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Examination of Extinguishment Method with Liquid Nitrogen Packed in a Spherical Ice Capsule

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Abstract. Liquid nitrogen which is a cryogenic fluid can be used as a fire extinguishing agent. This is because liquid nitrogen vaporizes rapidly under atmospheric condition, which results in cooling of burning materials and its surroundings in firefighting, and also the volume of the vaporized nitrogen becomes approximately 700 times larger than that of its liquid state, which results in reduction of oxygen concentration in air or fuel concentration in combustion zone. Moreover, liquid nitrogen has no water damage and can extinguish fires more cleanly than dry chemical extinguishing agents. However, it is difficult to delivery liquid nitrogen over long distance from the extinguishing equipment to fires through the surrounding air because of its rapid vaporization. If liquid nitrogen is filled into a capsule and the capsule wall suppresses heat transfer from the surroundings to the liquid nitrogen, it will be easy to transport liquid nitrogen to the targeted fire area without rapid vaporization. Moreover, by using the capsule, it may be possible to increase the extinguishing effectiveness of liquid nitrogen. In the present study, in order to clarify the fundamental characteristics of flame extinguishment by using the capsule filled with liquid nitrogen, extinguishing experiments of a methane-air jet diffusion flame have been performed. The spherical hollow ball made of ice was used as the extinguishing capsule and the ice capsule was formed by rotating casting machine. The wall thickness and the outer diameter were 2 mm and 20 mm, respectively. The filling volume of liquid nitrogen was 20 cm^3. The ice capsule was dropped freely from the height of 800 mm and impacted on the aluminum plate, in which the round burner to form a jet diffusion flame was embedded. The extinguishing probability was measured by varying the distance from the impact point of the ice capsule and the flame. The extinguishing processes were recorded with high-speed camera. Moreover, for comparison, the same extinguishing experiments have been performed using the ice capsule filled with water. As a result, liquid nitrogen shows the higher extinguishing effectiveness than water because liquid nitrogen droplets released from the ice capsule to the collided horizontal plate can travel over the longer distance due to the Leidenfrost effect and liquid nitrogen can be vaporized rapidly under room temperature condition. The extinguishable range of the ice capsule filled with liquid nitrogen is less than 200 mm.

Keywords: Extinguishment, Liquid nitrogen, Ice capsule, Diffusion flame

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1. Introduction

In Japan, the two large-scale earthquakes, that is, the Great East Japan Earthquake in 2011 and the Great Hanshin-Awaji Earthquake in 1995, happened. After the occurrence of the each earthquake, multiple simultaneous fires which were beyond the ability of local fire departments broke out in urban areas. At the same time, infrastructure, such as roads, power, gas and water lines and water utilization for firefighting, was destroyed violently due to the impacts of earthquake or tsunami. Under the emergency situation, fire engines cannot arrive at the fire sites and local residents have to fight the post-earthquake fires by themselves with a portable fire extinguisher and/or by a bucket brigade. However, if local residents cannot approach to the fire area due to damaged roads and/or piles of tsunami debris, it becomes impossible to extinguish the fires with the ordinary fire extinguishing methods whose effective ranges are several meters. Therefore, to mitigate and minimize the damage caused by post-earthquake fires, the development of a new firefighting method which can be easily used by the general public and deliver extinguishing agents over a long distance more than several tens of meters, is necessary.

The authors have proposed and experimentally investigated the capsule extinguishing method with gaseous extinguishing agents [1–6]. In the proposed method, extinguishing agents are filled into the capsule and transported from the application location to a fire site. For example, when an inert gas is filled into a capsule such as a soap bubble [1–3] and a rubber balloon [4], the liquid or rubber membrane inhibits mutual diffusion between the filled gas and the surrounding air, and easily ruptures when the capsule contacts with the high temperature region of the flame. Therefore, by using the capsule for fire extinguishment, the extinguishing gas can be easily transported without reduction of its concentration through the atmosphere over a long distance and released very close to the fire zone. Moreover, Iwatani et al. has experimentally examined the method to transport the extinguishing capsule (rubber balloon) filled with helium gas by using a quad rotor helicopter [5, 6]. Thus, utilization of the capsule for firefighting will be able to make the long-distance delivery of extinguishing agents easier and the maximum effective range of the portable extinguishing equipment wider. In the present study, a hollow ball made of ice is used as a capsule to transport extinguishing agents. The ice ball is a hard shell capsule and can be easily shot at the high velocity by a compressed gas gun like a paintball gun, whose firing range is over several tens of meters, and also when the ice capsule collides on a ground or wall, it can be easily crushed and releases the extinguishing agents inside it toward the surroundings.

