# Flame Spread over an Oil Slick Floating on Water

Hideo OHTANI, Kazunori OHBU, and Yoichi UEHARA
(Yokohama National University, Hodogaya, Yokohama 240, JAPAN)
Hiroshi KOSEKI
(Fire Research Institute, Mitaka, Tokyo 181, JAPAN)

## ABSTRACT

Flame spread phenomena over an oil slick floating on water was studied from a view of the surface tension flow. Two series of experiments were conducted. The first one was done for clarifying the critical Marangoni number for causing the surface tension flow. An oil slick floating on water was heated by a nichrome wire electrically in the experiment. The other experiment was done for ascertain whether the critical Marangoni number practically affects the flame spread rate over the oil slick.

It was found that the critical Marangoni number for an oil slick floating on water was fairly large, e.g. $7600 \pm 730$ for decane. However, the Marangoni number was larger than the critical value at sub-flash temperatures for a spreading flame over a thin liquid layer practically. Therefore, the surface tension flow existed in front of the spreading flame, and it caused the flame pulsation.

**Keywords:** Marangoni number, Flame spread, Oil slick, Surface tension flow

## 1. INTRODUCTION

Recently, there were two large scale crude oil leakages. The first one occurred by a crude oil tanker driven ashore in Alaska, 1989. The second one was caused by the Gulf war, 1991. In case of the oil leakage into the sea, oil slicks are formed on the surface of the sea. To incinerate the oil slicks is sometimes considered to be the best way to avoid contamination of the environment. Also there may be an accidental fire of the slicks. Knowledge on flame spread phenomena over an oil slick is indispensable to incinerate it effectively, or to control the accidental fire.

Flame spread over liquid fuels has been studied extensively[1-3]. It is well known that flame spread rate depends on the liquid temperature. If the liquid temperature is below its flash point, the spreading flame is driven by flow in the liquid. The flow is caused by surface tension difference along the liquid surface. This surface tension flow is a characteristic of flame spread over a flammable liquid at sub-flash temperatures.

When there is a difference in surface tension along a liquid surface, liquid is driven by the difference and flow occurs in the liquid[4]. This phenomenon is called as the Marangoni effect. The Marangoni effect appears when there is a surface tension difference caused by a temperature distribution or a concentration distribution along the surface. The former Marangoni effect caused by temperature distribution is generally referred as the thermocapillarity. In the case of a surface tension flow before the leading flame edge, there is a temperature distribution, and it causes the Marangoni effect.

The surface tension flow was found to arise when the Marangoni number exceeded 80 by a theoretical analysis of a thin oil layer, temperatures of the upper and the lower surface of which kept constant[5]. The Marangoni number is defined as follows.

$$Ma=\{\sigma_T \cdot d \cdot (\theta_1-\theta_2)\}/(\mu \cdot \kappa), \quad (1)$$

where $\sigma_T$ means the temperature coefficient of the surface tension variation($d\sigma/dT$), $\mu$ is the viscosity, $\kappa$ is the thermal diffusivity, d is the thickness of the layer, and $\theta_1$ and $\theta_2$ are the temperatures of the lower and the upper surface of the layer, respectively. It was considered that the critical number was different if surrounding conditions of a layer were different. To clarify the critical Marangoni number for an oil slick floating on water was the first objective of this study.

Flame spread over a liquid surface is governed by a flow in the liquid when the liquid is at sub–flash temperatures. In such a case, the flow velocity at the leading flame edge is considered to depend on the Marangoni number defined between the leading flame edge and liquid surface beyond the surface tension flow. The following equation was derived from dimensional analysis[6].

$$U=\kappa \cdot Ma/L \quad (2)$$

where L is the horizontal length of the surface flow. This equation shows the surface tension flow becomes faster as the Marangoni number becomes larger. It means that the flame spread rate becomes larger as the Marangoni number becomes larger. To clarify how the Marangoni number affects the flame spread rate was the second objective of this study.

