Open Journal of Safety Science and Technology, 2017, 7, 11-21
http://www.scirp.org/journal/ojsst
ISSN Online: 2162-6006
ISSN Print: 2162-5999

Flame Spread over Liquid Fuel on a Water Layer-Basic Research on Tsunami Fire

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How to cite this paper: Kuwana, S., Tamizu, H., Ito, A. and Torikai, H. (2017) Flame Spread over Liquid Fuel on a Water Layer-Basic Research on Tsunami Fire. *Open Journal of Safety Science and Technology*, **7**, 11-21.
https://doi.org/10.4236/ojsst.2017.71002

Received: January 11, 2017
Accepted: February 13, 2017
Published: February 16, 2017

Abstract

The purpose of this study is to reveal the flame spreading mechanism of tsunami fire. But the mechanism of tsunami fire is so complex that we couldn't assess qualitatively. So the basic research on tsunami fire is needed. As a first step, we did flame spread experiment on only liquid fuel and liquid fuel/water layer under static liquid fuel. We measured flame spread rate. As a result, fuel thickness is in range of 5 - 15 mm, and flame spread rate over only liquid fuel is faster than liquid fuel/water layer's at same fuel thickness. To reveal the gap of the flame spread rate at same liquid fuel thickness, we visualized current distribution by PIV and thermal boundary layer by shadowgraph method. By these results, we revealed that the thermal characteristic length is longer and the current characteristic depth of liquid fuel/water is deeper than that of liquid only fuel.

Keywords

Tsunami Fire, Flame Spread, Liquid Fuel, Liquid Fuel/Water Layer

1. Introduction

In the Great East Japan Earthquake of 2011, the Tohoku region was seriously damaged by fires which were caused by the tsunami (tsunami fires). The cause of the tsunami fires was basically electrical short circuits of some electricity such as from batteries, or car crashes of cars and so on. Liquid fuels that had leaked from cars, oil tanks and so on ignited. In addition, the ignited liquid fuels flowed on seawater and spread in unexpected directions. This was the mechanism of tsunami fires. According to some predictions, further earthquakes will occur. This means that tsunami fires will also be caused. To reduce the damage of tsunami fires, tsunami shelters and hazard maps are required. Many studies of flame spread over liquid fuel have been performed [1]-[13]. But there are few studies of flame spread over liquid fuel on a water layer like tsunami fires. So basic research on flame spread over a fuel/water layer is needed to reveal the mechanism of tsunami fires. In this study, as the first step in studying tsunami fires, we measured flame spread rate over static liquid fuel on solid board and liquid fuel on water and compared the results. To consider the results of measurement of flame spread rate, we visualized the current distribution by the PIV method and the thermal boundary layer by the shadowgraph method. From the experimental results, we compared and considered the influence of the current distribution and thermal boundary layer on flame spread rate over liquid fuel on board or on water.

2. Experimental Apparatus and Methods

2.1. Measurement of Flame Spread Rate

The fuel container for measurement of flame spread rate and visualization experiments, we used a heat-resistant glass casting fuel container. For the freeboard, we poured liquid fuel of a certain quantity and filled with water (fuel/water layers) or brass solid plate and heat-resistant glass plate (fuel only layer). We used nycrome wire for ignition. We used n-decane and kerosene as a liquid fuel.

Figure 1 shows the experimental apparatus to measure flame spread rate. Fuel thicknesses and initial temperatures are parameters. The flame spreading phenomena was recorded by video camera (SONY DSC-RX10M2 30fps) which was attached right over the experimental apparatus and measured the blue flame leading edge on captured images. Then we calculated the average flame spread rate $\bar{v}$ by least-squares method. We did the experiment three times at the same condition and defined flame spread rate $\bar{v}_{ave}$ by calculation of three times the average.

2.2. Flow Visualization Methods

Figure 2 shows the experimental apparatus for flow visualization to observe the current distribution. We measured it by laser sheet. The laser was a LD excitation Nd: YAG/YVO4 solid laser (Kato Koken CO, LTD PIV Laser G450 450 m