Moreover, in this study, liquid nitrogen is used as a fire extinguishing agent and filled into the ice capsule. There are several advantages to using liquid nitrogen for firefighting. Liquid nitrogen has much lower boiling point (77 K) and latent heat of vaporization (48 cal/g) than water. Therefore, liquid nitrogen vaporizes very rapidly even under standard atmospheric conditions, and also the volume of the vaporized nitrogen becomes approximately 700 times larger than that of its liquid state. If liquid nitrogen is supplied to a burning area, the vaporizing of liquid nitrogen results both in cooling of burning materials and in reduction of oxygen concentration in air and/or concentration of combustible components in the combustion zone. Furthermore, when a paper sheet consisting of cellulose fibers absorbs liquid nitrogen, there is no damage to the paper from liquid nitrogen because nitrogen molecule does not interact with hydrogen bond between cellulose fibers in the paper. Therefore, liquid nitrogen does not cause any damage like water damage to paper materials and furthermore can extinguish fires more cleanly than dry chemical extinguishing agents. However, it is difficult to delivery liquid nitrogen by a jet flow over the long distance from extinguishing equipment to a fire site through the surrounding air because of rapid vaporization of liquid nitrogen [7, 8]. Especially, if liquid nitrogen jet is separated into small droplets, which have a high surface area-to-volume ratio, during the transport process, the liquid nitrogen vaporizes faster and becomes more difficult to supply to the fire zone. However, if liquid nitrogen is filled into a capsule and transported without separation into small droplets, and the capsule wall suppresses heat transfer from the surroundings to the liquid nitrogen, it will be easy to transport liquid nitrogen to a targeted fire area without rapid vaporization of large amount of liquid nitrogen. Therefore, by using the capsule, it may be possible to deliver larger amount of nitrogen to a fire site as a liquid and increase the extinguishing effectiveness of liquid nitrogen more than the supplying method with a jet flow.

In the present study, in order to clarify the fundamental characteristics of the flame extinguishment by using an ice capsule filled with liquid nitrogen, extinguishing experiments of a methane-air diffusion flame have been performed. A spherical hollow ice capsule has been formed by rotating casting machine. In the extinguishing experiments, as a first step of the examination of the ice-capsule extinguishing method, the capsule has been dropped in free-fall and impacted onto a solid wall surface. To grasp the extinguishing mechanism, the extinguishing process has been observed with a high-speed camera, and extinguishing probability has been measured by varying the distance between the impact location of the ice capsule and the flame. For comparison, the same extinguishing experiments have been performed using the ice capsule filled with water.

2. Experimental Setup and Method

2.1. Forming Method of Spherical Ice Capsule

The hollow ice ball to encapsulate liquid nitrogen was formed using a rotary molding method. Figure 1 shows the molding machine of the ice capsule with semi-randomized two-axis motion. The frame No. 1 and No. 2 in Figure 1 were rotated vertically and horizontally, respectively. The driving force was given by the electric geared motor and its torque was transmitted with a rubber belt from the pulley No. 1 which was fixed to the main frame of the rotating machine to the pulley No. 2 which was movable one. Figure 2 shows the ice capsule mold, which was made of acrylic material. The outer and inner diameters of the acrylic hemispherical bowl were 25 mm and 20 mm, respectively. The volume of water to

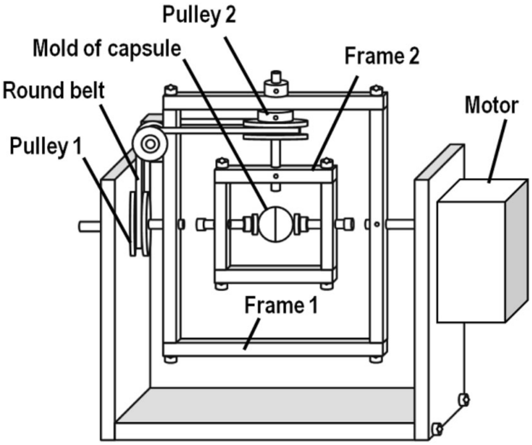

Figure 1. Double rotational axis casting machine.

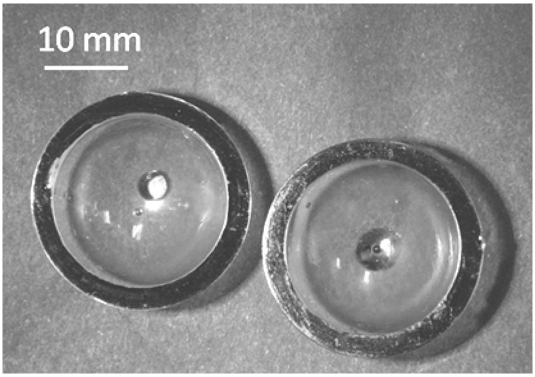

Figure 2. Hemispherical plastic bowls to form the ice capsule.

make one capsule was 1.8 cm^3. When the rotary molding machine at the rotating rate of about 72 revolutions per minute was placed in a freezer at about −10°C, it took approximately 35 min to form one ice capsule. In order to keep the movement of the electrical motor stable under the low temperature condition in the freezer, an electric heater was set in the motor section and its section was covered with a thermal insulating material.

