

Increasing energy saving of pilot-scale spray dryers with enhanced yield by low-adhesive surfaces

Jae Woo Sim^{a,1}, Haeyeon Lee^{a,1}, Sungwon Jo^a, Sanghyun Oh^b, Sungil Kim^b, Dong Rip Kim^{a,*}

^a School of Mechanical Engineering, Hanyang University, Seoul, 04763, South Korea

^b Energy Management System Laboratory, Korea Institute of Energy Research, Daejeon, 34129, South Korea

HIGHLIGHTS

- Pilot-scale spray dryer with low-adhesive surfaces was investigated.
- Yield of the spray dryer was monitored in terms of inlet drying air temperature.
- Low-adhesive surfaces greatly increased the yield of the spray dryer by 16.5%.
- Employing low-adhesive surfaces contributed the equivalent energy saving.

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ABSTRACT

Spray drying process, widely used in industrial applications, is highly energy-consuming. To reduce the energy consumption under the secured yield, optimizing the operating conditions of drying process or utilizing heat from the exhaust air of dryers has been carried out. Albeit their successful demonstration of energy saving, securing the yield of drying process still requires high temperature processing. Since high temperature processing often degrades or denatures the quality of dried materials in specific applications, further development of diverse strategies is necessitated for yield enhancement in low temperature environments. Herein, a spray drying method with low-adhesive surfaces is proposed to considerably increase the yield of drying process with no additional energy consumption or devices to accomplish the equivalent effects of the enhanced energy saving of spray dryers under the identical operating condition. The experimental results reveal that due to the significant reduction of the particle accumulations in the chamber of the spray dryer, equipping the low-adhesive surfaces to the conical walls of the pilot-scale spray dryer achieves up to 16.5% higher yield than control surfaces under identical operating conditions. This brings about the enhanced energy saving up to 14.2% to acquire the identical powder collection by the spray drying process.

1. Introduction

Drying process with thermal evaporation is widely used in many industrial plants including food [1–3] and chemical industry [4,5], which occupies the considerable portion of global energy consumption. For example, 9–25% of total industrial energy consumptions in developed countries were used to operate the dryers [6,7]. However, their energy efficiencies of drying (*i.e.*, the ratio of energy

* Corresponding author.

E-mail address: dongrip@hanyang.ac.kr (D.R. Kim).

¹ These authors contributed equally to this work.

required for evaporation to total supplied energy [8]) are still low [9,10], which needs further improvement.

As one of the most common dryers, spray dryers that change from liquid-state drying materials to solid-state particulates should be essentially used in the drying process owing to the capability to atomize thermally sensitive drying materials, including food and pharmaceuticals, thereby effectively controlling the sizes of dried particles [11]. However, thermal efficiency of spray drying is typically low, which results in a high degree of wasted energy [12]. In addition, it requires drying materials with high liquid contents to form droplets, which leads to high energy consumption to evaporate the liquid [13]. Hence, spray dryers are the relatively high energy consuming devices with low drying energy efficiencies, compared to other types of dryers, such as rotary dryer and drum dryers [12]. Although lowering the inflow drying air temperature can improve the drying energy efficiencies, it considerably decreases the yield of dried materials because the particle deposition on the chamber walls of spray dryers as mass loss is accelerated due to the liquid bridging phenomena on the chamber wall surfaces at the relatively low inlet drying air temperature [14]. For example, Maury et al. [15] and Magri et al. [16] conducted the spray drying experiment using the trehalose (*i.e.*, type of sugar) and maltodextrin (*i.e.*, type of carbohydrate) aqueous solution, respectively, resulting that the yield of spray drying effectively increased as drying air temperature increased. Likewise, Telang and Throat [17] experimentally investigated that the yield of soymilk spraying drying was effectively enhanced when the temperature of drying air was raised to near the glass transition temperature of drying materials. Venil et al. [18] experimentally investigated that the increasing the inlet drying air temperatures increase the yield of spray drying process for flexirubin powder solution. Kalkan et al. [19] demonstrated that increasing the inlet drying air temperatures increased the yield of a mixture of hazelnut oil and maltodextrin particle in spray drying process. As such, high-temperature drying air must be incorporated to

