Invited Lecture

Large Scale Pool Fires: Results of Recent Experiments

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ABSTRACT

Results of recent researches of large pool fires are reviewed. Researches on combustion characteristics of large petroleum fires have been conducted by many research groups. To do large fire experiments costs very much and huge open space is taken, but it is important to conduct large scale experiments for obtaining information of large real tank fires. Therefore, in order to promote large pool fire research, understandings of combustion characteristics of petroleum for fire safety design and fire fighting engineering, world wide collaboration is very important.

KEYWORDS: large pool fires, radiation, IR-camera, flame temperature, flame height, initial smoke particle, dike fire, boilover, slopover

1 INTRODUCTION

1.1 Necessity of large pool fire research

Since Blinov and Khudyakov[1], many researches concerning to petroleum fires, have been conducted globally, as academic researches with combustion science, large real tank size research and a part of fire training. Various size of pans were used in these researches, but it is well-known that there is scale dependency of combustion characteristics of pool fires.

FIGURE 1 shows scale dependency of burning rate (Fuel level regression rate) and flame height on pan diameter, obtained by Blinov and Khudyakov[1], which is of very classical data but still useful. Hottel[2] and Sibulkin[3] explained this relationship with a heat transfer mode from flame to fuel. Heat transfer controlled burning rate and flame height, and a flame was turbulent when D > 0.2 m, and soot radiation from a thick flame was dominant when D > 1 m. So we can understand these results with their explanation, and we should do experiment with a pan larger than 1 m in diameter when the purpose of experiment is to clarify the characteristics of real tank fire. A typical huge real tank is of more than 100 m in diameter and 20 m in height.

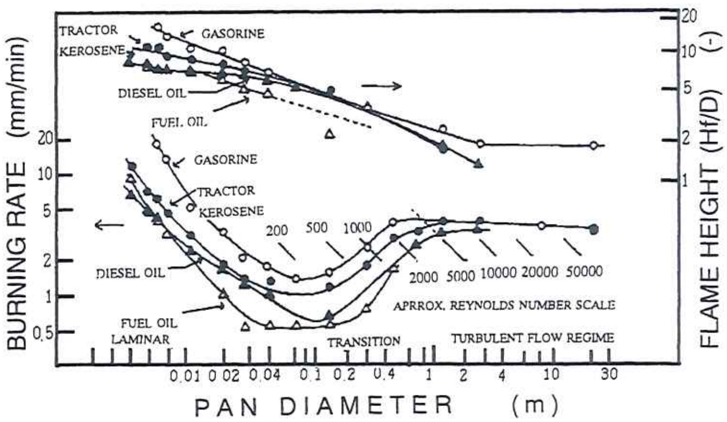


FIGURE 1 Scale dependency of burning rate, flame height with pan diameter[1]

FIGURE 2 shows relationship of radiative fraction[4], χ, (= total external radiation loss / total heat release, assuming complete combustion) and pan diameter[5]. Most data were taken on the ground and radiometer height was similar to pan rim height. It is clear that radiative fraction of pan of D < about 5 m was about 0.4 to 0.5 for major hydrocarbons fires, and then decreased with the pan diameter increasing. These relationship might be explained with smoke blockage effects, that is, produced smoke existed around the flame and reduced radiation outputs. Alcohols were less radiative fraction, about 0.1 to 0.2, and did not change its radiative fraction with pan diameter, but there is not enough data for estimating those of large alcohol fires.

Other characteristics of petroleum fires, for examples, smoke emission rate, smoke particle size, and tendency of boilover also depends on pool size[5,6]. Therefore experiments should be

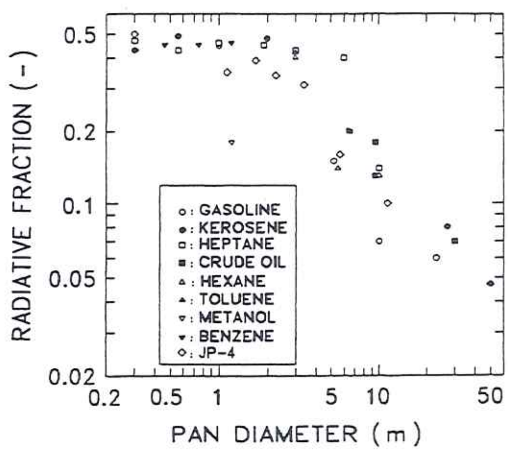


FIGURE 2 Relationship between radiative fraction and pan diameter for various fuels fires[5].

done in a pan larger than 5 m in diameter. Scale dependency of some of them are not clear. It may be difficult to estimate large scale fire phenomena with small scale experiment results. Computer based fire modeling and analysis tools, like to CFD (Computational fluid dynamic) model, also need a lot of experiment data.

1.2 Historical survey of large pool fire research in Japan

In Japan there have been done pool fire research by Akita[7], Yumoto[8,9,10] and other groups with various size pans. Large outdoor pool fire experiments were done several times in Japan and China[10-25]. TABLE 1 shows summary of large scale petroleum fire experiments which were done in Japan and China since 1975. Some of these experiments were for fire fighter training, but also for measurement of the radiation. Large crude oil fire experiments with 5 m, 10 m and 30 m diameter pans were conducted in Chiba[12], and then large scale experiments[13], in which kerosene was burned in 30 m, 50 m and 80 m pans, were done in Gotenba in May 1981. Large gasoline fire experiments were done in Tianjin, China[14], which were joint experiments between China and Japan. Many kinds of measurements were done in these experiments. Radiation was a primary item to measure in all experiments. Burning rate, flame height, flame and fuel temperatures, gas concentration inside the flame were also measured in some experiments.

Here these researches and current Japanese large scale experiments which were done in Tomakomai, Hokkaido[21,22,23,24] in 1998 and 1999, and Oga, Akita[25] in 1998 are introduced. We observed violent boilover of crude oil in a 5 m pan in Tomakomai in 1999, and slopover in Oga experiments in 1998[25]. The results give precious information for the technical regulation of oil storage tanks of the Japanese Fire Service Law, and fire fighting

TABLE 1 Summary of large scale pool fire experiments in Japan and China

Date	Place	Conductor	Diameter of Tank(Pan)	Fuel	Reference
Nov., 1975	Matsuo, Chiba	FRI(former name of NRIFD)	10 m	Crude Oil, Gasoline, Heptane, Hexane	11
Dec., 1978	Chiba	JSSE	5 m, 10 m, 30 m	Arabianlight Crude Oil	12
Aug., 1980	Tomakomai	Hokkaido	60 m(ring of 1 m width)	Kerosene	15
May, 1981	Gotenba	JSSE	30 m, 50 m, 80 m	Kerosene	13,16,17
1982~1984	Mitaka	FRI(former name of NRIFD)	~ 6 m	Heptane	10,18,19
Feb., 1987	Kitakyushu	Kitakyushu Fire Department	9 m	Kerosene	20
Oct., 1987	Tianjin, China	Chinese-Japanese Fire Fighters Associations	~ 22 m	Gasoline	14
Aug., 1996	Tomakomai	Hokkaido	60 m(ring of 1 m width)	Kerosene	-
Jan., 1998	Tomakomai	JNOC / NRIFD / U. of Tokyo	5 m, 10 m, 20 m	Arabianlight Crude Oil	21,22,23, 24
Aug. and Sept., 1998	Oga, Akita	JNOC / NRIFD / U. of Tokyo	2m, 4 m	Sarukawa Crude Oil	25
Feb., 1999	Tomakomai	JNOC / NRIFD / U. of Tokyo	5 m	Arabianlight Crude Oil	-

system. Results of international collaborations relating with large pool fires of NRIFD are also shown[6,23,26,27,28], which are very fruitful because it is difficult to do such large scale experiments only by the NRIFD or other individual Japanese group. Most studies focussed on radiation and burning rate of single tank fire, but also oil dike fire and multi-tanks fire, spilled oil fire, smoke emission and boilover have been studied.

2 SINGLE TANK FIRE RESEARCH

2.1 Research of FRI

A single tank fire is one of the most typical accident of oil storage facilities, and the most important item among pool fire researches, and has been studied by many researchers. The FRI (former name of NRIFD) conducted 10 m pan pool fire experiments in 1975 with various fuels for studying burning rate, irradiance, flame height and extinguishment[11], and Yumoto conducted smaller experiments[8,9,10].

Most experiments were done in a large indoor experiment facility of NRIFD[29], which is of a wide experiment space, 24 m × 24 m wide and 20 m high, with smoke abatement equipment. Large pool fire experiments up to about 25 MW can be done without worrying weather conditions, which size is nearly equal to a 3 m pan gasoline fire. Smoke and gas concentration, gas temperature and gas velocity can be measured at the smoke ducts.

The purpose of NRIFD experiments was to know scale dependency of radiation characteristics for various fuels. With a lot of data, Yumoto's conclusions on radiation from oil fires were; the flame was assumed to be a uniform radiator, and he explained with a very simple model (Cylindrical model, FIGURE 3) and Eqs.(1) and (2).

$q = E \cdot \phi$ (1)

$E = \varepsilon \cdot \sigma \cdot T_f^4$ (2)

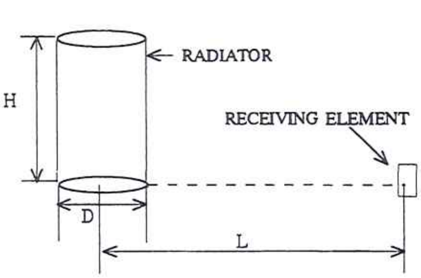


FIGURE 3 Cylindrical model of flame radiation[8,9]

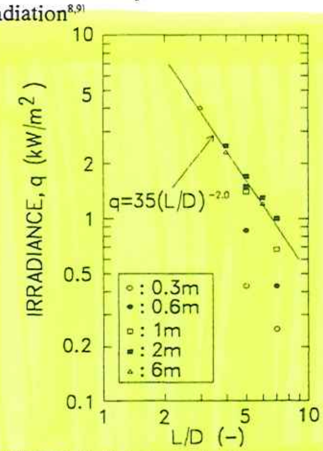


FIGURE 4 Relationship between irradiance and dimensionless distance from axis, L/D, for various sizes of heptane fires[19]

TABLE 2 Examples of E for various fuels[9] Data were from fires of D=1 to 3 (m).

