the flame. According to Beer et al [6], when ($CO_2$*/0.681)=0.99, it is indicative of flame tip for diffusion flame. At H/D=0.9 in the fire with tanks, and at H/D=2 in the fires without tanks and 1 m, and 2 m in diameter fires we find this condition, the $CO_2$*/0.681 =0.99. In the fire with tanks, the averaged visual flame height is about 2.33, so the presence of tanks accelerated the mixing of air and fuel gas and a more efficient combustion takes place within the flame.

## CONCLUSION

While heptane was burned in oil dike with and without 4 open-top tank fires, measurements of burning rate, flame temperature, vertical hot gas velocity, radiation, and gas concentration were performed. Based on the foregoing results, the following conclusions are presented.

(1) In the dike fire with 4 tanks fires, we found slightly higher total burning rate, more reduced radiation, lower flame height, and lower radiative fraction. This indicates more efficient combustion conditions in the fire with tanks. Although a difference between both fires is recognized, to estimate the dangerous of oil dike fire, it may be possible to use the data of oil dike fire without tank in stead of that of oil dike fire with tank fire on the total mass burning rate and thermal radiation.

(2) In the dike fire with 4 tanks there is frequent flame merging which increased the burning rate of 4 tanks within the dike, and made better combustion.

(3) $CO_2$ concentration data supports conclusion (1), and indicates most of the combustion reaction occurs at a lower position in the flame, especially in the dike fire with tanks, in spite of poorer air entrainment.

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