Experimental Study of Burning Rate in Jet-Fuel Pool Fires

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Abstract

Experiments were carried out in a 30 cm diameter pool fire, for both transient and steady-state conditions, utilizing jet fuel, Norpar-15, and a surrogate mixture of hydrocarbons that simulates jet-fuel behavior in a pool fire. Steady state pool fire tests match previous results well. The transient burning rate profile for jet fuel showed a high peak value early in the experiment, followed by a gradual decrease in burning rate as the balance of the fuel was consumed. Transient experiments with a jet fuel surrogate demonstrated similar behavior to the jet fuel. However, experiments performed with Norpar-15) yielded approximately the same value for both transient and steady-state burning rates. GC analysis of fuel samples taken from the pool fire pan over time clearly demonstrated a preferential burning of the light, volatile hydrocarbons during the early stages of the transient fires, which might result in a higher burning rate early on, follow by a slower rate when consuming the less volatile residual hydrocarbons. Results highlight the importance of understanding fuel chemistry when attempting to model, either experimentally or computationally, the pool fire behavior of complex fuel mixtures.

Introduction

Open hydrocarbon pool fires are present in many accident scenarios. The rate of pool burning is one of the most commonly used indicators to characterize pool fires. By far, the most systematic study on liquid pool fires were done by Blinov and Khudiakov [1]. Regression rates (mm/min) of pool fires of diameter range from 0.37 cm to 22.9 m were measured with different fuels. As Hottel [2] reviewed and interpreted their findings, the burning rate of large pool fire is determined by radiative heat transfer. Burgess [3] and Grumer [4] in their studies established correlations between the burning rate and fuel thermo properties for both pure and blended fuels. A more recent review [5] on this subject was given by Mudan and Croce. Despite these studies, few data available for jet fuels, especially JP-8/Jet-A. Furthermore, most previous studies focused on steady-state pool fires instead of transient pool fires, which is often a more realistic senario. The present paper presents research on the real-time behavior of Jet fuel, selected hydrocarbons, and fuel surrogates in a pool fire scenario. The burning rate for the pool fires was measured in real time, and these data were used to analyze the transient natureof pool fires.

Experimental Procedures

Jet fuel (Jet-A, density, 805 kg/m^3) was burned in a steel pan, 0.3048m in diameter and 0.1016 m deep, rigidly placed 0.5 m above the ground. The pan was enclosed by four walls, each 5 m wide and 6 m high and the exhaust was removed through a duct in the roof. Dampers in the walls below the level of the pool fire were provided to allow controlled infiltration of combustion air. The bottom of the pan was water-cooled. For both transient and steady state experiments, the pool was filled to within 0.100 ± 0.002m from the top and ignited with a propane torch. For continuous experiments, the fuel level was maintained constant by feed from a separate constant head tank, the level of which was monitored by a supersonic sensor used to control the fuel supply pump. The surface area of the burning pool is four times that of the head tank.

The burning rate for transient tests was determined through measurement of the variation in the fuel level of the head tank. An ultrasonic level sensor (Hyde Park, SM652A-BOB-11FP, Dayton, Ohio) was used to measure the fuel level variation. A micropump with an HG drive (Idex Corp., G-184, Vancouver, WA) was used to feed the head tank at a preset level in steady state pool fire tests. A flow sensor (McMillan, Model 101-5,

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Georgetown, TX) was used to provide fuel flow rate in steady state pool fire tests.

In addition to the experiments involving Jet-A, tests were carried out using a number of different chemical reagents or reagent mixtures. Norpar-15 is a very narrow boiling range mixture of hydrocarbons which can be acquired from Exxon Chemicals Inc. GC analysis of Norpar-15 gave the composition as (all in mol.%): *n*-tetradecane, 34.4 %, *n*-pentadecane, 49.0%, *n*-hexadecane, 13.5 % and *n*-heptadecane+, 3.1%. In addition, a surrogate mixture of reagents that simulates the pool fire behavior of Jet-A/JP-8 was previously formulated as reported in [6] is given by the following composition: *n*-octane, 3.5 %, *m*-xylene, 8.5%, decalin, 35%, tetralin, 8%, *n*-dodecane, 40%, *n*-hexadecane, 5%. GC analysis was done with a Hewlett Packard 6890 gas chromatography equipped with a Flame Ionization Detector (FID) and an HP-1 microbore column with a methyl siloxane stationary phase. Data were collected and processed with HP Chemstation.

