Experimental Study on the Pulsation Frequencies of Aviation Fuel Pool Fires

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ABSTRACT

In order to make a comparison between the pulsation frequencies of liquid fuel pool fires and diffusion flame of gas fuels, which had been investigated by some predecessors, experiments on flame pulsation frequency of aviation fuel pool fires were performed. Six different pans were used with diameters of 0.1, 0.15, 0.2, 0.3, 0.4 and 0.5 m. An electronic balance was used to record instantaneous fuel mass and to determine the quasi-steady state of the pool fire. The flame area was determined from flame images of a quasi-steady pool fire recorded by a CCD video camera. Binary images were generated with a Matlab program using a luminance threshold method. The instantaneous flame heights were then calculated based on these binary flame images. Frequency distribution of flame heights were obtained by means of fast Fourier transforms. The Strouhal and Richardson numbers were used to analyze the relationship of different influencing factors with the flame pulsation frequency. An empirical best fit relationship between the pulsation frequency of aviation fuel pool fires and pool diameters was established based on experimental data. It is found that for the same pool size, flame pulsation frequency results from the empirical relationship of this study are lower than previously found. The pulsation frequency differences between the two types of flames decrease with the increase of the pool size. In consideration of the periodical characteristic of the dynamic evolution process of pool flames, the phenomenon was analyzed qualitatively. The analysis indicates that it is due to the duration of lag time for radiant heat transfer from flames to liquid fuel that makes the fuel evaporation delay that, in turn, decreases the flame pulsation frequency.

KEYWORDS: Aviation fuel pool fires, fire hazard, flame image sequences, pulsation frequency.

INTRODUCTION

In some places such as aircraft carrier hangars and engine test-beds, aviation kerosene and electrical fire are the main fire risk factors. Damage to the fuel supply line or to a plane’s fuel tank may cause fuel leakage that forms an oil pool, which may be ignited by ignition source such as engine exhaust gas, exhaust heat surface, and electric spark and form an oil pool fire. In the early stages of the pool fire when the amount of fuel leaked is still small, it is of importance to detect and correctly judge the pool fire flame, to control the fire with a fire extinguishing system, or to protect expensive equipment such as engines with a water mist system.

The oil pool fire is a diffusion flame under the action of thermal buoyancy, and fuel evaporates while mixing with air for combustion. In the quasi-steady state, oil pool flame for a certain scale is easy to perform the regular pulsation characteristic. When disturbed by unstable environment airflow, the state of flame regular pulsation may be unstuck, which causes the unstable pulsation. But pool fire has a strong self-stable ability. After environment disturbances airflow disappears, it can quickly restore regular pulsation state. In some indoor environment that has a high tightness and little disturbance airflow, the regular pulsation state of oil pool flame appears more easily and is retained longer. Understanding the features of regular pulsation of pool fire has certain significance for
describing heat radiation characteristic and flame height characteristic. At the same time, flame pulsation can be treated as a regular random signal, understanding their frequency domain characteristic has reference significance for applying to the flame image recognition technology, achieving the early fire detection, and reducing the rate of false positives.

Pagni [1], Bejan [2], Cetegen and Ahmen [3] and Malalasekera et al. [4] have studied diffusion flame pulsation frequency of gas fuel. Li et al. [5], Sun et al. [6] and Zhang et al. [7] have carried out experiments and analyses for flame pulsation frequency of liquid fuel pool fire. Pagni et al., Bejan and Malalasekera et al. used some burners with the outlet diameters of 0.05, 0.1 and 0.14 m and used propane to study flame pulsation. They found that flame pulsation frequency is inversely proportional to a quadratic root of exit diameter, but the proportion coefficient is different. Li et al. used heptane and oil pool diameters of 0.1, 0.14, 0.2 and 0.14 m in a confined space to show that flame pulsation frequency is lower than the experience relationship predictive values that Pagni, Bejan. and Malalasekera et al. have concluded. Sun et al. thought pulsation of kerosene pool fire with square side length of 0.2 and 0.4 m is unstable. The former pulsation frequency changes between 0.6 and 2.5 Hz, and the flame pulsation frequency values is lower than model results of Malalasekera et al. In the study of Zhang et al., the pulsation frequency for No.100 aviation gasoline with square side length of 0.2, 0.4 and 0.6 m is also lower than the calculated value of empirical formula proposed by Pagni, Bejan, and Malalasekera. Li et al., Sun et al. and Zhang et al. did not perform a detailed analysis into why the pulsation frequency of liquid fuel pool fires is lower than the result of Pagni, Bejan, and Malalasekera et al. Sun et al. and Zhang et al. did not give any quantitative relationship of pulsation frequency of liquid fuel pool fire.

