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Evaporation and Ignition of a Fuel Droplet on a Hot Surface*

(Part 2, Ignition)

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The ignition process of a single fuel droplet (n-cetane, initial diameter approximately 2 mm) on a hot surface has been investigated. The mass evaporated in the very short duration soon after the initiation of contact with the hot surface has been measured. The following conclusions could be obtained.

(1) The ignition delay time curve concerning the wall temperature has a maximum and a minimum point as in the case of the evaporation life time. But these critical values in each of them do not coincide with each other, because the evaporation rate in the ignition delay time (τ_i), directly controlling τ_i , differs so much from that in time of total evaporation.

(2) The ignition delay time is controlled by the chemical reaction rate when the hot surface temperature (t_w) is lower than the Leidenfrost point, and by the physical process when t_w is higher than that.

1. Introduction

The present study is concerned with a process of evaporation to ignition of a fuel droplet on a hot surface and with precise discussion about the relation between them. As the first step the evaporation process of n-cetane and n-heptane whose diameter is approximately 2 mm has been investigated in the previous paper⁽¹⁾. In this paper the ignition delay time of n-cetane which could be ignited in a wide temperature range of the hot surface including the maximum evaporation rate point and the Leidenfrost point was investigated in detail, and the relation between the evaporation life time and the ignition delay time was discussed on the basis of the results obtained in the previous paper. Furthermore the mass which evaporated during the ignition delay time was measured, and the factor which controlled the ignition phenomena was discussed.

Nomenclature

d_o : initial diameter of the droplet mm
 L : distance along the hot surface mm
 M : evaporated mass mg
 R_z : roughness of the hot surface μm
 t : temperature $^{\circ}\text{C}$
 z : vertical distance from the hot surface mm
 ϵ : coefficient of variation
 θ : inclined angle of the hot plate deg
 σ : standard deviation
 τ : time sec

Subscripts

a: space over the hot surface
 c: ceiling of the test chamber
 chem: chemical
 e: evaporation

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i: ignition
 phys: physical
 w: wall of the hot surface
 w, v, w: phenomenological classification modes of evaporation

2. Experiment on ignition delay by the complete evaporation type apparatus

2.1 Experimental apparatus and procedure

2.1.1 Complete evaporation type apparatus: The same apparatus which was used in the previous paper⁽¹⁾ was used in this chapter in order to observe the ignition process of a fuel droplet which was dropped slowly on a horizontal hot plate. This apparatus was named the complete evaporation type apparatus in this paper in order to distinguish it from the apparatus used later.

2.1.2 Procedure: The gas temperature over the hot surface and the roughness of the hot surface were adopted as parameters which affected the ignition delay time (τ_i) just as in the case of the evaporation⁽¹⁾.

τ_i was measured keeping a steady oxygen concentration and a steady temperature in the test chamber. The steady gas concentration in this test chamber was approximately 82 vol.% O_2 + 18 vol.% N_2 . For the detection of ignition, the photomultiplier (Hokuto Riken Co., type 7696, sensitivity 4000-8000 Å) was used. The ignition delay time was measured repeatedly approximately 50 times under the same condition, and the arithmetic mean value of them was shown by τ_i . Other procedures were just the same as those mentioned in the previous paper.

2.2 Results obtained

Effect of the gas temperature around the droplet on the ignition delay time (τ_i) of cetane is shown in Fig. 1. In these cases τ_i was measured on a fine polished surface. In Fig. 1 the results of the evaporation life time (τ_e) which have been reported in the previous paper are plotted also for later discussion. One of the histograms of the ignition delay time is

shown in Fig. 2 for the hot surface temperature $t_w = 450^\circ\text{C}$. It is found from Fig. 1 that the higher the ceiling temperature of the test chamber (t_c), i.e. the higher the gas temperature around the droplet (t_a), the shorter τ_i for constant t_w except for a vicinity of t_w corresponding to minimum τ_i .

