Combustion Properties of Large Liquid Pool Fires

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Abstract

Data from a number of large liquid pool fire experiments, recorded at the Fire Research Institute of Japan over more than a dozen years, were gathered and compiled. Burning rate and radiative outputs of gasoline, kerosene, and heptane were of primary interest. It is difficult to deduce the behavior of large fires from data on small fires because of the likelihood of decreasing combustion efficiency and heavy soot generation with resulting blockage of radiation. The data compiled here is possibly the largest body of data available for study on large pool fires.

Introduction

Many studies have been conducted on liquid pool fires over dozens of years since Blinov and Khudiakov.[1] Examples of such studies are those by Babrauskas[2] and Muden.[3] However, there are only a small number of reports on large pool fires, due to high cost and technical difficulties.

The Fire Research Institute of Japan (FRI), has been concerned with large liquid pool fires for more than a dozen years. Many of the tests reported here were conducted by or in cooperation with the author. All tests were reported but many of the reports were in Japanese, so are not widely available to international researchers. This paper introduces, compiles, and discusses these test results. Several fuels, gasoline, kerosene, and heptane in particular, were burned in various sized tanks and the results are discussed.

Useful Data

Basically the data adopted here are from References 4–14. Results were tabulated by type of fuel in Table 1. Here only data for tanks larger than 3 m diameter (2.7 m square) were tabulated, but smaller tank tests were also conducted, and some of them have not yet been reported. These test results, and also some useful data compiled by other researchers, are

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shown in this paper. It is believed the largest tests were conducted during the kerosene pool fire discussed in Reference 7. In this series of tests, an 80 m diameter pool fire test was also conducted, but due to strong winds, the fuel did not spread over the entire pool surface, so the test was not a success. In other cases, tests were attempted in slight winds and the data were taken in the best wind condition.

Experimental

The experimental methods were stated in each paper, so they are mentioned only briefly here. To understand the test layout easily, Figure 1 shows a schematic diagram of the heptane 6 m pool fire in the test.[11] The burning rate was measured by float-type level meters which were connected with the piping of the tank. The lip (free board-distance between tank edge and fuel surface) was about 3–5 cm. Basically, the fuel level was not controlled during the test, but we believe only a few cm change of lip did not have a large influence on those large tank fires, despite of Orloff's report.[15] Radiation was measured by thermopile-type radiometers, which have a time constant of about 2.3 s. The radiometer faced the tank center, and its elevation was nearly equal to the height of the tank edge (about 70–90 cm from the ground level[9–11]). Temperatures were measured with K-type thermocouples of 0.3 mm diameter wire.

Discussion

Burning Rate

Burning rate was the most frequently measured factor, and is derived from the fuel surface regression rate. With the data in Table 1 and other data from References 1, 4–14,and 16-18, the relationships between tank diameter and the burning rates of gasoline, kerosene, and heptane are shown in Figure 2. We still do not have sufficient data, but in tanks larger than about 3–5 m diameter, we found that the burning rate was almost constant for these fuels. Here, for reference, Blinov's data[1] for gasoline and tractor kerosene were placed on the figure. Their test was done more than two decades ago, but the differences between the two sets of data were not great.

The effect of the carbon number of the fuel on the burning rate was also studied. The effect of the difference in C number of a fuel on the burning rate in a 1 m tank is shown in Figure 3. In these tests, alkanes from pentane (C_5) through octane (C_8), alcohols from methanol (C_1) through butanol (C_4), and acetone were burned. Mixtures of hydrocarbons were also tested, gasoline (major components: C_4 through C_{10}) and kerosene (C_{10} through C_{13}), and are represented in the figure as bars for their major carbon numbers. For alcohols, the larger the C number is, the higher the