This paper studies the pulsation rule of aviation kerosene pool fire. On the base of analyzing the quantitative relation between flame pulsation frequency and influence factors, this paper give the best fitting empirical correlations according to the experimental results of pulsation frequency in quasi-steady state, then makes a comparison between the previous predicting results. According to the dynamic characteristics of flame shape cycle evolution, this paper analyzed and explained the reason why pulsation frequency of liquid fuel pool fire is lower than pulsation frequency of gas fuel buoyancy diffusion flame.

**EXPERIMENTAL SITE AND DATA MEASUREMENT METHOD**

Experiments were carried out in a 5.0 m × 5.0 m room that was 4.5 m in height. The four wall were made of fire-resistant glass, the ceiling was made of steel board, and the ground was concrete. There was a natural square vent of area $S = 0.16$ m$^2$ in the centre of the northern wall. The vent was connected to the outside through a 1.0 m long horizontal exhaust duct. The exhaust duct had a steel mesh in its outlet. The distance from the top of the vent to the ceiling was 0.1 m. The experimental setup is shown in Fig. 1. Six different pans were used with diameters of 0.1, 0.15, 0.2, 0.3, 0.4 and 0.5 m.

![Figure 1. Schematic of the experimental setup.](image)
The bottom and side wall of oil pans were made of 0.003 m thick carbon steel. The height of all side walls were 0.04 m. An electronic balance (SHIMADZU-BX22KH type) that recorded the instantaneous fuel mass of oil pan was placed in the centre of ground. The electronic balance recorded mass data about once each second and its precision was 0.1 g. The oil pan is placed on an insulation board, filled with water up to 3/4 of the height, and topped up with fuel. A CCD video camera (Canon-60 type) is used to capture real-time dynamic images. The room door is closed after ignition in each experiment, which lasts about 5 minutes. The pool fire is extinguished with a cover.

EXPERIMENTAL RESULTS AND ANALYSIS

Quasi-steady state of pool fires

The pool fires are burnt in quiescent air. The fuel evaporation rate basically achieves stability after a brief period of growth and only fluctuates slightly over time. This state is referred to as the quasi-steady state of oil pool fire. Fig. 2 shows residual fuel quantities in the oil pan as a function of time. The curve gradually steepens at roughly $t = 10$ s, which demonstrates that the fuel evaporation rate is gradually increasing. The fuel evaporation rate basically remains unchanged until $t = 60$ s. The curve of residual fuel quality is approximated as a straight line whose slope is constant, as shown in red in Fig. 2.

In this case, the pool fire reaches a quasi-steady state at a period of growth roughly 50 s after ignition. The time for reaching quasi-steady state of oil pool fire varies with the oil pool size, oil pan material, fuel layer thickness, presence or absence of a water cushion, steady level of ambient air and physical thermal parameters of the liquid fuel. Quasi-steady state results from the balance of heat absorption by the liquid fuel and heat consumption of phase transition. The temperature of liquid fuel substantially remains unchanged and, thus, the evaporation rate changes only slightly. The time to reach thermal equilibrium for different experiments in this study ranged from 30 to 60 s. This demonstrates that growth period gradually becomes longer with increasing oil pan size.

