Effects of Discharge Area and Atomizing Gas Type in Full Cone Twin-Fluid Atomizer on Extinguishing Performance of Heptane Pool Fire under Two Heat Release Rate Conditions in an Enclosed Chamber

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Abstract: In this study, the effects of discharge area and atomizing gas type in a twin-fluid atomizer on heptane pool fire-extinguishing performance were investigated under the heat release rate conditions of 1.17 and 5.23 kW in an enclosed chamber. Large and small full cone twin-fluid atomizers were prepared. Nitrogen and air were used as atomizing gases. With respect to the droplet size of water mist, as the water and air flow rates decreased and increased, respectively, the Sauter mean diameter (SMD) of the water mist decreased. The SMD of large and small atomizers were in the range of approximately 12–60 and 12–49 µm, respectively. With respect to the discharge area effect, the small atomizer exhibited a shorter extinguishing time, lower peak surface temperature, and higher minimum oxygen concentration than the large atomizer. Furthermore, it was observed that the effect of the discharge area on fire-extinguishing performance is dominant under certain flow rate conditions. With respect to the atomizing gas type effect, nitrogen and air appeared to exhibit nearly similar extinguishing times, peak surface temperatures, and minimum oxygen concentrations under most flow rate conditions. Based on the present and previous studies, it was revealed that the effect of atomizing gas type on fire-extinguishing performance is dependent on the relative positions of the discharged flow and fire source.

Keywords: twin-fluid atomizer; discharge area; atomizing gas type; water mist; heptane pool fire; fire-extinguishing performance

1. Introduction

The water mist fire suppression system exhibits a variety of merits. It is an economical and eco-friendly system owing to the use of water as a fire-extinguishing agent and it can be applied to various fire-fighting properties. It has been reported that for certain applications it can extinguish fires with lesser amount of water and lower water damage when compared with those of other water-based fire suppression systems (e.g., sprinkler systems) [1]. Owing to these merits, water mist fire suppression systems have been highlighted and developed. The fire suppression mechanisms of water mist are complex and typically involve heat extraction, oxygen depletion and displacement, radiation heat
attenuation, and fuel-oxygen mixture dilution [1,2]. Additionally, when the water mist and atomizing gas are discharged into the fire, they can affect the chemical reaction kinetics, molecular transport, heat and mass transfer, and flow field (e.g., [3,4]). These coupled phenomena can be involved in the fire phenomena and extinguishing performance.

The spray characteristics of water mist are closely related to the performance of the water mist fire suppression system. In this view, the atomizer in the water mist fire suppression system is a critical component to generate a controlled and desired water mist for improving its fire suppression performance. Investigations on fire suppression via water mist have been performed extensively (e.g., [5–17]). Additionally, research on water mist fire suppression has been summarized thoroughly and reported in the literature [1,18–22]. Based on previous studies [1,5–22], investigations on water mist fire suppression using single-fluid atomizers have been performed actively. The single-fluid atomizer generates water mist via an atomization process, in which the liquid is discharged through the small orifice with relatively high velocity and pressure [23]. However, studies on water mist fire suppression using twin-fluid atomizers have been more limited. The twin-fluid atomizer produces water mist via the atomization process, in which the low-velocity liquid is finely broken by a relatively high-velocity atomizing gas [23]. When compared with water mist fire suppression systems using single-fluid atomizers, those using twin-fluid atomizers are potentially more complex because of the additional supply system of atomizing gas [1,20,22]. However, the water mist fire suppression systems of the twin-fluid atomizers can reduce the operating pressure of the overall system and produce a smaller water mist than those of single-fluid atomizers [1,20,22]. In the previous study [20], it was reported that the single-fluid atomizers can generate the droplets as small as 90–100 µm at the pressure conditions of approximately 5–6 bar, but to produce the tinier droplets (e.g., down to approximately 30 µm), the twin-fluid atomizers are required. Additionally, as the twin-fluid atomizer discharges the atomizing gas along with the water mist for fire suppression, the atomizing gas can significantly affect the enhancement of fire suppression performance. In other words, if the inert gas is used as the atomizing media, it can contribute to improving the fire suppression performance at the certain conditions. Hence, extensive experiments on fire suppression performance of water mist using twin-fluid atomizers should be conducted.