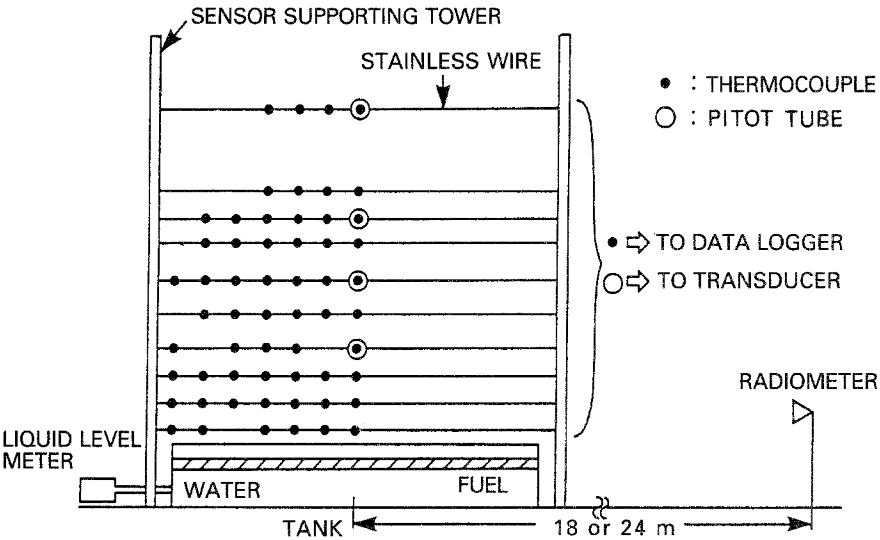

Figure 1. Schematic diagram of 6 m heptane pool fire in the test.

burning rate is. In large pool fires, burning rates appeared to depend on radiation from flame to fuel surface, which was controlled by the density of soot in the flame. On the other hand, for alkanes, the larger the C number, the lower the burning rate was.

Zabetakis et al.[19] suggested that the burning rate in a large pool, V, is expressed by the equation:

$$V = K \times \Delta H_{comb} \ / \ (\Delta H_{vap} + \Delta H_{heat}).$$

Here, ΔH_{comb} is the net heat combustion, ΔH_{vap} is the heat of vaporization of fuel at the boiling temperature, ΔH_{heat} is the heat produced in heating a fuel from the ambient temperature to the boiling temperature, and K is a constant. The burning rate in a 1 m tank is not V, but must be closely related to it. Figure 4 shows the effect of $\Delta H_{comb} \ / \ (\Delta H_{vap} + \Delta H_{heat})$ on burning rate in a 1 m tank. This ratio of heat governs the fuel burning rate, and the larger the ratio is, the larger the burning rate. The dotted line was from Zabetakis et al.[19] Their results gave nearly a line for many kinds of fuel. Our data in Figure 3 gave two lines. One was for the hydrocarbon series and the other was for the alcohols and acetone series.

Radiative Outputs

Radiative output was the most important factor; it was measured in almost all of the tests. Figure 5 shows the relationship between tank

Table 1. Summary of large hydrocarbon pool fire tests (burning area is more than 7 m^2).

Fuel	Tank Size (m)	Burn Rate (mm/min)	Radiation at $L/D = 5$ (kW/m^2)	Max. Temp. (°C)	Flame Height (H_f / D)	Other Meas.†	Ref.
Gasoline	3	4.8	1.9	1100	1.93		4
	5.4	4.59–6.49	0.94	1367	–	EX	11
	6	–	1.1	1000	1.5		3
	9.6	–	–	–	–	EX	11
	10	7.0	0.48–1.04	–	1.7	EX	5
	22.3	3.5–6.29	0.4	1331	–	EX	11
Kerosene	30	4.7	0.43	1380	–	Gas, FT	7
	50	4.7	0.23	1380	–	Gas, FT	7
Crude oil*							
1	3	3.1	0.81	–	–		3
2	6.5	3.52	0.67	–	1.8–2.5		6
3	10	3.8	0.33–0.67	–	1.5		5
2	11	3.4	0.57	–	1.4–1.8		6
2	31	3.37	0.27	–	1.7–1.8		6
Heptane	2.7 sq	7.1	2.88	1030	2.33	VV, Gas	12
	6	6.9	2.22	1200	1.93	VV, Gas	10
	10	8.6	0.94–1.86	–	1.5		5
Hexane	3	7.1	2.23	–	–		4
	6	–	1.28	–	–		3
	10	10.0	0.85–2.03	–	1.7		5
Toluene	2.7 sq	4.4	1.55	–	–	Soot	9

*1: Khafgi oil; 2: Arabian light; 3: Iran Gatti oil.
†EX stands for the test for extinguishment; gas stands for the measurement of major gas concentration inthe flame; VV stands for the measurement of vertical gas velocity in the flame; FT stands for the measurement of fuel temperature.

