Smoke Characteristics in Kerosene Pool Fires

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Abstract

Experimental measurements of flame structure and soot characteristics were performed for small kerosene pool fires, which is widely used as a fire source of experiments with scaling modeling. The flame length and flickering frequency were investigated for the flame characteristics and structures, and compared with the theory. Three measurement methods were introduced to clarify the exhaust smoke particle, i.e. various gas concentrations, smoke density and thermophoretic sampling with transmission electron microscopy (TEM). The yield of carbon dioxide and the consumption of oxygen were proportional to the heat release rate of pool fires, but there is no trend on carbon monoxide emission. Smoke density of turbulent flames was exponentially increased with the heat release rate. The soot morphology of the soot sample was investigated to address the degree of soot maturing. The results show that identical smoke morphology between an inverse jet flame and a pool fire exists despite of different combustion controlling mechanisms.

Keywords: Pool Fire, Smoke density, Flame Height, Morphology

1. Introduction

Pool fire is one of the basic fire scenarios that has received research interests for long time, and a large number of studies has been performed to understand the pool fire (Babrauskas, 2002; McCaffrey, 1995; Heskestad, 1983; Drysdale, 1985; Karlsson and Quintiee, 2000). It is, in general, a turbulent diffusion flame above a horizontal pool of vaporizing hydrocarbon fuel where the fuel has zero or low initial momentum. In the view of fire accident, pool fire can be characterized by oxygen limitation: ventilated (fuel-controlled) fires in the open and under-ventilated (ventilation-controlled) fires within enclosures (Karlsson and Quintiee, 2000).

Liquid pool fire can be applied to not only the fire of a spilled oil on ground directly but also to the heat source on reduced scale fire experiment due to most simple geometry. A large fire experiment is commonly used to model a real fire accurately because there is no rule that all properties in models cannot be conserved. However, the small scale experiment needs to fire research itself, and it is sometimes the only way such as the experiment on the tunnel fire because of high cost (PIARC, 1999). Therefore, small scale experiments of pool fires are necessary not only to research the flame dynamics but also to verify the reduced scale model as a significant element. This will contribute on the development of advanced reduced scale model.

However a buoyancy dominated combustion phenomenon is very complex, and flame radiation, flame height, turbulent flow field and their interactions are particularly important for better understanding flame structure. For the risk assessment under fire, smoke properties is more important than the flame structure. Indeed, statistics collected in the UK and USA suggests that more than 50% of all fatalities can be attributed to the inhalation of smoke and toxic gas such as CO (NFPA, 1997).

Although there are a few definitions on smoke in fire, we included the particles such as soot and product gas generated under combustion. Soot particles are emitted inevitably when a fossil fuel is used as a source of energy, and the fully developed fire of underventilated conditions causes soot evolution. To reduce the number of accident involving the inhalation of toxins under fire and to make the combustor more environmentally friendly, much effort has concentrated on the study of soot formation. The process of soot evolution from fuel consists of complex chemical and physical steps, including fuel pyrolysis, polycyclic aromatic hydrocarbon (PAH) formation, particle inception, coagulation, surface growth, carbonization, agglomeration, and oxidation (Bockhorn, 1994; Glassman, 1988; Kennedy, 1997). Toxic gases are represented by HCl and CO during solid combustion, but CO is most important species in
the case of liquid pool fires.

In this study, the flame structure and smoke properties were investigated at the exhaust of kerosene pool fires. Major gas species were measured to estimate the combustion condition and to consider the effect on human behavior. Laser extinction method was introduced for the smoke density and soot volume fraction. Thermophoretic sampling was also performed to estimate the carbonization of soot particles using TEM images.

2. Experimental Methods

The pool fire burner consisted of coaxial pans for the liquid fuel and water as shown in Fig. 1. The pan diameters for the fuel were set to 15, 30, 45, 60mm to change the size of pool and the heat release rates. The pans were tapered to minimize the effect of rim thickness. Commercial grade kerosene for a domestic boiler was used as fuel. The pan diameter of water in the outer co-annular region was 100 mm, and it is introduced to prevent the overheating of burner. Both fuel and water reservoir was used to preserve constant level in the pans.