A few investigations on water mist fire suppression systems using twin-fluid atomizers have been performed and reported. Liu et al. [24] reported that the fire suppression performance of water mist is influenced by the fire and ventilation conditions in the compartment and types of the water mist fire suppression systems (i.e., single-fluid and twin-fluid water mist fire suppression systems). Additionally, water mist fire suppression is more effective under natural ventilation conditions than under forced ventilation conditions. Liu et al. [25] examined the effect of continuous and cycling discharge modes of water mist on fire-extinguishing performance. The cycling discharge mode of the water mist leads to a shorter extinguishing time and lower water requirements when compared to its continuous mode. Furthermore, Liu et al. [25] reported that the enhancement of fire-extinguishing performance is due to the increased depletion and dilution rate of oxygen and the recurrent dynamic mixing. Lal et al. [26] conducted n-heptane pool fire suppression of water mist at different heat release rates (HRRs) in a large enclosure. They reported that the fire suppression of water mist was attributed to the evaporation cooling of fine water droplets and the oxygen displacement by water vapor. Additionally, the fire-extinguishing time decreased with a decrease in droplet size, and the total amount of water mist required for fire suppression decreased with an increase in fire size. Gupta et al. [27] conducted pool fire suppression experiments of water mist using a pair of twin-fluid atomizers to examine the effects of nitrogen pressure and fire source location. They measured and reported the characteristics of water mist (e.g., droplet diameter and velocity) and variations in temporal temperature and gas concentration. Jeong and Lee [28] conducted fire-extinguishing experiments using water mist discharged from a twin-fluid nozzle. They measured and analyzed various spray characteristics and heptane pool fire suppression performances.
of a twin-fluid nozzle. Then, their experimental data were compared and discussed in
detail with those reported in a previous study wherein a single-fluid nozzle was used.
Gupta et al. [29] investigated the effects of discharge mode, fire size, pre-burn period, and
atomizing fluid type on fire suppression characteristics by using a twin-fluid water mist
fire suppression system. They measured the fire-extinguishing time, water consumption
quantity for fire suppression, and temperature variation with respect to time. Based on the
experimental results, a fire suppression performance index was developed and discussed.
The experimental results indicated that the use of nitrogen, as the atomizing gas for water
mist, led to a shorter fire suppression time by approximately 30–50% when compared to
that of air. However, in a previous study by Gupta et al. [29], the water mist was not directly
discharged and penetrated the pool fire. The effect of atomizing gas type during discharge
of the water mist is potentially dependent on the discharged flow direction relative to the
fire source position. However, based on previous studies on twin-fluid atomizers [24–29],
there are limited studies that perform experiments to examine the effects of the discharge
area and atomizing gas type of the twin-fluid atomizer which can significantly affect the
fire-extinguishing performance. Hence, investigations should be intensively conducted
to better understand the detailed fire suppression mechanism of water mist and improve
further the performance of water mist fire suppression systems via adoption of twin-fluid
atomizers. Additionally, to utilize the water mist fire suppression systems in a wider range
of industrial fields, further research on fire suppression using water mist is required.

In the present experimental study, the effects of the discharge area and atomizing
gas type in a twin-fluid atomizer on heptane pool fire-extinguishing performance were
examined in an enclosed chamber. Two full cone twin-fluid atomizers of different sizes
were prepared. Nitrogen and air were used as atomizing gases. The Sauter mean diameter
(SMD) of the water mist generated from both twin-fluid atomizers was measured and
compared. A series of fire-extinguishing experiments were conducted under two different
heat release rate conditions to analyze the effects of the discharge area and atomizing gas
type on the fire-extinguishing times, peak surface temperatures, and minimum oxygen
concentrations in detail.

2. Experimental Details
2.1. Experimental Setup for Fire Extinguishment

Figure 1 shows the schematic diagrams of the experimental setup and measurement
locations for fire extinguishment. As shown in Figure 1a, the experimental setup was mainly
comprised of a twin-fluid atomizer, fire source, water pump, water tank, nitrogen tank, air
compressor, mass flow controller (MFC), gas analyzer, and data acquisition system. The
fire-extinguishing experiments were performed in an enclosed chamber with dimensions
of 1 m × 1 m × 1 m. To construct the frame of enclosed chamber, the aluminum profile was
used. The upper and bottom walls of enclosed chamber were made of aluminum plates,
and its side walls were made of transparent polycarbonate plates. The enclosed chamber
was placed at the height of 0.58 m from the floor. A full cone twin-fluid atomizer was
installed at the center of the ceiling. The fire source of the n-heptane pool was placed at the
center of the bottom in the enclosed chamber, where it was vertically below the full cone
twin-fluid atomizer. Hence, under these conditions, the water mist and atomizing gas were
directly discharged into the fire source. Furthermore, deionized water was used. Water
was supplied to the twin-fluid atomizer via water pump (micro gear pump or rotary piston
pump) from the water tank. The water flow rates were obtained by measuring the change
in the weight of the water tank, using an electronic balance, for a time interval of 1 min.
Nitrogen and air were used as the atomizing gases to examine the effect of atomizing gas
type on the fire-extinguishing phenomena. Nitrogen and air were supplied to the twin-fluid
atomizer from the nitrogen tank and air compressor, respectively. To control their flow
rates, an MFC was utilized. To measure the variation in oxygen concentration with time,
a gas analyzer with the paramagnetic oxygen cell was used. As shown in Figure 1b, the
gas sampling was performed via its probe at a height of 265 mm from the bottom of the
enclosed chamber and 100 mm away from the fuel source center. Additionally, to measure the temporal variation in temperature near the fuel surface, initially, K-type thermocouple of 1.5875 mm (1/16 inch) in sheath diameter was placed under the surface of liquid fuel pool within approximately 1.6 mm in depth. The temporal variations in gas concentration and fuel surface temperature were monitored and stored, using a data acquisition system and a laptop computer, at a sampling rate of 1 Hz. In addition, to record the videos of experiments, the digital camera was used.

