

Article

An Experimental Investigation on the Size Distribution of Snow Particles during Artificial Snow Making

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Abstract: For artificial snowfall, snow particle size can have a direct impact on snow quality. The operating conditions of the snow-makers and environmental factors will influence the atomization and crystallization processes of artificial snow making, which consequently affect snow particle size. This paper investigates the size distribution of snow particles during artificial snow making under different operating conditions and environmental parameters. For this purpose, an environmental chamber is designed and structured. The laser scattering method was used to measure the size distribution of snow under different parameters in the room. The results show that the distribution of snow crystal particle size aligns closely with the Rosin–Rammler (R-R) distribution. The higher the height of the snowfall, the longer the snow crystals grow and the larger the snow crystal particle size. It has been found that a higher air pressure favors atomization, while the opposite is true for water pressure, which results in a higher air–water pressure ratio, producing smaller snow particle sizes. Additionally, an ambient temperature in the range of -5°C to -15°C contributes to the snow crystal form transforming from plates to columns and then back to plates; the snow particle size first decreases and then increases. Snow crystal particles at -10°C have the smallest size. Outdoor snow-makers should be operated at the highest possible air–water pressure ratio and snow height, and at a suitable ambient temperature.



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Keywords: artificial snow making; snow particle size; laser scattering method

1. Introduction

The successful bid for the 2022 Winter Olympics has generated more interest in snow sports. However, due to climatic and regional constraints, natural snowfall cannot fully meet their requirements of skiing activities [1–3]. As a result, artificial snow-making techniques are needed to supplement the amount of snow that natural snowfall cannot provide [4]. For many winter sports, good snow conditions can create a secure sporting environment for people. Therefore, in order to improve the snow quality of artificial snow in different regions and meteorological conditions, an investigation into the factors that impact it is necessary.

Snow-makers are currently the main equipment used for artificial snow making; the internal mixing gas–liquid two-phase flow atomization nozzle is the core component of snow-makers. It utilizes high-pressure air and high-pressure water to mix and atomize before spraying into the environment. The atomized water vapor undergoes crystallization and grows into snow in a low-temperature environment [5]. The larger the amount of water provided, the greater the amount of snowfall produced by the snow-makers [6].

As can be seen from the working process of the snow-makers, the formation of artificial snow can be divided into two processes: atomization and crystallization [7]. Atomization is the process of spraying atomized droplets of high-pressure water into the nozzle, colliding

and mixing with high-pressure air [8,9]. When the nozzle structure and fluid type are constant, the main influencing factor of the atomization process is the fluid pressure. Ma et al. [10] studied two different mixing forms of air atomizers and found that air pressure affects the atomization angle as well as the velocity field at the nozzle outlet. Guo et al. [11] conducted atomization experiments on a two-phase flow nozzle and found that, for a given gas pressure, the diameter of the droplet increases with increasing liquid pressure, while for a given liquid pressure, the diameter of the droplet decreases with increasing gas pressure. Crystallization is the process by which atomized droplets are mixed through an atomizing nozzle and turned into snow in a cold environment. The formation of snow crystals can be divided into two parts: nucleation and crystal growth, and both processes are highly dependent on the ambient temperature. Zhao et al. [12] concluded that there exists a specific region in which a droplet exchanges heat and mass transfer with the surrounding gas, and that this region will increase with the increasing droplet radius and temperature difference. Satyawali et al. [13] found that thermal conductivity increases with increasing grain size by estimating the thermal conductivity of snow at different temperature gradients, and the results indicate that the size of snow crystals affects the quality of snow formation. This indicates that achieving high-quality snow production requirements can only be accomplished by controlling the influencing factors during the snow formation process. Cogné et al. [14] developed a new heat and mass transfer model for simulating the individual droplet-freezing process, and it was found that the freezing time was influenced by the droplet diameter and the initial droplet temperature. Mirabedin and Farhadi [15] used numerical simulations to investigate whether the Mpemba effect can occur in a single droplet, and found that a higher initial temperature of the droplet is favorable for achieving freezing. Liu et al. [16] studied the evaporative cooling and freezing phase transition process of individual water droplets as the first and second stages of artificial snow making. The results showed that the maximum diameter of water droplets that is allowed through artificial snow making increased with a decrease in the ambient temperature and relative humidity.

According to previous work, it can be seen that air pressure and water pressure influence the atomization process in the nozzle, which in turn affects the diameter of atomized droplets at the nozzle outlet. For the crystallization of atomized droplets, the ambient temperature influences the size of snow crystals formed by affecting the heat transfer of atomized droplets. As the ambient temperature decreases, the heat transfer between the atomized droplets and the environment intensifies. When the particles of the atomized droplets are large, a lower ambient temperature is required for the droplets to crystallize. This temperature can even be below the “freezing point”, which is referred to as supercooling. Consequently, the nozzle produces different atomization effects under different operating conditions. Previous studies have mainly concentrated on the atomization of droplets and the crystallization process of single droplets. There is limited research on the distribution of snow particle size after atomization. In artificial snow making, the quality of snow formation is intimately connected to the crystallization process. The size of the snow particles formed during crystallization plays a fundamental role in determining the quality of snow formation. Based on this, this paper investigates the particle size distribution of snow crystals after snow formation.

Currently, there are many methods for measuring particle size distribution. High-speed cameras and laser particle size measurements are the two methods commonly used for particle measurement [17–19]. Both can be used to observe the size of an object in a fluid, and have their own advantages and disadvantages. For the measurement of snow crystal particle sizes, the laser scattering method was utilized, which is a commonly used method in particle size measurement [20–22]. This method is based on the scattering phenomenon of lasers by particles. Through computerized processing and calculations of the scattering images, the particle size and distribution can be determined. However, there are few works on the use of the laser scattering method for snow crystal measurements. The objective of the present study is to investigate the size and distribution of the snow particle

size of atomizing nozzles under different operating conditions. The particle size of indoor artificial snow was measured using a self-developed split probe based on the laser scattering principle; meanwhile, the influence of different snowfall heights, air–water pressure ratios, and ambient temperature on the snow particle size distribution was analyzed. It provides a theoretical basis for the selection of operating conditions of outdoor snow-makers.

2. Experimental Methodology

2.1. Experimental Setup

2.1.1. Artificial Snow-Making System

In order to conduct a practical test of the snow-making effect of the atomizing nozzle, this research achieved indoor artificial snow making in an environmental chamber (as shown in Figure 1). This environmental chamber could provide a stable and controlled indoor environment for artificial snow making. The air cooler in the environmental chamber provided the cooling capacity that is required for artificial snow making (see Figure 2). Post and front heating devices were used together with the fan to control the temperature of the room's environment. The fan's wind speed could be adjusted to a low speed (6.5 m/s), medium speed (8 m/s), and high speed (9 m/s). This experiment was conducted in a low-temperature environment, for which a wind speed of 9 m/s was chosen. Electric humidification was used to control the humidity. There were temperature sensors and humidity sensors inside the sampling fan, which could be used to measure environmental parameters such as temperature and humidity in the environmental chamber. The wall material of the environmental chamber was crafted from a 100 mm thick colored steel polyurethane plate, which has an extremely low thermal conductivity coefficient of just 0.018~0.023 W/m·K.