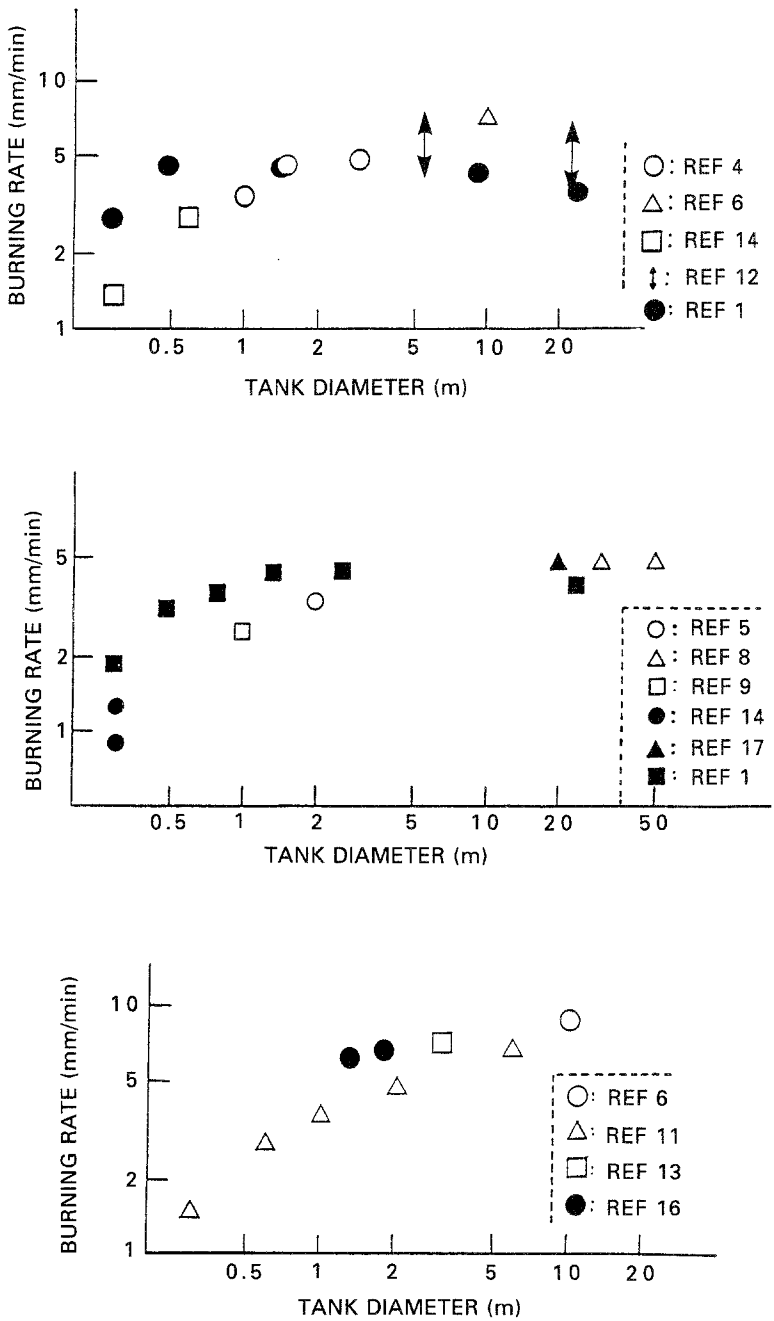

Figure 2. Relationship between burning rate and tank diameter: (a, top) gasoline (b, middle) kerosene (c, bottom) heptane.

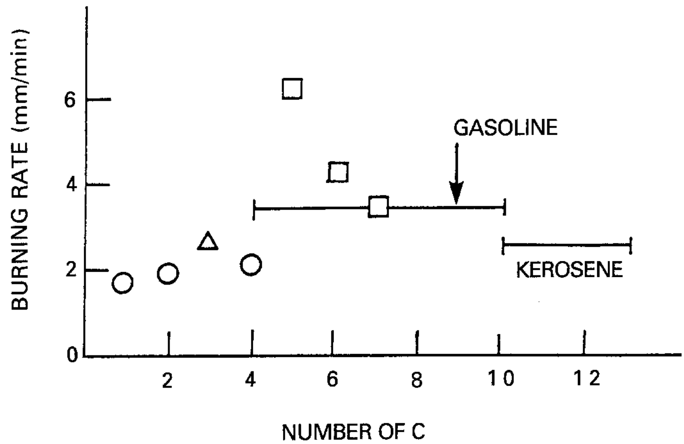

Figure 3. Effect of carbon number of fuel on burning rate in 1 m tank fire. Gasoline and kerosene are mixtures of many kinds of hydrocarbons, so their C numbers are shown as bars for their major components.