Image data processing method

After the pool fire achieves a quasi-steady state, flame pulsation is very regular and is not affected by airflow disturbances, which performs cycle changes of flame height and shape. It is observed that oil pool fires can maintain regular pulsation throughout the quasi-steady state. The flame occasionally appears to be deflected, rotated or distorted by the ambient air but has a strong self-stabilizing capacity. Such anti-interference and self-stabilizing capacity is enhanced with the increase of oil pan
scale. In order to obtain a continuous flame image sequence, a randomly selected quasi-steady period is used. Four different 8 s periods from each experiment are taken.

The cycle frequency of flame height is obtained by means of Chen et al. [8] flame image processing methods and a Matlab program compiled by the author. The procedure is as follows: Firstly, make a determination of flame areas according to the brightness of pixel points in flame image. That is, when each pixel point brightness is greater than a certain threshold value, it is determined to be a flame area, which is assigned a value of 1. Otherwise, it is assigned a value of 0. Each pixel point is processed, and then a flame image is transformed into a binary image as shown in Fig. 3.

![Binarization of the flame image](image)

**Figure 3.** Binarization of the flame image.

The instantaneous flame height can be obtained based on each binary image, as shown in Fig. 4. It can be seen that the flame height, \( H \), changes over time, \( t \), within 2 s in one experiment. The frequency distribution is obtained by means of fast Fourier transforms (FFT) after obtaining the result of flame height change over time in the intercepted image sequence. That is, the pulsation frequency of flame height is obtained. For example, Fig. 5 is the processed result of a continuous flame image sequence for an oil pool 0.2 m in diameter.

![Flame height](image)

**Figure 4.** Flame height.
**The result of flame pulse frequencies**

The results of flame pulse frequencies are shown in Table 1. It is observed that the random variation degree of flame pulse frequency is small for the same scale oil pan. The flame pulse frequency gradually decreases with increasing oil pan diameter.

**Table 1. Experimental results of flame pulse frequency (Hz).**

<table>
<thead>
<tr>
<th>Test number</th>
<th>Image sequence</th>
<th>The diameter of oil pan (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.10</td>
<td>0.15</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
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<tr>
<td></td>
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<td></td>
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<td>4</td>
<td>3.72</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>3.77</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>3.78</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>3.77</td>
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<td>3.62</td>
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<tr>
<td></td>
<td>4</td>
<td>3.58</td>
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<tr>
<td>5</td>
<td>1</td>
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<tr>
<td></td>
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<td>3.67</td>
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<td>3</td>
<td>3.67</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>3.68</td>
</tr>
</tbody>
</table>

Average value (Hz) 3.62 3.22 2.93 2.50 2.23 1.87
Quantitative relationship analysis

The dimensionless characteristic number is used to discuss and analyze probable quantitative relationship between flame pulsation frequency and its influence factors. The Strouhal number is a dimensionless quantity that is a suitable for quantifying dynamic cycle phenomenon in the fluid dynamics. It is defined as:

\[ St = \frac{fL}{U}, \]  

(1)

where \( f \) is the flame pulsation frequency. It is known that buoyancy and inertial forces play a leading role on dynamic characteristics of fire plumes by fire plume theory. The Richardson number, which is the ratio of gas buoyancy in the flame to inertial forces of the gaseous fuel at the oil pan surface, is defined as:

\[ Ri = \frac{\Delta \rho g L}{\rho U^2}, \]  

(2)

where \( g \) is the acceleration of gravity. There is a quantitative relationship between \( St \) and \( Ri \):

\[ St = f(Ri) \]  

(3)

It is necessary to apply Eq. (3) to determine characteristic quantities, including length, \( L \), velocity, \( U \), density, \( \rho \), and change in density \( \Delta \rho \). Becker and Yamazaki [9] thought that flame height is the most appropriate characteristic length. In fact, there is a proportion relationship between flame height and oil pan diameter, \( D \). Thus, \( D \) is chosen as the characteristic length. The initial velocity of fuel gas leaving liquid surface is \( U \), and fuel gas density at the oil pan surface is chosen as \( \rho \).