Effect of the hot surface roughness on τ_i of cetane is shown in Fig. 3. τ_e is also plotted in Fig. 3. As in the case of Fig. 2, the same histogram of τ_i for Fig. 3 was obtained. It is found from Fig. 3 that the temperature region of the ignition delay time curve in which τ_i changes from the minimum value to the maximum value tends to shift to the lower temperature with an increase of the surface roughness.

2.3 Discussion

2.3.1 General relation between the evaporation life time (τ_e) and the ignition delay time (τ_i): The most remarkable feature of the ignition delay time curve as shown in Fig. 1 and Fig. 3 is that it has the maximum and the minimum values just the same as the evaporation life time curve. This suggests that the ignition phenomenon of a fuel droplet on a hot surface is closely related to the evapo-

Fig. 1 Effect of gas temperature around the droplet on the ignition delay time of cetane

Fig. 2 Histogram of the ignition delay time of cetane

ration process and this is a distinctive feature of the ignition phenomenon under such system. However it is noticeable in Fig. 1 and Fig. 3 that the maximum and the minimum points of the ignition delay time curve and the evaporation life time curve do not coincide with each other, and the extreme values of the ignition delay time curve show at higher t_w than those of the evaporation life time curve.

Such a relation between the evaporation life time curve and the ignition delay time curve has been reported in the paper by Temple-Pediani, (2)(3). The results for initial diameter $d_o = 1.98$ mm of n-cetane obtained by Temple-Pediani are shown in Fig. 4. In the case of Temple-Pediani atmosphere was air, so the oxygen concentration around the droplet was lower than in the present study, furthermore the volume of the test chamber was smaller and the experimental condition was closely allied to the crucible method. Therefore it is difficult to compare the results of Temple-Pediani with the results of the present paper quantitatively, but the same tendency is observed qualitatively in both the results. However it is difficult to discuss in detail under use of the apparatus of Temple-Pediani, and in conclusion it is only mentioned that the ignition delay time curve is closely related to the evaporation life time curve and there is no precise discussion about the deviation between the extreme values of two curves.

In the previous paper (1) a mode of evaporation has been observed and discussed in detail with a high speed camera. In the present study, the ignition process was observed

Fig. 3 Effect of surface roughness on the ignition delay time of cetane

Fig. 4 Relation between the ignition delay time and the evaporation life time (2)(3)

in detail by the same method and the relation between the evaporation and the ignition process was discussed. Typical photographs near the ignition of cetane ($d_0 = 2.35$ mm) on the fine polished surface are shown in Fig. 5 in which the frame interval is 1 msec. Under $t_w = t_c = 300^\circ\text{C}$ (Fig. 5a), the droplet evaporates in contact with the hot surface in the shape of a plane-convex lens and an air bubble is observed in the center of it, and the ignition is observed at the third frame. Under $t_w = t_c = 350^\circ\text{C}$ (Fig. 5b), the droplet evaporates violently in contact with the hot surface and the shape of the droplet is deformed, and the ignition is observed at the third frame. Under $t_w = t_c = 380^\circ\text{C}$ (Fig. 5c), the droplet evaporates with bubbles at the interface between the droplet and the hot surface, and the ignition is observed at the third frame. Under $t_w = t_c = 400^\circ\text{C}$ (Fig. 5d), the droplet evaporates with bubbles at the interface between the droplet and the hot surface just as in Fig. 5c, and the ignition is observed at the second frame. Under $t_w = t_c = 450^\circ\text{C}$ (Fig. 5e) and $t_w = t_c = 550^\circ\text{C}$ (Fig. 5f), the droplet evaporates in almost spheroidal state, and the ignition is observed at the third frame. Furthermore under all of these conditions an initial flame is formed around the droplet approximately at a distance of 10 mm. As the shape of the droplet at the ignition can be shown in Fig. 6 in comparison with the observation of the mode of evaporation which has been mentioned in the previous paper⁽¹⁾. (Refer to §4.1 in the previous paper for the definition of the mode of evaporation and the symbols of the temperature range.)

