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Performance of Oil-Separator Adopting Nature-Inspired Surface

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KEYWORDS: Oil separator, Nature-inspired surface, Refrigeration system

In order to improve a refrigeration system's energy efficiency, the separation efficiency of its oil separator should be improved. To do so, we turned to nature for inspiration. A Namib Desert beetle collects water in fog by using its skin, which combines hydrophilic and hydrophobic surfaces. Inspired by nature's design, we applied a surface with oleophilic and oleophobic patterns to an oil separator used in a refrigeration system. In order to make the oil separator, an appropriate design was established using computational fluid dynamics. A cyclone-type oil separator was produced with an oleophobic-treated surface on its lower cup. The efficiency of the treated surface of this oil separator was tested with an open-type experimental setup using an oil mist generator. To obtain conditions similar to those of a refrigeration system in the open-type experimental setup, the oil particle diameter and working fluid pressure were set to yield a Stokes number similar to that of oil particles in the oil separator of the refrigeration system. The oil separator with the treated oleophilic–oleophobic surface improved its oil separation efficiency by 1.67% and its pressure drop by 2.48% compared to a conventional cyclone-type oil separator.

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NOMENCLATURE

D = Cyclone diameter [m]
d_p = diameter [m]
Q_d = Amount of oil remaining in the oil mist generator [mL]
Q_t = Amount of oil trapped in the oil separator [mL]
Q = Flow rate of gas and oil [m/s]
Stk = Stokes number
x_{ef} = Oil separation efficiency
μ_g = Viscosity of gas [kg/ms]
ρ_g = Density of gas [kg/m]
ρ_p = Density of particle [kg/m]

1. Introduction

Recent years have witnessed a growing concern over saving energy because of global warming issues and energy price hikes caused by increased oil prices. The need to improve energy efficiency to reduce energy consumption has been raised. Refrigeration systems are also expected to have their energy efficiency improved. A refrigeration machine consists of a compressor, condenser, expansion valve, and evaporator as in Fig. 1. A refrigeration system's the compressor uses lubricating oil. Lubricating oil, along with refrigerant, circulates in a refrigeration system. During this process, the pressure drop increases, and the heat transfer coefficient decreases. Moreover, insufficient lubricant may incur a decrease in performance and damage to a compressor. Therefore, an oil separator is used to separate the lubricant and return it to the compressor. Since an oil separator causes an additional pressure drop, energy consumption should be decreased by increasing the oil separator's separation efficiency and decreasing the pressure drop. The recent increase in development of large scale buildings such as skyscrapers and large supermarkets has also increased circulate up to the highest points. The rotary compressor, which has a higher efficiency and lower noise and vibration level, is increasingly replacing the conventional reciprocating compressor. However, rotary compressors are more susceptible to the risk of breakage than a reciprocating compressor if it lacks lubricating oil.