Buoyancy is related to density difference, \( \Delta \rho \), which is the most difficult to determine. Becker and Yamazaki [9] and Cetegen and Ahmen [3] believed that density difference between fuel gas of oil pan surface or ambient air and flame is suitable for \( \Delta \rho \); however, it is difficult to obtain the density of flame gas by experiment. It is worth noting that the study of Becker and Yamazaki [10] showed that values of \( \Delta \rho / \rho \) in a flame is a constant value of about 0.2, which implies that the Froude number can be used as the quantization parameter:

\[ Ri = \frac{\Delta \rho g L}{\rho U^2} = c \frac{g L}{U^2} = c \frac{1}{Fr}, \]

where \( c \) is a constant and \( Fr = U^2/(gL) \). Eq. (3) can be expressed as \( St = f(Fr) \) and the following expression can be obtained:

\[ \frac{fL}{U} = \Phi \left( \frac{U^2}{gL} \right), \]  

(4)

Malalasekera et al. [4] showed that the formation of function relationship may be expressed as:

\[ \frac{fL}{U} = c \left( \frac{U^2}{gL} \right)^{-1/2} \quad \text{or} \quad f = c L^{-1/2}. \]  

(5)

Determine the constants in the relationship based on the experimental data

Based on the experimental results, the oil pan diameter is considered as the characteristic length, \( D \), and the following function is used to describe pulsation frequency of oil pool fire:
\[ f = a D^{-b}, \quad (6) \]

where \( a = 1.55 \) and \( b = -0.3 \) were found by fitting the experimental data from the average values of pulsation frequencies for each pool fire diameter (shown in the last line of Table 1).

**Comparison with previous results**

The results of this study and the empirical results of [1-5] are shown in Table 2. Fig. 6 shows Table 2 data and previous empirical equation curves. It can be concluded from the figure that the power function, whose variable is oil pan diameter, can better describe the experimental results of this study. The experiment and empirical result of this study are lower than previous results obtained by using gas fuel, which is consistent with the study of [5] and [7]. At the same time, the differences between the previous and the present results decreases with increasing oil pool size.

**Table 2.** Flame pulsation frequency results of previous models and experimental results of this study.

<table>
<thead>
<tr>
<th>Souse model</th>
<th>Constant ( a, b )</th>
<th>Diameter of oil pool (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0.10</td>
</tr>
<tr>
<td>Pagni [1]</td>
<td>1.52 - 0.5</td>
<td>4.8</td>
</tr>
<tr>
<td>Bejan [2]</td>
<td>1.76 - 0.5</td>
<td>5.5</td>
</tr>
<tr>
<td>Malalasekera [4]</td>
<td>1.66 - 0.5</td>
<td>5.2</td>
</tr>
<tr>
<td>(Li Changhai) [5]</td>
<td>1.33 - 0.5</td>
<td>4.2</td>
</tr>
<tr>
<td>Experimental results of this study</td>
<td>1.55 - 0.38</td>
<td>3.6</td>
</tr>
</tbody>
</table>

**Figure 6.** Experimental and empirical results of flame pulsation frequency and empirical results of previous models.
ANALYSIS AND INTERPRETATION OF EXPERIMENTAL RESULTS

The results in Fig. 6 show that pulsation frequency of a liquid fuel pool fire is lower than pulsation frequency of a diffusion flame of the same scale gas fuel. This difference gradually decreases with increasing oil pool scale, although the former is always less than the latter. The following analyzes possible causes combing process of flame dynamic evolution.

The periodic dynamic evolution process of oil pool flame shape

For an oil pool in a quasi-steady state, liquid fuel evaporates as radiation from the flame is fed back. There are slight fluctuations for evaporation rates of liquid fuel, and this fluctuation that is caused by the change of heat radiation intensity can be considered to be the flame dynamic change. Fig. 7 shows an interception image sequences of a pool fire 0.15 m diameter.

