ISSN 1345-3041

Dec.2018 / Vol.164

Mitsubishi Electric

ADVANCE

Environmental Technologies for Sustainable Society

MITSUBISHI ELECTRIC
Changes for the Better

Dec. 2018 / Vol. 164

Mitsubishi Electric ADVANCE

Environmental Technologies for Sustainable Society

• **Editorial Inquiries**

Tomoyuki Kobayashi
Corporate Total Productivity Management & Environmental Programs
Fax: +81-3-3218-2465

Mitsubishi Electric Advance is published on line quarterly (in March, June, September, and December) by Mitsubishi Electric Corporation.

CONTENTS

Technical Reports

Precis

The technologies and products related to pillars: creating a low-carbon society, creating a recycling-based society, and strengthening our environmental foundations emphasized in the environmental plan are introduced. Mitsubishi Electric group contributes to a sustainable society by these technologies and products.

Overview

Author: *Hirofumi Nakano**

Environmental Technologies Contributing to a Sustainable Society

The Mitsubishi Electric Group, as a “Global, Leading Green Company”, contributes to the achievement of an affluent society that balances “sustainability” with “safety, security and comfort”.

As a manufacturer, we have a responsibility to reduce the environmental impact of not only our production activities, but also throughout the life cycle of products, from procuring resources and materials to the development, production, and sales of products, as well as reclamation and recycling of products after use.

The Mitsubishi Electric Group endeavors to develop energy-saving, highly-efficient products from the design stage. We also strive to conserve resources by making smaller products and developing technologies for improving the environment including purification of soil and water. In addition, we reduce waste through recycling and developing products with less environmental impact even at the disposal stage.

This special edition introduces our recent technologies that contribute to environmental protection. We seek to grow and contribute to a sustainable society through such environmental efforts as a company that is valued by society.

**Group President, Corporate Environmental Sustainability Group*

Magnetic Contactor with Cadmium-Free Contacts

Authors: *Takashi Inaguchi** and *Hideyasu Kawai***

Mitsubishi Electric Co. has developed magnetic contactors with cadmium-free electric contacts in the smallest case in the industry. To develop such magnetic contactors, taking the 50-A model as an example, the arc runner that decreases the arc discharge has been improved and its performance enhanced by more than 20% compared with the conventional type. In addition, Mitsubishi Electric has developed an original mechanism to exhaust the hot gas generated from the arc discharge, improving the cooling capacity by seven times. The improvements and new mechanism have made it possible to realize cadmium-free electric contacts and reduce the case size of the 50-A model by 40% compared with the conventional model. This development received the 2017 Environment Excellence Prize (sponsored by the National Institute for Environmental Studies in Japan and Nikkan Kogyo Shimbun, Ltd. and supported by the Japanese Ministry of the Environment).

1. Introduction

Magnetic contactors are industrial switches that can open and close (turn on and off) electric circuits remotely based on the behavior of the electromagnets. They are mainly used to automatically control motors for elevators and factory equipment. Recently, they have been broadly used for power conditioners for photovoltaic power generation and storage batteries for household use. Magnetic contactors must be able to interrupt an overcurrent under abnormal conditions to protect the equipment, in addition to current switching under normal conditions, and so require high reliability. They also need to be small to enable installation in a small space.

When a magnetic contactor interrupts (turns off) the current in a circuit, an arc discharge occurs between the electric contacts, which are key parts. To interrupt this current, the discharged arc needs to be eliminated. Silver cadmium oxide has been widely used as the material of electric contacts due to its good performance in eliminating the arc and thus realizing highly reliable magnetic contactors. Recently, however, demand has risen for cadmium-free magnetic contactors in view of environmental protection and the potential effect on humans. For example, the RoHS Directive regulates the use of cadmium even for industrial control equipment. Cadmium for electric contacts is not presently regulated, but its use should be avoided in the future.

To satisfy both the need for reducing environmental risks and for downsizing, Mitsubishi Electric has developed cadmium-free electric contacts and smaller magnetic contactors.

This paper introduces some current interruption technologies that we developed to eliminate the use of cadmium and to downsize the contactors.

2. Current Interruption Technologies to Make Contacts Cadmium-Free and to Downsize Contactors

When the electric contacts in a conventional magnetic contactor were replaced with a cadmium-free material, the performance in terms of suppressing the arc discharge generated between the electric contacts was insufficient and so the case size needed to be increased to ensure safety. This was a major disadvantage given the demand for smaller magnetic contactors. To solve this problem, Mitsubishi Electric developed technologies to efficiently control the arc discharge and realized magnetic contactors with cadmium-free electric contacts in the smallest sized case in the industry. This paper describes the technology developed for the 50-A model.

To quickly eliminate an arc discharged between electric contacts, an arc runner made of magnetic material (iron) is used. Figure 1 shows an arc runner around a contact. The current from the arc discharge magnetizes the arc runner, which attracts and extends the arc. This extension increases the arc voltage. In

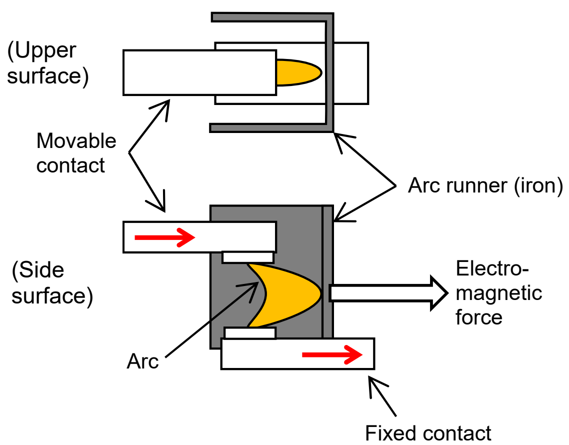

Fig. 1 Schematic diagram of arc attraction by arc runner

*Advanced Technology R&D Center **Nagoya Works

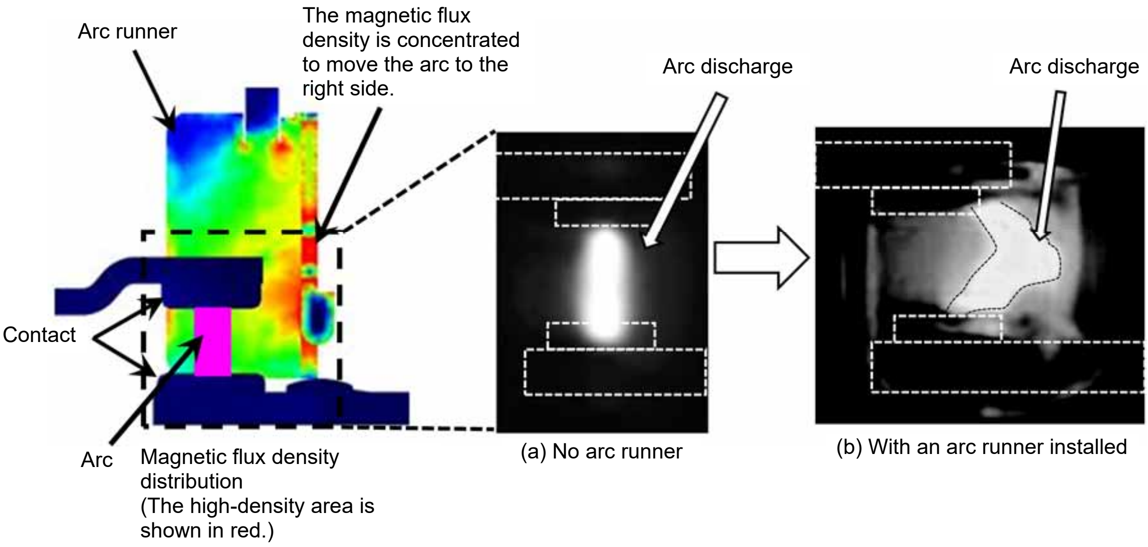

Fig. 2 Analytical results of the magnetic flux density distribution of an arc runner and photographs of arc behavior by a high-speed camera

addition, the extended arc is cooled more easily, which also has the effect of increasing the arc voltage. Further, the arc reaching the arc runner is discharged again to the contact, whereby the cathode-fall voltage is generated in the vicinity of the arc runner. These factors increase the arc voltage, which makes it easier to interrupt the current.

We optimized through electromagnetic field analysis to reduce the leakage of magnetic flux. As a result, the magnetic flux efficiently passes the arc runner, increasing the magnetic flux density in the arc runner. This mechanism has increased the electromagnetic force (Lorentz force) that attracts the discharged arc to the arc runner by 20% or more compared with the conventional model. Figure 2 shows the magnetic flux density distribution in the arc runner along with photographs of the arc behavior taken by a high-speed camera. Two photographs are provided to show the effect of an arc runner: one shows the behavior when there is no arc runner and the other shows that when an arc runner in the optimized shape has been installed.

The temperature of an arc discharge is high, and the interruption performance deteriorates in the high-temperature environment. In addition, the generated hot gas damages the electric contact and resin case. To prevent these problems, the case needs to be made larger or instead, large vents need to be provided to exhaust the hot gas. However, larger vents allow dust to get in, which causes additional problems. Therefore, through thermal fluid analysis, we studied a structure that prevents dust from getting in and efficiently exhausts hot gas, and developed a new exhaust structure. This structure has improved the arc discharge cooling capacity to seven times that of the conventional model (Fig. 3 and Fig. 4).

Thus, the width of the new model was reduced by 13 mm and the volume was reduced by 40% compared to the conventional model. Figure 5 compares the size of the conventional S-N50 and the newly developed S-T50.