Figure 3 show the features of the formed hollow ice capsule. It is seen from Figure 3a that the ice capsule had almost spherical shape. The outer diameter of the ice capsule was approximately 20 mm. Figure 3b shows the cross sectional view of the ice capsule cut in half. The wall thickness was almost constant and the value was about 2 mm. The capsule could be filled with up to 2.1 cm^3 of liquid. In the present study, we assume that capsules are fired with like a paintball gun. The commercially available paintballs have the diameter of about 17 mm and the

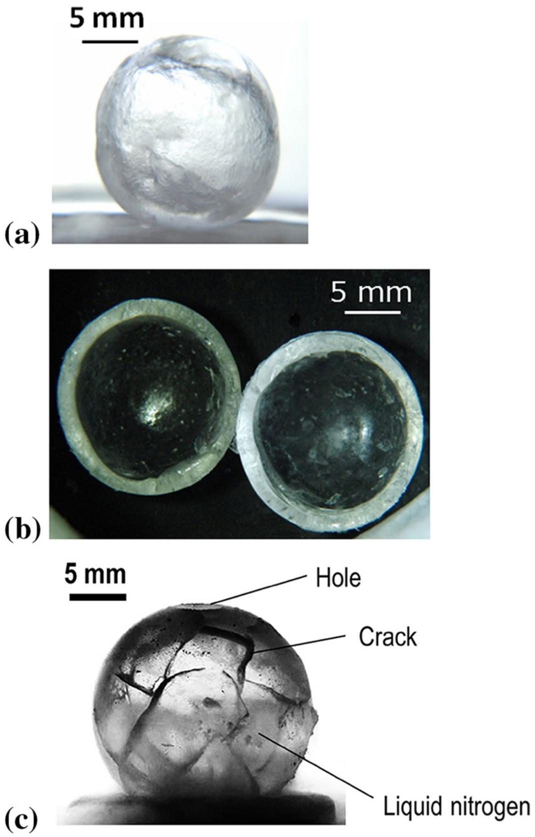

Figure 3. Ice capsule, (a) External appearance (b) Sectional view (c) Ice capsule filled with liquid nitrogen.

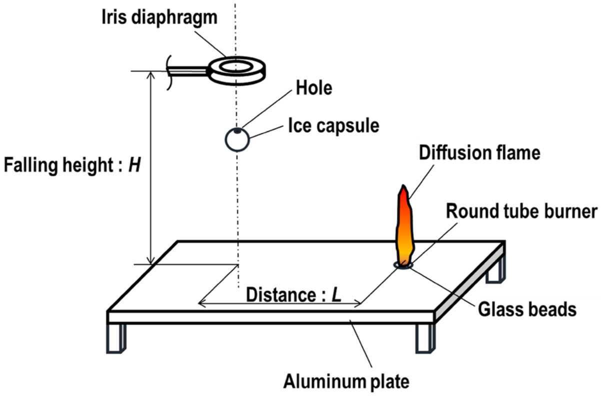

Figure 4. Experimental apparatus.

mass of about 3 g [9]. If the normal paintball gun is used for the capsule extinguishing method which we proposed in the study, the capsule is needed to have the similar shape, size and mass of a regular paintball. Therefore, the spherical ice capsule was made at the diameter of 20 mm and the mass of the capsule filled with liquid nitrogen was 3.5 g, which were almost the same size and mass as a paintball. With respect to the wall thickness of the ice capsule, we tried to make the thinner wall of the ice-capsule with the rotary molding machine, but it was not possible to make stably the ice capsule whose wall thickness was less than 2 mm. Thus, the dimensions of the ice capsule in this study were determined. In order to fill liquid nitrogen into the ice capsule, a round hole with the diameter of 3 mm was made in the capsule wall with a metal needle and then the ice capsule with the hole was submerged in the liquid nitrogen in the Dewar bath for 2 min. Figure 3c shows the ice capsule which was left under the atmospheric condition after filling of liquid nitrogen. Liquid nitrogen in the capsule is seen as a shadow in Figure 3c. Some cracks as shown in Figure 3c were formed due to thermal shrinkage of the ice wall when the ice capsule was put under liquid nitrogen. When the ice capsule was placed under the room temperature condition, boiling of liquid nitrogen occurred in the ice capsule and it took about 65 s for all liquid nitrogen filled in the ice capsule to be vaporized perfectly. In the extinguishing experiment, the ice capsule was dropped with the hole open. In order to compare the extinguishing characteristics of liquid nitrogen confined within the ice capsule, water whose temperature was close to 0°C was used, and put into the capsule through the hole with an injection needle.

2.2. *Extinguishing Experiments*

Figure 4 shows the experimental apparatus for the extinguishment experiments with liquid nitrogen packed in the ice capsule. A methane-air diffusion flame was used as an extinguishing target, and formed with the stainless tube burner, whose inner and outer diameters were 28 mm and 30 mm, respectively. The burner was embedded in the aluminum plate and the top of the burner tube was set at the same height of the aluminum plate surface. To form a uniform velocity profile of fuel flow, glass beads with the diameters of 1 mm were filled in the burner. The fuel gas was supplied to the burner at the volumetric flow rate of 17.5 cm^3/s and the measured flame height was about 124 mm.

