Experimental Investigation of Dry Ice Cyclone Separator for Ultra-low Temperature Energy Storage using Carbon dioxide

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Running Head: Experimental Dry Ice Cyclone Separator

Abstract

CO_2 cascade heat pump system has been developed to realize an ultra-low temperature below the triple point of 0.518 MPa and -56.6 °C or less by flowing dry ice solid-gas state of CO_2 in a refrigeration system. Solid CO_2 in the refrigeration system may cause to block the flow in the evaporation process and make the system operation failed. In order to overcome the blocking phenomena and farther challenging lower refrigeration temperature, the CO_2 cyclone separator was newly proposed instead of the conventional evaporator for ultra-low temperature energy storage. The basic characteristics of CO_2 dry ice cycle separator were investigated by constructing test rigs and visual experiments. The visualization tests were carried out by three type separators: non-swirling type separator, cylindrical, and conical type cyclone separators. The results of visualization tests showed that the size of the dry ice particles gets bigger by coalescing together with the strong

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swirling flow in the cyclone separator. In comparison with three type separators, particularly by using the conical type cyclone separator, the amount of accumulation of dry ice at the bottom of the separator was increased as a result of the growth in dry ice particle size.

Keywords: CO_2, Dry Ice Cyclone Separator, Ultra-low Temperature Energy Storage

1. Introduction

The natural substance CO_2 as a refrigerant was proposed by Lorentzen [1] in the 1990s followed by the technological improvements on CO_2 capture and storage in the early 2000s. From that time, it has gained great importance by researchers in refrigeration and heat pump areas. CO_2 is one of the promising environmentally friendly refrigerants because of its superior properties such as low Global Warming Potential (GWP), zero Ozone Depletion Potential (ODP), non-toxicity, non-flammability, and inertness [2]. As for other features of carbon dioxide, dry ice (solid phase of CO_2) is formed below the CO_2 triple point of the temperature of -56 °C and pressure of 0.518 MPa. The density of dry ice at atmospheric pressure is 790 times higher than the gaseous-phase itself. Based on these advantages, CO_2 can be utilized when CO_2 solid-gas phase used as a working medium in refrigeration systems.

Based on the above advantages, CO_2 refrigeration systems have received substantial interest from the researchers, especially for low-temperature applications. Liu et al. [3] conducted experimental research on dry ice particle production and agglomeration process. They used a specially designed hose, which was thermally insulated, and it was connected to an expansion nozzle where the dry ice particles were produced by the expanding of CO_2 passing through the nozzle. In another study, they investigated the dry ice particle production utilizing CO_2 by expanding lit through an expansion nozzle. They

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analyzed the size distribution and the produced dry ice amount for different conditions [4]. Ghazaani and Parvin [5] introduced a novel chilling system working with carbonic powder and the ethylene glycol mixture. The integrated system's works principle is based on the thermal exchange of liquid and solid CO_2 with lower energy consumption and higher refrigeration volume. A general review study on CO_2 based low-temperature refrigeration systems was performed by Bansal [6] that deals with the fundamentals and applications. Karampour and Sawalha [7] reviewed the studies on transcritical CO_2 refrigeration systems in terms of energy efficiency, performance, and environmental effects. A similar study was carried out by Gullo et al. [8] for European climate conditions in the retail food industry.

In 2008, a novel cryogenic refrigeration method that utilizes CO_2 solid-gas two-phase flow and the dry ice was introduced by Yamaguchi et al. [9]. They constructed and patented an experimental setup in order to maintain CO_2 solid-gas two-phase flow for achieving a refrigeration process less than the triple point of CO_2, -56.6 °C. In their following research, they developed a cascade refrigeration system working with CO_2 where the upper cycle was CO_2 trans-critical cycle, and the lower one was a trans-triple-point cycle. According to their results, the proposed cascade CO_2 cycle achieved the refrigeration below -56.6 °C, with an average COP value of 2.45 [10]. Two years later, Niu et al. [11], reported the results of their experimental study on the two-phase solid-gas flow of CO_2 for an ultra-low temperature cascade refrigeration system where they reached to -62 °C continuously and steadily. In their further studies, the heat transfer characteristics [12], dry ice blockage of CO_2 two-phase flow with dry ice sublimation [13], the performance of the system using tapered evaporator/sublimator [14] and CO_2 dry-ice comportments in the evaporator/sublimator [15] were investigated. An ultra-low temperature below the triple point of CO_2 achieved by the researchers by expanding the sufficiently cooled liquid CO_2

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into solid-gas two-phase, however, it has been reported that a blockage problem due to the dry-ice occurred in the evaporator/sublimator [13] that causes an operation failure when the system was operated at lower temperature conditions. One of the solutions to prevent the blockage phenomenon is to separate dry-ice particles from the CO_2 solid-gas two-phase flow using a cyclone separator or an electrostatic precipitator. However, in the utilization of the electrostatic precipitator for dry ice particles, the main problem is that the dry ice particle covers the dust collecting electrode and is sublimated immediately by corona discharge. On the other hand, a cyclone separator can separate dry-ice particles from the flow of solid-gas two-phase CO_2 by eliminating the external electric power and can be used for the collection unit as a low-temperature heat storage tank.

