FDS Analysis of Pool fire in Large Scale Flat Bottom Tank of Crude Oil

*Fire Dynamics Simulator (FDS) : Large eddy simulation model developed by NIST

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1. Introduction

2. Validation of FDS heat radiation analysis of large scale tank fire
   ➢ Comparison of the result of heat radiation analysis by FDS and experiments

3. Investigation of the effects of tank diameter and oil level to flame behavior
   ➢ Analysis of air entrainment to the base of flame

4. Comparison of the dangerous distances estimated by solid flame model and FDS analysis
Background

- **Huge oil storage tanks are increasing**

In the case of large scale tank, it is difficult to do combustion experiment.

- **Large earthquakes caused serious tank fire accidents**

  1964: Fire in a petro-chemical plant (Niigata Earthquake)
  1983: Rim seal fire (Middle Japan Sea Earthquake)
  2003: Whole surface tank fire (Tokachi-Oki Earthquake)
  2011: LPG tank fire (Great East Japan Earthquake)

Quantitative estimation of heat radiation from tank fire and disaster prevention plan are required
Mathematical analysis method using solid flame model

- Cylindrical model of tank fire by Yellow Book

\[ a = \frac{H_F}{R} \quad b = \frac{L}{R} \]

\[ A = \sqrt{a^2 + (b + 1)^2 - 2a(b + 1)\sin\theta} \]

\[ B = \sqrt{a^2 + (b - 1)^2 - 2a(b - 1)\sin\theta} \]

\[ C = \sqrt{1 + (b^2 - 1)\cos^2\theta} \]

\[ D = \frac{b - 1}{b + 1} \quad \frac{a \cos\theta}{b - a \sin\theta} \]

\[ F = \sqrt{b^2 - 1} \]

- Configuration factor \( \phi \): [Guideline by TNO Yellow Book, Netherlands]

\[
\pi \phi = -E \tan^{-1} D + E \left[ \frac{a^2 + (b + 1)^2 - 2b(1 + a \sin\theta)}{AB} \right] \tan^{-1} \left( \frac{AD}{B} \right) + \frac{\cos\theta}{C} \left[ \tan^{-1} \left( \frac{ab - F^2 \sin\theta}{FC} \right) + \tan^{-1} \left( \frac{F \sin\theta}{C} \right) \right]
\]

\[
E = \phi \cdot \varepsilon \cdot \sigma \cdot T^4 = \phi \cdot R_D
\]

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Crude oil</th>
<th>Gasoline</th>
<th>LNG (Methane)</th>
<th>Ethylene</th>
<th>Propane</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R_D ) (kW/m(^2))</td>
<td>41</td>
<td>58</td>
<td>76</td>
<td>134</td>
<td>74</td>
</tr>
</tbody>
</table>
The effects of tank diameter to the soot formation

Thermal shielding by black smoke which increase with size of tank diameter※

The relation between diameter of flame and radiative fraction※

\[ \chi = 0.35 \exp(-0.05D) \]

The solid line is a fitted curve:

Oxygen supply into the flame become insufficient in the case of large diameter tanks, which causes incomplete combustion

※K.McGrattan,”Thermal Radiation from Large Pool Fires”,Fire Safety Engineering Division,2000
A) There are a number of edge effects due to the “lip” of a pan, which exists where the pan extends above the fuel surface to confine the liquid.
   - Greater turbulence near the base of the flame
   - Shorter flame height
   - Higher gas emissivity
   (Hall, 1972)

B) These changes are consistent with an enhancement in the burning rate.
   (Orloff, 1981)

These studies showed that air entrainment have great effects to the flame behavior.

Purpose

- Analysis of the effects of tank diameter to the fire behavior
- Analysis of the effects of length from pan lip to oil surface

It is important to notice that air entrainment largely affect the flame behavior and heat radiation.

FDS is used to analyze heat radiation from pool fire in large scale flat bottom tanks

Fire Dynamics Simulator (FDS)

FDS is a large eddy simulation model, which was developed by the National Institute of Standards and Technology. The software solves numerically a form of the Navier-Stokes equations appropriate for low-speed, thermally-driven flow, with an emphasis on smoke and heat transport from fires.
Purpose

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FDS is used to analyze heat radiation from pool fire in large scale flat bottom tanks

Estimate the distances to the points at where receiving radiation of 2.3 kW/m² from the wall of the tank estimation
Outline

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Experiments of large scale pool fire (1998, Japan)※

Japan national oil corporation in Tomakomai

Horizontal view of experimental allocation

Flame behaviors (tank diameter D=10m)