The experiments were conducted for free burning conditions because the reduced ventilation can strongly affect the smoke production. A screen made by wire mesh was located around pool fire flames so that it minimized the flow disturbance and allowed the entrainment of ambient air during combustion. The large contraction, providing a uniform smoke stream like a plug flow, placed at 1m above a pan. The product gases and smoke was sampled just above the contraction, of which diameter is 80mm.

Soot formation and growth processes were affected by residence time in a high temperature field and by the concentration of carbonaceous particle precursors, such as PAH and microparticles (Bockhorn, 1994; Dobbins et al, 1995). Therefore, a flame length as well as a flickering frequency were observed with bare eyes and monitored by a digital video camera.

Laser diagnostics were performed to measure the soot volume fraction and smoke optical density emitted from pool fire. For the light extinction instrument, two key features are the use of monochromatic light and the elimination of forward scattered light at the detector. As shown in Fig. 1, the optical setup for laser light extinction method consisted of a He-Ne laser with a neutral density filter to adjust the laser power and a photo multiplier tube (PMT) as a detector. Laser beam, 30mW and 632.8nm, was divided by a beam splitter. One was for energy meter to monitor the energy fluctuation during experiment, and the other passed through the smoke region just above contraction. The intensity of the reduced laser beam due to smoke particle was detected using PMT (Hamamatsu R212, \(\lambda=185-650\)nm). To minimize the background noise from the flame-induced light and eliminate forward scattered light at the detector, the band pass filter (\(\lambda=630\)nm) was equipped in front of PMT.

The morphological characteristics and the carbonization process of soot were investigated by a thermophoretic sampling with a TEM grid. A pneumatic drive system to insert the grid into the smoke stream controlled the motion of the TEM grid, which moved into the flame at 1 m/s, and the residence time inside the smoke was 1 s considering the temperature difference between smoke and ambient air. TEM grids were examined with STEM (Scanning Transmission Electron Microscope, Philips Tecnal F20) using magnifications range from 22K to 1,350K.

The concentration of gas species of smoke is also important to define combustion efficiency as well as human behavior in fires. The product gases were sampled with a quartz sampling probe, and CO, O\(_2\) and CO\(_2\) concentration were analyzed with a gas analyzer (Horiba, PC250).

3. Results and Discussion

The direct pictures of kerosene pool fires are shown in Fig. 2. In a liquid pool fire, buoyancy is the predominant driving force and hence the flame structure is more complicated and easily affected by external disturbance than jet flames. The flame of small size is essentially laminar as shown in Fig. 2(a), but the flame becomes turbulent as the diameter is increased. From the investigation of pool fire flames with four diameters, the transition is occurred between 15 to 30mm. Once the flame become turbulent, large eddy motions like a vortex shedding are active with the larger pool size as shown in Fig. 2(b)-(d).
Fig. 2. Direct pictures of kerosene pool fires: D is pan diameter.

Overall behavior of pool fires such as the elongation and flickering depends on two heat transfer mechanisms. One is the heat conduction due to water of outer co-annular pan. In the experiment, the pan depth was designed with 2 cm for both fuel and water. As the water level of a pan is increased up to 2 cm, the smaller amount of fuel evaporates due to large heat transfer to water. The other mechanism is the height of fuel in a pan. If the fuel level is reduced, the fuel temperature of a pan boundary is decreased and fails to evaporate because of the large heat transfer to a stainless pan. That results in the smaller pool diameter than the pan inner diameter. In this study, it is observed that the reduced pool size effect is more dominant than the conduction by cooling water, and the effect was minimized by keeping maximum fuel level, where the fuel is not spilled over due to surface tension. However, these two heat transfer mechanisms are very important to characterize the pool fire flames, and more efforts will be needed in the future.

