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Extinguishing characteristics of a diffusion flame with water vapor produced from a water droplet impacting onto a heated plate

Hiroyuki Torikai*, Akihiko Ito

Faculty of Science and Technology, Hirosaki University, Bunkyo 3, Hirosaki, Aomori 036-8561, Japan

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ABSTRACT

In this study, we have investigated an extinguishing method of a diffusion flame with water vapor produced from a water droplet impacting onto a headed plate, which is called as indirect fire attack. In order to clarify the extinguishing characteristics, the extinguishing experiments of a methane-air diffusion flame have been performed by using a pure water droplet with the diameter of 3.2 mm. The droplet dropped from the height of 400 mm. The wall superheat and the burner height were varied from 0 K to 330 K and from 32 mm to 102 mm, respectively. As a result, under certain wall-heat conditions, the water-vapor vortex ring is formed and visualized by the white water fog. At wall superheat of 150 K, the formation probability of the vortex ring is unity and the extinguishing probability always shows the peak values regardless of the burner height. As a result, it can be said in our study that the wall superheat of 150 K is the most effective value for the indirect extinguishing method.

1. Introduction

A water is an effective extinguishing agent because its thermal properties are suitable for removing heat from flames and burning materials [1,2]. Moreover, the water vapor produced by the heat absorption from fire source affects the combustion reaction as a physically acting inert gas and also contributes to flame extinguishment by diluting the oxygen and fuel concentrations and extracting the heat from the flame zone. However, when liquid water is discharged to fire source in the form of a high-velocity solid jet, most of the water runs off from the fire area and it causes water damage. On the other hand, fine droplets of water with diameters less than several hundred micrometers, so-called water mist, indicate a high extinguishing effectiveness to compartment fires and can avoid the water damage because they have a high surface area-to-volume ratio which enhances the evaporation rate at the flame zone [1,2]. However, it is difficult to deliver fine droplets to the targeted fire area because the droplet mass is very small and they are easily blown away by the natural convective flow due to fires [2]. Conversely, when the droplet mass is increased to overcome the fire plume, it is easier to transport the water droplet to the targeted location in the fire because of its higher momentum but more difficult to evaporate rapidly it in the combustion reaction zone. If there is a way to make the large water droplets with diameters more than several millimeters evaporate instantaneously and effectively, it may be possible to deliver the water droplets to the targeted fire area over longer distance and to reduce the water damage. In the confined fire space, there are high-temperature solid surfaces such as wall, ceiling and floor heated by flames and fire plumes and pyrolysis region of the flammable materials. When the large water droplet is impinged onto the high temperature solid surface in the burning area, it can be expected that the water droplet 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. In addition, a lot of studies on evaporation of the water droplet impacting on the heated wall have been performed [3–6].

Base on the above consideration, we have investigated an extinguishing method with water vapor caused by impacting large water droplets onto the headed solid surface, which is called as indirect fire attack method. In order to clarify the fundamental extinguishing characteristics, the extinguishing experiments with a burner flame have been performed. We have observed the evaporation process of the water droplet on the heated plate and the behavior of the produced water vapor with a high-speed camera. Moreover, the extinguishing probability has been measured by varying the surface temperature.

2. Experimental setup and method

Fig. 1 shows the experimental setup. To simulate the heated floor in the fire area or the pyrolysis region of flammable solids, an electric plate heater (Autonics, HP-1SA) was used. The plate (180 mm long,

* Corresponding author.
E-mail address: torikai@hirosaki-u.ac.jp (H. Torikai).

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Nomenclature

T_s	plate temperature (K)
T_b	boiling point (K)
ΔT	wall superheat (K)
P_v	formation probability of vortex ring (–)
P_e	extinguishing probability (–)
z_b	burner height (mm)

180 mm wide and 20 mm thick) was made of the die-casting aluminum with ceramic coating. The surface roughness of the plane is less than 1.1 μm in arithmetic average roughness. The surface temperature, T_s, was varied from 373 K to 703 K. The *z*-axis was arranged vertically on the heated plate. A single water droplet was formed at the tip of a metal tube of the outer diameter 0.8 mm and dropped. The droplet diameter was about 3.2 mm. The water temperature was approximately 291 K. The dropping height of the droplet was set at 400 mm. The impact velocity of the water droplet to the heated plate was 1.17 m/s and the Weber number was 303. Wall superheat temperature, ΔT, was defined as the difference between the plate temperature, T_s, and the boiling point of water, T_b, that is, 373 K under atmospheric condition.