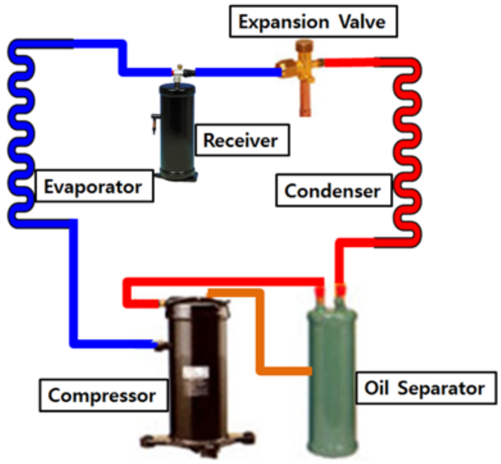


Fig. 1 Refrigerator cycle and oil separators

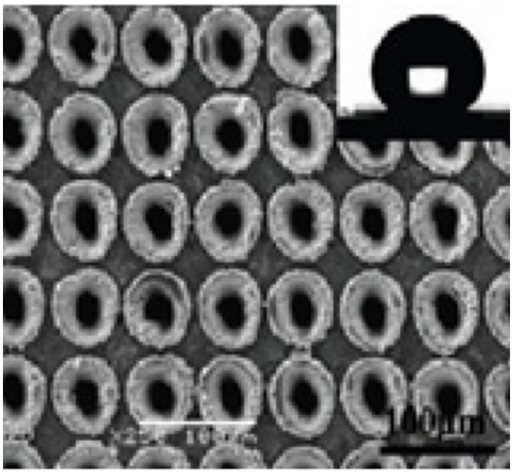
The increased length and fall height for lubricants to circulate with refrigerant increase the related energy loss. A rotary compressor is more susceptible to the risk of damage than a reciprocating compressor when it has insufficient lubricating oil. In order to use a compressor in a high-head long-piping refrigeration system, the separation efficiency of the oil separator must be improved.[3]

Doing so will also reduce energy losses. Even with an improved separation efficiency, however, an increased pressure drop means additional energy losses. Thus, an oil separator with high separation efficiency and low pressure drop should be designed. Two major mechanisms are used for oil separators in refrigeration systems: the cyclone and the porous media. The cyclone type separates oil by impinging it on the wall by centrifugal force. The porous type separates oil by collision with oil particles on a porous separator.

In this study, the anticipation was that the separation efficiency could be improved by adjusting the characteristics of the surface that the oil particles collide against. In nature, surfaces exist that collect water. For instance, a Namib Desert beetle's hydrophilic-hydrophobic surfaces (Figs. 2(a) and 2(b)) condense and collect water from fog.[1] Inspired by the concept of such a surface structure, the aim of this study was to generate oleophilic-oleophobic surfaces by forming microstructures for application to the oil separator's inner wall. After produced the oil separator, the separation efficiency should be verified. Refrigeration cycle in order to measure the separation efficiency, OCR (Oil circulation ratio) should be measured. The most general way to measure OCR is a sampling method. However, these measurements are time-consuming and reduce the amount of refrigerant in the cycle and oil in the compressor. Therefore, in order to apply the sampling method, large refrigeration system should be produced. If you use an open system, visually check the state of the separation of the oil and apply the sampling method. Testing setup consist of open system. In this study, an oil separator was modeled based on the structure of existing products.

The separation efficiency of the oil separator was also estimated by computational fluid dynamics (CFD). Improvements in separation efficiency were anticipated by adjusting surface characteristics, after which oil particles were separated through impingement. In order to adjust surface characteristics, techniques for hydrophobic surface

(a)



(b)

Fig. 2 Hydrophilic and hydrophobic surface in nature: (a) Namib Desert beetle,[1] (b) Hydrophobic surface[2]

production were developed. The surface of the oil separator was sandpapered and rendered hydrophilic-hydrophobic through surface processing. The experimental device was designed in an open system for the purpose of verifying the performance of the oil separator as well as reducing the pressure.

The results obtained from operating the experimental device were used to compare oil separation efficiencies and pressure drops.

2. Design and Production

Existing oil separators use porous media or cyclone. In this study, a cyclone-type oil separator was selected, as treatment of its surface is easier.

The diameter was the same as that of S-5182(Henry), but the length and pitch of the spiral oil pathline were designed to be longer than those of S-5182. The lower part had a funnel-like shape for oil to quickly flow down. The dimensions were 30 cm in total length, 15 cm in lower cup length, 10 cm in diameter, and 6.5 cm in the pitch of the spiral oil pathline. The separation efficiency was predicted using CFD. The computational domain was inside the oil separator (Fig. 3(a)). In total, 1,413,010 hexahedron grids were used (Fig. 3(b)).