Figure 3 depicts the flame height measured in averaged flame images and predicted flame heights based on theory (Heskestad, 1983). A dimensional heat release rate, \( Q^* \), is introduced to express a pool diameter in terms of the heat release rate of a fire. It implies the square root of a Froude number, and is used to classify fire type and correlate aspects of fire behavior (McCaffrey, 1995). \( Q^* \) is defined by

\[
Q^* = \frac{Q}{\rho_c C_p T_\infty \sqrt{g DD^2}}
\]

(1)

where \( Q \) is the total heat release rate, \( T_\infty \) and \( \rho_c \) are the density and temperature of ambient air, \( C_p \) is specific heat of air at constant pressure and \( g \) is acceleration of gravity.

From the original correlation of buoyancy regime (Heskestad, 1983), the mean flame height can be presented by

\[
\frac{L}{D} = -1.02 + 3.7Q^{2/5}
\]

(2)

The mean flame height is an important quantity that indicates the flame condition where the combustion reactions are essentially complete and the inert plume begins to evolve.

Flame intermittency defined as the fraction of time that at least part of the flame lies above the elevation can be used to define the mean flame length. Objective determinations of mean flame height according to intermittency measurements are fairly consistent with flame heights that are averaged by human eye (Zukoski et al, 1985). Therefore, we measured the flame height from time-averaged images.

The flame height of Fig. 3 increases with increasing the heat release rate except the height at largest \( Q^* \), in which the flame is laminar and the correlation of Equation 2 for buoyant turbulent regime is not valid. The Heskestad relation overestimates the flame height of pool fire although the slope corresponds to the relation of the theory. The discrepancy between experiment and theory may come from definition of flame heights and calculation of burning rates of kerosene. For the burning rate of kerosene to calculate the \( Q^* \), the constant value (= 43.2 MJ/kg) was used. In the radiative regime, it is found that the burning rate per unit area for most organic liquids can be well correlated with the product of two empirical constants, extinction-absorption coefficient and the mean beam length corrector. Alcohol fuels show minimal radiative flux, in comparison to other fuel type. Thus the best recommendation previously had been to use constant values of burning rate, independent of diameter (Babrauskas, 2002). However, the smaller value of burning rates might be applied for small scale pool because the relative high ratio of pan diameter to volume induces the larger conduction heat transfer.

Turbulent buoyant diffusion flames show the
intermittency based on oscillation. The flickering frequency was measured by digital video camera (30 frames/s), and the average frequency was in the range of 12.5-7 Hz as the pan diameter is increased from 30mm to 60mm. Cetegen and Ahmed (1993) reported that pulsation frequency is quite regular and proposed the simple curve fit

$$f(\text{Hz}) = 1.5D(m)^{-1/2}$$  \hspace{1cm} (3)$$

and Zukoski (1995) suggests

$$f(\text{Hz}) = (0.50 \pm 0.04)(g / D)^{1/2}$$  \hspace{1cm} (4)$$

which is essentially in good agreement with equation 3. The experimental results show slightly higher frequency and the difference is increased at the smaller pan diameter.

![Graph showing mean flickering frequencies measured and predicted with Zukoski formulation.](image)

Gas concentrations of combustion products were sampled to provide the information on combustion condition and the evacuation. Three major important species, CO, CO$_2$ and O$_2$, were investigated except NO$_x$ whose yield is so small that it is impossible to measure, and their concentration was shown in Table 1.

<table>
<thead>
<tr>
<th>Dia. (mm)</th>
<th>Q (KJ/m$^2$s)</th>
<th>O$_2$ (%)</th>
<th>CO$_2$ (%)</th>
<th>CO (ppm)</th>
<th>Temp. (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>0.29</td>
<td>20.79</td>
<td>0.25</td>
<td>0.1</td>
<td>42.6</td>
</tr>
<tr>
<td>30</td>
<td>1.19</td>
<td>20.58</td>
<td>0.38</td>
<td>5</td>
<td>59.6</td>
</tr>
<tr>
<td>45</td>
<td>2.67</td>
<td>20.40</td>
<td>0.52</td>
<td>10</td>
<td>99.8</td>
</tr>
<tr>
<td>60</td>
<td>4.76</td>
<td>20.08</td>
<td>0.74</td>
<td>12</td>
<td>102.4</td>
</tr>
</tbody>
</table>