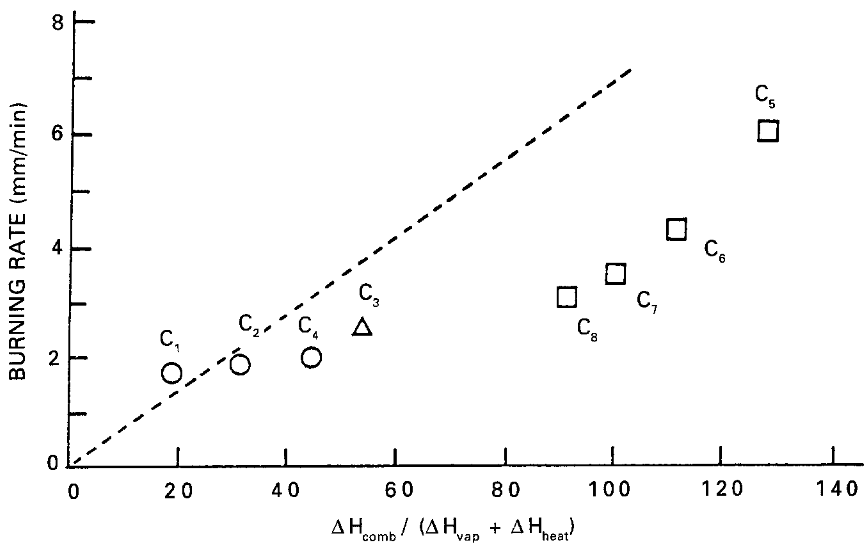

Figure 4. Effect of ΔH_{comb} / (ΔH_{vap} + ΔH_{heat}) on burning rate. Circles stand for alcohols, a triangle stands for acetone, and squares stand for hydrocarbon. C_n denotes carbon number of fuel compounds. That is, C_1 is methanol, C_2 is ethanol, C_3 is acetone, C_4 is butanol, C_5 is pentane, C_6 is hexane, C_7 is heptane, C_8 is octane. The data were from 1 m diameter fires. The dotted line was from Zabetakis et al.[19]

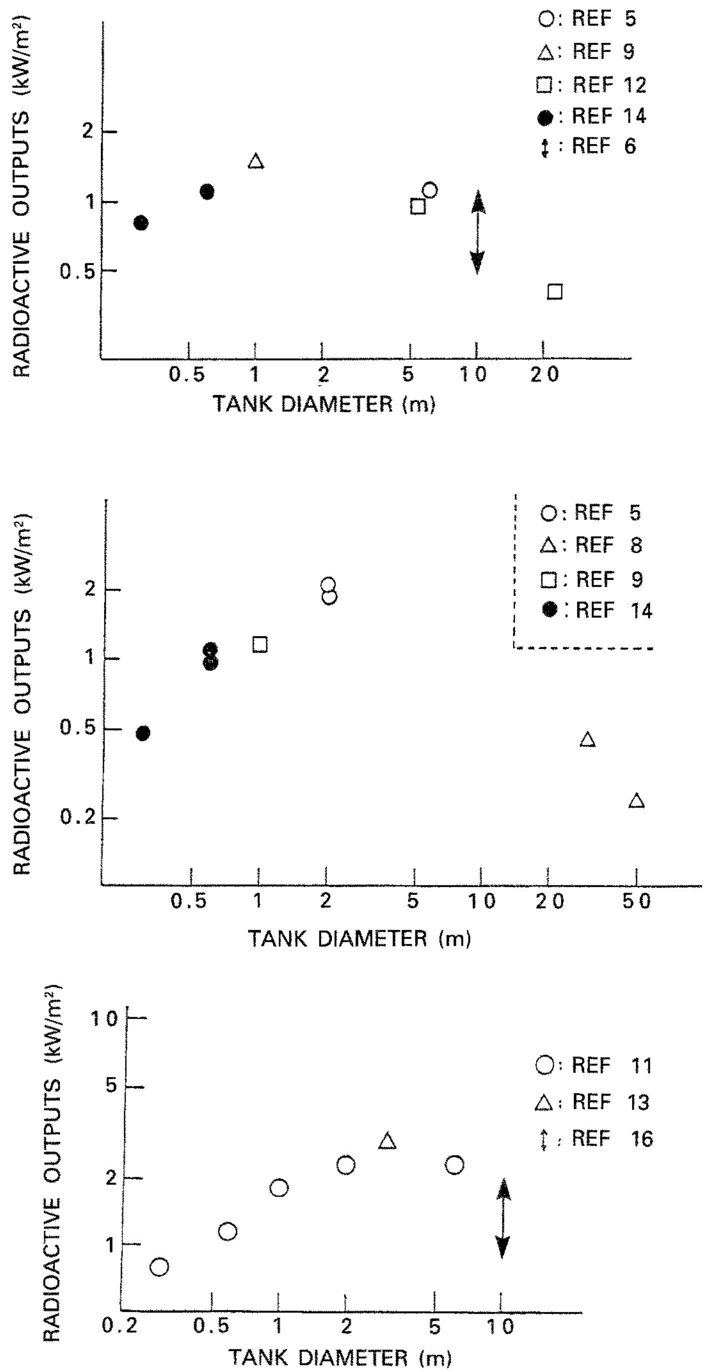

Figure 5. Relationship between radiation at L / D = 5 and tank diameter: (a, top) gasoline (b, middle) kerosene (c, bottom) heptane.