From the above reason, in this study, a dry ice cyclone separator for ultra-low temperature energy storage was proposed with a novel design of the evaporator/sublimator in order to prevent the dry ice blockage during evaporation/sublimation process. The essential characteristics of CO_2 dry ice cyclone separator were investigated by constructing test rigs and visual experiments. For the performance assessment, the analyses were carried out for three different type cyclone separators: non-swirling type separator, cylindrical, and conical type cyclone separators. Dry ice collection efficiency as a performance characteristic was studied for the different types of configurations.

2. Experimental CO_2 dry ice cyclone separator

For investigating the dry ice storage phenomenon, which might be occurring during the sedimentation/sublimation operation of the ultra-low temperature energy storage process using CO_2, a cyclone separator was developed and constructed, as shown in Figure 1. The experimental set-up has three components: a cylinder tank that contains liquid CO_2 at 12 MPa and 15 ˚C, an orifice nozzle, a cyclone separator. The cyclone separator, which is

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made of acryl for visualization consists of an inlet channel, outlet channel, separator chamber, and storage chamber. The cyclone chamber was designed for utilization in an actual refrigeration system, which is sufficiently long as 360 mm so that the required phenomenon can be noticed and examined at the chamber. A separator chamber coupled to the CO_2 cylinder is constructed from acryl, that has an inner diameter of 14 mm and a length of 150 mm. Besides, the diameter of the orifice nozzle is adjusted to 0.51 mm. The characteristic experiments are based on the temperature measurements from two different locations of the cyclone separator and mass measurements of CO_2 (Figure 1).

In a typical experiment, the liquid CO_2 contained in the cylinder expands through the expansion valve, and dry ice particles are produced by the Joule-Thomson effect. The solid-gas CO_2 flow induced by the inlet channel flows down along the inner wall of the separator chamber. Dry ice particles with relatively high density settle down into the storage chamber while the CO_2 in the gas phase flows up to the outlet channel because of the pressure difference induced by the strong swirling flow of solid-gas flow through the separation chamber.

For observing the difference of the dry ice particle characteristics, three separators with different shapes of conical, cylindrical, and non-swirling types were used. The schematic drawing and the structural parameters of three different separators are given in Figure 2. The cylindrical type cyclone separator is most classical cyclone design [16, 17], and it is considered that the smaller dry ice particles flow out by inner vortex flow because the density of dry ice particles will be changed by the sublimation. The other types are the non-swirling type (free fall separation by density difference), and the cylindrical type (expected to produce week cyclone separation by off-set centrifugal force). The experimental apparatus is made from acrylic for observing the flow of the dry ice pieces.

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In the cylindrical and the non-swirling types, inner and outer diameter of the inlet section, the separator, and the storage section are the same (with 160 mm of inner diameter and 180 mm of outer diameter), and in the conical type, the inner diameter of the lowest part of the separator section is 60 mm. During the experiments of the collection efficiency measurements, the storage chamber is covered by the glass wool type of insulator, which is 25 mm in thickness for avoiding the heat loss to the atmosphere.

During the experiments, T-type thermocouples with an uncertainty of 0.1 °C were used for the temperature measurements. The pressure was varied between 1.0 to 3.0 MPa at the entrance of the orifice nozzle with the help of a control valve. In the course of testing, the pressure was set as the same as the conditions of the actual cascade heat pump system's evaporator/sublimator. The mass of the accumulated dry ice, M_1, and liquid CO_2, M_2, are measured by a mass meter installed at the bottom of the cyclone separator, as illustrated in Figure 1. In order to measure the dry ice particle diameter in the separation process, a high-speed camcorder (flame speed of 3000 fps) is used. 4000 to 6000 particles are sampled at two positions of the separator (z=245-255) and the storage section (z=435-445), respectively. The biaxial mean diameter d is determined by measuring the primary axis diameter and minor axis diameter of the particles.