## Environmental conditions

### Experiment

<table>
<thead>
<tr>
<th>Date</th>
<th>Pan</th>
<th>Time</th>
<th>Remarks</th>
<th>Burning site</th>
<th>Temp.</th>
<th>Humid.</th>
<th>Wind</th>
<th>Wind spd.</th>
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</thead>
<tbody>
<tr>
<td>Jan. 26</td>
<td>20m-tank</td>
<td>7:00</td>
<td>10min before ignition</td>
<td></td>
<td>-14.7</td>
<td>90.7</td>
<td>N</td>
<td>1.35</td>
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<tr>
<td></td>
<td></td>
<td>7:10</td>
<td>Ignition</td>
<td></td>
<td>-14.3</td>
<td>90.9</td>
<td>N</td>
<td>0.94</td>
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<tr>
<td></td>
<td></td>
<td>7:15</td>
<td>5min after ignition</td>
<td></td>
<td>-11.7</td>
<td>79.3</td>
<td>NNE</td>
<td>1.28</td>
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<td></td>
<td></td>
<td>7:20</td>
<td>10min after ignition</td>
<td></td>
<td>-12.3</td>
<td>78.7</td>
<td>NE</td>
<td>1.40</td>
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<td>7:25</td>
<td>15min after ignition</td>
<td></td>
<td>-11.8</td>
<td>81.6</td>
<td>ENE</td>
<td>0.54</td>
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<td></td>
<td>7:30</td>
<td>20min after ignition</td>
<td></td>
<td>-13.1</td>
<td>84.4</td>
<td>ENE</td>
<td>0.80</td>
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<td></td>
<td>7:40</td>
<td>10min after extinguish</td>
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<td>-13.7</td>
<td>87.0</td>
<td>ENE</td>
<td>1.05</td>
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<td>Jan. 26</td>
<td>10m-tank</td>
<td>12:20</td>
<td>10min before ignition</td>
<td></td>
<td>-3.3</td>
<td>51.5</td>
<td>NW</td>
<td>0.73</td>
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<td>12:30</td>
<td>Ignition</td>
<td></td>
<td>-3.4</td>
<td>61.7</td>
<td>WNW</td>
<td>2.12</td>
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<td></td>
<td>12:35</td>
<td>5min after ignition</td>
<td></td>
<td>-2.2</td>
<td>51.0</td>
<td>NNW</td>
<td>1.21</td>
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<td>12:40</td>
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<td>55.5</td>
<td>N</td>
<td>1.68</td>
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<td>12:45</td>
<td>15min after ignition</td>
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<td>-4.4</td>
<td>63.4</td>
<td>NNE</td>
<td>2.31</td>
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<td>12:50</td>
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<td>-3.9</td>
<td>60.7</td>
<td>N</td>
<td>2.58</td>
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<tr>
<td></td>
<td></td>
<td>12:55</td>
<td>25min after ignition</td>
<td></td>
<td>-4.0</td>
<td>62.7</td>
<td>N</td>
<td>4.41</td>
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<td></td>
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<td>13:00</td>
<td>10min after extinguish</td>
<td></td>
<td>-4.4</td>
<td>60.9</td>
<td>NNE</td>
<td>2.52</td>
</tr>
</tbody>
</table>

### FDS analysis

- **20m-tank**: Temperature: **-15°C**, Wind velocity: **1m/s**
- **10m-tank**: Temperature: **-5°C**, Wind velocity: **4m/s**
Comparison of the results of FDS analysis and experiment

Formation of soot (D=10m)

View from leeward

Side view of the flame

View from windward
Comparison of the results of FDS analysis and experiment

Max value of heat radiations show good agreement with experiment
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The effects of tank diameter to air entrainment

![Diagram showing tank parts and oxygen concentration graph]

- **Black smoke**
- **Intermittent fireball**
- **Base flame**
- **Height**

**Graph:**
- **Average oxygen concentration above the oil surface**
- **D=10**
- **D=90**

**Legend:**
- **R:** Tank Radius (m)
- **L:** Length from center of tank (m)
Air flow and Temperature distribution around the flame

Temperature (°C)

1500

750

0

10m

90m

Average C₂ concentration (mol/mol)

L/R

D=10

D=90
The effects of tank diameter to air entrainment

Combustion efficiency goes down with decreasing of oxygen supply and that results formation of massive black smoke
The effects of length from pan lip to oil surface

Fully filled model

Half filled model

Oxygen concentration above the oil surface

Average oxygen concentration (mol/mol)

R: Tank Radius (m)
L: Length from center of tank (m)
Irregular turbulence flow occur in the firing tank
Flame behavior of underground-tank fire

- Fully filled model
- Half filled model
Distribution of vertical heat radiation

Measuring points of Heat radiation

Filled model

Half filled model

Ground level = 0

Averaged vertical heat radiation (kW/m²)

0 50 100 150 200 250

Height from ground (m)

3R

45 90 135

Filled model

Half filled model

Half filled tank is more dangerous than fully filled tank in the case of wholly surface pool fire
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Heat radiation analysis in the simulated tank in Sakai

Allocation of simulated model tank

Plant Area

Crude oil tank area
Allocation and dimension of simulated tank

D = 70 m
30 m
300 m
1.4 km
1.1 km
0.8 km
1.1 km
4 km
3 km
Allocation and dimension of simulated tank

- D = 70 m
- 2 pattern of Oil level:
  - Fully filled model: 21 m
  - Half filled model: 11.5 m

Tank dimension:
- Tank
- Fuel

Dimensions:
- Tank diameter: 70 m
- Fuel height: 23 m
- Fully filled model height: 21 m
- Half filled model height: 11.5 m

Distance:
- 4 km
- 3 km
- 1.1 km
- 0.8 km
Analysis domain and conditions

**Content:** Crude oil (Combustion heat: 45000kJ/kg)

**Wind velocity:** 0m/s

**Temperature:** 20°C

**Number of mesh:**
- Domain 1: $80 \times 80 \times 96$ (1.75m-cubic mesh)
- Domain 2: $90 \times 40 \times 48$ (3.5m-cubic mesh)
Distance from tank wall to the critical heat radiated point

Distance from tank wall to critical heat radiation point (2.3kW/m²)

Area of the average value of the distance of critical heat radiation point
Summary

- FDS analysis of pool fire in large scale flat bottom tank showed good agreement with experiment.

- The tank diameter and the oil level had effects on flame behaviors which include flame shape and heat radiation.

- The air entrainment from the tank rim into the flame bottom is considered to have principle effect to behavior of flame and soot formation.

Future Work

In the case of TSUNAMI disaster, fire on sea surface is very important, and we are trying investigation of the burning mechanism on the sea surface.
Thank you for your kind attention