This development received the 2017 Environment

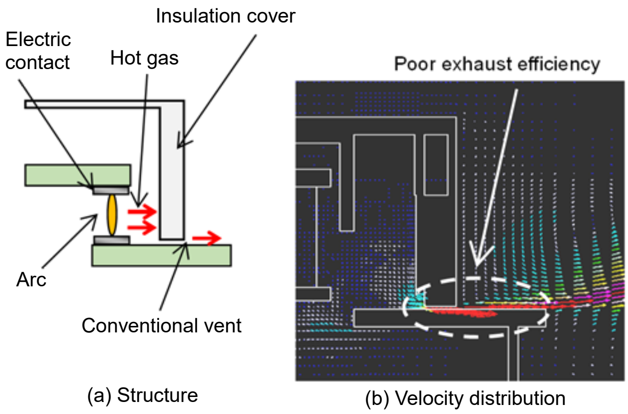

Fig. 3 Analytical results of the conventional exhaust structure and velocity distribution

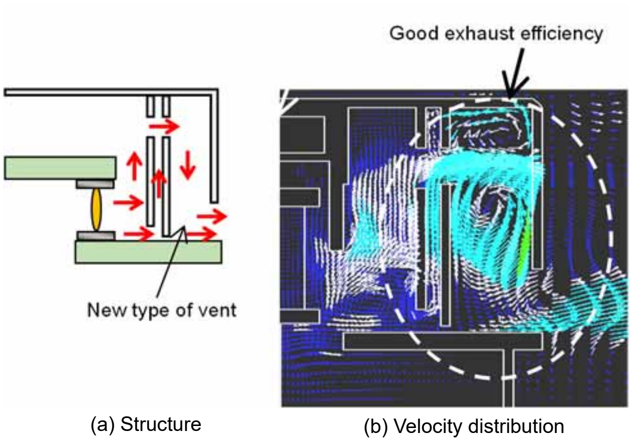

Fig. 4 Analytical results of the developed exhaust structure and velocity distribution

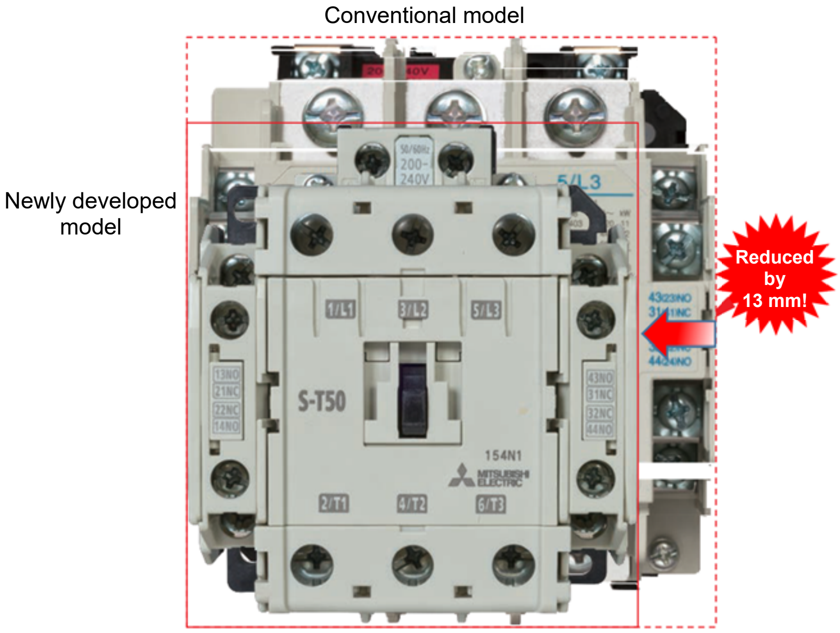

Fig. 5 Comparison of size of conventional product and developed product (50-A model)

Excellence Prize (sponsored by the National Institute for Environmental Studies in Japan and Nikkan Kogyo Shimbun, Ltd. and supported by the Japanese Ministry of the Environment).

3. Conclusion

Magnetic contactors are widely used for automatic control in industry and for power conditioners. Mitsubishi Electric has developed magnetic contactors with cadmium-free electric contacts in the smallest sized case in the industry. We will expand the application of cadmium-free magnetic contactors to various fields to reduce environmental risks.

Technologies for High-Efficiency Induction Motors

Authors: *Haruyuki Kometani** and *Norihiro Achiwa***

1. Introduction

Induction motors are widely used throughout industry, and account for 40–50% of the total electric energy consumed in the world. In Japan, they account for approximately 75% of the electric energy consumed by industry and approximately 55% of the country's total energy consumption.(1) Under such circumstances, the Japanese Top Runner Program in conformance with IEC standards for energy efficiency classes(2) was introduced in April 2015, and IE3 (Premium Efficiency) was made mandatory. To meet this obligation, Mitsubishi Electric Co. released the SF-PR Series of new general-purpose induction motors.(3) Their efficiency is remarkably higher than the IE3 level and offer compatibility(4) as an advantage for users. In addition, the application of IEC standards to single-phase induction motors was started in 2015, and high-efficiency motors for small ventilation fans are undergoing rapid development. This paper outlines the technologies for improving the efficiency of induction motors and realizing compatibility and mass productivity.

2. Compatibility

For a given output, larger motors can improve efficiency rather easily, but it may be difficult to install a larger motor on loading equipment that requires a motor, so upsizing should be avoided. Since induction motors are mass-produced at factories, extremely difficult manufacturing methods cannot be used. In addition, rated conditions vary from country to country. In Japan alone, the rated conditions for 200-V systems include 200 V/50 Hz and 200–220 V/60 Hz. Ideally, the IE3 level and all requirements should be satisfied with one type of motor.

2.1 Maximum torque

Maximum torque refers to the largest torque that a motor can output at the rated voltage and rated frequency. If the torque is low, the motor cannot cope with load changes. Maximum torque is determined mainly based on leakage flux rather than the main flux, which means that, to secure compatibility, the leakage reactance cannot be significantly changed.

2.2 Starting characteristics

When the secondary resistance is reduced, the rated slip factor becomes small, which reduces the secondary copper loss. However, the impedance at the starting time becomes smaller and the starting current becomes larger. When the starting current is larger, the capacity of the breaker and the power supply needs to be increased, so this condition should be avoided. In addition, if the number of turns is increased to reduce the starting current, the starting torque becomes smaller, which may make starting impossible. Thus, it is difficult to improve the efficiency by simply reducing the secondary resistance.

2.3 Power factor

When a load current becomes small due to improved efficiency and it nearly equals the exciting current, the power factor deteriorates. When the power factor is poor, the reactive power increases, which increases the capacity of the power supply. Thus, greatly reducing the load current compared with the exciting current should be avoided.

3. Technologies for improving efficiency

This section describes a technology for improving the efficiency of induction motors while satisfying compatibility, and another technology for improving the efficiency while maintaining mass productivity by short line takt time.

3.1 Shape of rotor slots

To reduce secondary copper loss, the resistance of the secondary conductors needs to be reduced, but this increases the starting current. Rotor flux at the rated load is slip frequency, which is rather low, but it becomes the rated frequency at the starting time. As shown in Fig. 1,

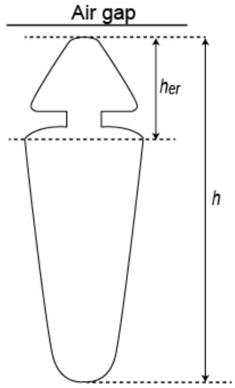

Fig. 1 Rotor slot

* Advanced Technology R&D Center **Nagoya Works

the resistance is high in the range (h_{er}) where a large current flows at the starting time and the overall resistance is low, whereby the secondary resistance can be designed to be low while the starting current is reduced by designing a rotor slot.

3.2 Air gap

Reducing the primary copper loss by reducing the exciting current is effective for improving the efficiency without the problem of a reduction in the power factor mentioned above. The exciting current can be reduced by reducing the air gap between the stator and the rotor. However, a reduced air gap is largely affected by any variation in the accuracy of construction and the rotor tends to deviate from the center of the stator (rotor eccentricity). When the rotor is eccentric, electromagnetic noise is generated and such products are not acceptable from the standpoint of reliability.

It has been found that when a rotor is eccentric, the voltage on the counter coil becomes uneven, and such voltage differences are nearly proportional to the eccentricity and they change in near-sinusoidal waveforms against the direction of eccentricity. Applying this knowledge, Mitsubishi Electric established a production technology (assembly method) for centering the motors.(5) In the production technology, the voltage differences on the counter coil are brought to nearly zero, and the stator and the rotor are press-fitted into a frame and brackets. In addition, counter coil voltage differences in two or more directions are used for centering the motors, so efficiency can be improved in short line takt time, with no deterioration in mass productivity. Figure 2 shows the change in efficiency with the change in size of the air gaps on a motor for small ventilation fans. It can be seen in the figure that as the air gap becomes smaller, the efficiency becomes higher. This centering technology has made it possible to improve the efficiency while reducing the increase in electromagnetic noise.

3.3 Inter-bar current loss

Stator wires are stored in a small slot, so the density distribution of flux in an air gap is not a sine wave in the circumferential direction and includes space harmonics. When these space harmonics interlink with the secondary conductor, stray load loss occurs. When the air gap is made smaller, the space harmonics occurring on the stator further interlink with the rotor secondary conductor, which increases the harmonic secondary copper loss. To reduce this loss, a rotor slot is skewed in the axis direction (rotor skewing). However, because the secondary conductor is manufactured by pouring fused aluminum into a slot, the secondary conductor and the laminated core on the side of the slot are brought into electrically conductive contact and a current flows between the bars (inter-bar current). To reduce this current, the secondary conductor and the rotor core should be electrically insulated. As a method for reliably insulating the secondary conductor and the core in a short line takt time, Mitsubishi Electric has succeeded in introducing twisting and twisting-back processing(6) for small motors. In this process, the rotor core is twisted and twisted back in the circumferential direction. This method has made it possible to provide a gap between the secondary conductor and the core, which significantly reduces the inter-bar current. Figure 3 shows the efficiency measurement results for a motor for small ventilation fans. It can be seen that the efficiency has been greatly improved. In addition, this process minimizes performance variations caused by inter-bar currents.