## 2. EXPERIMENTAL

### (1) Critical Marangoni Number

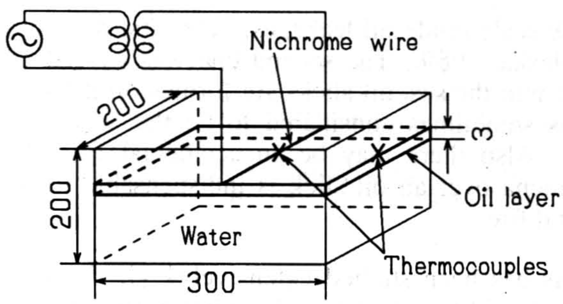


**FIGURE 1. Experimental setup for observing the surface tension flow.**

Figure 1 shows the experimental apparatus used to obtain the critical Marangoni number. Thin layers of decane, heptane and decanol were floated on water in a glass tank. The oil layer was heated electrically by a nichrome wire at the center. As shown in the figure, temperatures near the nichrome wire and far apart the wire were measured by C–A thermocouples. Movement of the oil surface was observed by movement of aluminum powders scattered on the surface. Temperature of the nichrome wire was varied a few degrees centigrade over the surrounding temperature to identify the critical Marangoni number for occurrence of the surface tension flow. Thickness of the layer was about 3mm, it was the thinnest one attained without any discontinuity along the layer.

**(2) Flame Spread Rate**

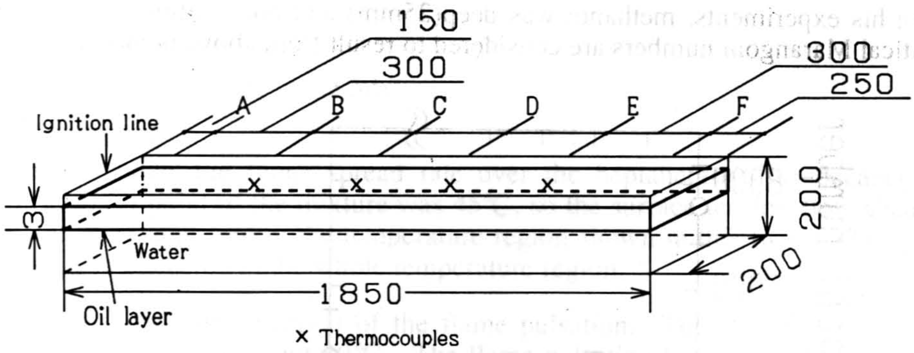


**FIGURE 2. Experimental setup for observing the flame spread.**

To investigate how the Marangoni effect affects the flame spread phenomena, flame spread over a thin oil layer floating on water was observed by using an apparatus shown in Fig. 2. Heptane(10vol%) and decane(90vol%) mixture was chosen as a sample oil. The Marangoni number was obtained by temperature difference between the initial temperature and the flash point of the oil. The initial temperature was controlled by a water jacket which covered the apparatus. Range of the initial temperature was from 10℃ to 40℃. On the other hand, the flash point of the oil was 45℃, so all flame spread experiments were done at sub–flash temperatures. Flame movement over the oil layer was recorded by a video camera, and analyzed on recorded pictures.

## 3. RESULTS AND DISCUSSION

**(1) Critical Marangoni Number**

Table 1 shows the critical Marangoni numbers defined in this study. Measurements of thickness and temperatures of the layer were very difficult because the layer expanded along the side walls and lead wires of the thermocouples by surface tension. The expansion was large compared with the normal layer thickness. They introduced fairly large error in defining the critical Marangoni number. However, it is clear that the critical Marangoni numbers observed are larger than 80 and they are different each other. The theoretical value 80 was obtained for a liquid layer, which had a temperature distribution in a perpendicular direction, and was heated from downward. In this study, the layer was heated from upward, and had a temperature distribution along the surface. These differences were considered to make the difference in the critical Marangoni number.