The working fluid was set to R-22, and the oil's physical properties, which were used as inputs, were based on those of mineral oil. The inlet condition was a mass flow inlet, and the flow rate was 30 g/s. The

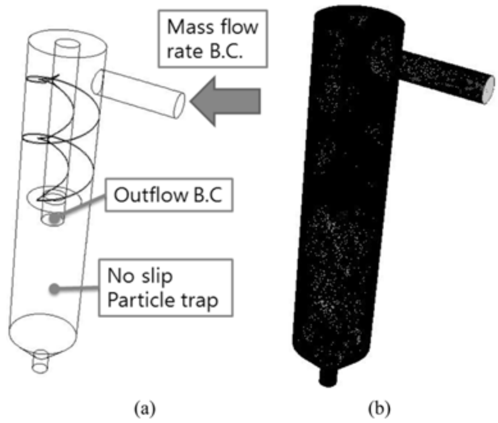


Fig. 3 CFD modeling of the prototype oil separator: (a) Computational domain, (b) Grid system

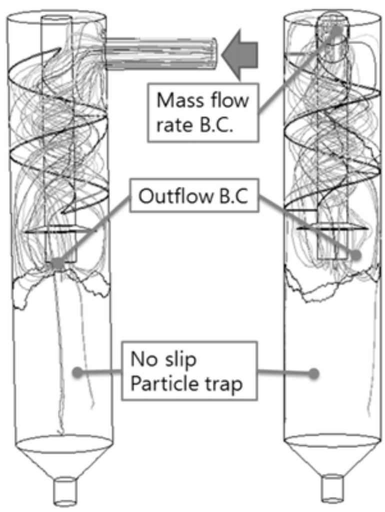


Fig. 4 Pathlines inside the oil separator from numerical analysis

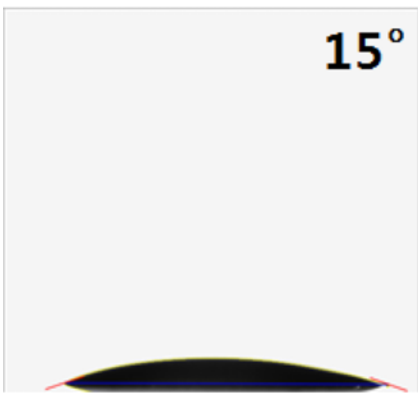


Fig. 5 Oil contact angle for RP-1000 before treatment

particle flow rate was 0.3 g/s:.[4-6] The outlet condition was set as an outflow. The particles were set as oil. The average particle size was set to 10 μm. The incompressible Navier-Stokes equation was used as the governing equation. The Rosin-Rammler was used for the particle

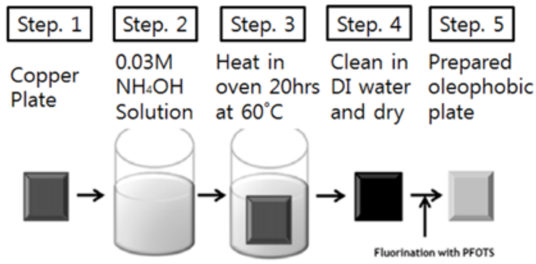


Fig. 6 Schematic diagram for procedure of oleophobic surface on a copper plate[3]