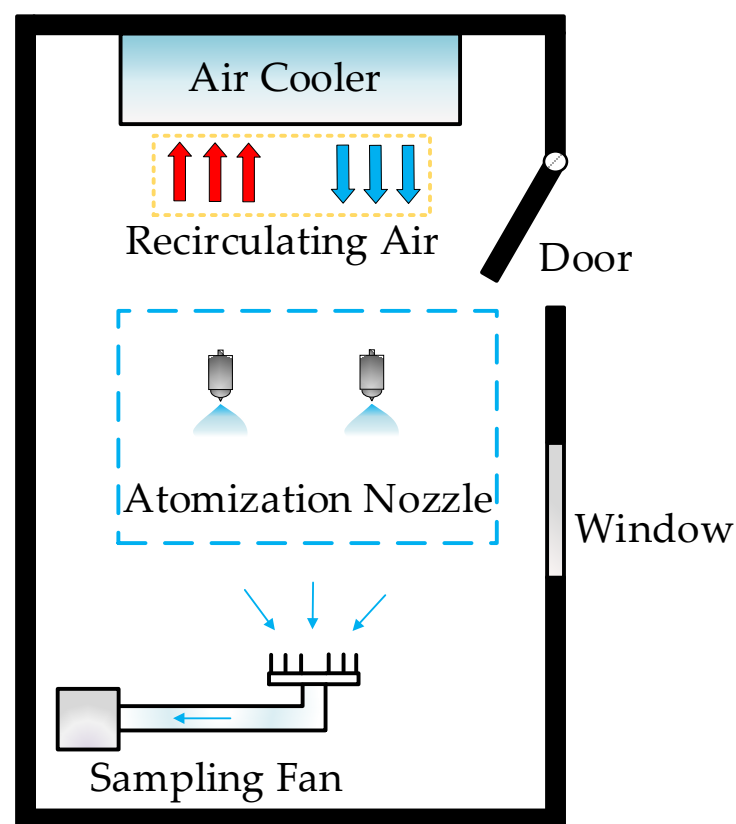


Figure 1. Schematic of the experimental setup. (The red arrows represent indoor air that has not been cooled by the air cooler, and the blue arrows represent indoor air that has been cooled by the air cooler).

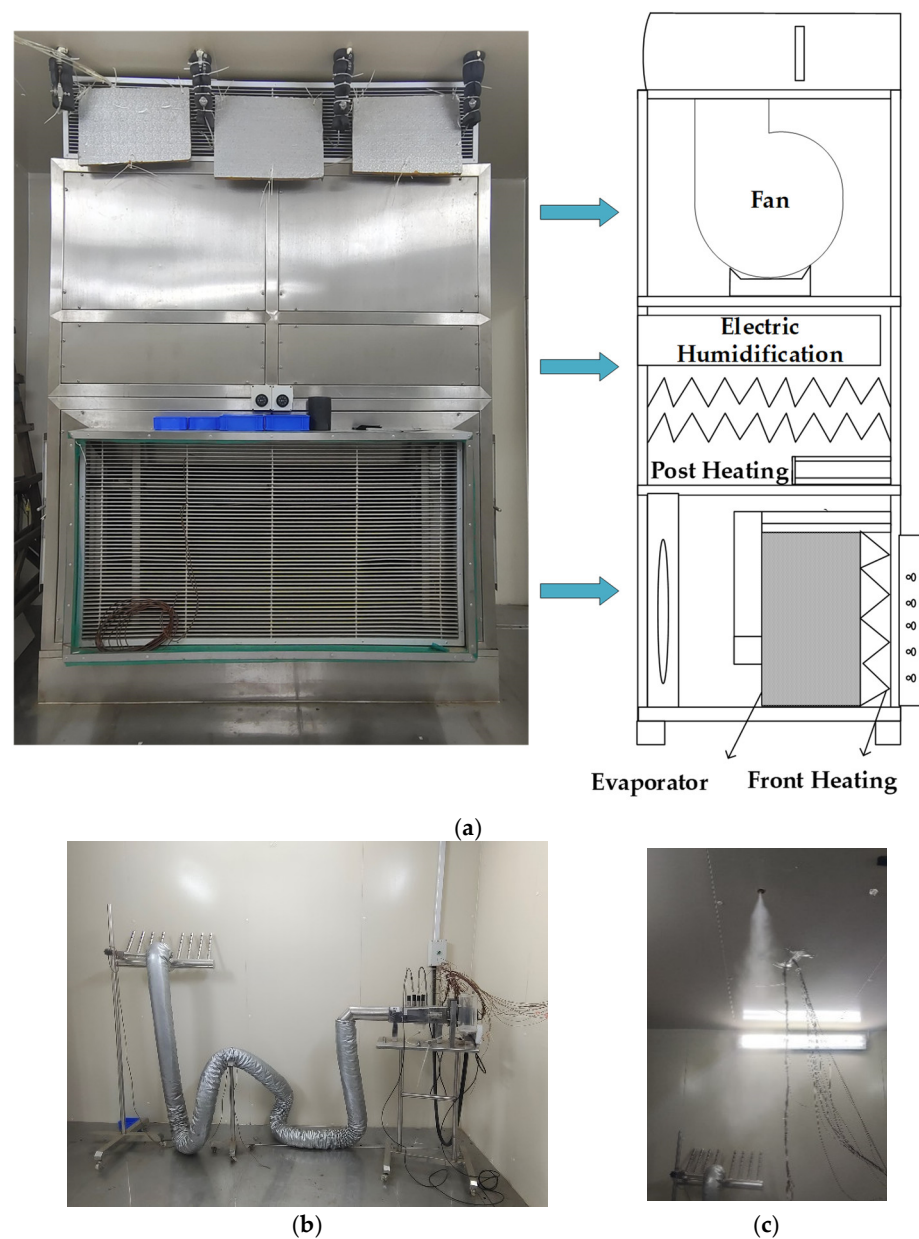


Figure 2. Picture of the experimental setup. (a) Air cooler, (b) sampling fan, (c) atomization nozzle.

The artificial snow-making system is shown in Figure 3. It consists of a water supply system and an air supply system. The water supply system consists of two main components, i.e., a thermostatic water container and a pump, which are used to control the temperature and pressure of the water, respectively. During the experiment, the excess water produced by the pump could be returned to the thermostatic water container through the electromagnetic valve to achieve circulation. The air compressor in the gas supply system was primarily for providing air for the experiments. The surge tank was used to regulate the pressure of the compressed air. The emptying valve was used to discharge water from the pipeline when the experiment was complete. The water and air were mixed in the atomization nozzle and sprayed out via atomization. The position of the atomization nozzle in the environmental chamber is shown in Figures 1 and 2.

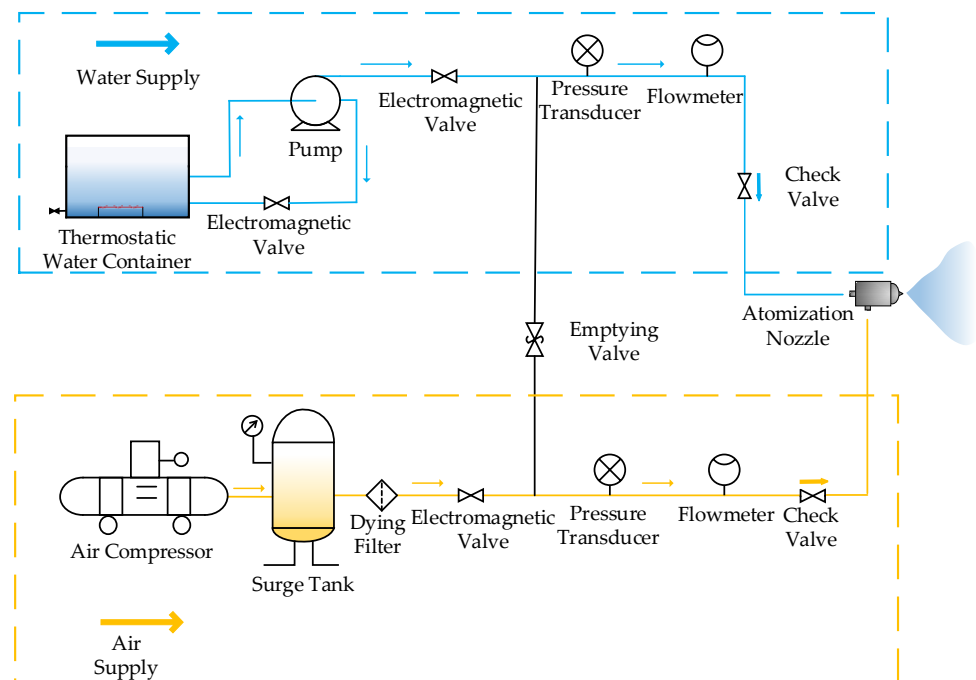


Figure 3. Schematic of the snow-making system. (The blue arrows represent the flow of water on the water supply system, and the yellow arrows represent the flow of air on the air supply system).