The formation of carbon monoxide (CO) is the major product of incomplete combustion in fires. The high concentration of CO is generated under fuel rich condition, and successfully predicted from the basis for the global equivalence ratio concept in enclosure fires (Pitts, 1995). It refers to the ratio of the mass of gas in upper layer derived from the fuel divided by that introduced from air normalized by the stoichiometric ratio. Although CO is not the most toxic of gases in terms of the effects of a particular concentration such as hydrogen cyanide (HCN), it is always one of the most abundant, and therefore, is the major threat in most fire atmospheres. The toxicity of CO is primarily due to its affinity for the hemoglobin in blood, resulting in formation of carboxyhemoglobin (COHb) and decreased capacity of the blood to transport oxygen to body tissues. In terms of CO concentrations required to reach hazardous COHb levels, a simple rule of thumb may be used. Any exposure in which the product of concentration with time exceeds approximately 35,000 ppm-min is likely to be dangerous (Kaplan and Hartzell, 1984). The measured CO concentration was increased with the pan diameter, and dramatically varied across the transition condition from laminar to turbulent. However the quantitative concentration is far from the critical one for human death, which results from the free burning condition to allow the air entrainment along the flame and hot plume.

Carbon dioxide (CO$_2$) usually is evolved in large quantities from fires. While not particularly toxic at observed levels, moderate concentrations of CO$_2$ increase both the rate and depth of breathing, thereby increasing the respiratory minute volume. This condition contributes to the overall hazard of a fire gas environment by causing accelerated inhalation of a toxicants and irritants. The rate and depth of breathing are increased about 50 % by 2 % carbon dioxide. The measured CO$_2$ concentration is below 1% in all cases, and proportional to pan diameter rather than the total heat release rate. For more fuel rich condition, CO$_2$ concentration is getting smaller because carbon from fuel consumes to be CO. Therefore, the ratio of CO/CO$_2$ used to an indicator for reaction completeness.

On the other hand, oxygen is consumed from the atmosphere during combustion. When the O$_2$ concentration from usual level 21% drops, a person loses consciousness and will die. Oxygen consumption during combustion provides very valuable information for heat release rates, which is that for most gases, liquids, and solids, a more or less constant amount of energy is released per unit mass of oxygen consumed. Huggett (1980) concluded that typical organic liquids and gases have $\Delta H_c = -12.72$ KJ/g of oxygen while polymers have $\Delta H_c = -13.02$ KJ/g of oxygen. The method that estimates the heat release rate from oxygen consumption is now widely used in fire research such as the cone calorimeter (Babrauskas, 2002). As shown in Table 1, it is reasonable that the
Reduced oxygen concentration is comparable to the total heat release rate because the oxygen consumed in ambient air should be proportional to fuel amount assuming complete reaction. Considering the \(O_2\) concentration in burned gas, fire plume is attributed mainly on entrainment of ambient air. A simple analytic expression can be considered for the mass flow rate of ideal plume at height \(z\) (Karlsson and Quintiee, 2000):

\[
m_p = 0.20 \left( \frac{\rho \, g}{C_p \, T_\infty} \right)^{1/3} Q^{1/3} z^{5/3}
\]

Assuming there are no radiative heat losses to the environment, plume temperature can be deduced from Eq. (5)

\[
T - T_\infty = 5.0 \left( \frac{T_\infty}{g C_p P_\infty^2} \right)^{1/3} Q^{2/3} z^{-5/3}
\]

Comparing the temperature measured on the contraction part, the simple theory predicts well the plume temperature.

\[
\frac{I}{I_0} = \exp(-K_{\text{ext}} L)
\]

where \(I / I_0\) is the reduction ratio of the light intensity passing through smoke. Then, the optical density is according to (Drysdale, 1985) defined as

\[
D = -10 \log_{10} \left( \frac{I}{I_0} \right)
\]

The visibility \((V)\) of light reflecting objects is approximately corrected the optical density per meter by

\[
V = \frac{10}{D_{10}} / L
\]

Figure 5 shows the reduction ratio of the light intensity, optical density and visibility. In the buoyant flames, the smoke density is almost constant at a relatively small heat release rate, but increases dramatically for the 60mm pool. The visibility is also decreased with increasing the heat release rate. The above definition of visibility is valid for light reflecting objects. If exit sign and the exit doors are light emitting, then the visibility will increase by a factor of approximately 2.5 (Drysdale, 1985).