The collection efficiency η is determined by the mass of the dry ice accumulated in the storage chamber (M_1) and the mass change of the liquid CO_2 (M_2) flowing in the cylinder, as expressed in Eq. (1).

$$\eta = \frac{M_1}{M_2} \tag{1}$$

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3. Results and discussion

3.1. Collection efficiency

As described in the previous section, the experiments for ultra-low temperature energy storage were performed for newly designed three types of cyclone separators, and the collection efficiency was examined with varying the inlet pressure from 1.0 to 3.0 MPa. Figure 3 shows the collection efficiencies of three types of cyclone separators. As seen from the left axes of the figure, the dry ice collection efficiency for the three types indicates an efficiency value of less than 25 %, which is a rather low efficiency compared with conventional cyclone separator for dust collection [18, 19]. However, all the CO_2 discharged from the cylinder does not become dry ice. When the liquid CO_2 in the cylinder expands at constant enthalpy at 12 MPa and 15 ˚C, the dry ice concentration of the discharged solid-phase CO_2 becomes 27%. Therefore, assuming that 27% of the discharged CO_2 is dry ice flowing into the separator, the right-hand side of the figure can be plotted. Based on the solid-phase, as shown on the right side, the dry ice collection efficiency would become 93.0 %, in case of using the conical pipe at 2.5 MPa, which is almost the same value by using conventional cyclone separators for small particles such as dust collection. From the above reason, it is found that the proposed cyclone separator with conical type has the best performance for dry ice particles.

According to the results, the collection efficiency increases with the increase of the pressure at the nozzle inlet for all separator types. When the inlet pressure increases, the collision frequency of dry ice particles becomes higher due to the increasing velocity of solid-gas two-phase flow with the retention time of dry ice particles. However, in the case of using the non-swirling type cyclone separator, the collision of dry ice particles was observed to happen at the wall of the separator and storage section. On the other hand, in case of using the cylindrical and conical type cyclone separators, the collision of dry ice

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particles was often happened at the wall of the separator section due to the centrifugal force acting on the dry ice particles by the induced swirling flow. By inducing the swirling flow at the separation section, the retention time of dry ice particles increases with the increasing of the velocity of particles resulting in particle aggregate growth. As the radius of the separator section decreases along the flow direction, the centrifugal force increases, and aggregation becomes stronger. In other words, by inducing a strong centrifugal force, the number of collisions between dry ice particles is increased to promote the particle growth, and it is possible to reduce disappearance due to the sublimation of dry ice, which leads an increase in collection efficiency. In this study, since the centrifugal force increases in the order of the conical type, cylindrical type, and non-swirling type, the conical type cyclone separator has the highest dry ice collection efficiency than others.

3.2. Temperature distribution

In order to investigate the performance of the novel cyclone separator for low-temperature energy storage, temperature distributions are examined at the upper and bottom part of the cyclone separator for the CO_2 inlet pressure of 2.5 MPa. Figures 4 (a), (b), and (c) show the temperature distributions in case of non-swirling, cylindrical, and conical type separators. In Figure 4(a), the temperature distribution before discharge (0 ~ 116 s) and after discharge (116 s ~ 900 s) is plotted against time for non-swirling type separator. The results showed that, during the discharge of the dry ice particles, the temperature at the upper wall and bottom wall decreases due to the heat absorption by the dry ice particles. The temperature at the upper wall dramatically increases after the discharge of dry ice (after 116 s). On the other hand, the temperature at the bottom wall continues to decrease until 164 s and after this time, the temperature increases gradually. The temperature variation is mainly due to the temperature at the upper wall is greatly affected by the trajectory of dry ice particles absorbing heat from the wall. After the

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discharge of dry ice particles, the temperature dramatically increases because of no dry ice particle passing through the thermocouple point. When the discharge of dry ice particles eased, the temperature at the bottom wall dramatically decreases owing to the reason that the pressure in the cyclone separator decreases after the discharge and temperature increases by the sublimation of the sedimentation of dry ice at the bottom of the cyclone separator. In the case of the cylindrical type separator, the temperature at the bottom wall remains nearly constant and slightly increases in the range of -77—-75 ˚C after the discharge of dry ice particles (112 s) as illustrated in Figure 4(b). For the conical type separator, as shown in Figure 4(c), the temperature at the bottom wall remains still constant at the value of -76 ˚C after discharge (112 s) of dry ice particles. The main reason for these lies in the dry ice sedimentation that absorbs a significant amount of heat by sublimation. However, in the case of the cylindrical type separator, it is considered that the temperature gradually increases since a sufficient amount of dry ice is not being formed. Therefore, by using the conical type cyclone separator, it is possible to maintain a constant ultra-low temperature at -76 ˚C for cold energy storage for eight times higher than the discharge time of 112 s.

3.3. Dry ice particle size distribution

Distribution of dry ice particle size is one of the most critical factors for better cold energy storage and heat transfer. For this reason, the visual experiments were also performed in order to investigate the separation mechanism of dry ice in the cyclone separators. However, in the case of non-swirling type separator, the dry ice particles disperse as small size particles and flow toward the outlet of the cyclone separator due to the large pressure drop. For this reason, the visualization of dry ice particles becomes very difficult for non-swirling type separator. Therefore, in order to investigate the dry ice particle size distribution, the experiments were only performed for cylindrical type and conical type

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cyclone separators.