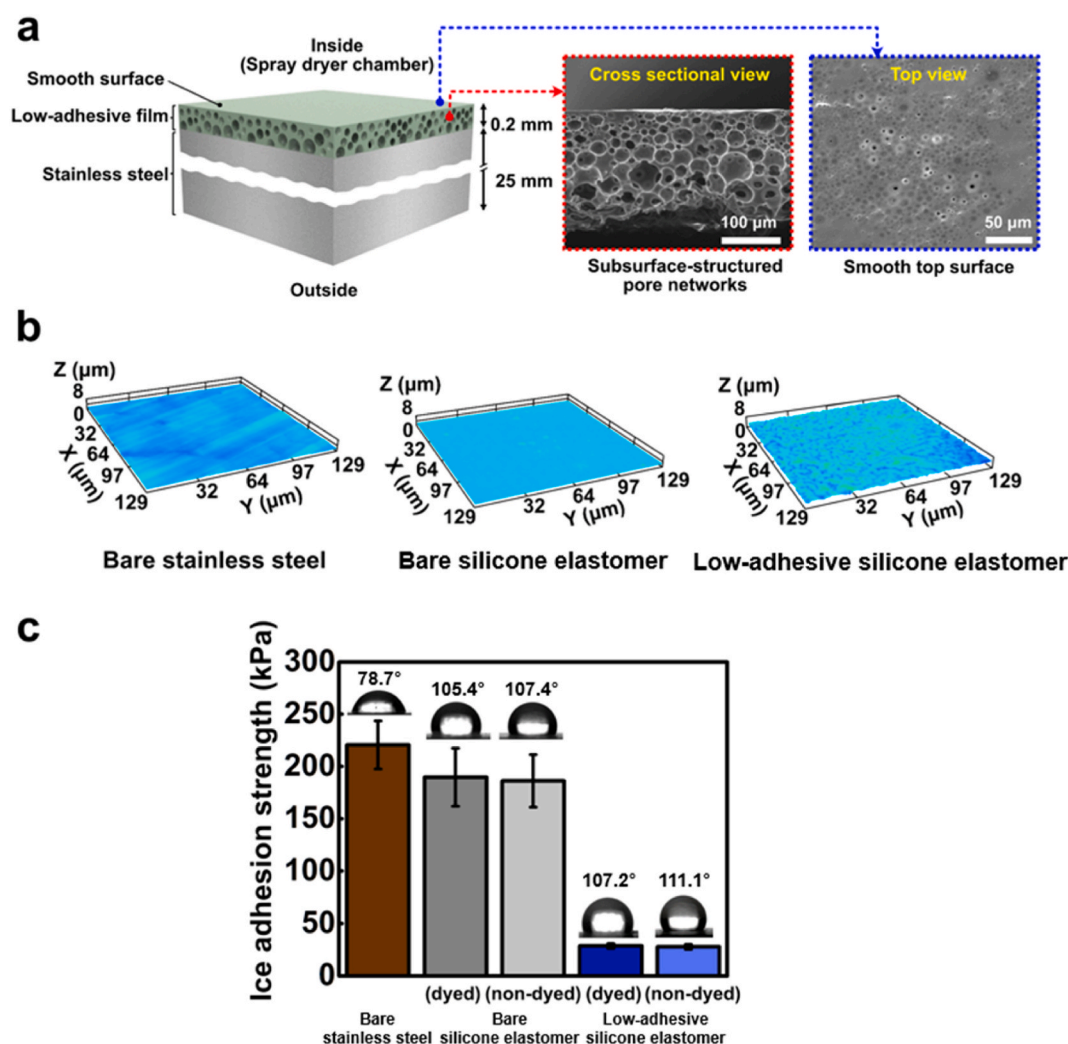


Fig. 1. (a) Schematic to illustrate low-adhesive silicone elastomer attached onto stainless steel surfaces (left) and scanning electron microscopy (SEM) images of low-adhesive elastomer films with cross-section view (middle) and top view (right). Scale bars: 100 μm (middle), 50 μm (right). (b) Three-dimensional (3D) surface morphology of samples (bare stainless steel (left), bare silicone elastomer (middle), and low-adhesive silicone elastomer (right)). (c) Ice adhesion strengths and contact angles of bare stainless steel, bare silicone elastomer (dyed and non-dyed specimens), and low-adhesive silicone elastomer (dyed and non-dyed specimens). Similar ice adhesion strengths and contact angles of dyed and non-dyed silicone elastomer show insignificant effects on their adhesion properties.

the spray dryers for securing the yield of drying process, which considerably decreases the energy efficiency of spray dryers [20,21].

Considering the fact that high-temperature drying air is inevitably used to secure high yield, utilizing heat from the exhaust air of spray dryers (i.e., exhaust air heat recovery) was actively studied to preheat the feed air and improve their energy efficiencies. Velic et al. numerically investigated the heat recovery system to directly mix the exhaust air with feed air [22]. However, the high moisture content in the exhaust air degraded the dryness of the feed air. Hence, the 60% of the exhaust air as the maximum was recirculated for the direct mixing with the feed air, leading to the energy consumption decrease of the spray dryers by 14%. To resolve the issues arising from the high moisture content in the exhaust air, Patel and Bade proposed the hybrid recovery system in which the feed air temperature first increased by the waste heat from the exhaust air and then the 90% of the exhaust air was mixed with the feed air, leading to the energy efficiency of the direct mixing method by 16.3% [23]. Ai et al. suggested the heat recovery system with no mixing between the exhaust air and the feed air by introducing regeneration heat exchangers to raise the temperature of the feed air with the heat from the exhaust air, resulting in the 21.3% energy saving, compared to the control spray dryers, based on the numerical results [24].

However, the high temperature processing for the enhanced yield in spray drying often degraded or denatured the quality (e.g., morphology, ingredient, etc.) of dried materials due to the increased thermal stress of targets in specific applications, such as pharmaceutical and biochemical materials. For example, Ameri and Maa [25] experimentally investigated the quality of biopharmaceutical materials (e.g., protein) obtained from spray drying process, which revealed that the protein was denatured in the inlet drying air temperature of $>100^{\circ}\text{C}$. The denaturation resulted from the high thermal stresses and the irreversible inactivation on drying materials