Results and Discussion

Steady State Experiments

In steady-state experiments, the pump setting (and therefore fuel flow-rate) is automatically adjusted to maintain a constant fuel level in the pan. The flow rate is measured continually during the test by the data acquisition system and is equal to the steady-state burning rate. This volumetric burning rate (m_v, mL/min) is then converted into a surface regression rate (in mm/min) by use of the pool surface area, and into a mass burning rate (in kg/m^2 s) using the fuel density. The liquid fuel density was assumed to be constant throughout the test. Both the level sensor signal (in mA) and the flow rate signal (in mL/min) from the mass flow controller are collected at a frequency of 1 Hz.

Instantaneous volumetric burning rates for the in steady state experiments are calculated and averaged over a time interval of 60 s, and the results for an experiment that utilized Jet-A are plotted in Fig. 1 as a function of time. After ignition, 24 minutes are required to reach steady state and the steady-state burning rate is ~ 2.07 mm/ min (0.0278 kg/m^2 s). Zabetakis and Burgress [7] suggested that, for liquid pools of diameters greater than 0.2 m, the mass burning rate (m'', kg/m^2·s) could be predicted with the following equation:

$$m'' = m''_{\infty} \cdot \left[1 - \exp\left(-k \cdot \beta \cdot d\right)\right] \qquad (1)$$

where:

m''_{∞}: Mass burning rate of an infinite diameter pool, kg/m^2 s

k: Extinction-absorption coefficient of the flame, 1/m

β: Mean-beam–length corrector

d: Diameter of pool, m.

Constant values of m''_{∞} and kβ of kerosene from Barauskas [8] are used, and these values are 0.039 kg/m^{2}s and 3.5/m, respectively. Using Equation 1, the calculated mass burning rate for kerosene would be 0.0258 kg/m^2 s (1.91 mm/min), which is very close to the experimental value for Jet-A reported in this work. The estimated rate is also in agreement with the value (1.9 mm/min) reported for a kerosene 30 cm pool fire in Blinov and Khudiakov[1].

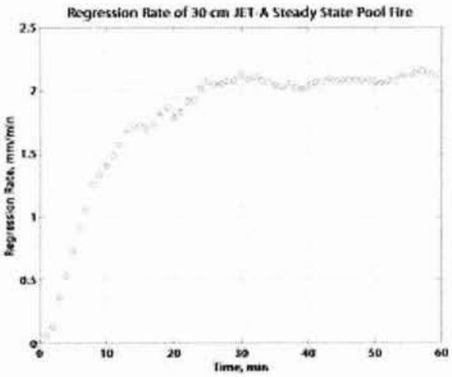

Fig.1 Measurement of Jet-A surface regression rate, 30 cm pool fire, steady-state (constant fuel depth)

Similar tests were performed with Norpar-15 to allow comparison with the Jet-A results. The minute-averaged Norpar-15 regression rates are plotted as a function of time in Fig.2. The only apparent difference is the profiles for Jet-A and Norpar-15 is that the steady state regression rate of Norpar-15 is 0.96 mm/min, which is about half that of Jet-A.

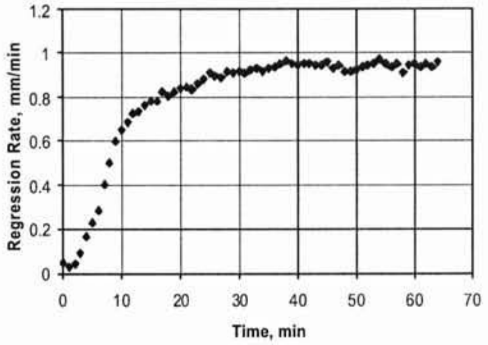

Fig.2 Measurement of Norpar-15 surface regression rate, 30 cm pool fire, steady-state (constant fuel depth)

If we assume that the two fuels have similar k and·β values, then the difference should come from m''_{∞}. According to the analysis from Burgess[3], m''_{∞} is determined by the ratio of the net heat of combustion to the sensible heat of vaporization. With data of JP-8 from Nicolette [9], Norpar-15 has a higher ratio of the net heat of combustion to heat of vaporization at the average boiling point than JP-8.

The JP-8 surrogate mixture was also tested under steady-state pool fire conditions. The minute-avearged regression rate was 2.10 mm/min, which is in agreement with that of the Jet-A. In all steady state experiments, the maximum surface level variation is controlled to less than 0.3 mm and the fuel depth in the pan is 100 mm.

Transient Experiments

During transient experiments, the feed pump is turned off and thus the pool fire becomes a batch experiment. The pan is filled to 0.100 ± 0.002m, and then after ignition the fuel surface level drops as the fuel is burnded off. The variation of the fuel level as a function of time in transient tests is shown in Fig. 3.