2.1.2. Atomizing Nozzle

The structure of different atomizing nozzles can result in different atomization effects, which in turn affect the quality of snow formation [23–25]. The atomization nozzle selected in this work is shown in Figure 4. On the side of the atomizer nozzle there are two air inlets for high-pressure air. Along the axis direction, one side is the liquid inlet. The other side is the atomization particles' outlet. The angle between the air inlet and the liquid inlet is 30° . The diameter of the atomization nozzle outlet is 1 mm.

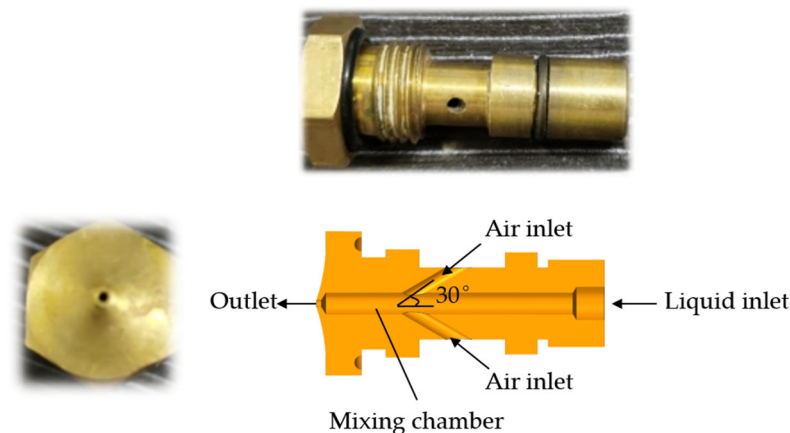


Figure 4. Gas-liquid two-phase atomization nozzle.

2.2. Snow Particle Size Measurement System

Snow particles usually have an irregular shape [26], and the air–water two-phase flow is very fast during artificial snow production. Therefore, conventional particle size measurement methods are not suitable for use. In this study, the snow crystal particle size is measured using the laser scattering method, and the schematic diagram is shown in Figure 5. The measurement system is divided into two parts: a transmitter and a receiver. The former includes a laser, filter, attenuator combination, collimated beam expander, and diaphragm. The incident light is emitted by the laser; the filter and attenuator combination

is used to screen the incident light. The collimated beam and diaphragm are used to screen the incident light during the intensity amplification process. The amplified light's intensity leads to the phenomenon of snow crystal scattering. The latter consists of a CCD camera, camera lens, diaphragm, focal plane, and Fourier lens set. The scattered light from the irradiated snow crystals is collected through the lens and gathered on the focal plane, the CCD camera collects the scattered light and transmits it to the computer in image format, and the computer calculates the snow crystal particle size and its distribution according to the light-scattering signal at different angles. This physical process can be integrated strictly using Mie's theory and solved in conjunction with inversion algorithms. The physical diagram of the measurement system is shown in Figure 6. The particle measurement needs to be carried out in the low-temperature environment of the experimental chamber. In order to prevent damage to the experimental apparatus and to prevent frost from blocking the lens during the experiment, the laser particle size meter is wrapped with insulation cotton outside to alleviate the above phenomenon.

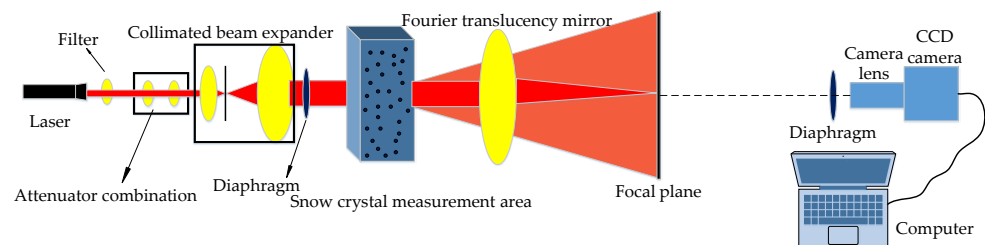


Figure 5. Laser scattering method test schematic diagram.



Figure 6. Laser scattering experimental setup diagram.

2.3. Calculation Method of the Snow Particle Size

Since the shape of snow crystals is irregular, there are many methods for the statistical analysis of their particle size distribution. This article uses the method of volume distribution to statistically analyze the distribution of snow crystals. Among them, D_v10 , D_v50 , and D_v90 represent the particle size corresponding to 10%, 50%, and 90% of the volume distribution, respectively. The physical meaning of D_v10 is that the total volume of all particles within this diameter constitutes 10% of the overall particle volume. D_v50 represents the median diameter, meaning that the total volume of particles above this diameter is equal to that of particles below. Meanwhile, D_v90 indicates that the total volume of all particles below this diameter accounts for 90% of the total particle volume. In addition to this, the Sauter mean diameter (SMD) is commonly used for evaluating atomization effects during the heat and mass transfer process; the formula is as follows [27]:

$$\text{SMD} = D_{32} = \frac{d_v^3}{d_s^2} \quad (1)$$

where d_v is the droplet surface diameter and d_s is the droplet volume diameter.

2.4. Experimental Equipment and Operating Conditions

The tested parameters, such as pressure, flow rate, temperature, and snow particle size, are directly gained using instruments. In this study, the uncertainties and equipment parameters are listed in Table 1.

Table 1. The specifications of the experimental equipment.

Equipment	Parameters	Uncertainty
Thermostatic Water Container	Volume: 0.35 m ³	\
	Temperature range: 4~10 °C	
Pump	Rated power: 4 kW	\
	Pressure range: 0.3~1.0 MPa	
Air Compressor	Rated power: 4 kW	\
	Rated speed: 750 r/min	
Surge Tank	Volume: 0.6 m ³	\
	Pressure range: 0.2~0.8 MPa	
Pressure Transducer	Measuring range: 0~0.8 MPa	±0.1%
Flowmeter	Max measuring range: 1 L/min	±3%
Split Laser Particle Sizer	Measuring range: 5~200 µm	±5%

The air–water pressure ratio, as an operating parameter of snow-makers, can directly affect the atomization effect of the nozzle, which in turn has a direct effect on the snow particle size and snow quality. In order to form continuous and stable artificial snow, artificial snow experiments were conducted under various conditions. It was found that when the air pressure and water pressure were less than 0.4 MPa, the atomizing nozzle could not form artificial snow continuously and stably. Therefore, this study selected air–water pressure ratios of 0.4 MPa:0.4 MPa, 0.5 MPa:0.4 MPa, and 0.5 MPa:0.45 MPa, respectively. For the snowfall height, the experiment selected 40 cm, 60 cm, and 80 cm to investigate the snow particle size distribution. However, due to the existence of a critical snow formation height between 40 cm and 60 cm (see Section 3.1), several heights within this range were selected for research. The maximum snowfall height selected for this study is 120 cm. When the snowfall height is higher than 120 cm, the laser scattering method cannot measure a sufficient number of snowfall particles due to the scattered snowfall. The ambient temperatures of −5 °C, −10 °C, and −15 °C were selected as the research objects. The inlet water temperature was kept at 4 °C. The detailed experimental conditions are shown in Table 2.