3. Conclusion

This paper described the technologies for improving the efficiency of induction motors while maintaining compatibility between their starting characteristics and the power factor. We will continue to contribute to a low-carbon society by developing technologies for improving efficiency to reduce electric energy consumption.

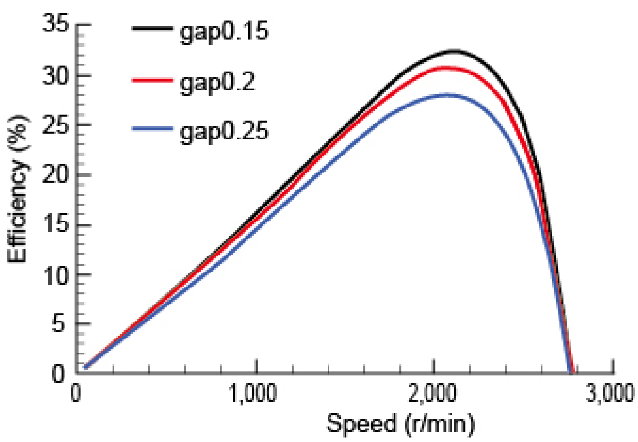

Fig. 2 Speed–efficiency characteristics

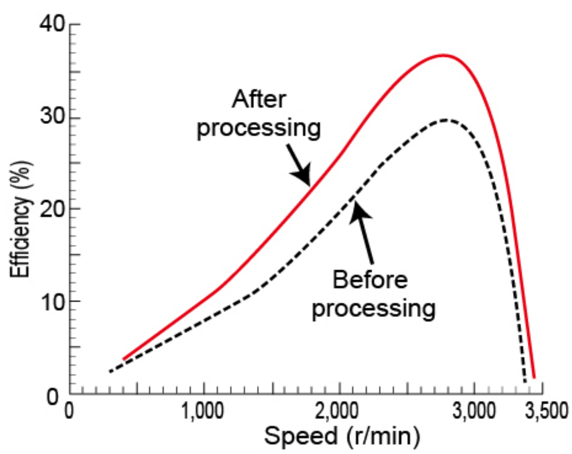

Fig. 3 Speed–efficiency characteristics

References

(1) Tomoya Abe: "Japanese Top Runner Program and IEC Standards Related to Motor Efficiency," IEEJ Journal, Vol. 137, No. 5 (2017)
(2) IEC 60034-30-1 (2014)
(3) Koki Naka: Premium Efficiency Motor SF-PR Series for the Japanese Top Runner Program, TECHNO-FRONTIER 2015, 35th Motor Technology Symposium (2015)
(4) Haruyuki Kometani: "Notices for Top Runner Induction Motors and High Efficiency Regulations," IEEJ Journal, Vol. 137, No. 5 (2017)
(5) Yoshio Yoshikuwa, Haruyuki Kometani, Masaki Kameyama, Manabu Deguchi, Toshihiko Mizutani and Yoshinori Miyamoto: Japanese Patent No. 5592688 "Eccentricity Estimation Method and Eccentricity Estimation System for Dynamo Electric Machines"
(6) Shinya Ohishi, Keiu Kawasaki, Takeshi Tsubouchi, Junji Okada and Haruyuki Kometani: "Development of Processing Method for Reduction of Inter-bar Current in Small Induction Motors," 63rd Okochi Memorial Grand Technology Prize, Business Report (2017)

Energy-Saving Technologies of Power Electronics Using SiC Devices

Author: *Takeshi Oi**

1. Introduction

The application of power electronics as a key energy-saving technology is expected to contribute to global environmental conservation. Advances in the performance of power devices has supported the development of power electronics equipment. Currently, the transistors used are mainly insulated-gate bipolar transistors (IGBTs). Silicon carbide (SiC) is a semiconductor material having excellent characteristics as a power device and is expected to be used for next-generation devices following Si. The bandgap of SiC is approximately three times that of Si and its breakdown electric field strength is approximately ten times higher. Mitsubishi Electric Corporation started developing SiC devices in the 1990s and has continuously released SiC products since 2010.

There are two methods for saving energy using SiC devices: One improves the power conversion efficiency by reducing the loss in the power electronics equipment themselves, and the other saves energy by reducing the loss of the entire system including the power electronics equipment. Photovoltaic inverters are a typical example of the former and railcar traction systems are a typical example of the latter. This paper describes SiC products used in these two methods.

2. Characteristics of SiC Devices

In a power electronics equipment, the power device switches the ON and OFF states to convert electric power. In power devices, power is lost during the ON state and during switching. During the OFF state, the voltage of power devices should be maintained at a high level, which is handled by the drift layers. As the withstand voltage of a drift layer increases, the impurity concentration needs to be lower and the thickness needs to be increased. In metal-oxide-semiconductor field-effect transistors (MOSFETs) and other unipolar devices, these are the main elements of the on-resistance. IGBTs are bipolar devices where holes are injected into the drift layers during the ON state and the carrier density increases by several orders of magnitude (conductivity modulation). Thanks to this characteristic, low ON-state voltage can be realized even for high-voltage devices. However, these bipolar devices have to discharge all the carriers that accumulated during the ON state at the time of turn-off, so the turn-off power loss is large. The IGBT's ON-state voltage has a trade-off relationship with the turn-off power loss. Using SiC, the concentration in the drift layers can be increased and the thickness can be reduced compared to Si, so even for high-voltage devices, MOSFETs with small switching loss can be used to achieve an ON-state voltage equivalent to that of Si-IGBTs. Currently, SiC-MOSFETs with a rated voltage of 3.3 kV are in practical use.

3. Photovoltaic Inverters with SiC

Photovoltaic inverters are equipment that convert the DC voltage output from PV cells to sine wave AC power. A photovoltaic inverter basically consists of a chopper that regulates the changing DC voltage output from the PV cells, an inverter that converts the DC voltage to AC, and a filter that converts the output from the inverter to sine wave output. Photovoltaic inverters are equipment for which power conversion efficiency is regarded as important. For that purpose, the loss in choppers, inverters, and filters needs to be reduced. Figure 1 illustrates a two-level pulse width modulation (PWM) inverter that is a basic configuration for photovoltaic inverters for home-use. For the two-level PWM inverter, the output voltage is a pulse voltage waveform as shown in the figure. The filter converts this voltage to sine wave output.

Figure 2 shows the configuration of a gradationally controlled voltage inverter adopting Mitsubishi Electric's method. Here, single-phase inverters with different voltages are connected in series, which allows voltage output closer to sine waves. Therefore, the loss in the filter can be significantly reduced. Applying this method achieved a power conversion efficiency of 97.5%, the highest at that time for PV inverters for home use. This efficiency value remained the highest until the introduction of photovoltaic inverters with SiC as described later.

Mitsubishi Electric has developed full SiC intelligent power modules (IPMs) and applied them to photovoltaic inverters.(3) An IPM contains a chopper circuit and a two-level inverter circuit. As shown in Fig. 3, the loss in the power device can be reduced by approximately 60% compared to Si and the power conversion efficiency is as high as 98% (at rated output), the highest in the industry as of 2015.