As a first step to examine the fundamental characteristics of the ice capsule extinguishment method, the ice capsule was dropped in free fall at the height of 800 mm from the aluminum plate surface. The volume of liquid nitrogen in the capsule was set at 2.0 cm^3 when the capsule was initiated to fall. For water, the same volume was filled in the ice capsule. For liquid nitrogen, the measured impact velocity of the ice capsule onto the aluminum plate was 3.75 m/s and for water, the impact velocity was 3.91 m/s. When the ice capsule collides on the aluminum plate, the wall of the ice capsule was broken and liquid nitrogen and water were released from the crushed capsule and scattered around the impact location. The extinguishable area of liquid nitrogen and water in the capsule extinguishing method was considered to vary depending on the distance from the center position of the tube burner to the impact location of the ice capsule, L [mm]. To reveal the extinguishable distance of the ice capsule filled with liquid nitrogen and water, the distance L was changed from 25 mm to 190 mm as a parameter.

To evaluate quantitatively the extinguishable range, measurements of the extinguishing probability, P, were conducted. The extinguishment experiments were performed in the following way. First, the location of the iris to release the ice capsule was set at a certain distance from the burner center, and the stable diffusion flame was formed. Second, the ice capsule was dropped and impacted on the aluminum plate, and then liquid nitrogen or water was scattered around. Third, we checked whether the flame was extinguished or not visually. When the flame was blown off perfectly, we recorded it as a success of the extinguishment. The probability was computed as the ratio of the number of successful extinguishments to the number of total experiments of 10.

3. Experimental Results

3.1. Extinguishing Process

Figure 5 shows an end view of the extinguishing process of a diffusion flame formed on the burner using the ice capsule filled with liquid nitrogen. The images were recorded with a high-speed camera (Nac, HX-3, frame rate: 6000 fps, exposure time: 1/6000 s). A metal halide lamp (Photron, HVC-UL, 250 W) was used as a lighting. The time in images of Figure 5 indicates the elapsed time from when the lowest part of the ice capsule contacts on the surface of the aluminum plate. The distance from the flame to the impacting location of the ice capsule on the plate, L, was 50 mm.

The first image in Figure 5 shows the moment just before the ice capsule hits the plate. As seen in the first image of Figure 5, white fog appears in the wake region at the back of the ice capsule, and is condensed to be formed by water vapor in the air due to cooling by the low-temperature capsule wall and/or the low temperature liquid nitrogen vapor issuing from the ice capsule. At 2.7 ms, the lower half of the ice capsule crushes and liquid nitrogen splashes in the lateral direction along the plate. At this time, liquid nitrogen released form the ice capsule can be considered to begin to vaporize on the aluminum plate and in the air. At 10.2 ms, the whole ice capsule is broken due to the collision. Droplets of liquid nitrogen are scattered from the crushed ice capsule to the lateral direction on and over the plate, and passes through the base region of the flame. In the image at 28.5 ms, liquid nitrogen droplets and also fragments of the broken ice capsule move more to the lateral direction along the plate. At the same time, white fog, condensed water vapor in the air, is observed over the area through which liquid nitrogen passes, and is caused by cooling due to mixing between the air and liquid nitrogen vapor. Therefore, the white fog is considered to show the presence of liquid nitrogen vapor. As a result, at 28.5 ms after crushing of the ice capsule, the liquid nitrogen vapor is supplied to the flame base and dilutes the concentrations of oxygen in the air and fuel. At 65.3 ms, several droplets of liquid nitrogen are present on the plate and also the layer of the liquid nitrogen vapor is formed over