Fuel	E (kW/m^2)
gasoline	58
kerosene	50
diesel oil	42
fuel oil A	23
hexane	85
heptane	90
benzene	62
toluene	86
methanol	10
ethanol	12
LNG (methane)	76
propane	74
butane	83

Here q is the irradiance at any place around the fire, ε is the emissivity and assumed to be 1 in a large fire, σ is the Stefan-Boltzmann constant, and T_f is the flame temperature. E is the radiant emittance of the flame, and E is able to be calculated from only fuel properties and burning rate, v, data. He obtained these relationship empirically that; $E=0.02\cdot\phi\cdot\rho\cdot v\cdot H_c$. Here ρ is the density of fuel, and ϕ is the view factor between the flame and the radiometer. H_c is the heat of combustion of fuel. Then, the radiant emittances of a lot of fuels, E, were calculated by Eq.(1) with the measurement results of q. Examples of E of various fuels are shown in TABLE 2. Yumoto assumed that E did not change with pan diameter. Though recent experiment data[5,12,13,19] and calculation results[17] show change of radiant emittance of flame with scale, Yumoto's results are still useful and basic pillars for the Japanese Fire Service Law and the assessment[30] made by the Fire and Disaster Management Agency. Examples of experimental results are shown in FIGURE 4, where heptane fires gave similar irradiance at the same dimensionless distance from the pan center, L/D, when the pan diameter was 1 m to 6 m. Smaller fire, D<1 m, gave smaller irradiance because ε is not able to be assumed 1[19]. ε is calculated with Eq. (3) using the absorption coefficient, k.

$$\varepsilon=1-\exp(-k\cdot D) \qquad (3)$$

2.2 Recent experimental results

In addition to Yumoto's works, studies with large experiments were done recently and gave the following results;

(1) Radiation from a fire, larger than 10 m in diameter, is very small compared with the expectation using Eqs.(1) and (2)[9], may be due to smoke blockage[17]. Therefore radiative fraction was very small in large scale fires(FIGURE 2). Radiative heat transfer to fuel surface was about 1 %, so upwards convective heat loss was very large, which was more than 90 % of the total heat loss in a 50 m pan fire though 40 to 60 % in a fire, smaller than 5 m in diameter. Therefore the top of the black smoke plume reached over 1,000 m in 30 m and 50 m kerosene fires[13].

(2) There are large distribution of temperature and radiant emittance in the flame. FIGURE 5 shows an example of isotherm of a 6 m heptane pan fire obtained by using 60 thermocouples[19]. The temperature gradient was the highest at the flame base. Strong steep density incline suggests that air entrained strongly from flame base above the pan edge to the fire core along with the dashed line. Local radiant emittance was measured with a narrowed view radiometer by Yumoto[13], and estimated by Akita / Hirano group[17] from video images in Gotenba kerosene huge fires. Hagglund and Persson also gave similar results of radiant emittance in JP-4 10 m pan fires using IR-camera[31]. Recently IR-camera has been used in measuring local radiant emittance in detail[5,32,33,34]. It gave radiation profiles of the object with high

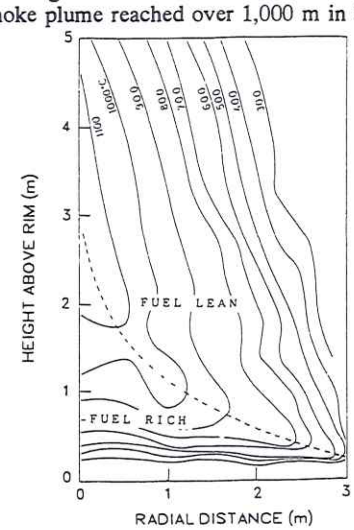


FIGURE 5 Example of isotherms of heptane flame in 6 m pan[19]

speed. It was found that the flame core, the maximum temperature zone along with the flame axis, was higher than the highest radiant emittance zone, especially in a large fire.

(3) Flame shape was not clear in such a large fire because of smoke cloud existing around the flame. In the calculation using the cylindrical model, the flame height, H_f is needed, but it might not be so important to decide the flame height of such a large fire for considering radiant emittance distribution for fire fighting[31,33]. Therefore Kashio and Akita[17] proposed a calculation model to estimate irradiance considering radiant emittance distribution.

Q* correlation compiled by McCaffrey[35] was applied into the estimation of flame height, H_f/D, with the results of these large pool fire experiments. Q* was in the range from 0.2 to 0.3 for such huge fires. Therefore the calculation results of flame height using the equations by Heskestad[36] (Eq. (4)) and Zukoski[37] (Eq.(5)) were about 1.0 and 0.8, though the experimental results were about 1.7 to 1.9 for 30 m pan crude oil fire[12]. The difference might be from uncomleteness of combustion in the flame. That is, poor air entrainment or poor air / fuel vapor mixing might make flame height larger. The results in heptane fires in pans up to 6 m in diameter[19] implied; the mixing might be poor, because dimensionless air entrainment, m_a/m_s, from the flame base to the flame tip, was about 4 and did not change with fire size using the calculated results from measurement of temperature and gas velocity inside the flames. Here m_a is the mass air entrainment and m_s is the mass air required for stoichiometric combustion of fuel.

$H_f/D = 3.7\ Q^{*2/5} - 1.02$ (Heskestad[36]) (4)

$H_f/D = 3.3\ Q^{*2/3}$ (Zukoski[37]) (5)

(4) The height of tank (pan) wall affected on burning rate of fuel, and irradiance at the ground level and fire fighting. The experiments in China were assumed to real oil tank fires (Diameter; 22.3 m(max.), Tank height; 11.2 m(highest))[14] therefore experiment results might be more useful for fire fighting engineering. Irradiance on the ground was smaller than that of the height of the pan wall edge. Existence of wall might make burning rate increasing at least 10 %[9].

3 OIL-DIKE AND MULTI-TANKS FIRES

Cases of oil-dike and multi-tanks fires are very rare, but more dangerous in oil storage facilities. Therefore in order to know combustion characteristics of these fires, four sort of fire models were examined by Yumoto where four 0.8 m diameter pans (as ITs(Inner tanks)) existed in a 2.7 m square pan (as a dike) using heptane as fuel[10,18].

TABLE 3 shows summary of sort of dike fire models and major data. It is found that radiation from the dike fire with four tank fires(Case 1) could be estimated assuming as a whole ground fire of the area of dike and tanks(Case 2) when the flames of dike and ITs were merged into a flame. Local radiant emittance of the flame was measured in the experiment using with a narrowed wide angle radiometer. The existence of tank did not influence on the whole radiation from the dike fires nor radiant emittance so much, and the difference was less than 5 %. When flames did not merge, radiation from the fire of dike ground and the fire of ITs could be calculated separately by Eqs.(1) and (2), and it was a less hazardous case than a merged dike fire because the flame merging made flame height and burning rate increased (FIGURE 6). The distance between the tanks, S, was important for the flame merging. When S/D > about 0.6, the flame merging was not observed, and each of four flames burned separately. When S/D was about 0.6, flame merging appeared with oscillation, and the flame merging appeared always when S/D < 0.6. Recently Sugawa et al. also did smaller multi-source fires research and explained the phenomenon[32].

In the Tomakomai experiment, radiation inputs and temperature increasing in the adjoining tanks were measured[21], and the maximum temperature of the adjoining tank wall surface measured with an IR-camera and thermocouples was about 130 °C.

TABLE 3 Burning rate and radiation from the flame in four sorts of dike fires using heptane[10,18]

Sort of dike fires	Total mass burning rate (kg/sec)	Irradiance at a point from 4.5 D from the center of dike (kW/m²)
(1) Dike fire with 4 open top IT fires	0.65 (0.40) (0.25)	3.40
(2) Dike fire without IT	0.62	3.55
(3) Dike fire with 4 floating roof IT fires	0.55 (0.33) (0.22)	2.88
(4) Dike fire without IT fire	0.31	1.36

1) The dike model was consisted with a 2.7 m square dike and four 0.8 m diameter inner tanks (ITs).
2) Dike diameter, D, was assumed to be 3 m.
3) Numerals in upper parentheses in second row show mass burning rate of heptane on the ground and those in lower ones show total mass burning rate of four ITs.

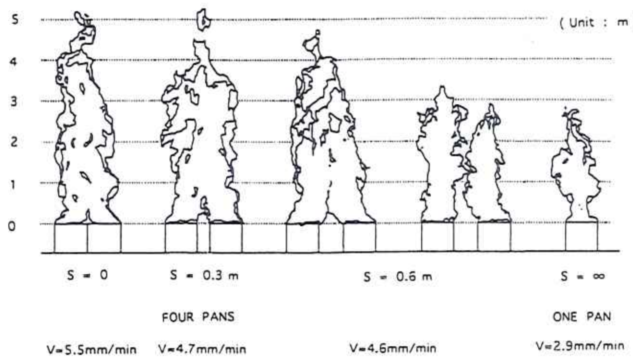


FIGURE 6 Schematic of flame merging of four 0.8 m open pan fires[10]
(S: Pan-pan space, v: burning rate of fuel, Four pans are not in a dike.)

4 SMOKE EMISSION FROM TANK FIRES

After large kerosene fire experiments in Gotenba[13] it has been pointed out that an interaction between radiation and smoke emission is important. Smoke emission from a fire is also important in environmental aspects. The smoke point is a parameter to estimate the tendency of smoke emission and used widely[38]. However smoke yield, sm, is more rudimentary, which is a dimensionless parameter of smoke emission from materials proposed by Mulholland et al[39]. sm was defined that; sm = m_{sm} / m_f. Here m_{sm} is the smoke emission rate (wt.), and m_f is the mass burning rate. There are several methods to obtain sm. NIST developed new method to get sm for the field experiment, which was so-called carbon balance method. In this method sm was obtained by the following equation(6).

$$sm = f_c \cdot Y_s \qquad (6)$$

Here, f_c is the carbon mass fraction in the fuel, and Y_s is the carbon mass fraction in the smoke aerosol as a fraction of the carbon mass in the total combustion products (CO_2, CO and smoke aerosols). Scale dependency of smoke yield up to 3 m in diameter was obtained by the collaboration between NIST(National Institute of Standards and Technology of USA) and NRIFD. NIST conducted large scale oil fire experiments, up to 15 m square pan fire, in the US Coast Guard Experiment Facilities in Mobile, AL of USA, concerning the method of clean-up spilled oil on the sea by in-situ burning for more than ten years[26,27,28,40,41,42,43]. A trial burning for clean up the spilled crude oil was done in Exxson Valdez oil spill accident in Alaska on March 1989[44]. The Sandia National Research Institute of Dept. of Energy, USA are also doing large petroleum fire research concerning smoke particle size and radiation[45]. The following results are obtained from recent smoke emission research.