![Figure 1. Schematic diagrams of experimental setup and measurement locations for fire extinguishment: (a) experimental setup and (b) measurement locations.](image)

The droplet size of water mist in the twin-fluid atomizer is a critical factor that significantly influences the fire-extinguishing performance. Before the fire-extinguishing experiments, the SMD of the water mist was measured utilizing the Malvern-type droplet measurement system. The measurements were conducted at 200 mm vertically below the exit of the twin-fluid atomizer under no fire conditions.

### 2.2. Full Cone Twin-Fluid Atomizer

In the present experimental study, two full cone twin-fluid atomizers of different sizes (Spraying Systems Co., Illinois, United States of America), namely large and small atomizers, were prepared to examine the effect of the discharge area in the twin-fluid atomizer on the fire-extinguishing performance. Figure 2 shows schematic diagrams of both the twin-fluid atomizers with their dimensions. Typically, large and small atomizers are comprised of a liquid discharge hole at the center and a gas discharge annular gap around the liquid discharge hole. The large and small atomizers were identical except for the center hole size for discharge of water and annular gap size for discharge of atomizing gas. The discharge areas (e.g., center hole and annular gap areas in Figure 2b) of atomizer have a great impact on the characteristics of water mist and discharged flow, which can affect the fire-extinguishing performance and mechanism. The discharge areas of center
hole and annular gap for large atomizer were 1.824 and 2.230 mm², and those for small atomizer were 0.203 and 0.809 mm², respectively. The spray angles of large and small atomizers were similar and corresponded to approximately 17–19° and 18–19°, respectively, as per the specifications.

Figure 2. Schematic diagrams of twin-fluid atomizers: (a) side view and (b) bottom view.

The flow rate conditions of large and small atomizers are summarized in Table 1. To investigate the discharge area effect, water and nitrogen were used as the liquid and gas, respectively, in large and small atomizers. The flow rates of water and nitrogen for both atomizers were determined, considering whether the water mist was successfully generated or not. For example, under high water flow rate and low gas flow rate conditions, water mist was not generated. To examine the effect of atomizing gas, nitrogen and air were used in the small atomizer.

Table 1. Flow rate conditions of large and small atomizers for fire extinguishment.

| Twin-Fluid Atomizer | Large Atomizer | Small Atomizer |
|---------------------|----------------|----------------|
| Water Flow Rate (g/min) | 0, 40, 85, 160, 240 | 0, 40, 85, 160 |
| Nitrogen Flow Rate (L/min) | 20, 30, 40, 60 | 10, 20, 30 |
| Air Flow Rate (L/min) | — | 10, 20, 30 |

2.3. Heptane Pool Fire Source

In Table 2, the fire sources are summarized. As the fuel, n-heptane was prepared. As the fuel pan, stainless steel round pans of 80 and 120 mm in diameters were used to control the HRR conditions. The HRR (\(\dot{Q}\)) was estimated by Equation (1).

\[
\dot{Q} = \dot{m} \chi \Delta H_c
\]  

(1)

Here, \(\dot{m}\), \(\chi\), and \(\Delta H_c\) are the mass loss rate, combustion efficiency, and complete heat of combustion, respectively. To measure the mass loss rates of both fuel pans, the fuel weights of 100 mL and their burning times were measured using the electronic balance and stopwatch, respectively. The combustion efficiency was assumed to be 0.92 based on the previous study [30]. The complete heat of combustion for n-heptane was used to be 44.56 MJ/kg [2]. The HRR conditions for fuel pan diameters of 80 and 120 mm were measured to be 1.17 and 5.23 kW, respectively.
Table 2. Summary of fire sources.

| Fuel       | n-Heptane |
|------------|-----------|
| Fuel Volume (mL) | 100       |
| Fuel Pan Diameter (mm) | 80, 120   |
| Fuel Pan Height (mm) | 45, 65    |
| Fuel Pool Depth (mm) | 20, 9     |
| Mass Loss Rate (g/s) | 0.0285, 0.1276 |
| Heat Release Rate (kW) | 1.17, 5.23 |

