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Extinction condition of counterflow spray diffusion flame with polydisperse water spray

Mega Nur Sasongko [a,*], Takehiko Seo [b], Masato Mikami [b]

[a] Department of Mechanical Engineering, University of Brawijaya, Veteran Street, Malang, East Java 65145, Indonesia
[b] Department of Mechanical Engineering, Yamaguchi University, Ube, Yamaguchi 755-8611, Japan

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ABSTRACT

The effect of polydisperse water droplet size distribution on the burning behavior and extinction condition of counterflow spray diffusion flame was investigated experimentally in this study. N-heptane as liquid fuel spray and nitrogen as a carrier gas were introduced from the lower duct while water spray and oxidizer consisting of oxygen and nitrogen was issued from the upper duct. The burning behavior of spray flame for different fuel droplet size with and without water spray was observed and the extinction condition of counterflow spray diffusion flame was characterized by oxygen concentration at extinction. The results show that the minimum value of oxygen concentration at extinction for counterflow spray diffusion flame with water spray is similar to the extinction condition without water spray for higher mean droplet diameter of water. The minimum value of oxygen concentration at extinction shifts to the smaller fuel droplet size when decreasing the water droplet size. For fuel droplet size higher than 48 µm, the optimum of water droplet size for suppressing counterflow spray diffusion flame was smaller than gaseous flame. The explanation of optimum water droplet size based on the coupled effect of Stokes number and vaporization Damköhler number can be used for prediction of the effectiveness of water droplet on the suppression of counterflow spray diffusion flame.

1. Introduction

Since the ban on production of Halon 1301 under the Montreal protocol amendment due to an adverse effect on the depletion of ozone layer, there has been a huge interest in the use of fine water spray as a promising replacement fire suppression agent for Halon. Water mist or fine spray with droplet diameter less than 1000 µm is understood to be more effective than large droplets that are commonly produced by a conventional water sprinkler. It is because a large surface area to volume ratio of small droplet results in rapid evaporation and faster cooling of the fires. Therefore, it can extinguish the fire quickly with small amount of water and without further damage to the protection object or environment.

A comprehensive review by Grant et al. [1] and Liu et al. [2] provides a great overview of the progress research works in fire suppression by water spray. These researches introduces the mechanism of water droplet suppresses fire as well as the concept of optimum water droplet size. In the literature, there is a series of investigation related to the optimum droplet size in order to optimize the effectiveness of water mist on fire suppression [3–8]. Utilizing counterflow flame configuration as a convenient laboratory design, the optimum of fine water droplet was deeply analyzed and determined related to the contributing of various mechanism of water droplet for extinguishing fire, the behavior of water droplet in the counterflow field and also the detail interaction between the water droplet and flame. As a result, some researchers showed that monodisperse small droplet size has a great capability for fire suppression [4,5]. It was also proved that it was more effective than Halon 1301.

In practice, however, single size droplet distributions in monodisperse spray are uncommon and hard to be generated associated with droplet generator requirement. Whereas, most sprays in the practical applications are polydisperse spray which consists of a wide range of droplet size distribution. Therefore, the effectiveness of polydisperse water spray for suppression fire should be investigated in the view of a practical approach. Mathematical analysis by Dvorjetski et al. [9] concerned the influence of polydisperse water spray on the extinction of counterflow diffusion flame. Since the difficulty to presenting an actual polydisperse droplet size distribution using numerical method, the mean droplet diameters such as d_{20} and d_{32} were employed as a representative of droplet size distribution. Further analysis [10] showed that with applying the slip effect between water droplet and gas flow field, the extinction of counterflow diffusion flame

* Corresponding author.
E-mail address: megasasongko@ub.ac.id (M.N. Sasongko).

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could be controlled by two competing mechanisms such as the droplet evaporation rate and droplet dynamics in the counterflow field. Our recent study [11] experimentally investigated the effect of polydisperse water spray on the extinction of counterflow methane diffusion flame. The experimental result showed that the optimum water droplet size existed in the area where the droplets have a large penetration to the stagnation flame and short time vaporization. This optimum condition can be determined based on the coupled effect of the droplet mechanism in the vicinity of counterflow field such as Stokes number effect and vaporization Damköhler number effect.

A review on the recent application of water mist in fire suppression [12] reported that water mist was also effective for extinguishing the spray fires hazard. Water mists have been tested for machinery space, turbine enclosure or pump room where the spray fires commonly occur due to the leaking of piping fuel or lubricant with high pressure in the system [13]. Since the counterflow configuration has been employed for fundamental study of spray combustion research, we attempt to extend our experiment technique to look into the effectiveness of polydisperse fine water spray on the extinguishing the counterflow liquid-spray diffusion flame. This research presents experimentally the effect of polydisperse water spray on the oxygen concentration at extinction of counterflow spray diffusion flame.