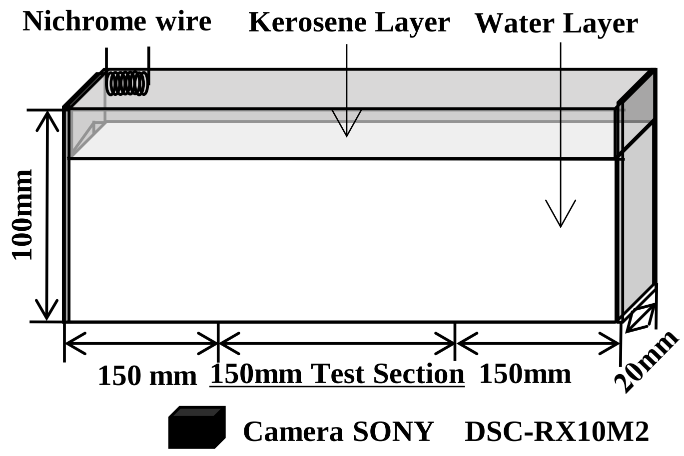

Figure 1. Experimental apparatus for measuring flame spread rate.

W/532 nm, sheet thickness is 2 mm) and was attached right over the experimental apparatus irradiated to width center of the fuel container. We used TiO_2 particles (average diameter is about 35 nm) as a tracer. We filmed the current distribution by camera (SONY DSC-RX10M2 60fps) and fitted it just beside the experimental apparatus. **Figure 3** shows how to analyze the current distribution. To analysis the experimental video, we used PIV and current characteristic depth h_f , the depth from the fuel surface to the point that convection velocity is smaller than 1 mm/s in water (fuel/water layers) or same value as the fuel thickness (fuel only layer). Fuel thicknesses and initial temperatures are parameters. We determined h_f the time average for condition.

2.3. Measurement of Thermal Boundary Layer

Figure 4 shows the experimental apparatus for the shadowgraph method to visualize the temperature field. We used a light fiber lamp as the light source. The light beam from the light source went through a beam expander and became a parallel light beam using a concave mirror. The parallel light beam went through the fuel container, reflected by the concave mirror and the image was recorded

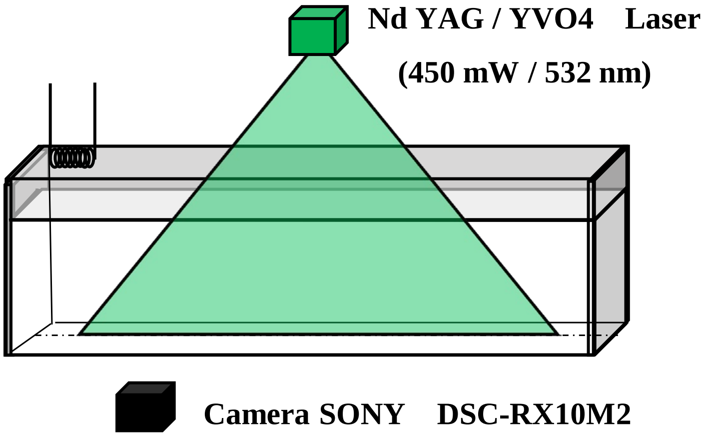

Figure 2. Experimental apparatus for flow visualization.

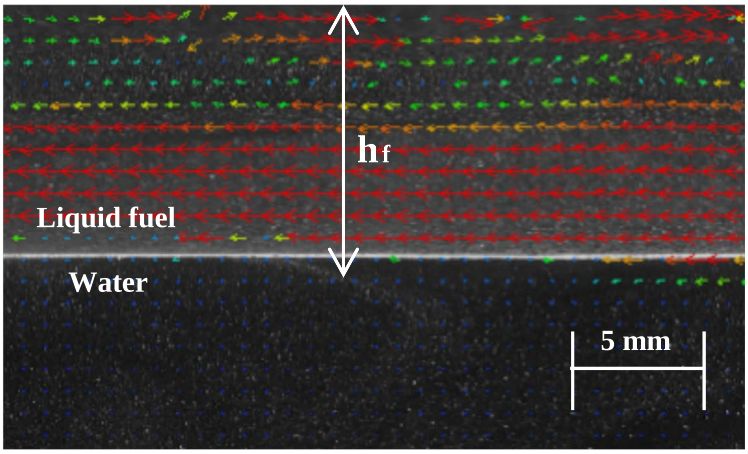

Figure 3. The method to determine h_f .