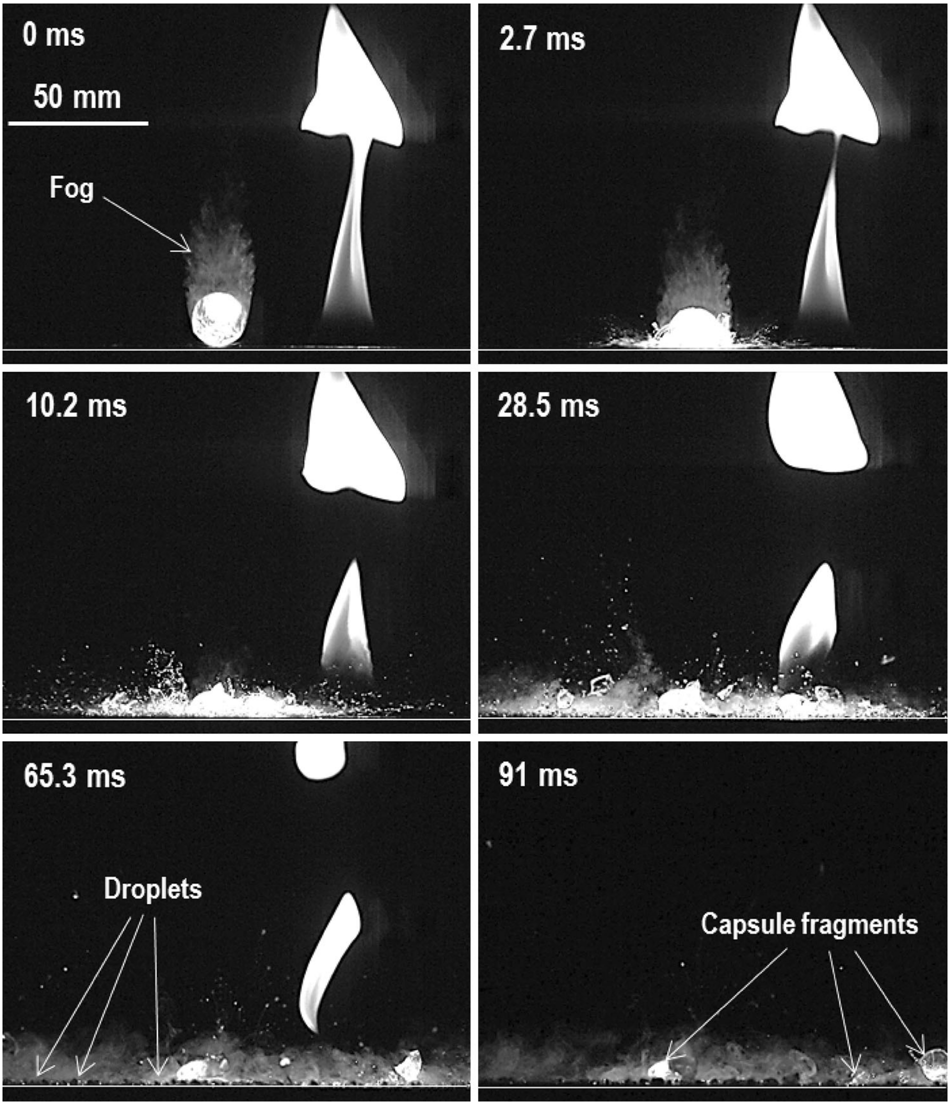

Figure 5. End view of the extinguishing process by using the ice capsule filled with liquid nitrogen ($L = 50$ mm).

the plate. Moreover, the flame base region is extinguished locally by liquid nitrogen vapor. Finally, at 91 ms, the flame which loses the flame base is blown off perfectly. Thus, the extinguishment occurs in short period, and the fragments of the crushed ice capsule does not melt and remains on the aluminum plate as observed in the image at 91 ms in Figure 5.