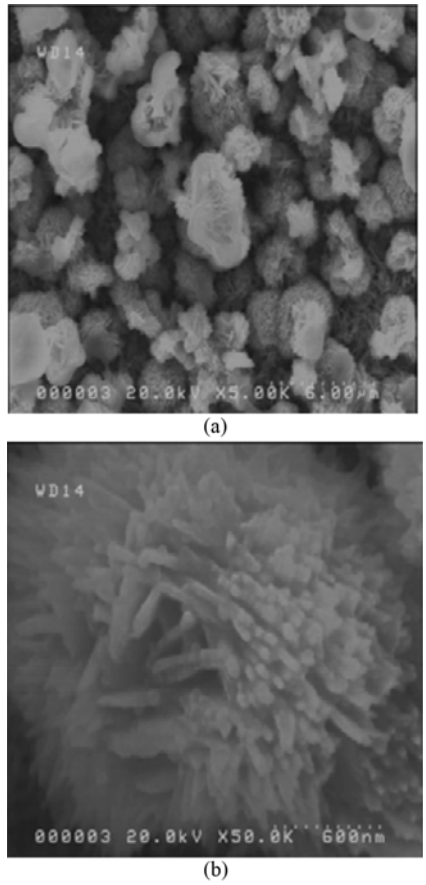
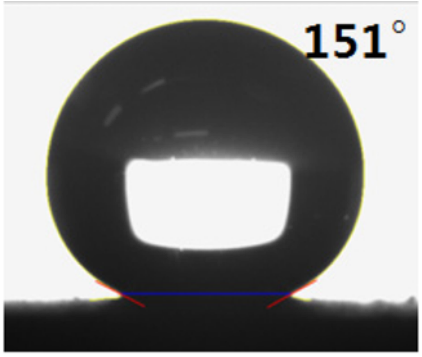


Fig. 7 SEM photos of treated surface:[3] (a) A magnification of 5000 times, (b) A magnification of 50000 times

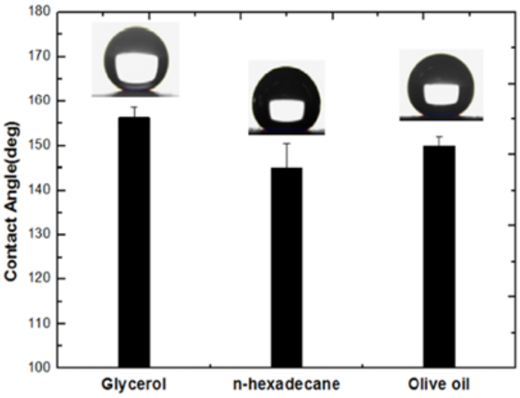
distribution model. The Reynolds stress model was used for the turbulence model.[7,8]

As shown in Fig. 4, present geometry yields a cyclone flow to separate oil particles from the mixture. Separation efficiency was estimated to be around 95%. Copper was used as the material for the oil separator: copper is commonly used for refrigerating pipes, has an essentially oleophilic surface, and can be made oleo-phobic through chemical treatment. The lubricant RP-1000, which is used in refrigeration systems, had a contact angle at copper prior to surface treatment of 15°, as shown in Fig. 5. This confirmed that its surface was inherently oleophilic.

In order to create the oil separator's oleophobic surface, the lower



(a)



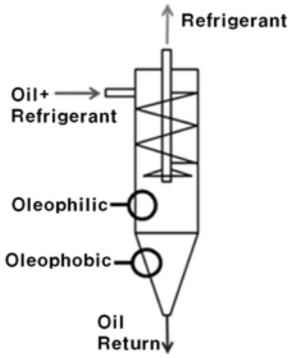
(b)

Fig. 8 Contact angle of oleophobic treated surface: (a) For RP-1000 oil, (b) For other types of oil

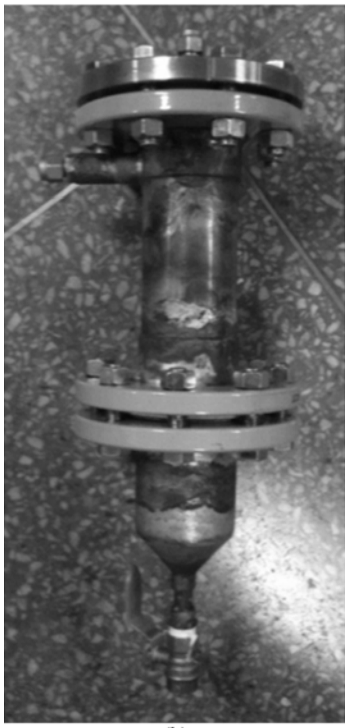
part was heated in a 0.03 M NH_4OH solution at 60°C for 20 hours. Once the surface was heated, it was washed in deionized water and treated with fluorine as in Fig. 6(a). Magnification of the treated surface showed micro structures that rendered the surface oleophobic as in Fig. 7. The contact angle of RP-1000 on the oleophobic surface was 151°, as illustrated in Fig. 8(a). Fig. 8(b) shows the contact angles measured for glycerol, n-hexadecane, and olive oil: these were 155.4°, 140°, and 152°, respectively. This confirmed that the surface became super-oleophobic. The oleophilic surface was applied to the oil separator's side wall so that oil particles will adhere to it, and the oleophobic surface was applied to its lower cup for oil to flow down quickly as shown in Fig. 9(a).