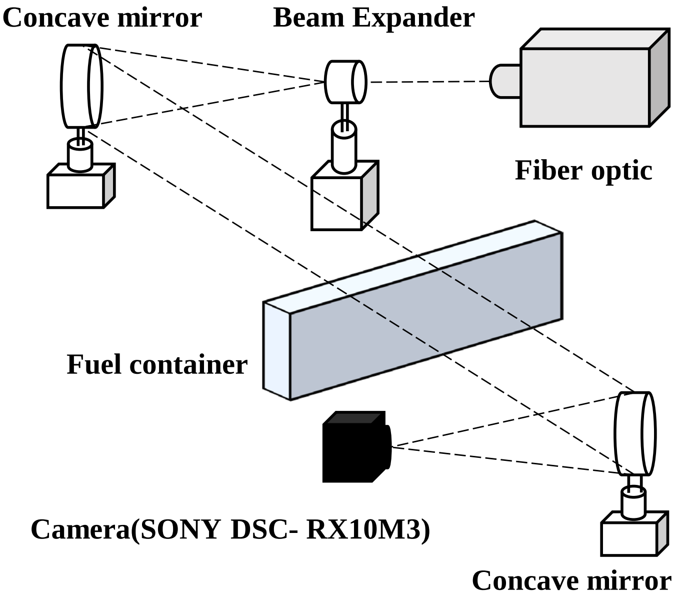

Figure 4. Experimental apparatus for shadowgraph.

by camera (SONY DSC-RX10M3) directly at the same time. **Figure 5** shows how to measure the thermal characteristic length L and depth h_t. L is the length from the flame leading edge to the front of the thermal boundary layer. The h_t is the depth from the fuel surface to the deepest thermal boundary layer edge just under the flame. Fuel thicknesses and initial temperatures are parameters. Flame leading edge position depends on the time because of pulsation. So we determined h_t and L averaged in certain time for the conditions.

3. Theoretical Analyses

3.1. Non-Dimensional Flame Spread Rate

We used the following equations referred to in the literature [13]. Then, we defined quenching distanceδ, diffusion coefficient D and flame spread rate v_{ave},

$$\frac{V}{V_D} = \frac{v_{ave}\delta}{D} \tag{1}$$

The quenching distance δ is almost constant (0.8 mm) independent of fuel [13]. V_D is the diffusion rate. On the other hand, the diffusion coefficient of fuel is calculated by Equation (2) [14],

$$D = D_0\left(\frac{T_{flame}}{T_f}\right)^2 \frac{101325}{P} \tag{2}$$

P is ambient pressure, T_{flame} is the temperature of the flame leading edge 1100 K [13]. T_f is the flashpoint in open cup [15]. D_0 is the diffusion coefficient at 300 K, 1atm [16], calculated by Equation (2) and we used it at 273 K. The flame spread rate v_{ave} was obtained by experiments. If the value of Equation (1) is more than 1, liquid fuel is in super-flash condition. If the value is less than 1, liquid fuel is in sub flash condition.

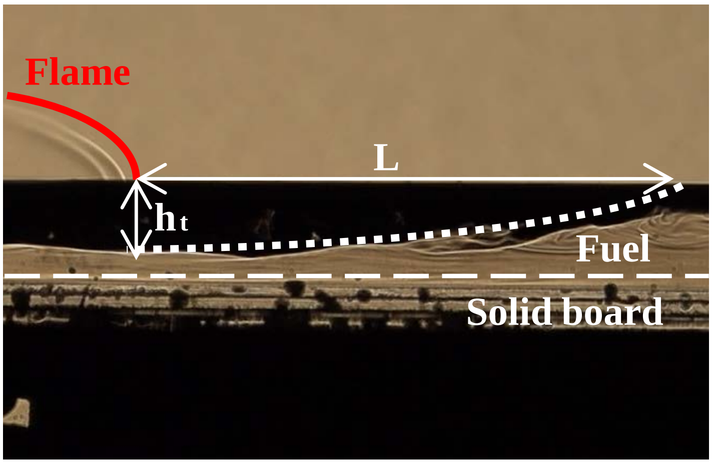

Figure 5. The method to measure L and h_t.

3.2. The Non-Dimensional Number

To organize pulsating flame spread rate, we defined the non-dimensional numbers below [13].