(1) Smoke sampling techniques and scale dependency of smoke emissions from a fire

Techniques developed by Lawson et al.[40] was to get smoke yield using an airborne blimp was used in field experiments. Smoke yields[39,43] were measured by three different ways, a flux method(smoke was sampled and was weighed on a filter with equivalent gas velocity), a light extinction method, and a carbon balance method. Notarianni et al. compared results of these methods, and found 15 % difference at the maximum with 0.09 m pan in the cone calorimeter[27]. The carbon balance method gave larger value than other two methods.

Results of Evans group using crude oil[40,41,43] are; smoke emission rate increased with the pan diameter until about 3 m pan, that is, from 0.055 in 0.09 m pan to about 0.2 in 3 m pan, but not increased in fires larger than about 3 m in diameter (FIGURE 7). Smoke yield of heptane fire was about one tenth of that of crude oil fire. On the other hand, radiation, here radiative fraction was adopted as a parameter, decreased with the pan diameter increasing when the pan diameter was larger than about 5 m. Until about 5 m in diameter it did not change and was about 40 to 50 % for most hydrocarbon fires (FIGURE 2).

(2) Initial smoke particle (ISP) size

Smoke agglomerates were sampled by an airborne blimp in large field fire and sampled at the smoke duct in indoor experiments[40]. Size of most smoke agglomerates from large field fire was within 0.05 to 2 μ, and its size increased with pan size increasing. It is consisted of a lot of primary spheres, so-called initial smoke particles (ISP). They were observed by a TEM (Transmission electron micrograph), in which the maximum magnitude was 30,000 times (FIGURE 8).

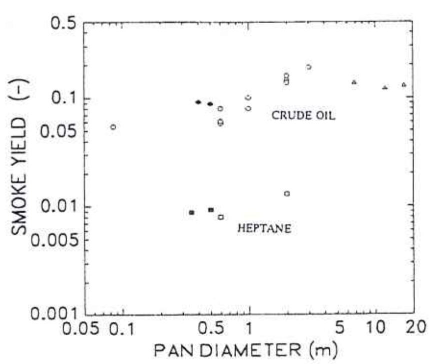


FIGURE 7 Relationship between smoke yield and pan diameter for crude oil and heptane fires[39,40]

FIGURE 9 shows the normalized size distributions of ISP from crude oil fires in 0.1 m, 1 m, 2.7 m sq. and 12 m pans. There are large difference among the results from smaller two fires and those from larger two

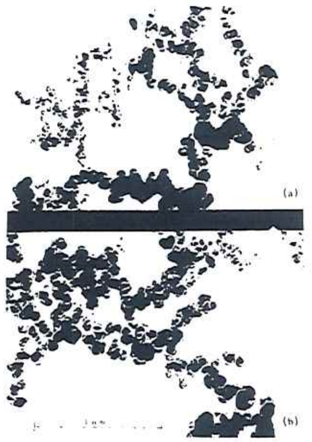


FIGURE 8 TEM photographs of smoke agglomerates from crude oil fires
(a) 2.7 m sq. pan fire
(b) 1 m diameter pan fire

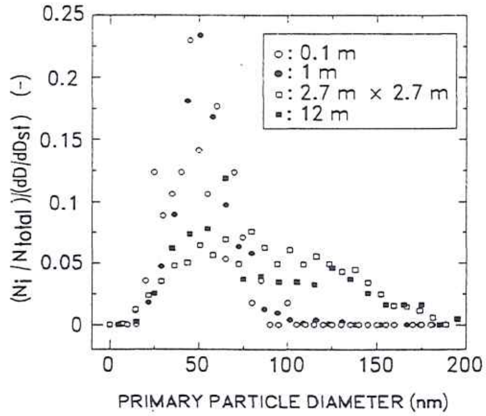


FIGURE 9 Distribution of normalized number of primary particle diameter of smoke agglomerate[47].

fires. In the smaller two fires, average diameter and their standard deviations of ISP are 47.4(± 17.1)nm in 0.1 m pan fire and 53.5(± 15.8)nm in 1 m pan fire, and more uniform, and are similar to the results of smaller toluene fire experiments by Koylu and Faeth[46]. In the larger two fires, they have wide distribution and larger ISP sizes, that is, 88.3 (± 39.3)nm in 2.7 m sq. pan fire and 90.2 (± 53.3)nm in 12 m pan fire. These results suggests; a residence time in the flame (high temperature zone) might govern the size of ISP. Growing of an ISP is made in high temperature zone. The large difference of the flame structure between smaller fires and larger ones might be related with the residence time[47]. About 2 m pan in diameter may be a kind of critical size of the flame structure. Therefore we need more data of ISP size and residence time in the fire using about 2 m pan, which are calculated from the temperature and gas velocity profiles inside the flame.

(3) Smoke trajectory

McGratten, Baum of NIST group[42,48] are developing a smoke trajectory simulation program based on a small scale eddy motion model (large eddy simulation (LES) model). Their model was evaluated using the data of large crude oil fire experiments in Alaska and Mobile of USA. The calculation results described experiment results well. PC-version program is available[49].

5 BOILOVER AND SLOPOVER

5.1 Boilover research and its back ground

When crude oil burns, it may occur boilover, which is one of the most dangerous case for fire fighting. In Tacoa Venezuela, 146 fire fighters and other people were killed by a boilover caused with Fuel oil A[50]. When even little water exists in tank like those of the

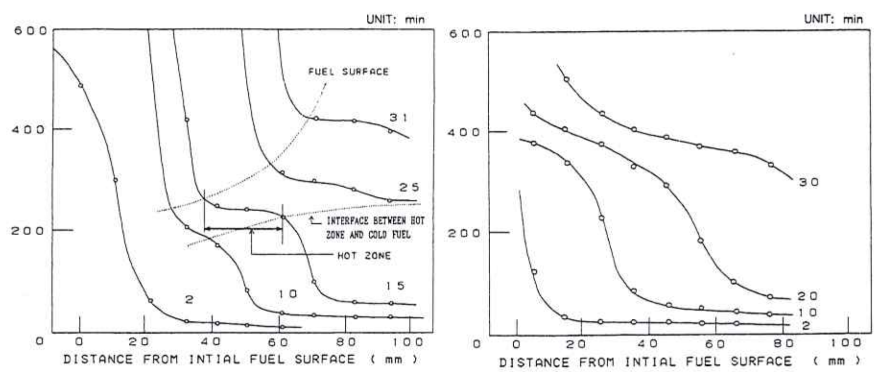
Japan National Oil Corporation, where crude oil is storing for a national stragety, still there is possibility of boilover or slopover accident after long burning and fire fighting. Boilover needs free long burning and formation of hot zone (isothermal zone) in the fuel layer. Sudden water boiling occurs and a kind of fire ball may be made when a hot zone reaches water layer and heat transfer from fuel to water is made[51]. Slopover should occur after long fire fighting. Fortunately it is very rare to occur large boilover in huge tank fires, because it needs long burning to make enough depth of hot zone for boilover. In Japan, it is reported that boilover accidents occurred only twice after the World War II.

5.2 Recent boilover research

Blinov and Khudyakov studied boilover[1], and then Hasegawa studied boilover concerning hot zone (isothermal zone) formation using fuel oil and/or gas oil, in which he observed hot zone layer through pan wall[52]. Hasegawa explained boilover phenomena with bubbling of fuel and convective flow inside the fuel.

We focussed on boilover of Arabianlight crude oil fire[6]. In most our experiments a 1 m pan was used, but various size pans, from 0.3 m to 3.1 m in diameter, were also used to obtain scale dependency of boilover. Temperatures in the fuel and water were measured. FIGURE 10 shows the change of the fuel temperatures along with the pan axis in 1 m pan of (a) Arabianlight crude oil and (b) kerosene fire experiments where fuel layer depth was 100 mm, and about 100 mm thick water existed at the bottom of pan. When a hot zone reached the water layer and water temperature may raise to 100 ~ 115 ℃, and then boilover occurred and radiation outputs increased suddenly. In the experiment of (a) radiation increased more than ten times as much as the steady state burning at 32 minute after ignition. Boilover may keep its peak of violence only few seconds and then the flame decreased its size or blew out, but the boilover occurred repeatedly in some cases.

FIGURE 11 shows scale dependency of burning rate, v, and hot zone regression rate, u, where data were from our previous experiments and references[6]. Hot zone depth was assumed to be the product of the difference, (u-v), between the burning rate and the heat wave regression rate multiplied by the lap time from the ignition. The burning rate increased



(a) Arabianlight crude oil (b) Kerosene

FIGURE 10 Development of vertical temperature profile with 100 mm initial fuel depth in 1 m pan fires. Numbers represent the elapsed times from the igition. (Unit: min)[6]

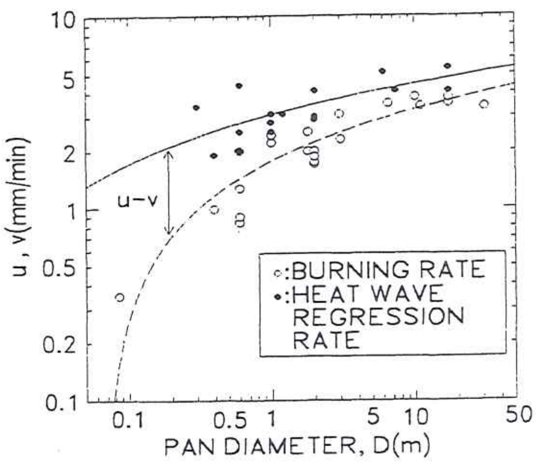


FIGURE 11 Scle dependency of burning rate, heat wave regression rate of crude oil fires with pan diameter[5,6)]

with the pan diameter increasing, though the heat wave regression rate increased with the pan diameter increasing slightly. The burning rate was controlled with the radiation heat transfer to the fuel surface, though the heat wave regression rate was controlled with the convective and the conductive heat transfer inside the fuel. So (u-v) is a controlling parameter, and it is rare boilover occurs in real large tanks because the difference, (u-v), in such large pan is very small. In kerosene fire it could not be found a hot zone formation in the fuel and a violent boilover was not observed. Only an water splashing was observed before the end of burning. Hot zone temperature is also a controlling parameter, and it depends on the fuel and the time after ignition. When the same fuel was used, the fuel temperature was higher, the stronger violent boilover was observed.