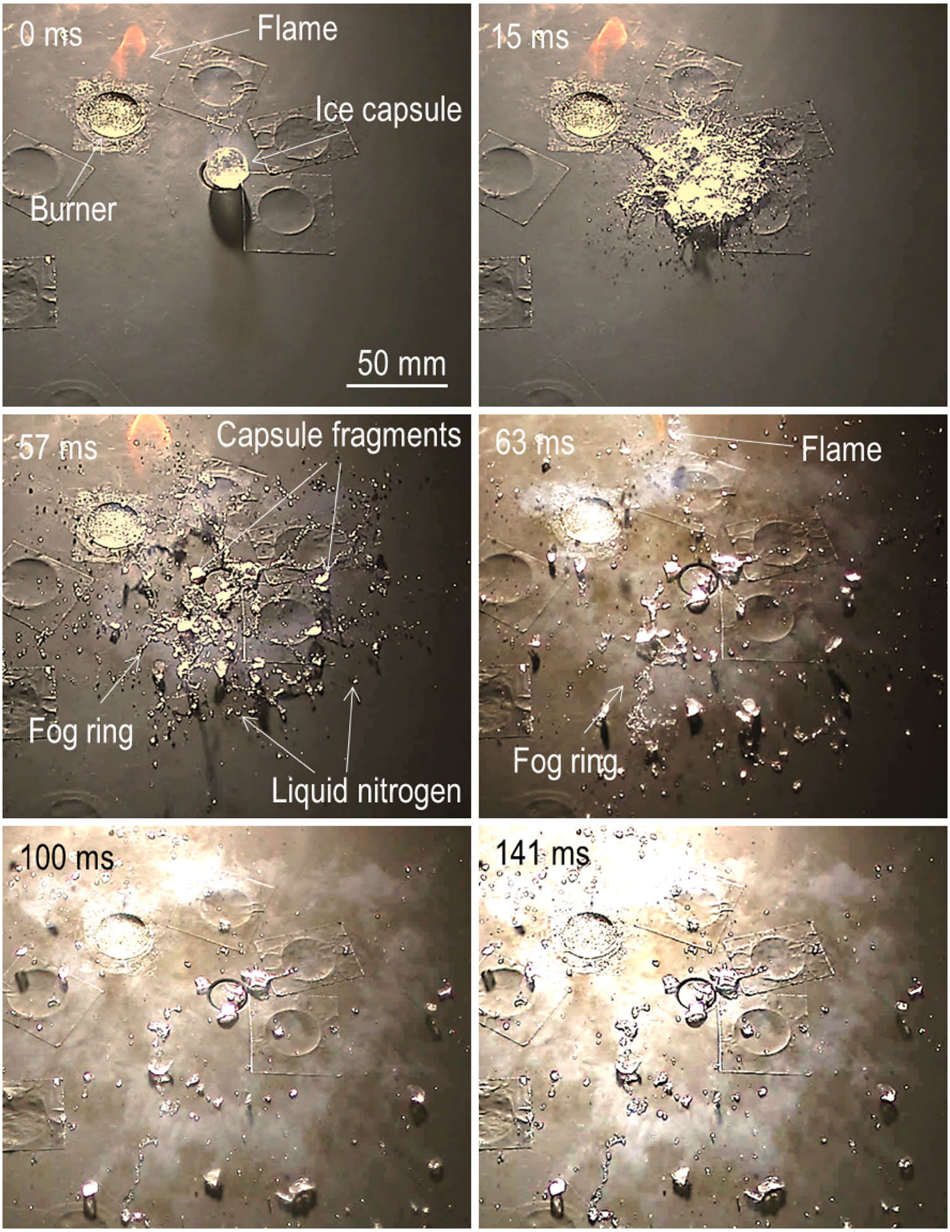

Figure 6. Bird's eye view of the extinguishing process by using the ice capsule filled with liquid nitrogen (L = 70 mm).

Figure 6 shows the bird's eye view of the extinguishing process with the liquid nitrogen packed in the ice capsule. The distance from the flame to the impacting location was 50 mm.

As seen in the image at 15 ms after collision of the ice capsule in Figure 6, the ice capsule is broken into the small fragments and liquid nitrogen splashes on the plate. At 57 ms, liquid nitrogen and the fragments of ice capsule are scattered to the radial direction over the plate. Furthermore, it is found that liquid nitrogen droplets can smoothly move outward on the aluminum plate, whose temperature may be about four times higher than the boiling point of liquid nitrogen. The behavior of liquid nitrogen droplet is caused by the Leidenfrost effect [10, 11], in which small liquid nitrogen droplet is levitated by its own vapor layer formed between the bottom surface of the droplet and the solid surface. Moreover, the ring shape of white fog appears over the plate. As described before, the white fog is formed due to mixing of liquid nitrogen vapor and the surrounding air, and can be considered to show the presence of liquid nitrogen vapor. The diameter of the white fog ring increases with increasing the time. As shown in the images during from at 63 ms to 141 ms, after the fog ring reaches the flame region, the flame is extinguished due to dilution the concentrations of oxygen and fuel with liquid nitrogen vapor.

Figure 7 shows the extinguishing experiment using water packed in the ice capsule. For the experiment, the distance from the dropping location of the ice capsule to the flame is 50 mm. In case of water, the flame is not extinguished.

From Figure 7, it is seen that the bottom part of the ice capsule is broken due to collision to the plate, and water is released in the radial direction from the broken ice capsule. However, unlike the case of liquid nitrogen, the whole of the ice capsule is not broken into small fragments because the ice capsule has the temperature close to its melting point and the capsule wall becomes softer than that filled with liquid nitrogen, and also water vapor is not produced over the plate because the plate temperature is lower than the boiling point of water. Moreover, although it is difficult to see from Figure 7, the large part of water released from the broken ice capsule does not flow smoothly on the plate and stays around the impact location because of the friction between water flow and the plate surface. As a result, although a part of the water released from the ice capsule can reach the flame base, local extinction does not occur in the base region of the flame and the flame extinguishment is not achieved.

Based on the above examination, it is said that in the capsule extinguishing method by using liquid nitrogen, the flame extinguishment is considered to be achieved not directly by liquid nitrogen but by liquid nitrogen vapor, which is mainly produced by heat transfer from the aluminum plate to liquid nitrogen.

3.2. Extinguishing Probability

To evaluate quantitatively the extinguishable range of the ice capsule filled with liquid nitrogen, the extinguishing probability, P, was measured by varying the distance between the flame and the impacting location. Figure 8 shows the profiles of the extinguishment probability.