Figure 4 shows the improvement in efficiency of

*Advanced Technology R&D Center

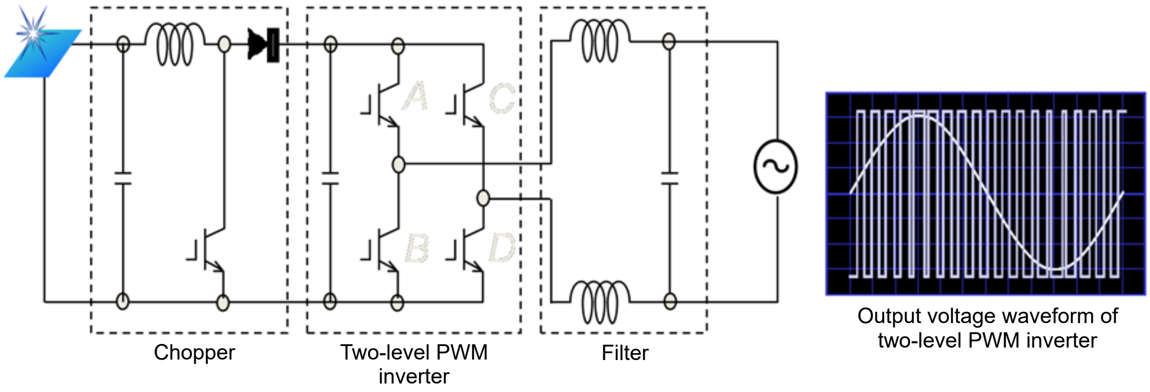

Fig. 1 Two-level PWM inverter

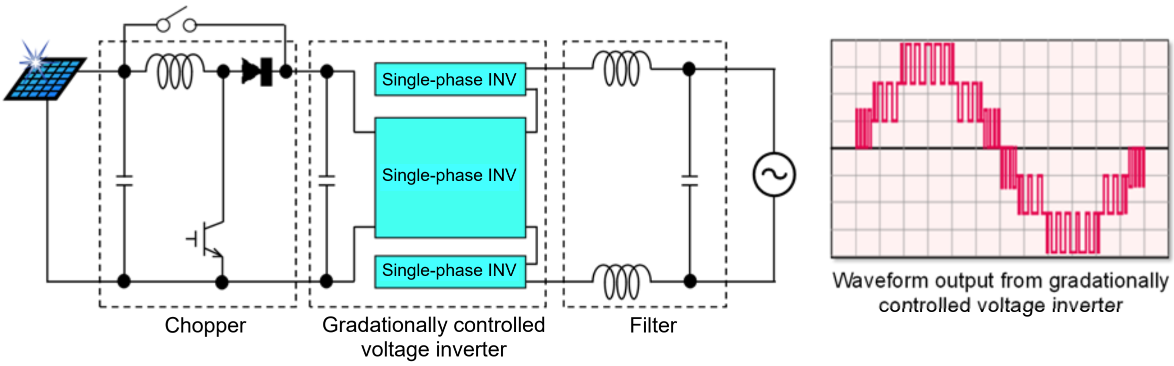

Fig. 2 Gradationally controlled voltage inverter

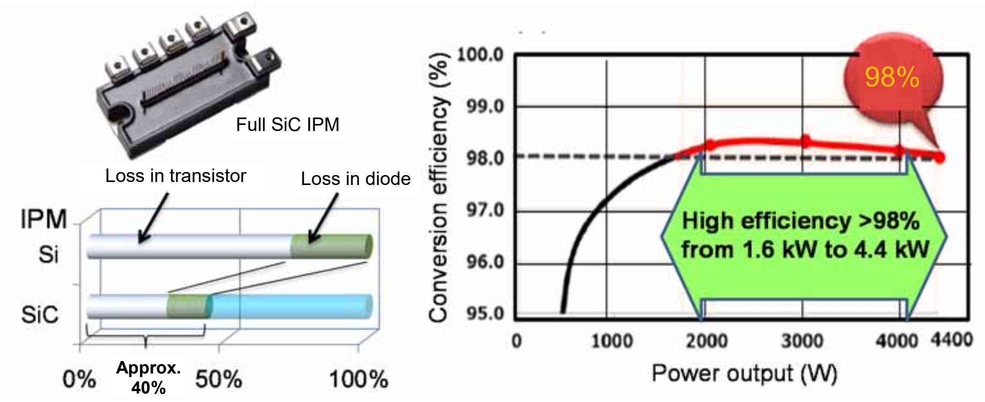

Fig. 3 Power conversion efficiency of PV inverter with SiC devices

Mitsubishi Electric's photovoltaic inverters for home-use. Thanks to the advances made in the Si devices' performance and innovations in the converter circuits, the power conversion efficiency has been improved. The application of SiC devices in 2015 achieved a conversion efficiency exceeding the limit of Si devices.

4. Railcar Traction Systems with SiC

Railcar traction systems are systems that convert the power from catenaries to AC power and control the main motors. When a train is accelerating, the inverter converts the power from the catenaries and supplies the converted power to the motor powering. At the time of deceleration, it converts the vehicles' kinetic energy and supplies the converted power to the catenaries regenerating. The regenerated energy is supplied to other railway vehicles.

According to the analysis results of electrical power consumed by the main circuits of railway vehicle systems, the loss in inverters is small at 2% of the total loss. The main elements of electrical power consumption are the loss in motors and the loss due to mechanical brakes. We considered reducing such loss by utilizing the performance of SiC. First, we considered how to reduce the loss in motors. In conventional control methods, the switching loss in Si devices is large, so the switching frequency is limited and the harmonic loss is large. On the other hand, the switching loss in SiC devices is small,

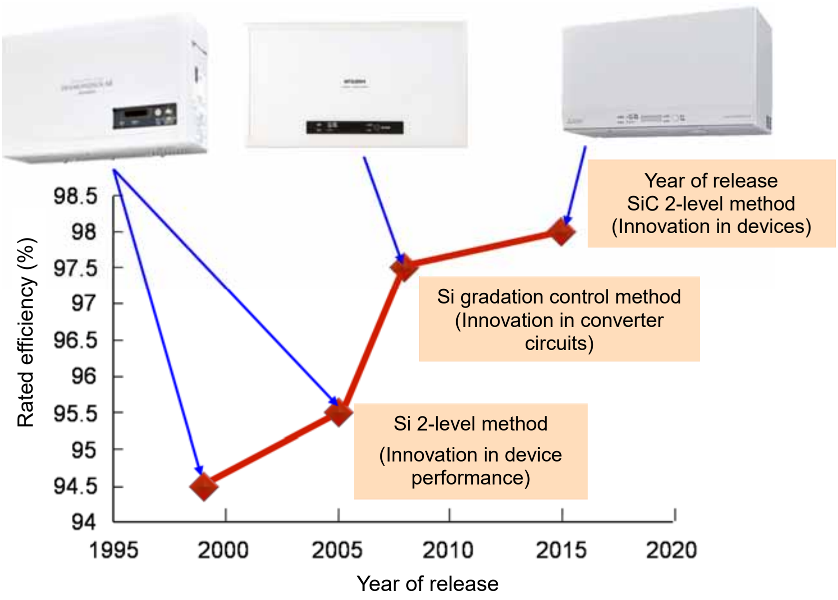

Fig. 4 Improvement of power conversion efficiency

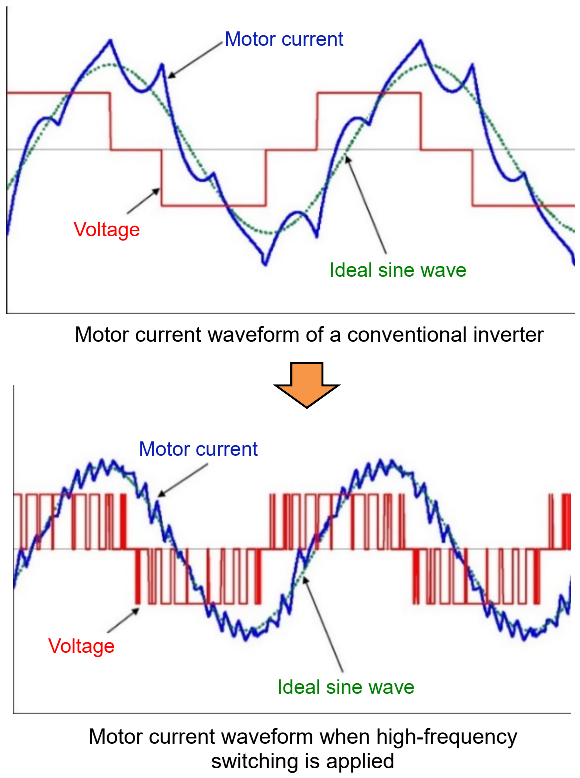

Fig. 5 Motor loss reduction using high-frequency switching

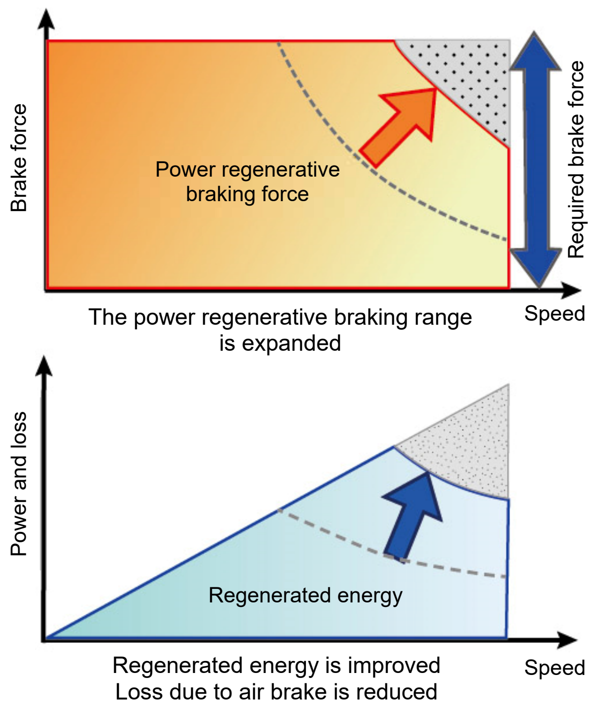

Fig. 6 Mechanical brake loss reduction

which enables high-frequency switching, so the motor currents include less harmonics (Fig. 5).

Next, we considered how to reduce the loss due to mechanical brakes. In the conventional method, the regenerative braking force decreases in the high-speed range, so mechanical brakes are used. With mechanical brakes, the vehicles' kinetic energy is converted into heat, causing a loss. Expanding the power regenerative braking range to the high-speed range can reduce the loss due to mechanical brakes (Fig. 6), but for this, the motor currents need to be increased, which increases the loss in inverters. Making the most of the SiC devices' low loss performance can reduce the increase of the loss in inverters and expand the regenerating brake range.