Table 1 Critical Marangoni Number

| Oil | Critical Value |
|---|---|
| Decane | 7600 ± 730 |
| Heptane | 4610 ± 930 |
| Decanol | 700 ± 30 |

According to Kamei's observation on the flame spread over methanol in a tray(25mm wide, 25mm deep and 800mm long), the surface tension flow appeared at methanol temperature between −0.3℃ and 0.5℃[7]. If the surface tension flow caused by temperature difference along liquid surface between the locations just below the leading flame edge and far apart from the leading edge, and temperature just below the leading flame edge is identical with the flash point(11℃), the critical Marangoni number for this case is about

8900. In his experiments, methanol was deep(25mm) and not floating on water, so these large critical Marangoni numbers are considered to result from above mentioned differences.

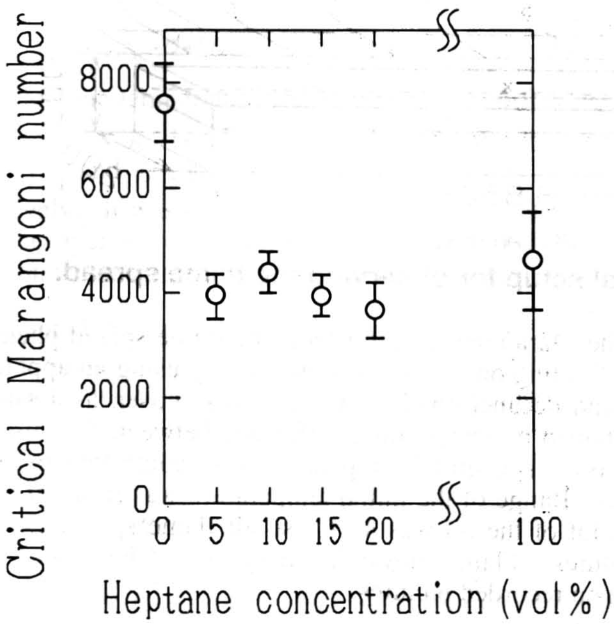


**FIGURE 3. Effect of heptane concentration on the critical Marangoni number.**

The mixture of decane and heptane was also tested because the surface tension force was known to be sensitive for impurity. Figure 3 shows the relation between the critical Marangoni number and heptane concentration of the mixture. It is obvious from the figure that the mixture shows almost the same critical Marangoni number with heptane if there

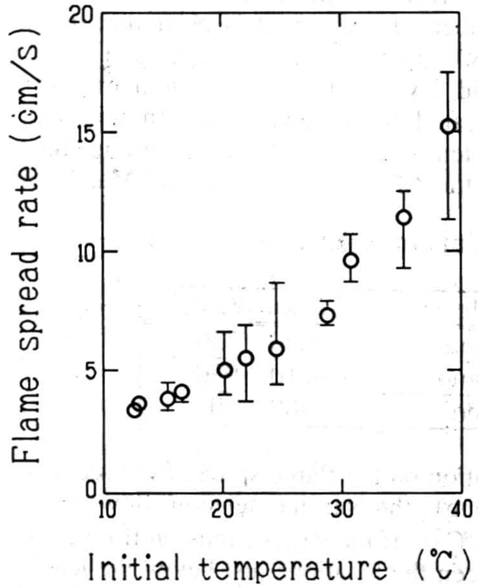


**FIGURE 4. Effect of the initial temperature on the flame spread rate.**

was a little amount of heptane in the mixture.

**(2) Flame Spread Rate**

Figure 4 shows the flame spread rate over the heptane(10vol%)–decane(90vol%) mixture. The flash point of the mixture was 45℃, so the surface tension flow ahead of the leading flame edge appeared in the temperature region shown in this figure. The pulsating flame spread also appeared in the whole temperature region.

Figure 5 shows time interval of the flame pulsation. The pulsating region can be divided into two regions at about 30℃. The flame pulsation becomes inactive toward the flash point in the upper region(>30℃), and the time interval of the pulsation is almost constant in the lower region. The upper region is considered to be correspond with the uniform region in Akita's paper[8]. The lower region should be correspond with the pulsating region.