Figures 5 and 6 show the particle distribution in the cylindrical and the conical type cyclone separators at two positions; separation and storage sections, respectively. The results of the particle distribution in the cylindrical type show that the particle size, which is less than 5.5 mm in diameter, dominates more than 90 % of the total amount for both separation and storage sections (Figure 5). This is because the dry ice particles fall into the storage chamber with relatively low swirling motion due to a weak centrifugal force that reduces the contact of particles with each other. The particle size distribution at the storage section in the cylindrical type cyclone separator thus keeps the same size distribution at the separation section, as shown in Figure 5. On the other hand, for the conical type cyclone separator, the particle sizes are distributed in the range of 0.5 - 40 mm, as shown in Figure 6. This is mainly due to the fact that in the swirling process at the separator section, the growing particles flow down to the storage chamber with collision to each other. Since the particles travel along the inner wall of the separation section with swirling motion caused by strong centrifugal force, the distance between particles becomes shorter, resulting in particle aggregation.

In Figure 7, the photos of the dry ice particles taken by the high-speed camera at the separation section are given. As seen from Figure 7(a) for cylindrical type separator, the dry ice particles disperse as small particles because of the lower aggregation amount. In the case of the conical type, the particle size distributes from 0.5 to 50 mm, as shown in Figure 7(b). Especially, it is important to pay attention to the small particle size of 0.5 mm. The increase of small size particles is caused by the splitting of the aggregated particles. When the particle growth increases in the separation section, the aggregations are formed as flat shapes due to the strong centrifugal force, as shown in Figure 7(b). Then the smaller

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size particles increase due to the splitting of the flat aggregated particles. As the dry ice aggregation is formed by the intermolecular forces, the aggregation can be easily split by the drag force induced by the centrifugal force.

In order to discuss the mechanism of dry ice aggregation, Figure 8 illustrates the behavior of dry ice particles in the cylindrical and conical type cyclone separators, which were drawn based on the visualization results, as shown in Figure 7. For the cylindrical type cyclone separator, dry ice powder forms small aggregation without growing to a larger size (Figure 8(a)). Thus, the collection efficiency of dry ice particles results in a lower value due to the weak centrifugal force. On the other hand, for the conical type cyclone separator, dry ice powder forms lower aggregation due to strong centrifugal force, and under the influence of large drag force, the collision frequency of aggregation increases resulting in aggregation growth. However, the growing aggregation particles are partially split by shear stress to form smaller particles, and the collision is repeated. It is observed that the aggregation of dry ice particles is the main cause of particle collection efficiency.

4. Conclusions

In this study, a preliminary investigation of a novel CO_2 dry ice cyclone separator for ultra-low temperature energy storage was introduced. The performance of the system was investigated experimentally using three different types of cyclone separators. The dry ice behavior in the cyclone separators was observed by the visual experiments. The main results are summarized as follows.

- The dry ice collection efficiencies were determined as 93%, 74%, and 61% for the conical type, cylindrical type, and non-swirling type cyclone separators, respectively.
- The conical type cyclone separator was found to have the highest dry ice collection

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efficiency than the others since the retention time of dry ice particles increased with an increase in the velocity of particles by a strong centrifugal force.

- The visualization results showed that the dry ice particles were widely distributed between 0.5 to 40 mm in the cyclone separator as spherical or flat-shaped particles due to the aggregation.
- In the case of using the conical type separator, the temperature at the bottom wall was kept at a constant temperature value of -76 °C due to the significant dry ice sedimentation. This result shows that the novel system can be successfully utilized in ultra-low temperature energy storage applications.
- The proposed cyclone separator, however, can still be developed by changing the configuration, and higher high collection efficiency rates can be achieved for a variable inlet pressure of the cyclone separator.