In 2011, Mitsubishi Electric commercialized inverters to which 1.7-kV power modules with SiC diodes and Si-IGBTs were applied for railway vehicles for DC 600-V/750-V overhead lines. Inverters with 3.3-kV SiC-MOSFETs for railway vehicles for DC 1,500-V overhead lines started commercial operation after the completion of running tests in 2014.[2] The energy-saving effect was

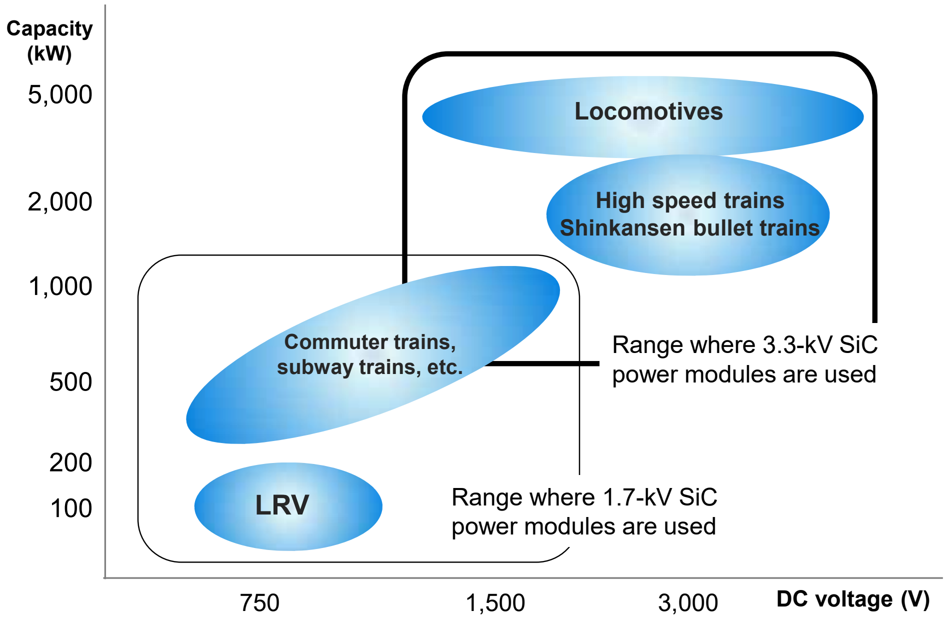

Fig. 7 SiC application range

tested for approximately four months: the energy saved was approximately 40% for the entire main circuit system compared to the previous models. In 2015, Mitsubishi Electric developed main converters with SiC for Shinkansen (bullet) trains. They were installed in Shinkansen trains and checked in running tests.(6)

As shown in Fig. 7, SiC devices have been applied in the railway field, from subway trains to Shinkansen trains, contributing to energy-saving in railway vehicle systems.

5. Conclusion

The practical use of SiC devices began as key energy-saving devices in power electronics devices after a long development period. We will introduce these devices to all sectors in power electronics including automobiles and high-voltage equipment (e.g. power electronics equipment for utility grids) to contribute to energy-saving on a global scale. To that end, technologies will be developed to further enhance the performance, and reliability of SiC devices and equipment to which such SiC devices are applied and to reduce the prices.

Part of this development was carried out under a contract with the New Energy and Industrial Technology Development Organization (NEDO) in Japan.

References

(1) Mitsubishi Electric Corporation News Release: Mitsubishi Electric to Release FY2011 Mitsubishi Electric Room Air Conditioners Kirigamine Move Eye Series, August 24, 2010
(2) Mitsubishi Electric Corporation News Release: Mitsubishi Electric to Supply Railcar Traction Inverter with All-SiC Power Module to Odakyu Electric Railway, April 30, 2014
(3) Mitsubishi Electric Corporation News Release: Mitsubishi Electric to Release New Power Conditioners for PV Generation Systems for Home Use in Japan, July 24, 2014
(4) Mitsubishi Electric Corporation News Release: Mitsubishi Electric to Release New Mitsubishi Electric Package Air Conditioners Mr. Slim Series, February 5, 2016
(5) Mitsubishi Electric Corporation News Release: Mitsubishi Electric to Release FY2017 Mitsubishi Electric Room Air Conditioners Kirigamine FZ and Z Series, August 23, 2016
(6) Mitsubishi Electric Corporation News Release: Mitsubishi Electric Installs Railcar Traction System with All-SiC Power Modules on Shinkansen Bullet Trains, June 25, 2015

Development of Energy-Saving Device for Hot Water Supply System in Europe

Authors: *Shigeru Iijima** and *Kazuhiro Shigyo**

Mitsubishi Electric Corporation developed a scale catching device to prevent scale deposits on our heating and hot water supply systems for Europe and evaluated their performance in a demonstration test. As a result, heating and hot water supply systems with scale catching devices and plate heat exchangers (P-HEXs) were introduced to the European market in 2014.

1. Background

In 2007, Mitsubishi Electric introduced air-to-water (ATW) systems for heating and hot water supply in the European market. ATW systems use heat pump outdoor units to efficiently convert heat in the air to heat energy that is used to heat water, and they have been remarked as energy-saving heat sources with reduced CO_2 emissions.

Europe, which is the main target of the ATW systems, has high calcium hardness in its tap water. As a result, calcium carbonate scale (hereafter, "scale") tends to adhere to the tap water circuits in heating and hot water supply systems, which can prevent the heat exchange and increase the pressure drop.

External P-HEXs for hot water supply were introduced into Mitsubishi Electric's ATW systems in a model change in 2014. As shown in Fig. 1, a P-HEX and pump were installed. The P-HEX heats the tap water in the storage tank with the circulating hot water through heat exchange. Small P-HEXs with high heat transfer efficiency have a low cost. However, when the heating surface of a P-HEX is covered with scale deposits, the cross section of the circuit becomes smaller and the increased pressure drop of the system may cause a pump failure or other faults.

Therefore, Mitsubishi Electric developed a scale catching device in order to introduce P-HEXs into ATW systems. This paper describes the structure of the scale catching device and the knowledge acquired through its development.

2. Structure of Scale Catching Device

Figure 2 illustrates the structure of the scale catching device. A copper pipe was used for the device and the inlet and outlet sections were reduced like a truncated cone to match the diameter of the peripheral pipes. Stainless steel spiral fibers were placed in the cylindrical section inside the copper pipe. In addition, the scale catching device was installed in the vertical direction as shown in Fig. 2. The water inlet was located at the bottom and the outlet was located at the top.

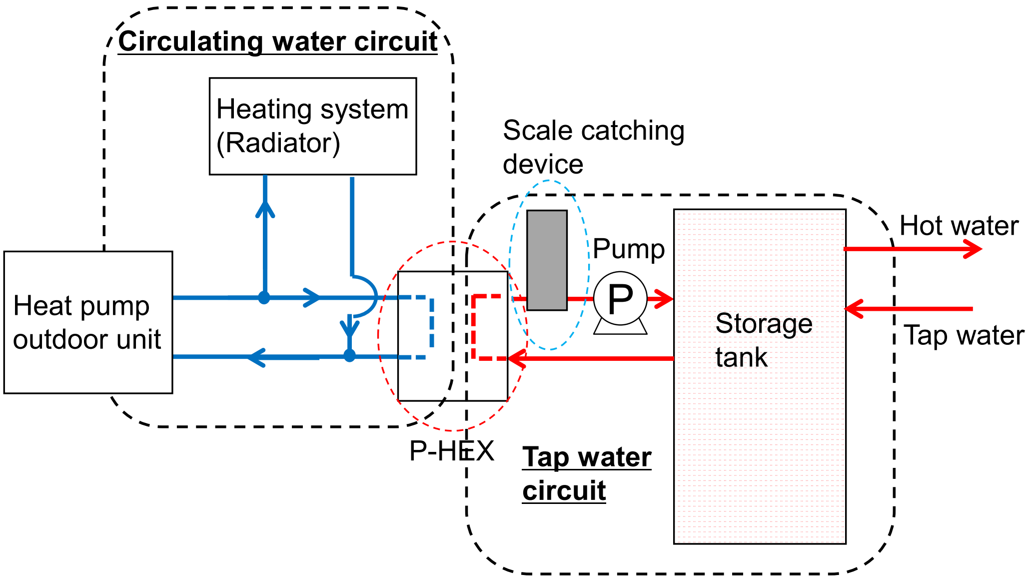

Fig. 1 Schematic of the 2014 ATW system

* *Advanced Technology R&D Center*

3. Scale Catching Device Demonstration Test

3.1 Test procedures

Demonstration tests using an actual ATW system were carried out to evaluate the performance of the scale catching device.

In the demonstration test, a circulation circuit with an ATW system was used. Simulated water was sent to the circulation circuit and continuous heating operation was carried out to reproduce the adhesion of scale to the P-HEX and the scale catching device. The water quality of the simulated water was similar to that of the hard tap water in Europe. The calcium hardness and M alkalinity were selected as parameters for the water quality. To maintain the water quality of the simulated water, it was replaced with newly prepared simulated water twice a week. In addition, the water quality was measured before and after each replacement and the weight of the scale deposits was calculated based on variations of the calcium hardness.

Usually, an ATW system is operated for approximately one hour per day to supply hot water for an ordinary household. However, in the demonstration test, the system was continuously operated to supply hot water for 24 hours per day to accelerate the deposit of scale. The longest operation time in the demonstration test was converted to a service period of 17 years for an ordinary household.

3.2 Test results

The scale catching device was tested for an operation time equivalent to the service period of 17 years for an ordinary household. The test results are shown below.

The total weight of the scale captured by the scale catching device was 190 g and the scale was evenly distributed on the stainless steel spiral fibers. On the other hand, the weight of the scale on the P-HEX was 3.0 g. Figure 3 shows the scale adhesion ratio for the heat exchanger and scale catching device to the weight of the scale on the entire system. Figure 3 shows that the scale adhesion ratio for the P-HEX was 1.0% to the weight of the scale on the entire system while that for the scale catching device was 81%. These results show that the scale catching device captured most of the scale, which reduced the weight of the scale on the P-HEX.

Figure 4 shows the changes in the weight of the scale on the P-HEX for the demonstration test time of the scale catching device. The values on the horizontal axis are the test times converted to the service periods for ordinary households. In addition, the slopes in the figure show the deposition rate of the scale on the P-HEXs. Installing a scale catching device decreased the deposition rate of scale on the P-HEX to 1/56, from 6.2 to 0.11 g/yr.

The above results show that the scale catching device is efficient and reduces the weight of the scale on P-HEXs. In addition, the device does not require maintenance during its service period. Therefore, Mitsubishi Electric introduced the ATW systems with P-HEXs and scale catching devices to the European market in 2014.

4. Mechanism of Scale Catching Devices

The mechanism of the developed scale catching device is described below. Figure 5 shows a model of the mechanism.