diameter and radiation at $L / D = 5$, for gasoline, kerosene, and heptane. Here D is the tank diameter, and L is the distance between the tank center and the radiometer. With a square tank, D was calculated with the equation:

$$D = (4/\pi)^{1/2} \times W.$$

Here W is the length of one side. In the small tanks, radiative output at $L / D = 5$ increased with increasing tank diameter. This trend is similar to that of the burning rate, because burning rate is ruled by radiation from flame to fuel, which is similar to that from flame to surroundings, except for soot blockage. Around a large-scale flame there are very large amounts of soot, but there is not so much soot between the flame bottom and the fuel surface. Therefore, in tanks of 1 to 5 m diameter, radiation was maximum, and decreased with increasing tank diameter, due to the soot blockage effect on the surroundings.

Figure 6 shows the relationship between radiation at $L / D = 5$ and the carbon number of fuels in a 1 m diameter tank. The trend is similar to that of burning rate.

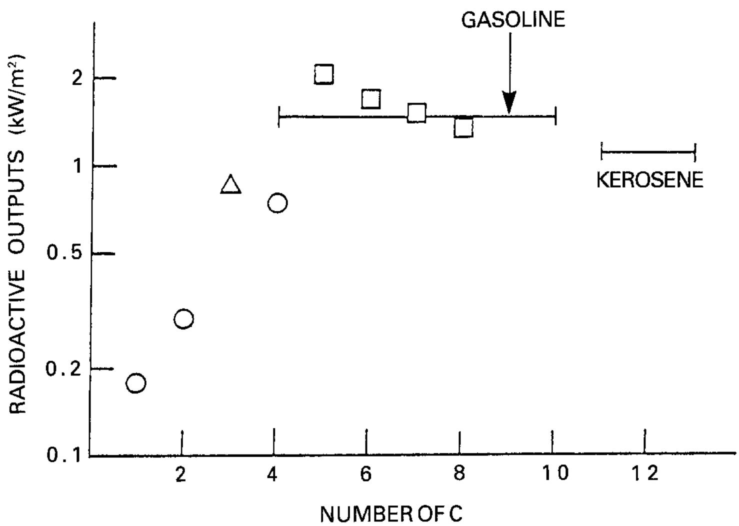

Figure 6. Effect of carbon number of fuel on radiation at L / D = 5 in 1 m tank fire. C numbers of gasoline and kerosene are shown as bars for their major components. Symbols as in Figure 4.

Radiative Fraction

Following the idea of Burgess et al.[18] we calculated the radiative fraction, X, which is represented as:

$$X = Q_{rad} \;/\; Q_{tot}.$$

Here Q_{rad} is the total radiative power output. Assuming isotropy it is simply the flux times the spherical surface area, in spite of flame height changing with tank size:

$$Q_{rad} = 4\pi \times R_o^2 \times q_o$$

where R_o is the distance between the center of the pool and the radiometer and q_o is the radiative flux measured by the radiometer. Q_{tot} is the net calorific potential of the flame, assuming complete combustion.

The data in Table 1 and Figures 2 and 5 were used to estimate the radiative fraction. Figure 7 shows the radiative fraction for various fuels in a 1 m pool fire. According to McCaffrey,[20] the radiative fraction is related to C/H of fuel compounds, so C/H was adopted as the horizontal axis. Radiative fraction increased with increasing C/H because the radiative fraction was controlled by the carbon particle density in the flame and carbon fraction of the fuel. The fire size was much larger than that of McCaffrey, but there is not much difference in the results of each experiment.

Figure 8 shows the radiative fraction plotted against the tank diameter for major hydrocarbons and methanol. In spite of the limited data, hydrocarbon radiative fractions are nearly on a line. That is, in a fire smaller than about 2 m diameter, the radiative fraction is between 0.3 and 0.5, but in a fire larger than about 2 m diameter, it goes down from 0.3–0.5 to about 0.07 (30 m diameter) and 0.04 (50 m diameter) in kerosene fires. The explanation for this phenomenon is probably smoke blockage and incompleteness of combustion efficiency in a large tank fire. The radiative fraction of methanol flames is about 0.17 in a 1.25 m diameter tank fire, which is much smaller than that of hydrocarbon fires.