$$Gr=\frac{\gamma^2\beta^2\rho^3g^2\Delta T}{4\mu^2\sigma_T}h_t^5\left(\frac{h_t}{L}\right)^2 \tag{3}$$

$$Ma=\frac{\gamma^2\rho\sigma_T\Delta T}{4\mu^2}h_t\left(\frac{h_t}{L}\right)^2 \tag{4}$$

$$\Pr=\frac{\nu}{\alpha} \tag{5}$$

$$\gamma\equiv\frac{h_f}{h_t} \tag{6}$$

$$h_t\left(\frac{h_t}{L}\right)^2=C_1\left(\frac{Gr}{MaPr}\right)^{C_2}=C_1\left(\frac{\beta^2\rho^2G^2\alpha}{\sigma_T\nu}h_T{}^4\right)^{C_2} \tag{7}$$

where Gr is Grashof number, Ma is Marangoni number, Pr is Prandtl number, β is the coefficient of cubic expansion, μ is the viscosity, a is thermal diffusivity, ν is kinematic viscosity, ρ is density, σ_T is the temperature derivative of surface tension coefficient [17] and ΔT is the gap between initial fuel temperature and flashpoint. Then, the Gr number is related to h_t, and the Ma number is related to L. The experimental data is expressed as,

By submitting Equation (7) into Equation (3) (4), we can obtain the following Equation (8).

$$\frac{Gr^{C_2/1+C_2}}{Ma\cdot\Pr}=\left(\frac{4\cdot C_1\cdot\mu^2\alpha}{\gamma^2\rho\sigma_T\cdot T\nu}\right)^{1/1+C_2\ 1/1+C_2} \tag{8}$$

C_1 and C_2 are fitted to the experimental data each fuel/water layers and fuel only layer: $C_1=5.27\times10^{-5}$, $C_2=0.195$, for fuel/water layers, $C_1=1.37\times10^{-4}$, $C_2=209$, for fuel only layer. Equation (3) includes h_f and h_t so it is valid for scaling analysis of flame spreading phenomena. Scaling analysis of pulsating flame spread rate using Equations (1) and (3) was performed only for alcohol fuel. In this study, we tried to estimate whether these equations can be used for n-decane and kerosene. Some properties of n-decane and kerosene are referred from the literature [15] [16] [17] [18].

4. Experimental Results and Examination

4.1. Flame Spread Rate

Figure 6 shows the flame leading edge position versus time in the test section. As can be seen, the flame spreading phenomena is pulsation [13]. The black line shows approximate line calculated by least-squares method. **Figure 7** shows experimental results of flame spread rate over liquid fuel on the fuel/water layer and fuel only layer versus fuel thickness. In the range of 5 - 15 mm of fuel thickness, flame spread rate on the fuel/water layer is slower than that on fuel only layer of n-decane and kerosene. And both flame spread rate and fuel thickness increase in this range. But when fuel thickness is more than 20 mm, flame spread rate is almost same between the fuel/water layer and the fuel only layer. **Figure 8** shows experimental results of flame spread versus initial temperature. In the all conditions, fuel/water layer is slower than that on fuel only layer. To reveal these results, we performed visualization of current and thermal distributions.

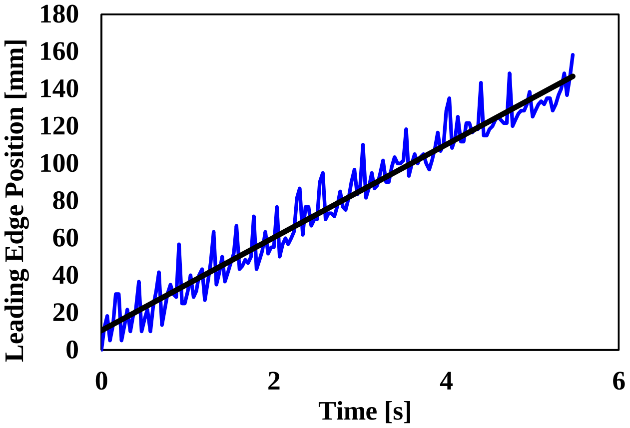

Figure 6. The relationship between flame leading edge and time.

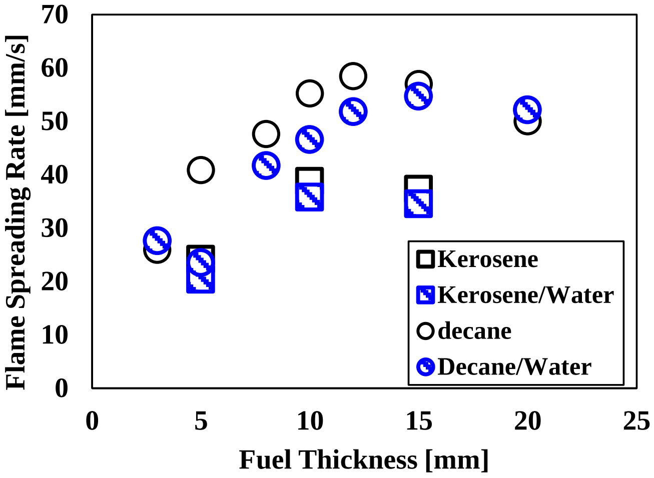

Figure 7. Experimental result of measuring flame spread rate.