Image 1 in Fig. 7 is a large-scale flame vortex ring. Liquid fuel of its lower portion is gasified due to heat radiation, as shown in images 1-4 or 9-12 for flame root changes. From form of flame root in these images, it is known that fuel gas has an obvious warm-up brewing period before a blast of fuel gas evaporates from the oil pool surface. It is obvious that when the warm-up period is shorter, the fuel evaporation is faster. The central region of fuel gas that just leaves liquid surface is fuel-rich. Oxygen in the ambient air driven by spatial concentration gradient is mixed with fuel gas. The combustion reaction occurs when a stoichiometric concentration is achieved, which increases gas temperature and decreases density. At this moment, the flame gas is in the range of a few centimeters distance from the liquid pool surface, and the flame of oil pool root presents a crown shape, as shown in images 4 or 12. The rising velocity for gas of flame root area increases under the effect of buoyancy, resulting in interface of flame area and the surrounding air forming a low pressure area. The air surrounding flame root produces a radial velocity to flame center driven by pressure gradient. Under the action of squeezing stack of centripetal air flow, flame root is necking, and the rising velocity for central area’s gas of flame becomes faster, which leads to forming a new large-scale vortex ring structure, as shown in images 5-9. Necking of fuel gas and the formation of large-scale vortex is partly the result of baroclinic torque caused by gas temperature gradient.

Fresh air was wrapped in the large-scale vortex ring. Under the effect of diffusion mechanism induced by random thermal motion of molecule, the gaseous phase fuel and the entrained oxygen further diffuse and mix evenly. When local oxygen and fuel gas composition achieving a suitable concentration, this part of fuel involved in combustion releasing chemical energy, which increases the resulting temperature greatly. At the same time, the gas expands and the flame volume increases, as shown in images 8-9. The smoke particles glow and show bright flame.

Under the effect of buoyancy, glowing gas rises at a growing velocity, flame is stretched and becomes slender, as shown in images 2-6 or 10-14, on the upper part of flame. In this process, the surrounding oxygen in the air continues to enter into flame zone due to molecular diffusion, and the fuel is gradually consumed and burnt out, as shown in images 7-8 or 15-16, on the upper part of flame, which depends on the sufficient mix of fuel and air, as well as reaching an appropriate velocity for the
concentration of combustion occurrence. After the completion of combustion reaction, products continue to rise rapidly under the effect of buoyancy and entrains ambient fresh air continuously, which makes the rate of the buoyant plume enlarge with increasing altitude. For example, the hot smoke layer may be formed on the indoor top.

Therefore, after the heating phase of the liquid, a new surge of gas fuel in image 11 began to evaporate. Fuel evaporation in images 4-6 or 12-14 continued and accelerated. Extrusion by around to supplement the air heart flow is to form the crown-shaped flame and necking, and fire continues to accelerate to rise with carrying plenty of fresh air and forms the large scale vortex, as shown in images 7-9. The flame in images 10-13 rises to the highest. Fuel in images 14-16 burns out gradually, a complete evolution cycle of fuel pool buoyancy diffusion flame ends. Meanwhile, it can be observed that the lower part of the flame germination and growing process for a new flame in images 1-8. The evolution process for upper flame is actually the large-scale vortex ring (to occur before flame image sequence in Fig. 7) that flame forms in the last period to flame to be stretched until the burning. The upper part of images 9-16 continue to evolve from the latter half of image 8. The change process of flame root is the fuel evaporation that is due to be heated to basic formation of large-scale vortex ring for the next cycle.

The above description and analysis for the dynamic evolution process of the flame shape show that the quasi-steady pool fire has a pulsation characteristics; flame appears periodically as fuel is evaporated due to heating. The initial reaction to rise, necking entraining air and forming a vortex ring, combustion expanding and rising, and flame stretching and burning; flame height and shape also perform periodic changes.