It is important to know what kind of fuel and crude oil makes boilover easily. To obtain this answer we did experiments with various crude oils and fuels. Fuel oil A made hot zone and occurred small boilover from 100 mm fuel floating above water in a 1 m pan. Compared with the results of Arabianlight crude oil fire, it is difficult to make a boilover from the fuel oil burning. In gasoline fire hot zone layer was made, but its temperature was lower than the boiling temperature of water, so a boilover was not observed. Most crude oils make boilover in a small pan fire. The results suggest that wide range of boiling temperature of fuel and higher boiling point than water's is needed for a violent boilover.

Recently, Saito group of U. of Kentucky[53)] studied boilover of various hydrocarbon liquids in order to conduct in-situ burn of spilled oil. Their boilover is different with the definition of NFPA[51)], fuel layer is thin and no hot zone layer is needed. Even toluene or kerosene fires in a small pan, it is observed that a kind of boilover occurred after long burning. We experienced boilover only with crude oil or heavy petroleum like to Fuel oil in large storage facilities. However In-situ burning of spilled oil is an urgent topic and discussed in the USA and Canada, because the number of oil spill accident is increasing and its damage is large. They did large crude oil spill burn on the sea near Newfoundland of Canada in 1993[54)]. It may be difficult to apply in-situ burn clean up for oil spill into a real accident around Japan.

5.3 Oga and Tomakomai boilover / slopover experiments

After the Tomakomai large crude oil fire experiments in January 1998, a series of large crude oil fire experiments have been conducting[25], in Oga, Akita in August and September, 1998, in Tomakomai in February, 1999. Oga experiments were done to know long burning characteristics of Sarukawa crude oil, which is produced in Japan, in 2 m and 4 m pans concerning slopover and boilover. Temperatures inside the fuel were measured to know heat wave regression rate. Slopover was observed after long burning but before the expecting time of boilover, because there might be about 0.5 %(vol.) water in the crude oil as suspension state. Just before the slopover occurred, temperatures inside the fuel were almost uniform, about 110 ～ 130 ℃. Boiling of water in the fuel layer gave similar effects of the mixing of fuel and water by fire fighting.

In the Tomakomai experiments in February, 1999, a large boilover was occurred after long burnings of Arabianlight crude oil in a 5 m pan. Radiation outputs increased more than ten times as much as the steady state burning. Hot zone formation and movement was observed through the measurement of the pan wall temperature by an IR-camera. Strong cross wind affected boilover occurrence because of much heat transfer from the flame to the fuel through the pan wall. The heat analysis from the flame to the fuel by Hottel[2] implied direct radiation to the fuel surface, but it might not be ignored the conductive heat transfer through the pan wall when strong cross wind exists. Details of experimental results will be reported in the future.

6 TOMAKOMAI LARGE CRUDE OIL FIRE EXPERIMENTS

6.1 Summary of experiments

JNOC(Japan National Oil Cooperation), NRIFD and group of Hirano, the University of Tokyo conducted a joint experiment using 5 m, 10 m and 20 m pans in January 1998[21,22,23,24]. The purpose was to obtain basic data for computer-aided fire fighting and controlling system which is building by JNOC. An equivalent crude oil to Arabianlight crude oil was chosen as fuel, because Arabianlight crude oil is major storaging crude oil in Japan. Burning was done in very good conditions with/without wind effects and data were obtained successfully. Summary of the experiments is shown in TABLE 4. It was done in winter, very cold in Hokkaido, but was chosen due to obtain proper wind direction from the land to the sea. The experiences of Gotenba experiments were very useful for conducting the experiments.

TABLE 4 Summary of Tomakomai crude oil fire experiments[21,22,23,24]

Date	January 26-27, 1998
Place	Tomakomai, Hokkaido, Japan
Pan diameter, pan shell height	5 m, 10 m, 20 m in diameter and abut 0.3 m to 0.6 m of pan shell height
Fuel, fuel depth	Equivalent crude oil to Aabianlight crude oil, 50 mm above water
Major measurements	Flame shape, external radiation, IR-image of flame, flame temperature, burning rate, gas composition inside the flame, smoke particle size, ionization current inside the flame, acoustic emission analyzing, smoke dispersion observation

6.2 Major experiment results

(1) Burning rate

Burning rate was measured by a level meter which was connected with pan wall, also calculated from burning time, initial fuel thickness and fuel residue thickness. Ethyleneglycol was added into the fuel of piping between the pan and the level meter to decrease freezing point. About 10 to 20 % of fuels (vol.) were remained. The smaller pan fire was, the larger residue was made. Results are slightly small compared with our previous results and references which were shown as a dotted line in FIGURE 11.

(2) External radiation and wind effect on it

Radiation should be the most important item for fire fighting, and 16 radiometers were used to measure radiation from fires. Distance between pan center to each radiometer was set at between L/D =1 and 3 which distance is very important for fire fighting. Here L is the horizontal distance from the pan center. The results are good agreement with experimental results and expectation from the previous experiments[12,13] when wind did not affect on the flame and the flame was vertically straight. In the distance, L/D=1 to 3, the irradiance from the flame at the down-wind side was quite larger than that at the up-wind side when wind made the flame tilt. Averaged radiative fraction was 26 % in 5 m pan, 22 % in 10 m pan and 16 % in 20 m pan fires, assuming complete combustion.

(3) IR-images and local radiant emittance

Totally six IR(Infrared)-cameras were used to observe the flame and the pan wall from the ground level and a helicopter. The flame base was also observed by an IR-camera in detail. Therefore the flame could be observed from various direction, up-wind and down-wind.

FIGURE 12 (a) to (d) shows a series of IR-images of 20 m fires taken by every second from up-wind side, which show the movement of the flame and its pulsation. The pulsation of the flame was about 3.5 second, and slightly longer than that of the calculation results by Porscht[55]. Pulsation is related with air entrainment into the flame, and longer pulsation implies poor air entrainment or poor air / fuel vapor mixing. In the IR images there are two regions which have strong radiant emittance, that is, the flame base and the intermittent flame zone. First one had strong and steady radiation, and second one had slightly stronger but the height of the strongest radiant emittance changed with pulsation. So the most radiation was from the flame base. These results[21] gave good agreement with the IR-image data of crude oil 15 m square pan fire experiments conducted by NIST, where 70% of the total radiation was from the flame base, which means the part of flame are lower than the height of 25 % of average flame height[5].

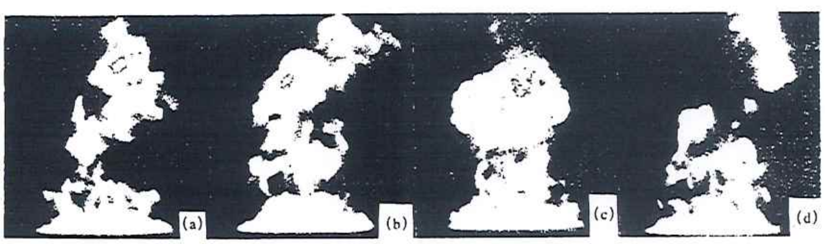


FIGURE 12 IR-images of 20 m pan fire from up-wind side, pictures from left to right, (a) to (d), were taken every second, show move and pulsation of flame.

From the down-wind side IR-image was different and no regular pulsation was observed. Average radiant emittance of up-wind side was larger than that of down-wind side, though irradiance measured by radiometer at L/D=1 to 3 of the up-wind side was lower than that of the down-wind side. The experiments in Oga may give the explanation of these results[25]. IR-images from a helicopter gave the whole profile of the flames. With these data averaged dimensionless flame height, H_f/D, of 20 m pan fire was obtained, and H_f/D was about 1.9, which was smillar to the JSSE 30 m crude oil fire results, 1.7 to 1.9[12].

(4) Flame temperature

The maximum flame temperature of 20 m fire measured by thermocouples was more than 1400 ℃, when the flame was straight vertically. The height of the highest temperature zone was higher than H/D= 0.25, which was much higher than the height of the peak of local radiant emittance zone (about H/D=0.1 ~ 0.15). Here H is the height from the initial fuel surface. Relationship between the average temperature along with the pan axis and the dimensionless height are shown in FIGURE 13. Here previous data[13,19] using kerosene and heptane are also shown in the figure. As the pan diameter increased, the maximum temperature inside the flame increased.

(5) Gas concentrations inside the flame

Gas concentrations inside the flame were measured[21]. In the base of flame a lot of decomposed gases(H_2, CO and Hydrocarbons) existed, but nearly no oxygen existed, and CO/CO_2 ratio was high. In the region which were higher than intermittent flame zone only CO_2 and H_2O were found as combustion products[10,19]. The results of Tomakomai experiments were good agreement with the results of smaller heptane experiments[10,19]. The decomposed gas and smoke near the fuel surface absorbed radiation heat from the flame to the fuel surface[56].

(6) Ionization current and acoustic analyzing

Ionization current inside the flame and acoustic emission were measured by Hirano group, the University of Tokyo[21]. First measurement was done with electrostatic proves to find a reaction zone in the flame, where a lot of ionic hydrocarbons species exist. Acoustic information should be useful for expectation of an onset of boilover[57]. When boilover occurred, water boiling made strong sound.