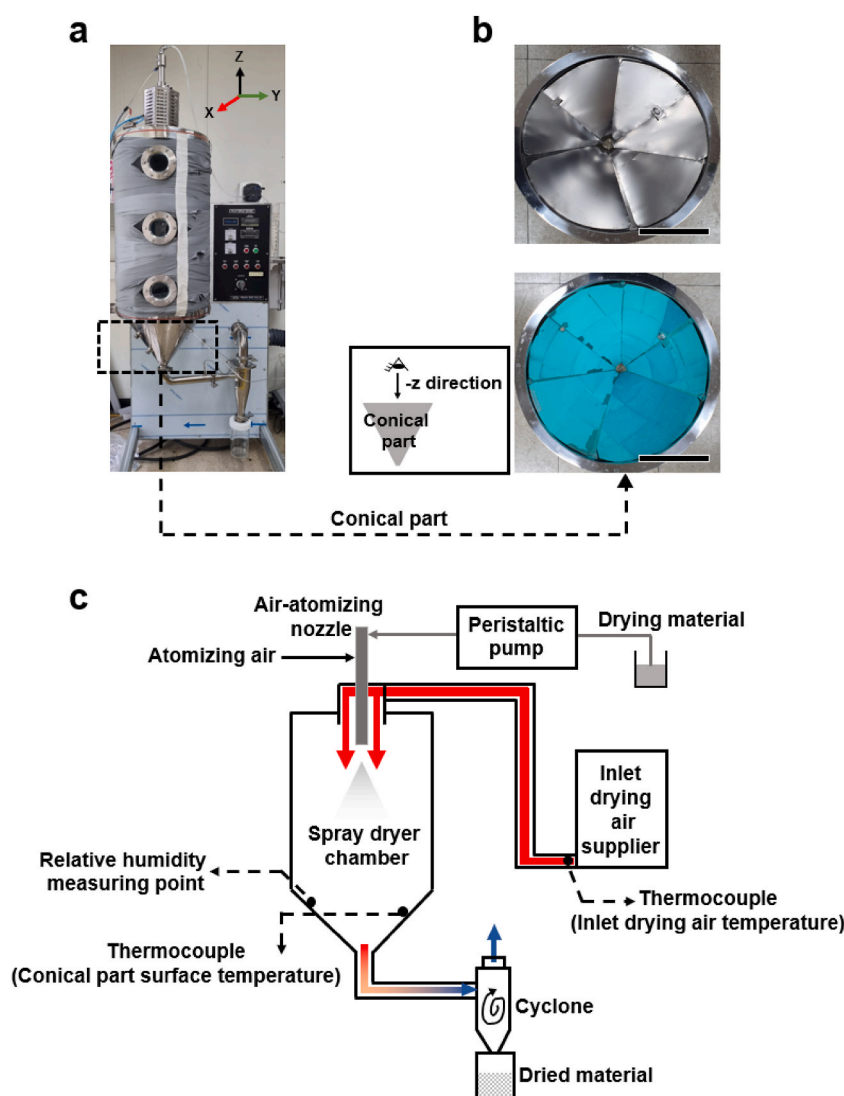


Fig. 2. Experimental setup of the pilot-scale spray dryer. (a) Photograph of the pilot-scale spray dryer. (b) Top-view photographs of the conical part in the spray dryer. Bare stainless steel surfaces (Top) and low-adhesive silicone elastomer surfaces (dyed samples for visual clarity) (Bottom) are attached on the conical part. Scale bar is 10 cm. (c) Schematic of the experimental setup.

by the high temperature of the air. Rodklongtan and Chitprasert [26] conducted the spray drying experiments using probiotics suspension to analyze the effects of the inlet drying air temperatures on the quality of probiotics as a model microorganism. In their experiments, probiotics were impaired in the inlet drying air temperatures of 130–150 °C, which indicated that low temperature processing was important in spray drying of heat-sensitive organic materials. Suryabhan et al. [27] experimentally investigated the quality of yeast powders obtained from the spray drying process with a mixture of yeast powders and solvents, which revealed that the yeast powders could be severely damaged in the inlet drying air temperature of 120 °C, while their quality was improved in the inlet drying air temperature of 100 °C. From that point of view, diverse strategies that can be applied in low temperature processing need to be further developed for performance enhancement of spray dryers. In addition, no additional equipment or energy consumption is preferred in developing those strategies. Herein, we propose a spray drying method with low-adhesive surfaces to considerably increase the yield of drying process with no additional energy consumption or devices, thereby increasing the yield of spray dryers under the identical process temperatures or increasing the energy saving of spray dryers under the identical yield. Specifically, the conical walls in the chamber of a pilot-scale spray dryer were rendered low-adhesive to significantly reduce the particle deposition on the chamber walls. Experimental investigations revealed that employing low-adhesive surfaces to the chamber walls of spray dryers led to up to maximum 1.17 times higher yield than the control one under identical operating conditions. The significantly increased yields under the identical operating conditions could be interpreted as the maximum 1.14 times decreased energy consumption to acquire the identical powder collection by spray dryers.

2. Experimental

2.1. Fabrication of low-adhesive silicone elastomer film with a smooth surface

Low-adhesive silicone elastomer film with a smooth surface morphology and subsurface-structured pore networks (Fig. 1a) was prepared by using a water steaming method as in our previous study [28]. Specifically, in the water steam environment, water droplets are injected to liquid-state silicone elastomer under curing. This process enables to construct the interconnected pore networks inside the solid-state silicone elastomer film after curing. The embedded-pore structures generate stress concentration effects to easily detach adherents from the surfaces. First, a liquid-state silicone elastomer (polydimethylsiloxane, PDMS) prepolymer a mixture of bare and curing agent (Sylgard 184, Dow Corning) as a weight ratio of 10:1 was prepared by using a centrifugal mixer (ARE-310, Thinky). 5 wt % green pigment was added to the prepared liquid-state silicone elastomer prepolymer in order to clearly visualize deposition of white drying materials. Second, the liquid-state green-pigmented prepolymer was spin-coated on the hydrophobic surface at a spin rate of 300 rpm for 5 min. It should be noted that a hydrophobic substrate was prepared by coating 1 wt% Teflon AF amorphous fluoroplastic resin (AF2400, Chemours) in fluorine solution (FC-40, Sigma-Aldrich) on a handling substrate, followed by curing at 165 °C for 10 min and 245 °C for 5 min. Lastly, it was placed in an autoclave containing boiling water and heated at 120 °C for 30 min. In the autoclave, the pressurized water vapor penetrated the liquid-state silicone prepolymer under curing. As a result, the cured silicone elastomer had the interconnected pore networks, while the pore sizes were small at the contact part between the silicone elastomer and the hydrophobic substrates due to the formation of small-sized water droplets on hydrophobic surfaces [28]. After the water steaming process, the silicone elastomer was further cured at 100 °C for 30 min for full drying. The silicone elastomer separated from the substrate was attached upside down onto the target stainless steel surfaces of the conical part of a spray dryer using a thin adhesive tape (DVA-T1405-5, DAVO C&M) with a thickness of 5 µm. The thickness of low-adhesive silicone elastomer film was controlled as 200 µm.