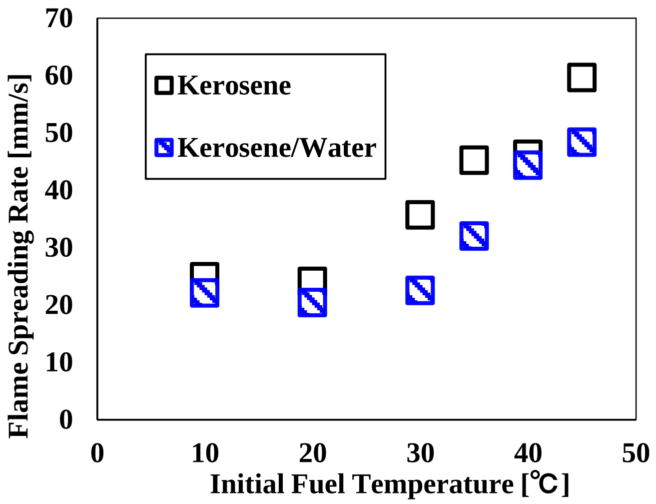

Figure 8. Experimental result of measuring flame spread rate.

4.2. Visualization of Current Distribution

Figure 3 shows a capture photo of the current distribution in the fuel/water layer. Table 1 shows experimental results of h_f. The h_f in the fuel/water layer is thicker than in the fuel only layer due to flow of water layer. And convection velocity in fuel/water layer is slower than the fuel only layer.

4.3. Visualization of Thermal Boundary Layer

Figure 5 shows a capture photo of the thermal boundary layer in only layer. Table 2 and Table 3 show the experimental results of temperature characteristic depth h_t. Table 4 and Table 5 show characteristic length *L*. Although h_t is almost the same, L on the fuel/water layer is longer than the fuel only layer.

Table 1. Experimental result of measuring h_f for kerosene.

Initial Temperature[K]	Fuel Thickness [mm]	Kerosene h_f [mm]	Kerosene/Water h_f [mm]
20	5	5	10.7
20	10	10	12
20	15	15	16
30	5	5	7.6
40	5	5	5

Table 2. Experimental result of measuring h_t for kerosene.

Initial Temperature [K]	Fuel Thickness [mm]	Kerosene h_t [mm]	Kerosene/Water h_t [mm]
20	5	3.4	3.4
20	10	5.2	5.8
20	15	8.3	3.8
30	5	3.8	3.9
40	5	2.5	2.8

Table 3. Experimental result of measuring h_f for n-decane.

Initial Temperature [K]	Fuel Thickness [mm]	N-decane h_t [mm]	N-decane/Water h_t [mm]
40	5	3.4	3.5
40	10	6.3	6.5

Table 4. Experimental result of measuring L for kerosene.

Initial Temperature [K]	Fuel Thickness [mm]	Kerosene L [mm]	Kerosene/Water L [mm]
20	5	53.2	72.8
20	10	75.3	123.8
20	15	14.1	177.8
30	5	50.5	58.1
40	5	29.7	43.7

Table 5. Experimental result of measuring L for n-decane.

Initial Temperature [K]	Fuel Thickness [mm]	N-decane L [mm]	N-decane/Water L [mm]
40	5	43.2	84.7
40	10	57.8	80.3

4.4. Consideration of Experimental Results

Figure 9(a) and Figure 9(b) show the current and thermal distribution models in the liquid fuel layer referred from experimental results. The vectors show the current model using the experimental results. The broken lines show a simple model for the thermal boundary layer using the results.

One reason for the gap of flame spread rate in range of 5 ~ 15 mm is that vortex scale is larger and convection velocity is slower than in the fuel only layer. The reason why the flame spread rate over liquid fuel on fuel/water layer is slower than with the fuel only layer is thought to depend on the vortex scale. Although L in the fuel/water layer is longer than the fuel only layer, convection velocity is slower and vortex scale is larger than with the fuel only layer. That is why the region of more than flashpoint of the fuel/water layer is smaller than fuel only layer due to the water layer. So it seems that the flame spread rate on the fuel/water layer is slower than with the fuel only layer. Also, the flame spread phenomena with fuel thickness more than 15 mm does not change according to the flame spread rate measurement results.