2. Experimental apparatus and procedure

Fig. 1 represents the schematic of a counterflow spray diffusion flame experiment with water spray. The main design of the counterflow burner is similar to that adopted in previous researches by Mikami et al. [14] and Sasongko et al. [11]. The counterflow burner consists of two main concentric double cylinders that have the same construction. The ducts were placed coaxially one above the other with a certain separation distance. Both of the inner ducts had an inner diameter of 23 mm with 1 mm thickness and a length of 700 mm. The inner diameter, thickness, and length of the outer cylinder were 40 mm, 1.2 mm and 300 mm, respectively. Experiments were performed with n-heptane spray as a liquid fuel spray and nitrogen as a carrier gas introduced from the lower inner duct while water spray and oxidizer consisting of oxygen and nitrogen was issued from the upper inner duct. In conformity, co-flows of nitrogen stream were supplied from both outer ducts to suppress the shear between the gas from the inner duct and the ambient gas and to maintain a stable counterflow diffusion flame. Fuel droplets from the lower duct were produced by a twin fluid atomizer (1/8 type, Spraying Systems Co. Ltd.) located at the base of the bottom lower duct. The atomizer was covered by an acrylic cylinder of 100 mm in radius and 100 mm in length. Since some of droplet impinged to the inner wall of the lower duct and went back to the bottom of the lower duct, a drain tank was installed to discharge the accumulated fuel. The total flow rate of liquid fuel injected to the stagnation area was gained by measuring carefully the difference in the amount of supplied fuel from the fuel tank and drain at a certain time. In the other side, the same type of atomizer was used to supply the water spray from the upper duct. In order to prevent water droplets from impinging to the duct inner wall and flowing downwardly through the wall, the atomizer was placed 280 mm above the inlet of upper duct. This distance was sufficient to make a spray loss in momentum and flow downward gravitationally. This water atomizer also covered by an acrylic cylinder of 100 mm in radius and 300 mm in length. Because some droplets did not enter the inlet of upper duct, the wasted droplets were collected in this cylinder and drained from it. The flow rates of liquid fuel, water, oxygen and nitrogen were controlled individually by rotameters (Kofloc, R1250).

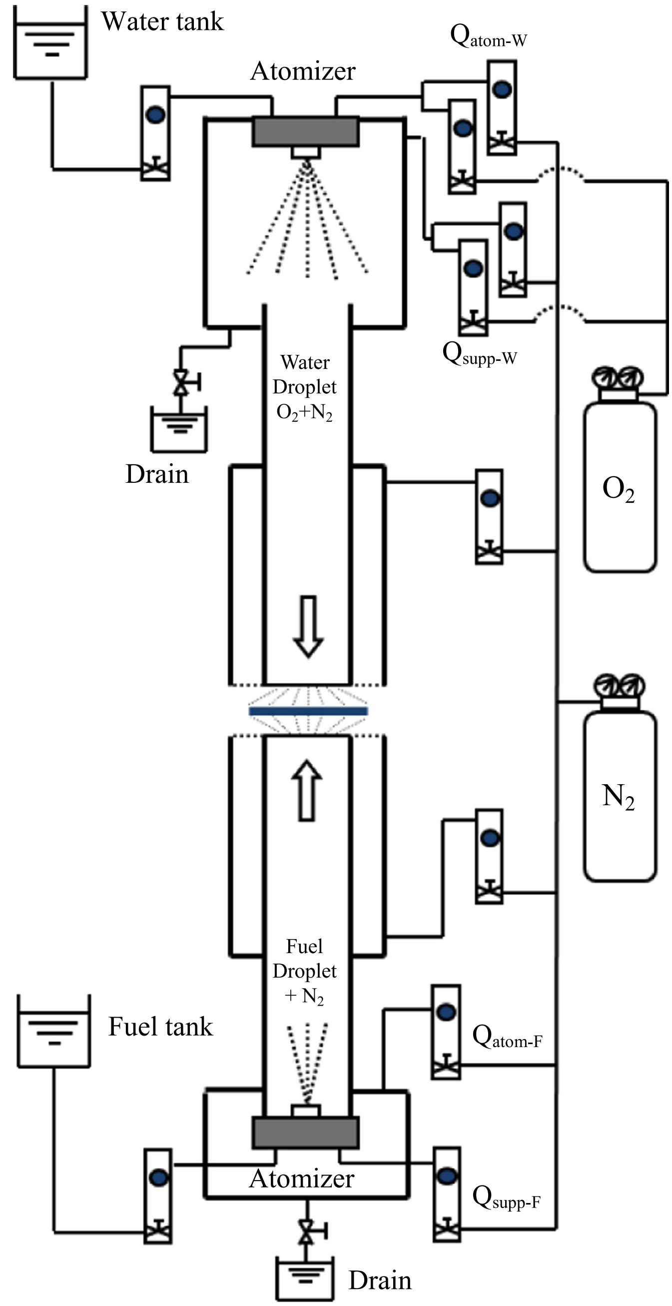

Fig. 1. Experimental apparatus.

The carrier gases of each spray supplied to the corresponding atomizer were divided into two routes. One was directly supplied to the atomizer as an atomization gas and the other was supplied through the acrylic cylinder as a supplementary gas. The droplet size distribution was varied by varying the atomizing gas flow rate supplied directly to the atomizer. Atomizing gas flow rate for liquid fuel (Q_{atom-F}) was varied from 3 L/min to 6.5 L/min with 0.5 L/min increments while atomizing gas flow rate for water (Q_{atom-W}) was varied at five different values of 3.5, 4, 4.5, 5 and 6 L/min. Fuel and water mass fraction in each spray jet were kept constant at 0.1 and 0.015, respectively. The total flow rate of carrier gases of each spray from both the lower and upper duct was kept constant at 15 L/min by adjusting the flow rate of each supplementary gas. The separation distance between both ducts were set to 10 mm so that the strain rate of counterflow in this experiment was 240 s^{-1}.