2.4. Experimental Procedure for Fire Extinguishment

The fire suppression experiments were performed as follows. The heptane pool of 100 mL was prepared in the certain fuel pan and ignited using the long refillable household gas lighter with small flame. Once the long refillable household gas lighter was turned on near the fuel surface, the heptane pool was ignited immediately. For stabilization, the heptane pool was burned for 30 s before activating the twin-fluid atomizer. Next, the water and gas were supplied to the twin-fluid atomizer at their desired flow rate conditions, respectively, and the water mist was then discharged to the fire source. In the only gas discharge conditions, the nitrogen or air was discharged to the fire source without supplying water to the twin-fluid atomizer. The fire extinguishment was considered as the moment when the visible flame disappeared. The fire-extinguishing time was measured by stopwatch, and then checked again using the video recorded by a camera. In the closed chamber, the fire is extinguished by various causes. One of various causes for fire extinguishment in the closed chamber is the exhaustion of fuel. It is noted that in all cases of present experiments, the heptane remained. In other words, the fire extinguishment by the exhaustion of fuel did not occur. After completing the fire-extinguishing experiments, the enclosed chamber was sufficiently ventilated as follows. The chamber has the round opening of 400 mm in diameter at the ceiling, as shown in Figure 1a. During the fire-extinguishing experiment, the round opening was closed by the cover to make the enclosed condition of chamber. After completing the fire-extinguishing experiment, the round opening was opened, and the exhaust hood, linked to the mechanical ventilator through the flexible round duct, was connected to the round opening. Next, the mechanical ventilator was turned on, and the chamber was sufficiently ventilated. In other words, the round opening at the ceiling of chamber was only opened during ventilating the chamber. On the contrary, during the fire-extinguishing experiment, it was closed, and the mechanical ventilator was turned off.

Before the fire-extinguishing experiment, the initial temperature in the laboratory, where the enclosed chamber is located, was controlled to be a certain temperature condition by heating, ventilation, and air conditioning (HVAC) system. The initial conditions of temperature and oxygen concentration in the enclosed chamber were measured for each experiment, which were 20 °C and 21 vol%, respectively. Fire-extinguishing experiments were performed twice under each condition. To examine the fire-extinguishing performance and mechanism of water mist and atomizing gas, the thermocouple and gas analyzer were used to measure the temperature near the fuel surface and oxygen concentration at a certain location, respectively. These measurement parameters are closely related to the fuel surface cooling, and oxygen depletion and displacement for the fire extinguishment, respectively. In addition, in this study, the fire-extinguishing experiments under the only gas discharge and the water mist discharge conditions were performed. Under the only gas discharge conditions without water mist, the effects of atomizing gas type on the fire-extinguishing performance can be clearly observed owing to no water mist effect on fire extinguishment. Moreover, under the water mist discharge conditions, the fire-extinguishing experiments were performed using nitrogen and air. Through the comparison of experimental data
under the only gas discharge and water mist discharge conditions, the effects of atomizing gas type on fire-extinguishing performance and mechanism were examined carefully.

3. Results and Discussion

3.1. Droplet Size of Water Mist in Twin-Fluid Atomizer

In Figure 3, the SMD of water mist sprayed from the twin-fluid atomizers is shown under varying water and air flow rate conditions. Measurements of droplet size were conducted three times under each condition. It is noted that in all the figures showing the experimental data, the average values of repeated tests are presented, and the error bars indicate their standard deviations. With respect to both twin-fluid atomizers, a decrease in water flow rate and increase in air flow rate led to a decrease in the droplet size of the water mist. Under the present experimental conditions, the SMD of large and small atomizers were in the range of approximately 12–60 and 12–49 μm, respectively. Under the same air flow rate conditions (i.e., 20 and 30 L/min), the SMD of large atomizer was larger than that of small atomizer because the discharge velocities of atomizing gas in large atomizer were reduced and the energy required to atomize the liquid decreased owing to its large annular gap area.

![Figure 3](image-url)  
**Figure 3.** Droplet size of twin-fluid atomizers: (a) large atomizer and (b) small atomizer.

3.2. Influence of Discharge Area

3.2.1. Extinguishing Time

In Figure 4, the extinguishing times of large and small atomizers under different HRR conditions are shown. The fire-extinguishing time was estimated using the interval between the timing of the water mist discharge (or only gas discharge) and fire extinguishment.

![Figure 4](image-url)  
**Figure 4.** Extinguishing time for large and small atomizers under different HRR conditions (note that the scales of y-axis in both figures are different): (a) large atomizer and (b) small atomizer.
As shown in Figure 4a, at the only nitrogen discharge condition (i.e., water flow rate = 0 g/min), as nitrogen flow rates increase, the extinguishing times decrease. This may be due to the fact that the high-velocity nitrogen flows contribute to cooling the flame and fuel surface and preventing the retention of fuel vapor in the reaction region. The extinguishing times for a higher HRR of 5.23 kW were shorter than those for a lower HRR of 1.17 kW, in particular, at the low nitrogen flow rate condition. A reason for this is that a fire with a higher HRR consumes the oxygen more quickly in the enclosed chamber and is extinguished within a shorter time when compared with a lower HRR. However, the difference in extinguishing times between two HRR cases decreased with increases in the nitrogen flow rates. This implies that the effect of the discharged nitrogen flow rate on the extinguishing time became predominant.