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Figures

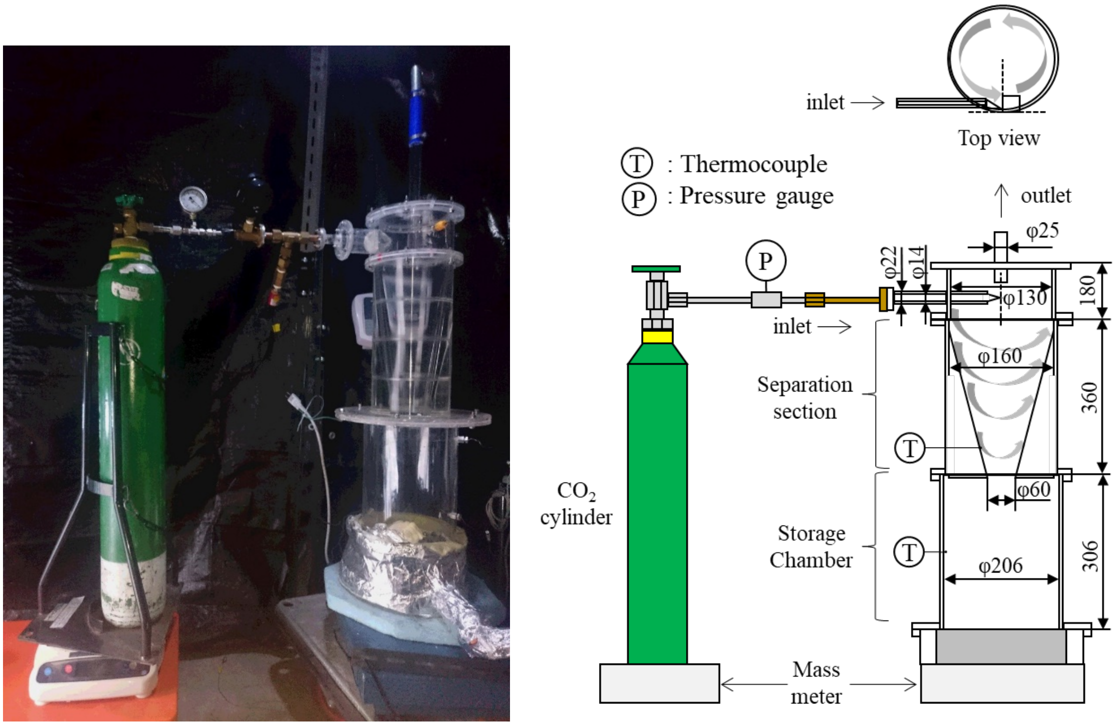

Figure 1. Schematic of the experimental apparatus of CO2 dry ice cyclone separator

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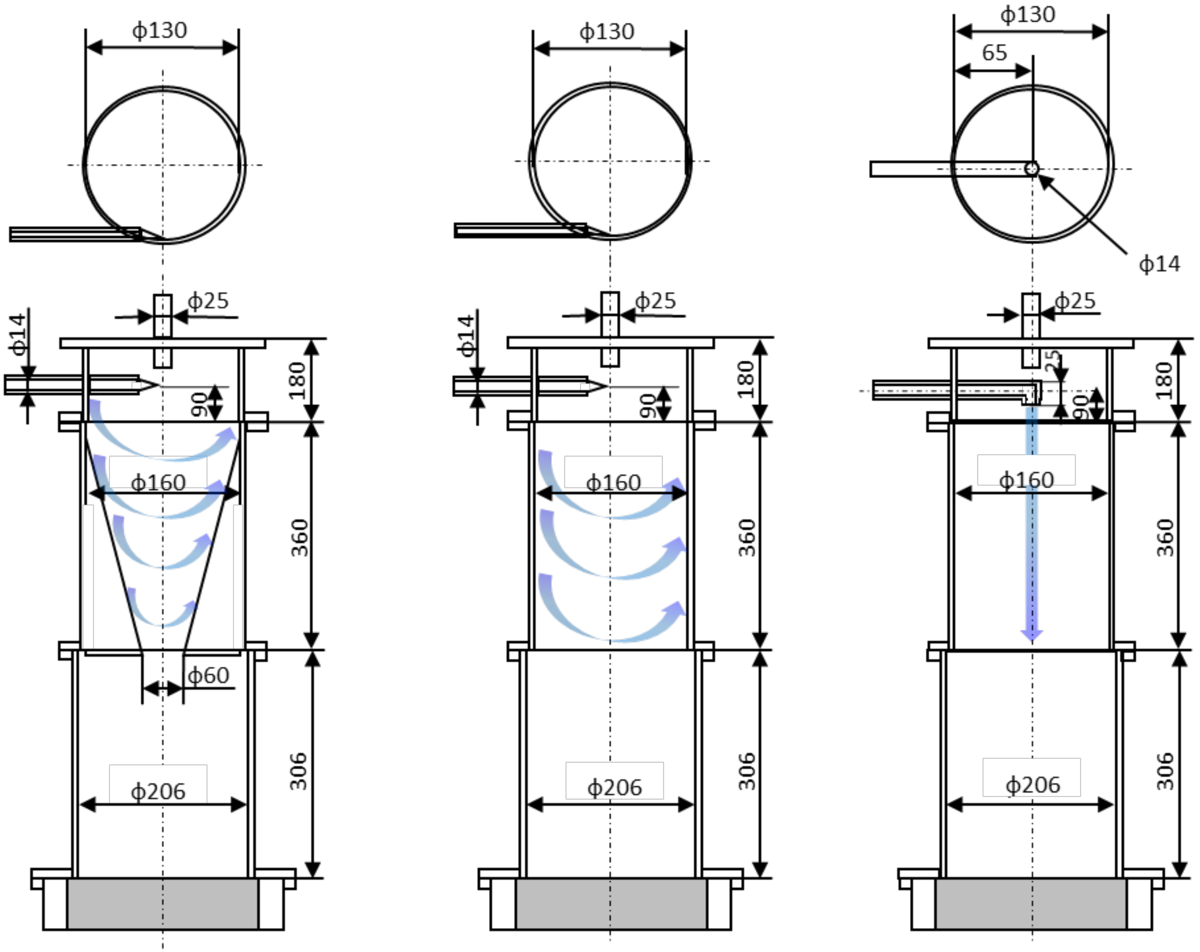