As shown in Fig. 5 (1), scale particles formed in the water enter the scale catching device. Particles that come into contact with the catching material get caught on the surface of the material. The catching material consists of 3D spiral fibers. The diameter of the openings in the spiral section is in the order of mm, which is sufficiently larger than the diameter of the scale particles (μm order) formed in the water. Therefore, the particles

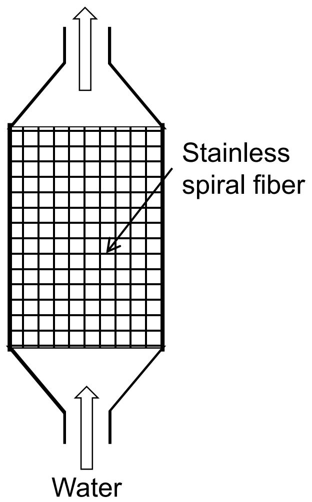

Fig. 2 Schematic of the scale catching device

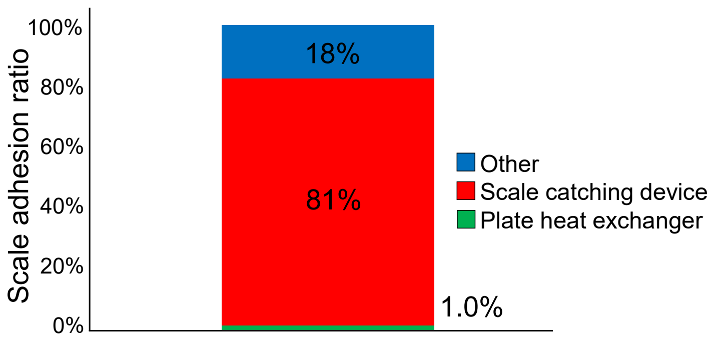

Fig. 3 Rate of scale deposition in the scale catching device demonstration test

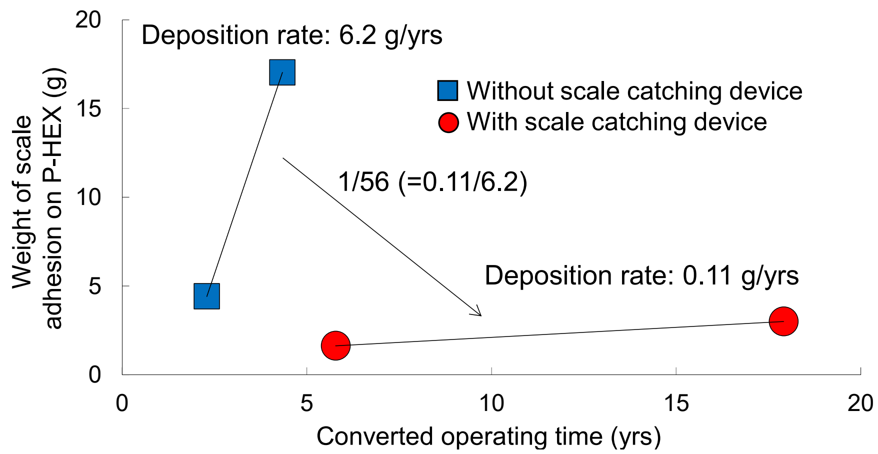

Fig. 4 Results of demonstration test (Comparison between with and without scale catching device)

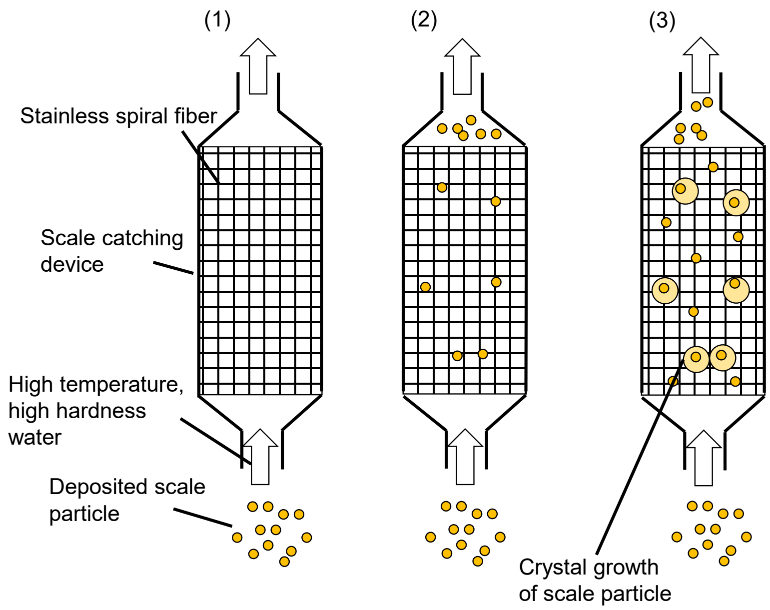

Fig. 5 Concept of scale capture process in the scale catching device

easily pass through the spiral section and come into contact evenly with the catching material at a certain probability. They get caught on the material that covers the area from the inlet to the outlet at a certain probability as shown in Fig. 5 (2). The high-temperature and high-hardness water flowing in the circulation circuit flows around the scale particles caught on the spiral fibers, as shown in Fig. 5 (3). Crystals start growing from the scale particles on the spiral fibers and they efficiently catch the scale components in the water.

As a future task, the performance of the scale catching device needs to be enhanced and the cost reduced.

Ultra-High Density Ozone Generation Technology

Authors: *Yoko Matsuura** and *Noboru Wada**

It is known that ozone with its highly oxidative effect can effectively treat excess sludge produced through wastewater treatment, but it is not widely used due to the high cost. Mitsubishi Electric Corporation proposes the application of an ultra-high density ozone generation system consisting of Mitsubishi Electric's exclusive high-efficiency ozonizer and ozone concentration storage device to significantly reduce the cost of sludge disposal.

1. Configuration of the Ultra-High Density Ozone Generation System

Figure 1 illustrates the configuration of the entire ultra-high density ozone generation system. The system consists of an ozonizer and an ozone concentration storage device. The ozonizer produces ozone gas using oxygen as the source gas and the ozone concentration storage device concentrates the ozone gas to an ultra-high density and supplies the concentrated ozone gas to the target.

2. High-Efficiency Ozonizer

Mitsubishi Electric's exclusive technology of narrow gap discharge has made it possible to efficiently generate high-density ozone. Figure 2 shows the running costs of Mitsubishi Electric's ozonizers in relation to the ozone density.(1) The running cost of an ozonizer is broadly divided into the electric power cost due to electric discharges and the cost of oxygen gas (raw material). At a certain ozone density, the cost becomes minimum due to the balancing of the two types of costs. The high-efficiency ozonizer can generate high-density ozone with electrical power consumption equal to that of the conventional ozonizer, as shown in the figure, so the running cost can be reduced compared to the conventional ozonizer. While the conventional ozonizer is most efficient at an ozone efficiency of 150 g/Nm^3, the running cost of the high-efficiency ozonizer becomes minimum when the ozone density is 210 g/Nm^3.

3. Ozone Concentration Storage Device

To concentrate ozone, the adsorption and desorption action of silica-gel is used. One of the characteristics of silica-gel is the selective adsorption of polar molecules, which means that it can selectively adsorb ozone molecules in ozonated gas. In addition, decompressing the silica-gel after adsorption allows preferential desorption of oxygen with weak adsorption power, so the ozone can be concentrated.

Operation of the ozone concentration storage device is described using Fig. 3. In the adsorption process (i), silica-gel packed in the adsorption tower selectively adsorbs ozone molecules. At that time, oxygen that was not adsorbed by the silica-gel is guided into the front section of the ozonizer by the circulation blower installed at the rear section of the adsorption tower, and this oxygen is reused as the source gas. In the concentration process (ii), the silica-gel in the adsorption tower that adsorbed ozone is decompressed

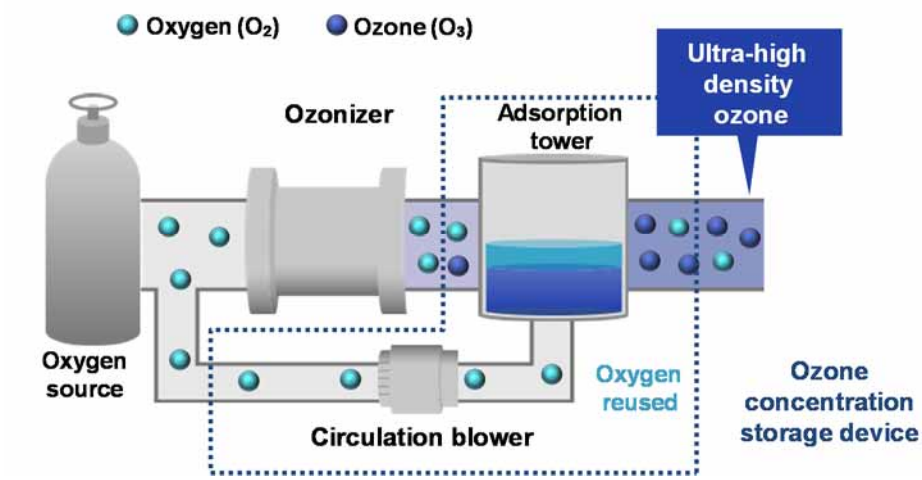

Fig. 1 Composition of ultra-high density ozone generation system

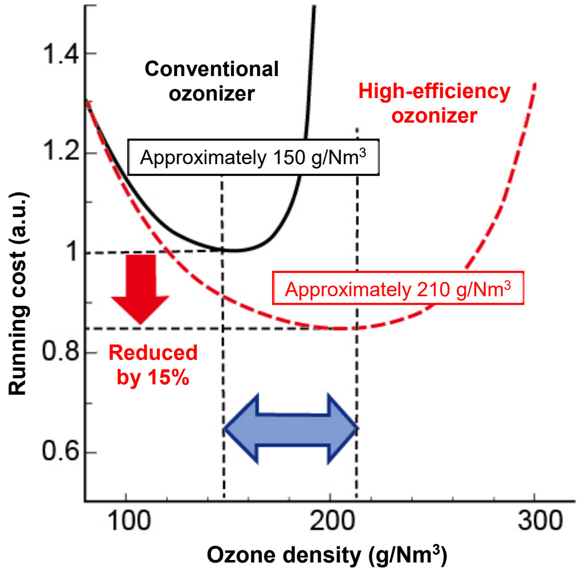

Fig. 2 Running cost as a function of ozone generation density

by suction to preferentially desorb oxygen. Through this process, the ozone adsorbed by the silica-gel is concentrated to ultra-high density. In the supply process (iii), ozone desorption is accelerated through gas displacement by oxygen purging to supply ultra-high density ozone gas.