Table 2. Experimental conditions.

Parameters	Value
Water temperature (°C)	4
Snow height (cm)	25~120
Air–water pressure ratio	0.5 MPa:0.4 MPa, 0.5 MPa:0.45 MPa, 0.4 MPa:0.4 MPa
Ambient temperature (°C)	−15~−5

3. Results and Discussion

3.1. Effects of Snowfall Height

Figure 7 shows the particle size parameters at different snowfall heights under the ambient temperature of −5 °C and the air–water pressure ratio of 0.5 MPa:0.4 MPa. From Figure 7, it can be seen that the snow crystal size changes significantly when the snowfall height is around 45 cm. This is because there is a critical height of snow formation when it is close to the atomizing nozzle. Near the critical snow formation height, the number of snow crystals and atomized droplet particles is similar, so the measurement data change significantly at this time. The height of the snowfall affects the snow particle size by changing the growth time of the snow crystals. The longer the height of the snowfall, the

more complete the snow crystal growth in the air and the larger the snow crystal particle size. Correspondingly, the shorter the height of the snowfall, snow crystals cannot fully grow, and the shorter the particle size of the snow crystals. When the heat transfer between the atomized droplets and the environment is complete and the atomized droplets are fully nucleated, the snow particle size increases with distance from the atomizing nozzle. This indicates that the atomized droplets grow as they fall after condensation, and the particle size gradually increases as the snowfall height increases. However, compared to natural snowfall from the atmosphere to the ground, the overall snow crystal particle size is smaller [28].

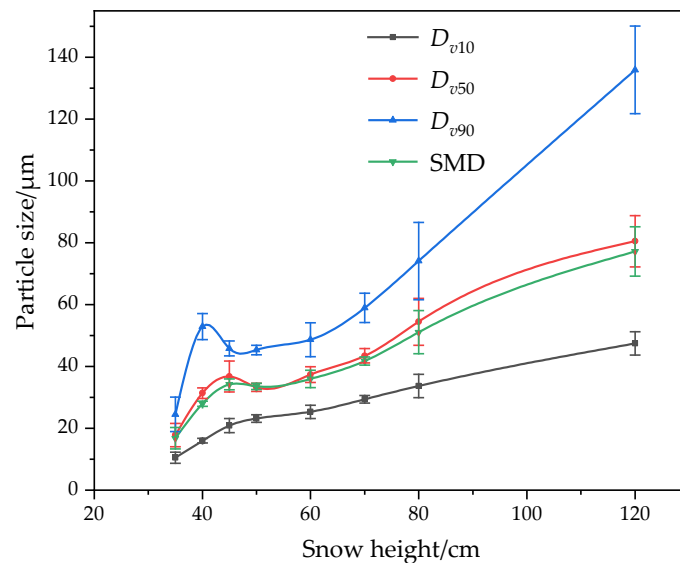


Figure 7. Snow particle size parameters under different snow heights.

The snow crystal particle size distributions for each working condition are shown in Figures 8 and 9. From the distribution diagram, it can be seen that the snow crystal particle size is distributed in the range of 0 to 100 μm. The particle size distribution is closely approximated using the R-R distribution [29]. Figures 8 and 9 show that when the air–water pressure ratio remains constant, the peak of the particle size distribution gradually shifts to the right as the snowfall height increases. This indicates an increase in the proportion of large snow crystals. This indicates that as the snowfall height increases, the overall snow crystal size gradually increases. And the proportion of larger snow crystal particle sizes also gradually increases.

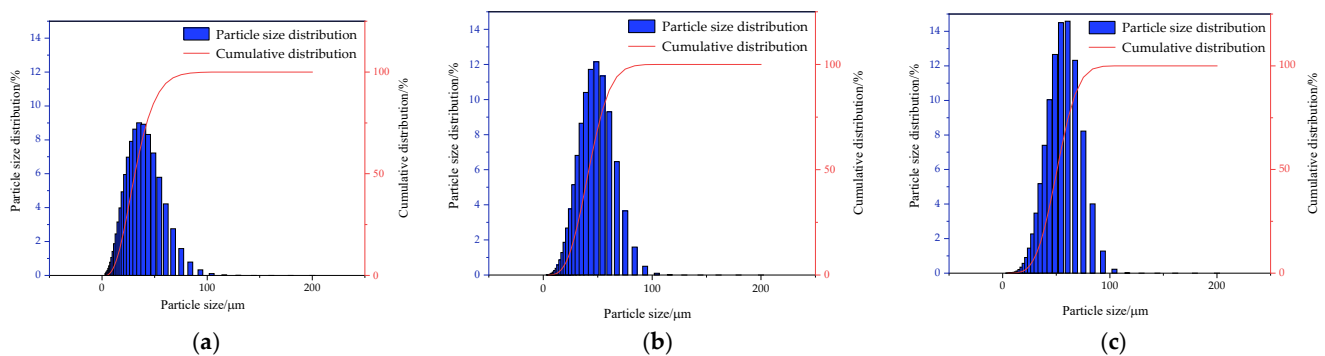


Figure 8. Particle size distribution for air–water pressure ratio of 0.5 MPa:0.4 MPa; (a) 40 cm, (b) 60 cm, (c) 80 cm.

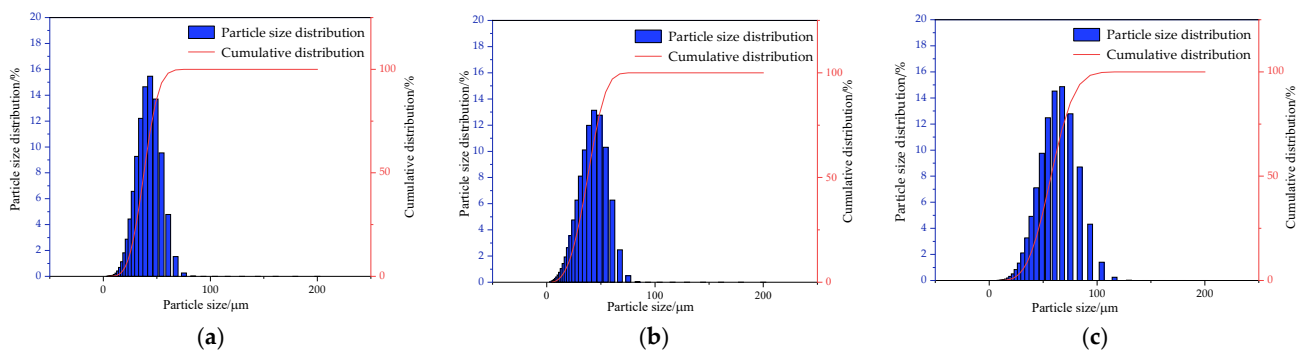


Figure 9. Particle size distribution for air–water pressure ratio of 0.5 MPa:0.45 MPa; (a) 40 cm, (b) 60 cm, (c) 80 cm.

3.2. Effects of Air–Water Pressure Ratio

The velocity of the two-phase flow at the atomizing nozzle outlet significantly affects the size of atomized droplets and the nucleation of snow crystals. A higher flow velocity results in more complete droplet breakage, leading to greater cooling through adiabatic expansion after spraying, and increasing the formation of snow crystals. Table 3 shows the flow velocity at the outlet of the atomizing nozzle under different air–water pressure ratios. In order to assess the type of convective flow around the particles, this study also estimated the Reynolds number at the outlet of the atomizing nozzle.

Table 3. Atomizing nozzle outlet parameters.