Swirling in the conical pipe

Swirling in the cylindrical pipe

Non-swirling

Figure 2. Three shapes of the separator

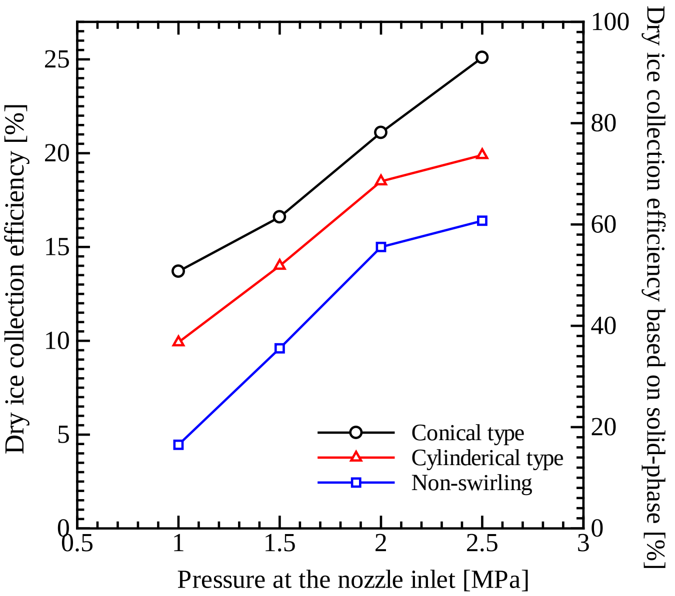

Figure 3. Relationship of the pressure at the nozzle inlet and collection efficiency

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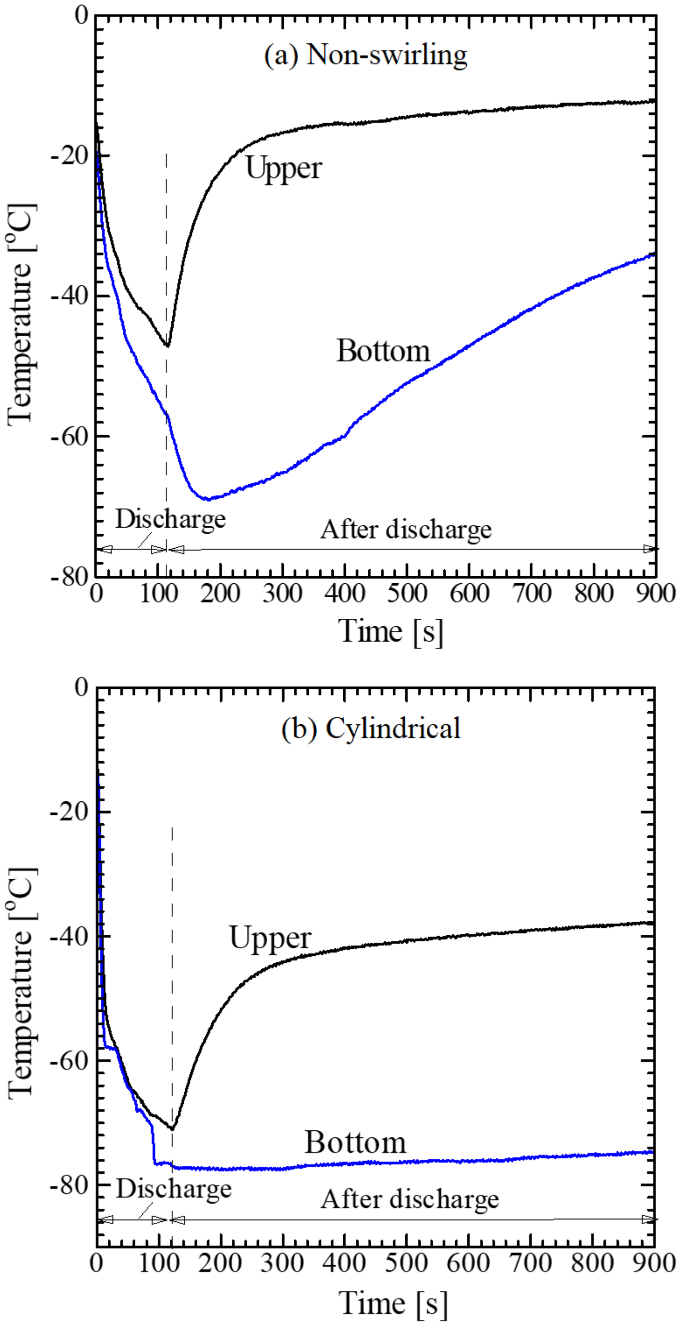
(a) Non-swirling
Temperature [°C]
0
-20
-40
-60
-80
Upper
Bottom
Discharge
After discharge
0
100
200
300
400
500
600
700
800
900
Time [s]
(b) Cylindrical
Temperature [°C]
0
-20
-40
-60
-80
Upper
Bottom
Discharge
After discharge
0
100
200
300
400
500
600
700
800
900
Time [s]