The relation between the evaporation life time curve and the ignition delay time

Fig. 5 Ignition process of cetane with the complete evaporation type apparatus

Fig. 6 Modes of evaporation of the droplet at the ignition

curve is discussed as follows on the basis of the results shown in Fig. 6. In the temperature range b-c, the droplet evaporates and ignites in contact with the hot surface. In this temperature range both τ_e and τ_i decrease monotonically with an increase of t_w . In the temperature range c-d, τ_e reaches the minimum value, and in the temperature range d-e, τ_e increases abruptly since the mode of evaporation changes continuously as $\text{IV} \rightarrow \text{V} \rightarrow \text{VI}$. However the droplet ignites under the mode of evaporation IV because τ_i is much shorter than τ_e . Therefore τ_i decreases continuously with an increase of t_w . In the temperature range e-f, although the change of τ_e is extremely small because the modes of evaporation V and VI occupy almost all of τ_e , the droplet ignites under the mode of evaporation IV since τ_i is exceedingly short. However, the mode of evaporation IV does not appear when t_w gets to the point f, and then τ_e is occupied by the mode of evaporation VI , so τ_i increases abruptly. In the temperature range f-g, both τ_e , τ_i decrease with an increase of t_w .

In short τ_i loses the proportional relation with τ_e in the transition region (temperature range d-f) where the mode of evaporation changes extremely during τ_e because τ_i is controlled directly by the mode of evaporation of the droplet (the evaporation rate) during τ_i , therefore the maximum and the minimum points of the evaporation life time curve and the ignition delay time curve do not coincide with each other.

2.3.2 Effect of the gas temperature around the droplet (t_a) and the surface roughness on the ignition delay time (τ_i): In order to discuss the effect of t_a on τ_i , two temperature ranges were considered in Fig. 1. When the hot surface temperature (t_w) is lower than the temperature near the Leidenfrost point (temperature range b-d), τ_e is hardly affected by t_c because the droplet evaporates

in contact with the hot surface (mode of evaporation II, III). On the other hand, τ_i is affected by t_c because the ignition is a reaction in gas phase and then it is affected by the temperature of the mixing layer between the evaporated fuel and the surrounding oxidizer where the reaction progresses. When t_w is higher than the temperature near the Leidenfrost point (temperature range d-g), especially in the temperature range d-f, $\tau_e = \tau_w + \tau_v + \tau_w$ as mentioned in §4.1 of the previous paper, then τ_e is affected by t_c since $\tau_w \ll \tau_v + \tau_w$, but the effect of t_c on τ_i is very small because τ_i is much smaller than τ_e and $\tau_i \leq \tau_w$. Furthermore in the temperature range f-g, the effect of t_c on τ_e appears because of $\tau_e \approx \tau_w$, and τ_i is affected by the change of the evaporation rate introduced by t_c because the mode of evaporation of the droplet at the ignition is also the mode of evaporation VI, after all τ_i is affected by t_c indirectly.

The effect of the surface roughness on τ_i (Fig. 3) is discussed same as mentioned above. When t_w is lower than the temperature near the Leidenfrost point (temperature range b-d), τ_e is strongly affected by the surface roughness because the droplet evaporates in contact with the hot surface (mode of evaporation II, III). On the other hand, the effect of the surface roughness on τ_i is small because the gas temperature around the droplet is constant regardless of the surface roughness. When t_w is higher than the temperature near the Leidenfrost point (temperature range d-g), the effect of the sur-

face roughness on τ_e is small. On the other hand its effect on τ_i is remarkable in the temperature range d-f, because in this temperature range the mode of evaporation changes remarkably and because τ_i is strongly affected by the initial mode of evaporation during τ_e , therefore τ_i is affected strongly by the change of the evaporation process introduced by the change of the surface roughness. In the temperature range f-g, the effect of the surface roughness on τ_e is extremely small.

3. Measurement of the evaporated mass with the apparatus interrupting evaporation

It has already been clarified in Chapter 2 that the ignition delay time (τ_i) is strongly affected by the mode of evaporation of the fuel droplet during τ_i , when the hot surface temperature (t_w) is higher than the temperature near the Leidenfrost point. Furthermore in this Chapter the evaporation process of the droplet was investigated in the very short duration soon after the initiation of contact with the hot surface, in order to discuss the relation between τ_i and the mode of evaporation.