It is noted that the dynamic evolution of flame is a process of periodic nested loop. Before a flame evolution cycle has been completed, the next cycle has started from the liquid surface. When the next evolution cycle begins sooner, the pulsation frequency of flame height may be higher, which is subjected to the rate of gas fuel released from the surface of fuel pool and continuous extent.

The flame height change cycle

It is observed that pulsation frequency of flame height is related to heating-evaporation cycle of liquid fuel, which is regarded as fuel heating-evaporation cycle. It is also related to the formation, development, and extinction of large-scale vortex structures in the flame, which is referred to as the fuel pneumatic-combustion cycle. Both relationships are cause and effect. That is, the pulsation cycle of flame height change is the result of coupling of the two cycles and largely determined by the nested degree of fuel heating-evaporation and pneumatic-combustion cycles. Flame pulsation frequency in this article refers to the frequency of flame height change cycle rather than that of a complete fire evolution cycle, which is the result of the coupling of the two evolutionary cycles.

For the pulsation experiment of diffusion flame of gas fuel, the supply rate of gas fuel during the experiment is constant, and gas fuel flows out smoothly from a burner. There is no coupling effect of the fuel heating-evaporation and pneumatic-combustion cycles. Therefore, the pulsation frequency of liquid fuel pool diffusion flame is different from that of gas fuel. Liquid fuel evaporates through absorbing radiation heat, and it takes time to absorb heat, which delays fuel evaporation. For a fire source of the same scale, pulsation frequency of flame height change of liquid fuel pool fire has a longer cycle due to the lagging of fuel supply.

It is obvious that when oil pan scale is bigger, intensity of thermal radiation is greater, preheating period of liquid fuel evaporation is shorter, fuel evaporation is faster, and fluctuation rate of fuel evaporation is smaller. And its gas supply continuity is almost consistent with gas fuel. At this time, the lagging influence of liquid fuel is reduced. The difference between pulsation frequencies of liquid fuel pool fires and diffusion flame of gas fuels is reduced, and even there is no difference between the both situations. The pulsation frequency is only determined by pneumatic-combustion cycle of this
Part II  Fire

scale oil pan. Thus, we can be seen from Fig. 6 that the deviation between the present experimental results and the pulsation frequency of diffusion flame of gas fuels is gradually reduced with the increase of oil pool size. However, the former is always less than the latter within the scale of this study.

In summary, the height change of oil pool flame is related to liquid fuel heating-evaporation cycle and fuel pneumatic-combustion cycle, and the two processes interact with each other. The pulsation cycle of flame height change is the result of the two cycles coupling. There exists the situation of coupling of heating-evaporation and pneumatic-combustion cycles for gas fuel. Flame pulsation frequency of gas fuel is only determined by fuel pneumatic-combustion cycle. Thus, compared to the gas fuel, pulsation frequency of height change of liquid fuel pool flame is smaller for fire source of the same scale due to fuel evaporation delay, which should be noted in the application of pool fire pulsation frequency used in previous models or in selecting a more suitable pulsation frequency model of liquid oil pool flame.

CONCLUSION

From the present results, it is shown that the relationship between pulsation frequency of liquid fuel pool fire and oil pool diameter can be described by a power function. The two constants of proportional coefficient and power are determined to be $a = 1.55$ and $b = -0.38$. Flame pulsation frequency of liquid fuel pool fire is smaller than pulsation frequency of gas fuel flame for the same scale, which is due to evolution cycle of liquid fuel pool flame is nested loop. Change cycle of oil pool flame height is the apparent result of coupling effect between heating-evaporation cycle of liquid fuel and fuel pneumatic-combustion cycle, which is determined by nesting degree of the both cycle. With the increase of oil pool size, the influence of delayed evaporation for liquid fuel becomes weak, and the difference between its pulsation frequency and gas fuel flame decreases.

REFERENCES