A cursory view of in Fig. 3 would indicate that, the change in fuel level, and therefore the burning rate is linear with the exception of the two ends. A least-squares linear fit gives a slope of 0.827 and R^2 of 0.98. If the data collected during the induction period (immediately after ignition) and the extinction period are excluded, then the apparent surface regression rate can be easily deduced from the slope of fuel level change, and the value obtained is 0.81 mm/min.

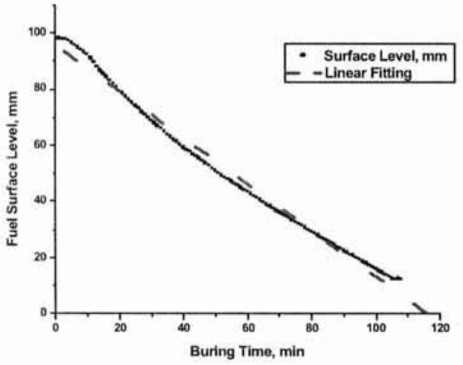

Fig.3 Measurement of fuel level Change, Jet-A, 30 cm transient pool fire

However, using our real time fuel level measurements as a basis, the surface regression rate (mm/Min) of transient pool fire tests can be computed accurately from the derivative of Fig.3, or the change in fuel level per minute through central difference formula on the data. The surface regression rate of Jet-A in transient tests computed from this approach is shown in Fig. 4. The figure shows that the surface regression rate is not a constant value but has an initial sharp peak followed by a gradual decline. The rate first increases very rapidly for times up to 10 min, and it reaches a peak value at approximately 11 min. The rate starts to fall off rapidly over the range of 12~35 min and decreases more slowly from 40~ 80 min until the end of burning. The peak value in the transient experiment, 2.11 mm/min was found to be very close to the steady state value for this fuel and the overall average burning rate was 0.82 mm/min as predicted above with linear fitting.

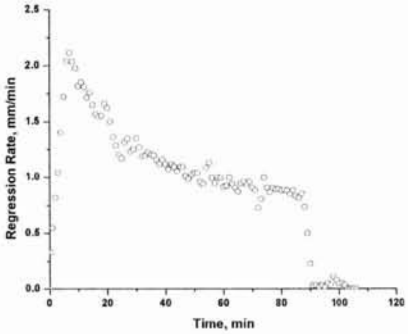

Fig.4 Computed regression rate of Jet-A in transient 30 cm pool fire tests

Iwata et al [10] studied 14 different crude oils and kerosene in a 90 mm pool fire (fuel depth 18 mm). It is believed that all of those tests were transient. They also found that the burning rate soon after ignition was higher than later stages of the experiment. They tried to explain the higher burning rates with two possible reasons. First, in the initial stages, there is no heat loss to the edges of fuel pan and the entire amount of heat transferred back from flame can contribute to the fuel vaporization. Second, light components burned much faster initially, and thus a lower burning rate was reached after the initial spike. They indicated that a steady state in these transient pool fires was reached quickly after ignition even crude oil is a complex mixture.

Blinov and Khudiakov [1] acknowledged the change in burning rate for transient pool fires. They concluded based on their observations that the rate will either show a continuous rise, e.g. toluene-rich ethanol-toluene mixtures, or continuous fall, e.g. ethanol-propanol mixtures. They also attributed the initial rise to the early heating transient and the composition change. In addition, it is not clear whether Blinov did a steady state or transient pool fire with kerosene.

Grumer and Burgess suggested that the burning rates of blended fuels are initially close to that of the light components and towards to close to the rates of the heaviest components based on their observation of a binary mixture.

A recent study[11] of gasoline and diesel large pool fire tests (d = 1.5 ~ 4.0 m) also produced mass burning rate vs. time curves with an initially rapid rate based on their real time mass measurements. The gasoline burning rate curve has a relatively flat top when compared with the initial rise and late decay. The desel curve, on the other hand, is much steeper. It takes three times longer to reach the peak burning rate than with gasoline, and then it falls off rapidly.

The issue of whether the high initial burning rate id due to intense thermal feedback or compositional variations might be addressed by utilizing a pure compound or a mixture of consecutive and homologous hydrocarbons. Since all (>99.8+%) components in Norpar-15 are normal hydrocarbons with consecutive carbon numbers, it has a rather narrow boiling range it is more likely to exhibit a relatively constant burning rate, as compared to jet fuel, under transient burning conditions. Thus, a transient Norpar-15 pool fire experiment was performed and the same method was used to process liquid level regression data, these surface regression rates are plotted as a function of time in Fig. 5. As expected, the surface regression rate for this narrow boiling range normal alkane mixture is relatively constant overall. If these results are compared to Fig.2, the steady-state Norpar-15 experiment, it is apparent that the mean regression rates of the two experiments match well. If the thermal transience was responsible for the high initial burning rates, this behavior would be evident even for the mixture of narrow boiling range. These results, however, indicate that this is not the case.