In case of water, the extinguishing probability always shows zero in dependent of the distance L. Therefore, in this experiment, the ice capsule filled with water has no extinguishing effectiveness. On the other hand, for liquid nitrogen, the extinguishing probability shows unity when the distance from the impact location

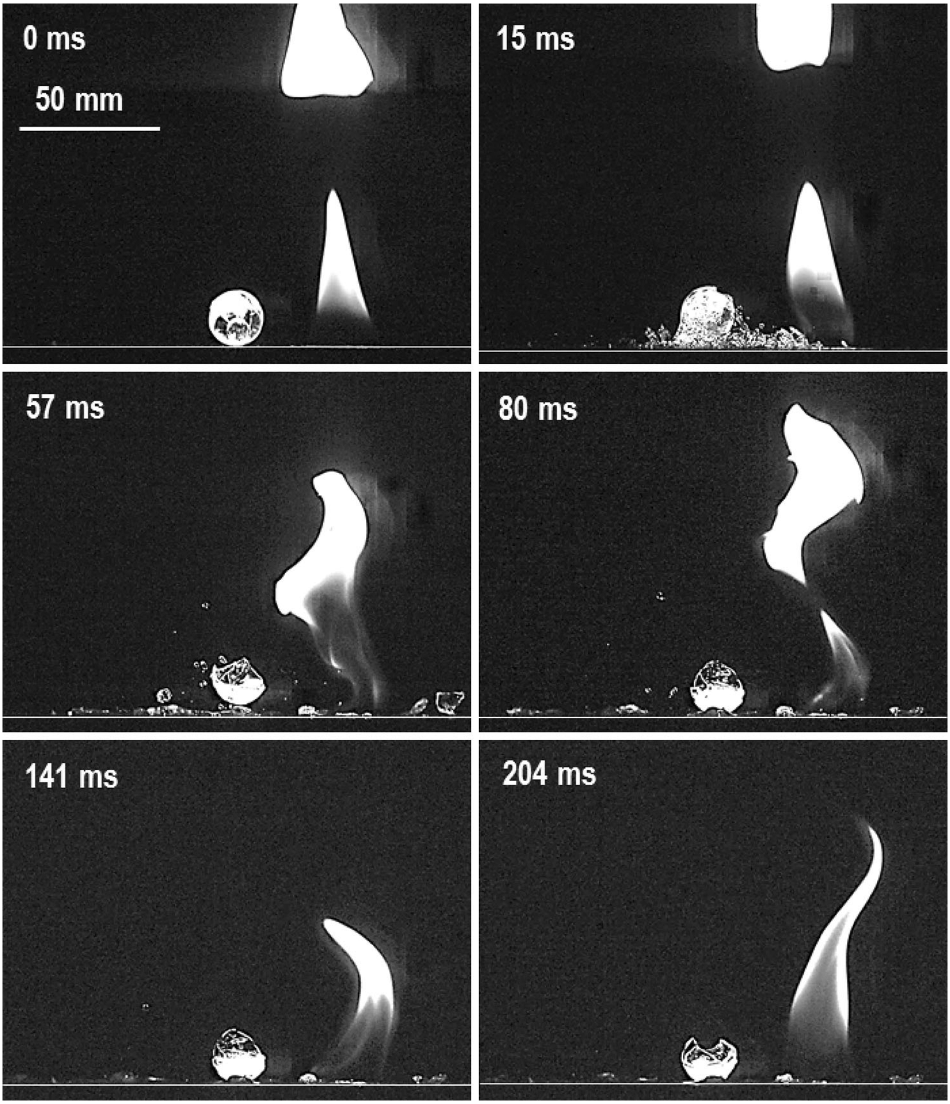

Figure 7. End view of the extinguishing process by using the ice capsule filled with water (*L* = 50 mm).

of the ice capsule is less than 25 mm. As the distance increases, the extinguishing probability decreases and then becomes zero at 200 mm. This is because as the distance from the impact location to the flame becomes larger, amount of liquid nitrogen and the concentration of the liquid nitrogen vapor to reach the flame region decreases more. Thus, in the ice capsule extinguishment method performed under the room temperature condition, liquid nitrogen shows the higher extinguishing effectiveness than water because liquid nitrogen droplets can travel over

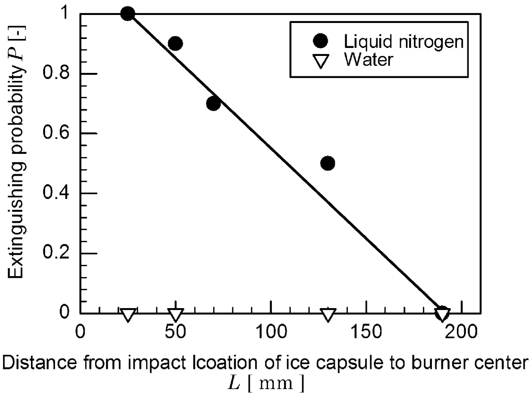

Figure 8. Profiles of extinguishing probability.

the longer distance on the plate due to the Leidenfrost effect and be vaporized rapidly at room temperature.

Although the extinguishable range, where the extinguishing probability indicates a finite value, is not wide in the extinguishing experiment of the ice capsule filled with liquid nitrogen, it is considered to be possible to increase it by using a gas gun. When a gas gun is used to fire the ice capsule, the impact velocity of the ice capsule will be higher and also the diameter of the liquid nitrogen droplets released from the crushed ice capsule will be smaller. If fine droplets of liquid nitrogen, which have high evaporation rate due to the large surface area-to-volume ratio, are formed, the volume of the liquid nitrogen vapor produced in the collision of the ice capsule will be larger and the extinguishing method will be able to show higher extinguishing effectiveness. Moreover, although the ice capsule filled with water shows no extinguishing effectiveness in this experiment, it is also considered that water can indicate the similar extinguishing tendency to liquid nitrogen by using a hot plate whose temperature is higher than the boiling point of water.