The biggest advantage of using ozone concentration storage devices is that the oxygen cost can be significantly reduced by recycling the oxygen. In the conventional sludge disposal methods where only ozonizers are used, the percentage of oxygen that can be effectively used is approximately 10%. On the other hand, for example, when the density of ozone to be supplied to the sludge is increased to approximately 1,000 g/Nm3 by concentrating the ozone, the percentage of oxygen that can be effectively used is increased to approximately 50%. Therefore, when the same quantity of ozone is supplied, using an ozone concentration

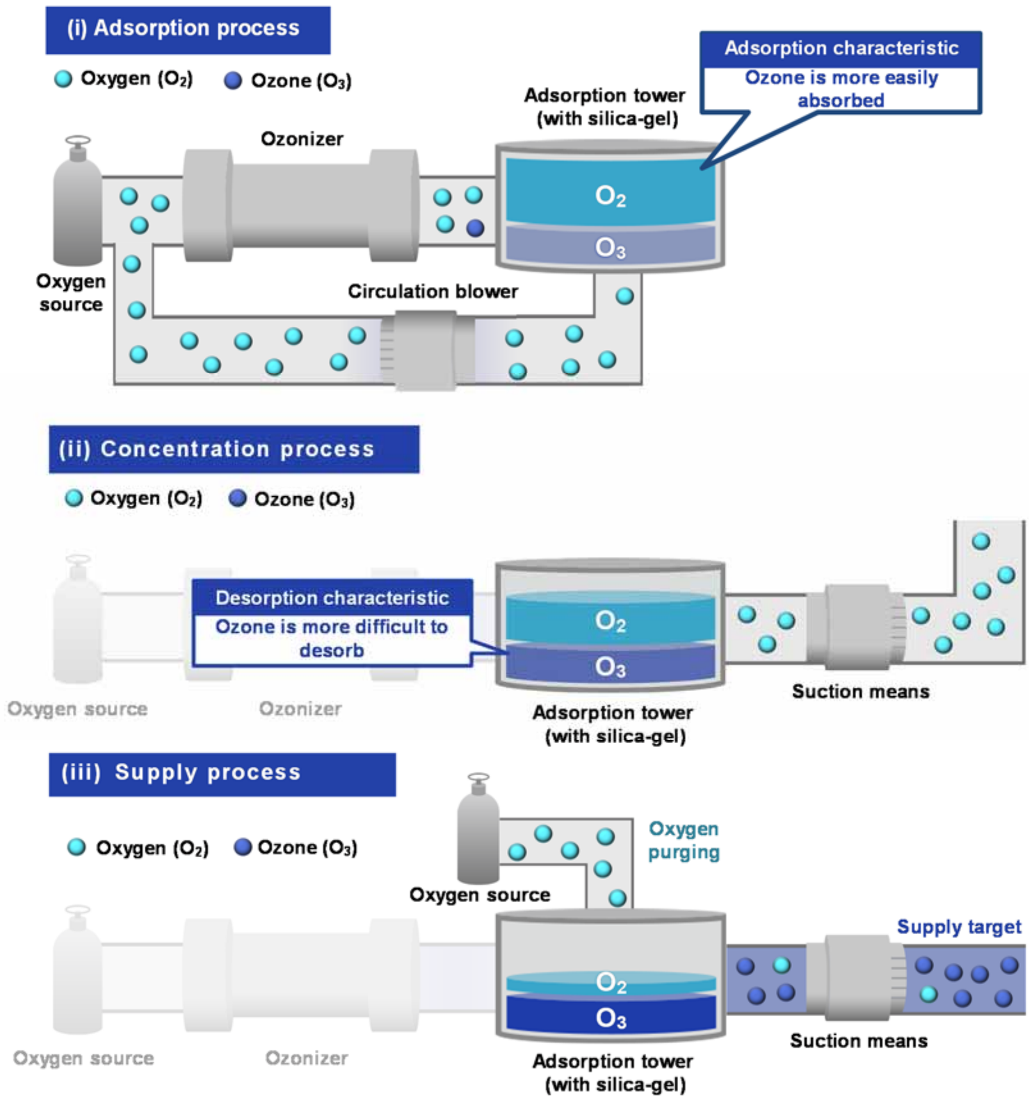

Fig. 3 Operation flow of ozone concentration storage device

storage device can significantly reduce the oxygen cost to 20% of that in the conventional method, allowing operation at a low cost.

4. Technology for Efficiently Generating Ultra-High Density Ozone

For Mitsubishi Electric's high-efficiency ozonizers, the ozone density at which the cost is minimum increases to 210 g/Nm^3 from the conventional 150 g/Nm^3. This highly efficient generation of high-density ozone further produces a synergy effect in combination with the ozone concentration storage technology.

Figure 4 shows the relationship between the pressure in the adsorption tower in the concentration process of ozone concentration storage devices and the output ozone density. The graph shows that an increase in the ozone density to be input to the ozone concentration storage devices in the adsorption process significantly changes the output ozone density's dependency on the pressure. When a high-efficiency ozonizer is used, the output ozone density increases up to 1,600 g/Nm^3, approximately 1.4 times that of the conventional ozonizer.

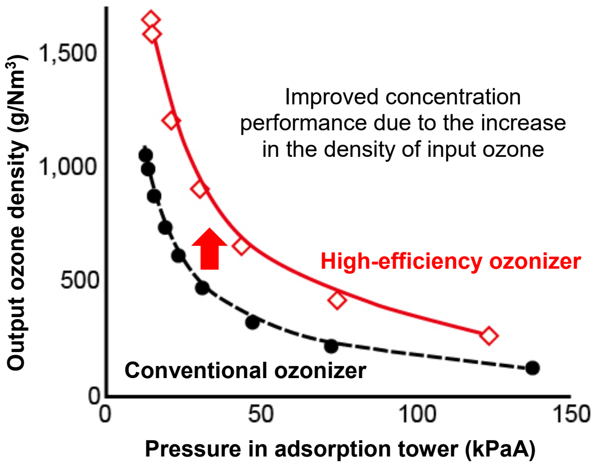

Fig. 4 Ozone desorption characteristics as a function of ozone input density

Applying high-efficiency ozonizer can supply higher density ozone to the ozone concentration storage device, so the quantity of oxygen consumed by the system is expected to be further reduced. As mentioned above, when the conventional type ozonizer is applied (input ozone density: 150 g/Nm^3, output ozone density: approximately 1,000 g/Nm^3), the oxygen cost can be reduced to 20% compared to operation with only a high-efficiency ozonizer. When a high-efficiency ozonizer is applied (input ozone density: 210 g/Nm^3, output ozone density: approximately 1,600 g/Nm^3), the cost can be significantly reduced to 12.5%. When making a trial calculation for the entire ultra-high density ozone generation system, applying a high-efficiency ozonizer and ozone concentration storage device can reduce the running cost to approximately 70% compared to operation with only an ozonizer.

Applying ultra-high density ozone to the process for reducing the volume of excess sludge can significantly reduce the cost of sludge disposal. This technology will help solve environmental problems with sludge disposal in China and emerging Asian countries.

Reference

(1) Noboru W., et al.: High Density Tubular Type Ozone Generator by Narrow Gap Discharge, Mitsubishi Denki Giho, 81, No.4, 59–62 (2007)

Material Modification Technologies for Plastics in Closed-Loop Recycling System

Author: *Yuichi Matsuo**

1. Introduction

Mitsubishi Electric Corporation has been promoting 3R (reduce, reuse, and recycle) with the aim of realizing sustainable resource circulation for a recycling-oriented society. For example, to recycle plastics contained in discarded household appliances, Mitsubishi Electric introduced lines with an annual throughput of approximately 15,000 tons at Green Cycle Systems Corporation, an affiliated company, in April 2010 to automatically sort polypropylene (PP), polystyrene (PS), and acrylonitrile–butadiene–styrene (ABS) copolymers. Mitsubishi Electric has realized "closed-loop recycling from household appliances to household appliances" in which PP, PS, and ABS are collected from plastics contained in discarded household appliances and sorted for recycling. They are then applied to household appliances such as air conditioners and refrigerators.(1) Figure 1 shows the closed-loop recycling flow that Mitsubishi Electric has established. To increase the number and types of parts to which closed-loop recycling is applied, material modification technologies are required for exterior parts and functional parts.

Recycling into only deep-colored (black and gray) interior parts used to be possible in closed-loop recycling.(2)(3) This paper describes the material modification technologies for plastics required to expand the scope of closed-loop recycling, in other words, to allow the recycling of applied parts into exterior parts and functional parts.

2. Expansion of Closed-Loop Recycling

This paper describes several material modification technologies for plastics toward the expansion of closed-loop recycling: Technology for lightening the color of recycled PP using color sorting equipment, technology for making recycled PS flame-resistant using the cabinets at the back of discarded TVs (discarded TV back cabinets), technology for removing contamination from the surface of recycled PP by polishing the surface of plastic flakes, and technology for improving the impact strength of recycled PP using low-cost tubes.