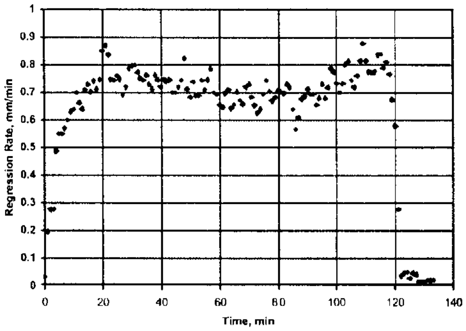

Fig. 5 Computed surface regression rate of Norpar-15 in transient 30 com pool fire tests

Another item which can significantly influence the apparent burning rate is the selection of time interval over which data is integrated by, changing the time interval, and thus effectively reducing the number of data points collected, different burning rate can be computed, based on the liquid surface height signal, by using forward difference. Liquid surface level data of Jet-A in transient pool fire was thus processed. The result is shown in Figure 6. It is apparent that with an increase in time interval, the initial peak in burning rate becomes obscured. With a 30 min interval, the first two burning rates would have a relative difference smaller than 10 % which could be neglected. Thus, if only a limited number of data points were collected, or the data was collected in a low resolution in terms of time frame during a transient pool fire experiment, the data could lead to the conclusion that the burning rate is constant.

Thermocouples are often used in pool fire tests to monitor fuel level variation over time and results from these tests usually conclude that the burning rates of blended fuels are constant. In these tests, the thermocouples are placed at different depths in the liquid fuel, and the point at which the liquid surface pass the thermocouple is evident by as sudden increase in temperature as the thermocouple is exposed to the flame. In general only a small number of thermocouples could be used in tests. Based on the results illustrated in Fig. 6, it would seem plausible that a test with a limited number of data points might yield an apparently constant burning rate for blended fuels like Jet-A.

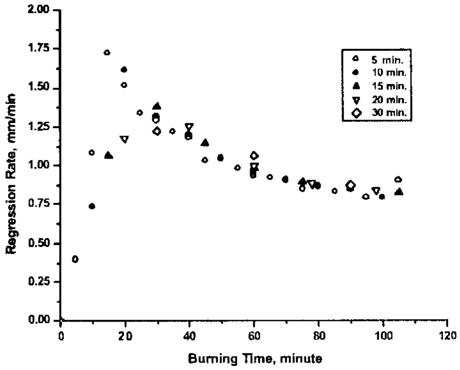

Fig.6 Computed surface regression rates with variable time interval on Jet-A 30 cm transient pool fire tests

There is direct evidence of compositional change over time from GC analysis of Jet-A samples taken from fuel pan. Fig. 7 shows the GC spectra of fuel sample taken from unburned fuel, fuel after approx. 40 vol.% burn off and fuel after approx. 95 vol.% burn off. It is apparent from the spectra that there is a preferential burning of lighter hydrocarbons. Light components, e.g. C_8 and below are consumed much faster then the heavier components, e.g C_{14} and above. The weight ratio of n-C_{12} to n-C_{17} in the unburned fuel is 7.7; whereas, in the final stage decreases to 1.0.

We also found that the preferential burning is different from the preferential boiling that is observed in conventional distillation. This observation is mainly due to limited mixing of the liquid in the pan during the burning process. To illustrate this effect, Jet-A samples were taken after ~ 40 vol.% burn off from both the liquid surface and the pan bottom, and these samples were compared with Jet-A sample taken from a 40 vol.% boil off (or distillation) experiment. GC spectra shown in Fig. 8 illustrate that both samples from pool fire are different from the sample taken from the distillation experiment. The top sample is closer in hydrocarbon distribution to the distilled sample; however, the bottom sample is closer to the initial unheated fuel sample. Same comparison can be made with late stage samples, e.g. 80 vol.% off. It can be seen from Fig 9 that in the distillation sample, all hydrocarbons with a boiling point lower than n-C_{11} have been distilled off. These lighter species still exist in pool fire samples, however, especially in the bottom of fuel pan.