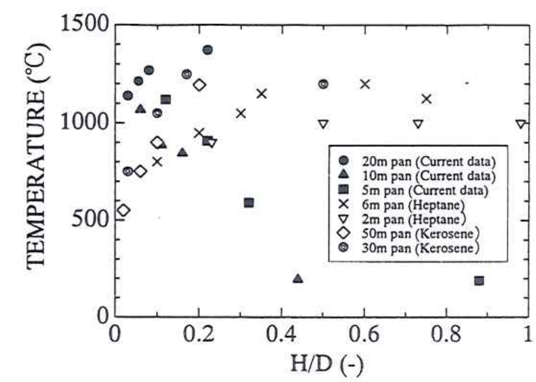


FIGURE 13 Relationship between the maximum temperature along with flame axis and dimensionless height from initial liquid surface

(7) Initial smoke particle size

Smoke particles from the fires were sampled on the ground where was about 50 m ~ 75 m from the pan center. Most smoke went away and reached the ground or the sea where located more than 10 km far away from the pan center. Smoke particles were taken by a SEM (Scanning Electron Microscopy). Diameters of most smoke aggregates were between 0.1 μ and 2 μ, and the average diameter and its standard deviation of the initial smoke particles (ISP), which consists of smoke aggregate, was 53.0 $\pm$ 10.5 nm. Their sizes were smaller than those from 1 m, 2.7 m sq. and 12 m pan fires, and distribution was narrow. As size of ISP is considered to be controlled by residence time[46,47,58]. Therefore the smoke particles which were sampled here might not represent major smoke particles emitted from the 20 m fire and might be emitted from the flame base in early growing stage of ISP, that is, period of residence time (existing time in the flame) is relatively shorter.

(8) Smoke dispersion model and smoke reducing agent

Yamada et al.[23] evaluated the calculation results of NIST large eddy simulation model by Baum et al.[48,49] with the observation results of smoke dispersion from the fires. This kind of expectation is very important for fire fighter training. Before the experiment the calculation was done to obtain the permission from the environmental section of the local government.

To reduce the smoke emission rate is one of the largest problems for fire fighter training and experiments. It has been studying and some of them are proposed as smoke reducing agents[59], and it is available commercially. It is possible to reduce smoke emission when some oxidizing materials are added into the fuel. We examined them during the series of Tomakomai experiments, and they might be used for our future large experiment or fire fighter training.

7 CONCLUDING REMARKS

Recent large pool fire experimental results concerning single tank and dike fires, smoke emission from tank fires, and boilover and slopover, are reviewed. Especially, a lot of data were obtained from the Tomakomai and Oga experiments in 1998 and 1999. However still we need data relating large pool fires in various conditions, fuels and fire modes. For examples we have little knowledge about slopover phenomena, effect of difference of crude oil on burning and boilover, and also we need more data concerning the weather conditions on radiation, smoke emission and boilover. Effect of fire fighting on burning should be studied because one of the goal of the study is to find the extinguishment method of the fire as soon as possible with safety.

Without these information, it may be not allowed even to conduct a fire fighter training with large fires in the future because of environmental problems. In order to conduct the Tomakomai large crude oil fire experiments, a lot of explanation concerning smoke fall was needed. Data are also useful for spilled oil cleaning method, and other purposes. To ignite and to keep burning of aged crude oil is difficult. Therefore we have to continue large oil burning research.

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Air Entrainment and Thermal Radiation from Heptane Pool Fires

Hiroshi Koseki and Taro Yumoto*

Abstract

An experimental study was made to explore the air entrainment into heptane pool fires and the smoke blocking effect on thermal radiation from fire. Heptane was burned in five different sized tanks 0.3 m, 0.6 m, 1 m, 2 m, and 6 m in diameter, and its burning rate, flame temperature, vertical hot gas velocity, and thermal radiation were measured. It was found that the total amount of air entrainment is about 5 times the stoichiometric air requirement. A smoke block effect appeared at tank diameter of 2 m or more.

Introduction

The most important combustion characteristics for evaluating hazards of oil tank fires are the burning rate of oil, radiation from the flame to the surroundings, flame temperature, and flame height. These characteristics from various liquid hydrocarbon pool fires, in different sizes, have been investigated by many researchers. Burning rate, especially, has been measured by many researchers, as seen in the review by Babrauskas.[1] Radiation is the second most frequently studied factor,[2–15] and flame temperature is the third.[8,12–14,16–20]

Liquid hydrocarbon pool fires, as do oil tank fires, generate black smoke, which increases in volume with tank diameter. The black smoke blocking effect on thermal radiation also increases with tank diameter. The amount of black smoke generated is related to the air entrainment into the flame. There are a few reports on this problem. Raj[19] measured hot gas velocity at one point on the axis of a JP-4 fire to correlate air entrainment. Yumoto et al.[20] measured velocities at several points on the axis of heptane fires and obtained

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Key Words: pool fire; air entrainment; burning rate; flame temperature; vertical velocity; heptane.

the amount of air entrainment on the basis of two assumptions: (1) that velocity and temperature are constant on any cross-section of the fire; i.e., top-hat profiles; and (2) that the flame shape is cylindrical, and its diameter is equal to that of the tank.

The first assumption was also adopted in Steward's flame model,[21] but needs to be verified.

Most reported radiation data are total radiation from the whole flame, and radiation data from portions of the flame are few.[13,15] The data from portions of the flame are important for fire protection of buildings near the fire. The purpose of the present study is to obtain information experimentally on air entrainment and smoke blocking effect on radiation. The measurements were made of the burning rate, flame temperature, hot gas velocity, and heat radiation from five different sized steel tanks (0.3 m, 0.6 m, 1 m, 2 m, and 6 m in diameter) under calm conditions.

Experiment

Burning Rate

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

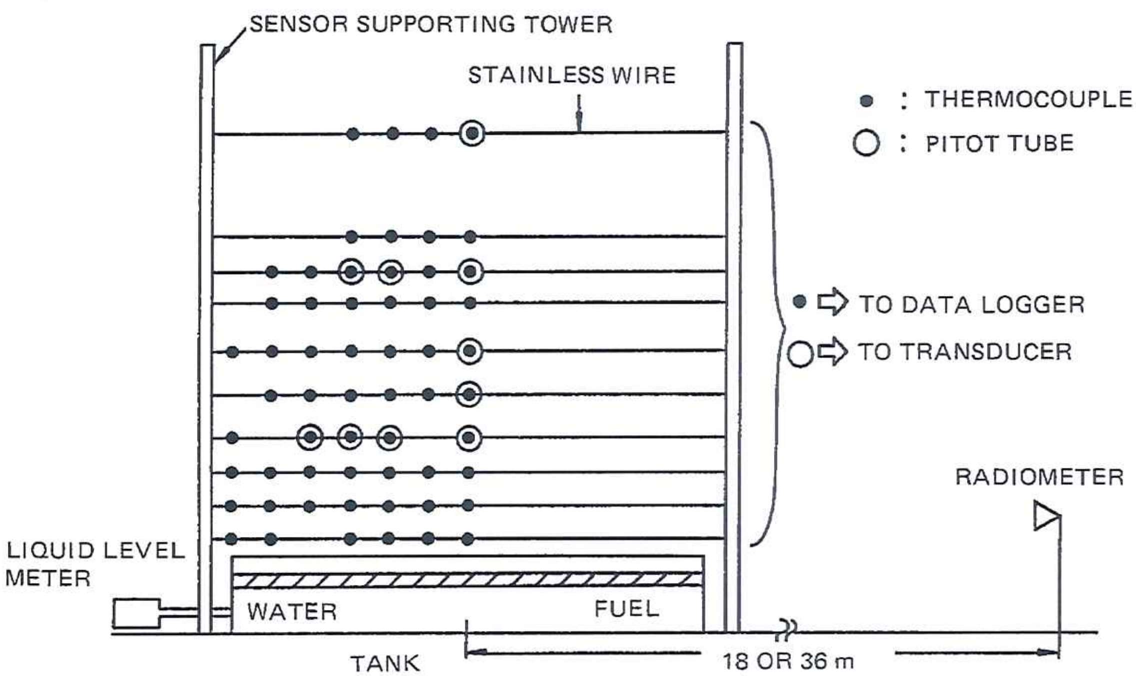


Figure 1. Positions of thermocouples and Pitot tubes in a 6 m tank. Solid circle: thermocouple; open circle: Pitot tube.

Vertical Velocity

Vertical gas velocities both on the axis of the tank and at radial positions were measured by nine bidirectional stainless steel pressure probes. The amplified signals from the differential pressure transducers (maximum range of measurement: 70 mm H_2O) were recorded on a digital data recorder and/or a pen-type recorder.

Temperature

Temperatures in the flame from 2 m and 6 m tanks were measured by arrays of 64 and 58 sheathed thermocouples, respectively. On the other smaller tanks, 80 sheathed thermocouples were used. All thermocouples were 0.32 mm diameter K-type, sheathed by 1.6 mm stainless steel or glass fibered tubes. For the 2 m and 6 m tank fires, only stainless steel sheathed thermocouples were used for convenience. As an example, Figure 1 shows the positions of the thermocouples and bidirectional tubes for the 6 m tank. Outputs of the thermocouples were recorded every 4 s using a digital data logger.

Radiation to Surroundings

Radiation from the whole flame to surroundings was measured by five thermopile-type radiometers, which cover a wide angle (at least 120°), and which were faced to the flame and located between $L/D = 3$ and $L/D = 7$, where L is the radial distance from the tank center to the radiometer and D is the tank diameter. All radiometers were installed at an elevation equal to that of the top edge of the tank.

Radiation from horizontal slices of the flame was measured by five narrow angle radiometers, each of which was masked using different sized hoods, such that each viewing angle was different. All radiometers were installed at an elevation equal to that of the top edge of the tank, faced to the flame, and were located between $L/D = 3$ and $L/D = 7$.

Thermocouples and bidirectional probes were positioned along ten stainless steel wires, above the tank, which were stretched horizontally between two steel poles. All fires in the test series, except for those in 2 m and 6 m tanks, were conducted in a large-scale test facility 15 m wide by 30 m long by 18 m high. Experiments using the 2 m tank and 6 m tank were conducted outdoors.

Experimental Result

Burning Rate

Figure 2 shows the relationship between burning rate and tank diameter. As tank diameter increased, the burning rate also increased in the range of the experiments, from 1.4 mm/min in the 0.3 m diameter tank, to 6.9 mm/min in the 6 m diameter tank. These values are small compared with Kung et al.[22]

and Tarifa et al.[23] The data can be represented using the same predictive form as Burgess et al.[2]

$$V = V_\infty (1 - e^{-k\beta D}) \quad (1)$$

Here, V is burning rate, V_∞ is burning rate for an infinite-diameter pool fire, k is the radiative emission coefficient, ß is the mean beam length corrector, and D is tank diameter (in meters). In the figure the dashed line is the prediction according to Equation 1 with the measured burning rate of the 6 m diameter tank (V = 6.9 mm/min) for V_∞, and 0.8 m^{-1} as the value of k ß. Experimental data are correlated well except for the 2 m tank. The value of 0.8 m^{-1} is within the range of Babrauskas' data [1.3 (± 0.5) m^{-1}].[1] In the range of the tests, radiation from flame to fuel surface rules burning rate dominantly, but only one-half to one-quarter of heat flux by radiation contributed to fuel vaporization,[24] probably due to absorption with vapor layer between flame and fuel surface.