2.2. Performance characterization of a pilot-scale spray dryer with low-adhesive surfaces

The experimental procedures of the pilot-scale spray dryer (PSD-05, Yoojintech) as shown in Fig. 2a were adopted from the previous study [29]. First, the inlet drying air with an absolute humidity of 0.0180–0.021 kg/kg, a temperature of 30 °C, and a flow rate of 32.6 kg/h was introduced by using a fan to the pilot-scale spray dryer, while deionized water was sprayed at a flow rate of 9.8 g/min until the humidity and the air temperature of the dryer were stabilized. In order to compare the drying performance with the low-adhesive surfaces, the conical part of the spray dryer was modified. Specifically, a total of eighteen stainless steel sheets with a thickness of 0.7 mm and a radius of 15 cm were prepared. Six stainless steel sheets were used for control stainless steel surfaces, bare silicone elastomer surfaces, and low-adhesive silicone elastomer surfaces, respectively. Those sheets were attached over the conical part of the spray dryer by using an aluminum tape as shown in Fig. 2b. The inlet drying air, the exhaust air, the conical part surface temperatures were monitored by using type K thermocouples as shown in Fig. 2c. Second, 450 ml of drying material was sprayed in the drying chamber by using an air-atomizing nozzle (XA-PR, Hanmi Nozzle) with a mass flowrate of 0.26 g/s and a pressure of 0.9 MPa and by using a peristaltic pump (YZ1515x, LongerPump) with a mass flowrate of 9.8 g/min to feed the liquid-state drying material. After feeding drying materials, the spray drying process was carried out for 50 min for all the experiments. The drying material was prepared by mixing deionized water with maltodextrin (Qinhuangdao Lihua Starch Co. Ltd) at a weight ratio of 100:25. Lastly, dried

Table 1
Accuracies of measured parameters.

Parameter	Accuracy	Unit
Temperature (Type K thermocouple)	±0.1	°C
Air velocity	±0.1	m/s
Weight	±0.01	g
Relative Humidity	±1.5	%

material (i.e., powder) was collected from the cyclone positioned at the end of the exhaust. The mass of the deposited powder on the conical part of the spray dryer and the mass of the collected powder were measured by using a precision scale (XS802S, Mettler) with a resolution of 0.01 g. The yield was defined as the ratio of the collected powder mass to the inlet powder mass. The accuracies of the measured values are listed in Table 1. All the experimental cases were repeated three times.

2.3. Experimental characterization of powder adhesion properties on sample surfaces

The powder adhesion properties on the sample surfaces, such as bare stainless steel and low-adhesive silicone elastomer, were experimentally investigated (Fig. 3). Specifically, 0.2 g maltodextrin powder was uniformly distributed on each sample surface with an area of $10\text{ cm} \times 1.5\text{ cm}$ by using a test sieve (16 mesh/inch). Then, air was blown through the nozzle with a diameter of 3 mm over the surface for 1 min at room temperature. Blowing air velocity was measured at the center of the surface by using a speedometer (AM130, KIMO). The critical air velocity was defined as the blowing air velocity at which $\sim 90\%$ of the powder located on the surface was removed. Each case was tested over three different samples, and the testing over each sample was repeated five times.

3. Result & discussion

3.1. Characterization of low-adhesive silicone elastomer surface

Low-adhesive silicone elastomer was fabricated by using a steaming process. Scanning electron microscopy (SEM) images in Fig. 1a show that the fabricated silicone elastomer film possesses pore networks as subsurface microstructures, while it has smooth top surfaces. The sample thickness of the low-adhesive silicone elastomer film was controlled as $200 \pm 10\text{ }\mu\text{m}$. Three-dimensional morphology and surface roughness were investigated by using confocal laser scanning microscope (OLS4100, Olympus). The surface roughness was characterized by calculating the arithmetical average roughness (R_a) for ten different lines of each sample at identical magnification. Three samples were characterized per each case. As shown in Fig. 1b, the surface roughness (R_a) of bare stainless steel, bare silicone elastomer, and low-adhesive silicone elastomer was $0.22 \pm 0.02\text{ }\mu\text{m}$, $0.16 \pm 0.03\text{ }\mu\text{m}$, and $0.46 \pm 0.04\text{ }\mu\text{m}$, respectively. In order to quantify the wettability and the adhesion of the prepared samples, water static contact angles and ice adhesion strengths were measured for the prepared samples (Fig. 1c). For better visible clarity, the low-adhesive silicone elastomer was colored with green pigment to clearly observe white dried materials in spray drying experiments. Static contact angle was characterized by using a goniometer (Phoenix-10, Surface Electro Optics) after placing a $10\text{ }\mu\text{l}$ of water droplet on the surface, and the static contact angle measurements were carried out five times per each sample. Water static contact angles of bare stainless steel, bare silicone elastomer (dyed), and low-adhesive silicone elastomer (dyed) were $78.7 \pm 3.4^\circ$, $105.4 \pm 2.7^\circ$, $107.2 \pm 3.6^\circ$, respectively. It should be noted that the non-dyed samples of silicone elastomer and low-adhesive silicone elastomer exhibited water static contact angles of $107.4 \pm 2.7^\circ$, $111.1 \pm 4.2^\circ$, respectively, showing that the dye process did not affect the wettability change. In addition, the ice-adhesion strengths were quantified by using a home-built apparatus [30,31]. Specifically, after a 200 ml deionized water-filled plastic tube (a diameter of 0.75 cm and a height of 1 cm) on the sample surface was frozen in an environmental chamber at -15°C , the force probe at