Flame Height

Figure 9 shows the relationship between the flame height, H_f / D, of a heptane fire and the tank diameter. Flame height is always changing even while in steady-state burning, so it is shown with a bar. The open circles stand for time-averaged flame heights which were obtained with an 8 mm movie camera (18 or 36 frames a second) or a 35 mm photograph. The dashed lines and open triangles show the results calculated with Thomas's equation,[21] which is expressed as:

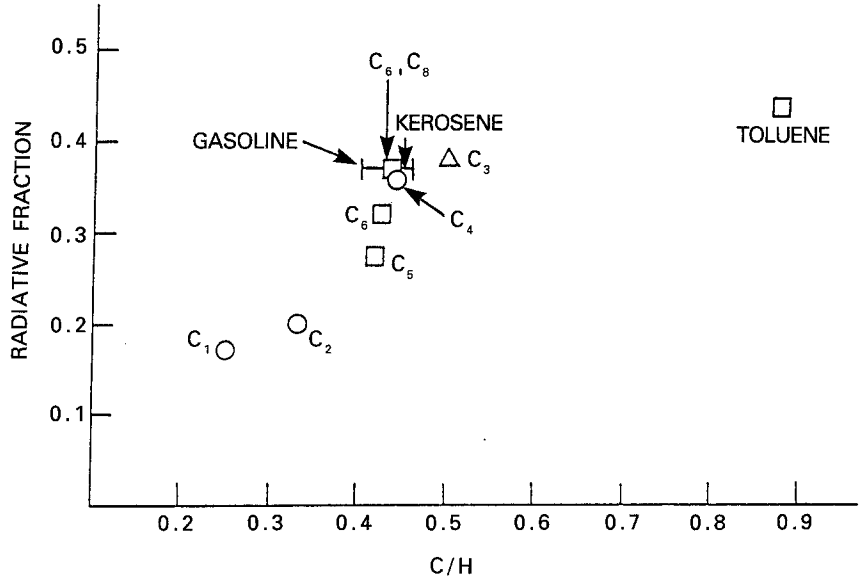

Figure 7. The effect of C / H of fuel on radiative fraction. The C numbers of gasoline and kerosene are shown as bars for their major components.

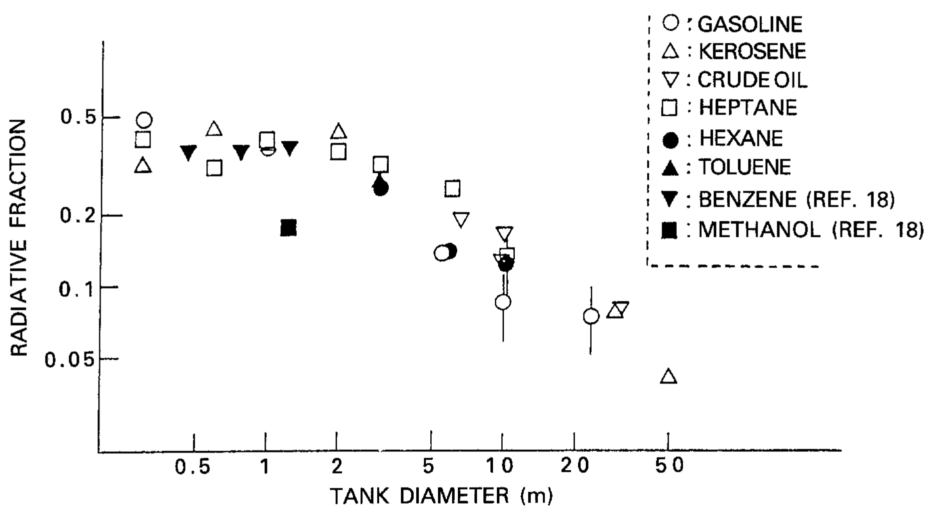

Figure 8. Relationship between radiative fraction and tank diameter for various fuels.

$$H_f / D = 42 [m / \rho (gD)^{0.5}]^{0.61}$$

Here, m is mass burning rate per unit area, ρ is density of surrounding air, and g is gravitational acceleration. This equation was derived entirely from experimental results for certain fuels, but gave good agreement with the data from a heptane pool fire. We did not have the burning rate data for tanks of more than 10 m diameter, so to estimate the flame height of fires greater than 10 m diameter we assumed that the burning rate was the same as that for a 10 m diameter tank fire. The test results and calculations indicated that flame height decreased with increasing tank diameter.

Figure 10 shows the effects of C numbers on flame height in a 1 m diameter tank. For three alcohols, flame height increased with increasing carbon number, but for alkanes, flame height decreased with increasing carbon number. In this figure, dashed lines and open triangles also show the results calculated with the Thomas equation. Here we found good agreement for liquid alkanes, alcohols, and acetone.