Air–Water Pressure Ratio	Flow Velocity (m/s)	Reynolds Number
0.5 MPa:0.4 MPa	690.1	38,339
0.5 MPa:0.45 MPa	550.3	30,572
0.4 MPa:0.4 MPa	524.2	29,122

Figures 10 and 11 are the ambient temperature of $-15\text{ }^{\circ}\text{C}$, and snowfall heights of 40 cm and 80 cm, respectively, under the different air–water pressure ratios of the particle size parameters. From Figures 10 and 11, it can be found that increasing the air pressure can make the snow particle size decrease. This is because as the air pressure increases, the proportion of air pressure increases, and the two-phase flow velocity increases, which is conducive to the atomization of liquid droplets. This improves the atomization effect of the atomizing nozzle better, allowing for the formation of smaller droplets, resulting in a reduction in the size of the snow particle size.

When the atomization nozzle atomizes water droplets with a larger diameter, it is more difficult for them to condense into snow crystals because the specific surface area for heat and mass transfer is smaller. This results in a longer snow crystal growth time and an increase in the critical snow formation height. It also increases the size of snow crystals and reduces the quality of the snow as large, atomized water droplets are more likely to collide and condense in the air. On the contrary, when the diameter of atomized water droplets is small, the critical snow formation height is short. The atomized water crystallizes completely into snow, with a small particle size and good snow quality. The air–water pressure ratio therefore has a significant effect on the snow particle size.

The snow crystal particle size distribution for each working condition is shown in Figures 12 and 13. Comparing the particle size distribution charts for 0.4 MPa:0.4 MPa and 0.5 MPa:0.4 MPa, it can be observed that increasing the air pressure leads to a decrease in the size of the larger snow crystals and an increase in the size of the smaller snow crystals. And the particle size distribution of the peak gradually shifts to the left; the diameter distribution range becomes narrower. Increasing the water pressure will make the snow crystal particle size larger overall, with a more uniform distribution, and the peak of the particle size distribution shifting to the right. From the snowfall height of 40 cm, an

air–water pressure ratio of 0.5 MPa:0.4 MPa can be found; because of the larger air pressure, the flow rate is faster, the snow crystal particle size is distributed at 50 μm or less. The reason for this phenomenon may be due to the increase in the air–water pressure ratio; the air phase in the mixing chamber becomes larger, the droplets are atomized into smaller particles, and the kinetic energy of the droplets increases with the increase in the gas phase pressure [8]. As a result, the snow particle size decreases as the air–water pressure ratio increases. When the air pressure is equivalent to the water pressure, a phenomenon of “secondary ice nucleation” occurs in the wake of the snow crystal [30]. This phenomenon happens when the temperature is low and the atomized droplets have a high water content. From Figure 13c, it is evident that, with a sufficient snowfall height, the distribution of the snow particle size becomes more dispersed, and the small snow crystal particle sizes are still present.

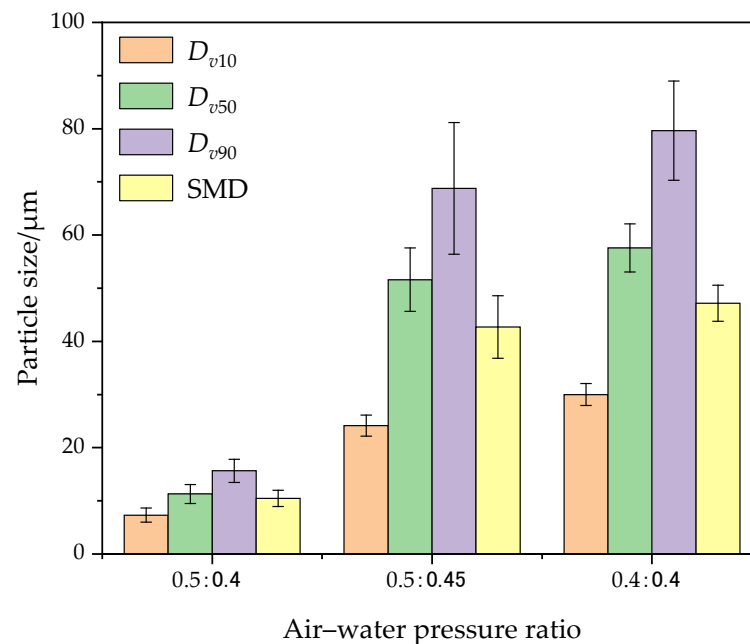


Figure 10. Snow particle size at 40 cm with different air–water pressure ratios.

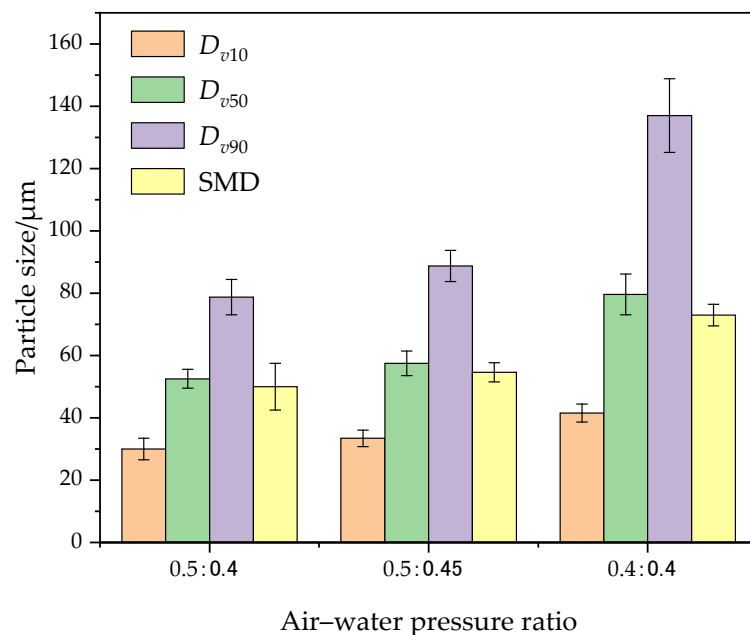


Figure 11. Snow particle size at 80 cm with different air–water pressure ratios.

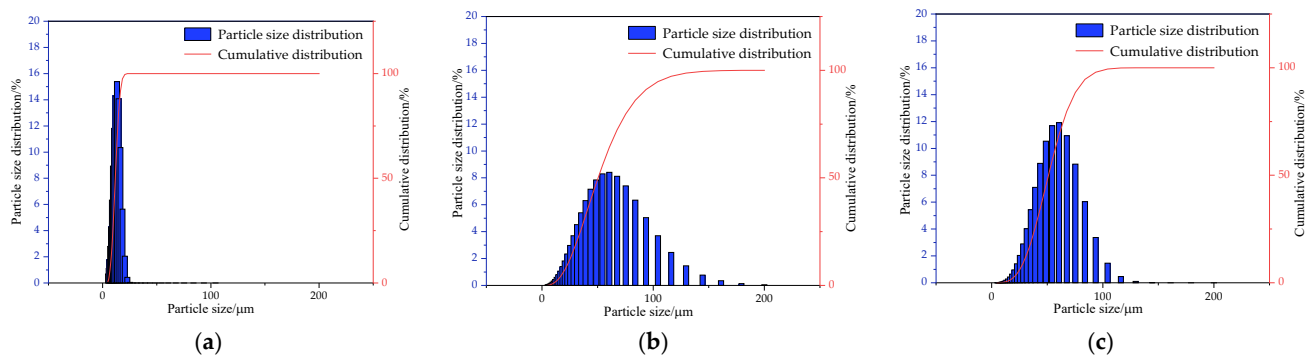


Figure 12. Particle size distribution for a snowfall height of 40 cm. (a) Air–water pressure ratio of 0.5 MPa:0.4 MPa. (b) Air–water pressure ratio of 0.5 MPa:0.45 MPa. (c) Air–water pressure ratio of 0.4 MPa:0.4 MPa.