3.1 Experimental apparatus and procedure

3.1.1 The apparatus interrupting evaporation: It was intended to interrupt the evaporation and to freeze the droplet at an arbitrary moment between 0.2 to 1.0 sec after the initiation of contact with the hot surface. A new experimental apparatus for this purpose, shown in Fig. 7, was made. This apparatus was named the interrupting evaporation type apparatus. The test chamber was 100 mm long, 240 mm wide and 61 mm high, and the volume was approximately 1.4 liters the same as that of the complete evaporation type apparatus. The detail of the hot plate (Fig. 7(1)) is shown in Fig. 8. The inclined angle of the hot plate (θ) is variable by the adjuster (Fig. 7 (17)). The droplet which is dropped on the inclined hot plate moves evaporating along the hot surface which has a lane of 500 mm radius, and the droplet gets free from the surface at the end of the lane, being collected with the droplet collector (Fig. 7(10)) immediately. The droplet is frozen as soon as it is collected because the droplet collector is cooled with water to below the melting point of n-cetane (18.17°C). Two independent heaters are mounted in order to keep the hot surface temperature (t_w) constant and t_w is measured with 20 C-A thermocouples (diameter 0.3 mm) whose beads are embedded along both sides of a lane. Other construction of the

Fig. 7 Interrupting evaporation type apparatus

interrupting evaporation type apparatus is the same as the complete evaporation type apparatus.

3.1.2 Procedure: The experimental conditions for the interrupting evaporation type apparatus were such that the hot surface was always polished fine and the ceiling temperature of the test chamber (t_c) was set equal to t_w .

Prior to the experiments of the interrupting evaporation, the gas temperature over the hot surface and the evaporation life time (τ_e) for the inclined angle of the hot surface $\theta = 0$ deg were measured in order to compare with the case of the complete evaporation type apparatus. The procedure of these measurements was just the same as in the case of the complete evaporation type apparatus.

Secondly the ignition delay time (τ_i) was measured with the interrupting evaporation type apparatus. It was desirable that the moving velocity of the droplet be as small as possible. Therefore θ was set at 0.2 deg, and the case of $\theta = 1.0$ deg was also measured in order to compare. It is not desirable that θ be less than 0.2 deg because the droplet moves along a zigzag path. The procedure for the measurement of τ_i was same as described in §2.1.2.

Subsequently the mass evaporated in arbitrary duration of 0.2~1.0 sec after the droplet contacted with the hot surface was measured with the interrupting evaporation type apparatus. In this case the test chamber was filled with nitrogen. The time during which the droplet contacted with the hot surface was variable by changing θ and the position where the droplet was dropped, and the time from the initiation of contact with the hot surface to the interruption of the evaporation was measured by the optical method. Ten droplets were collected with the droplet collector in one measurement and the evaporated mass was measured with a chemical balance. The measurement mentioned above was repeated about 10 times and M was taken as the arithmetic mean value of them. θ was chosen as $\theta = 0.2, 0.5, 1.0$ deg in

Fig. 8 Hot Plate

order to discuss the effect of θ .

3.2 Results obtained

The surface temperature (t_w) of the hot plate (Fig.7(1)) along which the drop moves must be constant. The temperature distribution along the lane on the hot plate is shown in Fig.9. In this figure the position where the droplet gets free from the hot surface is shown as $L=0$ mm. It is found from Fig.9 that a constant t_w is almost obtained in the range $L < 85$ mm which includes the maximum distance of the droplet movement. Furthermore the distribution of the gas temperatures (t_a) above the hot surface of the interrupting evaporation type apparatus was found similar to the complete evaporation type apparatus in the range $z < 15$ mm and $L < 85$ mm. Thus it was confirmed that the gas temperatures around the droplet of two apparatuses were not different from each other.