3. Experimental Devices and Methods

In order to validate the performance of the oil separator produced in this study, its separation efficiency and pressure drop were compared with those of existing oil separators: the porous-type OUB-1 and cyclone-type Henry S-5182. Oil separator prototypes with an unprocessed surface and with an oleophobic surface for its lower cup were also compared with each other The experimental equipment was set up as an open type system. When using an open system, the Stokes number-that is, a non-dimensional number that characterizes a cyclone's separation performance should be considered. The Stokes number is calculated through the following formulas:[9]



(a)



(b)

Fig. 9 Prototype oil separator: (a) design, (b) photograph

$$Stk = \frac{d_p^2 V_B(\rho_p - \rho_g)}{18\mu_g D} \quad (1)$$

$$V_B = \frac{4Q}{\pi D^2} \quad (2)$$

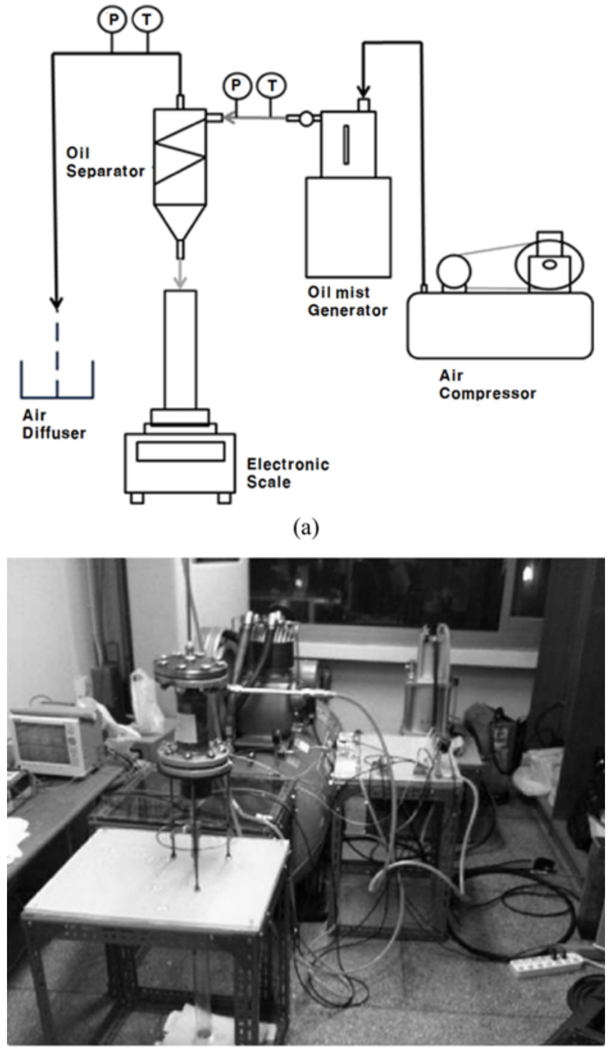
where Stk denotes the Stokes number, d_p is the particle diameter, ρ_p is the particle density, ρ_g is the density of gas, μ_g is the viscosity of gas, D is the cyclone diameter, and Q is the total flow rate of the gas and particle mixture. Air was used instead of refrigerant as the working fluid.