The smoke density is mainly attributed by soot particles among the combusted materials, and there is a well known relation between the extinction coefficient and soot volume fraction, \(\varphi\), assuming the Rayleigh limit that soot particle diameter, \(d_p\), is smaller than the laser wave length, \(\lambda\).

\[
K_{\text{ext}} = \frac{\pi^2}{\lambda} E(\tilde{m}) N_p \int_0^\infty P(d_p) d^3 d_p
\]

\[
\int_0^\infty P(d_p) d^3 d_p = f_v \frac{6}{\pi N_p}
\]

\[
f_v = \frac{\lambda K_{\text{ext}}}{6 \pi E(\tilde{m})}
\]

where

\[
E(\tilde{m}) = -\text{Im} \left( \frac{\tilde{m}^2 - 1}{\tilde{m}^2 + 2} \right)
\]

For the complex refraction index for soot particle, \(\tilde{m}\), it is the function of irradiated laser wavelength and has been investigated by many researchers. \(\tilde{m} = 1.57 - 0.56i\) is commonly used recently (Dalzell and Sarofim, 1969) and the value is adapted in this study to calculate the soot volume fraction.

Figure 6 depicts that the soot volume fractions increase according to the heat release rates, and their order is similar to those of inverse diffusion flames (Lee et al, 2004), which is the limit case of underventilated diffusion flames. If one chooses a soot volume fraction range covering the estimates and then uses a value of 1,800 Kg/m³ (Smyth and
Mallard, 1981) for the soot particle density, then the corresponding mass concentration range is $3.2 \times 10^{-5}$ Kg/m$^3$ – $6.4 \times 10^{-4}$ Kg/m$^3$.

The extinction coefficient is an extensive property and can be expressed as the product of extinction coefficient per unit mass, $k_{ext}$, and mass concentration (Mulholland, 2002). Seader and Einhorn (1976) obtained $k_{ext}$ values of 7,600 m$^2$/Kg for smoke produced during flaming combustion of wood and plastics and a value of 4,400 m$^2$/Kg for smoke produced during pyrolysis of these materials in the small scale experiments. The present results gave us a value $k_{ext}= 4,300$ m$^2$/kg, which is similar to the above pyrolysis value.

The TEM image (a) of 15mm pool appears more amorphous than the image (b) obtained at the 30mm pool, and the soot particle is close to precursor soot. On the larger pool, soot images in Fig. 7(c) and Fig. 7(d) are similar to those in Fig. 7(b). This fact supports that soot growth is insignificant in the post flame region of pool fires. Comparing these images with jet flames, it is very interesting that the soot particles are more transparent to the electron beam than normal diffusion flames and similar to the exhaust soot of inverse diffusion flames. The relative opaqueness of normal jet flames result from the carbonization of soot particle along the reaction zone. Although the soot particles on the larger pool are similar one another, the primary particle size is slightly increased with increasing pan size. This growth results from the longer flame height as shown in Fig. 2, which increases the residence time for soot growth.

### Conclusion

The major conclusions of this work follow:

1. The slope of flame height corresponds to the correlation of the theory, but it is overestimates the flame height of pool fire. The discrepancy between experiment and theory might mainly results from burning rates of kerosene, and the small burning rate should be applied for small scale pool fires.
2. The yield of carbon dioxide and the consumption of oxygen were proportional to the heat release rate of pool fires, but there is no trend on carbon monoxide emission.
3. Light extinction instrument Laser diagnostics were performed for smoke optical density, and enhanced the accuracy using two key features, use of monochromatic light and the elimination of forward scattered light at the detector.
4. The soot morphology by TEM showed that the soot particles evolved at pool fires were similar to those of inverse diffusion flames despite of free burning condition.

### References

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