Under the water mist discharge conditions in Figure 4a, the extinguishing times gradually decreased up to a water flow rate of 85 g/min for all nitrogen flow rate conditions. However, with respect to the water flow rate conditions of 160 and 240 g/min, an increase in the water flow rate led to a slight increase in the extinguishing time at the low nitrogen flow rate condition (e.g., 20 L/min). This may be due to the decreased extinguishing performance caused by the increased droplet size of the water mist. The larger water droplet can penetrate into the fire and reach the fuel pool. In such a case, in the reaction region of fire, the effects of water mist (e.g., chemical reaction and heat and mass transfer caused by the fine water droplets) can be reduced. With increasing the water flow rate under the constant nitrogen flow rate condition, the droplet size of water mist becomes larger, and the impact of water mist in reaction region becomes smaller. This is one possible reason that under the low nitrogen flow rate condition, the extinguishing time increases with increasing water flow rates. This result implies that there are optimal flow rate and droplet size conditions for maximizing the fire-extinguishing performance of the water mist. Under low nitrogen flow rate conditions (e.g., 20 L/min), the extinguishing time was sensitively affected by the water flow rate. Conversely, at the high nitrogen flow rate condition (e.g., 60 L/min), the extinguishing time remained almost constant and was nearly independent of the water flow rates. Additionally, the differences in extinguishing times between two HRR cases under water mist discharge conditions became smaller than those under the only nitrogen discharge conditions. In other words, under the water mist discharge conditions, the extinguishing times for an HRR of 5.23 kW were quite similar to those for an HRR of 1.17 kW.

These general trends of large atomizer are observed as nearly similar to those of small atomizer, as shown in Figure 4b. The higher HRR case exhibited shorter extinguishing times than the lower HRR case in certain flow rate conditions. Additionally, as the nitrogen and water flow rates increased, the extinguishing time decreased.

3.2.2. Peak Surface Temperature

In Figure 5, the peak surface temperatures of large and small atomizers under different HRR conditions are shown. The peak surface temperature indicates the maximum temperature value in the temporal temperature variation measured near the fuel surface. Overall, the peak surface temperatures of HRR at 5.23 kW were higher than those of HRR at 1.17 kW under the only nitrogen discharge and water mist discharge conditions. At the only nitrogen discharge conditions, the increases in nitrogen flow rates reduced the peak surface temperatures. The differences between two HRR conditions appeared to increase with increases in nitrogen flow rates.
With respect to the large atomizer, as shown in Figure 5a, under the water mist discharge conditions, the increases in the nitrogen flow rates led to decreases in the peak surface temperatures. At the given nitrogen flow rate condition, as the water flow rate increased up to a water flow rate of 85 g/min, the peak surface temperatures gradually decreased. This implies that the fuel surface was cooled by the discharged water mist. With respect to the water flow rate conditions of 160 and 240 g/min, the peak surface temperatures slightly increased under the low nitrogen flow rate condition (e.g., 20 L/min). This can be due to an increase in the droplet size of water mist. However, under the higher nitrogen flow rate conditions, the peak surface temperatures slightly decreased or remained almost constant with the water flow rate. Additionally, the dependency of peak surface temperature variations on water flow rates became weaker than that under the lower nitrogen flow rate conditions.

In Figure 5b, most of the general trends of the peak surface temperatures for small atomizer are similar to those for large atomizer. The higher HRR case exhibited higher peak surface temperatures than the lower HRR case. The peak surface temperatures decreased with increases in nitrogen and water flow rates.

In Figure 6, the relation between the extinguishing time and peak surface temperature for large and small atomizers, obtained from Figures 4 and 5, is shown. Increases in extinguishing times resulted in increasing the peak surface temperatures. In addition, the higher HRR case exhibited the shorter extinguishing times and higher peak surface temperatures, as compared with lower HRR case.

**Figure 5.** Peak surface temperature for large and small atomizers under different HRR conditions: (a) large atomizer and (b) small atomizer.

**Figure 6.** Extinguishing time vs. peak surface temperature for discharge area effect (note that the scales of x-axis in both figures are different): (a) large atomizer and (b) small atomizer.
3.2.3. Minimum Oxygen Concentration

Figure 7 shows the minimum oxygen concentrations of large and small atomizers under different HRR conditions. The minimum oxygen concentration indicates the minimum value in the curve denoting time variation in oxygen concentration measured by the gas analyzer at a certain sampling point.