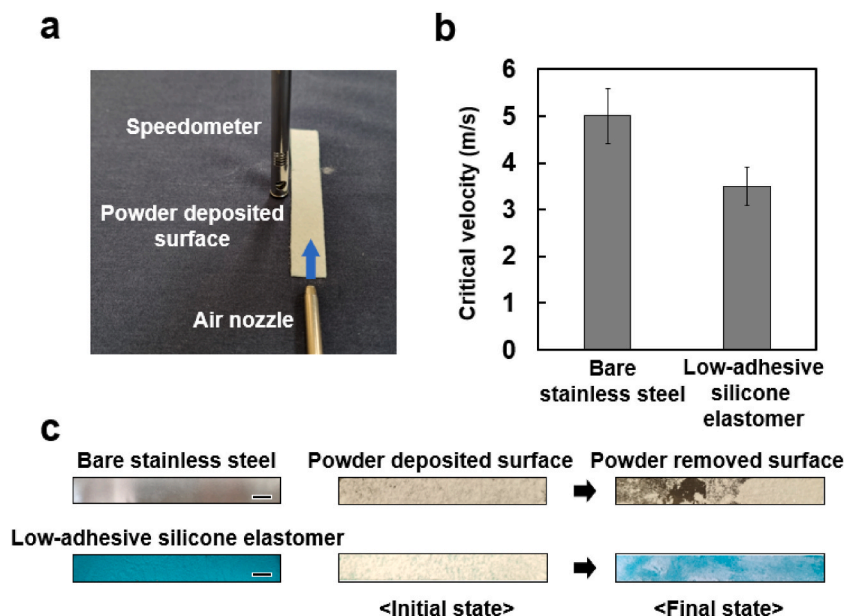


Fig. 3. Characterization of powder adhesion properties on bare stainless steel and low-adhesive silicone elastomer surfaces. (a) Photograph of experimental setup (b) Critical air flow velocities (i.e., the blowing air velocity at which $\sim 90\%$ of the powder located on the surface was removed), of bare stainless steel and low-adhesive silicone elastomer samples. (c) Photographs of intact surfaces, powder-deposited surfaces, and powder-removed surfaces for bare stainless steel and low-adhesive silicone elastomer. The blowing air velocity was 3.5 m/s. Scale bars: 1 cm.

a distance of 0.7 mm from the sample surface was moved with a speed of 0.05 mm/s in shear direction until the ice column was detached. The forces required to detach the ice column were measured by a load cell with a sensitivity of 5 mN. The ice-adhesion strengths were calculated by dividing the measured force with the projected area of the contact surface of the ice column (an area of 0.442 cm^2). The ice-adhesion strengths were measured five times in different locations of each sample, which was repeated for five different samples. As a result, ice adhesion strengths of bare stainless steel, bare silicone elastomer (dyed), and low-adhesive silicone elastomer (dyed) were $220.5 \pm 22.9 \text{ kPa}$, $189.6 \pm 27.7 \text{ kPa}$, $28.5 \pm 2.2 \text{ kPa}$, respectively. The non-dyed silicone elastomer and low-adhesive silicone elastomer exhibited the ice adhesion strengths of $186.1 \pm 25.0 \text{ kPa}$, $27.8 \pm 2.3 \text{ kPa}$, respectively. Although the low-adhesive silicone elastomer had similar water static contact angles with bare silicone elastomer, the ice adhesion strengths of low-adhesive silicone elastomer were 13% and 15% of those of bare stainless steel and bare silicone elastomer, respectively. The low adhesion strengths were attributed to the subsurface pore networks of silicone elastomer, which acted as a cavity to induce stress concentration between the deposited material and the surface, thereby realizing low-adhesive properties [28]. To investigate the effects of the low-adhesive properties on the detachment of powder accumulated on the surfaces, 0.2 g maltodextrin powder was uniformly distributed on each sample surface with an area of $10 \text{ cm} \times 1.5 \text{ cm}$ by using a test sieve. Then, air was blown through the nozzle over the surface for 1 min as shown in Fig. 3a. The critical air velocities which removed $\sim 90\%$ of the powder accumulated on the surfaces of bare stainless steel and low-adhesive silicone elastomer were $5.0 \pm 0.6 \text{ m/s}$ and $3.5 \pm 0.3 \text{ m/s}$, respectively (Fig. 3b). The residual masses of the powder on the surfaces at the blowing air velocity of 3.5 m/s were $0.13 \pm 0.03 \text{ g}$ and $0.02 \pm 0.01 \text{ g}$ for bare stainless steel and low-adhesive silicone elastomer samples, respectively (Fig. 3c). This represents that low-adhesive properties can effectively remove the accumulated powder from the surfaces by the shear force generated from the blowing air during the spray drying process.

3.2. Yield of the pilot-scale spray dryer with low-adhesive surfaces

Performance of the pilot-scale spray dryer was experimentally investigated in terms of different conical surfaces (Fig. 4). It should be noted that low-adhesive samples were attached on the conical part, because severe accumulation of powder was typically observed in the conical part of spray dryers [32]. First, in order to validate our experimental results in the pilot-scale spray dryer with the