4. Discussion

In the present study, the extinguishing method using an ice capsule filled with liquid nitrogen is considered to be used for post-earthquake fires which include burning of house, collapsed house, tsunami debris and so on. However, in the emergency situation such as outages of power, fuel gas and water, it might be difficult to produce and preserve ice capsules and also not easy to obtain liquid nitrogen. If local residents get ice capsules preserved in a freezer and liquid nitrogen from a storage tank, liquid nitrogen may have to be filled into the ice capsule at on-site. After that, the extinguishing capsule can be fired to fire areas with a low pressure gun like a paintball gun and finally extinguish flames. At the present moment, the techniques to produce several ice capsules at a time and on-site, to preserve them for a long term and to fill liquid nitrogen into several capsules quickly and easily in emergency situation are need to be developed.

On the other hand, as a first step on the examination of the ice-capsule extinguishing method by using liquid nitrogen, the experimental results have demonstrated the usefulness of a capsule on delivery of extinguishing agents and the effectiveness of liquid nitrogen which attacks and suppresses a flame not directly but indirectly by vaporized nitrogen gas. The nitrogen vapor is considered to be mainly produced by heat transfer from the solid surface at room temperature to liquid nitrogen.

Based on the above considerations and the experimental results, it is possible to say that even though it might be difficult to use the ice capsule and liquid nitrogen for firefighting in emergency situation, the concept of the extinguishing method using a hard-shell capsule filled with liquid extinguishing agent is considered to be useful. For example, in fire area, there are high-temperature solid surfaces such as wall, ceiling and floor heated by flames and fire plumes, and pyrolysis region of flammable materials. These solid surfaces are normally considered to be beyond the boiling point of water. In that case, water can replace liquid nitrogen. If water filled in the capsule contacts onto high-temperature solid surfaces in burning area, it can be expected that water absorbs heat from the solid surface and turns rapidly into water vapor, and by producing a large amount of water vapor, fire extinguishment may be achieved. Water packed in the capsule would show similar extinguishing characteristics to liquid nitrogen. Moreover, the ice capsule also can be replaced by a hollow ball made of non-flammable material like ceramics. Thus, if we use the capsule extinguishing method for the post-earthquake fire at the present moment in a practical manner, it may be appropriate that the material to form a spherical hollow capsule and the liquid extinguishing agent are replaced from an ice and liquid nitrogen because of no techniques to form many spherical hollow ice capsules at a time and on-site, to preserve them stable for a long term and also to storage liquid nitrogen easily. However, when these techniques are developed, the ice-capsule extinguishing method using liquid nitrogen will be usable for post-earthquake fires.

5. Concluding Remarks

In the present study, the extinguishment method with liquid nitrogen packed in the hollow capsule made of ice has been proposed and the extinguishing characteristics have been investigated experimentally. If a hard shell capsule filled with extinguishing agents is utilized for firefighting, it will be possible to transport the extinguishing agents to fire site over a long distance. Therefore, if the capsule extinguishment is established, the method is considered to be useful to mitigate and minimize the damage of post-earthquake fires because after a large-scale earthquake occurs, fire engines and also local residents cannot approach to the fire area due to damaged road or tsunami debris.

In this experiment, a hollow ball made of ice is used as a capsule to transport liquid nitrogen. Liquid nitrogen is filled into the ice capsule. A methane-air diffusion flame formed on a tube burner is used as the extinguished target. As a first step of the examination of the ice capsule extinguishing method, the capsule is dropped in free-fall from the height of 0.8 m in the extinguishing experiment. The ice capsule is formed by using the double rotational axis casting machine. The outer diameter of the ice capsule was approximately 20 mm. The wall thickness was about 2 mm. The volume of liquid nitrogen in the capsule was set at 2.0 cm^3.

The extinguishment of the flame which is about 124 mm high has been succeeded using liquid nitrogen filled into the ice capsule. The extinguishable range in the extinguishing method is less than 200 mm. Within the circle of the radius of 400 mm from the impact location of the ice capsule, the extinguishing probability is considered to have a finite value. Under free-fall condition of this study, the impact velocity of the ice capsule is too small to produce a lot of fine liquid nitrogen droplets. As a result, the extinguishable area of the ice capsule filled with liquid nitrogen is not wide. If the higher impact velocity is given to the ice ball by using a gas gun, it would be possible to supply liquid nitrogen vapor wider and increase the extinguishable range in the extinguishing method.

Moreover, in the ice capsule extinguishment method performed under the room temperature condition, liquid nitrogen shows the higher extinguishing effectiveness than water because liquid nitrogen droplets can travel over the longer distance on the plate due to the Leidenfrost effect and be vaporized rapidly at room temperature.

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