As shown in Figure 7a,b, the minimum oxygen concentrations for HRR at 5.23 kW are lower than those for HRR at 1.17 kW. Under most water and nitrogen flow rate conditions, the increases in both flow rates increased the minimum oxygen concentration. Additionally, at the higher nitrogen flow rate condition, the minimum oxygen concentration increased, and the dependency of minimum oxygen concentrations on water flow rates became weaker. However, for large atomizer in Figure 7a, at the low nitrogen flow rate condition (e.g., 20 L/min), the minimum oxygen concentration gradually increased from 0 to 85 g/min of water flow rates. They were then reduced with increases in water flow rates. These trends are also observed for small atomizer at the low nitrogen flow rate condition (e.g., 10 L/min), as shown in Figure 7b. A reason is that under these conditions, the extinguishing time became longer, and more oxygen was consumed.

In Figure 8, the relation between the extinguishing time and minimum oxygen concentration for large and small atomizers, obtained from Figures 4 and 7, is shown. Increases in extinguishing times resulted in decreasing the minimum oxygen concentrations. In addition, the higher HRR case showed the shorter extinguishing times and lower minimum oxygen concentrations, as compared with the lower HRR case.

![Figure 7](image-url)\(a\) Minimum oxygen concentration for large and small atomizers under different HRR conditions: \(a\) large atomizer and \(b\) small atomizer.

![Figure 8](image-url)\(a\) Extinguishing time vs. minimum oxygen concentration for discharge area effect (note that the scales of x-axis in both figures are different): \(a\) large atomizer and \(b\) small atomizer.
Based on Figures 4–8, under the higher nitrogen flow rate conditions, the extinguishing times were shorter, peak surface temperatures were lower, and minimum oxygen concentrations were higher, as compared with the cases under the lower nitrogen flow rate conditions. One of the reasons for these trends is enhanced cooling effect owing to decreased droplet size of water mist and increased velocity of discharged flow. Additionally, the increased nitrogen flow rates and tiny water droplets can be involved in the chemical reactions in the reaction zone. These combined effects caused by the increased nitrogen flow rate are considered to be related to the general trends of those experimental results.

3.2.4. Comparison between Large and Small Atomizers

In Figure 9, the extinguishing time, peak surface temperature, and minimum oxygen concentration for large and small atomizers are compared under the same experimental conditions. The differences in all parameters are defined as “Large atomizer–Small atomizer”. As shown in Figure 9, the differences in the extinguishing times and peak surface temperatures are mostly positive (Figure 9a,b), and the differences in the minimum oxygen concentrations are mostly negative (Figure 9c). This implies that the large atomizer exhibits a longer extinguishing time, higher peak surface temperature, and lower minimum oxygen concentration than the small atomizer. Given that the discharge areas of the small atomizer are smaller than those of the large atomizer, the small atomizer achieves higher velocities of discharged flows than the large atomizer under the same flow rate conditions, and enhances the entrainment. Additionally, the droplet size of the water mist for the small atomizer is smaller than that for the large atomizer, as shown in Figure 3. The high velocity of the discharged flow and small droplet size of the water mist can result in shortening of the extinguishing time, cooling of the flame and fuel surface, and preventing of fuel vapor retention in the reaction region. The early fire-extinguishing time implies that the duration of oxygen consumption in the enclosed chamber is reduced. Hence, the small atomizer showed shorter extinguishing times, lower peak surface temperatures, and higher minimum oxygen concentrations when compared with those of the large atomizer. Meanwhile, in Figure 9, at a water flow rate of 85 g/min, the differences in all measurement parameters between both twin-fluid atomizers are close to zero. This implies that under these conditions, the effect of the discharge area in the twin-fluid atomizer on fire-extinguishing performance is neglected. Based on Figure 9, it was observed that there are certain flow rate conditions in which the effect of the discharge area on the fire-extinguishing performance is dominant.

3.3. Influence of Atomizing Gas Type
3.3.1. Extinguishing Time

In Figure 10, the extinguishing times of nitrogen and air are shown for HRR conditions of 1.17 and 5.23 kW. For the low HRR case in Figure 10a, at the only gas discharge conditions, the extinguishing times shortened with increasing the gas flow rates. Additionally, the extinguishing times of nitrogen were shorter than those of air. Under the water mist discharge conditions, the extinguishing times were shorter and their differences between the nitrogen and air became smaller than those under the only gas discharge conditions. As the water and gas flow rates became smaller, the effects of the atomizing gas type on the extinguishing time appeared to be larger.
Figure 9. Comparison of differences in measurement parameters between large and small atomizers: (a) extinguishing time, (b) peak surface temperature, and (c) minimum oxygen concentration.

Figure 10. Extinguishing time for nitrogen and air (note that the scales of y-axis in both figures are different): (a) HRR = 1.17 kW and (b) HRR = 5.23 kW.

For the high HRR case in Figure 10b, increases in gas and water flow rates led to a shortening of the extinguishing times. Under the low gas flow rate condition (e.g., 10 L/min), the nitrogen appeared to slightly decrease the extinguishing times when compared with those of air. However, with increasing gas flow rate conditions, the differences between the extinguishing times of nitrogen and air decreased.