Vertical Velocity

Figure 3 shows time-averaged vertical velocity profiles along the flame axis. The values were calculated from pressure difference measured by bidirectional pressure probes and temperature measured by thermocouples. In the calculation, the gas density was assumed to be equal to that of air at the measured temperature. Velocities increased with tank diameter. The dimensionless height above the tank edge for mean peak velocity was slightly higher than that of mean peak temperature.

Figure 4 shows the relationship between mean velocity (measured at H/D = 0.75 and H/D = 1.5) and the logarithm of the tank diameter. This result indicates that mean velocity is almost proportional to the square root of tank diameter and is consistent with the scaling law.[25] For reference, data for a 15 m diameter JP-4 tank fire (Raj[19]) is also shown on this figure. Raj's data is slightly lower than our data, but we believe that it is in good agreement.

Flame Temperature

Figure 5 shows the relationship between time-averaged temperature on the flame axis and dimensionless height. These temperatures are not corrected for thermometric error due to radiation. Peak temperature increased with tank diameter. Maximum temperatures measured were about 1200–1300°C, which agrees with the results of Raj[19] and others.[13]

Figure 6 shows an example of isotherms in 6 m tank fires. The isothermal density is highest at the flame base. Strong steep density incline suggests that air entrained strongly from flame base above the tank edge to the fire core along the dashed line. This figure is an example of a 6 m tank fire, but the isothermal pattern is similar for fires in other sized tanks.

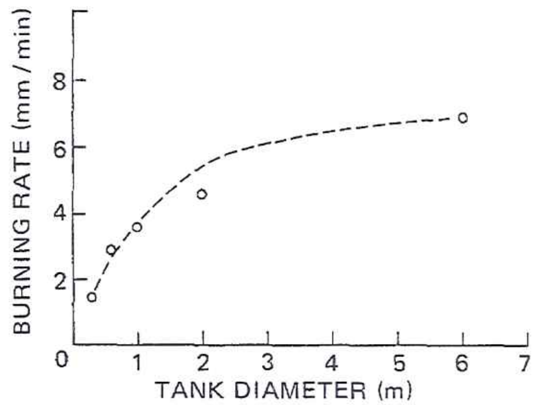


Figure 2. Effect of tank diameter on burning rate of heptane. (The dashed line is the prediction according to Equation 1 with V_∞ = 6.9 mm/min and $k\beta$ = 0.8 m^{-1}.)

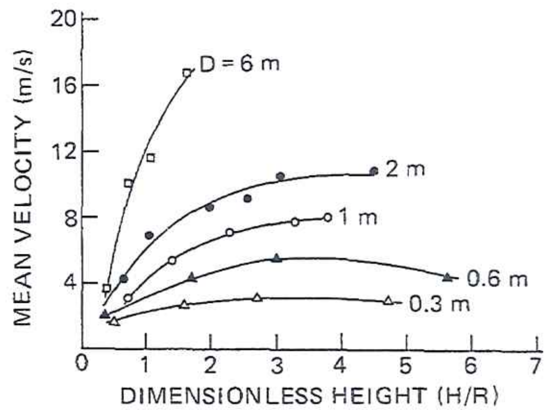


Figure 3. Mean vertical velocity profiles along the flame axis. H = height above top of tank; R = tank radius.

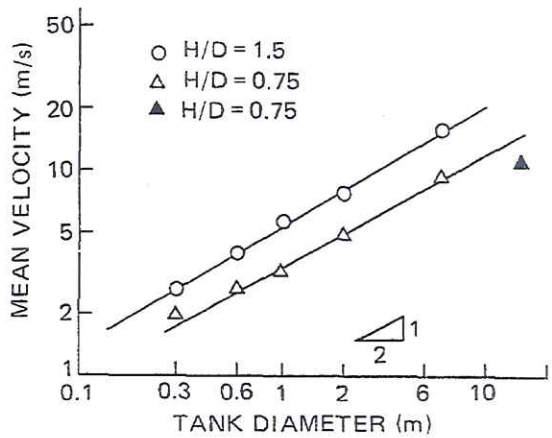


Figure 4. Effect of tank diameter on mean velocity at H/D = 0.75 and 1.5. Solid triangle: JP-4.[19]

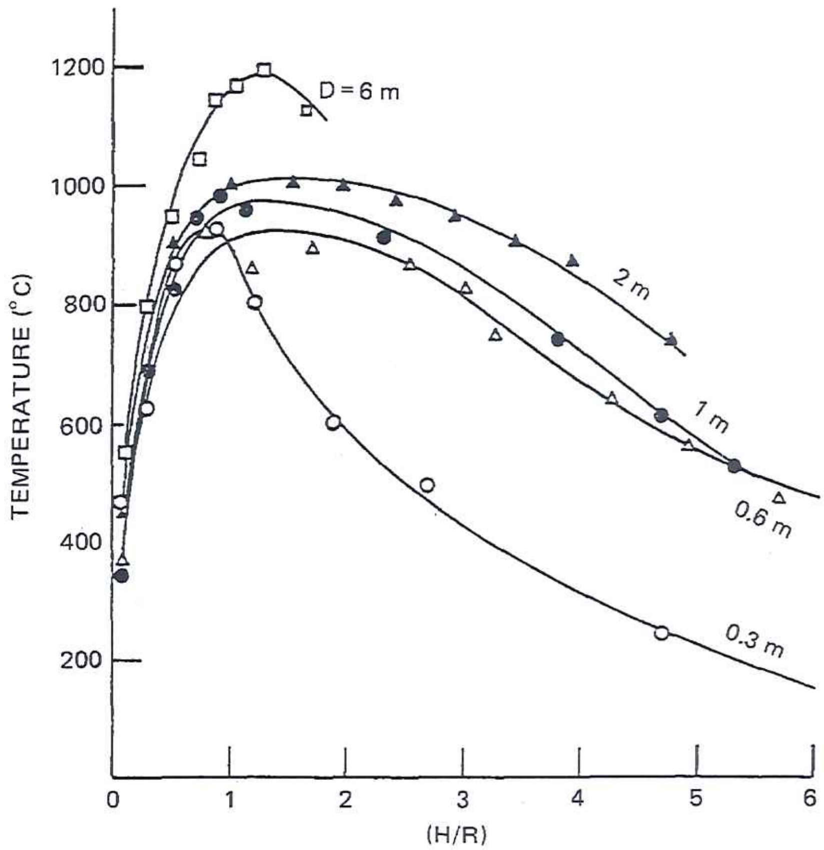


Figure 5. Temperature profiles along the flame axis.

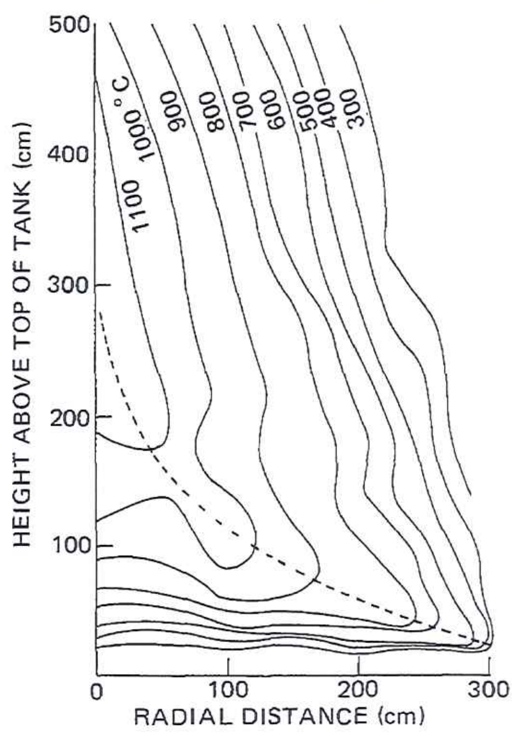
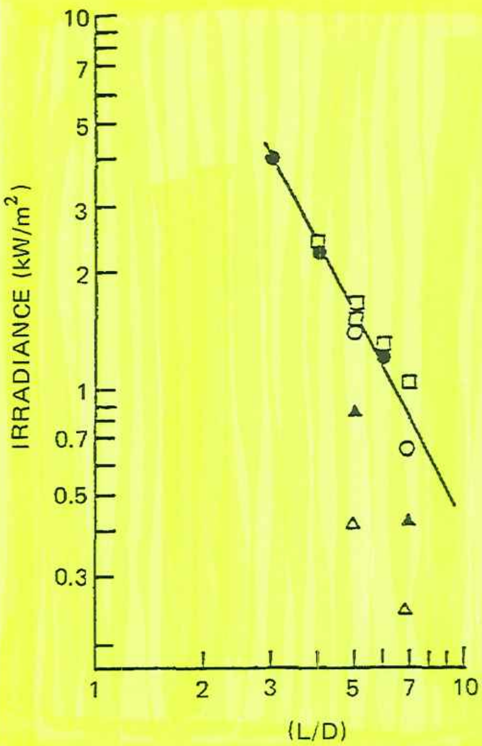


Figure 6. Isotherms in 6 m tank fire. (The dashed line shows the path of major air entrainment.)



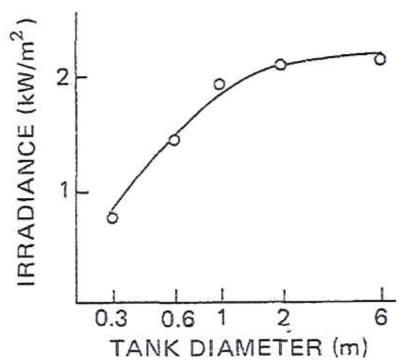


Figure 8. (top) Effect of tank diameter on irradiance at $L/D = 5$.