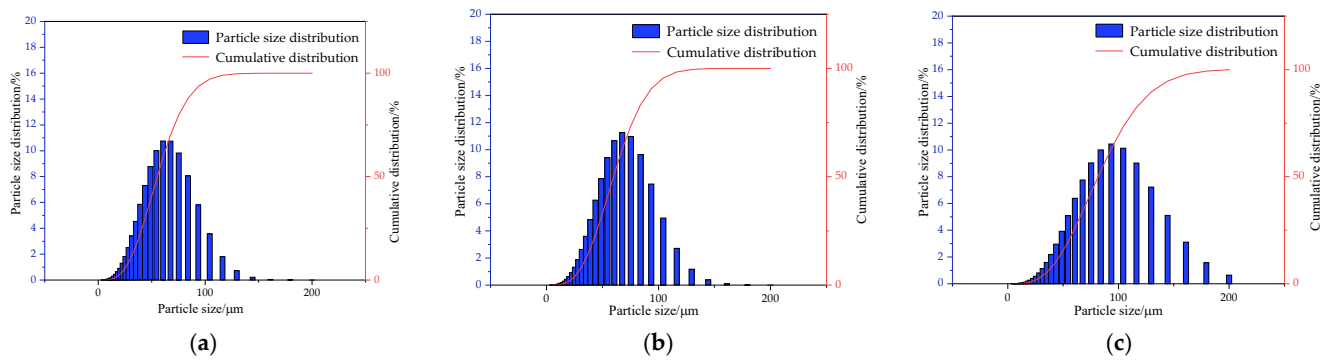


Figure 13. Particle size distribution for a snowfall height of 80 cm. (a) Air–water pressure ratio of 0.5 MPa:0.4 MPa. (b) Air–water pressure ratio of 0.5 MPa:0.45 MPa. (c) Air–water pressure ratio of 0.4 MPa:0.4 MPa.

3.3. Effects of Ambient Temperature

Figure 14 shows the particle size parameters for different ambient temperatures at a snowfall height of 80 cm and air–water pressure ratios of 0.5 MPa:0.4 MPa and 0.5 MPa:0.45 MPa. From Figure 14, it can be found that the particle size of snow crystals at $-10\text{ }^{\circ}\text{C}$ is smaller than that at $-5\text{ }^{\circ}\text{C}$ and $-15\text{ }^{\circ}\text{C}$. According to Libbrecht [31,32], the morphology of snow crystals mainly depends on the temperature. Plates are formed above $-2\text{ }^{\circ}\text{C}$, hollow columns are formed at $-5\text{ }^{\circ}\text{C}\sim-10\text{ }^{\circ}\text{C}$, plates are formed again at $-10\text{ }^{\circ}\text{C}\sim-20\text{ }^{\circ}\text{C}$, and columns or plates shapes are formed below $-25\text{ }^{\circ}\text{C}$. The reason for this phenomenon is determined based on the crystal structure. Snow crystals typically form as simple hexagonal prisms. The morphology of the crystal is either plates or columns, determined based on the inherent growth rate and diffusion of the crystalline surface. When the prism crystal face grows slower than the base crystal face, columnar crystals are obtained; when the base crystal face grows slower than the prism crystal face, plate crystals are obtained. From the morphology diagram, it can see that the velocity of both prismatic and basal crystal faces is very temperature-dependent. Between $-5\text{ }^{\circ}\text{C}$ and $-15\text{ }^{\circ}\text{C}$, the snow crystals change from plate to column and then back to plate. Compared with the column, the plate has a larger snow crystal area, and the particle size of the snowflake formed after the snow crystal grows outward is larger. As a result, the particle size at $-10\text{ }^{\circ}\text{C}$ is lower than the particle sizes at $-5\text{ }^{\circ}\text{C}$ and $-15\text{ }^{\circ}\text{C}$.

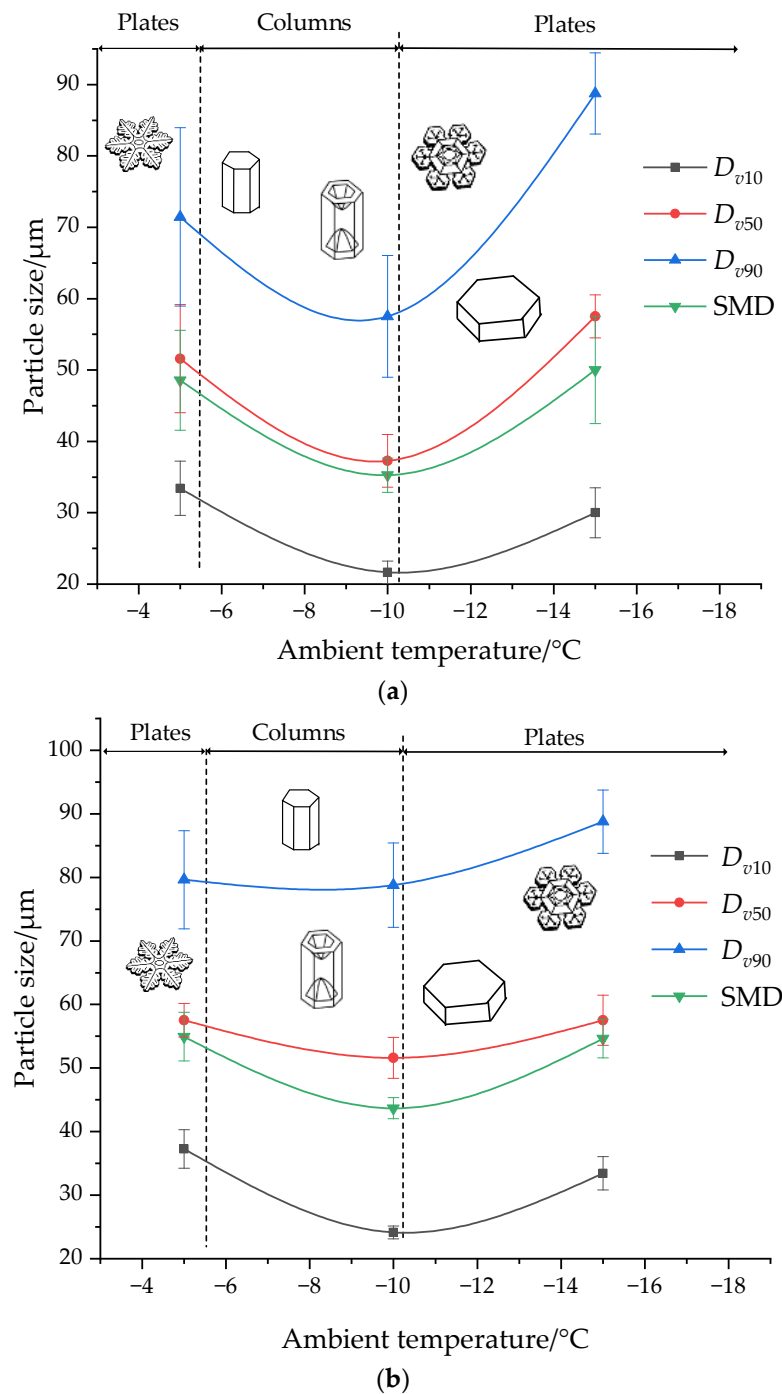


Figure 14. Snow particle size with different ambient temperatures. (a) Air–water pressure ratio of 0.5 MPa:0.4 MPa. (b) Air–water pressure ratio of 0.5 MPa:0.45 MPa.