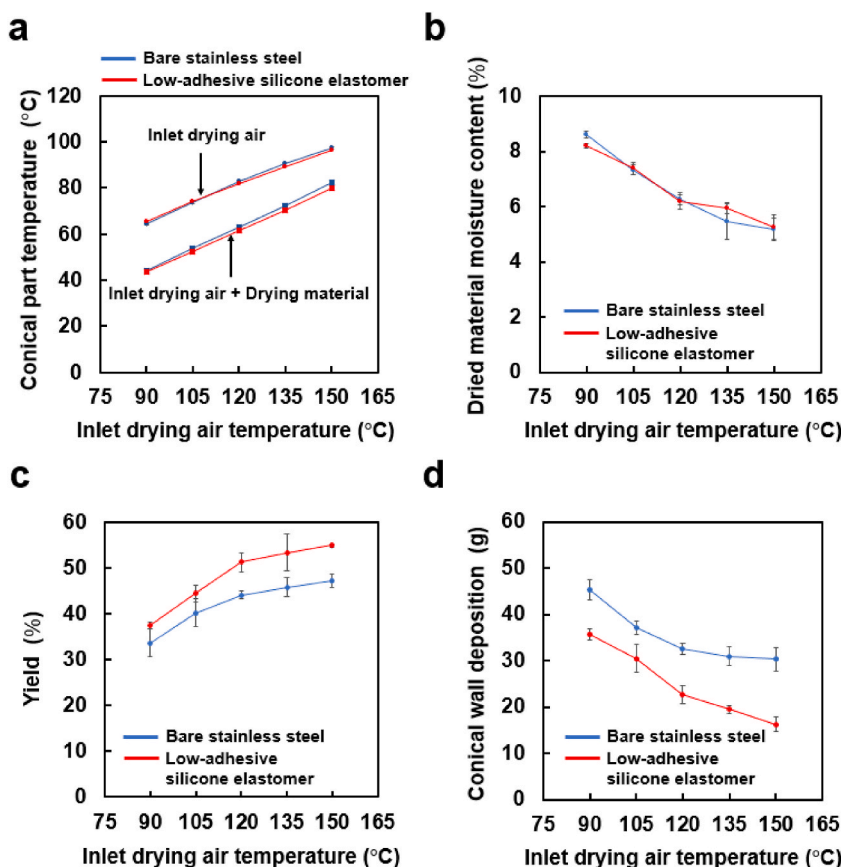


Fig. 4. Performance of the pilot-scale spray dryer in terms of different conical surfaces. (a) Surface temperature of the conical part, (b) moisture content of the dried materials, (c) yield, and (d) mass of the deposited powder on the conical surfaces in the pilot-scale spray dryer with the conical part with bare stainless steel (blue) and low-adhesive surfaces (red) in terms of inlet drying air temperature. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

previous study [33], the surface temperatures of the conical part and the moisture contents of the dried material were monitored in terms of different inlet drying air temperatures (Fig. 4a and b). It should be noted that the steady-state temperatures of inlet drying air and conical part surface were used in this study. Specifically, while the conical part surface temperatures increased as the inlet drying air temperatures, incorporating drying materials to the spray dryer chamber significantly decreased the surface temperature of the conical part, which was consistent to the previous report [33]. This implies that the considerably low temperatures of the conical part at low drying air temperatures can induce significant powder accumulation on the conical part due to the aggravated liquid bridging phenomena [14], which can lower the yield of the dried materials. In addition, all the dried materials in our experimental conditions showed the moisture contents less than 10 wt% (Fig. 4b), which was acceptable quality in the spray drying process, meaning that our experimental conditions can be regarded as representative sets in normal spray drying process [34]. Lastly, as shown in Fig. 4a, the surface temperatures of the conical part with bare stainless steel were similar with those with low-adhesive silicone elastomer surfaces (an average temperature difference between bare stainless steel and low-adhesive silicone elastomer-attached surfaces as 1.8 °C). The similar surface temperatures of the conical parts indicate that the insulation effects by the attachment of the low-adhesive silicone elastomer film on the conical part are negligible.

Interestingly, rendering the conical part surfaces low-adhesive remarkably increased the yield (*i.e.*, the ratio of the collected powder mass to the inlet powder mass) in the pilot-scale spray dryer (Fig. 4c). As the inlet drying air temperatures increased from 90 °C to 150 °C, the yield in the spray dryer with bare stainless steel and low-adhesive conical surfaces increased by ~40.1% and by ~46.5%, respectively. The increase of the inlet drying air temperatures in the spray drying process typically accompanied the increased yield because the lower relative humidity in the higher air temperature environments significantly suppressed the liquid bridging phenomena and the corresponding capillary forces between the powder and the surfaces [35]. Remarkably, equipping the low-adhesive conical surfaces considerably resulted in the 14.3% higher yield on average than the control bare stainless steel conical surfaces. The powder deposition in the conical wall was further quantified after the spray drying process, which showed the 17.7% (the inlet drying air temperature of 105 °C) - 46.2% (the inlet drying air temperature of 150 °C) (30.2% on average) lower powder deposition on the low-adhesive conical surfaces than on the bare stainless steel ones in the inlet drying air temperatures between 90 °C and 150 °C (Fig. 4d). Shear forces over the deposited powders in the conical part of the spray dryers arose from the continuous flow in the spray dryer [36], which induced the effective detachment of the deposited powders from the low-adhesive surfaces in the conical part of the

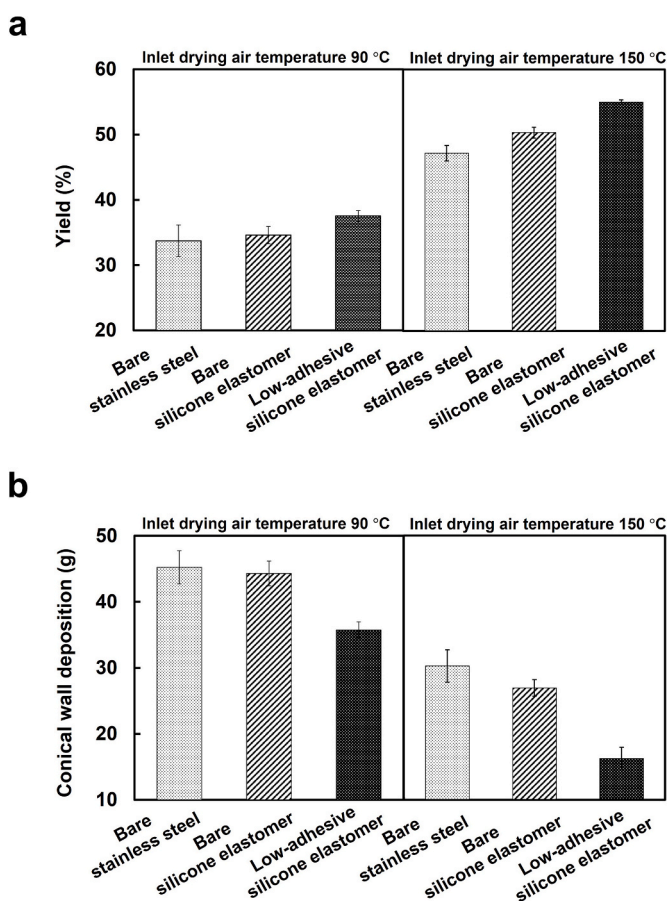


Fig. 5. (a) Yield and (b) conical wall deposition of the pilot-scale spray dryer with different conical part surfaces (bare stainless steel, bare silicone elastomer, and low-adhesive silicone elastomer surfaces) in the inlet drying air temperatures of 90 °C and 150 °C.

pilot-scale spray dryer. It should be noted that the lowered mass of the powder deposition on the conical part was higher than the increased yield of the spray dryer, which could be attributed to the powder loss (e.g., the powder deposition in the pipe or the powder escape through the vent pipe) during the spray drying process.