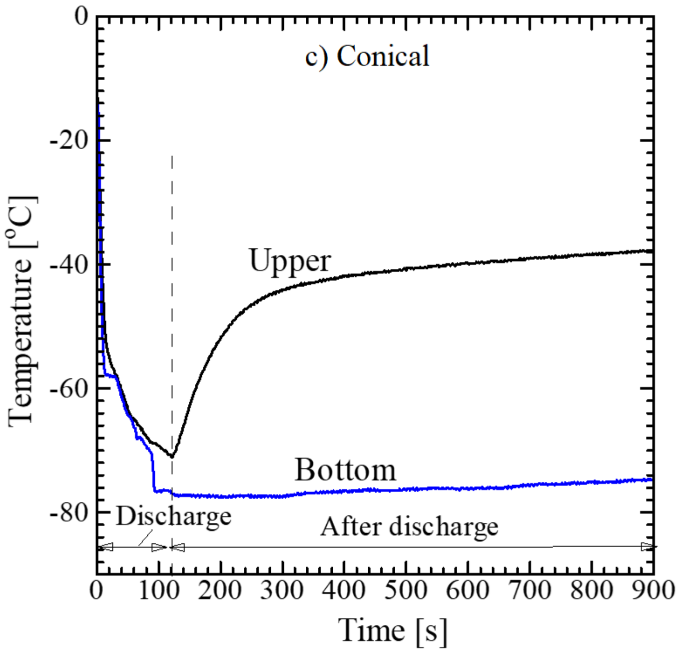

Figure 4. Temperature distributions at the upper and bottom part of the cyclone separator; (a) Non-swirling type (b) Cylindrical type separator (c) Conical type separator.

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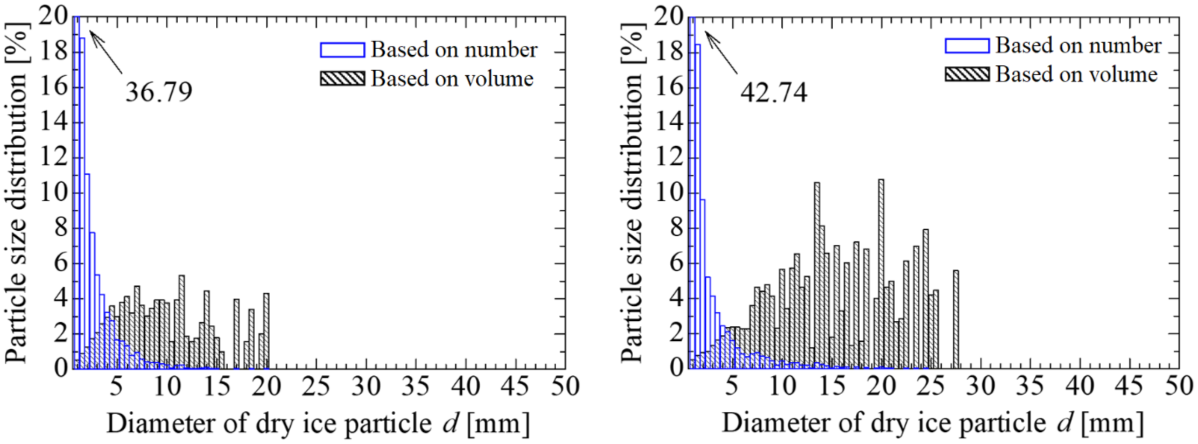

(a) (b)

Figure 5. Dry ice particle size distribution for cylindrical type cyclone separator at (a) separation section (b) storage section

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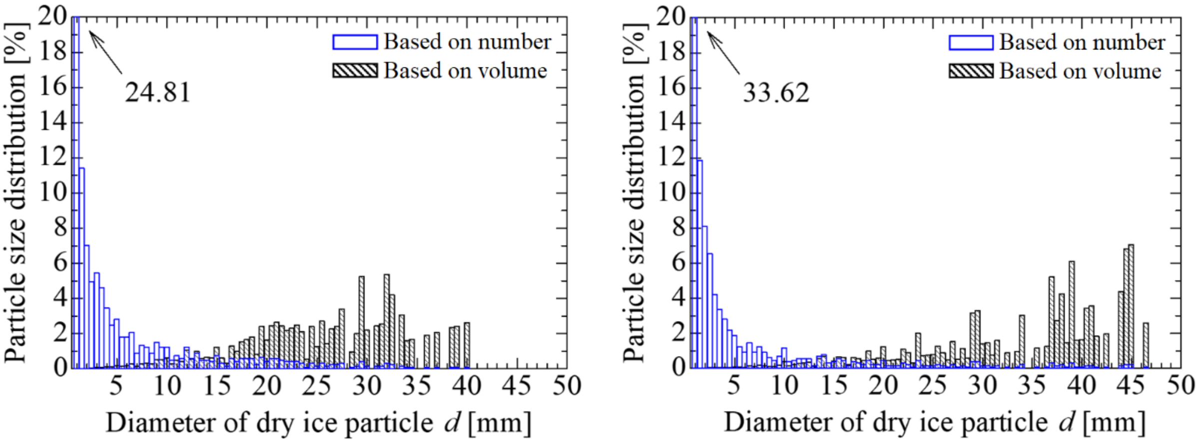