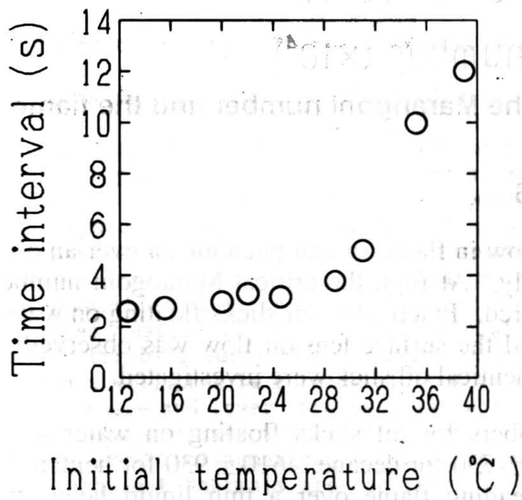


**FIGURE 5. Time interval of the flame pulsation.**

As shown in Fig. 3, the critical Marangoni number of the mixture in this situation was about 4000. The surface tension flow would arise if the Marangoni number of the mixture was larger than the value, and it causes the pulsating flame spread. Figure 6 shows the relation between the Marangoni number and the flame spread rate. The Marangoni number was defined by temperature difference between the flash point and the initial temperature. In this experiment, the Marangoni number observed was larger than 20000 in all cases. Therefore, the surface tension flow should be arisen, and it caused the flame pulsation. Moreover, this figure suggests that the flame spread rate decreases as the Marangoni number increases. As mentioned previously, the surface tension flow becomes faster as the Marangoni number increases. In the case of flame spread over liquid fuel, large Marangoni number means lower initial temperature, because temperature at the leading flame edge is fixed. Consequently, if the liquid fuel had the large Marangoni number, large amount of heat must be supplied from flame to cold liquid before flame propagating. It causes the flame pulsation, and the flame spread rate does not depend directly on the surface tension flow rate, that is the Marangoni number.

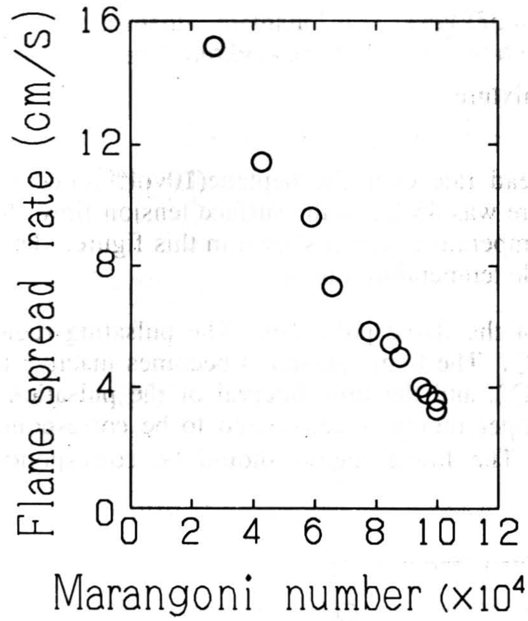


**FIGURE 6. Relation between the Marangoni number and the flame spread rate.**

## 4. CONCLUSIONS

Role of the surface tension flow in flame spread phenomena over an oil slick floating on water was studied experimentally. At first, the critical Marangoni number for causing the surface tension flow was measured. Practically, oil slicks floating on water were heated by a nichrome wire electrically, and the surface tension flow was observed. Then, actual flame spread phenomena over the identical oil slick were investigated.

The critical Marangoni numbers for oil slicks floating on water and heated from upward were fairly large, i.e. $7600 \pm 730$ for decane, $4610 \pm 930$ for heptane, and $700 \pm 30$ for decanol. However, for a spreading flame over a thin liquid layer, the Marangoni number was larger than the critical value at sub-flash temperatures in practice. Therefore, the surface tension flow preceded the flame in all cases, and it caused the flame pulsation.

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