Flame Temperature

Temperature was also frequently measured. Figure 11 shows time-averaged centerline temperatures against height above the fuel in various sizes of heptane fires.[10] About 1–2 min from ignition, with burning of fuel reached in a quasi–steady-state condition, flame temperatures (logged every 10 s in the tests) were averaged when the flame was straight. Here $H / Q^{2/5}$, which was proposed by McCaffrey,[22] was adopted as the horizontal axis for normalized height. H is the height above the fuel surface, and Q is the total heat release rate of the fire, assuming that perfect combustion occurred in the flame. The scaling factor $Q^{2/5}$ for H is a purely empirical finding by McCaffrey, but it is useful for flame dynamics. ΔT is the difference between measured temperature and ambient temperature. In the test, temperature was measured near and within the flame region. Three regions in the temperature distribution were found. The first is for small values of H, nearest the fuel surface, where ΔT increases with $H / Q^{2/5}$. The increase begins at about 80 K, because the fuel surface temperature is near the boiling temperature of the fuel (98.4°C for heptane). In the next region, ΔT is at a maximum and is constant. In this region, height is nearly equal to 1 D above the fuel surface. The third region is an intermittent one. Here, a pulsating flame made ΔT fall with H to the first power. In the test, we did not measure the temperature in the plume region, so the tendency of characteristic $H^{-5/3}$ variation to be dependent on ΔT in the plume region, which has been found by McCaffrey, could not be clearly seen. The temperature in the plume region was measured in one 0.3 m diameter

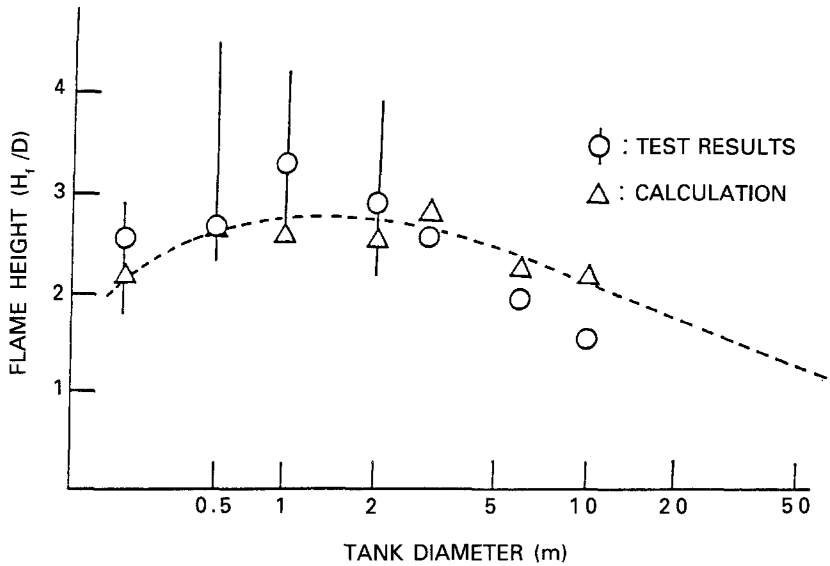

Figure 9. Relationship between flame height and tank diameter in heptane fires. Circles and bars were from test results, and triangles and dotted line were from results calculated with Thomas's equation.

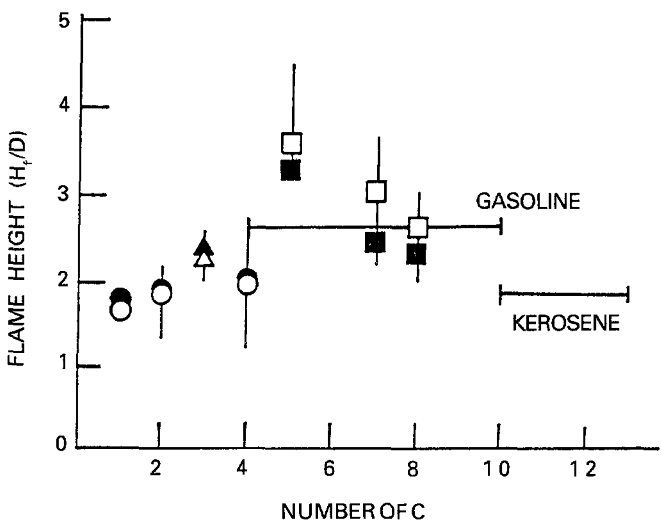

Figure 10. Effect of carbon number on flame height in 1 m tank fire. Open symbols and bars were from test results, and solid symbols are results calculated with Thomas's equation. Circles stand for alcoholic compounds, triangle stands for acetone and squares stand for hydrocarbons.