(a) (b)

Figure 6. Dry ice particle size distribution for conical type cyclone separator at (a) separation section (b) storage section

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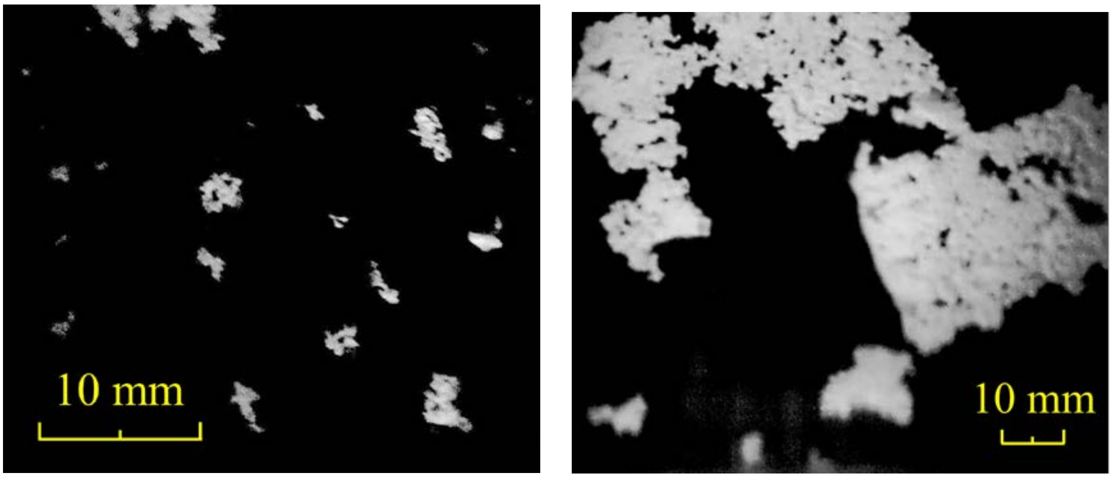
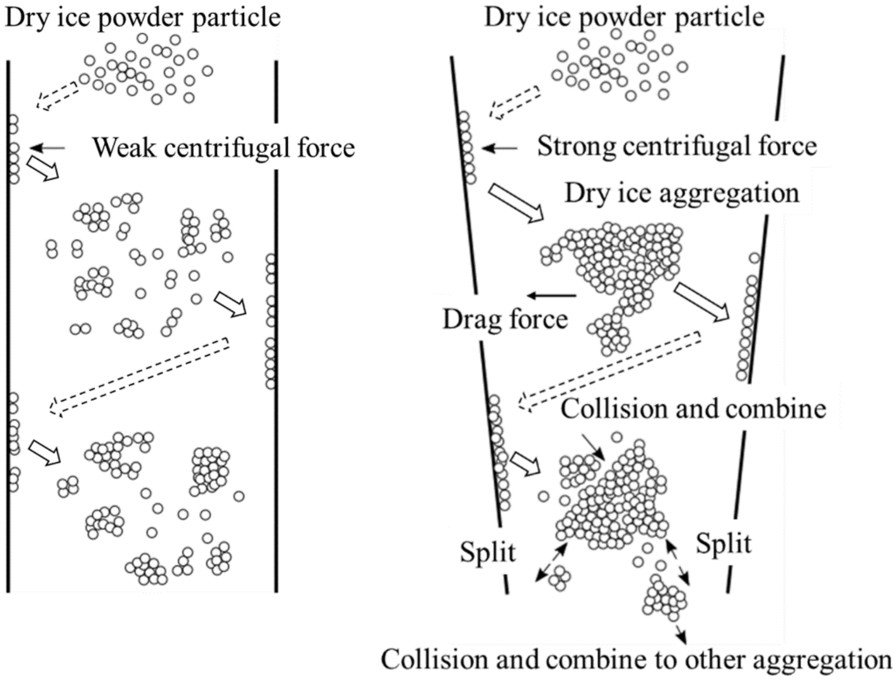


(a) (b)

Figure 7. Snapshot of dry ice particles by the high-speed camera (a) Cylindrical type (b) Conical type



(a) (b)

Figure 8. Illustration of dry ice particle behavior inside of the cyclone separator; (a) cylindrical type and (b) conical type

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