Based on Figure 10a,b, the high HRR case exhibited shorter extinguishing times than the low HRR case, particularly under low water (including no water) and gas flow rate conditions. This is due to the fact that the high HRR case consumes oxygen more quickly in the enclosed chamber than the low HRR case, which contributes to a reduction in the
extinguishing time. Conversely, under higher water and gas flow rate conditions, the differences in extinguishing times between both HRR conditions became smaller. This implies that the higher flow rates of water and gas became dominant parameters for extinguishing both fires.

3.3.2. Peak Surface Temperature

The peak surface temperatures for the HRR conditions of 1.17 and 5.23 kW are shown in Figure 11a,b, respectively. Overall, the peak surface temperatures for HRR of 5.23 kW were higher than those for HRR of 1.17 kW. For both HRR conditions, increases in water and gas flow rates led to a decrease in peak surface temperatures. One of the reasons for this is the cooling effect of the discharged flows. Under low water and gas flow rate conditions, the effects of the atomizing gas type on the peak surface temperatures appeared to increase. The air case showed slightly higher peak surface temperatures when compared with those of the nitrogen case. This may be due to the fact that the discharged air slightly increases the combustion rate by supplying oxygen to the fire [29]. However, overall, the differences between the peak surface temperatures of nitrogen and air were quite small.

![Figure 11. Peak surface temperature for nitrogen and air: (a) HRR = 1.17 kW and (b) HRR = 5.23 kW.](image)

In Figure 12, the relation between the extinguishing time and peak surface temperature for nitrogen and air, obtained from Figures 10 and 11, is shown. Increases in extinguishing times resulted in increasing the peak surface temperatures, which were similar to Figure 6. However, their relations in the nitrogen case were not much different from those in the air case.

![Figure 12. Extinguishing time vs. peak surface temperature for atomizing gas type effect (note that the scales of x-axis in both figures are different): (a) HRR = 1.17 kW and (b) HRR = 5.23 kW.](image)
3.3.3. Minimum Oxygen Concentration

In Figure 13, the minimum oxygen concentrations for nitrogen and air, as the atomizing gas, are compared. As shown in Figure 13a, the increases in the water and gas flow rates increase the minimum oxygen concentration. However, at a gas flow rate of 10 L/min, the minimum oxygen concentration decreased with an increase in water flow rate from 85 to 160 g/min. This is due to the fact that the water flow rate of 160 g/min is a slightly longer extinguishing time than that of 85 g/min, as shown in Figure 10a. Furthermore, the effect of the atomizing gas type on the minimum oxygen concentration was negligible. The trends for HRR of 5.23 kW are similar to those for HRR of 1.17 kW, as shown in Figure 13b. The minimum oxygen concentrations increased with increases in the water and gas flow rate conditions, and no significant differences between nitrogen and air were observed.

![Figure 13](image13.png)

**Figure 13.** Minimum oxygen concentration for nitrogen and air (note that the scales of y-axis in both figures are different): (a) HRR = 1.17 kW and (b) HRR = 5.23 kW.

In Figure 14, the relation between the extinguishing time and minimum oxygen concentration for nitrogen and air is shown. Increases in extinguishing times resulted in decreasing the minimum oxygen concentrations, which were similar to Figure 8. However, the relations in the nitrogen case were similar to those in the air case.

![Figure 14](image14.png)

**Figure 14.** Extinguishing time vs. minimum oxygen concentration for gas type effect (note that the scales of x-axis in both figures are different): (a) HRR = 1.17 kW and (b) HRR = 5.23 kW.

3.3.4. Comparison between Nitrogen and Air

In Figure 15, the effects of nitrogen and air on the extinguishing times, peak surface temperatures, and minimum oxygen concentrations are compared. The differences in all parameters are defined as “Nitrogen–Air”. With respect to the differences in extinguishing times in Figure 15a, under relatively low gas and water flow rate conditions, a few
experimental data on the differences in extinguishing times appeared to be negative, but largely scattered. However, under high gas and water flow rate conditions, their values were close to zero. The differences in peak surface temperatures and minimum oxygen concentrations between both atomizing gases are shown in Figure 15b,c, respectively. Their average values were mostly close to zero, with the exception of a few data with large error bars. Given the scattering of experimental data, the effect of the atomizing gas type on the peak surface temperatures and minimum oxygen concentrations was not clearly observed. The experimental results in the present study appear to be different from those of a previous study [29]. Gupta et al. [29] compared the fire-extinguishing performances of nitrogen and air, as atomizing gases, in a twin-fluid atomizer. They reported that nitrogen reduces the fire-extinguishing times by 30–50% when compared with air because nitrogen leads to a faster oxygen dilution effect than air. However, in this study, no significant enhancement of the fire-extinguishing performance due to nitrogen was observed. This inconsistency between the present and previous studies can be due to the differences in water mist and atomizing gas discharge directions towards fire sources in two studies. In a previous study [29], the water mist and atomizing gas from the twin-fluid atomizer were not discharged and penetrated directly into the fire source. However, in the present study, a twin-fluid atomizer was installed vertically above the fire source, and the water mist and atomizing gas were discharged directly and intensively into the fire source. Hence, in a previous study [29], the oxygen dilution can be an important fire-extinguishing mechanism, and thus the effect of the atomizing gas type is large. Conversely, in the present study, the heat extraction (i.e., cooling) of discharged water mist and atomizing gas is potentially the predominant fire-extinguishing mechanism wherein the effect of the atomizing gas type becomes small. Based on the present and previous studies, it was observed that the effect of atomizing gas type on fire-extinguishing performance is dependent on the relative positions of the discharged flow (i.e., water mist and atomizing gas) and fire source.