The considerably high yield of the pilot-scale spray dryer with the low-adhesive conical parts was attributed to the low-adhesion properties of the surfaces. In order to confirm this, the yield and the conical wall deposition of the pilot-scale spray dryers were compared in terms of the different conical part surfaces, such as bare stainless steel, bare silicone elastomer, and low-adhesive silicone elastomer surfaces (Fig. 5). As seen in Fig. 5a and b, the yield and the conical wall deposition of the spray dryer with low-adhesive surfaces were 11.4/16.5% higher and 21.0/46.2% lower than those with bare stainless steel surfaces in the inlet drying air temperatures of 90/150 °C, respectively, while bare silicone elastomer surfaces exhibited slightly higher (1–6%) yield and slightly lower (2–9%) conical wall deposition than bare stainless steel surfaces. Although the electrostatic forces between powder and surface can play an important role on the powder deposition in the less humid environment (<14% of relative humidities) of the spray drying process [14], our experimental results of bare stainless steel and bare silicone elastomer surfaces showed no considerable change in conical wall deposition (deposition mass differences of 0.9–2.4 g) as shown in Fig. 5b. This result confirmed that the enhanced yield mostly came from the low-adhesion properties of the conical surfaces rather than the wettabilities or the electrostatic properties of the conical surfaces. Interestingly, the relative enhancement of the yield of the spray dryer deployed with the low-adhesive conical surfaces was more distinct in the inlet drying air temperature of 150 °C than 90 °C. The higher temperatures of the inlet drying air resulted in the less humid environment to considerably reduce the conical wall deposition. The results indicate that low-adhesion properties more benefit the reduction of the conical wall deposition in less humid environment.

3.3. Thermal performance of the pilot-scale spray dryer with low-adhesive surfaces

Increased yield of spray dryers under the same operating condition was interpreted as their energy saving. To quantify the energy saving effects of the pilot-scale spray dryer with low-adhesive surfaces in the conical part, the energy analysis was conducted based on the experimental results in this section. Evaporation energy of moisture per collected powder is calculated and compared in terms of inlet drying air temperatures for the pilot-scale spray dryer with bare stainless steel and low-adhesive conical surfaces (Fig. 6). Evaporation energy of moisture per collected powder is defined as the ratio of the latent heat to evaporate the supplied liquid-state drying materials to the collected powder as equation (1).

$$q_{\text{evap}} = \frac{\lambda_{\text{latent}} m_{\text{evap}}}{m_{\text{cp}}} = \frac{\lambda_{\text{latent}} (m_{w,i} - m_{w,f})}{m_{\text{cp}}} \quad (1)$$

, where λ_{latent} [kJ/kg] is latent heat of evaporation, m_{evap} [kg] is the mass of evaporated moisture, m_{cp} [kg] is the mass of collected powder, and $m_{w,i}$ and $m_{w,f}$ are the moisture mass of drying material and dried material, respectively. After measuring the moisture content of dried material (%), the moisture mass of dried material is calculated by using the definition of the moisture content of dried material (= (the mass of dried material – the solid mass of drying material)/(the mass of dried material) × 100(%)). Rendering the conical part surfaces of the spray dryer low-adhesive decreases the evaporation energy of moisture per collected powder by up to 14.2% under the inlet drying air temperature of 150 °C (decreased by 12.4% on average). One of the operation goals of the spray dryer is to collect as much powder as possible while using relatively little energy. Although the same amount of energy was used to evaporate moisture under the same operating conditions at each inlet drying air temperature, the more amount of powder is collected when a low-adhesive silicone elastomer surface is attached. From that point of view, the attachment of low-adhesive silicone elastomer can bring about the equivalent effects of energy saving to collect the identical amount of powder, which enables efficient energy use of the spray dryer. We further analyzed their energy efficiencies. First, the energy efficiency of spray dryers (η) can be defined as a ratio of evaporation energy for operation time (t_{op}) ($\dot{Q}_{\text{evap}}$) to supplied heating energy ($\dot{Q}_{\text{heat}}$), considering the equations in the previous reports [21,23].

$$\eta = \frac{\dot{Q}_{\text{evap}}}{\dot{Q}_{\text{heat}}} = \frac{\lambda_{\text{latent}} m_{\text{evap}}}{t_{\text{op}} \dot{m}_{\text{da,in}} (C_{\text{pa}} + Y_{\text{da,in}} C_{\text{pv}}) (T_{\text{da,in}} - T_{\text{amb}})} \quad (2)$$

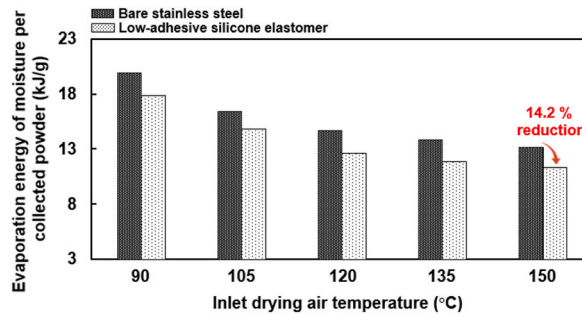


Fig. 6. Energy saving effects of the pilot-scale spray dryer with different surfaces in the conical part. Evaporation energy of moisture per collected powder at each surface in terms of inlet drying air temperatures.