3. Material Modification Technologies for Plastics

3.1 Technology for lightening the color of recycled PP

Refrigerators, air conditioners, and washing machines are called white goods and they include many white parts. To increase the number and types of parts to which closed-loop recycling is applied, recycling into white (light color) parts is necessary. However, recycled flakes as shown in Fig. 1 are a mixture of white, black, gray, and other colors. When they are melted and

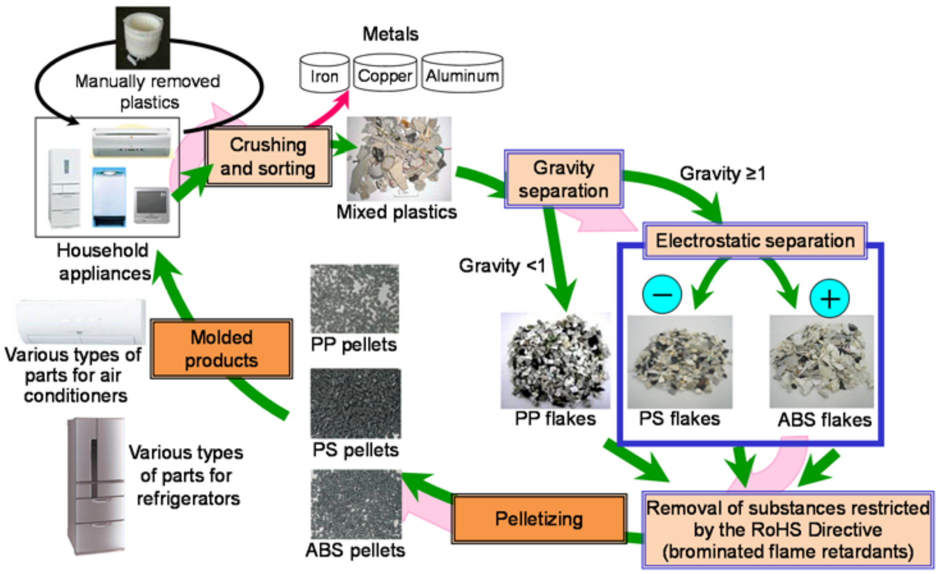

Fig. 1 Flow chart of closed-loop plastic recycling technologies

*Advanced Technology R&D Center

blended to make raw materials (turned into pellets), the color of the obtained pellets is gray (Munsell color value 5.2 for recycled PP). The Munsell color value shows the degree of brightness of a color based on the decimal system. Black (minimum brightness) is zero and white (maximum brightness) is ten on the scale.

One method for lightening the color of plastics is the addition of titanium dioxide, which works as a white colorant. However, adding titanium dioxide decreases the impact strength. Therefore, we decided to use color sorting equipment to separate the deep-colored flakes and lighten the color of the recycled PP. Separating the flakes with a Munsell color value equal to or smaller than the designated value (e.g., 7.6) from the recycled PP flakes makes it possible to obtain light-colored pellets with a Munsell color value of 7.9. In addition, adding a small amount of titanium dioxide can adjust the Munsell color value equal to or more than 8.0, which makes it possible to use recycled PP for light-colored parts.

Example parts that were closed-loop recycled by lightening the color of recycled PP are the partition walls between refrigerator cells, as shown in Fig. 2.

Fig. 2 Example of the parts of a refrigerator using light-colored recycled PP

3.2 Technology for making recycled PS flame-resistant

A large quantity of different types of flame-resistant parts are used around the substrate in household appliances, so making recycled plastics flame-resistant will likely increase the quantity of recycled plastics to be used. However, flame retardants are more expensive than resin. As higher flame retardancy is required, the amount to be added must be increased, which tends to increase the material cost. Therefore, in place of a flame retardant, Mitsubishi Electric decided to use the back cabinets of discarded TVs (only those with brominated flame retardants that are not prohibited by the RoHS Directive) collected by Hyper Cycle Systems Corporation (household appliance recycling plant). Table 1 lists the flammability properties of recycled PS and discarded TV back cabinets.

Although the flammability of the back cabinets varies from V-2 to V-0, it is equal to or higher than V-2, so adding them can reduce the amount of flame

Table 1 Flame-retardant characteristics of exterior parts of discarded televisions

Raw material / Physical property	Recycled PS	Discarded TV back cabinet
Flammability (UL94 standard)	Horizontal burning/1.5 mm Without self-extinguishing properties	V-2 to V-0/1.5 mm With self-extinguishing properties

retardant to be added. The flammability of parts around the substrate of an air conditioner needs to be V-0 at 1.5 mm. Therefore, for the developed flame-resistant recycled PS, recycled PS and discarded TV back cabinets were mixed in equal proportions so as to satisfy this requirement and then flame retardant was added. The amount of flame retardant added to the developed material could be reduced to half compared to a material that was made flame-resistant using only recycled PS without adding the discarded TV back cabinets, so the cost of flame-resistant recycled PS can be reduced.

Example parts that were closed-loop recycled by making recycled PS flame-resistant are parts around the substrate for an air conditioner, as shown in Fig. 3.

Fig. 3 Example of the parts of a room air conditioner using flame-resistant recycled PS

3.3 Technology for removing contamination from the surface of recycled PP

Regarding contamination of recycled plastics, even a very small amount remaining on the surface can become the starting point of a fracture and deteriorate the impact strength. In addition, if the contamination comes into contact with the surface of molded products, the design will be regarded as inferior. We thought it might be possible to remove the contamination by polishing the surfaces of the flakes. We used the light-colored recycled PP flakes separated as described in Section 3.1 and a dry-friction polisher to polish the surfaces (zero to two times). A specified quantity of antioxidant was added to the flakes for long-term heat-resistance to prepare test samples for evaluation. Table 2 lists the relationship between the area of contamination and the amount of contamination by the number of times of polishing the surface of the light-colored recycled PP. The amount of contamination on

Table 2 Amount of contamination on the recycled PP plate

Contamination area (mm^2) \ Average amount of contamination (pieces)		Number of times of polishing the surface (times) 0	1	2
Invisible domain	<0.05	17	11	9
Visible domain	0.05–0.10	1	0	0
	>0.10	0	0	0
Total contamination in the visible domain (pieces)		1	0	0
Reduction rate of contamination (%)		—	100	100

the test samples (observation area: 7,200 mm^2) was calculated by area while referring to the dirt comparison chart (National Printing Bureau, Japan).

With a larger number of polishing times, the amount of contamination reduced and the contamination area tended to be smaller. Polishing the surface twice could reduce the amount of contamination in the visible domain to zero from one (100%).

Next, Table 3 lists the heat life of light-colored recycled PP. The threshold of the life was determined as 75%[(4)] of the mechanical property retention (ultimate tensile strength). The long-term heat life at 140ºC was calculated. As the number of times of polishing the surface of light-colored recycled PP increases, the heat life becomes longer, so a clear correlation was seen between the heat life and the amount of contamination. Polishing the surface of recycled PP to remove contamination works well to improve the design and heat life, so we are confident that the method can be applied to exterior parts.

Table 3 Heat life of light-colored recycled PP at 140°C

	Number of times of polishing the surface (times) 0	1	2
Heat life (h)	1,310	1,723	2,295

3.4 Technology for improving the impact strength of recycled PP

The exterior parts for household appliances require sufficient strength to withstand falling impact. A conventional method for improving impact strength is the addition of agents that are highly compatible with PP (e.g., thermoplastic polyolefin (TPO)). We have improved the impact strength using tubes (from daily necessaries) made of low-cost recycled plastics with excellent impact strength. The main component of the tubes is low-density polyethylene (LDPE) and the cost is approximately one-fifth that of TPO (as of June 2017).

To check how the tubes would improve the impact strength, the percentage of tubes to be added was adjusted such that the Charpy impact strength became approximately twofold (140 kJ/m^2) that of recycled PP. The results in Table 4 show that when the additive rate (10 wt%) of the tubes is the same as that of TPO, the Charpy impact strength of recycled PP can be doubled.

Adding tubes for which the main component is LDPE to recycled PP can enhance the impact strength at low cost, so we are confident that the method can be applied to parts requiring impact strength.

Table 4 Impact strength of modified recycled PP

Physical property \ Raw material	Recycled PP	High-impact recycled PP: Tube 10wt% added	High-impact recycled PP: TPO 10wt% added
Charpy impact strength (kJ/m^2) (without notch)	70	133	136

4. Conclusion

Mitsubishi Electric has been actively working on closed-loop recycling of plastics collected from discarded household appliances. As a result, we successfully applied closed-loop recycled plastics to our Kirigamine MSZ-Z series of room air conditioner and MR-JX, WX, B, RX, and MX series of refrigerators. We will continue developing material modification technologies for recycled plastics to further increase the quantity of recycled plastics in use.

References

(1) Matsuo Y., et al.: High-purity separation and modification technologies for recycled plastics from waste household appliances, Seikei-Kakou, Vol. 23, No. 10, 599–604 (2011).
(2) Tsukasa T., et al.: Closed-Loop Recycle System of Plastics in Household Electrical Appliances, Mitsubishi Denki Giho, Vol. 84, No. 6, 35–38 (2010).
(3) Iseki Y., et al: Most-Advanced Recycling Technologies for Home Electrical Appliances, Mitsubishi Denki Giho, Vol. 87, No. 9, 51–54 (2013).
(4) Kabuki K.: Reliability Design Technology for Structural Plastic Mold Goods, Japan Plastics, Vol. 53, No. 2, 91–93 (2002).

MITSUBISHI ELECTRIC CORPORATION