Figure 15. Comparison of differences in measurement parameters between nitrogen and air: (a) extinguishing time, (b) peak surface temperature, and (c) minimum oxygen concentration.
4. Conclusions

In the present experimental study, the influences of discharge area and atomizing gas type in full cone twin-fluid atomizer on heptane pool fire extinguishment were investigated under the heat release rates of 1.17 and 5.23 kW in an enclosed chamber. With respect to the effect of discharge area, the large and small full cone twin-fluid atomizers were used. Nitrogen and air were used to examine the effect of the atomizing gas type. The Sauter mean diameter (SMD) of the water mist for both twin-fluid atomizers was measured and discussed. Then, the effects of the discharge area and atomizing gas type on the extinguishing times, peak surface temperatures, and minimum oxygen concentrations were analyzed via a series of fire-extinguishing experiments. The conclusions of the present study are summarized as follows.

1. With respect to the droplet size of the water mist, as the water and air flow rates decreased and increased, respectively, the droplet sizes of the water mist decreased. The SMD of large and small atomizers were in the range of approximately 12–60 and 12–49 µm, respectively. The SMD of the large atomizer was larger than that of the small atomizer. This is due to the fact that the discharge velocities of the atomizing gas in the large atomizer were reduced and the energy required to atomize the liquid decreased owing to its large annular gap area.

2. Increases in extinguishing times resulted in increasing the peak surface temperatures and decreasing the minimum oxygen concentrations.

3. With respect to the discharge area effect, the large atomizer exhibited longer extinguishing times, higher peak surface temperatures, and lower minimum oxygen concentrations than the small atomizer. One of the reasons for these trends is that the small atomizer with a small discharge area showed the higher velocity of the discharged flow and smaller droplet size of the water mist. This can lead to shortening of the extinguishing time, cooling of the flame and fuel surface, and preventing of fuel vapor retention in the reaction region. Additionally, the effect of the discharge area on fire-extinguishing performance was dominant under certain flow rate conditions.

4. With respect to the atomizing gas type effect, under the most flow rate conditions, the nitrogen and air appeared to show nearly similar extinguishing time, peak surface temperatures, and minimum oxygen concentrations. In the present study, water mist and atomizing gas were discharged directly and intensively into the fire source. Hence, heat extraction (i.e., cooling) of discharged water mist and atomizing gas can be a predominant fire-extinguishing mechanism wherein the effect of the atomizing gas type becomes small. Based on the present and previous studies, it was observed that the effect of the atomizing gas type on the fire-extinguishing performance is dependent on the relative positions of the discharged flow (i.e., water mist and atomizing gas) and fire source.

In this study, it was found that the discharge area of twin-fluid atomizer significantly affects the fire-extinguishing performance, and the effect of atomizing gas type on fire suppression performance can be dependent on the discharge flow direction relative to fire source. The experimental data reported in this study were valuable and they were interpreted in the consideration of fire-extinguishing mechanism. The present experimental results can be utilized to improve the performance of water mist fire suppression systems under the given situation and to understand in more detail the influences of water mist and discharged gas in twin-fluid atomizers on fire suppression phenomena.

However, the present experiments were performed under limited conditions. Hence, the future works recommended are summarized as follows. Under various conditions (e.g., different fire sources, twin-fluid atomizer types, discharge flow directions relative to fire sources, and ventilations), further investigations should be conducted to examine the relationship between the discharged flow of twin-fluid atomizer and fire-extinguishing performance. In such a case, the additional measurement data of oxygen and carbon dioxide at various locations are considered to be informative. Moreover, the effects of water mist and atomizing gas on chemical reaction kinetics, molecular transport, heat and
mass transfer, and flow field for fire phenomena and extinguishing performance need to be investigated. Additionally, the detailed examination of quantitative relationships among the extinguishing time, peak surface temperature, and minimum oxygen concentration can be a worthwhile and useful contribution. In view of practical applications, the fire suppression performance of a twin-fluid atomizer should be carefully compared with that of a single-fluid atomizer under similar conditions.

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