where $\dot{m}_{da,in}$ [kg/h] is the mass flow rate of inlet drying air that entered the chamber of spray dryer, and C_{pa} [kJ/kg K] and C_{pv} [kJ/kg K] are specific heats of air and vapor, respectively. $Y_{da,in}$ is absolute humidity [kg/kg] of the inlet drying air, and $T_{da,in}$ [°C] and T_{amb} [°C] are temperatures of inlet drying air and ambient air, respectively. The numerical values used in our calculations are tabulated in Table 2. Fig. 7a shows that energy efficiency decreases as the inlet drying air temperature increases. It should be noted that equation (2) does not reflect the effects of low-adhesive surfaces on the yield. Therefore, we introduce the modified energy efficiency, considering the yield as follows.

$$\eta_{mod} = \eta \times \text{Yield}(\%) \quad (3)$$

Fig. 7b indicates the modified energy efficiency in terms of the inlet drying air temperatures. Equipping the low-adhesive surfaces onto the conical part of the spray dryer considerably increased the modified energy efficiencies of spray dryers from 16.1/10.6% (bare stainless steel case) to 18.0/12.3% (low-adhesive silicone elastomer case) in the inlet drying air temperatures of 90/150 °C, respectively. Therefore, the spray dryer with the low-adhesive surfaces exhibited 1.10–1.16 times higher modified energy efficiencies than the control case with bare stainless steel surface. More importantly, our strategy to increase the yield of the spray dryer without additional devices can be combined with the exhaust heat recovery methods to generate synergistic effects in the enhancement of energy saving effects of spray drying processes.

4. Conclusion

In this study, we demonstrated that integrating low-adhesive silicone elastomer to the conical part in the chamber of a pilot-scale spray dryer brought about the significant increase in the yield of the spray dryer, compared to the control spray dryer in which conical part surfaces are stainless steel. The low-adhesive silicone elastomer reduced the ice adhesion strengths of bare stainless steel by ~87%, and the powders accumulated on the surfaces of low-adhesive silicone elastomer (a critical air velocity of 3.5 m/s to detach ~90% of the powders from the surfaces) were more easily detached by shear force generated from the blowing air, compared to bare stainless steel (a critical air velocity of 5.0 m/s). The low-adhesive silicone elastomer was attached onto the conical part known as the location where powder was severely accumulated in the chamber of a spray dryer. The yield of the pilot-scale spray dryer with and without low-adhesive silicone elastomer on the conical part was experimentally investigated in terms of inlet drying air temperatures from 90 °C to 150 °C. As a result, integrating the low-adhesive silicone elastomer onto the conical part in the chamber of a pilot spray dryer decreased the conical wall deposition of the powders by 17.7–46.2% (30.2% on average) and increased the yield by 10.7–16.5% (14.3% on average). The energy analysis revealed that employing the low-adhesive silicone elastomer to the spray dryer considerably decreased the evaporation energy of moisture per collected powder of spray dryer by up to 14.2%. Importantly, our strategy can be combined with the exhaust heat recovery methods for further improving the energy efficiency of spray dryers. Although the silicone elastomer employed in this study is widely used in the industry, the compatibility of using the polymer to specific drying process should be further studied. In addition to the yield, the influence of the low-adhesive surfaces on the quality of dried materials (e.g., morphology, ingredient, etc.) needs further investigation. This study represents an effort to enhance energy saving of highly energy consuming processes by employing the functional surfaces to devices.

Credit author statement

Jae Woo Sim: Conceptualization, Methodology, Investigation, Writing – original draft. **Haeyeon Lee:** Conceptualization, Methodology, Investigation, Writing – original draft. **Sungwon Jo:** Methodology, Investigation. **Sanghyun Oh:** Methodology, Investigation. **Sungil Kim:** Methodology, Investigation. **Dong Rip Kim:** Conceptualization, Methodology, Writing-Review & Editing, Supervision.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Dong Rip Kim reports financial support was provided by the Korea Institute of Energy Technology Evaluation and Planning

Table 2
The numerical values used in calculations.

Variable	Value	Unit
λ_{latent}	2110~2280	kJ/kg
m_{evap}	356~361	g
$m_{w,i}$	367.5	g
$m_{w,f}$	11.53~6.58	g
m_{cp}	41.2~67.1	g
t_{op}	50	min
$\dot{m}_{da,in}$	32.6	kg/h
C_{pa}	1.005	kJ/kg·K
C_{pv}	1.865	kJ/kg·K
$Y_{da,in}$	0.0180~0.021	kg _{H2O} /kg _{DA}
$T_{da,in}$	90~150	°C
T_{amb}	30	°C

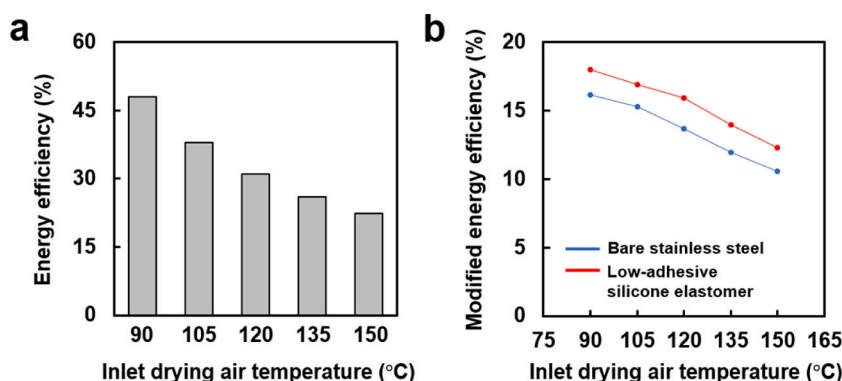


Fig. 7. (a) energy efficiency and (b) modified energy efficiency of spray dryers in terms of inlet drying air temperatures.

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Data availability

Data will be made available on request.

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