4.5. Scaling Analysis

Figure 10 shows calculation results using Equation (1) and (3). The results can be obtained in our plots in the different from the result of alcohol fuels due to difference in physical property value and analysis method. Assuming that condition of 5 mm fuel thickness in fuel only layers is shallow liquid pools and other condition is deep liquid pools, a difference between both condition can be seen.

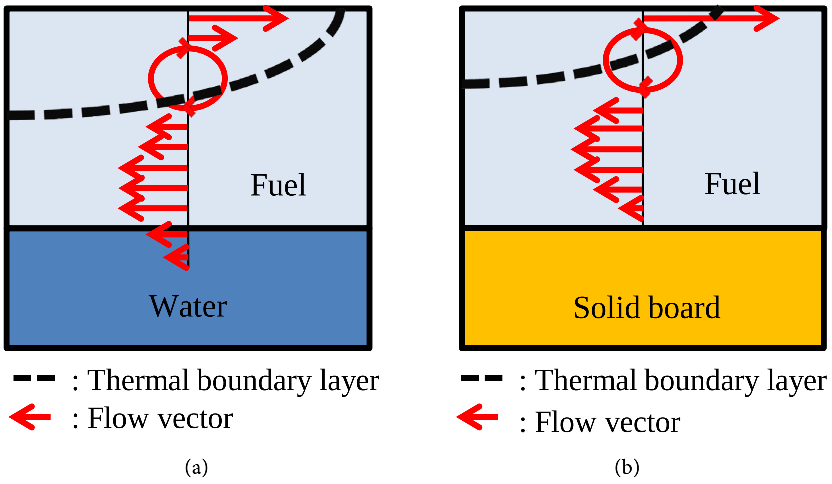

Figure 9. (a) Current and thermal distribution model in fuel/water layer; (b) Current and thermal distribution model in fuel layer in fuel only layer.

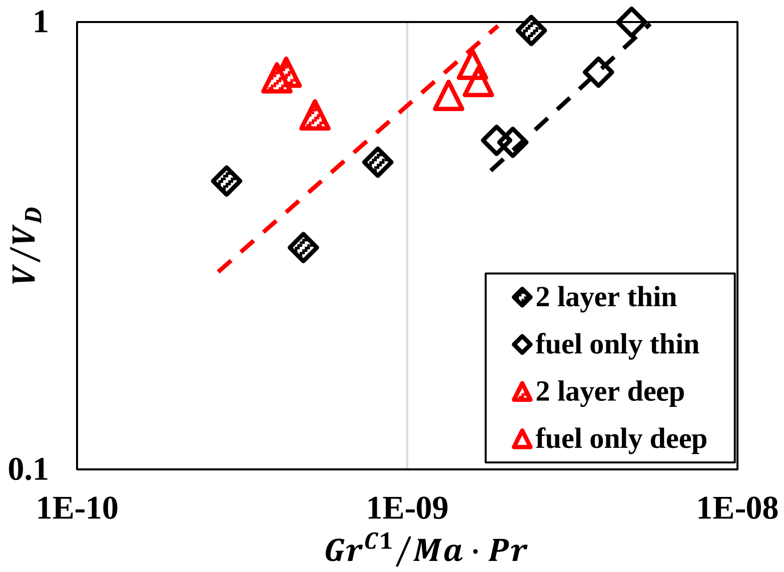

Figure 10. Experimental result of measuring flame spread rate.

5. Conclusions

Based on measurements of flame spread rate and visualization of current and thermal boundary layers of the fuel/water layer and fuel only layer as basic research on tsunami fires, we arrived at the following conclusions.

1) The flame spread rate in a fuel thickness range of 5 - 15 mm on a fuel/water layer is slower than on a fuel only layer. And the flame spread rate is almost the same in the case of fuel thickness 3 mm and more than 20 mm.

2) By visualizing the current distribution, the current characteristic depth in the fuel/water layer is deeper than the fuel only layer. On the other hand, the convection velocity of the fuel/water layer is slower than the fuel only layer at fuel thickness of 10 mm.

3) Using thermal visualization, although the temperature characteristic depth

h_t is almost the same, the temperature characteristic length of the fuel/water layer is longer than that of the fuel only layer.

4) By scaling analysis using our experimental data, the same tendency as alcohol fuel is obtained because the plots have constant upward gradient. Fuel/water layers condition is classified deep pools.

Acknowledgements

This work is supported by Grants-in-Aid for Scientific Research (KAKENHI), No. 15H03924.

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