The distribution of snow crystal particle sizes under different working conditions is shown in Figures 15 and 16. It can be seen from the graph that, as the ambient temperature decreases, the peak of the particle size distribution first shifts to the left and then to the right, and the total particle size first decreases and then increases. It can also be seen from Figures 15 and 16 that when the air–water pressure ratio remains constant, the number of large particle sizes gradually increases as the ambient temperature decreases. This is because as the ambient temperature decreases, the undercooling between the atomized droplets and the ambient temperature increases. Convective heat transfer becomes more intense and the formation of snow crystals becomes more likely. The result is an increase in the number of snow crystals formed and also an increase in the probability of the formation

of large-particle snow crystals. However, due to the dominant role of small-particle snow crystals, the total snow crystal particle size first decreases and then increases as the ambient temperature decreases.

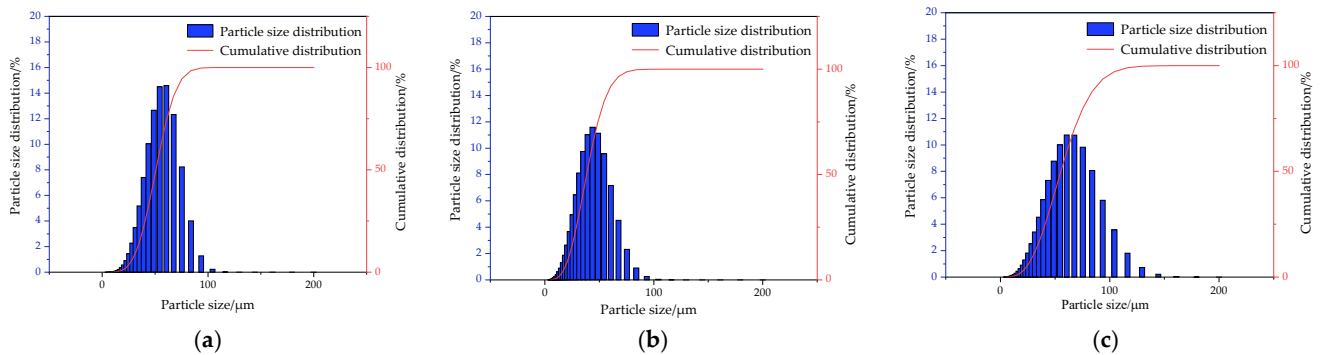


Figure 15. Particle size distribution for an air–water pressure ratio of 0.5 MPa:0.4 MPa. (a) Ambient temperature: $-5\text{ }^{\circ}\text{C}$. (b) Ambient temperature: $-10\text{ }^{\circ}\text{C}$. (c) Ambient temperature: $-15\text{ }^{\circ}\text{C}$.

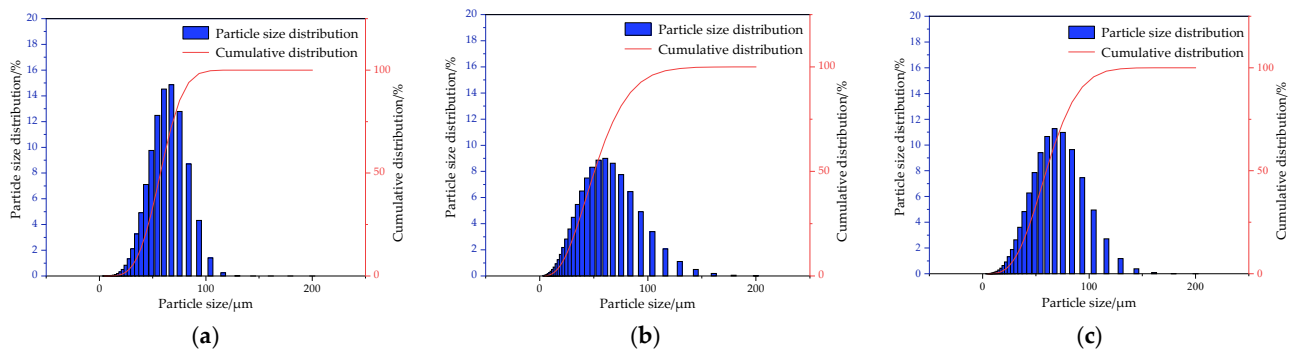


Figure 16. Particle size distribution for an air–water pressure ratio of 0.5 MPa:0.45 MPa. (a) Ambient temperature: $-5\text{ }^{\circ}\text{C}$. (b) Ambient temperature: $-10\text{ }^{\circ}\text{C}$. (c) Ambient temperature: $-15\text{ }^{\circ}\text{C}$.

4. Conclusions

The aim of this study is to investigate the particle size and distribution of atomizing nozzles under different operating and environmental parameters, so that the operating conditions of snow-makers can be controlled to achieve the desired result. In this paper, an artificial snow-making system was constructed and artificial snow experiments were performed on a gas–liquid two-phase flow atomizing nozzle using the laser scattering method. The main conclusions are summarized as follows:

- (1) The snow particle size distribution is close to the R-R distribution. When the air–water pressure ratio and ambient temperature remain constant, within the range of 120 cm of snowfall height, as the snowfall height increases, snow crystals continue to grow, and the particle size of snow crystals gradually increases with the increase in the snowfall height. Therefore, in outdoor snow-makers, the growth status of snow crystals varies at different snowfall heights. It is particularly important for external mixed snow-makers.
- (2) When the snowfall height and ambient temperature are constant, air pressure can effectively improve the atomization effect. On the contrary, water pressure is unfavorable for atomization. The air–water pressure ratio increases from 0.4 MPa:0.4 MPa to 0.5 MPa:0.4 MPa, the two-phase flow velocity increases, the atomizing effect of the atomizing nozzle increases, and the snow particle size decreases. In outdoor snow-making applications, it is recommended to choose a higher air–water pressure ratio according to the necessary snow production to enhance atomization.
- (3) When the snowfall height and air–water pressure ratio are constant, the ambient temperature decreases from $-5\text{ }^{\circ}\text{C}$ to $-15\text{ }^{\circ}\text{C}$, and the particle size of snow crystals

first decreases and then increases. The snow crystal particle size reaches its minimum at around -10°C . This is because the growth rates of snow crystals on the base crystal surface and prism crystal surface are different, resulting in the shape of snow crystals being plates at -5°C or above, columns at -5°C to -10°C , and returning to plates at -10°C to -15°C . Compared with columnar snow crystals, plates snow crystals have a larger area, and the snowflake particle size formed when snow crystals grow outward is also larger.