The experimental results of the evaporation life time (τ_e) of *n*-cetane obtained with two different apparatuses are shown in Fig.10. There are slight differences between two results. However, the maximum evaporation rate points and the Leidenfrost points coincide with each other. Therefore the effect of two different apparatuses on τ_e can be ignored for the purpose of this study.

The experimental results of the ignition delay time (τ_i) of *n*-cetane obtained with two different apparatuses are shown in Fig.11. As the result it is found that the effect of two different apparatuses and the inclined angle of the hot plate (θ) of the interrupting evaporation type apparatus on τ_i can be ignored for the purpose of this study.

The experimental results of the evaporated mass with the interrupting evaporation type apparatus are shown in Fig.12. In Fig.12 the abscissa τ is the time between the initial contact of the droplet with the hot plate and the interruption of evaporation, and the ordinate M is the mass evaporated in τ . The evaporated mass (M) could not be measured by the method mentioned above in $\tau < 0.4$ sec at $t_w = 380^\circ\text{C}$, 400°C , because

Fig. 9 Temperature distribution of the hot plate along which the droplet moves

the droplet evaporated in contact with the hot surface and did not move on the hot surface.

3.3 Discussions

3.3.1 Effect of the moving speed of the droplet on the ignition delay time (τ_i):
The effect of the inclined angle of the hot plate (θ) on τ_i does not appear in Fig. 11 at $t_w > 450^\circ\text{C}$, even in the case of ignition in moving state. The ignition process was observed with a high speed camera just as in § 2.3.1, in order to investigate the effect of the moving speed of the droplet on τ_i . The experimental conditions were as follows, the hot surface was polished fine, $\theta = 0.2, 1.0$ deg and the initial diameter of the droplet $d_o = 2.26$ mm. Under $t_w = t_c = 300^\circ\text{C}, 350^\circ\text{C}, 400^\circ\text{C}$ the droplet rests on the hot plate before the ignition because of the modes of evaporation II, III, IV respectively, therefore the ignition process is the same as in Fig. 5a, b, d respectively. Under $t_w = t_c = 450^\circ\text{C}, 550^\circ\text{C}$, the droplet takes the mode of evaporation V as soon as it contacts with the hot surface, and begins to move on the hot surface. The droplet moves on the hot surface keeping the mode of evaporation VI and ignites. The initial flame at the ignition is formed around the droplet just as in Fig. 5e and Fig. 5f, and no difference in starting of initial flame is recognized. The moving speed of the droplet differs by θ , for example it is found by the high speed camera that the moving speeds of the droplet at the ignition are approximately 4 cm/sec and 10 cm/sec

Fig. 10 Comparison of the evaporation life time with different two apparatus

Fig. 11 Comparison of the ignition delay time with different two apparatus

for $\theta = 0.2$ deg and 1.0 deg respectively under $t_w = 450^\circ\text{C}, 550^\circ\text{C}$. Then in the experimental range of this study, $380 \leq t_w \leq 550^\circ\text{C}$ and the mode of evaporation $\text{IV} \rightarrow \text{VI}$, the moving speed of the droplet does not affect τ_i even if the droplet moves on the hot surface less than 10 cm/sec.

Furthermore it is found from Fig. 11 that the effect of the difference of the apparatuses on τ_i is not recognized and such an effect of d_o on τ_i as appeared on τ_e (Fig. 10) does not appear. The reason is considered that τ_i is much shorter than τ_e and the mass evaporated in the early stage of the evaporation controls τ_i .

3.3.2 Relation between the ignition delay time (τ_i) and the evaporated mass (M):
The effect of the inclined angle of the hot surface (θ) on M does not appear in Fig. 12. The moving speed of the droplet does not affect M as shown in Fig. 12 just as mentioned in § 3.3.1 for τ_i .