Olive oil was used instead of lubricating oil. The particle size was set to 2 μm to make its Stokes number similar to that of actual refrigeration systems, assuming that the average particle size inside refrigeration machines is 10 μm.[10] Table 1 lists the Stokes numbers for R-410A and R-22 in refrigeration systems and for compressed air at 200 kPa.

Preliminary experiments confirmed that the contact angles of olive

Table 1 Oil separation efficiency

	2 μm	10 μm
R-410A (30.61 bar)	7.36×10^{-3}	1.84×10^{-4}
R-22 (19.43 bar)	8.57×10^{-3}	2.14×10^{-4}
Air (2 bar)	1.82×10^{-4}	4.54×10^{-3}



(a)

(b)

Fig. 10 Experimental setup: (a) Schematic diagram, (b) Photograph

oil at the unprocessed and oleophobic-processed copper surfaces were 15° and 152°, respectively. The latter is similar to the lubricating oil's contact angle of 151° at the surface of copper used in refrigeration systems. The air pressure was set to 2.13 bar, and the flow rate was set to 7.7 g/s; these are similar to the properties of a 1 hp refrigeration system. The oil discharge rate was 0.022 g/s, and the mass fraction of air to oil was 0.29%.

Fig. 10 shows a schematic diagram and photographs for the experimental devices. The air was compressed in the compressor (Woolee WLPT-3HP). As the compressed air passed through the oil mist generator, it was sprayed with oil particles. As the compressed air mixed with oil passed through the oil separator, the oil particles were trapped in the container at the bottom of the oil separator, and the air was released from the oil separator.[11] The amount of oil sprayed in the oil mist generator was measured, and then the weight of the oil collected in the container connected to the bottom of the oil separator was measured. The ratio of the amount of collected oil to the amount of sprayed oil was calculated, and then the separation efficiency was measured. This may be expressed by the following equation:[5,6,12]

$$\frac{O_t}{O_d} = x_{ef} \tag{3}$$

where x_{ef} denotes the separation efficiency, Q_t is the amount of oil trapped in the oil separator, and Q_d is the amount of sprayed oil.

Pressure sensors were installed at the inlet and outlet of the oil separator, and the pressure drops were measured. Four different oil separators were experimented with: an existing cyclone-type oil separator, an existing porous-type separator, an oil separator prototype with an untreated surface, and an oil separator prototype with a treated surface. The timeframe for each experiment was 100 h, and the amount of separated oil was measured. Experiments were performed three times for each oil separator.

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4. Results and Discussion

Fig. 11 presents the separation efficiencies of each oil separator and those resulting from numerical analyses. The average separation efficiencies of the existing porous- and cyclone-type products were 91.9% and 91.6%, respectively. For the prototypes, the average separation efficiencies of the oil separator with untreated and treated surfaces were 92.2% and 93.1%, respectively. Numerical analysis estimated the efficiency of the prototype to be 95.1%. The prototype with the lower cup part having an oleophobic-treated surface showed the best separation efficiency, and the untreated prototype showed a separation efficiency slightly higher than the existing porous-type product (OUB-1, Danfoss). The oil separator with the untreated surface had a body and spiral pathline longer than those of the existing cyclone-type separator (S-5182). Thus, it was considered to have better separation efficiency. The oil separator with the oleophobic-treated surface demonstrated better separation efficiency than the untreated oil separator. The lower cup had an oleophobic-treated surface to return oil to the compressor without a ball tap, but it also improved the oil separation performance.