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References

- Deng, J.; Che, T.; Hu, Y.-X.; Yue, S.-N.; Pan, J.-H.; Dai, L.-Y. Climate Change Risk Assessment for Ski Areas in China. *Adv. Clim. Change Res.* **2023**, *14*, 300–312. [\[CrossRef\]](#)
- Steiger, R.; Posch, E.; Tappeiner, G.; Walde, J. The Impact of Climate Change on Demand of Ski Tourism—A Simulation Study Based on Stated Preferences. *Ecol. Econ.* **2020**, *170*, 106589. [\[CrossRef\]](#)
- Elsasser, H.; Bürki, R. Climate Change as a Threat to Tourism in the Alps. *Clim. Res.* **2002**, *20*, 253–257. [\[CrossRef\]](#)
- Damm, A.; Greuell, W.; Landgren, O.; Prettenhaler, F. Impacts of $+2^{\circ}\text{C}$ Global Warming on Winter Tourism Demand in Europe. *Clim. Serv.* **2017**, *7*, 31–46. [\[CrossRef\]](#)
- Wang, R.; Zhang, B.; Xu, R.; Xing, M.; Zhang, H.; Zhang, H.; Yan, G.; Wu, H. Sensitivity of Atomization Characteristic to Operation Conditions for Air-Assisted Atomizers in Snow-Makers. *Int. J. Refrig.* **2023**, *149*, 146–154. [\[CrossRef\]](#)
- Hanzer, F.; Marke, T.; Strasser, U. Distributed, Explicit Modeling of Technical Snow Production for a Ski Area in the Schladming Region (Austrian Alps). *Cold Reg. Sci. Technol.* **2014**, *108*, 113–124. [\[CrossRef\]](#)
- Dong, P.; Chen, Q.; Liu, G.; Zhang, B.; Yan, G.; Wang, R. Effects of Geometric Parameters on Flow and Atomization Characteristics of Swirl Nozzles for Artificial Snowmaking. *Int. J. Refrig.* **2023**, *154*, 56–65. [\[CrossRef\]](#)
- Kang, Z.; Wang, Z.-G.; Li, Q.; Cheng, P. Review on Pressure Swirl Injector in Liquid Rocket Engine. *Acta Astronaut.* **2018**, *145*, 174–198. [\[CrossRef\]](#)
- Vijay, G.A.; Moorthi, N.S.V.; Manivannan, A. Internal and External Flow Characteristics of Swirl Atomizers: A Review. *At. Sprays* **2015**, *25*, 153–188. [\[CrossRef\]](#)
- Ma, R.; Dong, B.; Yu, Z.; Zhang, T.; Wang, Y.; Li, W. An Experimental Study on the Spray Characteristics of the Air-Blast Atomizer. *Appl. Therm. Eng.* **2015**, *88*, 149–156. [\[CrossRef\]](#)
- Guo, L.-J.; Li, G.-J.; Chen, B.; Chen, X.-J.; Papailiou, D.D.; Panidis, T. Study on Gas-Liquid Two-Phase Spraying Characteristics of Nozzles for the Humidification of Smoke. *Exp. Therm. Fluid Sci.* **2002**, *26*, 715–722. [\[CrossRef\]](#)
- Zhao, F.; Liu, Q.; Zhao, C.; Bo, H. Influence Region Theory of the Evaporating Droplet. *Int. J. Heat Mass Transf.* **2019**, *129*, 827–841. [\[CrossRef\]](#)
- Satyawali, P.K.; Singh, A.K.; Dewali, S.K.; Kumar, P.; Kumar, V. Time Dependence of Snow Microstructure and Associated Effective Thermal Conductivity. *Ann. Glaciol.* **2008**, *49*, 43–50. [\[CrossRef\]](#)
- Cogné, C.; Nguyen, P.U.; Lanoisellé, J.L.; Van Hecke, E.; Clausse, D. Modeling Heat and Mass Transfer during Vacuum Freezing of Puree Droplet. *Int. J. Refrig.* **2013**, *36*, 1319–1326. [\[CrossRef\]](#)
- Mirabedin, S.M.; Farhadi, F. Enquête Numérique Portant Sur La Solidification de Gouttelettes Uniques Avec et sans Mécanisme d'évaporation. *Int. J. Refrig.* **2017**, *73*, 219–225. [\[CrossRef\]](#)
- Liu, B.; Hu, H.; Bi, L.; Theodorakis, P.E. Analysis of the Characteristics of the Gas-Liquid Mixed Artificial Snow-Making. *Int. J. Refrig.* **2023**, *149*, 155–167. [\[CrossRef\]](#)
- Zhang, B.; Wang, R.; Wu, H.; Dong, P.; Xu, R.; Xing, M.; Zhang, H.; Cui, Z.; Yan, G.; Zhang, H. Atomization Characteristics of Twin Nozzles for Outdoor Snow-Makers Application. *Int. J. Refrig.* **2022**, *139*, 60–69. [\[CrossRef\]](#)

18. Liu, C.; Liu, F.; Yang, J.; Mu, Y.; Hu, C.; Xu, G. Experimental Investigations of Spray Generated by a Pressure Swirl Atomizer. *J. Energy Inst.* **2019**, *92*, 210–221. [[CrossRef](#)]
19. Li, Y.; Ning, Z.; Lü, M. Experimental Study on Fusion and Break-up Motion after Droplet Collision. *Chin. J. Chem. Eng.* **2020**, *28*, 712–720. [[CrossRef](#)]
20. Han, J.; Liu, X.; Jiang, M.; Wang, Z.; Xu, M. An Improved On-Line Measurement Method of Particulate Matter Concentration Using Tri-Wavelength Laser Light Scattering. *Fuel* **2021**, *302*, 121197. [[CrossRef](#)]
21. Huang, Y.; Liu, X.; Wang, Z.; Jiang, M.; Zhou, Z.; Xu, M.; Han, J.; Yang, B.; Fan, X. On-Line Measurement of Ultralow Mass Concentration Particulate Based on Light Scattering Coupled with Beta Ray Attenuation Method. *Fuel* **2022**, *329*, 125461. [[CrossRef](#)]
22. Jin, Z.; Charlock, T.P.; Yang, P.; Xie, Y.; Miller, W. Snow Optical Properties for Different Particle Shapes with Application to Snow Grain Size Retrieval and MODIS/CERES Radiance Comparison over Antarctica. *Remote Sens. Environ.* **2008**, *112*, 3563–3581. [[CrossRef](#)]
23. Rashad, M.; Yong, H.; Zekun, Z. Effect of Geometric Parameters on Spray Characteristics of Pressure Swirl Atomizers. *Int. J. Hydrogen Energy* **2016**, *41*, 15790–15799. [[CrossRef](#)]
24. Dafsari, R.A.; Vashahi, F.; Lee, J. Effect of Swirl Chamber Length on the Atomization Characteristics of a Pressure-Swirl Nozzle. *At. Sprays* **2017**, *27*, 859–874. [[CrossRef](#)]
25. Nguyen, D.; Duke, D.; Kastengren, A.; Matusik, K.; Swantek, A.; Powell, C.F.; Honnery, D. Spray Flow Structure from Twin-Hole Diesel Injector Nozzles. *Exp. Therm. Fluid Sci.* **2017**, *86*, 235–247. [[CrossRef](#)]
26. Gordon, M.; Taylor, P.A. Measurements of Blowing Snow, Part I: Particle Shape, Size Distribution, Velocity, and Number Flux at Churchill, Manitoba, Canada. *Cold Reg. Sci. Technol.* **2009**, *55*, 63–74. [[CrossRef](#)]
27. Chen, L.; Li, G.; Ma, X.; Lim, J.; Sivathanu, Y. A Method for Measuring Planar Sauter Mean Diameter of Multi-Component Fuel Spray Based on the Combined Statistical Extinction Tomography and Particle Imaging Velocimetry. *Fuel* **2018**, *214*, 154–164. [[CrossRef](#)]
28. Ma, W.; Li, F.; Zhou, X. An Empirical Model of Snowdrift Based on Field Measurements: Profiles of the Snow Particle Size and Mass Flux. *Cold Reg. Sci. Technol.* **2021**, *189*, 103312. [[CrossRef](#)]
29. Kumar, R.; Gopireddy, S.R.; Jana, A.K.; Patel, C.M. Study of the Discharge Behavior of Rosin-Rammler Particle-Size Distributions from Hopper by Discrete Element Method: A Systematic Analysis of Mass Flow Rate, Segregation and Velocity Profiles. *Powder Technol.* **2020**, *360*, 818–834. [[CrossRef](#)]
30. Chouippe, A.; Krayner, M.; Uhlmann, M.; Dušek, J.; Kiselev, A.; Leisner, T. Heat and water vapor transfer in the wake of a falling ice sphere and its implication for secondary ice formation in clouds. *New J. Phys.* **2019**, *21*, 043043. [[CrossRef](#)]
31. Libbrecht, K.G. Morphogenesis on Ice: The Physics of Snow Crystals. *Eng. Sci.* **2001**, *64*, 10–19.
32. Libbrecht, K.G. The physics of snow crystals. *Rep. Prog. Phys.* **2005**, *68*, 855–895. [[CrossRef](#)]

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