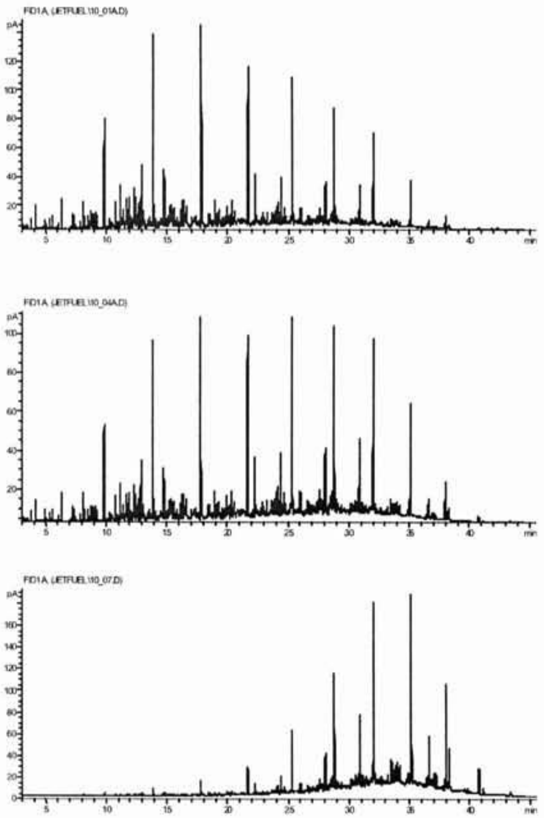

Fig. 7 GC spectra of Jet-A samples taken from fuel pan in a 30 cm transient pool fire, from top to bottom, samples are taken from 0 vol.% burn off, 40 vol.% burn off and 95 vol.% burn off.

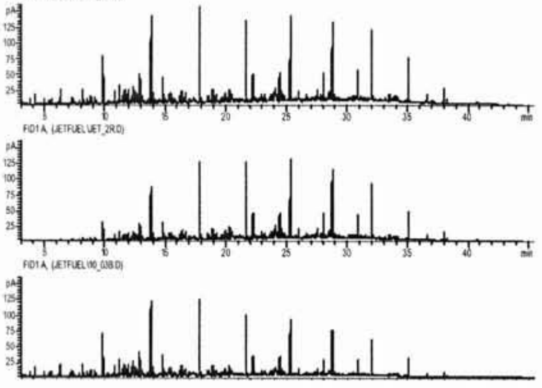

Fig. 8 GC spectra of Jet-A samples at 40 vol.% off, from top to bottom, samples are taken from, liquid surface in pool fire, distillation, and bottom of the fuel pan in pool fire.

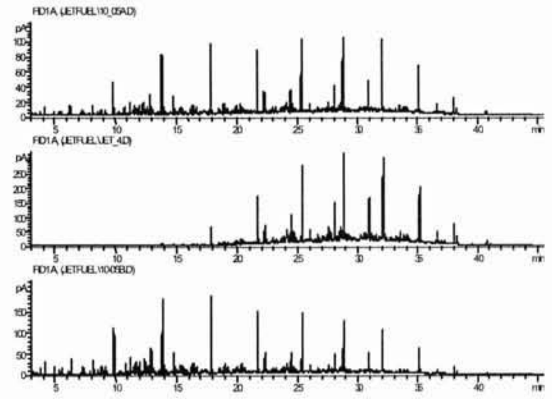

Fig. 9 GC spectra of Jet-A samples at 80 vol.% off, from top to bottom, samples are taken from, liquid surface in pool fire, distillation, and bottom of the fuel pan in pool fire.

Conclusions

The surface regression rate of jet fuel from steady-state tests in a 30 cm pool fire is in good agreement with reported data on similar fuels. The transient burning rate profile for jet fuel showed a high peak value early in the experiment, followed by a gradual decrease in burning rate as the balance of the fuel was consumed. The magnitude of the steady-state jet fuel burning rate was consistent with the peak value measured in the transient experiment, and the steady-state burning rate was a factor of two greater than the average burning rate determined for the transient jet fuel pool fire. Experiments performed with a Norpar 15 yielded approximately the same value for both transient and steady-state burning rates, which eliminated the possibility of a thermal transient being responsible for the initially high burning rate.

The composition of the liquid fuel in the pool fire pan over time was also determined through the use of GC/MS, and these results clearly demonstrated a preferential burning of the lighter, more volatile hydrocarbons during the early stages of the transient fires. This preferential burning would result in a higher burning rate early on, followed by a slower rate when consuming the less volatile residual hydrocarbons. The steady state experiments, however, had a continual replenishment of lighter components, and were thus able to maintain a steady-state burning rate equivalent to the early peak burning rate.

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