Four curves in Fig. 12 can be divided into two groups, i.e. one is a group including $t_w = 380^\circ\text{C}, 400^\circ\text{C}$ and the other is $t_w = 450^\circ\text{C}, 500^\circ\text{C}$. M of the low temperature group ($t_w = 380^\circ\text{C}, 400^\circ\text{C}$) is larger than that of the high temperature group ($t_w = 450^\circ\text{C}, 500^\circ\text{C}$) at the same τ regardless of t_w . This can be explained by the difference in the mode of evaporation as follows. Although the mode of evaporation at t_w of the lower temperature group changes $\text{IV} \rightarrow \text{V} \rightarrow \text{VI}$, the mode of evaporation at t_w of the higher temperature group is the mode of VI. That is, the evaporation rate of the lower temperature group is higher in spite of lower t_w because the droplet evaporates in contact with the hot surface (mode of evaporation IV) within a certain period of time. M for $t_w = 380^\circ\text{C}$ is larger than that for $t_w = 400^\circ\text{C}$ at same τ because the time in which the mode of evaporation IV is kept is longer for $t_w = 380^\circ\text{C}$. M for higher t_w is larger in the higher temperature group because the phenomenon mentioned above does not appear.

τ_i for each t_w is plotted in Fig. 12 in order to discuss the relation between τ_i and M. As the result it is found that the evaporated mass at the ignition is approximately 0.2 mg regardless of t_w . This means that in the range of t_w shown in Fig. 12 the ignition process of the fuel droplet on the hot surface is closely related to the fuel mass evaporated in τ_i ; in other words the ignition occurs when a certain amount of the combustible mixture was built up around the droplet. τ_i can be divided into the physical delay time (τ_{phys}) needed to build up the combustible mixture and the chemical delay

Fig. 12 Mass evaporated in the very short duration soon after the initiation of contact with the hot surface

time (τ_{chem}) needed to promote the chemical reaction in the mixture. Therefore as shown in Fig. 12 τ_{phys} is much longer than τ_{chem} in the range of t_w 380~500 °C, i.e. the physical process controls the ignition process.

It has been attempted by Kumagai et al. (4)(5) to express τ_i by the addition of τ_{phys} and τ_{chem} , from the viewpoint that the ignition phenomenon has to be treated as a statistical phenomenon. They measured τ_i of a fuel droplet in a heated crucible, and then they divided τ_i into τ_{phys} and τ_{chem} . For example τ_{phys} of a light oil droplet whose initial diameter $d_0=1.9$ mm increased gradually with a decrease of the crucible temperature, but τ_{chem} increased abruptly to below the crucible temperature approximately 580 °C. From the same point of view, Sakai et al. (6) showed that for the spray of n-cetane in hot air $\tau_{chem} > \tau_{phys}$ when the air temperature was lower than approximately 260 °C and $\tau_{chem} < \tau_{phys}$ when the air temperature was higher than that. El-Wakil et al. (7) discussed τ_{phys} and τ_{chem} , experimentally and theoretically, in case of a single fuel droplet being supported in a high temperature air stream. They intend to divide τ_i into τ_{phys} and τ_{chem} , and obtained reasonable results that the rate determining step was the chemical reaction process in the lower temperature region and the physical process in the higher temperature region, which coincide with the results of this study. However in contrast with another work mentioned above τ_i was not divided into τ_{phys} and τ_{chem} in the present study, but it was mainly discussed about the temperature range of the rate determining step and the substance of the physical process, from the viewpoint that τ_{phys} and τ_{chem} overlap each other and it seems difficult to separate them clearly.

Some ignition delay models of a single fuel droplet in a high temperature atmosphere have been proposed, for example, El-Wakil et al. (7) considered that a combustible mixture would be formed around the droplet during τ_{phys} . And after being heated up to the ignition temperature, the chemical reaction progressed during τ_{chem} until the ignition occurred. And, Faeth et al. (8) considered that the ignition occurred when the intermediate product of the reaction around the droplet reached a certain critical concentration. And, Henein (9) considered that the ignition occurred when the stoichiometric mixture was formed around the droplet at the ignition point. From these points of view, they tried to analyze the ignition delay phenomena respectively. However, the ignition model of a single fuel droplet on a hot surface, in which the ignition occurs when a certain amount of a combustible mixture is formed around the droplet, has not been verified by the experimental method as shown in the present paper.