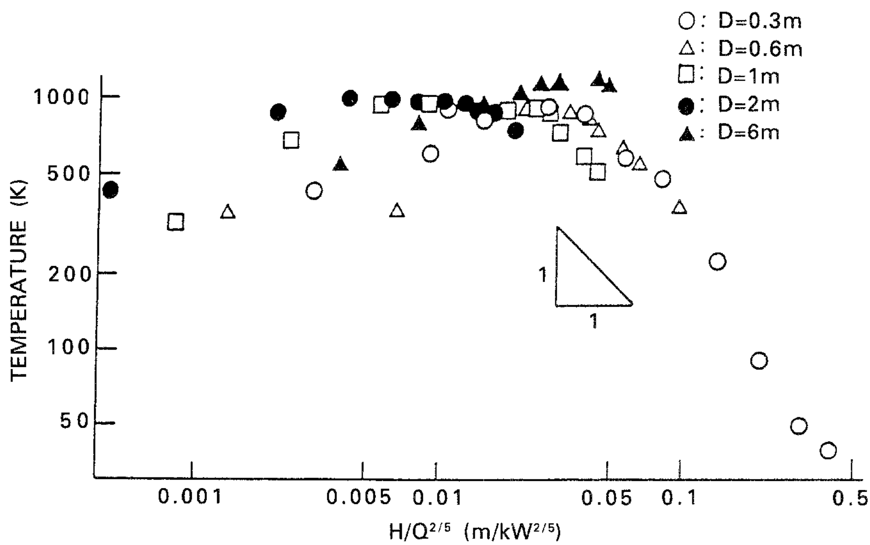

Figure 11. Temperature distribution along the heptane flame axis.

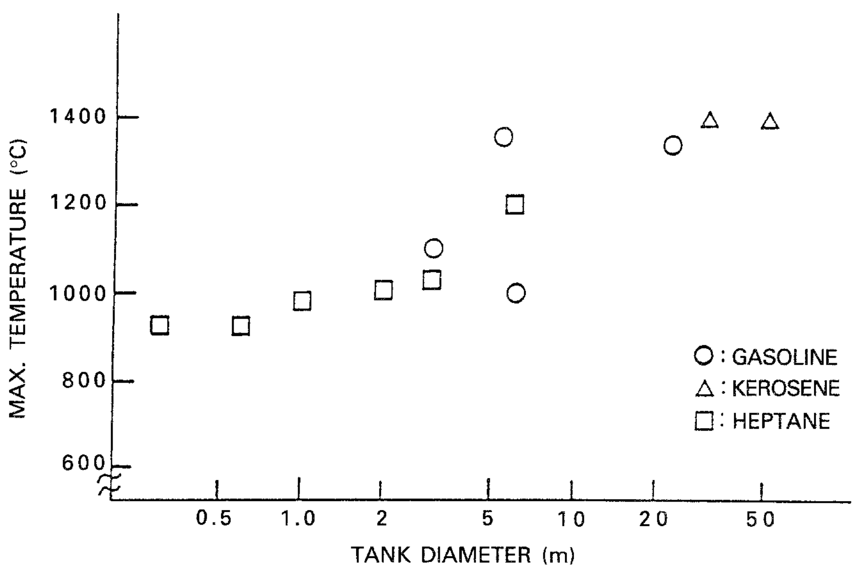

Figure 12. Relationship between maximum temperature in the flame and tank diameter for various fuels.

tank fire; these data may correlate with McCaffrey's.

Figure 12 shows the relationship between the maximum temperature of various flames and the tank diameter. Maximum temperature was obtained from all data of each test. These results indicated that maximum temperature rises with increasing tank diameter. Table 1 also shows the maximum temperature of other fuels, and these results indicate that the probable maximum temperature of this free pool burning is about 1300–1400°C for 30–50 m diameter fires. Although temperatures were high in large fires, they gave less radiative output and huge smoke emission. The reason is not clear, but air entrainment into the flame and mixing of fuel vapor and entrained air is related to this problem.

Conclusions

This paper presents test results from a great number of liquid pool fires. In particular, the combustion property related to fire size and carbon number were most useful. Based on the foregoing results, the following conclusions are presented.

1. As Burgess et al.[18] reported, the burning rates of fuel increased with increasing tank diameter, and they reached a maximum at about 3–5 m diameter. For fires of greater size, they were almost constant with increasing tank diameter.
2. The trend of radiative outputs was similar to that of burning rate, but in a large-scale tank, radiative outputs decreased with increasing tank size. This was probably caused by smoke blockage effects and/or incompleteness of combustion in the flame.
3. Flame temperature also increased as tank diameter increased. In all tests, the position of the maximum temperature was on the axis of the flame and the height of this maximum temperature was about 1 D above the fuel surface.

Acknowledgements: This paper introduces many test results, which were conducted or concerned with FRI people for more than a dozen years. The author appreciates deeply these people, in particular, Dr. Yumoto and Mr. Sato, who participated in many of these tests as leaders.

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