Separation efficiency data are summarized in Table 2 for comparison. The oil separator prototype manufactured in this study showed a separation efficiency that was 0.23% higher than that of an existing porous-type oil separator and 0.64% higher than that of an existing cyclone-type oil separator. The separation efficiency of the treated oil separator was 1.01% higher than that of the untreated oil separator,

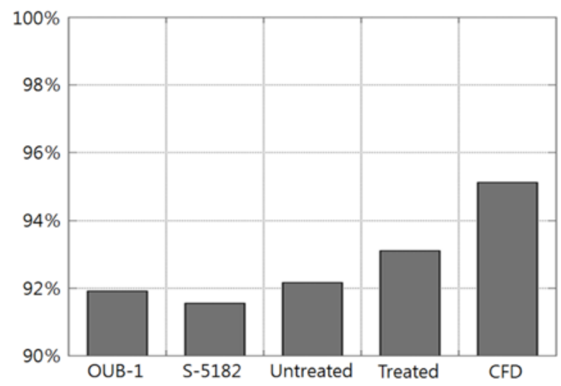

Fig. 11 Oil separation efficiency

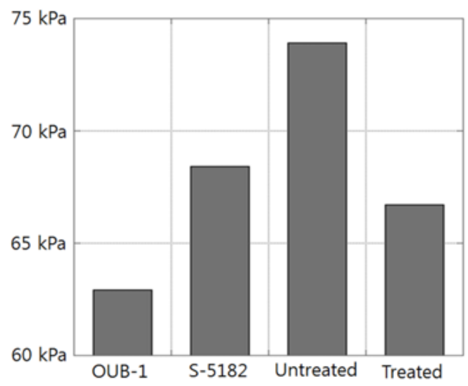

Fig. 12 Pressure drop across the oil separator

Table 2 Oil separation efficiency

Oil separator	Separation efficiency
OUB-1	91.93%
S-5182	91.57%
Untreated	92.17%
Treated	93.10%
CFD Result	95.11%

Table 3 Pressure drop across the oil separator

Oil separator	Separation efficiency
OUB-1	62.93 kPa
S-5182	68.43 kPa
Untreated	73.90 kPa
Treated	66.73 kPa

1.27% higher than the existing porous-type separator, and 1.67% higher than the existing cyclone-type separator. Simple surface treatment renders more than 1% improvement of separation efficiency at the efficiency level as high as over 90%.

Fig. 12 presents the pressure drop of each oil separator. With regard to the oil separator pressure drops, the average pressure drop of OUB-1 was 62.9 kPa, and that of S-5182 was 68.4 kPa (see Table 3). For the prototypes, the average pressure drops of the untreated and treated oil separators were 73.9 and 66.7 kPa, respectively. In other words, the prototypes showed an increase of the pressure drop by 17.5% against the existing porous-type separator and 8.0% against the existing cyclone-type separator. The treated oil separator showed a decrease of 9.7% against the untreated surface, an increase of 6.0% compared with the existing porous-type separator, and a decrease of 2.5% compared with the existing cyclone-type separator. These phenomena occurred because air gaps formed and slips occurred on the super-hydrophobic surface.[13] Accordingly, drag caused by surface friction was reduced.[14] On the super-oleophobic surface, air gaps also formed; thus, the drag and pressure drop were reduced accordingly.

Using an oleophilic surface for the oil separator's body and an oleophobic surface for the lower cup appeared to produce the best separation efficiency. When the lower cup surface was oleophobic-surface treated, the pressure drop was further reduced. Therefore, an oleophilic surface should be applied to the body, and an oleophobic surface should be applied to the lower cup.

5. Conclusions

Based on the experimental results in this study, the oil separator with a treated surface showed the highest separation efficiency and lowest pressure drop. The results confirmed that proper adjustment of the oil wettability of each part improves the oil separation performance and reduces the pressure drop. These results confirmed that proper adjustments of the oil wettability of each part improve the oil separation performance and reduce the pressure drop at the same time.

There are differences between an open-type experimental device and an actual refrigeration system. Accordingly, an oil separator for use in the refrigeration system needs to be examined in an experimental device that uses an actual refrigeration system for accurate examination. Therefore, future plans involve producing and experimenting on an experimental device using an actual refrigeration system.

ACKNOWLEDGEMENT

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