Furthermore, the results about the rate controlling factor being obtained from Fig. 12 may be ascertained with the experimental results shown in Fig. 1 and Fig. 3. As a simple model, the hot surface temperature was divided into three regions as follows.

In the case where t_w is lower than the temperature near the Leidenfrost point (temperature range b-d), it is found from Fig. 1 that the effect of t_c on τ_e is very small as

mentioned in §2.3.2, i.e. the effect of the surrounding gas temperature on the physical process of the evaporation is small, but t_c has an important effect upon τ_i , i.e. the surrounding gas temperature has an important effect upon the reaction process because of the lower surrounding gas temperature. Furthermore it is found in Fig. 1 that the surface roughness of the hot plate has an important effect upon τ_e but a small effect upon τ_i , i.e. τ_i is hardly affected by the change of the physical process in spite of its remarkable change, because the surrounding temperature is constant regardless of the surface roughness. Then it can be concluded that the rate determining step is a chemical reaction in the temperature range b-d.

In the temperature range d-f which is higher than the temperature near the Leidenfrost point it is found from Fig. 1 that τ_e is considerably affected by t_c but τ_i is only slightly affected by t_c , i.e. τ_i is hardly affected by the change of the chemical reaction process caused by the change of t_c under the consideration that τ_i is hardly affected by the effect of t_c on the evaporation rate because $\tau_i \leq \tau_w < \tau_e$. Furthermore it is found in Fig. 3 that τ_e is only slightly affected by the roughness of the hot surface but τ_i is remarkably affected by it, i.e. as mentioned in §2.3.2 the change of the physical process, the evaporation in τ_i , caused by the change of the roughness of the hot surface affects considerably τ_i in spite of the constant surrounding temperature regardless of the roughness of the hot surface. Then it can be concluded that the rate determining step is a physical process in the temperature range d-f.

In the temperature range f-g it is found from Fig. 1 that both τ_e and τ_i are affected by t_c , but from Fig. 3 that both τ_e and τ_i are hardly affected by the roughness of the hot surface. In this temperature range the rate determining step is a physical process under the consideration that τ_i is indirectly affected by the effect of t_c on the evaporation rate (Fig. 1) because the droplet evaporates and ignites in the spheroidal state without contact with the hot surface (mode of evaporation ∇) immediately after it contacts with the hot surface and that the chemical reaction time is short because of the high surrounding gas temperature.

The above discussions support the results obtained by the measurements of the evaporated mass (Fig. 12). Then it is concluded that the chemical reaction process controls the ignition phenomena when t_w is lower than the temperature near the Leidenfrost point, but the physical process, the formation of a combustible gas mixture around the droplet, dominates the ignition process when t_w is higher than the temperature near the Leidenfrost point.

4. Conclusions

The ignition process of a single droplet of n-cetane (initial diameter is approximately 2 mm) on a hot surface has been investigated in detail over a wide range of the hot surface temperatures including the maximum

evaporation rate point and the Leidenfrost point of the evaporation life time curve. Furthermore the mass evaporated in the very short duration soon after the initiation of contact with the hot surface (less than 1 sec) has been measured and the relation between the evaporation process and the ignition process has been discussed precisely. The following conclusions could be obtained.

- (1) The relation between the hot surface temperature (t_w) and the ignition delay time (τ_i) (the ignition delay time curve) has the maximum and the minimum point just as the evaporation life time curve. However τ_i loses the proportional relation with the evaporation life time (τ_e) and therefore the extreme points of the evaporation life time curve and the ignition delay time curve do not coincide with each other in the transition region where the mode of evaporation changes remarkably during τ_e because τ_i is directly controlled by the mode of evaporation in the time of τ_i .
- (2) The ignition phenomenon is controlled by the chemical reaction process when the hot surface temperature (t_w) is lower than the temperature near the Leidenfrost point, but is controlled by the physical process when t_w is higher than the temperature near the Leidenfrost point. Namely, the ignition occurs when a certain amount of a combustible mixture is formed around the droplet.

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