Figure 7. (left) Radiative heat flux from fires. Solid circle = 6 m tank; open square = 1 m; solid triangle = 0.6 m; and open triangle = 0.3 m. L is the distance from center of tank to radiometer, and D is the tank diameter.)

Radiation to Surroundings

The relationship between irradiance, measured by a wide angle radiometer, and dimensionless distance from the tank center (L/D) is shown in Figure 7. For any size tank, irradiance is inversely proportional to the second power of L/D, as the slope of the straight line in the figure is –2.

In Figure 8, the variation of irradiance with tank diameter at the same dimensionless distance ($L/D = 5$) is shown. Irradiance increases with the diameter of the tank, up to 6 m tank diameter, due to increasing emissivity of the flame.

Values of emissivity, ε, are calculated using

$$\varepsilon = 1 - \exp(-k\beta D),$$

where $k\beta$ is assumed equal to 0.8 m^{-1}. If temperature is constant regardless of tank size for the same fuel, and the smoke blockage effect is ignored, irradiance should be in proportion to emissivity. Calculated with this equation, emissivity is equal to 0.21 for a 0.3 m tank, 0.38 for a 0.6 m tank, 0.55 for a 1 m tank, 0.80 for a 2 m tank, and 0.99 for a 6 m tank. Approximately, experimental results of irradiance are proportional to calculated results of emissivity, but flame temperature increased slightly with tank diameter (see Figure 5), and smoke appears in the large fires. The smoke blockage effect is particularly important here.

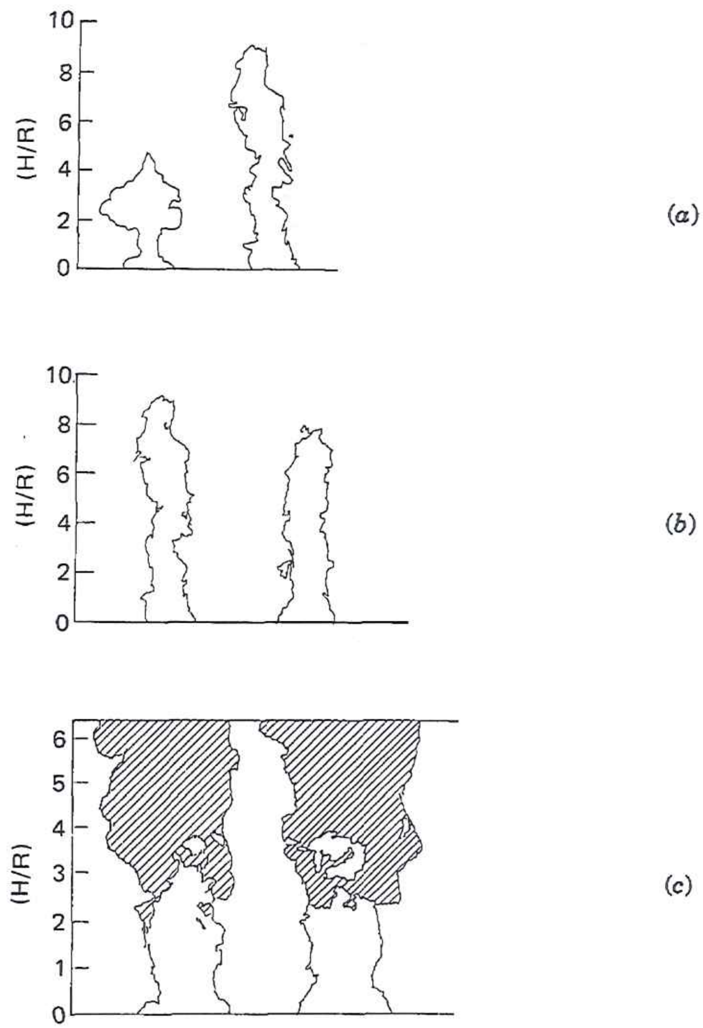


Figure 9. Typical shapes of flame copied from photographs: (a) 0.6 m tank, (b) 2 m tank, and (c) 6 m tank. Shaded areas show black smoke.

Figures 9 (a) to (c) show patterns of variation in flame shape, both the highest and the lowest, for each tank fire while in steady state. Shaded portions show areas of black smoke, which appears voluminously in the 6 m tank fire.

Figure 10 shows the radiant emittance measured by narrow angle radiometers. Except for the 6 m tank fire, the larger the tank, the higher the radiant emittance of each part of the flame, as measured by a narrow angle radiometer at any dimensionless height of the fire. Radiant emittances of the 6 m and 2 m tank fires are almost the same. The peak radiant emittance value for the 2 m tank fire is slightly higher than that for the 6 m tank. However, this result is consistent with the results of total irradiance in Figure 7. The dimensionless height of maximum temperature and maximum emittance are nearly equal, $H/R = 1.4$.

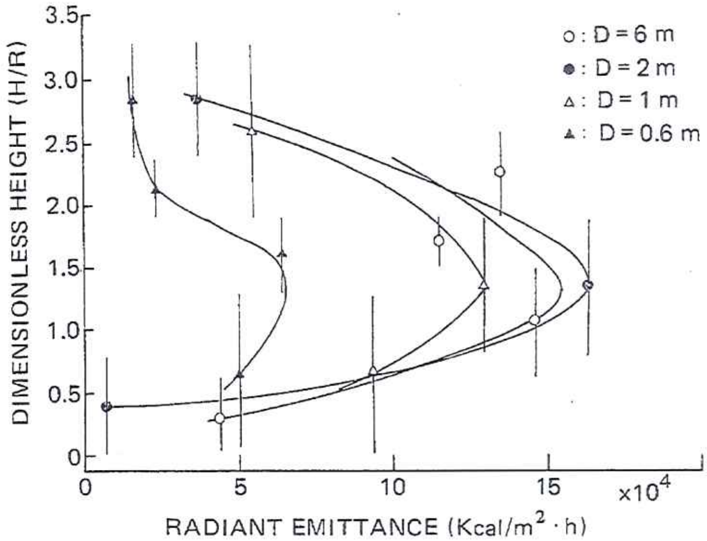


Figure 10. Radiant emittance measured by narrow angle radiometers.

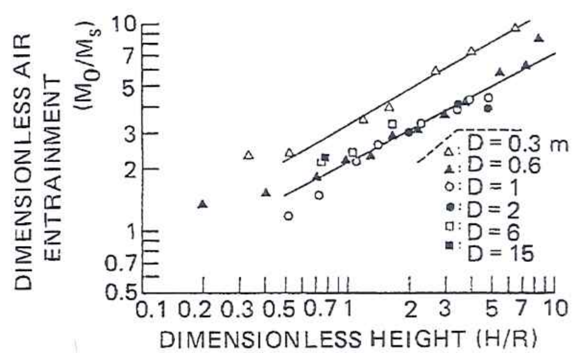


Figure 11. Dimensionless mass air entrainment based on top-hat profile assumption (M_0 = mass air entrainment; M_s = mass air required for stoichiometric combustion of fuel). Raj's data[19] is indicated by the solid square.

Discussion

Air Entrainment into Flame

The vertical mass flow rate at any height is equal to the amount of vaporized heptane plus the air entrained up to that height. According to Steward's method[21] of estimating flame height, velocity in the vertical direction is assumed to be constant for all radial positions. This is known as a "top-hat profile." Also, the flame is assumed cylindrical with its diameter equal to the diameter of the tank. With these assumptions, air entrainment can be easily calculated with the measured velocities and temperatures.

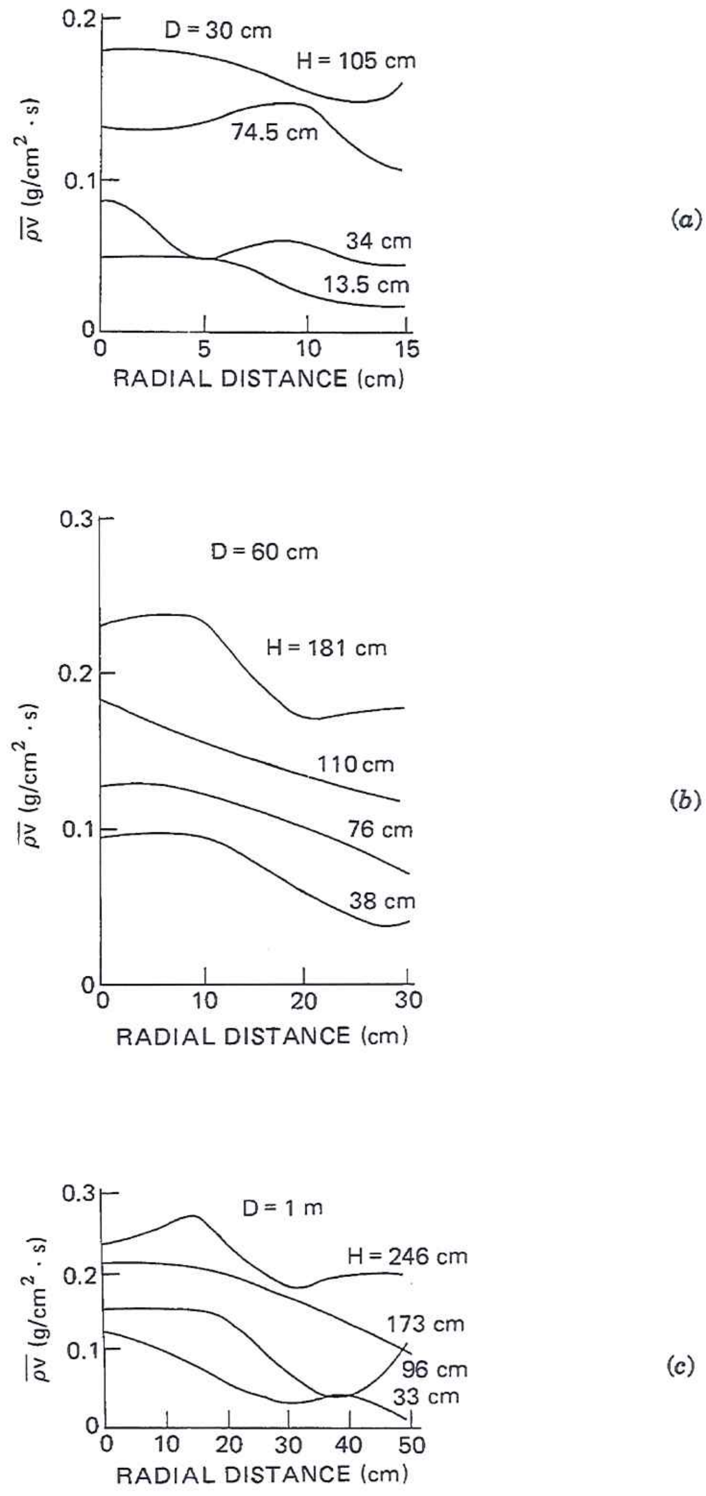


Figure 12. Vertical mass flow profiles in the flame: (a) 0.3 m tank, (b) 0.6 m tank, and (c) 1 m tank.