A methane-air diffusion flame was formed with the horizontally opposed tube burner. The tubes were made of stainless steel and its outer and inner diameters were 3 mm and 2.6 mm, respectively. The distance between the burner exits was 10 mm. The volumetric flow rate of methane was 0.23 l/min. The flame was established as shown in Fig. 1, and the flame height was about 40 mm. The distance from the burner to the heated plate surface was expressed as z_b. Although the combustion situation of our targeting flame is unrealistic in practical confined fires, it is possible to elucidate the extinguishing effectiveness of water vapor produced from a single water droplet impacting onto heated plate by using this kind of a small flame like a cup-burner method which clarifies an extinguishing effectiveness of gaseous extinguishing agent. To understand a boiling regime of the heated plate, lifetime of the water droplet were measured. In this experiment, the water droplet was dropped freely from the height of 20 mm. The experiments were repeated at least three times in each condition. The results are shown in Fig. 2. From the graph, the profile of the lifetime showed basically the same trend as the previous study [3]. The nucleate boiling regime is $\Delta T \leqq 120$ K, the transition boiling regime, 120 K $< \Delta T <$ 240 K and the film boiling regime, $\Delta T \geqq 240$ K. The impacting dynamics and the boiling behavior of the water droplet impacting on heated plate were observed by using a high-speed camera (NAC, Memrecam GX-8, exposure time: 1/10,000 s and frame rate: 10,000 fps). A metal halide lamp (Photron, HVC-UL) was used. The images were recorded from the position of the camera A as shown in Fig. 1.

In this study, it was observed that under certain conditions, a water-vapor vortex ring was driven by the volume expansion of water due to phase change from liquid to vapor and it was visualized as shown in Fig. 3 because the excess water vapor was condensed into the white fog in the surrounding air. The formation of the water-vapor vortex ring can be considered to indicate the production of a large amount of water vapor in short duration and in the early stage of the droplet impact onto the heated plate. Generally, a vortex ring travels straight in the still surrounding fluid and over longer distance than a several times of the vortex-ring diameter until decay [7]. Moreover, a vortex ring can trap fine particles inside it and entrain them [7–9]. Therefore, by using the water-vapor vortex ring in our experiment, it may be possible to carry the water vapor and the condensed water particles over a longer distance.

The formation probability of the water-vapor vortex ring was measured. The water vapor is invisible but the water fog formed by condensation of the water vapor due to cooling is visible. Therefore, in this study, the motion of the visible water fog was considered to be almost same as the water vapor behavior. The images of the water fog were recorded with the camera B (Casio, EX-F1, the exposure time: 1/2000 s, frame rate: 300 fps) as shown in Fig. 1. When the water-vapor vortex ring traveled upward over the height of 60 mm from the hot plate surface, we recorded it as the success of the vortex ring formation. The probability of the vortex ring formation, P_v, was computed as the ratio of the number of success cases to the number of total experiments of 10.

The extinguishing experiments were performed. The water droplet always dropped freely onto the heated plate. Before the water droplet impacted on the heated plate, it passed through the space between the opposed tube burners. The flame was never extinguished by the droplet passing. The produced water vapor was always supplied from under the flame. We checked visually whether the flame was extinguished or not. When the flame was extinguished perfectly, we recorded it as successful extinguishment. The probability of the extinguishment, P_b, was calculated as the ratio of the number of successful extinguishments to the number of total experiments of 20. The extinguishment experiments were performed at least over three times. The burner height, z_b, was varied from 32 mm to 102 mm. The extinguishing process was recorded from the position of the camera B (Casio, EX-F1, exposure time: 1/640 s, frame rate: 300 fps).

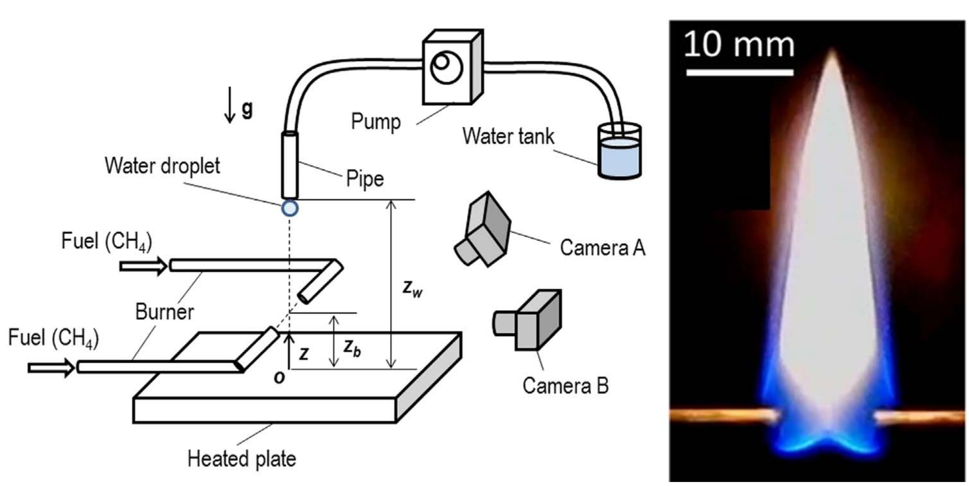

Fig. 1. Experimental setup.