On the other hand, because burning rate changes with tank size, combustion efficiency cannot be discussed adequately using the amount of air entrainment (M_0) alone. It is reasonable to use dimensionless air entrainment M_0/M_s where M_s denotes the theoretical air entrainment needed to complete combustion of the measured vaporized fuel.

Figure 11 shows the relationship between dimensionless air entrainment and dimensionless height (H/R); here dimensionless air entrainment was calculated using mass velocity ρv calculated from velocity and temperature measurements at different heights along the flame axis, assuming the top-hat profile. Raj's data (15 m diameter tank JP-4 fire)[19] is shown in this figure for reference. All data except those for the 0.3 m tank are nearly on one straight line. The straight line is described by $M_0/M_s = 2.13(H/R)^{0.53}$ for tank diameters of 0.6 m to 15 m when $H/R > 0.5$. For the 0.3 m tank, the line is described by $M_0/M_s = 3.26(H/R)^{0.56}$. The air entrainment needed for complete combustion of heptane was calculated using stoichiometric ratio (15.3 g air for 1 g heptane), burning rate, density of heptane, and tank diameter.

Figures 12 (a) to (c) show vertical mass velocity, ρv, versus radial position at various heights calculated from measured gas velocity and temperature distributions in the radial direction for fires in 0.3 m, 0.6 m, and 1 m tanks. These results contain a large amount of variation, which makes the data difficult to interpret.

Figure 13 shows the ratio M_0/M_s. Here M_0 was calculated with the result of ρv radial profiles shown in Figure 12. For this calculation, we also used the assumptions that flame shape is cylindrical, and its diameter is equal to that of the tank.

Figure 14 shows the ratio of mass air entrainment calculations based on measured radial profiles of vertical mass flow, to calculations based on only the top-hat profile assumption using only the data of vertical mass flow along the flame centerline. As a result, air entrainment calculated with radial profiles (former) is smaller than the top-hat profile at any height. This ratio changes with dimensionless height, increasing from about 0.6 at $H/R = 1$ to

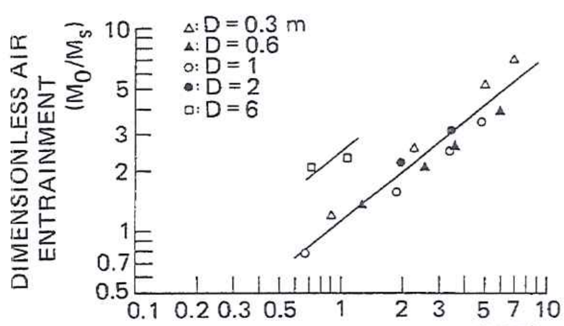


Figure 13. Dimensionless mass air entrainment based on radial profiles of vertical mass flow.

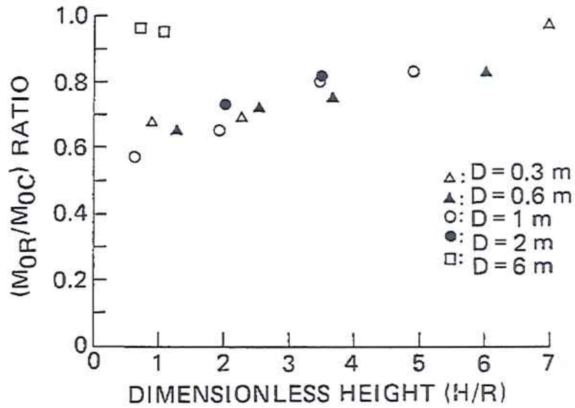


Figure 14. M_{OR}/M_{OC} ratio (M_{OR} = mass air entrainment based on radial profiles of vertical mass flow; M_{OC} = mass air entrainment based on top-hat profile assumption.)

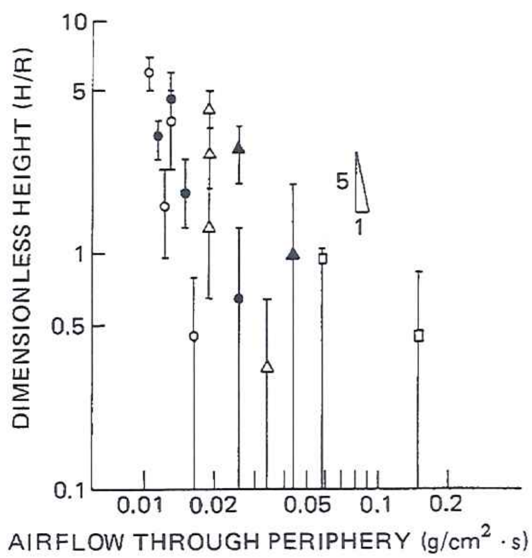


Figure 15. Airflow through cylindrical surfaces of different diameters. Open circle: D = 0.3 m; solid circle: D = 0.6 m; open triangle: D = 1.0 m; solid triangle: D = 2.0 m; open square: D = 6.0 m.

0.8 or more at $H/R \geq 4$, for all tanks except the 6 m tank. For the 6 m tank, the ratio is about 0.95. As seen in Figures 9 (a) to (c), the shape of the 0.6 m tank flame is slightly tapered, but the 6 m fire is almost cylindrical. So it is reasonable to conclude that the top-hat assumption is good for calculating the amount of air entrainment for fires greater than or equal to 6 m in diameter.

In Steward's mathematical model,[21] the height at which 400% excess air has been entrained corresponds to the visible flame height. His prediction is consistent with the present results except for the 6 m tank fire (see Figures 9 (a) to (c) and Figure 13). For the 6 m tank, air entrainment at the visible flame height (H/R=3) corresponds to the straight line, if this line is projected to H/R =3. The straight lines fitted in Figure 13 describe as $M_0/M_s = 1.10(H/R)^{0.80}$ for 0.3 m to 2 m tanks, and $M_0/M_s = 2.40(H/R)^{0.80}$ for the 6 m tank. Figure 13 shows that the amount of air entrainment for the 6 m tank is greater than that of any other tank, even on a dimensionless basis. Presently the reason for this result is not clear, but crosswinds in the 6 m tank fires are a possible explanation.

Figure 15 shows differential airflow through cylindrical surfaces in the flame as calculated by the air entrainment between any two heights, from the data in Figure 12. On any size tank, the amount of air entrainment is maximum at the flame base. This result is consistent with the result inferred from the isotherms of Figure 6.

Radiative Fraction Calculated by the Radiative Flux and Total Heat Release Rate Data

Assuming isotropy, the total radiative power output, Q_{rad}, is simply the flux times the spherical surface area:

$$Q_{rad} = 4\pi L^2 E.$$

Total heat release rate, Q_{tot}, is:

$$Q_{tot} = \pi R^2 V \rho H_c.$$

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

$$X = Q_{rad} / Q_{tot} = 4\pi L^2 E / \pi R^2 V \rho H_c,$$

where V is burning rate (surface regression rate), ρ density of fuel, H_c combustion heat release rate, and E irradiance at distance L.

The results of these calculations are shown in Figure 16, with results for crude oil fires[11] and kerosene fires[13] shown for reference. This indicates that the heptane fire's radiative fraction is maximum at 2 m tank diameter. For tanks smaller than or equal to 2 m, the heated carbon fine particles in the flame may increase the emissivity of the flame, and therefore increase the radiative fraction. For tank diameters greater than 2 m, the radiative fraction decreases in spite of emissivity increasing, due to the smoke block effect. For real tank fires (for example, in 30 m or 50 m diameter tanks) the radiative fraction decreases to one-third of the 2 m tank radiative fraction.[11,13]

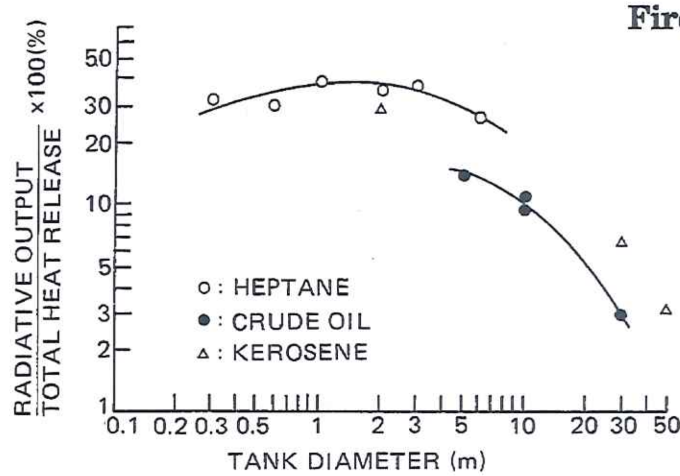


Figure 16. Effect of tank diameter on the ratio of radiative output to total heat release. Kerosene and crude data taken from Japan Society of Safety Engineering,[11,13] except for lower data from 10 m tank.[9]

Conclusion

While heptane was burned in five different sized tanks (0.3 m, 0.6 m, 1 m, 2 m, and 6 m in diameter) measurements of burning rate, flame temperature, vertical hot gas velocity, and radiation were recorded. Based on the foregoing results, the following conclusions are presented.

1. From base to flame tip, the amount of air entrainment is about five times that necessary for stoichiometric complete combustion.
2. For large-scale tanks, it is possible to calculate air entrainment only from velocity and temperature data on the flame axis, to estimate air entrainment.
3. On any size tank, the rate of air entrainment is maximum at the base of the flame.
4. Black smoke blocking effect of the luminous zone of a heptane fire appears for tank diameters larger than 2 m.
5. In the range of the experiments, the maximum radiant emittance measured by a narrow angle radiometer is at $H/R = 1.5$.

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